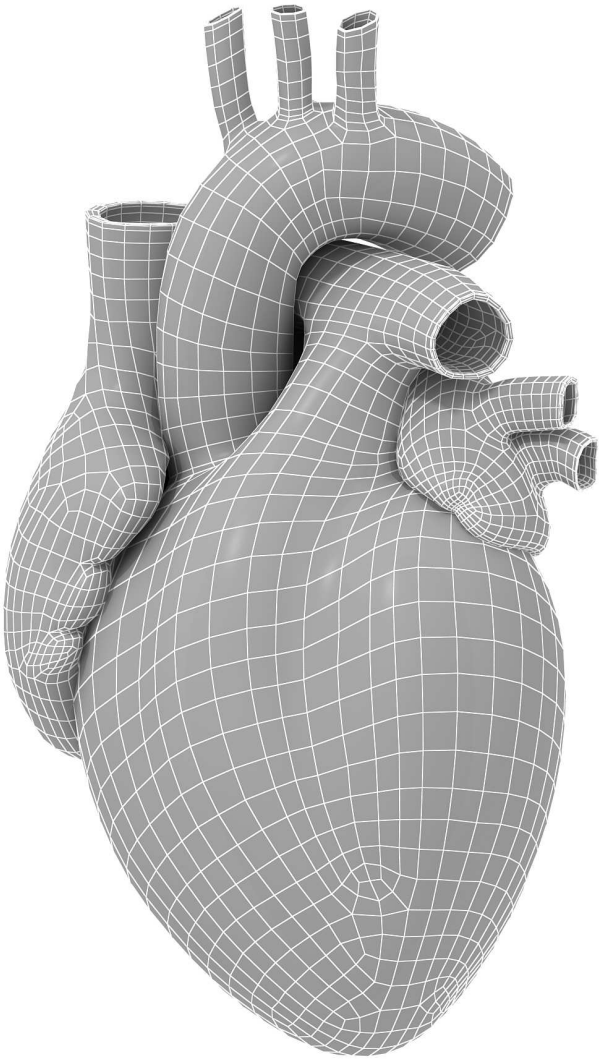
Norwegian Centre of Excellence

Center for Biomedical Computing



Annual Report 2009

Words from the Director

Being awarded a Norwegian Center of Excellence obviously provides unique opportunities for any research group. After almost three years in operation, CBC is very satisfied to see that these opportunities have led to substantial growth in research quantity and quality since the start-up. For example, the number of peer-reviewed papers in archival journals and conference proceedings has more than doubled in 2009 as compared to previous years.

However, even more important than modern metrics of research productivity is the increased intensity in the center: there is an overflow of creativity and novel research directions, earlier recruitments prosper, ambitions are bolder, all current activities are highly promising, challenging future goals seem closer, collaborations are improved, better outlet channels for results are found, and external invitations and recruitments indicate that CBC people are highly visible in their specialities. Unfortunately, we have used our budgets to the very limit, so 2009 and 2010 are years with minor opportunities to employ more talented people to further accelerate these positive trends.

When working on the CBC proposal in 2005, identification of a new and exciting multi-disciplinary application area was required, and our choice was biomedical flows and structures. Entering a new research field that entails significant recruitment of new staff is always challenging. We are therefore extremely pleased with the position we have attained in this new field, both internally at Simula and within the collaborating groups, in only a few years. Output volume is increasing in general, and more papers, based on mathematical modeling and computations, find their way to pure medical journals. It is striking to note the same trend in our Computational Geosciences group, which now addresses geoscientific journals and conferences, and experiences increasingly enthusiastic support from their close industry partner Statoil.

CBC is advantageously hosted by Simula Research Laboratory. The continued governmental funding of Simula is tightly connected to successful evaluation of the institution every five years. A comprehensive scientific evaluation of Simula took place in the first half of 2009 by an international committee of experts covering the three principal research areas of Simula. The committee was appointed by the Research Council of Norway. The resulting evaluation report was very positive overall. In particular, the Scientific Computing Department, being the core and vast part of CBC, was regarded as "excellent in every aspect". Besides being impressed by the effective organization of the research and the volume and quality of the results obtained, the committee had also highly useful comments on future improvements and potential upcoming challenges. There is no doubt that the increased ambitions, efforts, and collaborations that naturally arise from running a Center of Excellence constitute a main reason for the top marks given by the committee. More information about this thorough evaluation of a large part of CBC is found in a separate section of this report.

The year of 2009 has been characterized by a steady focus on established research projects and collaborations. Implementing a strong, long-term research focus is believed to be a key factor for successfully harvesting investments in basic research. 2010 will continue in this philosophy, which has yielded fruitful results, but there will also be additional focus on strategy related to research plans for the final five-year period of CBC. Most of the research carried out in 2009 was, in fact, shaped in 2005 as part of developing the proposal for a Center of Excellence and renewal of research projects at Simula. Successful research is about balancing the need for renewal, the need to concentrate resources over long periods of time to achieve results of lasting impact, and a short-term demand of steady output of papers and candidates. The management of CBC, in close collaboration with the management of Simula, strives to reach an optimal balance between these competing requirements in today's research world, a goal which has been largely successful.

The CBC research projects remained scientifically unaltered through 2009. As a follow-up to the scientific evaluation of Simula, the Basic Research unit performed a reorganization where the three departments were replaced by 10 research groups, effective from January 1, 2010. Four of these constitute the former Scientific Computing department - the core of CBC. Simula's strong focus on research leadership at all levels, and the eagerness to revise and improve the organizational model when needed, is a great benefit for a Center of Excellence that is expected to implement an effective management of research, education, and outreach activities.

An immediately important and useful result of fundamental research is the training of candidates for industry and academia. The year of 2009 was a successful year for CBC in this respect. Monica Hanslien, Mary MacLachlan, and Emil Løvgren moved on to challenging research and consulting positions in industry and academia, after finishing their postdoctoral engagements at CBC. Two other central CBC researchers, Svein Linge and Marius Lysaker, managed to get permanent positions as associate professors, both at Telemark University College. Five Ph.D. students in CBC defended their theses this year, while nine Master of Science candidates were produced by the center's staff. All of CBC's Ph.D. and Master candidates have quickly found promising career tracks in academia or industry.

Kirsten ten Tusscher recently accepted an offer as an associate professor at the University of Utrecht. CBC is proud of having hosted her group, and not particularly surprised that that such an internationally profiled scientist would be recruited as permanent faculty at a highly renowned university. Dr. ten Tusscher also received the Simula Research Award for 2009, in competition with the 100 researchers at our host institution. When highly talented and productive researchers move to pursue additional career opportunities, it is a loss for a center such as CBC. However, we must ourselves that it is the very nature of such centers to host and train great talents for a shorter period and make them qualified for other opportunities. Fortunately, we will collaborate closely with ten Tusscher, Linge, and Lysaker – all of them are employed in part-time positions at CBC, and continue with their current research projects at their new institutions.

