Introduction

This is the annual scientific report over 2015 of the "Johann Bernoulli Institute for Mathematics and Computer Science (JBI)".

Some statistics

In 2015 the institute had ... tenured scientific staff members and ... support staff members. .... PhD candidates were enrolled, including ... Ubbo Emmius scholarships for students from abroad, .... PhD positions funded by the Netherlands Organisation for Scientific Research (NWO) and ... PhD positions funded by the European Union, industry or other external funding. Also .... postdocs worked at the institute of whom 2 funded by NWO.

... doctoral dissertations were successfully defended.

A total of .... journal papers, ... (contributions to) books, ... refereed contributions to conference proceedings and ... other professional publications were published.

Members of the institute served as editors-in-chief, associated editors or members of the editorial boards of international journals and book series.

The institute was visited by .... foreign scientists.

Personalia

In September 2015, Jiří Kosinka was appointed as a tenure track assistant professor in the research group Scientific Visualization and Computer Graphics. Jiří obtained his PhD from Charles University in Prague, Czech Republic, in 2006. From 2006 to 2014, he held post-doctoral positions in geometric modelling at Johannes Kepler university in Linz, Austria, at the University of Oslo, Norway, and at the University of Cambridge, UK. From 2014 to 2015, he was a senior research associate and an EPSRC IAA KT Fellow at the Computer Laboratory, University of Cambridge. His research focuses on curve and surface representations in geometric modelling and computer graphics.

In September 2015, Mircea Lungu was appointed as tenure track assistant professor in the research group Software Engineering. He obtained his PhD degree in 2009 from the University of Lugano in Switzerland. Between 2010 and 2015 he was a post-doctoral research fellow at the University of Bern in Switzerland. His research is in analyzing software systems and their evolution to improve the tools and processes of software engineering. He is also researching tools and techniques that accelerate the
way people learn.

Prof. dr. J.B.T.M. Roerdink
Scientific Director
Johann Bernoulli Institute for
Mathematics and Computer Science
Contents
Governing body and support staff 2015

Scientific director
Prof.dr. H.W. Broer

Scientific Board
Prof.dr. J.B.T.M. Roerdink – chairman
  (professor of computer science, RUG)
Prof.dr. M. Aiello
  (professor of computer science, RUG)
Prof.dr. E.C. Wit
  (professor of mathematics, RUG)
Prof.dr. G. Vegter
  (professor of mathematics, RUG)

Management team
J. de Jong-Schlukebir (controller) 0.6
R.G.A. Gmelig Meyling (controller) 0.4

International Advisory Panel (IAP)
Prof dr H.A. van der Vorst (chair)
Prof dr J. van Mill
Prof dr G. Grimmett
Prof dr M. Lenzerini
Prof dr F. Vaandrager

Administrative staff

Secretary of Research Institute
H.M. Steenhuis 0.5
D.J. Hansen 0.8

Secretaries
E.D. Elshof 1.0
I. Schelhaas 0.8
Address:

 Postal address:  
P.O. Box 407  
9700 AK Groningen

 Visiting address:  
Bernoulliborg  
Nijenborgh 9  
9747 AG Groningen  
The Netherlands

 Tel  : 050-3633973  
Fax  : 050-3633800  
email: jbibureau@rug.nl  
www: http://www.rug.nl/jbi
## List of scientific programmes and tenured scientific staff

### Mathematics

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<th>Programme</th>
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<td>Programme 1</td>
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Computer Science

Programme 5  :  Distributed Systems  
Prof.dr. M. Aiello  
Dr. A. Lazovik  
Dr. D. Bucur  

Programme 6  :  Fundamental Computing Science  
Prof.dr. G.R. Renardel de Lavalette  
Dr. J.A. Pérez  

Programme 7  :  Intelligent Systems  
Dr. M. Biehl  
Prof.dr.sc.techn. N. Petkov  
Dr. M.H.F. Wilkinson  

Programme 8  :  Scientific Visualization & Computer Graphics  
Dr. H. Bekker  
Prof.dr. J.B.T.M. Roerdink  
Prof.dr. A. Telea  

Programme 9  :  Software Engineering  
Prof.dr. P. Avgeriou  
Dr. A. Ampatzoglou
Research schools

Researchers of the JBI participate in the following research schools:

1. **Dutch Research School in Mathematics (WONDER)**
   - Coordinating institution: University of Utrecht
   - Director: Prof.dr. J.E. Frank
   - Participating JBI programme(s): DS&MP, Geometry

2. **Dutch Institute of Systems and Control (DISC)**
   - Coordinating institution: Delft University of Technology
   - Director: Prof.dr.ir. P.M.J. van den Hof
   - Participating JBI programme(s): SCAA

3. **The J.M. Burgers Centre for Fluid Dynamics**
   - Coordinating institution: Delft University of Technology
   - Director: Prof.dr.G.J.F. van Heijst
   - Participating JBI programme(s): CM&NM

4. **Institute for Programming Research and Algorithmics (IPA)**
   - Coordinating institution: University of Eindhoven
   - Director: Prof.dr. W.J. Fokkink
   - Participating JBI programme(s): SE

5. **Advanced School of Computing and Imaging (ASCI)**
   - Coordinating institution: Delft University of Technology
   - Director: Prof.dr.ir. H. Bal
   - Participating JBI programme(s): IS, SV&CG

6. **School of Behavioral and Cognitive Neurosciences (BCN)**
   - Coordinating institution: University of Groningen
   - Director: Prof.dr. R.A. Schoevers
   - Participating JBI programme(s): SC&CG
1. **Algebra**

**Group leader:** Prof.dr. J. Top

**Tenured staff (JBI members)**

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<td>Dr. A.V. Kiselev</td>
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**Emeritus**

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**PhD students**

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<td>S. Ringers</td>
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<tr>
<td>T.T. Nguyen</td>
<td>VIED (Vietnam)</td>
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**Guests**

- M. Kronberg, Oldenburg, Germany
- J.S. Chahal, Provo, USA
1.1 Research Program

1. **Number theory and Algebraic geometry**
   Arithmetic properties of elliptic curves over a number field or a function field, like the rank and generators of the Mordell-Weil group, are the subject of study. Also work is done on applications to Diophantine equations, coding theory and arithmetic algebraic geometry; in particular a study of the number of rational points on curves over finite fields. Moreover, the history and the algebraic geometry of various series of geometrical models is studied.

2. **Geometry of differential equations**
   This concerns algebraic, analytic (e.g., multizumability) and algorithmic aspects of linear differential and linear difference equations; differential Galois theory and its applications, in particular to symbolic (algorithmic) solvability of equations; (Lie) symmetries of non-linear differential equations; isomonodromy and in particular the six Painlevé equations; nonlinear first order equations.
   Moreover, developing and applying algebraic, geometric, and algorithmic techniques to nonlinear partial differential equations of Mathematical Physics arising, in particular, from the basic models for the geometry of fundamental interactions. This research centers around the construction of the Schouten and Poisson brackets and aims at the BV- and deformation quantisation of such models.

1.2 Overview of scientific results

*J. Top*

With M. van der Put, Top finished a project on applying the geometry of isomonodromic families of certain differential modules, to the theory of Painlevé equations. Joint papers by Top and Van der Put appeared in the Journal of Nonlinear Mathematical Physics and also in SIGMA. Moreover, Van der Put wrote a survey on applications of the Stokes phenomenon in this theory, which was submitted to a special issue of SIGMA dedicated to Algebraic Methods in Dynamical Systems.

Top continued his collaboration with M. van der Put on first order (nonlinear) differential equations. Two papers on this are accepted for publication in the Journal of Symbolic Computation (available online in 2014, in print in 2015): a joint one with L.X. Chau Ngo (Quy Nhon University, Vietnam) and K.A. Nguyen (HUTECH, Ho Chi Minh City, Vietnam) motivated by older work of Van der Put and Muntingh, and a second one on positive characteristic phenomena.

Top continued his collaboration with J.S. Chahal (Provo, Utah). A joint paper with him on “albime triangles” was accepted by Expositiones Math., and a second more expository paper by Nieuw Archief voor Wiskunde (both papers will appear in 2015). A third joint paper is scheduled to be finished and published in Rocky Mountain J. of Math., in which (several years after its submission) in 2014 also a joint paper by Chahal, Soomro, and Top on the Hasse inequality appeared.
With Josef Schicho (Linz), Top published a paper on algebraic approaches to the game FlipIt in the Clay Mathematics Proceedings, Volume 20.

Top participated in DIAMANT workshops, and in a North German Algebraic Geometry Seminar (Hamburg) where he gave an invited lecture on K3 surfaces.

During 2014, several researchers visited our group: M. Kuwata (Tokyo, Japan; February), M. Kronberg (Oldenburg, Germany; several days in the Spring), A.G. Nikitin (Kiev, Ukraine; June), D.A. Leites (Stockholm, Sweden; June).

**A. Kiselev**
Via an in-depth analysis of the geometry of iterated variations, Kiselev completed the intrinsic self-regularisation of the Batalin–Vilkovisky (BV) formalism for quantisation of gauge systems.

Continuing another line of research (joint with A. Krutov), Kiselev realised the geometry of zero-curvature representations for kinematically integrable nonlinear models in terms of the BV master-functional; this result, which creates a novel approach to quantisation of systems that are integrable by the inverse scattering, is published in J. Nonlin. Math. Phys. in 2014. Building on the earlier results which are joint with J. van de Leur (2011), Kiselev revealed a classical Lie algebroid structure on the quantum BV-cohomology groups that arise for the non-Abelian variational Lie algebroids (see above) or for gauge-invariant models in Quantum Field Theory.

In June, A.O. Krutov defended his PhD thesis in Groningen, on a project proposed and supervised by Kiselev (promotor: Top).

**A.S.I. Anema**
Anema finished his work on the Hesse pencil. He is now finishing the last subject intended to be part of his PhD thesis: a description of the simple isogeny factors appearing in some construction of J.-F. Mestre.

**S. Ringers**
Sietse Ringers finished his research concerning the variational Schouten brackets on jet spaces, and on deformation quantization. The part of his PhD thesis discussing this work, is now finished. Ringers started in May 2014 a new research topic, co-supervised by J.H. Hoepman (RU Nijmegen), on anonymous credential protocols in cryptography. This quickly led to some results, and papers on this (in part jointly with people from Nijmegen) are being finished.

**Thien Phan Van**
In September 2014 Thien Phan Van left our group, after being here as a postdoc for a year. He completed a manuscript on so-called finite sets of fat points and their invariants, which will now be submitted for publication.

**Nguyen Tu Thinh**
Tu continued his PhD research in our group on so-called midpoint surfaces. He proved various results
on these, and a manuscript is in preparation. Tu also participated in some workshops: DIAMANT (Arnhem), NoGAGS (Hamburg), and Moduli/arithmetic of K3s (Schiermonnikoog).

**Eduardo Ruiz Duarte**
Eduardo joined our group in September, on a PhD project dealing with hyperelliptic curves and applications to cryptography and number theory. He began a project of extending results by Soomro and Top to the case of genus two curves.

**Andrey O. Krutov**
Andrey joined our group in February in order to complete his PhD project which he had been working on at Ivanovo State Power University for several years supervised by Kiselev. The main topic of this is Gardner’s deformations for a number of hierarchies of partial differential equations. The thesis was completed here, and successfully defended in June.

### 1.3 Research subjects

**A.S.I. Anema:** elliptic curves and surfaces.

**E. R. Duarte:** Hyperelliptic curves, applications to cryptography and number theory.

**A. Kiselev:** Geometry of differential equations, integrable systems, geometry of fundamental interactions, BV- and deformation quantisation, brackets, mathematical physics.

**A.O. Krutov:** Gardner’s deformations and zero curvature representations.

**T.T. Nguyen:** Midpoint surfaces and cubic surfaces.

**S. Ringers:** Geometry of differential equations, brackets, mathematical physics.

**J. Top:** Arithmetical algebraic geometry, in particular: elliptic curves and surfaces, curves over finite fields and over function fields, history of geometrical models, Galois representations, number theory; differential equations.

**Th. Ph. Van:** geometry of sets of fat points.

### 1.4 Publications

**Dissertations**

Articles in peer-reviewed refereed journals


Chapters in books


Articles in peer-reviewed refereed proceedings


1.5 External funding and collaboration

*External funding*

The Ph.D. position of Ane Anema (2012–2015) is funded by NWO via the cluster DIAMANT.

The PhD project of T.T. Nguyen and the postdoc year of Th.Ph. Van are funded by the Lotus program (Vietnam).

*External collaboration*

See 1.2.
1.6 Further information

Top served on two PhD evaluation committees: for Willem Jan Palenstijn (Leiden, supervisor Peter Stevenhagen), and for Gergely Alpár (Nijmegen, supervisor Bart Jacobs).

Top and his PhD students are involved in the North German Algebraic Geometry Seminars (NoGAGS, a collaboration between Göttingen, Hannover, Berlin, Hamburg, Bremen and Groningen), and in the NWO-cluster DIAMANT. Top and T.T. Nguyen attended the NoGAGS meeting in Hamburg, where Top presented a lecture. Ringers lectured in a DIAMANT intercity seminar day organized by our group in February, and he presented an overview lecture on anonymous credentials in Groningen in October.

Top gave several lectures popularizing math, e.g., for the Groningen “college caroussel”, as invited speaker of the symposium “In perspective” organized by the Nijmegen mathematics student organization DESDA, during the Groningen mathematics alumni day, as invited speaker at a national symposium “Wiskunde en geloof” in Veenendaal, and at the annual day for high school mathematics teachers organized at the RuG. Moreover (as in previous years) he organized the regional math olympiad at the RUG, followed by several training sessions for gifted high school children. Finally, Top presented some mathematics colloquium lectures, in Utrecht and in Groningen.

Kiselev gave talks at

- MPIM (Bonn, Germany) on 1 April 2014,
- Mathematical Physics seminar (Institut de Mathématiques de Bourgogne, Dijon, France) in May,
- Department of Applied Research seminar (Institute of Mathematics NAS Ukraine, Kiev), Mathematical Physics seminar (Faculty of Mathematics and Mechanics, Taras Shevchenko National University, Kiev, Ukraine), Complex analysis seminar (Steklov MI RAS, Moscow, Russia), and I. E. Tamm Theoretical Department seminar (Lebedev Physical Institute RAS, Moscow, Russia) in October,
- Dynamical Systems seminar (Johann Bernoulli Institute for Mathematics and Computer Science, University of Groningen, The Netherlands) and seminar on Lie algebras, Riemannian surfaces and Mathematical Physics (Independent University of Moscow, Russia) in December.

Through the entire year 2014, Kiselev himself was the co-organizer of the JBI Math colloquium.

Kiselev is involved in the EC project GECOM (New geometrical and cohomological methods in non-linear PDEs with applications to mechanics and theoretical physics), and in the NWO-cluster GQT.
2. *Computational Mechanics and Numerical Mathematics*

**Group leader:**
Prof.dr.ir. R.W.C.P. Verstappen

**Tenured staff (JBI members)**

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<td>Prof.dr.ir. R.W.C.P. Verstappen</td>
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**Emeritus**
Prof.dr. A.E.P. Veldman

**Postdocs**

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**PhD students**

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<td>M.H. Silvis MSc (supervisor: Verstappen)</td>
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### PhD students

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2.1 Research Program

With the continuing progress in numerical mathematics and computer technology, the impact of computer simulation on society is rapidly increasing. Our group specializes in numerical algorithms for the simulation of fluid dynamics and transport phenomena (Computational Fluid Dynamics CFD). On the one hand research is focussed on basic advancement of numerical algorithms; on the other hand - through extensive cooperation with external research groups - these methods are made available to advance knowledge in other (applied) areas of science and technology.

**Turbulence**  In most applications, the Navier-Stokes equations do not provide a trackable model for turbulent flow. Therefore, finding a coarsed-grained description is one of the main challenges to turbulence research. A most promising methodology for that is large-eddy simulation (LES). The basic idea of LES is that the large scales of motion remain virtually unchanged, whereas the calculation of all small-scale turbulence for which numerical resolution is not available is avoided. This keeps the computational effort within reasonable limits, but a price is paid in terms of accuracy. To improve the accuracy, we perform research into scale-truncation models for large-eddy simulation. The mathematical rationale behind our approach focusses on approximations that preserve the underlying PDE structure as well as on regularizations that truncate the nonlinear interactions with small scales of motions.

**Free-surface flow and fluid-structure interaction**  The main free-surface flow research concerns application in maritime and coastal engineering. Numerical simulation methods are developed to predict hydrodynamic wave loading on moving and/or deforming offshore platforms (fluid-structure interaction) and coastal structures. The basic tool is the in-house developed simulation method ComFLOW. Fluid-structure interaction is also central in our research concerning bio-medical fluid dynamics (with UMCG), like flow in elastic arteries or in the human ear (cochlea).

**Sparse-matrix solvers**  The repeated solution of large systems of equations in most simulation methods makes the quest for improved matrix solvers another major research area. In-house a number of multilevel preconditioners have been developed. For general systems, we designed MRILU (Matrix renumbering ILU) and VBARMS (Variable Block Algebraic Recursive Multilevel Solver). MRILU can be applied to discretizations of coupled PDEs. It particularly performs well for convection-diffusion equations. VBARMS almost automatically exploits any available block structure during the factorization, achieving increased throughput during the computation and improved reliability on realistic applications. Additionally, the special purpose multilevel preconditioner HYMLS (Hybrid Multilevel solver) is designed to meet the incompressibility constraint efficiently. Both VBARMS and HYMLS are parallelized using MPI. Typical application areas of the solvers are fluid flow, structural problems, electro magnetics and bifurcation analysis.
**Bifurcation analysis**  Here the emphasis is on numerical methods for investigating the bifurcation behaviour of fluid flow, also in the presence of noise. Applications range from academic to real world problems like the lid-driven cavity problem and the global ocean circulation, respectively.

### 2.2 Overview of scientific results

In cooperation with NLR a PhD project (Rozema) was completed in which low-dissipation discretizations for subsonic turbulent flows and minimum-dissipation models for LES are developed. In a parallel project (Bandringa) the low-dissipation methods and models are extended to unstructured grids, in cooperation with MARIN. The joint work with Stanford University (Center for Turbulence Research) has resulted into a journal paper. The PhD project on scale truncation models for LES (Silvis) has led to a list of requirements that a subgrid model should satisfy in order to possess the symmetry and conservation properties of the Navier-Stokes equations. Results have been presented at various international conferences.

The previous phase of the STW-funded free-surface project on hydrodynamic wave loading has been formally finalized with the release of ComFLOW version 3.9.5 In the new phase, called ComMotion, several extensions to the method are being designed featuring the interaction with moving and deforming objects. For the numerical coupling between solid-body dynamics and fluid dynamics a quasi-simultaneous class of methods is developed that is stable for any added-mass ratio. With the same approach, the coupling with elastically deforming objects can be simulated in a numerically stable way. Further, the influence of current is studied; an important ingredient is an absorbing boundary condition, generalizing the work of Duz (who defended his PhD thesis). Finally, local grid refinement and parallelization enhance the simulation efficiency.

![Numerical simulation (with local grid refinement) of a lifeboat falling into a breaking wave.](image)

Figure 1: *Numerical simulation (with local grid refinement) of a lifeboat falling into a breaking wave.*

In the research on sparse-matrix solvers three new parallel block solvers are produced, based on the block Jacobi, the restricted additive Schwarz method and the Schur complement preconditioners. Their performance was assessed for solving turbulent Navier-Stokes equations on a suite of two- and three-dimensional test cases, among which the DPW3-W1 wing configuration of the third AIAA
Drag Prediction Workshop. The results show that the solver may be noticeably more robust than other state-of-the-art solvers for comparable memory usage. Additionally, a new algebraic recursive multilevel sparse approximate inverse preconditioner has been developed for solving general systems of linear equations. This solver combines recursive combinatorial algorithms, multilevel mechanisms and overlapping techniques to maximize sparsity in the approximate inverse factors and to reduce the overall factorization costs. In a joint project with the University of Chengdu, China, a new quasi-minimal residual variant of nonsymmetric Krylov methods has been developed.

In the numerical bifurcation analysis the Jacobi-Davidson QR method available in the software package PHIST has been extended to cases with singular mass matrices and nonsymmetric system matrices. Next we focussed on the solution of a generalized Lyapunov equation which results from a study into the influence of noise on the state of an ocean model. The system matrix is sparse and huge. Moreover the occurring mass matrix is singular, which leads to additional complications. A first variant has been made that is able to solve a 2D problem more efficient than methods proposed in the literature. Results of these tests will be compiled into a paper. Currently the method is improved to make it run efficiently for 3D ocean models.

2.3 Research subjects

S. Baars: Efficient solution of generalized Lyapunov equations.
H.J. Bandringa: simulation of complex flows in maritime applications.
B. Carpentieri: numerical linear algebra, Krylov subspace methods, parallel multilevel solvers, electromagnetics, cardiac modeling.
X.M. Gu: Krylov subspace methods for solving non-Hermitian linear systems with application to fractional differential equations.
D.J. Kort: numerical flow simulations with local grid refinement
S. Kotnala: efficient solution of stochastic PDEs.
R. Luppes: two-phase flow modeling for maritime applications.
P. van der Plas: local grid refinement for free-surface flow simulation.
W. Rozema: detailed numerical simulation of turbulent flow.
J.H. Seubers: interaction between extreme waves and floating bodies.
Z. Li Shen: matrix solvers for Markov chains problems.
M.H. Silvis: models for the larger eddies in turbulent flow.
W. Song: numerical linear algebra for bifurcation analysis on high-performance computers.
D.-L. Sun: numerical linear algebra methods in computational nanophotonics
A.E.P. Veldman: modeling and simulation of fluid flows in engineering applications, free-surface flows, fluid-structure interaction.
**R.W.C.P. Verstappen:** mathematics of Computational Fluid Dynamics (CFD), modeling and simulation of turbulence.

**F.W. Wubs:** preconditioners for sparse systems and Lyapunov equations in CFD; application to stability and bifurcation analysis and the study of the influence of noise on bifurcation points.

### 2.4 Publications

#### PhD defenses


#### Articles in scientific journals


– R. Wemmenhove, R. Luppes, A.E.P. Veldman and T. Bunnik. Numerical simulation of hydro-

**Articles in conference proceedings**


– R. Verstappen, A minimum-relaxation model for large-eddy simulation, In *Proc. 4th Int. Conf. on Turbulence and Interactions (TI2015)*, November 2-6, 2015, Cargese, France.

### 2.5 External funding and collaboration

Most of our PhD projects are being funded externally from national and international resources. The PhD-students with an Ubbo-Emmius funding perform two years of research at RUG and two years at a partner institute. We summarize the situation:
The ComMotion project concerning the interaction between extreme waves and moving or deforming objects, in cooperation with TU Delft and MARIN, is funded by STW, the Topsector Water and several offshore companies. Its budget is around 1 MEuro. Researchers involved are Veldman, Van der Plas and Seubers.

The STW Perspectief programme granted the SLING proposal, which aims to study sloshing of liquid natural gas (LNG) in large cargo tanks onboard LNG carriers. The project is a cooperation with TU Delft, TU Eindhoven, University Twente and MARIN, with a total budget of more than 5 MEuro (3.4 MEuro funded by STW and 1.9 MEuro by the European maritime industry). As part of SLING, a PhD-project at RuG will start in 2016.

Most of the turbulence research is funded by the Free Competition of NWO EW (Silvis), the Netherlands Enterprise Agency (RVO), Topsector Water (Bandringa) and the Ubbo Emmius Fund (Rozema). The exchange with UPC Barcelona is mainly paid by the spanish Ministerio de Economia y Competitividad and the Generalitat de Catalunya. Silvis and Verstappen received a grant of $7,000 from Stanford University to participate in their 2016 Summer Program on Turbulence.

The Ubbo Emmius Fund and the German Aerospace Laboratory each sponsor two years of a PhD project on numerical algorithms for exascale computers (Song). The NWO-complexity program funds a PhD project on the analysis of the Kurosishio Current using Stochastic Partial Differential Equations (Kotnala). The NWO program Mathematics of Planet Earth supports a PhD-project on the study of efficient Lyapunov solvers for the oceanographic applications (Baars).

The Ubbo Emmius Fund and the National Natural Science Foundation of China sponsor a PhD project on the design and parallelization of multilevel matrix solvers for partial differential equations (Bu). The Ubbo Emmius Fund and the University of Electronic Science and Technology of China sponsor two years each of two PhD projects on the design and parallelization of multilevel matrix solvers for solving partial differential equations (Gu Xianming and Shen Zhaoli). They also fund a follow-up project on numerical linear algebra methods and applications in computational nanophotonics that started in August 2015 (Dong-Lin Sun).