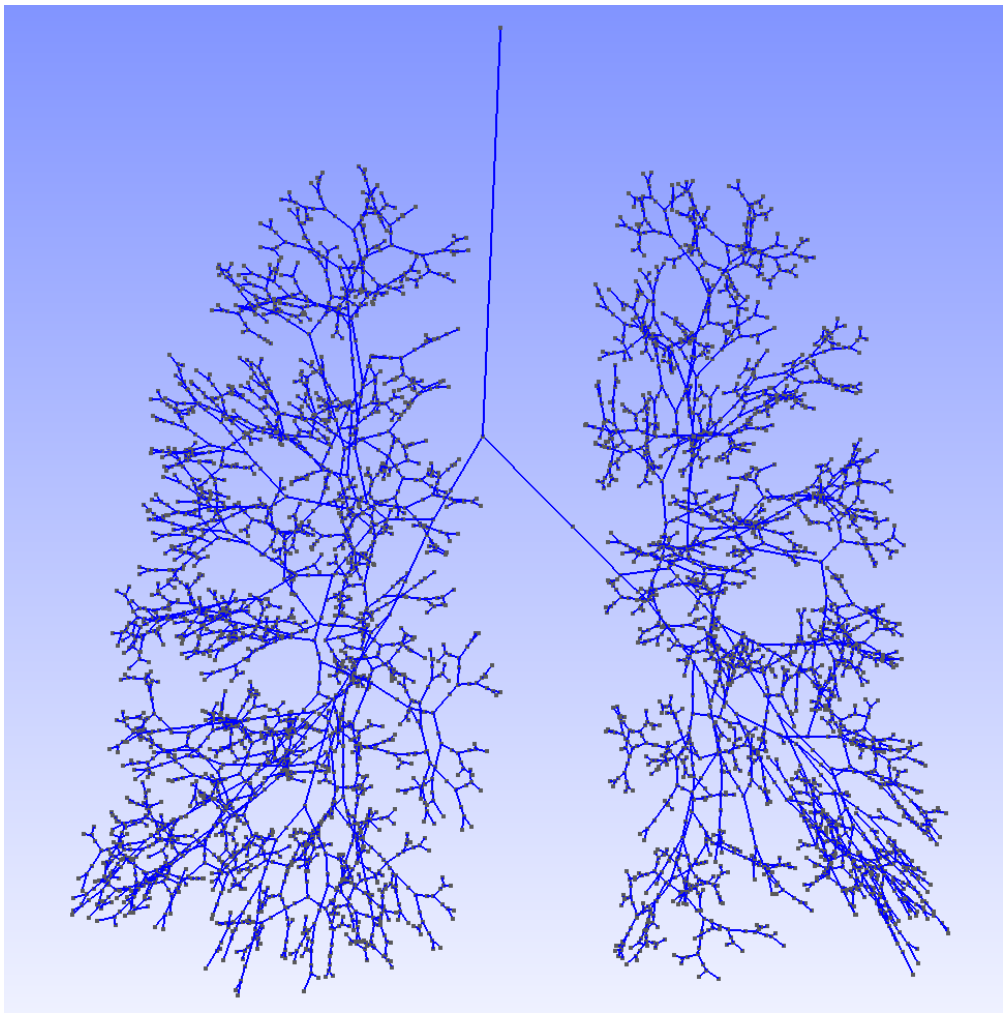
We are also very proud to report that the CBC-funded postdoc Murat Tutkun received a position as an adjunct professor at Ecole Centrale de Lille in France. This is one of the most famous French engineering schools, belonging to the Grandes Ecoles group. Dr. Tutkun works in the CBC-FFI collaboration project with analysis of very detailed simulations of turbulent

flow. His science has received significant recognition, which is clearly manifested by the fact that an elite engineering school in France has hired him as a full professor.

Much attention and many resources at CBC have been put into the development of a software framework, named FEniCS, for solving partial differential equations. This software framework is completely novel in that it combines four key features that are normally viewed as contradictory: *generality* in the range of applications supported, *simplicity* in usage, *efficiency* of computations, and *reliability* of computed results. Several institutions world wide contribute to FEniCS, but CBC is, at present, the driving force in the development, testing, and distribution of this is software. FEniCS is a long-term effort, and will likely achieve substantial impact in the scientific community. Already before the first official release, planned for 2010, FEniCS is quite popular, and has gained users from more than 70 countries. A separate featured article in this report details what FEniCS is specifically, and why it has such a great potential in science.

Understanding heart function and heart disease are both focal research points at CBC. The other featured research article in this annual report explains how a complicated mathematical model of coupled, highly nonlinear ordinary and partial differential equations can describe the interaction between the electrical activity in the heart and the mechanical deformations of the heart wall. Computer simulations based on this model contribute both to increased fundamental understanding of physical processes in the heart and improvements in specific treatments of heart failure.

Examining the original CBC proposal, it is evident that none of the planned activities and milestones have faced significant obstacles or delays. Some of the research activities which appeared most challenging at the time of the proposal writing, such as biomedical flow applications or fluid-structure interaction, are now far ahead of original plans. In general, we believe, CBC has far exceeded our most optimistic expectations for performance as anticipated at the time of final proposal submission in 2006.



17 generations of a branching lung geometry.

Running the Center

Organizational Changes

CBC has, from its inception, adopted Simula's organizational structure. It is therefore natural to describe the impact of changes in this structure on CBC. During the period 2001-2009, the basic research at Simula has been organized through three departments: Network and Distributed Systems, Scientific Computing, and Software Engineering. These departments have grown large over the years and, as a follow-up to comments in the 2009 evaluation of Simula and the planning of a new 5-year period, it was decided to replace the three departments by 10 smaller *research groups*, effective from January 1, 2010. The Scientific Computing Department was split into four research groups:

- AC/DC: Automated and Distributed Computing
- Bioflows: Biomedical Flows and Structures
- CaMo: Compuational Cardiac Modeling
- CG: Computational Geoscience

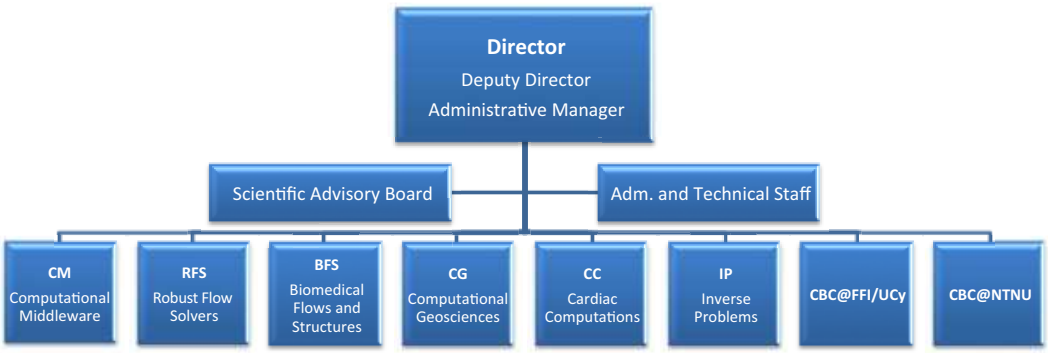
Training of future research managers is one of the goals of CBC and Simula, so we took the reorganization as an opportunity to appoint young and upcoming research talents as group leaders. The existing CBC projects are naturally distributed among the new groups, as the latter three are identical to previous project groups and the first group consists of the Computational Middleware and the Robust Flow Solver projects together. Projects are still a concept in the Simula and CBC organization, but less rigid than in the past – now projects are formed as found convenient, whether large or small, long-term or short-term. We believe that this move will provide a more flexible and effective way of organizing research and education in the center. The original names and scopes of the CBC research projects (as described in this and previous annual reports) have remained unaltered during the organizational changes at Simula.

Each group is, in the Simula system, an independent unit with its own budget, strategy, and research plan. However, the four groups listed above are participants in CBC and must follow strategies that are compatible with the overall strategy of CBC. 2010 will be a year where the groups in mutual interaction with the CBC leadership develop new strategies and research plans for the period until the next Simula evaluation (2014) and the end of CBC (2017).

In total, CBC now consists of

- 4 groups at Simula
- 6 members of the *Biomechanics Division* at the Norwegian University of Science and Technology (NTNU)
- 7 members of the *Applied Fluid Mechanics Group* at the Norwegian Defense Research Establishment (FFI)
- 3 members of the *UCY-CompSci Center* at the University of Cyprus
- 2 members of the *Scientific Computation Group* at the University of California at San Diego

There is an everlasting discussion among scientists on academic freedom versus directed research. One one hand, Norwegian Centers of Excellence are expected to implement an effective management to ensure that the scientists work together toward common goals in the long-term. On the other, the scientists' freedom to pursue goals of strong interest is necessary to foster creativity and groundbreaking ideas. Finding the right balance between freedom and coordination is a fundamental issue in science, especially if the aim is multi-disciplinary research at a top international level. It is a great advantage for CBC to be hosted by a research center that pays so much attention to the mentioned balance in how basic research is best organized. From the very start, CBC was able to benefit from a staff at Simula that had several years' experience in project organization and scientific leadership. This provides the opportunity for CBC to spend less time struggling with organizational structures and more time doing science.



Management and CBC project organization 2007–2009.

leadership for many years. This gives an opportunity for CBC to spend less time on struggling with organizational structures and more time on doing science.

People, Recruitment and Gender Diversity

During the last few years, we have managed to recruit several excellent young researchers to CBC, even though the competition for the best researchers has become more difficult. The latter is particularly true when it comes to finding, and keeping, top level female researchers. In 2007, we recruited the young Dutch researcher Dr. Kirsten ten Tusscher to the center, and gave her responsibility for a new research group in order to give her a unique opportunity to grow. She started her work at the center in 2008, and proved herself by being awarded with the Simula Researcher of the Year in 2009. Sadly for us, she was recruited back to a permanent position at the University in her home town, Utrecht. It was, unfortunately, an offer that we couldn't match, but we have secured her a 10% position at CBC for the remainder of the project period.

Another of our younger researchers, Dr. Murat Tutkun, was awarded an adjunct professor position at the prestigious Ecole Centrale de Lille in October, less than two years after finishing his Ph.D.

Project leader Dr. Ola Skavhaug qualified for, and was awarded, a permanent position as a Research Programmer at Simula. We have seen an increasing need for very high technical competence on advanced scientific software development, as many of the CBC projects are crucially dependent on such competence to reach their scientific goals. It is extremely demanding and seldom possible to pursue a classical academic research career along with gaining very high technical competence on software development. The Research Programmer position was created to give young promising researchers a choice between these two career paths. The formal requirements of a Research Programmer are at the same level as the permanent Research Scientist position, but the volume of scientific papers can be lower to compensate for a proven record of advanced scientific software development qualifications.

Gender Diversity

It is internationally recognized that the number of young people studying and choosing careers in mathematically-oriented natural science as well as in information and communication technology (ICT) is decreasing. The supply of good candidates is not keeping up with growing demand. It is also a fact that women are under-represented at all levels in the ICT sector. Nevertheless, we are aware of our responsibility and challenges to become a gender diverse research center with respect to gender at all levels of expertise.

The case of Dr. Kirsten ten Tusscher illustrates the challenge of recruiting young, talented researchers; other universities and research centers may try to recruit them from us at a later stage. This is especially true for female researchers, as women in our research field are under-represented. A telling example of this under-representation is that only 20% of the applicants among the last two vacant positions at CBC were female. In this case, we ended up by hiring one male and one female Ph.D. student. We are, at present, on a continuous lookout to hunt talented female researchers for employment at the center and hope to secure yet another by mid-2010.

During 2009, a committee investigated the situation regarding gender equality and diversity at CBC and our host institution. The committee studied various resources, sent questionnaires to our employees, collected ideas and facts through both formal and informal meetings, and participated in conferences and workshops that discussed the lack of gender diversity in ICT in both Norway and EU.

Based on their findings, the group has suggested several actions that may increase gender diversity at Simula and CBC. This includes both targeted recruitment and hiring, and making improvements to the working environment. As a first step to avoid gender bias in our hiring procedure, we strive to find qualified female candidates for every position, and to have a female representative in the evaluation and interview process. A forum for women has been established at CBC's host institution Simula, and we also arranged an internal, widely attended seminar on gender equality. The aim of the seminar was to raise gender awareness among our employees, and to find a strategy and action plan for further developing gender equality in our organization.

It is also worth mentioning that Simula, and thereby CBC, has signed *Code of Best Practices for Women in ICT*[1]. The Code provides for practices which aim not only to attract women in ICT, but also to keep them in the sector and help them reach their full career potential. The CBC is thus on the leading edge of gender diversity management within the ICT sector and looks forward to further adopting best practices which encourage this diversity at all levels.

Integration of Foreign Researchers and Students

CBC and Simula employ researchers and Ph.D. students with very diverse cultural backgrounds. During 2009, a committee investigated the situation for international students and researchers moving to CBC and Simula, with the aim of suggesting improvements that would facilitate integration. Since we look for the best scientists in our research fields, it is important to be sensitive to our international employees' different cultural and educational backgrounds, and their integration into our work environment and society at large. It is not enough to simply recruit people; we need to provide a good framework for their work situation in order to integrate them and have a work environment in which they can thrive.

Evaluation

The governmental funding of Simula depends on successful scientific evaluations of the research. Such evaluations are carried out by a committee of international experts every five years. The Research Council of Norway conducts the evaluations, while the consequences of the evaluation are determined by the government. The first evaluation took place in 2004, and the second in 2009. For the latter, the evaluation committee consisted of four members, including three internationally recognized experts

[1] *http://ec.europa.eu/information_society/activities/itgirls/doc/code.pdf*

in each of Simula's three areas of research. Professor Jan Hesthaven from Brown University acted as the expert for the Scientific Computing area.

The Simula researchers and management were, in general, very impressed with the committee's evaluation report, which demonstrates a thorough understanding of the research activities, their organization, and their strengths and weaknesses. The report provides a judgement of the current status along with recommendations for the future. Since the Scientific Computing area of Simula constitutes the core of CBC, and since this evaluation in part can tell us the state of our research, our strengths and weaknesses, and provide future directions of research, we find it highly relevant to give a summary of the evaluation in this year's annual report.