**Societal relevance**

As indicated above, part of our PhD and MSc research is carried out in physical or technological applications. Close cooperation exists with several university research laboratories, with all Dutch Technological Institutes (GTI’s), and with several industries: multi-nationals as well as small and medium enterprises.

**(Inter)national collaboration**

Various bilateral contacts exist with research groups inside and outside the Netherlands, leading to
e.g. joint PhD projects, participation in summer schools, traineeships for Master’s students and/or to joint publications.

- The research on free-surface flows and hydrodynamic wave loading, focussed around the ComFLOW development, is embedded in world-wide joint-industry projects with main partners the Maritime Research Institute MARIN, TU Delft, Deltares, FORCE Technology Norway and several offshore companies and shipyards throughout the world.

- The research on methods for bifurcation analysis for ocean circulation models is carried out in close cooperation with prof. H.A. Dijkstra from the Institute for Marine and Atmospheric Research (IMAU) in Utrecht. The project on numerical linear algebra for bifurcation analysis on high-performace computers is a cooperation with Dr. J. Thies and Dr. A. Basermann from DLR and Prof. A. Klawonn from the Technical University of Cologne. Furthermore there is cooperation with Prof. M. Bollhoeffer from the Technical University of Braunschweig on the solution of sparse linear systems by multilevel ILU preconditioners, and with Dr. Hochstenbach from TUE on Krylov subspace methods and the numerical solution of Lyapunov equations.

- Our turbulence research comprises cooperation with the Universitat Politècnica de Catalunya in Barcelona, TU München, TU Berlin, KU Leuven and Stanford University. We also work together with MARIN (PhD-project Bandringa) and NLR (PhD-project Rozema).

- Activity on sparse matrix solvers has been conducted in cooperation with the University of Chengdu (China), leading to two successful joint proposal submissions under NSFC’s (National Natural Science Foundation of China) talent funding program series, namely the Young Scientists Fund on block Krylov subspace methods for solving linear systems with multiple right-hand sides, and the Tianyuan Fund for Mathematics on Krylov subspace methods with applications in electromagnetic scattering.

- Cooperation is continued with Prof. Eric Deleersnijder (TUD and Institute of Mechanics, Materials and Civil Engineering (IMMC) & Earth and Life Institute (ELI) at Universit catholique de Louvain, Belgium) on the numerical analysis of mixing models for geophysical flows.

(Inter)national PhD committees

Carpentieri participated in one PhD defense at RUG. Veldman was a (joint) PhD promotor at TU Delft, and participated in 3 PhD defense committees outside RUG: University Twente (2×) and TU Eindhoven. Verstappen participated in 3 PhD defense committee (UPC Barcelona and 2x RUG) Wubs participated in one PhD defense at RUG.
2.6 Further information

Carpentieri is on the editorial board of the *Journal of Applied Mathematics* He was co-presenter at ParCFD 2015 (Montreal), SIAM Applied Linear Algebra 2015 (Atlanta), the Burgersday 2015 (Delft) and Preconditioning 2015 (Eindhoven). He co-authored two poster presentations at the Woudschouten Conference on Scientific Computing (Woudschouten).

Veldman is a scientific consultant of the National Aerospace Laboratory NLR (Amsterdam) and he is a member of the Advisory Board of the Maritime Research Institute MARIN (Wageningen). Further, he is on the editorial board of *Journal of Engineering Mathematics* and *Journal of Algorithms and Computational Technology*. He (co-)presented lectures at the 34th International Conference on Ocean, Offshore and Arctic Engineering OMAE2015 (St. Johns), the ECCOMAS Conference on Computational Methods on Marine Engineering MARINE2015 (Rome) and the International Symposium on Offshore and Polar Engineering ISOPE2015 (Kona, Hawaii).

Verstappen is member of the NWO committee for Scientific Use of Supercomputers (WGS), the Steering Committee of the Special Interest Group Large Eddy Simulation of ERCOFTAC (European Research Community On Flow Turbulence And Combustion), and the International Scientific Committee of the Foundation for the Progress of Heat and Mass Transfer (FTCM). He is member of the Scientific Advisory Board High Performance Computing and Visualisation (WAR HPC/V) of the University of Groningen and Erasmus coordinator University Groningen–UPC Barcelona. He gave 5 presentations, co-presented 9 papers. He is on the editorial board of *Computers and Fluids*.

Wubs and Carpentieri organized a minisymposium at the international conference on preconditioning techniques for scientific and industrial applications in Eindhoven. Wubs and the PhD students Baars, Song, Liao and Bu also gave talks at this conference. Wubs represents the group in the committee of the Werkgemeenschap Scientific Computing.

Several PhD students gave presentations at conferences and workshops, e.g. Seubers at the Spring Meeting of the Dutch-Flemish Working Community on Scientific Computing (Antwerpen), Van der Plas at the ASME 34th International Symposium on Offshore Mechanics and Arctic Engineering (St. John’s, Canada), Liao at the 27th International Conference on Parallel Computational Fluid Dynamics ParCFD (Montreal), Silvis at the 15th European Turbulence Conference (Delft) and the 4th International Conference on Turbulence and Interactions (Cargese, France). Also talks and posters at the “J.M. Burgersdag” (Delft) and the Dutch-Flemish Conference on Scientific Computing (Woudschoten) can be mentioned.
## 3. Dynamical Systems, Geometry & Mathematical Physics

**Group leader:** Prof.dr. G. Vegter  
*(since September 2014)*

### Tenured staff (JBI members)

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<td>Dr. K. Efstathiou</td>
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<tr>
<td>Prof.dr. A.C.D. van Enter</td>
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<td>Dr. A. Sterk</td>
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<td>Prof.dr.ir. H.S.V. de Snoo</td>
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<tr>
<td>Dr. D. Valesin</td>
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<td>Prof.dr. G. Veger</td>
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<td>Prof.dr. E. Verbitskiy</td>
<td>RuG/Leiden</td>
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<tr>
<td>Prof.dr. H. Waalkens</td>
<td>RuG</td>
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### Postdocs

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<td>Dr. R. Dyer (until 31 July 2015)</td>
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<tr>
<td>Dr. K. Kuoch (until 30 September 2015)</td>
<td>NWO/STAR</td>
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<td>Dr. L. Zhao (until 1 September 2015)</td>
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### PhD students

- **J. Hidding** (Kapteyn Institute/RuG)  
  *(supervisor: Van de Weijgaert)*  
  *(co-supervisor: Vegter)*  
  *(supervisor: Broer)*  
  *(supervisor: Sterk)*  
  *(supervisor: Waalkens)*  
  *(supervisor: Efstathiou)*  
  *(supervisor: Vegter)*  
  *(co-supervisor: Van de Weijgaert)*  
  *(supervisor: Waalkens)*  

- **H. Jardón Kojakhmetov** (until 1 September 2015)  
  *(Conacyt)*  

- **D. L. van Kekem**  
  *(RuG)*  

- **V. Krajňák** (until 15 November)  
  *(RuG)*  

- **N. Martynchuk**  
  *(RUG)*  

- **M.H.M.J. Wintraecken** (until 1 February 2015)  
  *(EU/RuG)*  

- **M. Zaman**  
  *(HEC Pakistan)*
Guests
J. Behrndt, TU Graz, Austria
E. Broman, Uppsala University, Sweden
C. Efthymiopoulos, Academy of Athens, Greece
J. Eldred, University of Indiana, US
E. Endo, Universidade de Sao Paulo, Brazil
A. Giacobbe, University of Padova, Italy
H. Hanßmann, Utrecht University, The Netherlands
B. Kolesnik, University of British Columbia, Canada
B. de Lima, Universidade Federal Minas Gerais, Belo Horizonte, Brazil
R. MacKay, University of Warwick, UK
P. Mardešić, University of Bourgogne, France
J.-C. Mourrat, ENS Lyon, France
R. Roussarie, Université de Bourgogne, France
D. Strub, University of Warwick, UK
H. Winkler, Ilmenau, Germany
3.1 Research program

The research group *Dynamical Systems, Geometry and Mathematical Physics* has grown out of the two groups *Dynamical Systems and Mathematical Physics* and *Geometry* which have merged in September 2014. The research activities cover a broad and diverse spectrum of subjects in the fields of fundamental, applied and computational dynamical systems theory, classical, statistical and quantum mechanics and their interfaces in the light of dynamics, and theoretical and applied aspects of geometry with many connections to dynamical systems theory.

General description

The interest of dynamical systems theory is the behaviour of systems that evolve in time. This first of all concerns the long-term behaviour which comprise stationary, periodic, multi-periodic and chaotic dynamics, but also transient behaviour is of interest. Moreover bifurcations or transitions between asymptotic states – in particular transitions between regular and chaotic motions – under variation of parameters are of great importance. We develop mathematical tools using methods from analysis, geometry and measure theory to grasp, study and develop the structures involved. Moreover, we develop methods to detect and understand the dynamics in specific models, employing numerical and graphical tools and computer algebra. Many applications are from the field of mechanics. This concerns the motion of point masses like planets and their satellites in celestial mechanics, and also the motion of atoms and molecules which again can be described as point masses or rigid bodies. Here also relativistic or quantum effects may play a role. This is a wide area with great outreach, also in the direction of life sciences. If the number of constituent particles is huge then such systems are best described by statistical means. Statistical mechanics deals with the question of how global observables, like temperature, can be explained from the microscopic behaviour. There is a close relationship with dynamical systems theory in particular with regard to random and chaotic behaviour and the so-called non-equilibrium systems. Mathematical physics is the encompassing discipline of all the above and still larger areas of theoretical physics. The research is very geometrical in nature. It involves many tools from differential and computational geometry where the research in the field of geometry has many facets also in its own right.

Dynamical Systems Theory

The discipline of Dynamical Systems is concerned with mathematical models for deterministic time evolutions. A simple example is derived from the oscillator, which generally only displays periodic dynamics. If subject to periodic driving or to coupling with another oscillator, it can illustrate many parts of the Dynamical Systems research program.

One possible state of the system is resonance, where the combined system assumes one globally periodic state, the frequency of which is an integer combination of the individual periodic motions. Another possible state is multi- or quasi-periodicity, where the individual periodic motions combine in a rationally independent way. When coupling three oscillators, a third possible combined state exists, where a continuous range of frequencies is present: this is the state of chaos.
The occurrence of resonance, quasi-periodicity and chaos as well as the transitions or bifurcations in between, is the central theme of research in the current Dynamical Systems program – not only for a few coupled oscillators but for a wide class of systems.

The questions posed vary from fundamental to applied, where the focus can be on different classes of systems. Examples of this are the world of general ‘dissipative’ systems with a finite-dimensional state space, the classes of Hamiltonian or reversible systems or systems with a very low-dimensional state space. Also concrete examples are being studied, where sometimes numerical or symbolic algorithms have to be developed. The mathematics of these different levels strongly interact. For instance, in order to know what to look for in a special case, one has to know beforehand what can be expected and what is logically possible.

There is cooperation with groups in other sciences on the analysis of specific systems. This concerns the Department of Engineering, University of Bristol (A. Champneys), the University of Auckland (B. Krauskopf, H.M. Osinga), the University of Eindhoven (H. Nijmeijer), the Department of Applied Mathematics and Analysis of the University of Barcelona (C. Simó and À. Jorba) as well as the University of Utrecht (O. Diekmann, H.A. Dijkstra, H. Hanßmann, T. Opsteegh, F. Verhulst), Boston University (R.L. Devaney, T. Kaper), the University of Exeter (M.P. Holland and D.B. Stephenson) and the Radboud University Nijmegen (M. Krupa). Various PhD students and postdocs at all these institutions are involved as well. The theoretical work is also internationally oriented and involves intensive cooperation with the universities of Dijon (R. Roussarie), Ohio State University (M. Golubitsky), IMPA Rio de Janeiro (J. Palis, W. de Melo, M. Peixoto and M. Viana), the Université de Marseille (J.C. Poggiale and S. Troubetzkoy), the Russian Academy of Sciences (M.B. Sevryuk) and other places, resulting in joint publications on a regular basis.

**Geometry and Geometric Approximation**

The research topics in geometry fall within several subfields of Geometry, like Differential Geometry and Singularity Theory on the more theoretical side, and Computational Geometry on the more applied side. In collaboration with other local and international groups in Mathematics and Computer Science, this research is also focused on applications in Geometric Modeling, Dynamical Systems, and Astrophysics. The goal is to obtain constructive and certified methods for the study of geometric and topological structures arising in a wide range of scientific problems. The approximation of shapes in various representations by ‘simple’ geometric objects, like polyhedral objects or piecewise quadratic surfaces, is one of the central topics of our research program. This field has attracted a lot of interest from researchers in Computer Aided Geometric Design, where mainly numerical aspects of the problem are emphasized. However, our scope is rather different in that we focus on topological correctness, a criterion often disregarded in applications: the topology of the approximating object should be the same as that of the original shape.

We also apply techniques from Algebraic and Computational Topology to Data Analysis in Cosmology. This project involves an investigation of the Cosmic Web, the space-filling foamlike pattern
permeating the Universe. The Cosmic Web represents the most striking example of a complex geometric pattern in nature and defines the cosmic environment in which galaxies emerge. In both the observed galaxy distribution as well as in computer simulations of cosmic structure formation we see matter accumulate in walls, filaments and dense compact clusters, surrounding vast near empty Voids.

The research is carried out in collaborations with the Cosmology group of R. van de Weygaert at the Kapteyn Astronomical Institute of the University of Groningen, with the INRIA-groups Geometrica (Boissonnat, Dyer, Wintraecken) at Sophia Antipolis and VEGAS (Lazard, Teillaud) at Nancy, France, with C.K. Yap of the Courant Institute at New York University, and with A. Chattopadhyay at IIIT-Bangalore, India.

Statistical Mechanics and Stochastics
Statistical mechanics forms a substantial part of the research in the group. Both equilibrium and non-equilibrium questions are considered. In comparison with dynamical systems, the emphasis is on systems with infinitely many, rather than finitely many, degrees of freedom. Links between the two can be fruitfully studied in the thermodynamic limit, where one can consider the asymptotics of systems with a large (but finite) number of degrees of freedom. Such questions often lead to the use of stochastic methods.

The general aim of the stochastics part of the program is to understand interacting stochastic systems on a mathematical level. Even when the interaction is local, such systems typically exhibit a complex global behavior, with a spatial long-range dependence resulting in phase transitions. In this picture phase transitions are characterized by discontinuous behavior of the possible states of the system as a function of external parameters.

The equilibrium properties of such systems can often be described by Gibbs measures. These are probability measures on the set of possible states of the system given in terms of the energy resulting from local interactions. For specifically tuned values of the parameters there can be more than one Gibbs measure, and Gibbs measures can be highly non-trivial. In one direction of research we are focusing on these. Moreover we are also interested in the time-evolution of such measures. It was discovered a few years ago that time-evolved measures may lose (and recover) their Gibbsian nature as a function of time. Related to this is the preservation of the Gibbs property under discretisations and spatial coarse-graining. We are trying to approach this phenomenon in case studies. In a related line of research we are investigating continuous interfaces. With former STAR-postdoc S. Taati and R. Fernández we study the nematic transition in hard-rod models.

Percolation theory is another field in which the study of phase transitions and other statistical-mechanical phenomena have been very fruitful. The object of study of percolation theory are the connectivity properties of random sets obtained after some stochastic procedure is applied to a lattice or graph. We are currently working on models of percolation in which this stochastic procedure presents some form of long-range dependence, a theme that has received considerable attention in recent years. We also investigate how stable long-range models models are in the sense of changing infinite range to finite
but sufficiently large range in some models in 3 and more dimensions.

We are also working on models for temperature-dependence of $n$–vector models, on diffraction theory with M. Baake (Bielefeld) and D. Lenz (Jena), on the theory of disordered systems and on models for metastability such as bootstrap percolation and in general on examples of phase transitions of physical and conceptual interest. We are also starting to develop the theory in relationship with the theory of networks.

Finally, we have conducted research on the statistical mechanics of systems that are out of equilibrium. Metastability is an ubiquitous phenomenon involving systems whose transition to equilibrium is hindered by the presence of energy barriers or “traps”. We are conducting research on the metastable behavior of a model called the contact process, which can both be taken as a toy model for out-of-equilibrium dynamics and as a model for the evolution of an infection in a biological population. We consider this model on different classes of random networks and study how the topological properties of the network affect the transition to equilibrium.

The work is done in various collaborations, including in the last years M. Baake (Bielefeld), J.-R. Chazottes (Paris), P. Collet (Paris), H. Duminil-Copin (Genève), R. Fernández (Utrecht), A. Fey (Delft), F. Redig (Nijmegen-Delft), A. Le Ny (Orsay), W. Th. F. den Hollander (Leiden), C. Külske (Bochum), R. Morris (IMPA, Rio de Janeiro), A. A. Opoku (Sunyani, Ghana), E. Orlandi (Rome), R. van der Hofstad (Eindhoven), H. G. Dehling (Bochum), S. Shlosman (Marseille), V. Zagrebnov (Marseille), M. Formentin (Padova), S. Romano (Pavia), K. Netocný (Prague), S. Roelly (Potsdam), D. Lenz (Jena), T. Hulshof (Eindhoven), J-C. Mourrat (ENS Lyon), T. Mountford (EPFL Lausanne), Bálint Ráth (BME Budapest), B.N.B. de Lima (Belo Horizonte, E. Saada (CNRS and Paris-Descartes), M. Mourragui (Rouen), Anna Levit (Vancouver), Bernardo de Lima (Belo Horizonte), Bruno Schapira (Marseille).

Some of the more specific directions studied under the umbrella of the two main themes mentioned above are the following.

**Classical and Quantum Transport**

Many questions in dynamical systems theory can be phrased as transport problems. The research of H. Waalkens concerns the study of reaction type dynamics which is associated with the phase space transport across certain types of saddle equilibrium points. A general theory has been developed which describes how this transport is controlled by various high-dimensional invariant manifolds. The manifolds can be explicitly constructed from normal forms. This opens the way to understand many key problems in reaction dynamics like the realization of Wigner’s transition state theory for multidimensional systems. The research has a wide range of applications ranging from chemical reactions to ballistic electron transport problems and even capture and escape problems in celestial mechanics. Using methods from semiclassical analysis like the Weyl symbol calculus the theory can be carried over to quantum transport problems. Based on a quantum normal form an efficient
algorithm has been developed to compute quantum reaction rates. This research is of central interest for recent spectroscopic results in molecular collision experiments. The research is carried out in collaboration with Ü. Çiftçi (Namık Kemal University), H. R. Dullin (Sydney University), R. Schubert and S. Wiggins (both Bristol University) and G. Ezra (Cornell University).

**Optics**

New fabrication techniques allow one to build lasers and optical resonators on a microscopic scales. Here the light is trapped in micro-scale cavities utilizing the principle of total internal reflection. Such micro resonators have great potential for miniaturizing spectroscopic devices and diagnostic tools. For many applications, it is of crucial importance to optimize the quality factors of these devices together with the directionality of the optical output. This can be achieved by, e.g., a suitable choice of the morphology of the cavity boundary. Significant insight into the output directionality for a given cavity shape can be obtained on the level of the ray dynamics from studying the corresponding billiard map. Combining this with techniques from semiclassical quantum mechanics (short wavelength asymptotic) leads to the design of cavities with laser modes which are both long lived and directional. Further ideas like perturbing circular disk cavities by a point scatterer are also exploited. This research is carried out by H. Waalkens in collaboration with C. Dettmann, M. Sieber (both Bristol University) and G. Morozov (University of the West of Scotland).

**Hamiltonian Systems**

In the theory of Hamiltonian dynamics the geometry of the phase space plays an important role, in particular the bundle structure of invariant tori in integrable systems. The nontriviality of such bundles is studied by methods from differential geometry and algebraic topology, where this has led to the development of monodromy and Chern classes. These results have a counterpart in semi-classical quantum theoretical approximations where quantum monodromy helps to explain certain spectral defects. Molecular and atomic systems are also studied from this point of view. This research is carried out in cooperation with various groups like the Université du Littoral, Dunkerque (B. Zhilinskiĭ, D. Sadovskii), University of Calgary (R.H. Cushman), Utrecht University (H. Hanßmann), the University of Padova (F. Fassò, A. Giacobbe), Université de Bourgogne, Dijon (D. Sugny, P. Mardešić), Sydney University (H.R. Dullin).

**Earth and Life Science**

Applications of dynamical systems theory to biology provide new insights into the behaviour of biological systems. Continuing previous work on synchronization in coupled cell networks, we study in collaboration with the Chronobiology Department (D. Beersma, R. Hut, I. Hoveijn) the circadian rhythms of organisms through the use of appropriate mathematical models.

A.E. Sterk maintains collaborations with M.P. Holland and D.B. Stephenson (both at University of Exeter) on Extreme Weather Events. This collaboration has grown of out of the EU network Complexity-NET which concluded in 2013.
Analysis – Operator Theory
The central theme is the extension theory of symmetric and sectorial operators in Hilbert spaces and in spaces with an indefinite metric. This extension theory is closely connected to mathematical physics (explicitly solvable models, singular perturbations), to system theory (the realization in terms of transfer functions) and to analysis (moment problems, interpolation problems, differential operators, canonical systems).

The research is concerned with the development of the general theory and the applications to the above mentioned fields. This is done in collaboration with the following group of mathematicians: J. Behrndt (Graz), A. Fleige (Dortmund), S. Hassi (Vaasa), J.Ph. Labrousse (Nice), M. Möller (Johannesburg), A. Sandovici (Iasi), Z. Sebestyén (Budapest), F.H. Szafraniec (Krakow), C. Trunk (Ilmenau), H. Winkler (Ilmenau), H. Woracek (Wien).

3.2 Overview of scientific results

KAM theory
In KAM theory several projects are running in cooperation with Broer. A monograph entitled ‘Quasi-periodic bifurcation theory: the geometry of KAM’, co-authored by Hanßmann and F.O.O. Wagener (UvA) is in preparation. The postdoc Lei ZHAO started working end 2013 on De Sitter’s work on the Galilean satellites of Jupiter that exhibit a 1 : 2 : 4 orbital resonance. De Sitter found an approximating periodic solution along which the system seems to librate. This work was published in the early 20th century and deserves retelling also in terms of the KAM theory. We reconstruct and update De Sitters work and add the KAM theoretical part. One paper has been submitted to Celestial Mechanics, another is still in preparation and will be submitted to the special issue Geometry and Dynamics of Indagationes Mathematicae. In 2015 also Heinz Hanßmann from Utrecht joined the project.

Slow Fast Systems
The PhD project of H. Jardon-Kojakhmetov concerns the geometric regularization in terms of slow-fast dynamics of the constrained differential equation paper by Takens in the LNM 525. This research involves a collaboration with G. Vegter (Groningen), F. Dumortier (Hasselt) and R. Roussarie (Dijon).

Geometry
Vegter, together with his PhD student Wintraecken and postdoc Dyer, studied a natural intrinsic definition of geometric simplices in Riemannian manifolds of arbitrary finite dimension, and exploit these simplices to obtain criteria for triangulating compact Riemannian manifolds. A Riemannian simplex is defined as the image of the barycentric coordinate map associated with a finite set of vertices on the manifold, defined using so-called Karcher means. We articulate criteria that guarantee that the
barycentric coordinate map is a smooth embedding. If it is not, we say the Riemannian simplex is degenerate. Quality measures for the thickness or fatness of Euclidean simplices can be adapted to apply to these Riemannian simplices. For manifolds of dimension 2, the simplex is non-degenerate if it has a positive quality measure, as in the Euclidean case. However, when the dimension is greater than two, non-degeneracy can be guaranteed only when the quality exceeds a positive bound that depends on the size of the simplex and local bounds on the absolute values of the sectional curvatures of the manifold. An analysis of the geometry of non-degenerate Riemannian simplices leads to conditions which guarantee that a simplicial complex is homeomorphic to the manifold.

This work has been published in Geometriae Dedicata, and has been presented at the 31st Symposium on Computational Geometry. It is also part of Wintraecken’s PhD thesis, defended successfully in September 2015.

In joint PhD projects with Van de Weygaert of the Kapteyn Astronomical Institute we are applying topological methods to detect one- and two-dimensional structures in large cosmological data sets, representing the distribution and evolution of cosmic matter. Together with our PhD students P. Pranav and J. Hidding at the Kapteyn Astronomical Institute have developed methods to detect geometric patterns in the large scale structure of the universe. These methods are based on topological persistence, a topological framework that distinguishes essential topological features from topological noise. Part of this work forms the contents of Pranav’s thesis, defended successfully in December 2015.