The general assessment of the research was expressed as follows:

> *The Scientific Computing department has maintained its high level of visibility, increased its activity and impact, and developed extensive collaborations with outside partners, including major industrial partners. The department is excellent in every aspect.*

In the annual report for 2007, we mentioned that "it is challenging to turn a significant increase in budget into research within a few months". The evaluation committee commented in particular on this aspect:

> *The Evaluation Committee was extremely impressed by the breadth and depth of the research activities in the department, and by the clear evidence being presented, that the rapid expansion of the department over just a few years had not resulted in any dilution of the quality and quantity of the research. This is a clear sign of a strong scientific base of active and involved researchers, supported in the process by a well-qualified group of scientific leaders with a clear vision.*

The national importance of our work was also recognized:

> *The potential impact on Norwegian industry and research is substantial through the important education of computational scientists, and by lifting the international visibility of the quality of Norwegian led science.*

The scientific output was characterized as follows:

> *The Evaluation Committee is impressed by the exceptionally high scientific production, including books (6), journal papers (84), and high-level conference contributions (44), as well as the dedication to many other scientific activities such as teaching and advising of students, memberships of editorial committees (10), and the development of close research-based industrial partnerships and collaborations.*

It was decided to include the Computational Geosciences project at Simula as part of CBC from 2008. The evaluation committee supports this step:

> *The department has undertaken a new geophysical modeling direction enabled by close and very fruitful research driven collaborations with Statoil. The application focus is on computational geoscience, but the inherent multi-scale, multi-physics nature of such problems makes this new research direction less of a stretch than one may think in light of the past biomedical application focus. In other words, there is every reason to believe that this new research initiative can benefit from the ongoing extensive activities in biomedical modeling and computation, and that the cross-fertilization between researchers in the two groups may be of significant mutual benefit.*

We work hard in CBC to define and run projects that fit together and that will be of mutual benefit for our long-term goals. Therefore we appreciate that

> *The Evaluation Committee was impressed with the strong interaction between the individual projects.*

Recruitment of excellent young researchers for senior positions is one of CBC's goals. The committee explicitly mentioned our hiring of Kirsten ten Tusscher and Anders Logg:

> *Both are excellent recruitments of international researchers, adding to the core activities and expertise in the department. The Evaluation Committee commends the department for pursuing excellence, rather than more narrow national interests in hiring senior researchers.*

The committee also pointed out future challenges and observed that the department is

> *...moving from discipline specific modeling efforts to what can be characterized more broadly as computational science. ...Such a change will likely drive the activities in the department away from the development of more fundamental computational and mathematical tools, and toward areas related to data-driven science, data-assimilation, uncertainty quantification and management, and the extensive validation of complex models.*

CBC is well aware of this natural development of the activities, which is in line with the visions of the Center of Excellence project proposal. The IP project is deep into comprehensive validation of their model, and other projects are involved with expensive validation studies to a steadily increasing extent. From 2010 we are also building up an activity on stochastic uncertainty quantification and management, in close cooperation with a group at Texas A&M University. These initiatives are time consuming and will most likely dampen the current publication rate.

One concern of the committee was the size of the department and the diversity of activities:

> *The committee encourages the leadership to begin a discussion of suitable models to address this concern, including a focusing of the research through the elimination and absorption of smaller projects, deputizing the department, or a genuine split of the department.*

The split of the Scientific Computing department into four research groups, being effective from 2010, is a direct response to this remark.

A clear recommendation concerned increasing the number of master and doctoral students:

> *The Evaluation Committee feels that the department should be able to successfully absorb and educate a larger number of MSc and Ph.D. students.*

CBC sees a need to apply more aggressively for external research funding of Ph.D. students and to focus even more on recruitment of MSc candidates.

The committee also expressed a disappointment regarding our funding situation:

> *A weak point of the department, indeed perhaps the only genuinely weak point in an otherwise excellent department, is its lack of internationally funded research activities, either through EU projects or through the formation of other international research partnerships. ... However, the committee also acknowledges that the Simula Research Laboratory as an organization is well aware of this shortcoming, and that several significant steps have recently been taken to address this concern.*

One such step was starting (in 2009) a partnership with the UK-based consulting company PERA to increase the knowledge about the EU framework programs, and help with identifying projects and writing proposals. Applications for the prestigious European Research Council's Starting Grant were submitted in late 2009, and one application has qualified for the second round. However, we should add that CBC has attracted substantial national funding: the Center of Excellence grant from the Research Council of Norway constitutes under 1/4 of CBC's total research resources in 2009.

Additional Evaluation. Since many CBC researchers have adjunct positions at the University of Oslo (UiO), and some also hold permanent positions at UiO, the Faculty of Natural Science and Mathematics views CBC as a so-called *top-tier research group* closely linked to UiO. Qualified top-tier groups, along with emerging top-tier groups, are subject to evaluation by the Faculty, and CBC was evaluated in 2009. This evaluation included a site visit by the Faculty and presentation of the CBC research and education. In a letter, the Faculty concluded that the group had

> *a unified environment with excellent scientific and social relations. We found that the group completely fulfills the expectations of the Faculty. The Faculty did not find any immediate subjects for improvement.*

Being a top-tier research group may result in funding from UiO, and as part of the mentioned successful evaluation, the Faculty funded a new Ph.D. position at CBC for the period 2010-2013.

Scientific Activities

While the years 2007 and 2008 were characterized by starting new activities and collaborations, 2009 was devoted to consolidating research projects and focusing our efforts on the most promising activities. The center progressed mostly as planned through the year, with no major new activities or changes in focus. Below we give an overview of the main activities and the specific results obtained in 2009. The sections cover the seven CBC projects: Computational Middleware, Robust Flow Solvers, Biomedical Flows and Structures, Cardiac Computing, Inverse Problems, Computational Biology, and Computational Geosciences. The activities at FFI/UCy and NTNU contribute to the Robust Flow Solvers and Biomedical Flows and Structures projects, but the size of these activities are now so substantial that the research is described in separate sections.

Computational Middleware

Computers and software constitute the laboratory in computational science. When investigating real life scientific problems, such a software laboratory must do more than solve partial differential equations (PDEs) numerically. We also need flexible tools for creating meshes, specifying boundary conditions and problem-specific parameters, handling uncertainty, checking software correctness (verification), post-processing and visualizing computed results, and comparing results with physical measurements (validation). All these tools pose scientific challenges on the efficiency, flexibility, and maintainability of the software components. International collaboration often brings scientists with complementary skills and software together. Dealing with software environments that are very heterogeneous, both with respect to computer languages and coding standards, is also an issue that CBC pays attention to.

The Computational Middleware project is CBC's means to address the challenges mentioned above, and meet the demands for software components and development methods that are generic in nature with applications to many different projects. Other CBC projects are also involved in creating software, but those activities are more geared toward the specific needs of a particular application.

In 2009, the Computational Middleware project continued its effort in building a high-quality software laboratory which enables the application-oriented research activities in CBC to focus more on their core challenges than on tedious programming details. We also kept up the tradition of publishing the ideas behind our novel software tools and development techniques.

The majority of the software developed is part of the FEniCS project, an internationally recognized, open source initiative for discretizing, solving, and visualizing PDE problems (FEniCS is described in more detail in the Featured Research section). Last year, we extended DOLFIN, the package dealing with finite element computing in FEniCS, with parallel computing capabilities, a long demanded feature that enables FEniCS to solve larger and more time-consuming problems. Any standard FEniCS finite element solver will now automatically run in parallel. Several issues must be solved, nevertheless, to make the parallel version scale well on large-scale clusters and supercomputers.

Another major activity in 2009 was the finalization of UFL, the Unified Form Language, which is a domain-specific language for declaration of finite element discretizations of variational forms. Users can specify their finite element problem using a Python syntax that is very close to the mathematical exposition of the problem. UFL is particularly useful in nonlinear problems because the Jacobian, needed in Newton methods, can be automatically derived. This feature simplifies the implementation of nonlinear finite element problems dramatically. The two form compilers in FEniCS, FFC and SyFi, both use UFL as their user interface. These form compilers constitute powerful tools for discretizing a large class of variational forms in a computationally efficient manner.

During 2009, we continued our effort toward a stable release of the FEniCS software. Several abstractions in DOLFIN needed to be reimplemented before making this release, as extensive changes to the software interface is hard once released in a stable version. Such changes are time consuming, but our automatic procedure for building and testing the software on 17 different computer platforms every night has greatly eased this process.

Another important change in 2009 was the move to a new development platform. Software, issue tracking, and mailing lists are now hosted on Launchpad. This change brings many new features and simplifies maintenance of the FEniCS main server.

As the software from the Computational Middleware project has matured, it is now beginning to be accepted into the unstable section of the Debian Linux distribution. The importance of this achievement is explained later, in the section "Education and Outreach". For other operating systems, including different flavors of Mac OS X, RedHat and OpenSuse GNU/Linux, FEniCS provides an automated build system named Dorsal, which currently supports 17 different platforms and automatically downloads and builds FEniCS and its dependencies.

The annual FEniCS'09 meeting was hosted by CBC in June 2009. This was a very successful meeting with close to 40 participants and 18 talks. Notable speakers included Scott Baden (UCSD), Johan Hoffman (KTH), Michael Holst (UCSD), Claes Johnson (KTH), Robert C. Kirby (Texas Tech), Mirko Maraldi (University of Bologna), Christophe Prud'homme (Universite de Grenoble), Garth N. Wells (University of Cambridge) and Ragnar Winther (Center of Mathematics for Applications, University of Oslo).

We also organized two smaller workshops or code sprints in 2009. The first workshop was held on Smögen and consisted of an intense week of parallel programming. The result of the workshop was the first parallel version of DOLFIN. The second workshop was held in Cambridge and focused on maintenance and reorganization of the FEniCS Form Compiler (FFC) to prepare for addition of new features.

Graphical Processing Units (GPUs) constitute a promising platform for performing high-speed floating point computations. Didem Unat, under the supervision of professor Scott Baden at University of California at San Diego, investigates how GPUs can be utilized to speed up codes for PDEs. In 2009, this team worked on source to source code translators for easing the task of migrating two-dimensional finite difference stencil computations from CPUs to GPUs. A parallel explicit solver for GPU clusters for differential equations modeling the electrophysiological

activity in heart cells has also been implemented. The GPU implementation gives speed-up factors up to 50 for single precision floating-point computations, and up to 12 for double precision floats, when compared with traditional message passing (MPI) on CPU clusters.

Robust Flow Solvers

The purpose of the Robust Flow Solvers project is to develop numerical methods and software for solving fluid flow problems and coupled fluid-structure interaction (FSI) problems in a reliable way. Increasing the robustness of numerical methods and software in flow applications are in focus in other parts of CBC too (Biomedical Flows and Structures, Computational Geosciences, and CBC@FFI/UCy), but the present project is particularly concerned with developing a framework for automated error control to obtain robustness. This research is primarily financed by Anders Logg's Outstanding Young Investigator (YFF) award for the proposal *Automation of Error Control with Application to Fluid-Structure Interaction in Biomedicine*.

Automated error control allows a researcher to specify a differential equation, a functional of interest, and an error tolerance, and then automatically compute an approximate numerical solution of the differential equation by the press of a button. The solution will then have an error in the functional of interest less than the given tolerance. More precisely, given a (nonlinear) differential equation

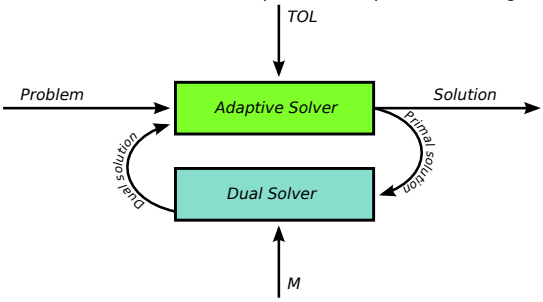
$$A(u) = f,$$

a (nonlinear) functional $\mathcal{M} = \mathcal{M}(u)$, and a tolerance $\mathrm{TOL} > 0$, an approximate solution $u_h \approx u$ is computed such that

$$|\mathcal{M}(u_h) - \mathcal{M}(u)| \leq \mathrm{TOL}.$$

Furthermore, the computational mesh should be automatically adapted to compute the approximate solution u_h with minimal resources in terms of CPU time and memory usage.

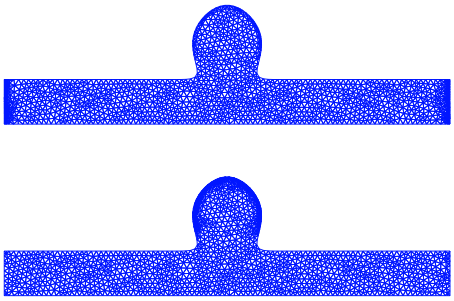
Automated error control is based on the automatic generation and solution of an auxiliary dual problem, which accounts for the stability of the problem being solved.



The technique outlined has far-reaching implications on computational modeling of biomedical and other problems since it allows the researcher to target a computation at a specific quantity of interest, like for example the shear stresses in a specific region, and to obtain reliable numerical results with error bounds.

Last year, we developed a prototype implementation in Python that is able to solve stationary nonlinear differential equations with automated error control. The prototype has been used to solve nonlinear model problems like the (stationary) Navier-Stokes equations on simple domains. We expect to submit a first manuscript on automated error control in 2010 and further extend the framework to time-dependent problems. This includes research on the efficient approximation of the dual problem in connection with classical error estimators such as recovery based and hierarchic based estimators as well as the investigation of efficient data structures for storage of primal and dual data. We also plan to improve the prototype implementation, move parts of the functionality from Python to C++ for speed, and distribute the tool as part of the FEniCS project.

The figure below exemplifies how the automated error control tool can be used to adapt a finite element mesh for simulating blood flow in a vessel with an aneurysm. The top mesh is based on normal stress as functional $\mathcal{M}$, while the bottom mesh is designed for shear stress computations. Observe the difference in the location of mesh density!



An important activity in 2009 was the initiation of a new software infrastructure for simple and efficient FEniCS based solvers implemented in Python. The solver collection, called CBC.Solve, currently consists of two applications:

- CBC.Flow: incompressible flow (Navier-Stokes equations)
- CBC.Twist: hyperelasticity

The CBC.Solve collection is publicly available as free/open-source software as part of the FEniCS project. A third component has been planned, named CBC.Beat, for solving the bidomain equations in cardiac electrophysiology. This would be a valuable tool for the Cardiac Computing, Inverse Problems, and Computational Biology projects, and could be coupled with CBC.Twist to build a full-scale cardiac electro-mechanics simulator. The development of CBC.Beat is still at the planning stage, mostly due to the limited resources available.