Chattopadhyay, Vegter and Yap have completed earlier work on certified computation of the Morse-Smale complex of two-dimensional gradient systems in the plane. This Morse-Smale complex is an important tool for global topological analysis in various problems of computational geometry and topology. We developed certified algorithmic methods, based on interval arithmetic, for the topologically correct computation of such complexes for systems satisfying mild non-degeneracy conditions. This work has been accepted for publication in the Journal of Symbolic Computation.

Statistical Mechanics
About the Gibbsian-non-Gibbsian program, around which the previous PhD projects of Iacobelli, Ermolaev, Opoku and Ruszel were centered there were a number of developments. In this program one studies which measures can and cannot be written as a Gibbs measure for an effective Hamiltonian. This is often done in physics, although it turns out to be not always mathematically justified. Various examples of physical interest occur, e.g., in Renormalization Group theory, in the theory of disordered systems and in the study of non-equilibrium problems, and in the theory of discrete approximations.

A study by van Enter, with Baake and D. Lenz (Jena) on diffraction and factors appeared in Ergodic Theory and Dynamical Systems.

On bootstrap percolation, a paper by van Enter was accepted for a conference proceedings. This was based on a follow-up paper by Van Enter, Duminil-Copin, Hulshof and Morris which is in preparation. K. Kuoch (postdoc under van Enter and Redig, NWO-STAR) worked on contact processes with
Mourragui (Rouen) and Saada (Paris) and on inclusion processes with Redig. Two papers have been submitted.

In 2015 Verbitskiy continued the study of renormalized Gibbs states and algebraic properties of dynamical systems. M. Göll (a PhD student under the supervision of E. Verbitskiy) successfully defended the PhD thesis *Principal algebraic actions of the discrete Heisenberg group* in June 2015.

E. Verbitskiy was a visiting professor at the Institute of Mathematics for Industry, Kyushu University, Japan. He taught a graduate course on Hidden Gibbs Processes, and established collaboration with T. Shirai and M. Tsujii.

With H. Duminil-Copin (Genève), T. Hulshof (Vancouver) and R. Morris (Rio de Janeiro) van Enter studied the existence of correction terms to sharp thresholds in anisotropic bootstrap percolation models. With S. Taati and R. Fernández he continued the study of the nematic transition for hard-rod models. With Valesin and B.N.B. de Lima (Belo Horizonte) he studied the stability of long-range oriented percolation models. A paper has been submitted. With E. Endo who is visiting Groningen for a year and R. Bissacot he started working on systems in inhomogeneous external fields.

In collaboration with Bruno Schapira (Université Aix-Marseille), Valesin has shown that the contact process exhibits metastable behavior on arbitrary graphs. A paper has been submitted.

In Percolation, together with Bernardo de Lima (Universidade Federal de Minas Gerais), van Enter and Valesin have proved a result about phase transition of truncated long-range percolation on oriented graphs. The corresponding publication has been submitted.

In Interacting Particle Systems, D. Valesin has collaborated with Anna Levit (University of Columbia) to study the contact process with exclusion-type dynamics on $d$-dimensional lattices. A paper has been submitted and will appear in the Proceedings of the Brazilian School of Probability. Additionally, in collaboration with Tom Mountford (EPFL), D. Valesin has studied a competition model defined as a modification of the contact process, and proved a convergence result about the interface of this model. A paper has been submitted.

**Algebraic Dynamical Systems**

Papers by Verbitskiy jointly with collaborators on algebraic dynamics has been accepted for publication in Indagationes Mathematicae, Monatshefte für Mathematik, Springer Lecture Notes in Applied Mathematics and Mechanics, and will appear shortly. Jointly with T. Shirai (Fukuoka, Japan), Verbitskiy is studying probabilistic properties of spanning trees on infinite graphs, and their link to algebraic systems. In collaboration with C. Kalle (Leiden) and in M. Tsujii (Fukuoka, Japan), he investigated existence of smooth invariant densities for random continued fraction transformations. The paper is currently being finalized. Verbitskiy started a new project on renormalization of algebraic dynamical systems in collaboration with K. Schmidt (Vienna) and D. Lind (Seattle).
**Hamiltonian Systems**

H. Waalkens continued his work on monodromy in scattering problems with H. Dullin (Sydney). Results on scattering monodromy in the two-center problem were presented at a conference in Trento (Italy). A paper is in preparation. In a collaboration with the Zernike Institute for Advanced Materials (W. H. Broer, G. Palasantzas, J. Knoester) H. Waalkens studies the influence of surface roughness on the actuation dynamics of driven Casimir oscillators. A paper has been published in *Physical Review Applied*.

K. Efstathiou continued his work on monodromy together with A. Giacobbe (Padova) and P. Mardešić (Dijon). A paper is in preparation. Efstathiou is also working with H. Hanßmann (Utrecht) and A. Marchesiello (Prague) on the bifurcations and geometry of 3-DOF oscillator systems with resonance 1:1:-2. A paper is in preparation. Efstathiou is working on the geometry of integrable Hamiltonian systems and, together with Martynchuk, has submitted a paper while a second one is near completion.

**Classical and Quantum Transport**

In collaboration with R. Schubert (Bristol University), A. Goussev (MPI Dresden/Northumbria University) and S. Wiggins (Bristol University), Waalkens is working on a uniformization of the periodic orbit formula for quantum reaction through transition states they developed earlier. A paper is in preparation. Together with Ünver Çiftçi Waalkens has been studying reaction type dynamics induced by saddle type relative equilibria in rotational symmetry reduced N-body systems. A paper in collaboration with G. Ezra (Cornell) and S. Wiggins (Bristol) concerning the application to the HCN isomerization problem is in preparation. Waalkens has started a collaboration on Morse bifurcations of transition states and its application to roaming reaction dynamics with D. Strub from Warwick University. A paper also involving V. Krajňák is in preparation.

**Optics**

Waalkens continued his collaboration with C. Dettmann, M. Sieber (both Bristol University) and G. Morozov (University of the West of Scotland) on optical micro cavities with point scatterers. A paper is in preparation.

**Extension theory**

The Lebesgue decomposition and Radon-Nikodym derivatives in the context of relations are being studied with Hassi and Sebestyén; abstract operator decompositions are worked on with Labrousse, Sandovici, and Winkler. Normal intermediate extensions of symmetric operators are being studied with Hassi and Szfraniec. A survey of sectorial relations and their factorizations is in preparation with Hassi, Sandovici, and Winkler. The decomposition of linear relations in a finite-dimensional space is a project with Trunk and Winkler. Almost Pontryagin spaces and the operators in them are being studied with Woracek. A monograph on boundary value problems is in preparation with Behrndt and Hassi.
Extreme events
A paper by Sterk in collaboration with D.B. Stephenson, M.P. Holland (University of Exeter) and K.R. Mylne (Met Office) was accepted by the Quarterly Journal of the Royal Meteorological Society. The paper, investigating the predictability of extreme wind speeds, will be published in early 2016.

PhD research
Jardon-Kojakhmetov completed his research on the Takens list of constrained differential equations. This project was supervised by Broer and Vegter. One paper has been published in the *Journal of Differential Equations*, other papers are in preparation. The thesis was defended successfully in June 2015. Afterwards he moved to the ENgineering and TEschnology Institute Groningen for a postdoctoral position. Krajňák follows various projects on transport in Hamiltonian systems. A paper with his supervisor H. Waalkens on the Hydrogen exchange reaction is about to be completed. Another paper involving a collaboration with D. Strub (Warwick) concerning Morse bifurcations of transition states is in preparation. Zaman is studying the integral manifolds of 3-body problems. His research involves a collaboration with his supervisor H. Waalkens and I. Hoveijn and L. Zhao. Martynchuk is studying the geometry of integrable Hamiltonian systems under the supervision of K. Efstathiou. He has submitted one paper while a second one is near completion. Li started his research on the bifurcations of pulse-coupled oscillator networks with delay in November 2015. He has a research position supported by the China Scholarship Council as part of his PhD study. In September 2014 Dirk van Kekem joined the group as a PhD student under the supervision of A.E. Sterk. Presently, we studies bifurcations in the Lorenz–96 model. He is making good progress: one paper is ready to be submitted and a second paper is in preparation.

3.3 Research subjects

**H.W. Broer:** perturbation and KAM-theory, bifurcation theory, non-integrable and resonance phenomena, applications of singularity theory, exploration of complicated systems.
**A.C.D. van Enter:** lattice statistical mechanics and thermodynamic formalism, Gibbs-non-Gibbs transitions, bootstrap percolation, nonlinear vector models, disordered systems and spin-glasses, metastates and chaotic size-dependence, non-crystalline long-range order.
**K. Efstathiou:** integrable and near-integrable Hamiltonian systems, applications of Hamiltonian mechanics in physical systems, generalized monodromy, network dynamics with applications to biology and engineering.
**J. Hidding (Kapteyn Institute/RuG):** Mathematical simulation of cosmic structure formation.
**H. Jardon-Kojakhmetov:** geometric regularization in terms of slow-fast dynamics of constrained equations, applications of catastrophe theory to Hodgkin–Huxley like systems.
**D.L. van Kekem:** bifurcation analysis of large-scale systems, such as the Lorenz-96 system.
**V. Krajňák:** transport in Hamiltonian systems; reaction type dynamics.
**K. Kuoch:** probability theory, interacting particle systems.
**P. Li:** bifurcations in pulse-coupled oscillator networks with delay.
N. Martynchuk: geometry of integrable Hamiltonian systems.
P. Pranav (Kapteyn Institute/RuG): geometry and topology of the cosmic web.
H.S.V. de Snoo: extension and realization theory with their applications to analytical problems.
A.E. Sterk: numerical exploration of dynamical systems, extreme value statistics of dynamical systems, applications to climate models and analysis in infinite-dimensional spaces; in particular related with (partial) differential equations.
D. Valesin: interacting particle systems, percolation theory, metastability
G. Vegter: certified geometric approximation, computational topology, computational differential geometry, singularity theory and its applications, dynamical systems.
E. Verbitskiy: lattice statistical mechanics, thermodynamic formalism, Gibbs-non-Gibbs transitions, dynamical systems and time-series prediction.
H. Waalkens: theoretical and application oriented aspects of Hamiltonian systems including integrable systems, monodromy, reaction type dynamics, invariant manifolds, normal forms, and semiclassical quantum mechanics (short wavelength asymptotics) with applications to micro lasers and quantum reaction dynamics.
M. Wintraecken: Sampling and approximation of manifolds of high dimension and high codimension.
M. Zaman: N-body systems.
L. Zhao: celestial mechanics and Hamiltonian systems.

3.4 Publications

Dissertations


– M.H.M.J. Wintraecken, Ambient and intrinsic triangulations, and topological methods in cosmology, Promoters: G. Vegter and M. van de Weijgaert, Johann Bernoulli Institute for Mathematics and Computer Science and Kapteyn Astronomical Institute, University of Groningen, 4 September 2015, 332 pages.

– P. Pranav, Persistent holes in the Universe: A hierarchical topology of the cosmic mass distribution, Promoters: M. van de Weijgaert and G. Vegter, Kapteyn Astronomical Institute and Johann Bernoulli Institute for Mathematics and Computer Science, University of Groningen, 18 December 2015, 298 pages.
Articles in scientific journals


**Articles in conference proceedings**


**Other publications**


**3.5 External funding and collaboration**

*External funding*

PhD grants (supervisor Broer): Hildeberto Jardon-Kojakhmetov was appointed in September 2011 as a PhD student on a Mexican scholarship. The research concerns the geometric regularization of constrained differential equations following a classification by Takens. The supervision is jointly with G. Vegter.
NWO/STAR funding was obtained for a joint project with F. Redig (Delft). On this project Dr. K. Kuoch was appointed.

The PhD position of J. Hiddink (PI: R. van de Weygaert, Kapteyn Institute) is funded by NWO.

The PhD position of M. Wintraecken is funded by the European Commission in the Information Society Technologies (IST) program, funded under the 7th Framework Program of the European Commission, project Computational Geometric Learning (CGL).

PhD grant (supervisor H. Waalkens): Drs M. Zaman has a HEC Pakistan grant and was appointed on October 1, 2012.

PhD grant (supervisor H.W. Broer, co-supervisor K. Efstathiou): Drs P. Li has a China Scholarship Council grant for a research position as part of his PhD study at Fudan University, Shanghai, and has started working in Groningen on 1 November, 2015.

The nation wide NWO-cluster NDNS+ that has supported the Groningen infrastructure from 2005–2011 was extended in 2011 and the management has been transferred to the VU University in Amsterdam. End 2013 by this cluster a 3-year NWO prefinancing of a tenure track UD was obtained for the JBI, which involves an amount of 240.000 EURO.

External collaboration

E. Verbitskiy collaborates with the graduate program Math-for-Industry, Kyushu University, Japan.

3.6 Further information

H.W. Broer is a member of the Royal Academy of Arts and Sciences (KNAW), afdeling Naturkunde, sectie Wiskunde. He is acting chairman of this sectie. He is Editor-in-Chief of Indagationes Mathematicae, which forms the Proceedings of the KNAW. Broer moreover is Associate Editor of Discrete and Continuous Dynamical Systems – Series S and he chairs the jury of the NG de Bruijn prize. This is a bi-annual prize handed out on behalf of the KWG (the Royal Dutch Math Society); the funding is made available by Elsevier.

Broer participated in a conference in the Pyrenees where he gave an invited lecture. In May he retired and became an honorary professor and the Lorentz Center workshop Geometry and Dynamics was dedicated to this event. Also Broer gave a farewell lecture in November and was decorated as Knight in the Order of Lion of the Netherlands.
K. Efstathiou gave invited talks at the Geometry, Topology, and Dynamics Seminar at University of Illinois at Chicago, at the Dynamical Systems Seminar at Kyoto University, at the Dalian Nationalities University, and at the Lorentz Center workshop “Dynamics and Geometry”. He also made a 1-month research visit at Fudan University as Senior Visiting Scientist at the Shanghai Key Laboratory of Contemporary Applied Mathematics.

A.C.D. van Enter gave invited talks at the May and December Rutgers Statistical Mechanics Meetings, at meetings at Marseille and Utrecht University, and at Bell Labs, at Bristol University and at the Dublin Institute of Advanced Studies. He also visited Princeton University.


K. Kuoch gave a talk at the probability days in Rouen.

H.S.V. de Snoo was a guest professor at the Technische Universität Graz (Jussi Behrndt). There were visits to the University of Vaasa (Seppo Hassi) and the Technische Universität Ilmenau (Henrik Winkler). He attended a conference on spectral theory for differential operators in Oberwolfach and gave a talk at the Gamm Tagung in Lecce.

A. E. Sterk gave a presentation about the predictability of extreme weather events at conference Bifurcations & Instabilities in Fluid Dynamics in Paris, France. He also gave a presentation about extreme value statistics in deterministic systems at the Lorentz Center workshop “Dynamics and Geometry”. He maintains collaborations with Mark Holland and David Stephenson at the University of Exeter.

D. Valesin gave invited talks at Leiden University, TU Eindhoven, ENS Lyon, Université Aix-Marseille and Université de Genève. He was also a plenary speaker at the Brazilian School of Probability.

G. Vegter co-organized the Fifth Quantum Universe Symposium (April 12, 2015, University of Groningen, The Netherlands) the workshop Dynamics and Geometry (June 1519, 2015, Lorentz Center, Leiden, The Netherlands), and the conference The Information Universe (October 79, 2015, Infoversum/University of Groningen,The Netherlands). He also gave a lecture on The History of Space and Time (Geschiedenis van het ruimtebegrip in de loop van de tijd), for participants of the Senioren Academie (Hoger Onderwijs Voor Ouderen in Groningen en Drenthe) in March 2015.

E. Verbitskiy presented his research results the following international workshops and conferences: β-transformations and related topics (Fukuoka, Japan), Probabilistic models with determinantal structure (Fukuoka, Japan), Dynamics and Geometry (Leiden, Netherlands) and Dynamics, Combinatorics, Representations (St. Petersburg, Russia).
Verbitskiy serves as a chairman of the Committee for Innovation of the national platform for Mathematics (Platform Wiskunde Nederland), editor of the Pacific Journal of Mathematics for Industry, and as a member of the editorial board of Springer series Mathematics for Industry. In 2015 he served as a (co-)chair of the 51st Netherlands Mathematical Congress.

*H. Waalkens* has coorganized two international workshops: the workshop *Dynamics and Geometry* at the Lorentz Center (together with H. Hanßmann, I. Hoveijn, S. van Strien and G. Vegter) and the workshop *Geometry of Chemical Reaction Dynamics in Gas and Condensed Phases* in Telluride (Colorado, US). He has given invited talks at the conference ICTON 2015 in Budapest (Hungary), the ECT* workshop *Excited-State Quantum Phase Transitions* in Trento (Italy) and the University of Marburg (Germany). H. Waalkens has given a plenary talk at the inauguration of the Research Center of Mathematics for Social Creativity (Math. for Social Creativity), Research Institute for Electronic Science at Hokkaido University, Japan. He has served in the reading committees for PhD theses at the University of Marburg (Germany) and University of Sydney (Australia).
## 4. *Probability and Statistics*

**Group leader:** Prof.dr. E.C. Wit

### Tenured staff (JBI members)

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### PhD students

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4.1 Research program

The Statistics and Probability research programme spans the wide range of methodological developments and applied projects, from sparse network model inference and systems biology, high-dimensional inference and inference of ODEs, to consultation for statistical safeguards in electronic voting.

4.1.1 Network modelling and inference

Modern computational biology is caught between a rock and a hard place: simple models cannot capture the true underlying biology, while more sophisticated ones cannot be inferred properly from the available data. Especially in the topical field of systems biology, where one of the major goals is to infer large gene regulatory networks from high-throughput post-genomic data, more advanced statistical methodologies are required. Recent developments

**Bayesian networks.** In many biological applications the underlying biological systems, including several key regulatory parameters, change dynamically. The Wit-Grzegorczyk group has pursued various efforts to relax the traditional homogeneity assumptions. Grzegorczyk introduced a popular approach to complement graphical models with multiple change-point processes. The changepoints divide the time series into segments, where each segment is associated with different regulatory processes. However, for sparse data these non-homogeneous graphical models are suspicious to overfitting and inflated inference uncertainty.

**Penalized graphical models.** One of the major goals of our research is therefore to address those over-fitting problems without losing too much modelling flexibility. To this end, our research focus is on developing novel regularized statistical methodologies and information-coupling schemes, which infer the right trade-off between flexibility and inference accuracy automatically from the available data. Our advanced methods offer maximal flexibility along with various possibilities for learning and tuning coupling strengths in light of the data, such that features which are not supported by the data are automatically down-rated. This maximizes inferential certainty for better-fitting model features. An example of such regularized inference is in Figure ??.

**ODE inference.** Differential equations are the bread and butter of many quantitative sciences, from climate studies to genomics. Often the aim is to match systems of ordinary differential equations (ODE) with data observed on the real-life process. Two important questions are (i) how to match the ODE to the data by varying various parameters and (ii) how to choose between alternative descriptions
Figure 2: Reconstructed genomic map for *Arabidopsis thaliana* using penalized graphical models, clearly showing its 5 chromosomes and potential “chromosomal interactions” or epistasis.

of the system based on the data. We have expanded our previous approaches to a more general Tychonov regularization setting, where the aim is to also allow for only partially observed systems.

### 4.1.2 High-dimensional inference

Traditional statistical model, such as linear regression, considered a small number of covariates relative to the number of observations. With the advent of high-throughput and sensing technology, in many areas the data situation has reversed. Although the typical number of independent observations has not changed, the potential number of features has exploded. The field of high-dimensional inference is concerned with discovering and estimating the effect of true features that are hidden as needles in a haystack. Together with collaborators from Palermo, Wit has worked on differential geometric extensions of the least angle regression method for generalized linear models.

### 4.1.3 Electronic voting and statistics

In the fall of 2014 Wit has been approached by the Van Beek Committee, who has been asked by the minister of Internal Affairs to study the reintroduction of electronic voting in the Netherlands. The Van
Beek committee concluded in its report “Every vote counts” in December 2013 that the time is right to start using again electronic equipment in the voting and counting process. It formulated essential guidelines to guarantee the proper functioning of the vote counter. On top of this, the committee wanted a transparent way of checking the process in order to guarantee trust in the proper functioning of the counting of the votes. Wit was asked to write a report to advise on the feasibility of statistical control of the electronic vote counting process. The Wit report was sent to the Parliament in early March 2015. In the course of 2015, the Ministry of Internal Affairs has been implementing the Wit method and further consultation has been provided to aid this process.

4.1.4 Statistics for measurement reliability

Edwin van den Heuvel is associated with the research unit through a zero appointment. His work is a welcome addition to research lines within the group. Van den Heuvel is working on various aspects of statistics for measurement reliability, specifically in the context of mixed models. A measurement system quantifies or identifies one or more characteristics of an object. There are many types of measurement systems for measuring biological, medical, chemical and physical phenomena, including sensory measurements. In 2015 Wit and Van den Heuvel have worked together on a number of projects, involving a number of PhD students and a postdoc, focussing on intraclass correlation coefficients (N. Demetrashvili) and modelling longitudinal ordinal data (N. Nooraee, F. Abegaz).

4.2 Overview of scientific results

In 2015, the research group has obtained the following scientific results:

**Penalized graphical models.** The graphical lasso has proven an important tool to infer parsimonious networks from normally distributed data on the nodes of the network. However, the normality assumption and the lack of structure within the network, means that it is appropriate for only exploratory purposes. In 2015, we have published a number of extensions:

- Wit and Abbruzzo have considered time-course extensions of the traditional graphical model, through partitioning the precision matrix. The general theory of such factorial graphical models has been described in a *Network Science* paper, whereas an extension to systems biology was published in a *BMC Bioinformatics paper*.

- Abegaz and Wit extended the graphical lasso to non-Gaussian data via a Gaussian copula approach. The method was published in *Statistica Neerlandica*.

- Vujacic, Abbruzzo and Wit considered the issue of model selection in graphical lasso. Traditional methods ignored the penalized nature of the likelihood would typically underpenalize the
network, resulting in too many edges. By going back to first principles, a cross-validation based way of estimating the Kulback-Leibler divergence turns out to be much more accurate. This research was published in *Journal of Statistical Computation and Simulation*.

**ODE inference.** Inferring the parameters in a ODE can be computationally very involved. Vujacic, Wit, Dattner and Gonzalez published a computationally efficient algorithm with proven theoretical properties in *Statistics and Computing*.

**Bayesian networks.** Grzegorczyk and collaborators extended their non-homogeneous dynamic Bayesian network inference and published the results in *Machine Learning* and *Proceedings of the IWSM2015*. An in-depth study of inferring bi-directional interactions of circadian clock genes was published in *SAGMB*.

**Other.** ChIP-Seq data measures the temporal binding of proteins to certain DNA sequences. Ran-циати, Viroli and Wit published a Bayesian method to detect such binding pattern in *Statistical applications in genetics and molecular biology*. Wit was involved in a publication in *BMC medical research methodology* that compared various methods to detect networks of symptoms in depression patients. Abegaz and Wit were involved in the methodological set-up of a simplified way of estimating the effects in a mixed treatment comparison, which was published in *Pharmaceutical Statistics*.

**PhD research.** During 2015 two PhD students graduated and obtained their PhD degree. In April 2015 Abdolreza Mohammadi defended his PhD thesis, entitled “Bayesian Model Determination in Complex Systems”. In June 2015 Nino Demetrashvili defended her PhD thesis, entitled “Statistical inference in variance components models for biomedical applications”.