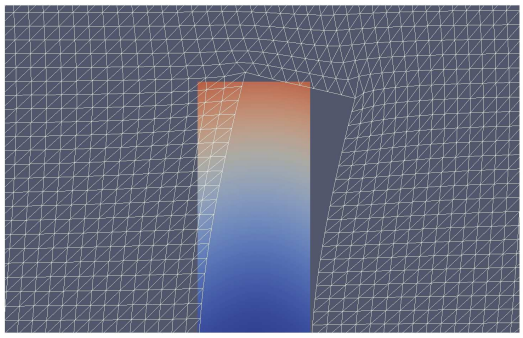
To test FEniCS as a platform for the implementation of efficient fluid flow solvers in Python, we have carried out a benchmark study comparing Python implementations of a collection of well-known finite element based solution algorithms for the Navier-Stokes equations. We focus on laminar incompressible flows and Newtonian fluids. The implementations have been compared with respect to efficiency and accuracy for a number of well established benchmark tests. The benchmark study is near completion, and we expect to submit the results in 2010. Early results from the benchmark study have indicated that splitting methods may be more efficient than fully implicit methods. For this reason, we have developed adaptive time-stepping and mesh refinement schemes for splitting methods. This effort will become a part of CBC.Flow, and will leverage the work on automated error control.

The work with the benchmark study is a collaborative effort between researchers at Simula and FFI. This collaborative effort also started to address turbulent flows, and in 2009 we explored the flexibility of FEniCS to create a solver collection for

Reynolds Averaged Navier-Stokes (RANS) turbulence models. This research will be extended further in 2010.

Fluid-structure interaction (FSI) problems are of particular importance in biomedical flows, where the movements of the fluid and the surrounding tissue influence each other. Robust flow solvers must therefore interact with solid mechanics solvers (known as structure solvers) for the deformation of tissue. To address FSI problems, and solid mechanics problems in general, we have implemented a general nonlinear elasticity solver as part of CBC.Twist. The solver allows a researcher to easily experiment with material models, and many standard models are provided (Mooney-Rivlin, neo-Hookean, Isihara, Biderman, Gent-Thomas and linear isotropic Hookean). Both a static and an energy-momentum preserving time-dependent solver are offered. In the article about FEniCS, appearing later in this report, we give an example on the use of CBC.Twist. The CBC.Twist solver will also be beneficial to the Biomechanics Division at NTNU and strengthen the collaboration between Simula and the NTNU group regarding solid mechanics and material modeling.

Coupling of the fluid and structure solvers implemented in CBC.Solve allows addressing FSI problems. This coupling can also be combined with the framework for automated error control. To this date, a prototype solver coupling CBC.Flow and CBC.Twist has been implemented and good progress has also been made on error analysis and adaptivity for fully coupled FSI problems. The figure below shows an example on FSI where an elastic structure is moving in response to an oscillating fluid flow flow.

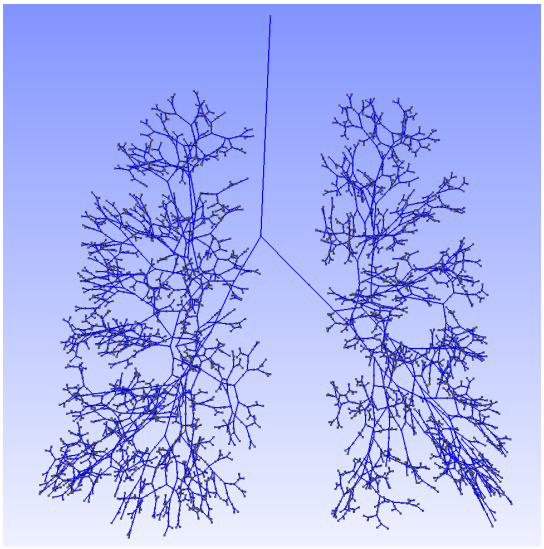


Mixed finite element methods constitute an important tool for constructing robust numerical methods. A postdoc has previously studied the stability of novel mixed methods for elastic and viscoelastic problems. This work in 2009 spurred the development of an automated stability condition tester package (ASCoT), now released as a part of the FEniCS project.

As an alternative to the standard ALE (Arbitrary Lagrangian-Eulerian) formulations of fluid-structure interaction on matching meshes, where stresses may be exactly mapped from one mesh to the other, we have considered the use of Nitsche's method (discontinuous Galerkin formulations) on overlapping non-matching meshes. If the structure undergoes large deformation, difficulties may arise as a result of the corresponding large deformations of the fluid mesh. A promising alternative approach is to apply Nitsche's method for overlapping non-matching meshes to allow the fluid mesh to move independently of the structure mesh. The implementation is challenging, especially in 3D, since it involves the detection of arbitrary intersections between meshes.

In 2009, we have developed new functionality for mesh intersection based on the computational geometry library CGAL. Next year will see the implementation of the full set of functionality needed for realization of Nitsche's method as part of FEniCS.

Biomedical flows normally involve very complex geometries, and we have therefore started developing methods and software for handling complex geometries. For example, the lung geometry is a bifurcating tree of bronchi and bronchioles, where each bifurcation is unique and asymmetric. The lack of symmetry and the wide variety of different bifurcations makes meshing a difficult task. To reduce memory usage and speed up the mesh generation process, we generate meshes for single bifurcations of the geometry and patch the bifurcations together to form the mesh of the complete lung geometry. In 2010, we will use CBC.Flow to adaptively simulate flow in the lungs and extend CBC.Flow with capabilities for parallel simulation on large clusters.



The postdoctoral fellow working with reduced basis function methods continued his development of these methods toward biomedical FSI problems in 2009. His research has resulted in a series of journal publications and conference presentations, and the methods have been implemented in the LifeV software package. However, there is still a significant way to go before reduced basis function methods are readily used in time-dependent and coupled problems. In 2009 he also used LifeV to simulate interactions between the spinal chord and the surrounding cerebrospinal fluid (see the Biomedical Flows and Structure project for more information on this problem).

The Robust Flow Solvers project focuses on developing new software as part of FEniCS. However, FEniCS is not the only software platform that is used among CBC researchers. Commercial codes as well as other open source codes are also in regular use where appropriate. Solid knowledge of the capabilities and limits of other software packages is essential to guide the further development of FEniCS, and to justify spending significant resources on writing generic software.

Biomedical Flows and Structures

The purpose of the Biomedical Flows and Structures project is to apply the numerical methods and software developed in the Computational Middleware and Robust Flow Solvers projects in a few selected important applications that have the potential for making an impact on clinical medicine.

The first application concerns the blood flow in the Circle of Willis, and its relation to the development and rupture of aneurysms. The Circle of Willis is a blood vessel system at the bottom of the brain, and aneurysms are balloon-shaped structures on the vessel wall. The project is motivated by the fact that 1-6% of the general population develop aneurysms during a lifetime, and if these aneurysms rupture, they often cause fatal strokes. The risk for rupture is, however, low – usually estimated to less than 1% annually. The problem is that it is hard to assess risk in a patient-specific manner. We are investigating how computational fluid dynamics can be used to improve individual risk determination. The reasoning behind this effort is that the vessel anatomy varies a lot between patients and that this variation naturally causes differences in the flow pattern and forces acting on the vessel wall. Our aim is to establish flow characteristics that can assist neurosurgeons in their assessment of which patients and aneurysms to treat.

Blood vessels in the brain.

The second application concerns the oscillating flow of cerebrospinal fluid (CSF) in the cranio-cervical region, and the flow's association with the development of syringomelia (cysts within the spinal cord). Such cysts are often found in patients with the Chiari I malformation, a state characterized by having abnormal position of the cerebellar tonsils (i.e., the brain is somewhat sunken down in the neck). The abnormal position of the tonsils obstructs the natural flow of CSF, and it is hypothesized that the abnormal flow pattern is a cause for syringomelia. The knowledge of the fundamental physical and medical processes is still limited, but surgery has proven to be an effective treatment. To increase the understanding of syringomelia and the the effect of tonsilar obstructions on CSF flow, we use advanced medical imaging techniques and fluid dynamics simulations to get a detailed picture of the velocity field and in particular the stress that acts on the spinal cord. We work with both idealized and patient-specific geometries.