During 2015 three new PhD students were appointed: as of 1 Februari 2015 Mirko Signorelli started to work on a Double PhD degree in collaboration with the University of Padova, entitled “Modelling the underlying genomic causes of replicative ageing in yeast”. In November 2015 Francisco Richter-Mendoza started his PhD project, in collaboration with Rampal Etienne (GELIFES), entitled “Simultaneous estimation and selection of species diversification models.” Both students are under the supervision of Prof. Ernst Wit. Furthermore, in January 2015 Mahdi Shafiee started his PhD with Dr. Marco Grzegorczyk, entitled “Development of advanced dynamic Bayesian network models for systems biology”.
4.3 Research subjects

F. Abegaz: Copulas, Chain graphical models
P. Behrouzi: Sparse Gaussian copula graphical models
N. Demetrashvili: Variance component models
N. Gill: Generalized additive models
M. Grzegorczyk: Dynamic Bayesian networks
E. van den Heuvel: Measurement reliability inference
M. Mahmoudi: Causal inference, ODE inference
R. Mohammadi: Bayesian graphical models
H. Pazira: Differential geometric least angle regression
D. Pellin: Sparse stochastic differential equation modelling
S. Ranciati: Bayesian inference for biomedical applications
F. Richter: Inference of species diversification models
M. Shafiee: dynamic Bayesian network inference
M. Signorelli: Inference of stochastic block models
E. Wit: network inference, high-dimensional inference, biostatistics

4.4 Publications

Articles in scientific journals


### 4.5 Research indicators

#### 4.5.1 External funding

During this year, the group has been involved in a successful grant proposal:


The members of the group are supported in a number of ways. Reza Mohammadi and Francisco Richter are funded by NWO grants (STAR and MPE, respectively). Nazia Gill and Mahdi Mahmoudi are funded by their home governments in Pakistan and Iran, respectively. Danilo Pellin, Saverio Ranciati and Mirko Signorelli are funded by their home institutions in Italy (San Raffaele Milano, Bologna and Padova, respectively) and the Statistics and Probability unit for conference travel. Fentaw Abegaz, Pariya Behrouzi and Mahdi Shafiee are funded in various ways by the RuG. Nino Demestrashvili is funded by the UMCG. Hassan Pazira is self-funded.
4.5.2 External collaboration

- Wit is leading the EU-funded Cooperation in Science and Technology (COST) project on statistical network science. The collaboration involves some 100 people across Europe and will be funded for 4 years.

- Wit is collaborating with L. Augugliaro and A. Abbruzzo (University of Palermo), C. Viroli (University of Bologna), M.C. di Serio (University of San Raffaele Milano) and V. Vinciotti (Brunel University).

- Grzegorczyk is collaborating with D. Husmeier and Dr. Andrej Aderhold (University of Glasgow) and with plant biologist Prof. Andrew Millar (Edinburgh University) on Arabdiopsis gene expression in the context of the EU-funded “Timing Metabolism” (TiMet) research project.

4.6 Further information

Wit is an associate editor of *Statistical Applications in Genetics and Molecular Biology* and *Biometrics*. He is member of the Board of Directors of the International Biometrics Society. He is vice-president of the Dutch Biostatistics Society (BMS-ANed). In 2015 he was invited to the International Mathematics Institute, Singapore (1 June 31 July 2015) for the special programme Networks in Biological Sciences and he received an invitation to the Isaac Newton Institute Cambridge (July 2016 December 2016) for the special programme Theoretical Foundations for Statistical Network Analysis. Besides giving seminars in Amsterdam (UvA), Bologna, Montpellier, Milan and London, he was invited speaker at the STAR Outreach day (12 December 2014, Eindhoven), Networks in Biological Sciences workshop (11 June 2015, Singapore), Workshop ”Dynamical processes on networks - theory and applications in social sciences and biology” (19 June 2015, Sigtuna, Sweden), European Meeting of Statisticians (9 July 2015, Amsterdam), International Statistics Institute World Congress (26 July 2015, Rio de Janiero, Brazil), ECAS (1 October, Munich) and at the 8th International Conference of the ERCIM (14 December 2015, London). He also was the keynote speaker at the 12th Applied Statistics Conference, 22 September 2015, Ribno, Slovenia.

Grzegorczyk is an associate editor of *Computational Statistics*. He was successfully elected to chair the 32nd International Workshop on Statistical Modelling (IWSM) at the IWSM 2015 in Linz, Austria. As a consequence, the IWSM in 2017 will take place in Groningen. Grzegorczyk is now chairing the Local Organizing Committee and a Scientific Programme Committee and an excellent range of international invited speakers have been selected.
5. **Systems, Control and Applied Analysis**

**Group leader:** Prof.dr. A.J. van der Schaft

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<th>Tenured and tenure-track staff (JBI members)</th>
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<tr>
<td>Dr. M.K. Camlibel</td>
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<td>Prof.dr. H.L. Trentelman</td>
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<td>Prof.dr. A.J. van der Schaft</td>
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<td>Prof.dr. M.E. Dür</td>
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**PhD students**

A. Everts (supervisor: M.K. Camlibel)

L. Gijben (supervisor: M.E. Dür)

O. Ivanov (supervisors: A.J. van der Schaft, F.J. Weissing (CEES))

B. Jargalsaikhan (supervisor: M.E. Dür)

H-J. Jongsma (supervisors: H.L. Trentelman)

M. Josza (from September) (supervisors: M.K. Camlibel)

F. Koerts (from October) (supervisors: M.K. Camlibel)

N. Megawati (supervisors: A.J. van der Schaft)

P. Monshizadeh (supervisor: H.L. Trentelman)

F. Veldman-de Roo (until June) (supervisor: H.L. Trentelman, co-supervisor: C. de Persis)

T. Stegink (from September) (supervisors: A.J. van der Schaft, J.M.A. Scherpen (ITM))

E. Vos (supervisors: A.J. van der Schaft, J.M.A. Scherpen (ITM))
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<tr>
<th>Name</th>
<th>Position</th>
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<td>J. Wei</td>
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<td>External PhD students</td>
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<td>G.A. Folkertsma</td>
<td>University of Twente</td>
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<td>Guests</td>
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<td>G. Como, Lund University, Sweden</td>
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<td>L. Lapichino, University of Konstanz, Germany</td>
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<td>G. Xie, Peking University, China</td>
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<td>A. Medvedev, Uppsala University, Sweden</td>
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<td>G. Stacey, Australian National University, Australia</td>
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<td>M. Illic, Carnegie Mellon University, USA</td>
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<td>Y. Kawano, Kyoto University, Japan</td>
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<td>P. Rapisarda, University of Southampton UK</td>
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<td>D. Siegel-Gaskins, California Institute of Technology, USA</td>
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<td>A. Rantzer, Lund University, Sweden</td>
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<td>R. Mahony, Australian National University, Australia</td>
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<td>H. Cendra, Universidad Nacional del Sur en Conicet, Argentinia</td>
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<td>S. Stramigioli, University Twente</td>
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<td>C. Hadjicostis, University of Cyprus, Greece</td>
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<td>G. Notarstefano, University del Salento, Italy</td>
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5.1 Research Program

The research program Systems, Control and Applied Analysis (SCAA) is devoted to the analysis, control and optimization of complex systems. The mathematical research in this program is motivated by a wide range of applications in the engineering and natural sciences.

Mathematical systems and control theory deals with the mathematical modeling, analysis and control of open systems evolving in time. The dynamics is typically described by ordinary or partial differential equations, but can be also a mixture of continuous and discrete dynamics. This dynamical behavior is not only sought to be analyzed, but to be influenced (‘controlled’) and optimized as well; by the addition of feedback loops, and by the interconnection to other dynamical systems (controller design), or the optimal selection of parameters. Furthermore, dynamical data are used to identify the underlying model, or to approximate it by a model of lower complexity.

Typically the system models under consideration are described by under-determined sets of differential equations. As a result, there are free variables in the system description (corresponding to ‘inputs’), which together with information about the current state of the system (corresponding to ‘outputs’) model the interaction with other systems or the environment. Furthermore, the systems point of view is emphasized, in the sense that large-scale, possibly heterogeneous, dynamical systems are viewed as networks of interconnected system components, where the overall dynamics is determined by the dynamics of the components plus the network and feedback structure. This point of view is prevailing in many areas of engineering science and economics, and is receiving increasing attention in the life sciences (systems and synthetic biology, biological feedback systems, etc.).

Mathematical optimization theory is concerned with the development of solution algorithms for optimization problems involving under-determined algebraic equations. Special emphasis in the research program is given to nonlinear quadratic problems which at the same time involve binary variables. These problems have numerous applications in science, engineering and economics. They can be modeled as linear problems over special matrix cones (semidefinite programming, copositive programming), which permits a new approach to tackle these problems.

The members of the program have close collaboration with colleagues working in other scientific disciplines such as control engineering, smart energy systems, sensor networks, robotics, management science, and systems biology. In particular, there is a close collaboration with the control engineering groups at the neighboring Engineering and Technology Institute (ENTEG), under the umbrella of the Jan C. Willems Center for Systems and Control.

Structure of the program

The main lines of research in the program are:

1. **Network dynamics** (Kanat Camlibel, Harry Trentelman, Arjan van der Schaft, Jieqiang Wei,
Nima Monshizadeh, Fan Zhang, Hidde Jan Jongsma, Monika Jozsa, Oleksandr Ivanov)

Network dynamics and dynamical multi-agent systems arise in many fields of engineering and science. Systems and control theory contributes to this area by providing concepts and tools for the study of structural properties such as controllability (leader-follower networks) and model reduction, and for their control including synchronization and consensus dynamics. This entails a close interplay between geometric systems and control theory on the one hand, and algebraic graph theory, as well as convex analysis, on the other. Applications include power and sensor networks, dynamical distribution networks, as well as large-scale chemical reaction networks as arising in systems biology.

2. Modeling and control of multi-physics systems (Arjan van der Schaft, Jieqiang Wei, Filip Koerts, Pooya Monshizadeh, Tjerk Stegink, Rodolfo Reyes Baez)

Port-Hamiltonian systems constitute an extension of Hamiltonian systems where external interaction and energy-dissipating ports are taken into account. Furthermore, the underlying geometric structure is derived from the interconnection structure of the complex system. The aim of this research is to provide a systematic geometric theory for the modeling, analysis and simulation of multi-physics, mixed lumped- and distributed parameter, systems. Current research themes include model reduction, and modeling and analysis of power systems and dynamical distribution networks. Furthermore, the port-Hamiltonian framework is employed for controller design, by attaching controller port-Hamiltonian systems and shaping the Hamiltonian and other conserved quantities to a desired Lyapunov function for the controlled system, leading to physically inspired and robust control strategies. Applications include stabilization and demand-supply matching in power systems, mechatronic systems, and the control and optimization of distribution networks.

3. Mathematical systems theory (Kanat Camlibel, Harry Trentelman, Arjan van der Schaft, Anneroos Everts, Hidde-Jan Jongsma, Nima Monshizadeh, Monika Jozsa, Noorma Yulia Megawati)

Physical systems in general do not exhibit an a priori fixed information flow direction. In the behavioral approach, all external system variables are therefore in first instance treated on an equal footing, while the mathematical model specifies a subset of the set in which the external variables take their values as being possible. This subset is called the behavior of the system, which is sought to be influenced by interconnection with a controller behaviour (‘control by interconnection’). Many modeling and control questions are fruitfully studied in this novel setting. Furthermore, equivalence and approximate equivalence notions for linear systems are studied, with a view towards model reduction. Hybrid systems are a mixture of interacting continuous and discrete dynamics, and arise naturally in embedded systems and physical systems modeling. Important research issues concern the analysis of hybrid systems and their solution trajectories, the analysis of structural properties of controllability and stabilizability, and the design of controllers. The mathematical analysis of piecewise-affine and hybrid systems is heavily intertwined with optimization theory and non-smooth analysis.
4. **Modeling and control of power networks** (Pooya Monshizadeh, Tjerk Stegink, Filip Koerts, Arjan van der Schaft, Kanat Camlibel)

Power networks, from high-voltage distribution networks to AC or DC micro-grids, constitute an application area of growing importance and interest. The aim of this theme is to develop a sound mathematical framework for the modeling, analysis and control of power networks. This includes the systematic modeling of components such as synchronous generators and converters, as well as the transmission line network structure, taking the theory of port-Hamiltonian systems as a starting point. Based on these models fundamental problems of stability, power sharing and optimization are addressed. Furthermore, problems of optimal demand-supply matching are addressed by dynamic pricing algorithms, leading to the analysis of the coupled physical and market dynamics. This research is carried out in a collaborative effort with colleagues from ENTEG.

5. **Mathematical optimization theory** (Mirjam Dür, Luuk Gijben, Bolor Jargalsaikhan)

Mathematical optimization theory is concerned with studying structural properties of and developing solution methods for mathematical optimization problems. The focus is on combinatorial problems and on nonconvex quadratic optimization problems. The studied methodology is to transform the problem into a higher dimensional matrix space, permitting to move the difficult constraints (quadratic and/or binary) entirely into a certain cone constraint. This leads to copositive and semidefinite programming.

5.2 **Research subjects**

**M.K. Camlibel**: analysis of piecewise affine dynamical systems, model reduction of switched linear systems, controllability of multi-agent systems, optimisation of energy systems.

**M. Dür**: mixed-integer nonlinear optimization, optimization over convex matrix cones, copositive programming, quadratic and binary optimization problems.

**A. Everts**: geometric control of differential-variational inequalities.

**L. Gijben**: quadratic programming problems.

**O. Ivanov**: chemical reaction networks in systems biology.

**B. Jargalsaikhan**: semi-infinite approaches to copositivity.

**H.-J. Jongsm**: analysis, robust control, and model reduction of linear multi-agent systems.

**M. Josza**: input-output properties of interconnected systems, network structure and control and estimation.

**F. Koerts**: optimization of dynamical models of power networks.

**N. Monshizadeh**: power networks, synchronization, consensus and model reduction of multi-agent networks.

**P. Monshizadeh**: analysis of micro-grids; frequency and voltage regulation.
A.J. van der Schaft: geometric network modeling, analysis and control of complex engineering and hybrid systems, nonlinear systems and control theory, network dynamics and model reduction, modeling and analysis of chemical reaction networks and power systems.

R. Reyes Baez: port-Hamiltonian systems and incremental passivity.


H.L. Trentelman: network dynamics, model reduction of network dynamics, synchronization, control in a behavioral setting, robust stabilization.

J. Wei: analysis and control of dynamical distribution networks.

N. Yulia Megawati: bisimulation of linear systems and approximation theory.

Fan Zhang: robust synchronization of linear and nonlinear multi-agent systems.

### 5.3 Publications

**Dissertations**


- L. Gijben, *On approximations, complexity and applications for copositive programming*, Promotor: Mirjam Dür, Johann Bernoulli Institute for Mathematics and Computer Science, Faculty of Mathematics and Natural Sciences, University of Groningen, 2015, 125 pages.


**Edited Books**


**Chapters in books**


Articles in scientific journals


**Articles in refereed conference proceedings**


### 5.4 External funding

– M.K. Camlibel is co-principal applicant and investigator of the NWO ESI-project *Hierarchical and distributed optimal control of integrated energy systems*.

– M. Dür is co-Principal Investigator and vice speaker, DFG Research Training Group GK 2126 *Algorithmic Optimization* at the University of Trier, Germany. Joint project with colleagues from the Departments of Mathematics and Economics at the University of Trier, funded by the German Research Foundation DFG Duration: 2016–2020, Amount of funding: 4.200.000 Euro

### 5.5 Editorial activities

M.K. Camlibel:
Associate Editor for the journal *IEEE Transactions on Automatica Control*.
Associate Editor for the journal *SIAM Journal of Control and Optimization*.
Associate Editor for the journal *Systems & Control Letters*.
Member of the Conference Editorial Board of the *IEEE Control Systems Society*.  
Member of the Conference Editorial Board of the *European Control Association*.  
Conference Associate Editor for the *IEEE Conference on Decision and Control*.  
Conference Associate Editor for the *American Control Conference*.  
Conference Associate Editor for the *European Control Conference*.  

M. Dür:  
Editor of the book series *SpringerBriefs in Optimization*.  
Member of the Editorial Board of the journal *Optimization Methods and Software*.  
Member of the Editorial Board of the journal *Mathematical Methods of Operations Research*.  
Member of the Editorial Board of the journal *Journal of Global Optimization*.  

H.L. Trentelman:  
Senior Editor for the journal *IEEE Transactions on Automatic Control*  
Guest Editor for the journal *Systems and Control Letters*  

A.J. van der Schaft:  
Member of the Editorial Board for the journal *Annual Reviews in Control*  
Member of the Editorial Board for the journal *Journal of Geometric Mechanics*.  

### 5.6 Further signs of recognition and news items

- *Kanat Camlibel* is member of IFAC Technical Committee of Discrete Event and Hybrid Systems;  
  IFAC Technical Committee of Control Design;  
  IFAC Technical Committee of Linear Systems;  
  Subject Editor for International Journal of Robust and Nonlinear Control;  
  Conference Editorial Board Member of the IEEE Control Systems Society;  
  Conference Associate Editor for the IEEE Conference on Decision and Control;  
  Conference Associate Editor for the American Control Conference;  
  Conference Editorial Board of the European Control Association;  
  Co-organizer of Mathematical systems theory: from behaviors to nonlinear control Workshop dedicated to the 60th birthdays of Arjan van der Schaft and Harry Trentelman  
  International Program Committee 22st Int. Symp. Mathematical Theory of Networks and Systems (MTNS), Minneapolis, USA  
  International Program Committee Member 2nd Indian Control Conference, Hyderabad, India  

- *Mirjam Dür* was a visiting researcher (1 week) at the Department of Mathematics, Technion Haifa, Israel,  
  gave a plenary talk at MOPTA 2015 (Modeling and OPtimization: Theory and Applications),
Lehigh University in Bethlehem, PA, USA, was a member of the jury for the JoGO Best Paper 2014 Award of the Journal of Global Optimization.

- Harry Trentelman is a member of the IEEE Technical Committee on Behavioral Systems and Control. He was an appointed member of the Board of Governors of the IEEE Control Systems Society, and a member of the advisory board of the Lorentz Center.
  He is international Program Committee Member 22st Int. Symp. Mathematical Theory of Networks and Systems (MTNS), Minneapolis, USA

- Arjan van der Schaft is Chairman of the international Steering Committee of the International Symposium on Mathematical Theory of Networks and Systems (MTNS).
  He is member of the
  IFAC Technical Committee on Non-linear Control Systems;
  IFAC Technical Committee on Distributed Parameter Systems;
  IEEE Control Systems Society Technical Committee on Systems Biology.
  He was long-term visitor (August 25 - October 31, 2015) of the Institute of Mathematics and its Applications (IMA), University of Minnesota, Minneapolis.

5.7 Further information

List of seminars 2015:

- 2015, December 3, 11:00-12:00
  Luigi Iannelli (University of Sannio in Benevento)
  The I3RES EU project: ICT based management for the smart grid optimal operation

- 2015, November 26, 11:00-12:00
  John W. Simpson-Porco (University of California, Santa Barbara)
  Voltage control of micro and power grids

- 2015, November 25, 15:00-16:00
  Luigi Iannelli (University of Sannio in Benevento)
  A receding horizon approach for the optimal power flow in storage equipped electrical grids

- 2015, November 19, 11:00-12:00
  Luigi Iannelli (University of Sannio in Benevento)
  A colored Gauss-Seidel approach for the distributed network flow problem

- 2015, November 5, 11:00-12:00
  Stephan Trenn (University of Kaiserslautern)
  Funnel synchronization for multi agent systems
– 2015, November 4, 11:00-12:00  
Aneel Tanwani (University of Kaiserslautern)  
Using norm estimators for sampled-data control of nonlinear systems with dynamic output feedback  

2015, July 9, 11:00-12:00  
Serkan Gugercin (Virginia Tech)  
Input-independent, optimal model reduction: Moving from linear to nonlinear dynamics

– 2015, June 25, 11:00-12:00  
Matin Jafarian (University of Groningen)  
Coordination with binary controllers: formation control and disturbance rejection

– 2015, June 12, 11:15-12:15  
Mario Sznaier (Northeastern University)  
The interplay between big data and sparsity in systems and control

– 2015, June 9, 16:00-17:00  
Fan Zhang (University of Groningen)  
Distributed control of networked Lur’e systems

– 2015, May 12, 16:00-17:00  
Arjan van der Schaft (University of Groningen)  
A network dynamics approach to chemical reaction networks

– 2015, April 24, 11:15-12:15  
Alessandro Macchelli (University of Bologna)  
Towards a port-based formulation of macro-economic systems

– 2015, April 23, 16:00-17:00  
Mauricio Munoz Arias (University of Groningen)  
Energy-based control design for mechanical systems

– 2015, March 27, 11:00-12:00  
Steffen Waldherr (University of Magdeburg)  
Dynamic optimization of metabolic-genetic networks

– 2015, February 19, 11:00-12:00  
Ewoud Vos (University of Groningen)  
Formation control in the port-Hamiltonian framework

– 2015, February 3, 11:30-12:30  
Jonathon Mayo Maldonado (University of Southampton)  
Introduction to micro and smart grids
– 2015, January 28, 11:15-12:15
Jonathon Mayo Maldonado (University of Southampton)
Switched linear differential systems

– 2015, January 23, 14:00-15:00
Jonathon Mayo Maldonado (University of Southampton)
Introduction to power electronics
6. Distributed Systems

Group leader:
Prof. dr. ir. M. Aiello

Tenured staff (JBI members)  source  fte
Prof. dr. ir. M. Aiello  RuG  1.0
Prof. dr. A. Lazovik  RuG  1.0

Non-tenured staff (JBI members)
Dr. D. Bucur  RuG  1.0

Administrative staff
E.D. Elshof  RuG  0.15

Postdocs
G.A. Pagani  IBM/RUG  0.2
I. Georgievski  NWO  0.2
T.A. Nguyen  RuG  0.1

PhD students
F.A.S. AlSaif  KKU-SA  1.0
    (supervisor: Aiello)
F. Blauw  Espria  1.0
    (supervisor: Aiello)
I. Georgievski (Until September)  NWO  1.0
    (supervisor: Aiello)
H. Groefsema  NWO  0.5
    (supervisor: Aiello)
T.A. Nguyen (Until November)  V322 Vietnam  1.0
    (supervisor: Aiello)
F. Nizamic  JoinEU-SEE  1.0
    (supervisor: Lazovik)
A. R. Pratama  LPDP  1.0
    (supervisor: Aiello)
A. Sha  CSC  1.0
    (supervisor: Aiello)
B. Setz  NWO  1.0
    (supervisor: Aiello)
Guests
B. Rochdi, University of Skikda, Algeria
D. Amendola, La Sapienza University of Rome, Italy
E. Sosa, Universidad Nacional de Misiones, Argentina
6.1 Research Program

Distributed Information Systems are concerned with the delocalization of computation on several hosts and their coordination via message passing. Looking at today’s information systems, one notices that most of them, if not all, have some form of distribution. The key issues that emerge for research become those of addressing heterogeneity, scalability, and run-time adaptation. In the context of distributed systems, the group focuses on a number of sub-areas: Service-Oriented and Cloud Computing, Pervasive Computing and Sensor Networks. While interesting applications areas for the group are: Health care, Domotics and Smart Energy Systems.

6.1.1 Service-Oriented and Cloud Computing

Service-Oriented Computing (SOC) is an emerging computing paradigm for building distributed information systems in which the concepts of distribution, openness, asynchronous messaging and loose coupling take a leading role. In this context, applications are built out of individual services that expose functionalities by publishing their interfaces into appropriate repositories, abstracting entirely from the underlying implementation. Published interfaces may be searched by other services or users and subsequently be invoked. The interest in SOC is a consequence of the shift from a vision of a Web based on the presentation of information to a vision of the Web as computational infrastructure, where systems and services can interact in order to fulfill users’ requests. Web Services (WS), the best-known example, are the realization of service-oriented systems based on open standards and infrastructures, extending the XML syntax. The ‘servicization’ of software envisioned with SOC has brought to the idea of Cloud Computing. In the latter approach, services are further abstracted and clustered in opaque and remote “clouds” of computational and storage services. This allows for virtually infinite scalability from the service consumer perspective, while promoting the ‘offering’ of underutilized resources on the producer’s side. Our group is active on three main lines of research: (1) Artificial Intelligence (AI) planning for taking advantage of the dynamicity of SOC and Cloud frameworks; (2) Cloud provisioning; and (3) Service-based business process management.

Automatic Service Composition

Service domains constitute an application field where automated planning can significantly contribute towards achieving customizable and adaptable composition. In many cases, domains can be characterised with composite services that describe more complex situations than basic services. The composite services contain advice on how to perform efficient compositions. Among planning techniques, Hierarchical Task Network (HTN) planning supports representing such composite information and enables automatic service composition. HTN planning uses a domain description that contains methods as possible ways of decomposing composite services. We investigated the use of HTN planning for service composition in the domains of ubiquitous computing and cloud computing.
Automation and Decision Making in Buildings

The vision of a future in which environments support the people occupying them requires computing facilities that could help evolve these environments. At the same time, the overall objective to save energy as much as possible should be maintained. All this can be accomplished by bringing a degree of sophistication to the processing of and reasoning over the information provided by a network of diverse devices and sensors. The processing refers to the achievement of some goal (or performing a task), and the selection and combination of tasks at run-time. In this way, the goal achievement can result in different solutions depending on the current state of the environment.

Modern indoor spaces form an environment that is particularly suitable for the application of automated planning. While the environment is well structured and usually well defined, it is also partially controllable, which makes the added value gained by non-trivial automated composition and monitoring of operations a feasible and realistic task. Given such setting, automated planning can perform powerful reasoning for complex tasks which considerably advance the level of environment intelligence. We have deployed our HTN planner in the restaurant of our own office building Bernoulliborg. The planner computes a plan as a sequence of actions that control restaurant lamps in such a way that lamps are turned on only if necessary with respect to the natural light level and the presence of people in the restaurant. This enables us to achieve interesting results on energy saving.

Model Checking for Business Process Variability and Compliance

Business Process Management is deployed by organizations to support their main business goals. When similar business processes are deployed in different organizations, one typically adapts a template process manually to the different execution environments and organizational needs. In more extreme cases, however, organizations are forced to adapt their methods to match the template process in order to reduce initial development costs. However, throughout each process adaption, organizations must also continue to adhere to governmental laws and international regulations to avoid large fines. Current techniques verify such compliance either during or after process execution. Non-compliant processes then need to be rolled back, either partially in the best case scenario, or entirely. However, by offering temporal logic based business process templates and a translation from a business process to a Kripke structure, a process can be verified against its template specification using model checking techniques pre-runtime. As a result, non-compliant processes can easily be detected prior to process execution, avoiding process execution and roll-back costs. The research is focused on offering model checking of business processes pre-runtime for compliance and variability needs. We propose a translation from a business process to a Kripke structure through colored Petri net patterns such that temporal logic formulas (e.g. CTL or LTL) can be verified using established model checkers. An early prototype was developed to support the definition of template specifications, translate business processes through Petri nets into Kripke structures, and subsequently call the NuXMV model checker while interpreting its results to provide the user with visual feedback.

Data Centre

In “Metrics for Energy-aware and Sustainable Data Centers. V. Dinesh Reddy, B. Setz, G.R. Gangadharan, M. Aiello. To be published“, we look at the numerous metrics available for different aspects
of data centers and analyse these metrics to discover relationships between different metrics. There is still unfathomable information on the efficiency of the data centers. It is essential to have this information to predict the growth or set effective metrics and targets in Data Centers. With the rapid growth of data center demands and environmental issues people have identified this as one of the fastest rising sectors in this decade. Continuous monitoring and measuring will help the data center operators pro-actively identify and resolve potential issues, serve the growing business demands and thus improve the financial growth of an organization. This is a clear end goal for metrics development work streams. In this work, we explore diverse metrics that are currently used in various data center infrastructure components and propose a taxonomy of metrics based on various dimensions of a data center. Based on our observations, we believe that new metrics should be developed considering different factors like age, location, type of data center and managerial issues.

6.1.2 Pervasive Computing and Sensor Networks

Pervasive computing envisions a future in which computers seamlessly blend into the fabric of daily life and eventually “disappear” in the environment. Domotics and building automation consider indoor environments daily used by humans where large numbers of small, inexpensive and networked processing units are embedded into everyday objects. These units are organised and interoperate in Wireless Sensor Networks (WSNs). Applications range from support for healthy aging, for people needing medical assistance, or for saving energy by means of automatic control.

Sensor Networks

In “Characterizing Topological Bottlenecks for Data Delivery in CTP using Simulation-Based Stress Testing with Natural Selection“ (Ad Hoc Networks) we analyze the performance of routing protocols for ad-hoc networks. Protocols such as the Collection Tree Protocol (CTP) are designed with simple node-local behaviour, but are deployed on testbeds with uncontrollable physical topology; exhaustively verifying the protocol on all possible topologies at design time is not tractable. We obtain topological insights on CTP performance, to answer the question: Which topological patterns cause CTP data routing to fail? We stress-test CTP with a quantitative testing method which searches for topologies using evolutionary algorithms combined with protocol simulation. The method iteratively generates new test topologies, such that the execution of the protocol over these topologies shows increasingly worse data-delivery ratios (DDR). We obtain a large set of example topologies of different network sizes up to 50 nodes, network densities, data rates, table sizes, and radio-frequency noise models, which, although connected, trigger a data delivery of nearly zero. We summarize these topologies into three types of topological problems, the root cause of which is the presence of certain asymmetric links and cycles, combined with a certain size of the routing table. We verify causality, i.e., show that randomly generated topologies having these particular features do cause low DDR in CTP. This testing methodology, while computationally intensive, is sound, fully automated and has better coverage over the corner cases of protocol behaviour than testing a protocol over manually
crafted or random topologies.

In “Black Holes and Revelations: Using Evolutionary Algorithms to Uncover Vulnerabilities in Disruption-Tolerant Networks” (Evo*) we do a security analysis of Disruption-Tolerant Networks. A challenging aspect in open ad hoc networks is their resilience against malicious agents. This is especially true in complex, urban-scale scenarios where numerous moving agents carry mobile devices that create a peer-to-peer network without authentication. A requirement for the proper functioning of such networks is that all the peers act legitimately, forwarding the needed messages, and concurring to the maintenance of the network connectivity. However, few malicious agents may easily exploit the movement patterns in the network to dramatically reduce its performance. We propose a methodology where an evolutionary algorithm evolves the parameters of different malicious agents, determining their types and mobility patterns in order to minimize the data delivery rate and maximize the latency of communication in the network. As a case study, we consider a fine-grained simulation of a large-scale disruption-tolerant network in the city of Venice. By evolving malicious agents, we uncover situations where even a single attacker can hamper the network performance, and we correlate the performance decay to the number of malicious agents. In future works, there will be included a functional analysis of other types of networks, such as social networks, for relevant performance factors.

**Green Computing**

In “Power Management of Personal Computers based on User Behaviour. B. Setz, F. Nizamic, A. Lazovic and M. Aiello. International Conference on Smart Cities and Green ICT Systems.”, we propose a method to decrease the energy consumption of personal computers by learning the user’s behaviour. It has been shown that up to 64 percent of personal computers in office buildings are left running during after-hours. Enabling power management options such as sleep mode is a straightforward method to reduce the energy consumption of computers. However, choosing the right timeout can be challenging. A sleep timeout which is too low leads to discomfort, whereas a timeout which is too high results in poor energy saving efficiency. Having the users choose their own sleep timeout is not viable as research shows that most users disable the sleep timeout completely, or choose a suboptimal timeout. Unlike existing context based power management systems which use predefined rules, we propose a solution which can determine a personalized sleep timeout for any point in time solely based on the users behaviour. We propose multiple models which have the goal of maximizing the energy savings while minimizing discomfort. The models are tested on the computers of employees of the University of Groningen over several weeks. We analyse the results of the experiments and determine which model performs best. We can potentially save between 4.02 and 17.17 kWh per computer per year, depending on the model that used.

**Online Fault Detection and Classification in WSNs**

In pervasive computing environments, wireless sensor networks play an important infrastructure role, collecting reliable and accurate context information so that applications are able to provide services to users on demand. In such environments, sensors should be self-adaptive by taking correct decisions based on sensed data in real-time in a decentralised manner; however, sensed data is often faulty. We
thus design a decentralised scheme for fault detection and classification in sensor data in which each
sensor node does localised fault detection. The question we are trying to answer is how to process as
much data as possible while keeping the communication overhead, memory and computational cost
low.

**Automation and Decision Making in Buildings**
The vision of a future in which environments support the people occupying them requires computing
facilities that could help evolve these environments. At the same time, the overall objective to save
energy as much as possible should be maintained. All this can be accomplished by bringing a degree
of sophistication to the processing of and reasoning over the information provided by a network of
diverse devices and sensors. The processing refers to the achievement of some goal (or performing a
task), and the selection and combination of tasks at run-time. In this way, the goal achievement can
result in different solutions depending on the current state of the environment.

Modern indoor spaces form an environment that is particularly suitable for the application of auto-
mated planning. While the environment is well structured and usually well defined, it is also partially
controllable, which makes the added value gained by non-trivial automated composition and moni-
toring of operations a feasible and realistic task. Given such setting, automated planning can perform
powerful reasoning for complex tasks which considerably advance the level of environment intelli-
gence. We were working on applying HTN planning to the domain of office buildings. Future work
includes a deployment and testing of our planner in an actual environment.

**WSNs Techniques for Energy Savings in Buildings**
We strive to apply our smart solutions to new buildings to make them even more energy-efficient. To
realised such solutions, we believe that buildings should be able to understand not only their outside
and inside environment conditions (e.g., temperature, natural light, etc.) but also their occupants’
activity, thus they can adapt their operations in order to reduce their energy consumption while mainta-
ining the same level of service. For the sake of environment monitoring and context information
gathering, we rely on wireless sensor networks (WSNs) to monitor and collect context information as
well as for actuating and controlling the environment accordingly.

Existing buildings are responsible for more than 40% of the world’s total primary energy consumption.
Office buildings are responsible for a significant fraction of the energy consumption and greenhouse
gas emissions worldwide. Moreover, current building management systems fail to reduce unnecessary
energy consumption while preserving user comfort because they are unable to cope with dynamic
changes due to users’ interaction with the environment. Therefore, to cope with the dynamicity of
building’s environment and users’ activity, we study, both theoretically and practically, middleware for
sensing and controlling buildings with emphasis on human activity recognition and adaptive control to
reach savings of up to 30% in building energy consumption. As a future work, we focus on extending
our smart energy system to automated control of heating systems.

We developed a prototype that uses processes sensory and actuator data and reasons over such context
information to compute a plan. The plan is sequence of actions that control restaurant lamps in such a way that lamps are turned on only if necessary with respect to the natural light level and the presence of people in the restaurant.

6.1.3 Smart Energy Infrastructures

Energy markets are undergoing important changes in latest years, especially the unbundling tendency in the energy sector is changing the rules of the game. In addition, at the same time, economies of scale for technologies once unaffordable for the end user, are helping the spread of small-scale energy generators (i.e., combined heat and power, photovoltaic panels, small-wind turbines) that allow even the end user to produce its own energy. In this landscape we envision a future energy system in which every user in the power-grid network becomes a peer who can either sell its own produced energy surplus to everybody else in the network, or buy energy from someone else, at a give point in time. The main research focus is to investigate how it is possible to exchange energy in a peer-to-peer oriented network grid both from a network topology perspective and from a software service perspective. Moreover, this approach can also be a good driver to the spread of renewable energies generation, which is easier to implement at small and local scale, reduce losses and inefficiencies in energy transmission and distribution and overall contribute to reach a zero-impact energy system on the environment.

In 2015, the focus has been on collaboration with the industry and other institutions. Common ground concerning network reliability in an attack-healing process have been evaluated. Another side of the research has focused on the evaluation of failure conditions in complex network of electric assets and data analytics on such assets. This last research topic was realized in collaboration with IBM Research T.J. Watson. Together with University of Pisa and University of Modena, the optimal location of stage resources in the power grid have been investigated during student exchange programs.

Future efforts will be devoted to go further in evaluating the economic relationships with evolved distribution networks and on investigating new and additional services required in the Smart Grid panorama.

6.1.4 Health Care

There is a paradigm shift in modern day health care towards a patient-centered approach, where patients are in control of managing their disease, often through the use of web applications. For patients suffering from schizophrenia however, little has been done so far and this is often attributed to the fact that these patients have different needs with respect to the structure, content, and user interface of a web site. This is why the University Medical Center Groningen (UMCG) and the University of Groningen cooperate to design an intelligent web application specifically for this group of patients.
By data mining patients’ questionnaire answers, test results, health records, and demographic information, relevant information and intelligent suggestions can be offered, personalized and localized for each patient.

Another project we are working on is based on automating vector autoregression (VAR) of patient diary data. VAR techniques allow medical professionals to see, for individual patients, for example whether depression causes a lack of activity, or whether a lack of activity causes depression. VAR is a promising technique when applied in the analysis of patient diary data, but the construction of VAR models requires expertise and time. Currently, vector autoregression on patient diary data is strictly done manually by statisticians, which causes a delay of weeks between when patients enter their data and when clinicians can interpret the results. In 2013, we have created a web application that automates most parts of the VAR approach and can provide medical professionals with quick results. This project is also in cooperation with the UMCG.

Each person is different and should be treated as such. Comparing personal data to group averages can give a basic idea on how a person compares to the general population, but does not suffice for providing ‘true personal feedback. In order to personalize feedback, measuring changes within the person (e.g., over time) could be much more informative.

In psychopathology, a paradigm shift takes place towards a more person-centred approach. Healthcare group Espria has set up a project to include a person-centred approach for assessing the well-being of elderly people. Espria plans to measure a large group of elderly people by conducting questionnaires. With these questionnaires we want to provide the participants with interesting feedback about their well-being. Such feedback could provide insight into their well-being and help to sustain or even enhance it. The University Medical Center Groningen (UMCG) and the University of Groningen (RuG) are collaborating on the development of a system to conduct these questionnaires, to analyse the data, and to provide meaningful and personal feedback. The research in this project focuses on novel and effective ways to analyse the collected data and to provide feedback. In the first phase the research focussed on the general population of the Netherlands (i.e., all people aged 18 and above), in a project known as HowNutsAreTheDutch? (www.hoegekis.nl). In the second phase (the current phase) the focus shifts towards the elderly people in the Netherlands. For this second project we are applying novel methods to analyse the data and provide feedback, but are also tailoring the questionnaires conducted to the participants, by asking only the questions relevant to the person under study.

In the last phase of the project we will also research various machine learning techniques, and determine which of them could best be used for analysis in the field of mental health. For example, as a means to determine response to treatment.
6.1.5 Electronic Learning

Even though there are rubrics being utilized to evaluate quality in on-line course materials, so far, most of the industries did not agree on the instruments being utilized to assess the information systems aspects on web-based learning programs. Many institutions profusely promote that they provide quality on-line education yet they do not have a way to assess or benchmark their programs. Higher education is in need of new ways to classify and evaluate the information systems for electronic learning. To improve this situation, in 2013, we started the study by searching the literature, comparing, and noting the most recently designed Web-based information systems models. The planned study outcome is to compare different information systems models to identify and quantify quality aspects of Web-based learning in comparison to its traditional and hybrid counterparts; what is in turn needed to support the development of strategic planning and decision making.

6.2 Research subjects

F. Blaauw: Time series analysis, e (mental) health, machine learning, self-tracking, personalized medicine.
I. Georgievski: Automated planning, service composition, ubiquitous computing, energy-saving systems.
A. Sha: Smart Grid, Smart Energy Systems, Peer-to-peer Network.
6.3 Publications

Patents


Dissertations

- I. Georgievski, Coordinating services embedded everywhere via hierarchical planning, Promotor: M. Aiello, Faculty of Mathematics and Natural Science, University of Groningen, 9 October 2015, 264 pages.

Articles in scientific journals


**Articles in conference and workshop proceedings**


**6.4 External funding and collaborations**

External funding: active large projects.
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Name</th>
<th>Funding Agency</th>
<th>Programme</th>
<th>PI</th>
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<tbody>
<tr>
<td>DEMRE</td>
<td>Design Electricity Market and Renewable Energy</td>
<td>NWO</td>
<td>Responsible Information</td>
<td>Aiello</td>
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<tr>
<td>BIGS</td>
<td>Beijing Groningen Smart energy cities</td>
<td>NWO</td>
<td>JSTP Smart Energy in Smart Cities</td>
<td>Aiello</td>
</tr>
<tr>
<td>NextGen SmartDC</td>
<td>Next Generation Smart Data Centers</td>
<td>NWO</td>
<td>Indo Dutch Science Industry Collaboration in Computer Science</td>
<td>Aiello</td>
</tr>
<tr>
<td>EnSO</td>
<td>Energy Smart Offices</td>
<td>NWO</td>
<td>Smart Energy Systems</td>
<td>Aiello</td>
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<tr>
<td>EnS</td>
<td>Energising Services: Energy Aware Services and Services for the Energy Sector</td>
<td>NWO</td>
<td>China Netherlands Joint Scientific Thematic Research Programme</td>
<td>Aiello</td>
</tr>
<tr>
<td>Nerdalize</td>
<td>Heating Houses with Computing Power in the Form of Radiators</td>
<td>STW</td>
<td>STW Take-off Grant</td>
<td>Lazovik</td>
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</tbody>
</table>

The DS group has active a number of research projects funded mostly by NWO in areas tied to smart energy systems, sustainability, collaboration with industry (see Table External funding). A number of PhD positions are also funded by foreign funding agencies (see Table PhD study Grants).
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Name</th>
<th>Funding Agency</th>
<th>Recipient</th>
<th>PI</th>
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<tr>
<td>JoinEU-SEE</td>
<td>Testing for Highly Distributed Service-Oriented Systems</td>
<td>European Commission</td>
<td>Nizamic Lazovik</td>
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<tr>
<td>V322</td>
<td>WSN for energy saving</td>
<td>Vietnam</td>
<td>Nguyen Aiello</td>
<td>Aiello</td>
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<tr>
<td>CSC</td>
<td>CSC-RUG joint scholarships programme</td>
<td>China Scholarship Council</td>
<td>Sha Aiello</td>
<td>Aiello</td>
</tr>
<tr>
<td>LPDP</td>
<td>Indonesia Endowment Fund for Education</td>
<td>Ministry of Finance of the Republic of Indonesia</td>
<td>Pratama Aiello</td>
<td>Aiello</td>
</tr>
</tbody>
</table>
**External Collaborations**

Most notable collaborations were active with the following individuals and institutions:

Robin Hagemans, Pieter den Hamer, and Floran Stuijt, Alliander N.V., Tarun Kumar, Aanchal Aggarwal, Mark Lavin, and Abhishek Raman all, IBM Research, Marti Rosas-Casals, Polytechnic University of Catalonia, Lingen Luo, Shanghai Jiao Tong University, Prof. J. Slaets, Espria Academy, Prof. P. de Jonge, UMCG, Ester Kuiper and Chantal Bosman, Lifely, Dr. Blagoj Risteveski, St. Kliment Ohridski University in Bitola, V. Dinesh Reddy and Prof. G R Gangadharan, the Institute for Development and Research in Banking Technology (IDRBT), Hyderabad, India, A. Berfu Unal and Ellen Van Der Werff, Environmental Psychology RUG, Giovanni Squillero, Politecnico di Torino, Alberto Tonda, French National Institute for Agricultural Research, Giovanni Iacca, INCAS3, Dr. Guram Beshanshvili, New Mexico State University, Prof. Dr. Dustdar, Technical University of Vienna, Prof. Dr. Wim van Gemert, Hanzehogeschool, Prof. Dr. Gottlob, Technical University of Vienna, Prof. Dr. George Huijtema, RUG and TNO, Peter Kamphuis, Hanzehogeschool, Groningen, Prof. Dr. Eiter, Technical University of Vienna, Prof. Dr. Han Slootweg, TU/e and Enexis, Prof. Dr. Stefan Tai, Karlsruhe Institute of Technology, Prof. Dr. Apt, Arbab CWI, Prof. Dr. Michael Beigl, KIT, Prof. Dr. Daniele Nardi, UoR, Prof. Dr. Bernhard Nebel, FU, Prof. Dr. Roberto Baldoni, UoR, Dr. Massimo Mecella, UoR, Prof. Dr. HT Yang, National Cheng Kung University, Dr. Rix Groenboem, Parasoft, Hemmo Halzebos, Enexis, Dr. Heiko Ludwig, IBM, Wico Mulder, Logica, H. Zwaal, TenneT, Emiliano Binotti, Fluid Solutions, Dr. Paul Shrubsole, Philips Research Laboratories, Dr. Chun Yu Chen, ITRI, Jose J de las Heras, Advantic Sistemas Y Servicios S.L., Prof Dr. Marti Rosas-Casals, Polytechnic University of Catalonia, Will West Control4 Corporation, Prof. Dr. Christian Claudel, King Abdullah University of Science and Technology, Prof. Dr. Kenji Tei, Japanese National Institute of Informatics.

### 6.5 Further activities

Aiello is an honorary professor at Bournemouth University, UK. Aiello is the Information Director of the *Transactions on Computational Logic* of the Association of Computing Machinery (ACM). He is a member of the reviewing board of Frontiers in Energy Systems and Policy. He is a member of the editorial board of the *Journal on Service Oriented Computing and Applications*, Springer; *International Journal of Web Services Research*, IGI-Global; and a member of the senior editorial board of *Annals of Computer Science and Information Systems of the Polish Information Processing Society*. He has been in the programme committee of more than 30 international conferences and workshops. Since 2014, he sits on the board of the startup Nerdalize BV as representative of the crowd-funders coop.

Georgievski was a member of the editorial board of the Journal of Emerging Research and Solutions
6.6 Awards

B. Setz has been awarded SURFSara Duurzaamheid & ICT innovatieregeling 2015: 10,000 Euro grant for the project "Sustainable Buildings Competition". F. Nizamic has been awarded some prestigious awards: Best business model and pitch in Startup FastTrack weekend, Community Award at the Pioneers Festival 2015, Energy Academy Europe for Startup FastTrack competition: 10,000 Euro grant, Sustainable Campus International Competition 2015: 3,000 $ grant, and Top 100 out of 2300 competing startups at the Hello tomorrow 2015 startup conference.
7. **Fundamental Computing Science**

**Group leader:** Prof.dr. G.R. Renardel de Lavalette

<table>
<thead>
<tr>
<th>Tenured staff (JBI members)</th>
<th>source</th>
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<tbody>
<tr>
<td>Dr. J.A. Pérez Parra</td>
<td>RUG</td>
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<tr>
<td>Prof.dr. G.R. Renardel de Lavalette</td>
<td>RUG</td>
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</tr>
</tbody>
</table>

**Emeritus**
Prof.dr. W.H. Hesselink

**External PhD student**

**PhD student**
M. Cano  
Drs. P. Dykstra  
(supervisor: Renardel de Lavalette and Verbrugge (AI))

**Guest**
J. Dedeić, University of Novi Sad, Serbia (January 8 - February 1, 2015)
7.1 Research Program

The objective of this programme is to contribute to the understanding of the logical and mathematical foundations of computing science and to realize a two-way transfer between this fundamental research and more applied subdisciplines of computing science. Our research focuses on formal methods, which are based on concepts and theories from discrete mathematics and logic. They are applied to enhance the reliability of computer systems and computer software, and also to further the understanding of the possibilities of computing in general. The following themes are studied: formal methods for concurrent systems, programming methodology, multi-agent systems, mathematical logic.

In formal methods for concurrent systems, the main issues are specification and analysis. The research for specification focuses on process calculi, formal languages that express the interaction of concurrent processes in a compositional style, while the research for analysis focuses on type systems for process calculi, often referred to as behavioral type systems. Intuitively, types represent the structured protocols that a process specification should implement. By coupling process calculi with behavioral types, we obtain a compositional approach to the validation of safety and liveness properties on specifications of communicating systems. A particular class of behavioral types is session types, and thus one talks of session-typed concurrency to refer to concurrent processes which adhere to protocols specified as session types.

For programming methodology, the aim is to contribute to the design, specification, and verification of sequential, parallel and distributed algorithms, programs, and systems. We prove properties of such algorithms or systems by assertional means, i.e., by reasoning about individual states and computation steps, rather than considering entire execution sequences. Even so, seemingly modest algorithms may require a host of case distinctions that a human prover finds difficult to control. In such situations, we use mechanical theorem provers for the administration of proof obligations.

Multi-agent systems is a subdiscipline of both Computing Science and Artificial Intelligence. Agents are intelligent, possibly mobile processes to which intentions can be attributed: beliefs, desires and commitments. A multi-agent system consists of agents that cooperate to perform a task. We focus on social simulation with reasoning and communicating agents, for which we build agent communication models based on dialogues, involving dialogical and fuzzy logic. We aim to apply our techniques and result to better understanding of the emergence of extreme opinions in groups.

In mathematical logic, we focus on the proof theory of equational logic and Horn logic, and on intuitionistic logic. Intuitionism was created by L.E.J. Brouwer; its logic, formalized by A. Heyting, reappeared as the foundation of type theory with applications in programming and theorem proving. Equational logic is the formalization of algebraic equational reasoning, used in tools like Mathematica. Horn logic is the logic of formulae of the form $A_1 \land \cdots \land A_n \rightarrow B$; it is the basis of the logic programming language Prolog. We focus on fundamental properties like completeness (is a given proof system strong enough to prove all true statements?) and exactness (does a certain model
correspond to the structure of a logic?).