The year of 2009 has been particularly successful as we managed to get three papers accepted in clinical journals. Two of the papers are in American Journal of Neuroradiology and concern the flow of CSF flow in the upper spinal canal. Both studies focus on the effects of cerebellar tonsils obstructions on the pressure and velocity field, using idealized geometries to capture the essential flow physics. The papers are co-authored with Victor Haughton, our collaborating professor of neuroradiology at the University of Wisconsin. The work will be extended by a new Ph.D. student starting up in 2010. Then also the flow and deformations within the porous spinal chord will be considered.

A third paper is accepted in Gender Medicine and concerns sex difference in blood flow in the internal carotid and media arteries. The article analyzes differences in bifurcation angles, vessel diameters, and flow velocities between men and women. These differences combine to cause an increased shear stress on the female vessel wall. This may explain why women are more prone to have aneurysms than men. The study was conducted together with our collaborating clinicians Haakon Lindekleiv and Tor Ingebrigtsen from the University Hospital of Northern Norway (UNN). A presentation [188] of the results at a neuroradiology conference attracted attention and received the award for "Best Young Presenter".

In 2008 we received a grant for the project "New and improved methods for risk assessment of unruptured intracranial aneurysms" by the program NevroNor of the Research Council of Norway, together with our collaborating neurosurgeons at UNN, Jørgen Isaksen and Tor Ingebrigtsen. With this funding, we have together with Simula's commercial subsidiary Kalkulo extended the open source tool VMTK with better mesh generation algorithms and subdomain marking. In 2009, we also received a grant from "Helse og rehabilitering" on the project "Head Injuries in Children - Evaluation of the Injury Mechanism by Biomechanical Studies and Computer-Animation" together with Arne Stray-Pedersen from Institute of Forensic Medicine at the University of Oslo. A master student is working on this project, which will be continued with a Ph.D. study in 2010.

In 2009, we have also worked with Jingfeng Jiang and Charles Strother from the University of Wisconsin on a comparison between our blood flow simulations and their MRI measurements of blood flow in canine models. Preliminary results show close correspondance, and we expect to publish the results during next year. We have also established collaborations with Søren Bakke and his co-workers at Rikshospitalet, and will together conduct a study of cerebral blood flow under rest and exercise in 2010.

Finally, we have put quite some efforts into the development of FEniCS for biomedical flow problems. Additional biomedical flows and structure applications carried out by our collaborating group at the Norwegian University of Science and Technology (NTNU) are described below.

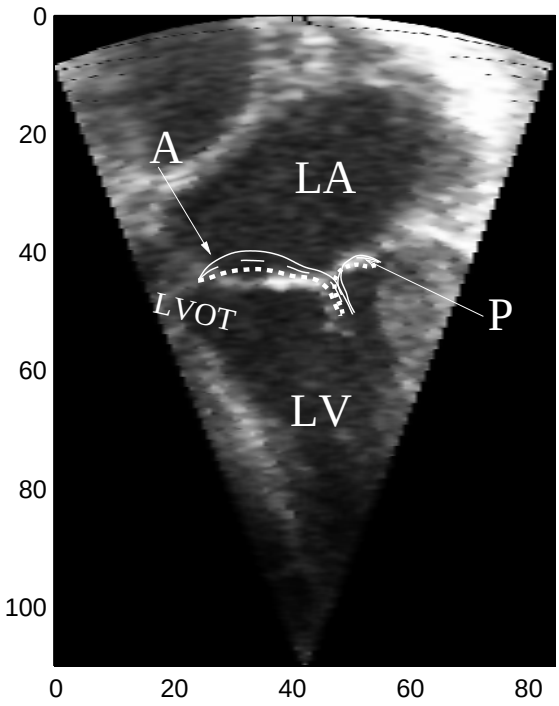
CBC@NTNU

The *Biomechanics Division* at the Department of Structural Engineering at the Norwegian University of Science and Technology (NTNU) has a focus on mathematical modeling of cardio-vascular and orthopedical systems. The focus has mainly been aimed at numerical simulations for improved physiological understanding of the mitral valve, fluid-structure interaction in the left part of the heart, wave propagation in elastic arteries subjected to pulsating blood flow, patient specific hip prostheses in total hip arthroplasty, and leg lenghtening (distraction osteogenesis) analysis.

Some of the topics have a relatively clinical scope, whereas others are of a more fundamental research type. Substantial efforts are put into establishing representative material models which are of paramount importance in computer simulations. Nonlinear finite element and finite volume methods are the basic numerical approaches for solving the governing equations. Irrespective of having to solve basic research issues, the overall goal is to develop tools that can assist in clinical practice by means of better diagnosis and treatment. A strong interaction with clinicians and researchers with medical background is required to make success in this direction.

Professor Leif Rune Hellevik in the Biomechanics Division is currently on sabbatical leave from his position at NTNU and works as visiting professor at INRIA Rocquencourt. In collaboration with the two groups headed by Jean-Frederic Gerbeau and Dominique Chapelle, he is working on a project aiming at FSI simulation of the mitral valve. This project is a natural extension of the work carried out over many years on the constitutive modeling of the mitral valve.

The mitral valve, located between the left atrium and left ventricle of the heart, is one of the four valves of the heart. The valve prevents blood from flowing back into the atrium when the ventricle contracts. Recently, we presented a novel transversely isotropic hyperelastic material model for solid elements for the mitral leaflets in which we add a contractile element in order to simulate the mechanical function of the muscle cells present in the leaflets. Then, finite element analysis of a porcine mitral valve are conducted in order to investigate the influence of the contractile force of the muscle fibers on the valve response between beginning and peak systole. Our simple approach to model the contractile cells in the leaflets shows that their contraction promotes the flat shape to the closed mitral valve, see figure below.



Comparison between echo-cardiography of mitral valve at peak systole with finite element simulations. Fully drawn line: passive material; dashed line: muscle activation 100kPa; dotted line: muscle activation 300kPa.

A paper addressing this has been submitted. However, more data on the distribution of the different muscle fibers present in the mitral valve are needed, both for human and porcine valves. Further work on active stress in the mitral valve will benefit from a closer collaboration with the researchers in electrophysiology and heart mechanics at Simula.

A study on constitutive modeling of the fetal umbilical vein and ductus venosus is pursued by a Ph.D. student. The study resulted last year in a conference article, where several different approaches for vascular material parameter estimation was tested on existing experimental in vitro data. A pilot study and preparation for future in vitro study on the material behavior of human umbilical veins was done at the Technical University Eindhoven. Ongoing work on 2D/3D wave propagation in the umbilical vein and ductus venosus with the implicit and partitioned FSI code Tango, which (in this case) strongly couples the solid mechanics code ABAQUS and the computational fluid dynamics solver ANSYS FLUENT. With Tango we can address FSI problems using industry-standard computational mechanics software, and a careful evaluation of the numerical performance of this approach will provide important input to the further development of fully coupled FSI solvers in the FEniCS framework.