7.2 Research subjects

**Cano**: session-typed concurrency, behavioural types, synchronous programming.

**Dykstra**: simulation of social and mobile agents, involving dialogues and group forming.

**Hesselink**: design and verification of concurrent and geometric algorithms.

**Pérez**: process calculi, type systems, session-typed concurrency.

**Renardel**: proof theory of equational logic and Horn logic; intuitionistic logic.

7.3 Publications

**Chapters in books**


**Articles in scientific journals**


**Articles in conference proceedings**

90


7.4 External funding, collaboration and internationalization

Dykstra and Renardel collaborate with R. Verbrugge (RUG, Artificial Intelligence), W. Jager (RUG, Faculty of Economics and Business Sciences) and C. Elsenbroich (University of Surrey, Guildford, U.K.) on multi-agent based social simulation.

Hesselink collaborates with P.A. Buhr (University of Waterloo, Canada) and D. Dice (Oracle Labs, Burlington, USA) on design and verification of mutual exclusion algorithms for shared memory systems, and with Alex Aravind (University of Northern British Columbia) on algorithms for group mutual exclusion.

Pérez is a member of the management committees of the EU COST Actions IC1201 (BETTY: Behavioral Types for Reliable LargeScale Software Systems) and IC1402 (ARVI: Runtime Verification Beyond Monitoring).

Pérez collaborates with L. Caires and B. Toninho (University NOVA of Lisbon, Portugal), M. Cano and C. Rueda (Universidad Javeriana, Colombia), I. Castellani (INRIA, France), M. Dezani-Ciancaglini (University of Turin, Italy), C. Di Giusto (University of Nice, France), O. Dardha (University of
Glasgow, UK), N. Yoshida and D. Kouzapas (Imperial College London, UK) on diverse aspects of session-typed concurrency.

### 7.5 Further information

*Hesselink* is a member of the Editorial Board of the international scientific journal *Science of Computer Programming*. 
8. Intelligent Systems

**Group leader:** Prof.dr.sc.techn. N. Petkov

**Tenured staff (JBI members)**

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<th>Name</th>
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<td>Prof. dr. M. Biehl</td>
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<td>Prof.dr.sc.techn. N. Petkov</td>
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<td>Dr. M.H.F. Wilkinson</td>
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**Researchers**

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**PhD students**

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<tr>
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<td>M. Lange</td>
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<tr>
<td>F. Melchert</td>
<td>IFF Magdeburg, RUG</td>
<td>UE</td>
</tr>
<tr>
<td>D. Nebel</td>
<td>HS Mittweida</td>
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<tr>
<td>G. Owomugisha</td>
<td>Makerere University</td>
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<td>A.C. Emerencia</td>
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<td>L. Fernandez Robles</td>
<td>Univ. Leon</td>
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<td>J. Guo</td>
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<td>M. Lopez Antequera</td>
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<td>UE</td>
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<td>A. Neocleous</td>
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<td>N. Striscuglio</td>
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<td>C. Shi</td>
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<td>E. Schiza</td>
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<tr>
<td>E. Talavera Martinez</td>
<td>Univ. Barcelona, RUG</td>
<td>UE</td>
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**PhD students**

M. Babai  
(supervisor: Wilkinson)  
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(supervisor: Wilkinson)  
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1.0

Jasper van de Gronde  
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R. Nakibuule  
(supervisor: Wilkinson)  
NUFFIC  
external

**Guests**

A. Witoelar, University of Oslo, Norway  
G. Zacchary, Arizona State Univ., USA  
A. Schulz, Bielefeld University, Germany  
M. Lux, Bielefeld University, Germany  
T. Villmann, Hochschule Mittweida, Germany  
N. Caticha, Univ. Sao Paulo, Brazil  
P. Bosilj, Universite de Bretagne-Sud, IRISA Vannes, France  
J. Westerinck, Philips Research, Eindhoven  
L. Brun, Univ. Caen, France  
D. Pleiter, FZ Juelich and Univ. Regensburg, Germany  
G. Kruithof, Astron, Netherlands  
C. K. Neocleous, Tech. Univ. Cyprus, Cyprus  
C. N. Schizas, Univ. Cyprus, Cyprus  
J. Oostveen, TNO, Netherlands  
J. Tavares, Univ. Porto, Portugal  
P. Radeva, Univ. Barcelona, Spain  
R. van Wezel, Radboud University Nijmegen, Netherlands
8.1 Research Program

High quality research in the area of intelligent computer systems is our mission. We aim at publishing in top journals and presenting results at leading international conferences. Strong emphasis is put on training graduate students and mentoring post-doctoral researchers to achieve outstanding results, having in mind also relevant interdisciplinary applications of computer science in life sciences, health care, finance, astronomy, etc.

A large variety of interrelated topics is addressed in our research program, including image processing and analysis, computer vision, pattern recognition, machine learning and brain-inspired computing.

We intend to continue developing efficient methods and algorithms in the general area of Intelligent Systems. By doing so, we will participate in the grand challenge of giving computers the abilities to perceive, analyse, learn, take decisions and to enhance human creativity. Various trans-disciplinary applications from areas such as medicine, life sciences in general, animal breeding, astronomy, robotics, surveillance, law enforcement or the financial industry continue to provide inspiration for our work. Notably, life-science, bio-medical and health-care applications constitute one important focus for our future research and a number of long-term collaborations have been established.

We participate in the school of Behavioural and Cognitive Neurosciences (BCN) with the brain-inspired computing aspects of our research. We are also members of the Advanced School of Computing and Imaging (ASCI) and we contribute to its course programme. We participate in the EU H2020 project TrimBot and the STW special programme Breed for Food. Our group plays an instrumental role in the Intelligent Systems specialisation of the MSc programme in Computer Science, by offering courses in Computer Vision, Pattern Recognition and Neural Networks and by providing research projects for graduate students. These graduate courses are followed also by many students of Artificial Intelligence and other programs.

Brain-inspired computing in pattern recognition and computer vision

We develop models of information processing in brain cortex and use them in computer algorithms. This research is relevant for the areas of image and audio processing, computer vision, pattern recognition, visual perception, and computational neuroscience. Our goal is to understand how people see and to deploy principles of natural vision in computer algorithms for artificial vision. Using facts from neuroscience and visual perception, we build models of visual and audio information processing in the brain and use them in computer simulations to obtain insights and derive practical computer vision algorithms.

One example is a model of a grating cell that we developed [Petkov, Kruizinga: 1997 Biol. Cyb. 76: 83-96] and used in a texture operator [Kruizinga, Petkov: 1999 IEEE Trans. Im. Proc. 8: 1395-1407], [Grigorescu, Petkov, Kruizinga: 2002 IEEE Trans. Im. Proc. 11: 1160-1167]. By means of computer simulations we demonstrated that grating cells may play an important role in the disambiguation of
edge information in early vision (texture vs. contours).


We also studied the orientation and speed tuning properties of spatio-temporal 3D Gabor and motion energy filters with surround suppression as models of time-dependent receptive fields of simple and complex cells in primary visual cortex (V1) [Petkov, Subramanian: 2007 Biol. Cyb., 97: 423-439]. We demonstrated how these filters are related to motion detection, noise reduction, texture suppression and contour enhancement.


We call our approach to model design ‘combination of receptive fields’ (CORF). We developed an efficient implementation of the mentioned models that we call ‘combination of shifted filter responses’ (COSFIRE). CORF models and COSFIRE filters are trainable as they can be configured by the automatic analysis of a user-specified prototype pattern.

Another example of our research that is inspired by psychophysical research on the human visual system is a method for the evaluation of the robustness of shape recognition algorithms to incompleteness of contours [Ghosh, Petkov: 2005 IEEE Trans. PAMI 27: 1793-1804].
Image and audio processing, computer vision, health care, big data, applications

We study processing operations that are fundamental for computer vision, such as contour detection. This resulted in a large survey: G. Papari and N. Petkov: Edge and line oriented contour detection: State of the art, J. Im. Vis. Comp., 29 (2-3), 2011, 79-103. Moreover, we have proposed a novel contour detector that relies on simple operations: convolutions with difference-of-Gaussian filters, blurring, shifting and multiplication [Azzopardi, Petkov (2012): LNCS 7552: 395-402].

In shape analysis we study geometrical approaches in which a feature point is characterized by the spatial arrangement of other feature points around it. The collection of local geometrical descriptors for the different feature points of an object is used as a shape characteristics of that object [Grigorescu, Petkov: 2003 IEEE Trans. Im. Proc. 12: 1274-1286]. In the same context we developed a method for the automatic construction of trainable filters that we called COSFIRE (Combination of Shifted Filter Responses) [Azzopardi, Petkov: 2013 IEEE Trans. PAMI 35 (2): 490-503] and we demonstrated the effectiveness of this approach in various practical applications.


We have recently proposed a novel delineation algorithm and demonstrated that it is highly effective and efficient for the segmentation of the vessel trees in retinal fundus images [Azzopardi, Strisciuglio, Vento, Petkov: 2015 Medical Image Analysis vol.19(1), 46-57].

Together with researchers from the Univ. of Salerno, we develop algorithms for audio surveillance [Foggia et al.: IEEE Trans. on Intelligent Transportation Systems, PP (99): 1-10, 2015], [Foggia et al.: Pattern Recognition Letters, Available online 9 July 2015].

Together with researchers from the Universities of Malaga and Bielefeld, we develop algorithms for odour recognition [Schleif et al.: Pattern Analysis and Applications. p. 1-14, 8 Jan. 2015].
Another application to health care is the system for personalized advice for schizophrenia patients that we develop with the group Distributed systems (M. Aiello) and researches from the psychiatry department of UMCG [Emerencia et al 2013 *AI in Medicine* 58 (1): pp. 23-36].

Together with researchers from the Univ. of Cyprus, we work on eHealth systems [Schiza et al.: Technology and Health Care Journal, 23 (4): 509-522, 2015].

In the area of big data, we designed a method that helps a large international bank recognise automatically in an early phase who among the delayers of mortgage rate payments will default [Sun et al., CIFEE, 489-496, 2014]. Early recognition is important because banks need to block certain capital in such cases and early arrangements with a client may reduce the overall amount. The method and its computer implementation are in use at the concerned bank since mid-2013 and led to large reduction of operation costs.

**Connected filters, Connectivity Theory and Segmentation**

Connected filters are a comparatively new field of research within mathematical morphology. They are edge preserving operators which have found use in noise removal, texture analysis, image compression and description, and feature extraction. Research on connected operators in our group entails algorithm development (including parallelization), development of new classes of filters, applications to 2-D and 3-D medical images, and the development of new connectivity measures for these filters for increased robustness. Recently, processing of giga-pixel and tera-pixel scale images for remote sensing and astronomy has been added to this list of applications.

One line of this research links to visual cortex modelling: developing morphological analogues of texture operators based on models of certain visual cortical cells. It is hoped these morphological counterparts will be an order of magnitude faster, whilst retaining the useful properties of the cortical cell models. Finally, fast visualization based on connected attribute filters is being explored. Recently, work has begun expanding this line into hyperconnected filters and attribute-space-connected filters, which increase the flexibility of perceptual groupings available, and allow dealing with overlap explicitly.

Extensions to colour, or other vector images, and even tensor images are being developed, both for regular colour and multi-band processing and for diffusion tensor imaging (DTI). Applications include brain imaging, astronomical imaging, and work is being started on surveillance applications.

This research also has close links to machine learning, because machine learning techniques are becoming incorporated into the morphological filtering methods themselves. Learning Vector Quantization has been used to teach filters to enhance certain objects in images.

Segmentation is a core problem in image analysis, and methods based on both simple thresholding methods and more advanced methods such as watersheds and deformable models are being explored. Application areas are many, but the focus lies on biomedical imaging, both macroscopic (MRI, CT) and microscopic. New application domains in astronomy are also being explored, and in particular
automatic detection of astronomical sources in massive image databases.

**Machine learning**

Three major goals can be identified in our research activities in computational intelligence and machine learning: to obtain a thorough theoretical understanding of machine learning based data analysis, the development and putting forward of efficient methods and algorithms, and their development in relevant practical applications.

Theoretical investigations of model situations provide valuable insights into machine learning processes and helps to optimize existing training schemes or to develop entirely new methods. Here, the use of adaptive measures and relevance learning in distance based classifiers is in the center of our interest. The method of Matrix Relevance Learning, for instance, is based on adaptive metrics in Learning Vector Quantization (LVQ). It has proven to improve classification performance significantly in many cases and, at the same time, provides valuable insights into the problem at hand.

With respect to algorithm development, important recent examples include specific approaches for functional data and the analysis of complex-valued feature vectors. Frequently, real world data combine qualitatively different observation or measurements. An obvious example is that of patient data, which stem from a variety of sources, frequently. The design and data driven optimization of suitable methods for such multi-modal data sets is one of the most interesting challenges in the field.

Practical applications of newly developed methods and algorithms constitute an essential part of our research. In this context, it is instrumental to establish and maintain intense collaborations with experts from the application domain.

In the following, a few recent examples of application oriented projects are highlighted:

A very successful on-going project concerns the classification of adrenal tumors and aims at the development of a reliable classifier based on steroid metabolomics data. The developed diagnostic tool is currently evaluated for clinical use in a prospective study. The approach is also being extended with respect to the monitoring of treated patients and the detection of tumor recurrences.

The recent investigation of cytokine expression data in the context of Rheumatoid Arthritis aimed at the selection of relevant markers in the context of chronic inflammatory diseases. The results triggered the identification of novel disease mechanisms in the early phases of Rheumatoid Arthritis.

As a third example of our activities in the analysis of bio-medical data, we would like to mention the efficient detection and classification of crop plant diseases based on photographic images is the topic of a joint project with Makerere University in Kampala, Uganda. This research will be extended significantly with respect to the use of hyperspectral images and models of disease dynamics in the framework of a project recently funded by the Melinda and Bill Gates Foundation.

Many scientific disciplines, in particular the life sciences, are experiencing an impressive increase of
the rate at which data are acquired. In the bio-medical context, for instance, genomics, proteomics, metabolomics, or other omics data play a role of increasing importance in areas ranging from basic research to clinical practice. Several methodological challenges can be identified immediately: The huge amount of potentially relevant data calls for automated analyses tools. High-dimensional, complex data sets need to be made accessible by means of compression and visualization techniques. Similarly, problems related to clustering, classification, or regression trigger the search for efficient dimension reduction tools and practical schemes for the selection of relevant features in the data.

Ultimately, the integration of information from various sources and technical platforms, e.g. clinical, imaging, and -omics data poses the question of how to combine and relate mixed data sets effectively.

Methodological challenges like the ones mentioned above will continue to be in the focus of our research interests. The close contact with real world applications constantly reveals interesting problems and generates new research questions.

### 8.2 Overview of scientific results

**Brain-inspired computing, pattern recognition, audio and image processing,**


Together with researchers from the Univ. of Salerno, we developed new algorithms for audio surveillance [Foggia et al.: IEEE Trans. on Intelligent Transportation Systems, PP (99): 1-10, 2015], [Foggia et al.: Pattern Recognition Letters, Available online 9 July 2015], [Foggia et al.: Proc of 12th IEEE Int. Conf. on Advanced Video and Signal Based Surveillance (AVSS), 2015, 1-6],

Together with researchers from the Universities of Malaga and Bielefeld, we developed effective algorithms for odor recognition [Schleif et al.: Pattern Analysis and Applications, 1-14, 8 Jan. 2015].


We achieved good results in the recognition of architectural and electrical symbols by COSFIRE filters with inhibition [Guo et al.: CAIP 2015, LNCS 9257, 2015, 348-358].

We achieved good results in cutting edge localisation in an edge profile milling head [Fernandez-Robles et al. CAIP 2015, LNCS 9257, 2015, 336-347].

We achieved good results in the automatic differentiation of u- and n-serrated patterns in direct immunofluorescence images [Shi et al.: CAIP 2015, LNCS 9256, 2015, 513-521].

We achieved good results in the ornamentation detection and recognition in singing folk music [Neocleous et al: CAIP 2015, LNCS 9256, 2015, 558-569].

Connected filters, Connectivity Theory and Segmentation

In terms of connected filters, several improvements of attribute filtering were made, along with forays into hyperconnected attribute filters. The work on automatic attribute-threshold selection, to eliminate the need for user intervention presented at International Conference on Pattern Recognition 2010, was extended, and this extended study was published in the thesis of F.N. Kiwanuka. A more extensive study has been accepted for publication in Pattern Recognition (online version available December 2015, in print 2016).

The work on implementing vector attribute filters in 3D and incorporating machine learning techniques into them has been extended. Previously we have shown that several methods for unsupervised learning (clustering) using vector attributes work better than automatic attribute threshold selection. Initial results were presented at the International Conference on Pattern Recognition 2012, and this work was extended to a wider study published in the thesis of F.N. Kiwanuka. Improvements have been presented at the International Symposium on Mathematical Morphology 2015 in Reykjavik, and an extended version has been accepted for a special issue of the new open access journal Mathematical Morphology, Theory and Applications and has appeared in January 2016.

An important new development is the study of remote sensing data, in collaboration with the European Commission Joint Research Centre, in Ispra, Italy. This entails multi-scale morphological studies of huge data sets, ranging from gigapixel to terapixel scale, with the aid of Differential Morphological Profiles (DMP). The aim is to use this type of analysis to detect, e.g., rubble in images of areas affected by earthquakes, tsunamis or other disasters. We have improved the previously published versions of the DMP algorithm to improve cache coherence and reduce computational overhead, leading to speed increases of a factor of three.

Further extensions include the Differential Area Profile, and the derived multi-scale levelling segmentation. Building on previous results, and using a new 64-core parallel machine obtained through funding from NWO, we are able to perform multi-scale analysis at a rate of about 4 Gpixels per minute, on this one compute server, attaining speed ups of up to 50× on 64 cores. The results have

An important new application is that of the Global Human Settlement Layer http://ghs1sys.jrc.ec.europa.eu/, which aims to give a complete, up-to-date overview of all human habitation on earth, and an unprecedented resolution. We are now moving to distributed memory algorithms for tera-pixel images. For this purpose a new algorithm is being devised, which changes the maximum communication and memory loads per node back from $O(N)$ to $O(\sqrt{N})$. Apart from work on remote sensing applications, very large stitched, 360 deg images can be processed using these methods.

We have continued our research into developing a better type of source extractor for astronomical imaging. We previously improved on the state-of-the-art program Source Extractor, by incorporating a real Max-Tree implementation, and implementing a new strategy for Max-Tree filtering called bi-variate statistical attribute thresholding. In methodology, we determine a threshold based on one attribute based on a statistical test on the likelihood that the feature detected is due to noise, as a function of the area of the feature. In this case the user needs to supply a $p$-value which determines the probability that a noise feature is rated as a true object. For large objects, a small deviation of, e.g., the image power within it over the local background suffices to rate as a detection, whereas a small object needs to have a higher image power. The results show great promise, as the sensitivity of the method to extended sources seems to be an order of magnitude better than SExtractor, whilst retaining excellent sensitivity for compact sources, and negligible false positive count, even at a conservative $p$-value of $10^{-6}$. We have since improved the background estimation and the detection method and presented the results at *International Symposium on Mathematical Morphology 2015* and the *International Conference on Image Processing 2015* in Quebec.

Given the data sizes and types, this means that we must develop a parallel Max-Tree algorithm for floating point and other high-dynamic-range data. The new algorithm has been developed and is a combination of a bottom-up flooding approach to compute a coarse approximation Max-Tree, followed by top-down refinement phase based on the union-find methods, thus combining the two leading schools of thought on these algorithms into a single “diplomatic” algorithm. Speed-up of up $40\times$ have been achieved on 64 cores, which translates to a 30-fold speed increase with respect to the fastest sequential algorithm. This work has been submitted to *IEEE trans. Pattern Anal. Mach. Intell.* A major revision under review at the moment.

A new parallel max-tree based algorithm for *local* pattern spectra was developed for classification of merging vs overlapping galaxies. The results were presented at the CAIP 2015 conference in Malta, where it received an honourable mention in the HPC paper award competition.

In collaboration with the Universities of Rennes and Vannes, France, we have investigated the use of local pattern spectra for content-based image retrieval. These patterns spectra provide similar performance to methods like SIFT, but with a much smaller feature vector size (65 vs 128 dimensions). These results were presented at the *International Symposium on Mathematical Morphology 2015* in Reykjavik, and the *International Conference on Image Processing 2015* in Quebec.
Machine learning and its applications

Here we highlight key results which were obtained and published in 2015 in the context of machine learning and its practical application.


In a collaboration with researchers from Bielefeld University, techniques for Inferring Feature Relevances from Metric Learning were introduced by A. Schulz, B. Mokbel, M. Biehl and B. Hammer in: IEEE Symp. Series on Computational Intelligence, Cape Town, IEEE, 8 pages (2015).

First results concerning the Polynomial Approximation of Spectral Data in LVQ and Relevance Learning were presented by F. Melchert at the Workshop New Challenges in Neural Computation at the GCPR 2015 in Aachen/Germany. This work was published, with co-authors U. Seiffert and M. Biehl, in Machine Learning Reports 03-2015: 25-32 (2015).

In a collaboration with Dagmar Scheel-Toellner from the School of Immunity and Infection, University of Birmingham/UK we have analysed cytokine expression data in Rheumatoid Arthritis (RA) patients. The application of Generalized Matrix Relevance LVQ, a method developed within our group, revealed that two specific bio-markers seem to play an essential role in the early stages of RA. This insight generated novel hypotheses about the disease mechanisms, which could be confirmed by targeted studies of tissue samples. The main findings were published by Y. Leo, N. Adlard, M. Biehl et al. in Annals of the Rheumatic Disease, avaliable online (2015).


Several journal and conference publications are currently in press which indicate that our research activities continue to yield significant output.
8.3 Research subjects

G. Azzopardi: visual cortex modeling, object recognition and localization.
L. Fernandez Robles: visual pattern recognition.
J. Guo: inhibition in trainable feature detectors.
M. Lopez Antequera: pattern recognition for robotics.
A. Neocleous: signal processing and classification for music analysis.
C. Shi: inhibition in trainable feature detectors.
N. Strisciuglio: vascular segmentation, audio processing.
E. Talavera Martinez: life-logging with a camera.

M. Biehl: machine learning, similarity based methods, life science applications.
K. Domaschke: Analysis of time-resolved fluorescence spectra.
M. Gay: Sparse models for information transmission.
M. Lange: Information theoretical aspects of prototype based learning.
F. Melchert: Classification of hyperspectral images and other functional data.
D. Nebel: Learning from relational data, rejection mechanism for outliers.
G. Owomugisha: Crop plant disease detection in images and spectral data.

M.H.F. Wilkinson: morphology, connectivity, biomedical imaging.
M. Babai: (hyper)connected morphology for particle track extraction.
U. Moschini: astronomical data analysis using (hyper)connected filters.
8.4 Publications

Dissertations


Edited books and volumes


Articles in scientific journals


**Articles in conference proceedings**


Other publications


8.5 External funding and collaboration

External funding

We acquired a research grant of 640 kEuro within the EU H2020 project TrimBot in which we collaborate with leading universities and industrial companies.

We acquired a research grant of 240 kEuro from STW for the project SmartBreed in which we collaborate with researchers from Wageningen University and agro-industrial companies.

Godliver Owomugisha is an external PhD candidate from Makerere University, Uganda, supported by the Melinda and Bill Gates Foundation.

Kristin Domaschke, David Nebel, Mandy Lange, and Mathias Gay are external PhD candidates from the University of Applied Sciences in Mittweida, Germany.

F. Melchert is a PhD candidate in the framework of the ‘sandwich’ program of the Graduate School Groningen, supported by the Fraunhofer Institute IFF in Magdeburg, Germany.

Rose Nakibuule is an external PhD candidate from Makerere University, Uganda, supported NUFFIC.

Laura Fernandez Robles from the University of Leon, Spain, is enrolled as an external PhD student in Groningen and is jointly supervised by Enrique Alegre (University of Leon) and Nicolai Petkov. A contract between the Universities of Groningen and Leon concerning a double PhD degree has been signed.

Eirini Schiza from Cyprus is enrolled as an external PhD student in Groningen and is jointly supervised by Nicolai Petkov (RuG) and C. Schizas and C. Pattichis (Univ. of Cyprus).

Nicola Strisciuglio is a PhD student in the framework of a ‘sandwich’ program of the graduate school. He spends half of the time at the University of Groningen and the other half at the University of Salerno and will obtain a double PhD degree from the two universities. He is supervised by Nicolai Petkov and Mario Vento from the University of Salerno.

Manuel Lopez Antequera is a PhD student in the framework of a ‘sandwich’ program of the graduate school. He spends half of the time at the University of Groningen and the other half at the University of Malaga and will obtain a double PhD degree from the two universities. He is supervised by Nicolai Petkov and Javier Gonzalez from the University of Malaga.

Andreas Neocleous is enrolled as a PhD student in the framework of a ‘sandwich’ program of the graduate school. He spends half of the time at the University of Groningen and the other half at the University of Cyprus and will obtain a double PhD degree from the two universities. He is supervised by Nicolai Petkov and Christos Schizas from the University of Cyprus.
Estefania Talavera Martinez was enrolled as a PhD student in the framework of a 'sandwich' program of the graduate school. She will spend two years at the University of Groningen and another two years at the University of Barcelona and will obtain a double PhD degree from the two universities. He is supervised by Nicolai Petkov and Petia Radeva from the University of Barcelona.

Jiapan Guo and Chenyu (Astone) Shi are PhD students at the group with financing from the People Republic of China and private funds, respectively.

Ugo Moschini is a PhD student on a (HyperGAMMA) project on hyperconnected filtering in an astronomical context, financed from a grant to Wilkinson from NWO-EW in the free competition 2011.

The project Connected Morphological Operators for Tensor Images (COMOTI) was awarded to Roerdink and Wilkinson in the Open Competition 2010 of NWO. A PhD student (Jasper van der Gronde) is appointed in the Computational Science and Visualization group.

External collaboration

Biehl collaborates with Barbara Hammer from Bielefeld University in the context of the theory and application of prototype based clustering, classification, and visualization of high-dimensional data. The development of novel algorithms and alternative distance measures is also studied in collaboration with Thomas Villmann in Mittweida, Germany. The application of LVQ in steroid metabolomics and tumor classification is in the center of an intense collaboration with Wiebke Arlt from the University of Birmingham, UK. Another medical application, the early diagnosis of inflammatory diseases based on bio-markers, is studied in collaboration with Dr. Dagmar Scheel-Töllner, also from the Medical School at Birmingham/UK. Biehl furthermore collaborates with Gyan Bhanot (Rutgers University, New Jersey) in the context of genomics and proteomics data analysis. The application of machine learning in the context of life science applications is also the main topic of the collaboration with former PhD student Ernest Mwebaze and with John Quinn at Makerere University in Kampala, Uganda. In collaboration with Prof. Udo Seiffert, Fraunhofer Institute IFF Magdeburg, Germany, Biehl investigates the clustering and classification of hyperspectral data representing samples of organic material. A collaboration concerning the analysis of large prescription databases was initiated with Eelko Hak and Katja Taxis from the Groningen Research Institute of Pharmacy.

Biehl has signed Erasmus-Socrates agreements with Profs. Hammer (Bielefeld), Villmann (Mittweida), and Wöhler (TU Dortmund).

N. Petkov leads the UG research team that participates in the EU H2020 project TrimBot of a consortium of leading universities and industrial companies. He also leads the UG research team that participates in the STW project SmartBreed in which we collaborate with researchers from Wageningen University and agro-industrial companies. He collaborates with M.F. Jonkman from the Department of Dermatology of UMCG on the application of content based image retrieval and expert systems to dermatologic problems. He also collaborates with N. Jansonius from the Ophthalmology department.
of UMCG on the processing of retinal fundus images for large scale screening purposes. N. Petkov and Biehl collaborate with J. Gonzalez Jimenez from the University of Malaga on the automatic classification of odor from data collected by multiple sensors (e-nose). N. Petkov and J. Gonzalez Jimenez jointly supervise a 'sandwich’ PhD student, M. Lopez Antequera. N. Petkov collaborates with Vento from the University of Salerno in computer vision and audio processing; they jointly supervise the 'sandwich’ PhD student N. Strisciuglio. Petkov and Ch. Schizas from the University of Nicosia collaborate on the automatic analysis of music; they jointly supervise the 'sandwich’ PhD student A. Neocleous. N. Petkov, Ch. Schizas and C. Pattichis from the Univ. of Cyprus collaborate in the area of ‘electronic patient file’ and jointly supervise the PhD student E. Schiza. N. Petkov collaborates with E. Alegre from the University of Leon; they jointly supervise the PhD student L. Fernandez Robles. N. Petkov collaborates with P. Radeva from the Univ. of Barcelona; together they supervise the 'sandwich’ PhD student E. Talavera Martinez.

G. Azzopardi and N. Petkov organised and co-chaired CAIP 2015 held in Malta, co-chaired by them. The proceedings of CAIP 2015 were published as LNCS 9256 and LNCS 9257. G. Azzopardi and N. Petkov are guest editors of a special issue of the journal Machine Vision and Applications (Springer) dedicated to CAIP 2015. N. Petkov, L. Grandinetti (Cosenza), K. Amunts (Duesseldorf) and T. Lippert (Juelich) organised BrainComp 2015 in Cetraro, Italy, and prepare the proceedings as a volume in the LNCS.

In 2015, Petkov published scientific papers with 13 colleges from 9 foreign universities: Salerno (Foggia, Saggese, Vento), Malaga (Monroy, Jimenez), Nicosia (Schizas, Neokleous), Bielefeld (Hammer), Birmingham (Schleif), Almeria (Blanco Claraco), London (Land), Malta (Azzopardi), Leon (Alegre). He had 14 foreign visitors, most of whom were also speakers in the CS colloquium: P. Radeva (Barcelona), X. Jiang (Muenster), H. Unger, W. Halang (Hagen), L. Grandinetti (Cosenza), T. Lippert (Juelich), J. Kaempfer (Juelich), K. Amunds (Duesseldorf), L. Sanchez (Leon), A. Sanchez (Madrid), S. Stankovich (Monte Negro), C. Schizas (Nicosia), C. Pattichis (Nicosia), M. Sodanil (Bangkok).

Wilkinson collaborates with the Dermatology department of the University Medical Centre Groningen on hand eczema analysis. The collaboration with the Kapteyn Institute is longstanding, and currently focuses on exploring the use of hyperconnected filters, and especially vector-attribute filters in automatic source extraction in image data bases. This has resulted in the HyperGAMMA project funded by NWO-EW. This has been extended into a new project into a much larger European collaboration in the SUNDIAL project (ITN submitted January 2016, funding awarded in May 2016). He collaborates with L. Najman and H. Talbot (ESIEE, Paris) on mathematical morphology, and in particular topological watersheds, and also within the SUNDIAL project. A collaboration of biomedical imaging has been set up with K.E. Purnama and T.A. Sardjono of the ITS in Surabaya, Indonesia. He collaborates with Sebastien Lefèvre of the Université de Bretagne-Sud on connective morphology. A further collaboration with the Nuclear Accelerator Institute in Groningen on tracking subatomic particles has been strengthened further within the new Data Science and Systems Complexity centre.
8.6 Further information

Biehl is associate editor of the journals *Pattern Recognition* and *Neural Processing Letters*. He is member of the scientific committee of the European Symposium on Artificial Neural Networks (ESANN) conference series and has served as Program Committee member of numerous international conferences.

*Biehl* co-edited a special issue of the journal *Neurocomputing* which appeared in 2015 and comprises selected contributions to the 22nd ESANN conference in 2014.

*Biehl* was invited to give tutorial lectures at the Conference on Computer Analysis of Images and Patterns (CAIP 2015, Malta) and at the International Workshop on Brain Inspired Computing (BRAIN-COMP 2015, Italy).

Biehl participated (upon invitation) in a Working Group on *Gene, protein and RNA regulation in health and disease* at the Aspen Center for Physics, Colorado/USA.

*N. Petkov* is member of the editorial boards of the following journals: *J. Image and Vision Computing* (Elsevier), *J. Neural, Parallel and Scientific Computations* (Dynamic Publ.), *Int. J. Computational Vision and Biomechanics* (Serials Publ.) and *Int. J. Hybrid Intelligent Systems* (IOS Press). He was member of the programme committees of several international conferences.

He was member of PhD examination committees at the TU Delft (January 2015) and the Univ. Malta (December 2015). Petkov lectured in the Erasmus programme at four universities: Leon (March), Nicosia (April), Salerno (July), Nicosia (November).

He is currently chairman (2015-2017) of the steering committee of the CAIP (*Int. Conf. on Analysis of Images and Patterns*) series of conferences.

In July 2015 Petkov was keynote speaker at IC2IT in Bangkok.

In 2015, Petkov organised three workshop with international participation in Allersmaborg and Groningen.

*Wilkinson* is (technical) programme committee member of several conferences, including the *International Conference on Image Processing 2011*, the *International Conference on Pattern Recognition 2012*, and the *International Symposium on Mathematical Morphology 2011*. He resigned as associate editor for *Pattern Recognition Letters* at the end of 2012. He also retired as board member of the Dutch Society for Pattern Recognition and Image Processing (NVPHBV) after serving for over 6 years. He is on the steering committee for the *International Symposium on Mathematical Morphology* conferences. He has put forward a proposal for an IAPR Technical Committee for Mathematical Morphology. He has given tutorials on connected filters and connectivity at various national and international conferences, and organized the course on Advanced Morphological Filters for the national research school Advanced School for Computing and Imaging (ASCI). Finally, he is member
of the cluster Computer Vision Noord Nederland, a consortium of companies and academia seeking to stimulate the field of computer vision in the Northern Netherlands.
Impact

A number of our research articles in the period 2005-2015 belong to the group of highly cited publications of their corresponding years in Computer Science, Electrical Engineering, Biology and Biochemistry, or Clinical Medicine, according to the number of citations they collect in the Web of Science of Thompson Scientific (as of January 2016):

- **top-1%**:
  - N. Aghaeepour *et al.*: 2013 *Nature Methods* 10: 228-238
  - C.F. Davies *et al.*: 2014 *Cancer Cell* 26: 319-330

- **top-10%**:
  - Bunte, Schneider, Hammer, *et al.*: 2012 *Neural Networks* 26: 159-173.
  - Bunte, Biehl, Jonkman, Petkov: 2011 *Pattern Recognition* 44: 1892-1902
  - Bunte *et al.*: 2011 *Neurocomputing* 74: 1340-1350
- Schneider, Biehl, Hammer: 2009 *Neural Computation* **21**: 2942-2969
- Schneider, Biehl, Hammer: 2009 *Neural Computation* **21**: 3532-3561

**Software**

- We have made available a Matlab toolbox *Relevance and matrix adaptation in LVQ (GRLVQ, GMLVQ, LiRaMLVQ)* at [http://matlabserver.cs.rug.nl/gmlvqweb/web/](http://matlabserver.cs.rug.nl/gmlvqweb/web/).
- Matlab implementations for Gabor filters, COSFIRE keypoint detector, and CORF contour detector are available on [http://matlabserver.cs.rug.nl/](http://matlabserver.cs.rug.nl/)

**Group leader:** Prof. dr. J.B.T.M. Roerdink

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<td>RUG</td>
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</tr>
<tr>
<td>Prof. dr. A.C. Telea</td>
<td>RUG</td>
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**Tenure track assistant professors**

| Dr. J. Kosinka (from 1-9-2015)                        | RUG    | 1.0 |

**PhD students**

| P. Barendrecht                                      | RUG    | 1.0 |
| (supervisor: Kosinka, Roerdink)                     |        |     |
| D. Coimbra                                          | Capes-Nuffic | external |
| (supervisor: Telea)                                 |        |     |
| C. Feng                                             | personal grant | 1.0 |
| (supervisor: Telea)                                 |        |     |
| J.J. van de Gronde (until 1-3-2015)                 | NWO    | 1.0 |
| (supervisor: Roerdink)                              |        |     |
| C. Ji                                               | CSC    | external |
| (supervisor: Roerdink)                              |        |     |
| J. Kustra (until 18-05-2015)                        | Philips | external |
| (supervisor: Telea)                                 |        |     |
| R. Martins                                          | Capes-Nuffic | external |
| (supervisor: Telea)                                 |        |     |
| R. Rodriguez                                        | Capes-Nuffic | external |
| (supervisor: Telea)                                 |        |     |
| P. Rauber                                           | Ubbo Emmius | 1.0 |
| (supervisor: Telea, Roerdink)                       |        |     |
| R.R. da Silva                                       | Capes-Nuffic | external |
| (supervisor: Telea)                                 |        |     |
| V. Soancatl Aguilar                                 | CONACYT | external |
| (supervisor: Roerdink)                              |        |     |
| A. Sobiecki                                         | CNPq   | 1.0 |
| (supervisor: Telea)                                 |        |     |
| M. van der Zwan                                     | Lely Tech. | 1.0 |
| (supervisor: Telea)                                 |        |     |
Postdocs
J.J. van de Gronde (from 16-3-2015) RUG 1.0
(supervisor: Roerdink)
D. Williams (until 15-6-2015) NWO 1.0
(supervisor: Roerdink)

Guests
J. Ahrens, Los Alamos National Laboratory, US
B. Burgeth, University of Saarland, Germany
A. Falcao, Univ. Campinas, Brazil
C. Jung, Federal Univ. Rio Grande do Sul, Brazil
F. Leymarie, Goldsmiths Univ. of London, UK
R. Minghim, University of São Paulo, Brazil
L. Najman, Université Paris-Est, France
M. Walter, Federal Univ. Rio Grande do Sul, Brazil
9.1 Research Program

The research group Scientific Visualization and Computer Graphics carries out research in the area of scientific visualization, information visualization, visual analytics, shape processing, geometric modelling, and computer graphics. With respect to applications, the research concentrates on fundamental and applied problems from the life sciences (in particular medical imaging and bioinformatics), astronomy, large-scale software engineering, and business intelligence.

Large data visualization
Visualization of large data sets requires advanced techniques in image processing and segmentation, hierarchical data management, and data reduction. Both the increasing size, high dimensionality, and complexity of these data ask for new techniques for interactive visualization, so that the speed of the data processing stage matches that of the visualization step. We address this demand by developing efficient algorithms and/or by mapping the involved computations to programmable Graphics Processing Units (GPUs), which are capable of outperforming CPUs for certain compute-intensive applications. We develop scalable techniques for e-Visualization of big data, with a particular focus on time-dependent data, graphs, and networks.

Tensor field morphology
The processing and visualization of tensor fields has become very important over the last decade. A prime application area is medical imaging of the brain, where diffusion tensor magnetic resonance imaging enables the in-vivo exploration of nerve fiber bundles. We develop a solid mathematical and algorithmic framework for connectivity-based morphological filtering and visualization of tensor fields. The work is based on (extensions of) the complete lattice framework of mathematical morphology and builds upon existing work on morphological operators for matrix fields, with special attention to invariance properties, such as translation, rotation or scale invariance. Applications are in fields such as neuroscience or material science.

Multiscale shape processing
Recent 3D data acquisition and segmentation techniques have made it possible to gather large collections of complex 3D shapes. These come in a variety of formats, such as point clouds, range data, or volumetric densely-sampled fields. Shape processing targets the extraction of high-level information from such datasets, aiming at an easier and better understanding of the structure, topology, and geometry of 3D shapes embedded in the data. We address this using 2D and 3D medial descriptors, or skeletons, which jointly capture shape structure and properties in a compact, multiscale, fashion. We have designed several 3D skeletonization algorithms that reach, or surpass, state-of-the-art methods in terms of speed, scalability, accuracy, robustness to noise, and coverage of all types of Euclidean skeletons known in the literature. We next use these algorithms to address several shape processing problems, including 3D shape segmentation and simplification and digital hair removal from 2D dermatoscopic images.
Multidimensional data exploration
Data collections having a large number of attributes recorded per data point, also known as multidimensional datasets, are increasingly present and important in many application fields. We support multidimensional data exploration by using dimensionality-reduction projections, which generate scatterplot-like views of tens of thousands of observations having tens of dimensions. To ease the interpretation of projections, we develop new explanatory techniques that enable end users to interactively retrieve high-dimensional information such as identities and ranges of dimensions from the compact, simplified, scatterplot views. We apply our explanatory methods to problems from machine learning, software understanding, and astrophysics.

Applications
In medical visualization the group studies the analysis and visualization of data obtained by structural and functional imaging techniques such as fMRI, DTI, PET, or EEG. The detection process is complex, requiring image processing to obtain high quality images, mathematical and statistical analysis for quantitative characterization of significant effects, and visualization for interpretation of the results. New work in this area focuses on a combination of machine learning and visualization for predicting neurodegenerative diseases.

The group participates in a research effort on problems from astronomy. Astronomical data sets are growing to enormous sizes. To explore these data sets effectively, new and scalable tools must be developed that can cope with the sheer data volume which has entered the tens of terabytes regime. In this research the focus is on feature extraction, interactive visualization and visual analytics techniques for high-dimensional data.

A new application of our earlier research in multiscale shape skeletonization involves digital hair removal (DHR) from dermatoscopic imagery. In this context, we use skeletal descriptors to locate hairs in dermatoscopic images, and next remove these by image inpainting. Our method is able to handle a wide variety of hair morphologies (stubble, long, curled), thicknesses, and color (from opaque, high-contrast to weakly pigmented), works fully automatically, and shows a higher rate of detection and similar removal quality as compared to state-of-the-art DHR techniques. We validate our work by testing our method on the most comprehensive collection of dermatoscopic images known in the literature so far (over 300 images), and having our results visually checked by dermatologists. The student co-author of this work, J. Koehoorn, has received the GUF-100 prize of the university.

For shape segmentation, we apply our 3D skeletal descriptors to the problem of identifying the natural parts of various types of 3D shapes. In particular, we target the domain of anatomic shape segmentation, which is challenging due to the high variability and complexity of shapes under processing (e.g., bone structures and organs having a fuzzy part-whole structure). Our extended medial features, constructed atop of classical 3D surface skeletons, show a good ability to produce meaningful segmentations of such complex shapes.

For traffic control, we explore innovative interactive visualization methods for analyzing large col-
lections of time-dependent trajectories, or trails. Applications include the simplified visualization of
vehicle traffic datasets (airplanes) and the visual analysis of eye-tracking datasets describing how sub-
jects study a scene and/or accomplish a visual task. By extending our earlier work on bundled trails
to handle attribute information for eye-tracking data, we developed a technique allowing instructors
of commercial pilots to assess the effectiveness of novel cockpit designs in a flight simulator.

9.2 Overview of scientific results

Tensor field morphology
Path-based morphology for tensor fields was extend by constructing directed graphs representing such
data, and then modifying the traditional path opening algorithm to work on these graphs. New results
for morphological “sponges” were obtained, that are less restrictive but still allow useful definitions
of various properties and concepts from morphological theory. A generalized version of the scale-
Invariant rank operator was obtained, which can be used to create a nearly scale-invariant generaliza-
tion of path openings that is robust to noise. Efficient algorithms were developed for sequences and
directed acyclic graphs with binary or real values.

Multiscale unified skeletonization
A major challenge in the computation of all types of medial descriptors is their well-known sensitivity
to noise – small details, or noise, present in the input shape cause large changes in the computed skele-
tons, in terms of so-called spurious branches. Multiscale regularization methods are the technique of
choice to reduce such undesired effects. To date, however, no single regularization technique was able
to handle all types of skeletons known in the literature (2D, 3D surface, and 3D curve). To address
this, we developed a unified model that casts skeletonization into a mass and momentum conserving
advection process, and computes all known skeleton types by solving a system of partial differen-
tial equations. Besides providing, for the first time, a theoretical unification of regularized skeletons
definitions, our method is also faster and simpler to use than existing state-of-the-art skeletonization
techniques. This research was done in collaboration with the Eindhoven University of Technology,
the Netherlands.

Multidimensional data exploration and explanation
Dimensionality reduction (DR), or the use of multidimensional projections, is one of the methods of
choice for finding patterns and groups of related observations in multidimensional data. Many DR al-
gorithms have been proposed in the literature and are increasingly more often used in visual analytics
applications. However, users of such algorithms have little insight in what patterns that are present in
a projection scatterplot, such as outliers and groups, actually mean. We support users in this context
by designing a set of so-called interactive explanatory techniques for multidimensional projections.
These techniques automatically highlight the position, in the visual space, of the original data dimen-
sions and their ranges; extract and annotate groups of observations by the key dimensions explaining
their presence; and highlight the most important dimensions responsible for the presence of outlier
observations. This research was done in collaboration with the Institute of Math. and Computing Sciences, Univ. of São Paulo, Brazil; and the Institute of Computing, Univ. of Campinas, Brazil.

**Medical data visualization**

We developed a visualization technique for brain fiber tracts from DTI data that provides insight into the structure of white matter through visual abstraction. We achieve this abstraction by analyzing the local similarity of tract segment directions at different scales using a stepwise increase of the search range. Locally similar tract segments are moved toward each other in an iterative process, resulting in a local contraction of tracts perpendicular to the local tract direction at a given scale. This not only leads to the abstraction of the global structure of the white matter as represented by the tracts, but also creates volumetric voids. This increase of empty space decreases the mutual occlusion of tracts and, consequently, results in a better understanding of the brain’s three-dimensional fiber tract structure; see Fig. ??.

The Principal Component Analysis in conjunction with the Scaled Subprofile Model was applied to FDG-PET brain imaging data to obtain features which were used as input for a supervised decision tree classifier. New results were obtained by combining data collections from several medical centers in the Netherlands and Spain, leading to more robust classification.

**Large data visualization**

In the NWO-NLeSC project on e-Visualization of Big Data, we continued work on decision tree classification, by augmenting each decision node with thumbnails of the principal component (PC) images from which the subject scores are computed, and also provide labeled scatter plots of the
Figure 4: DTI fiber tract abstraction based on similarity and proximity (tractography was performed for the complete brain, but all images show only one hemisphere of the brain). Tracts are colored according to direction; top-down: green; left-right: red; perpendicular to view-plane: blue. Central structure in red: corpus callosum; green structure directly above the corpus callosum: cingulum. ?? uncontracted; ?? contracted at a scale of 5 mm; ?? a subset of the contracted structure highlighted. Taken from: M.H. Everts, E. Begue, H. Bekker, J.B.T.M. Roerdink, Exploration of the Brain’s White Matter Structure through Visual Abstraction and Multi-Scale Local Fiber Tract Contraction. IEEE Transactions on Visualization and Computer Graphics, 2015, 21(7), 808–821.

distribution of scores. These plots allow the progress of individual subjects to be traced through the tree and enable the user to focus on complex or unexpected classifications. In addition, we present a visual representation of a typical brain activity pattern arriving at each leaf node, and show how this can be compared to a known reference to validate the behaviour of the tree.

In joint work with the Kapteyn Astronomical Institute, we studied interactive visualization in blind surveys of HI in galaxies. Our aim is to develop a fully interactive visualization tool with 1-D/2-D/3-D, quantitative, and comparative capabilities combined with supervised semi-automated analysis. This will enable flexible and fast human interaction with the data. Also, 3-D visualization, coupled to modelling, provides additional capabilities helping the discovery of subtle structures in the 3-D domain.

9.3 Research subjects

P. Barendrecht: morphing for subdivision curves and surfaces.
H. Bekker: visualization of diffusion tensor imaging data, computational geometry.
D. Coimbra: dimensionality reduction methods.
C. Feng: skeleton-based shape processing.
J.J. van de Gronde: morphological operators for tensor field analysis and visualization.
C. Ji: Visualization of brain connectomics data.
J. Kosinka: Geometric modelling; computer graphics.
J. Kustra: 3D point cloud segmentation and analysis using medial axes.
R. Martins: dimensionality reduction methods.
P. Rauber: visual analytics for classifier design.
J.B.T.M. Roerdink: scientific visualization; morphological and wavelet-based multidimensional data processing; neuroimaging; bioinformatics.
V. Soancațl Aguilar: Visualization of gaming data.
A. Sobiecki: 3D shape reconstruction using inpainting.
A.C. Telea: information visualization; software visualization; dimensionality reduction; multiscale shape processing.
D. Williams: e-visualization of big data.
M. van der Zwan: 3D shape reconstruction for automatic navigation.

9.4 Publications

Dissertations


Contributions to books


JBI Annual Report


**Articles in scientific journals**


**Articles in conference proceedings**


Other publications


9.5 External funding and collaboration

External funding


NWO, project Connected Morphological Operators for Tensor Images (COMOTI), 2011-2015, one PhD.


External collaboration

Roerdink participates in the Groningen Neuroimaging Center of the research school BCN (Behavioural, Cognitive and Neurosciences), and collaborates on visualization problems related to neuroimaging with the Dep. of Neurology of the University Medical Center Groningen (prof. dr. Maurits, prof. dr. K.L. Leenders). He collaborates with the Kapteyn Astronomical Institute of the University of Groningen on scalable visualization of astronomical data (prof. J. van der Hulst, prof. E. Valentijn). On tensor field morphology he collaborates with dr. J. Angulo, Center for Mathematical Morphology (CMM), Fontainebleau, France.

Telea collaborates with the Institute of Mathematics and Computing Sciences, Univ. of São Paulo, Brazil (prof. R. Minghim, prof. F. V. Paulovich, prof. L. G. Nonato) on image-based information visualization in a three-year researcher exchange and joint-supervision PhD project co-funded by CAPES (Brazil) and Nuffic (Netherlands). He also collaborates in medial axis theory and applications with prof. A. Falcao (Univ. of Campinas, Brazil), profs. M. Walter and C. Jung (Federal Univ. Rio Grande do Sul, Brazil), dr. A. Jalba (Eindhoven University of Technology, the Netherlands), and dr. J. Kustra (Philips Research). In information visualization applications for trail analysis, he collaborates with dr. C. Hurter (ENAC/Univ. of Toulouse, France).

Kosinka collaborates with the Computer Laboratory at the University of Cambridge (prof. N. Dodgson) on CAD model processing and with the Institute of applied Geometry at Johannes Kepler University (Linz, Austria; prof. B. Jüttler) on hierarchical schemes for spline and subdivision surfaces. Further, he collaborates with the Faculty of Applied Sciences at the University of West Bohemia (dr. M. Lávička) on various curve and surface interpolation techniques, and with the Numerical Porous Media Center at Kaust (dr. Bartoň) on selected topics in geometric modelling.
9.6 Further information

Roerdink has a joint appointment with the Neuroimaging Center of the University Medical Center Groningen. He is member of the Graduate School for Behavioral and Cognitive Neurosciences (BCN Groningen) and the Advanced School for Computing and Imaging (ASCI). He is director of the Johann Bernoulli Institute for Mathematics and Computer Science, co-chair of the FMNS center for Data Science and Systems Complexity (DSSC), and member of the Board of Directors of Energysense. He is JBI-representative for Informatics Europe, management committee member of European Concerted Research Action: Enhanced X-ray Tomographic Reconstruction (COST Action MP1207), chairman of the Computer Science Board of the Lorentz Center Leiden, member of the international steering committee on Visual Computing in Biology and Medicine, member of the international steering committee on Biological Data Visualization, member of the Netherlands Organisation For Scientific Research steering committee Neuroinformatics.NL, and member of IPN (Informatics Research Platform Netherlands). He is member of ACM and the Eurographics Association, and Senior Member of the IEEE. He was reviewer for a number of international journals; program committee member of EuroVis, BioVis, VCBM, and CAIP; and papers co-chair of IEEE SciVis 2015 (25-30 Oct., Chicago, USA). He was member of the PhD reading committees of Zhigang Tu (University of Utrecht), Stef van den Elzen (TU Eindhoven), and Kasper Dinkla (TU Eindhoven).

Telea acts as chair of the joint IEEE VISSOFT – ACM SOFTVIS steering committee. He was on several conference program committees, notably EuroVis, IEEE Visualization, SCAM, Graph Drawing, VAST, and EuroVA. He is a member of the Scientific Advisory Board High Performance Computing & Visualization (WAR HPC/V) of the University of Groningen, of the national research school ASCI, and of the Board of the University of Groningen Graduate School of Science (GSS). In 2015 he was keynote speaker at several data-analytics related national events such as the Science of Big Data Analytics and Visualization organized by the Netherlands e-Science Center (Nov 2015).

Kosinka is a member of ASCI and regularly reviews papers for several computer graphics and geometric modelling journals.
10. Software Engineering

**Group leader:**
Prof.dr.ir. P. Avgeriou

**Tenured staff (JBI members)**

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**Non-tenured staff (JBI members)**

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**Postdocs**

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(supervisor: Avgeriou)

**PhD students**

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<td>Ubbo Emmius and Wuhan University</td>
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<tr>
<td>Ar. Ampatzoglou</td>
<td>University of Macedonia</td>
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<td>E. M. Arvanitou</td>
<td>University of Macedonia</td>
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PhD students
J. S. van der Ven Independent Consultant external
(supervisor: Bosch)
A. Hoffman Siemens external
(supervisor: Stal)

Guests
Philippe Kruchten, University of British Columbia, Canada
Vassilios Vescoukis, National Technical University of Athens, Greece
Farhad Arbab, CWI, the Netherlands
Danny Weyns, Linnaeus University, Sweden
Thomas Slotos, Leuphana University of Lueneburg, Germany
Jose Carlos Maldonado, University of Sao Paulo, Brazil
Elisa Yumi Nakagawa, University of Sao Paulo, Brazil
Georgios Gousios, University of Nijmegen, the Netherlands
Matthias Riebisch, University of Hamburg, Germany
The Software Engineering research program is concerned with theoretical and practical aspects of engineering software and software-intensive systems. The program focuses on one particular field of Software Engineering: Software Architecture. Software Architecture is one of the key disciplines that can help to deal with the hard but also interesting challenges that we are currently facing: increasing integration of Systems and Software Engineering; focus on the end user and the offered added value; increasing demand on software dependability and other critical qualities; dealing with rapid, accelerating change; continuous distribution, mobility, interoperability and globalization; emergence of ultra-large systems (systems of systems); demand for reusability and legacy integration; proliferation of data- and computation-intensive applications; the trend of autonomous or self-managing software; the combinations of biology and computing.

The group aims to contribute in architecting and designing industrial software-intensive systems that meet quality standards by carrying out joint research projects with universities, research institutes, and industrial partners, thus combining academic know-how with industrial practice. The group focuses on three major application domains: embedded systems (e.g. Healthcare systems), energy (and particularly the smart grid) and healthy ageing (through smart homes). The research topics of the group include: Architectural Knowledge, Architecting Embedded Systems, Quality Metrics and Analytics, Architecting Self-Adapting Systems, Technical Debt, and Software Ecosystems. These topics are further elaborated in the following paragraphs.

Architectural Knowledge. There is a growing awareness of the importance of Architectural Knowledge (AK) in the software architecture community. Starting with the Griffin project (2005), we have investigated what AK entails, how this can be captured in architectural documentation, the relationship between architectural analysis and AK, and architectural decisions. Documenting architecture decisions has significant benefits for system design and evolution, but is rarely practiced in industry. Therefore, we have developed a framework (published in 2011) that captures all relevant concerns for documenting architecture decisions. In the context of an industry-research collaboration with ABB (2013) we developed a tool for documenting architecture decisions called Decision Architect. The tool has been extended in recent years (2013-2016) and has been released under an open source license. Moreover, we investigated support for architectural decision making using an approach from knowledge engineering (the repertory grid technique), for which we offer open source tool support (2010-2014). Currently, we are extending the scope of Architectural Knowledge Management to the domain of embedded system engineering, which is characterized by multi-disciplinary, multi-lifecycle and multi-site development processes. The objectives of this research direction are to: (1) adapt AK management approaches to the domain of embedded systems, (2) facilitate AK sharing and reuse across disciplines and projects, (3) track the interactions and relations between various artifacts such as design decisions, models and implementation artifacts, (4) carry out and evaluate AK management activities in industrial organizations.
Architecting Embedded Systems. Embedded Systems (ESs) have become pervasive in modern society. However, the development of these systems is still challenging, as their complexity grows together with the innovations and necessities of modern society. In order to facilitate the development of ESs and support the guarantee of quality within their design, we are performing research on two topics: process models and the architecting process. The first topic aims at developing a new process framework mechanism for defining and handling process components, with respect to specific requirements that apply in the domain of ES development, i.e. the multi-disciplinary, multi-lifecycle, multi-site and multi-organisation development. Such a framework is expected to reduce the effort for process engineers in designing and applying high-quality processes. The second topic aims at defining an architecting process for designing critical-embedded systems, a special type of ESs. In Critical Embedded Systems (CES) the assurance of critical quality attributes plays an important role as failures of the system may cause serious damage to the environment, to human lives, to expensive equipment, or non-recoverable financial losses. To this end, we investigate critical quality models for CES and their use in the design and evaluation of CES architectures.

Quality Metrics and Analytics. The object-oriented paradigm is a dominant way in developing software systems. A basic argument that software developers pose in favor of object-orientation is that it is closer to the way that human brains think, i.e. in terms of objects and actions. However, in order for object-oriented software development to preserve its main advantage, the developed software should stay modular and understandable. The group’s focus in terms of object-oriented design is on methods and techniques that guarantee the internal and external product quality. Our work until now has been focused on GoF design patterns, code refactoring, and quality assessment. We have applied our research on some emerging application domains like game development. As future development, we aim at investigating approaches on artifact traceability, the validation of existing metrics, the introduction of new metrics and metric suites, and continue the work of the group on patterns, refactorings, component extraction and OO game development.

Architecting Self-Adapting Systems. Self-adaptive systems are resilient and flexible systems capable of autonomously adapting themselves. Due to the continuous evolution of software-intensive systems, a self-adaptive system monitors itself in order to change its behavior to deal with uncertain operating conditions such as unpredicted system faults, changing stakeholders needs, and changing environment and system characteristics. In this project we study a systematic approach for self-adaption of multiple concerns at runtime. Until now we have systematically reviewed the literature and investigated existing methods. In addition, we have been studying and classifying the main uncertainties in the self-adaptive system domain to have a better understanding of the problem domain. We are currently focusing on developing models that capture the required knowledge of quality concerns and investigate how these models can be employed at runtime to support tradeoff analysis and conflict resolution.

Technical Debt. Technical debt, which refers to immature software artifacts that fail to meet the required level of quality, has recently attracted increasing attention from both academia and industry in
the software engineering field. To date, little work has been done on technical debt at the architecture level, the so-called Architectural Technical Debt (ATD). In the short term, ATD may be incurred to fulfill specific business advantages; but, in the long term, ATD can to a great extent reduce the maintainability and evolvability of a software system. Our group focuses on ATD management in terms of achieving a balance between value and cost of architectural debt. Until now, we have proposed a conceptual model of architectural debt and an ATD management process applying this ATD conceptual model in order to facilitate the decision-making in a value-oriented perspective of architecting. Our current work is focusing on identifying, measuring, and documenting architectural debt. In addition, we have validated that two system-wide modularity metrics can indicate the amount of ATD. In parallel, we work on economic theories that could be applied to technical debt management and measurement.

**Software Ecosystems.** Many challenges in software development emerge at the limit between systems, and not within a single system itself. One first step towards solving these challenges is developing infrastructure that treats the entire codebase and associated artifacts as a single ecosystem (One company which treats its entire source code in this manner is Google). By analyzing the entire ecosystem in a holistic manner and applying data science to software engineering artifacts, we can (1) Provide a more efficient way to get feedback about which are the weak points of the development process (2) Detecting and preventing intra- and inter-project quality problems, and (3) Improving software engineering tools beyond the capabilities of the programming language.

### 10.2 Research subjects

**P. Avgeriou:** software architecture design and evaluation, patterns and pattern languages, architectural knowledge, technical debt, architecture metrics.  
**Ap. Ampatzoglou:** object-oriented design, artifact traceability, software quality measurement.  
**Ar. Ampatzoglou:** economics, technical debt.  
**E. M. Arvanitou:** software quality measurement.  
**J. Bosch:** software ecosystems, agile software development, continuous deployment, software architecture, software process, software product lines.  
**S. Charalampidou:** artifact traceability, processes, object-oriented refactorings, object-oriented componentization.  
**V. H. S. Durelli:** architectural evaluation, mutation testing.  
**D. Feitosa:** architectural design, object-oriented design, embedded systems, software quality measurement.  
**Z. Li:** architectural knowledge, technical debt.  
**M. Lungu:** software ecosystems, software analytics, software evolution and maintenance.  
**S. Mahdavi-Hezavehi:** architectural design, self-adaptive systems.  
**C. Manteuffel:** architecture decisions, architecting embedded systems.  
**R. Smedinga:** oo-approach, architecture design decision representation.
M. Stal: software architecture, architectural patterns.
D. Tofan: architecture decisions, repertory grid technique, architecture variability.
J.S. van der Ven: software architecture.
C. Yang: architectural assumptions, architecture-agility combination.

10.3 Publications

PhD Theses


Articles in scientific journals


Articles in conference and workshop proceedings


- S. Charalampidou, A.s Ampatzoglou, and P. Avgeriou, Size and cohesion metrics as indicators of the long method bad smell: An empirical study, 11th Int. Conf. Predictive Models and Data Analytics in Software Engineering (PROMISE), ACM, Article 8, 2015, 10 pages.


Edited Proceedings of Conferences and Workshops

- N. Ernst, P. Avgeriou, P. Kruchten, Seventh Int. Workshop on Managing Technical Debt (MTD 2015), in conjunction with ICSME 2015, October 2nd 2015, Bremen, Germany.


Workshop Reports


10.4 External funding and collaborations

External funding

137
Projects funded in the previous years and running in 2015 are:

- Semantic-enabled collaboration Towards Analysis, Negotiation and Documentation on Distributed Requirements Engineering (STAND), funded by Fonds National de la Recherche (FNR) Luxembourg under the AFR scheme (15/1/2011 until 15/1/2015) [Zengyang Li].


External collaborations The group works together with the University of Luxembourg in the context of the STAND project. In the context of the TSDAD project we have worked with ABB (Germany). Two of the group’s new grants (ACES and ESECES) are in collaboration with the University of São Paulo in Brazil. In the context of the PROMES project we work with Oce, ESI-TNO, KE Works, Vector Fabrics, VTT (Finland), Nokia (Finland), Haloila (Finland) and Metso (Finland). We have an informal project with the University of Macedonia (Greece), where Elvira Maria Arvanitou and Areti Ampatzoglou are both located and co-supervised. Finally, we have joint PhD projects with the Linnaeus University (Sweden) [S. Mahdavi-Hezavehi] and the Wuhan University (China) [Y. Chen].

In addition to the above, the group has collaborated with the following foreign universities and organizations in terms of joint publications, co-supervision of theses and research projects: Wuhan University, China (Prof. Liang), Swinburne University, Australia (Dr. Tang), University Rey Juan Carlos, Spain (Dr. Capilla), Limerick University, Ireland (Prof. Fitzgerald), University of Vienna, Austria (Prof. Zdun), Katholieke Universiteit Leuven, Belgium (Prof. Holvoet), University of Canterbury, New Zealand (Dr. Galster), Siemens AG, Germany (Prof. Stal), Tampere University of Technology, Finland (Prof. Koskimies), Linnaeus University, Sweden (Prof. Weyns and Andersson), Chalmers University of Technology, Sweden (Prof. Bosch and Chaudron), HSR, Switzerland (Prof. Zimmermann), Polytechnic University of Catalunya, Spain (Prof. Franch), University of British Columbia, Canada (Prof. Kruchten), University of Helsinki, Finland (Prof. Mannisto), University of South Brittany, France (Prof. Oquendo), University of Pretoria, South Africa (Dr. Solms).

The group has ongoing Socrates-Erasmus agreements together with the Tampere Technical University (Finland), Universidad Rey Juan Carlos (Spain), Linnaeus University (Sweden), University of L’Aquila (Italy), University of Piraeus, (Greece), University of Cyprus (Cyprus), Wroclaw University of Technology (Poland), University of Macedonia (Greece), Aristotle University (Greece), National Technical University of Athens (Greece).
10.5 Further activities

*P. Avgeriou* was co-organizer of three international workshops: the 3rd International Workshop on Software Engineering for Systems-of-Systems (SESoS 2015), the 2nd Workshop on Software Architecture Metrics (SAM 2015), and the Seventh International Workshop on Managing Technical Debt (MTD 2015). He was Workshop and Tutorial chair of the 16th International Conference on Product-Focused Software Process Improvement (PROFES 2015), Bolzano, Italy. He served in numerous Program and Steering Committees of international conferences and in the editorial boards of IEEE Software and Springer Transactions on Pattern Languages of Programming. He served in the Board of the Research School ‘Institute for Programming and Algorithmics’ (IPA), in the board of the Dutch National Association for Software Engineering (VEReniging Software Engineering Nederland VERSEN), and in the Expert Committee for the Best IPA Dissertation Award. He has continued service as member of the International Software Engineering Research Network (ISERN) and as Senior Member of IEEE. Finally he served in three PhD Committees in other universities and as reviewer on 19 scientific journals.

*M. Lungu* joined the group in September 2015. Since then he has reviewed articles for the Journal of Software and Systems as well as the open access journal PeerJ Computer Science. He also co-organized the International Workshop on Software Ecosystems that was co-located with ECSA 2015 in Cavtat, Croatia.

*R. Smedinga* was secretary in the board of Stichting Nioc (http://www.nioc.nl), responsible for organizing conferences on computing science education.

10.6 Distinctions

The TSE article of *A. Ampatzoglou, A. Chatzigeorgiou, S. Charalampidou, P. Avgeriou* entitled “The Effect of GoF Design Patterns on Stability: A Case Study” was accepted as a Journal First and invited for presentation at the European Software Engineering Conference and the ACM SIGSOFT Symposium on the Foundations of Software Engineering (ESEC/FSE 2015), Bergamo, Italy from August 30 to September 4.

*P. Avgeriou* gave invited talks at the Chalmers University of Technology (Sweden) and the University of Utrecht.
Colloquium Computer Science 2015 – List of Speakers

– December 9
  Dr. A. Witoelar, University of Oslo, Sweden
  Extracting the last bits of information from GWAS summary statistics

– December 3
  Prof. M. Riebisch, University of Hamburg, Germany
  Reuse in Architectural Decision-Making

– November 19
  Dr. M. Galster, University of Canterbury, New Zealand
  Trends in software architecture research and practice

– October 29
  Dr. G. Gousios, University of Nijmegen, The Netherlands
  Mining GitHub for fun and profit

– October 8
  Prof. A. Tate, University of Edinburgh, United Kingdom
  The Helpful Environment - Geographically Dispersed Intelligent Agents that Collaborate

– October 7
  Dr. M. Sodanil, King Mongkut’s University of Technology, Bangkok, Thailand
  Neural Networks in Speech Recognition for Acoustic Modeling of Tonal Language

– September 23
  Prof. C.N. Schizas
  eHealth for the Citizen for Better Privacy and Data Protection

– September 21
  Prof. C.S. Pattichis, University of Cyprus, Greece
  Cardiovascular Health Informatics: Predicting the Risk of Stroke Based on Ultrasound Image Analysis of the Atherosclerotic Carotid Plaque

– June 29
  Prof. B. Burgeth
  Elementary Morphology for Color Images and Orientation Fields

– June 29
  Prof. L. Najman
  Graph-based mathematical morphology
– June 24
  J.C. Maldonado, ICMC-USP, Brazil
  INCT-SEC: an overview of the results and perspectives

– June 17
  Prof. R. van Liere, CWI, The Netherlands
  Automated Extraction and Interactive Visualization of Line-Like Structures from Electron Tomograms

– June 12
  Prof. J. Ahrens
  Implications of Numerical and Data Intensive Technology Trends on Scientific Visualization and Analysis

– June 10
  T. van der Storm, CWI, The Netherlands
  Live Little Languages

– June 3
  Dr. T. Slotos, Leuphana University of Lueneburg, Germany
  The Golden Age of Software Architecture better named The Middle Age of Software Architecture - some provocative thoughts

– June 2
  Prof. G. Zachary, Arizona State University,
  The CS development dividend: how one African university gave rise to a research cluster

– May 21
  Prof. J. Comba, Federal University of Rio Grande do Sul (UFRGS), Brazil
  Visualization and Computer Graphics research at UFRGS/Brazil

– May 20
  Prof. A. Sanchez, Universidad Rey Juan Carlos, Spain
  Automatic Linguistic Reports in Deforestation Analysis

– May 19
  Prof. F.F. Leymarie, Goldsmiths University of London, UK
  Medial scaffolds of 3D data

– May 27
  Dr. G. Azzopardi
  Combination Of Receptive Fields (CORF): A novel computational simple cell model with application to contour detection and delineation
– May 13
  M. Lux, Bielefeld University, Germany
  Clustering of DNA sequences

– A. Schulz, Bielefeld University, Germany
  Visualization of Classifiers

– May 6
  Dr. L. Sanchez, University of Leon, Spain
  Boar sperm cell classification using digital image processing

– April 15
  Prof. Dr.-Ing. habil. H. Unger, FernUniversität Hagen, Germany
  Fully decentralised search engines: just a dream?

– March 25
  D. Nebel, University of Mittweida, Germany
  Learning interpretable models from Dissimilarity Data

– March 18
  Prof. F. Arbab, CWI, The Netherlands
  Coordinated Composition of Components

– March 4
  Prof. X. Jiang, University of Münster
  Biomedical Imaging: A Computer Vision Perspective

– Prof. A. Montanari, University of Udine, Italy
  Past, present, and future of Interval Temporal Logics

– Prof. J. Baeten, CWI, The Netherlands
  Computability revisited
Colloquium Mathematics 2015 – List of Speakers

– December 1
Dr. M. Kool, MI Utrecht, The Netherlands
Enumerative geometry: from Ancient Greeks to Modern Physicists

– November 24
Prof. J. Stokman
Recursion relations in dense loop models

– November 12
J. Liao, University of Groningen, The Netherlands
VBARMS: A variable block algebraic recursive multilevel solver for sparse linear systems

– November 10
Dr. A. Giacobbe, University of Padova, Italy
Quasi-periodicity of relative quasi-periodic tori

– October 29
W. Rozema, University of Groningen, The Netherlands
Low-dissipation methods and models for the simulation of turbulent subsonic flow

– October 27
Prof. J. van den Berg
Growth models where large clusters are frozen

– October 20
Prof. R. Cooke, Delft University of Technology, The Netherlands
Vine Regression

– October 13
Dr. R. van der Veen, JBI, KdV Institute (UvA), The Netherlands
Knots and quantum groups

– September 29
Prof. C. Dutilh Novaes, University of Groningen, The Netherlands
Reductio Proofs From A Dialogical Perspective

– September 15
M. Atiyah, VideoMATH
The Millenium Prize Problems

– July 14
C-Q. Cheng, Nanjing University, China
Arnold diffusion in nearly integrable Hamiltonian systems with multiple degrees of freedom
– June 29
  F. Zang
  Distributed Control of Networked Lure’s Systems

– June 11
  H.J. Kojakmetov, University of Groningen, The Netherlands
  Classification of constrained differential equations embedded in the theory of slow fast systems

– June 8
  B. Nunes Borges de Lima, Federal University of Minas Gerais, Brazil
  Embedding binary sequences into Bernoulli site percolation on $\mathbb{Z}^3$

– May 26
  Dr. C.C.C.J. Kalle, University of Leiden, The Netherlands
  Local dimensions for the Bernoulli convolution

– May 12
  Prof. A. van der Schaft, University of Groningen, The Netherlands
  A network dynamics approach to chemical reaction networks

– May 7
  B. Jargalsaikhan, University of Groningen, The Netherlands
  Linear conic programming: genericity and stability

– April 28
  Dr. H. Peters, University of Amsterdam, The Netherlands
  A polynomial map with wandering Fatou components

– April 23
  Prof. S. Hassi, University of Vaasa, Finland
  Boundary pairs, boundary triplets and Weyl functions of nonnegative operators

– April 23
  Prof. J. Berhrndt, Graz University of Technology, Austria
  Spectral and Extension Theory of Elliptic Partial Differential Operators

– April 20
  Prof. B. Rink, VU Amsterdam, The Netherlands
  The hidden symmetries of network dynamics

– April 14
  R. Mohammadi, University of Groningen, The Netherlands
  Bayesian Structure Learning in Sparse Graphical Models
– March 31
  Prof. J. Wiegerinck
  Plurifine potential theory

– March 17
  Prof. G.L.M. Cornelissen, University of Utrecht, The Netherlands
  Reconstruction of walks in graphs

– March 3
  Math movie "Fermat’s Last Theorem"

– February 19
  E. Vos, University of Groningen, The Netherlands
  Formation control in the port-Hamiltonian framework

– February 17
  Prof. E.C. Wit, University of Groningen, The Netherlands
  Ernst for President! (or: How Statistics helps to achieve fair elections)

– February 10
  Dr. D.R. Valesin, University of Groningen, The Netherlands
  The Contact Process on Power Law Random Graphs

– January 22
  L. Gijben, University of Groningen, The Netherlands
  On Approximations, Complexity and Applications for Copositive Programming