We have also developed an FSI algorithm for the implicit coupling of two rigid leaflets, modeling the mitral valve in the left ventricle of the heart. Simulations of the opening of the valve have been performed using a patient specific rendering of the left ventricle. A 2D study has been carried out to investigate whether the inlet boundary conditions in the left atrium are important for the left ventricle hemodynamics and mitral valve dynamics. According to our results, important features of the flow field may not be predicted in the absence of an adequate model for the left atrium, particularly during diastasis and atrial contraction. A new study has been started where we look at the hemodynamics in the ventricle during systole.

A Ph.D. thesis was finished in 2009, addressing the use of the finite element method and computed tomography (CT) to solve problems relevant to clinical orthopaedics. A new procedure relating the gray-scale values from CT images to the local density of bone has been developed. The geometry of the bone is extracted from the CT images to build the finite element models and assigned material properties according to local densities derived from the gray-scale values. The resulting finite element model can be used to simulate surface conditions between implants and bone in order to study the mechanical stability of a leg lengthening process. In particular, we have simulated the stress-shielding effect and stability of a cementless femoral stem in human cadaver femurs. With this computational tool one can find the most appropriate prosthesis for a patient and do simulations to check optimality of new prosthesis designs.

CBC@FFI/UCy

Parts of the *Applied Fluid Mechanics* group at Norwegian Defense Research Establishment (FFI) and the *UCY-CompSci Center* at the University of Cyprus contribute with their fluid mechanics competence to the biomedical flow activities in CBC. Their contribution is organized as a part of the consortium project "Aerosols: Dispersion, Transport, and Consequences", managed by Bjørn Anders Pettersson Reif at FFI. The purpose of the project is to advance our ability to computationally predict the dispersion and transport of aerosols (droplets or solid particles) in open air and in the human airways. The dispersion of aerosols is important in a wide range of biomedical, security, and environmental applications, ranging from medicine delivered in the form of aerosols through the use of inhalator sprays to the dispersion of chemical, biological, and radiological (CBR) agents due to serious accidents

or terrorist acts.

To attack the challenges in this project, a series of fundamental fluid mechanics and numerical problems must be solved, which have numerous applications to other activities in the CBC projects Robust Flow Solvers and Biomedical Flows and Structures. Some research in this project also uses FEniCS software components developed in the two mentioned projects.

By nature, the prediction of the aerosol transport and dispersion processes is extremely complex. The complexity arises from interdependency of the many complex physical processes involved, such as turbulence, agglomeration/break-ups, gravity, deposition, and physical characteristics and size of the aerosol itself, and its dependence on for instance humidity, sun light, and temperature. The project is concerned with numerical simulations at various levels of sophistication and with different objectives. Direct numerical simulations (DNS) will be conducted in order to systematically study fundamental physical characteristics, whereas computational fluid dynamics (CFD) models such as Large-Eddy simulations (LES) and the Reynolds averaged Navier-Stokes (RANS) approaches are employed in applications.

Two work packages, WP1 and WP2, are defined to facilitate both the fundamental and applied aspects of the project, respectively. In WP1, DNS and high resolution LES are employed as primary research tools. The objectives are to examine the dispersion processes in different well defined configurations in order to (i) examine in detail the physical processes involved, (ii) develop sufficient knowledge to improve predictive CFD models, and (iii) to generate benchmark data for CFD model verification and development. The main focus of the study is aerosol dispersion in transitional flows with time-varying mean flows. This is a fundamental research challenge in fluid mechanics.

In WP2, state-of-the art CFD modelling strategies based on both LES and RANS are applied to a range of applications with focus on biomedical and environmental flows, including health and safety aspects. Existing models are scrutinized using the benchmark data produced in WP1, as well as other benchmark data generated by the CBC partners, in order to identify weaknesses and to suggest remedies to those. Improved turbulence, based on novel concepts, are also being developed.

Flow and particle deposition in the airway system must take into account that the flow is partially turbulent and laminar. This is a challenging scientific problem, which can be attacked by LES. Through 2009 we have used LES to establish a reference solution, and investigated the possibility to simulate the flow in the upper airways by the computationally much more efficient standard RANS models.

LES modeling of wall bounded flows benefits greatly from higher-order numerical schemes. LES solutions are inherently dependent on grid resolution. The methodology is therefore especially susceptible to numerical errors which are prone to greatly influence the results. We have investigated this topic, implementing a variational multiscale LES model into an inhouse higher-order spectral finite element code. The results are very promising – accurate solutions have been obtained even with very coarse grid resolution as compared to standard LES methodologies.

Particle transport in turbulent flows are usually assumed to be one-way coupled, i.e., the aerosols are transported passively by the air flow without affecting the dynamics. As the concentration of aerosols increases, as it for instance will close to the walls in airways simulations, it starts to affect the flow field. This has potentially a very large impact on the rate of deposition. We have implemented a two-way coupling within the LES framework and the results show significant effects.

Researchers at FFI and UCy work on developing a promising new and improved framework for single-point turbulence modeling. In order to obtain a complete single-point description of turbulent flows, turbulence structures must be incorporated. This is the main idea behind the single-point structure tensor approach to RANS models. Here not only the kinematic structure (fluctuating velocity field) is included, but also the rotational and dimensional characteristics of the energy containing large scale turbulence structures. In 2009, this approach was integrated with an advanced elliptic relaxation scheme especially developed to account for non-local effects in wall-bounded turbulent flows.

In 2009 we have continued our study of a biomedical flow application concerning air pollution from an existing large-scale industrial site. More precisely, we study dispersion and transport of aerosols containing biological material released from the site. The problem at hand is very complex and needs to be simplified. The outcome of the simulations depends intrinsically on the validity of the simplifying assumptions made. In order to assess this aspect of the problem a 1:500 scale wind tunnel model has been manufactured and used at the Environmental Flow Research Centre, University of Surrey, UK. The scaled model covers approximately a distance of 10 km downstream the industrial site, including the complex topography in that particular area. This is one of very few existing campaigns that include a thermally stratified (stable) atmosphere: in this unique testing facility it is possible to set up a controlled vertical temperature gradient by cooling the floor and heating the ceiling. A 1:300 model has also been manufactured and will be tested in 2010. These measurements will provide invaluable reference data for the computational model for a number of selected wind directions. A successful validation will enable an extrapolation of the method to a large number of wind directions and speeds. The data comprises velocity and concentration fields, including turbulence statistics.

The use of CFD has recently found its way to assist emergency response planning and exercises for civilian authorities. A hypothetical scenario in which a toxic chemical agent was released through the ventilation system inside a large convention center was modeled using LES. The scenario described in detail the evolution of the toxic chemical inside the building and the exposures and possible consequences could be assessed in a realistic way. This served as the starting point for an exercise involving emergency response personnel, the police, a number of civilian authorities, medical personnel, and many others. The challenges associated with such an incidence could be evaluated and important gaps could be identified. This investigation provides an excellent example on how biomedical flow simulations can impact new areas such as practical emergency planning, where there is little tradition for using mathematical models. This research therefore expands the market for the knowledge and tools created in CBC.

In 2010 we will use LES and the competence and experience from simulations of airway flow to investigate whether the blood flow in the vicinity of aneurysms in the Circle of Willis is turbulent or not. Preliminary physical experiments carried out at the hydrodynamical laboratory at the University of Oslo clearly point to turbulent effects around aneurysms. The investigation will be a joint effort between researchers at Simula, University of

Cyprus, and FFI.

Cardiac Computations

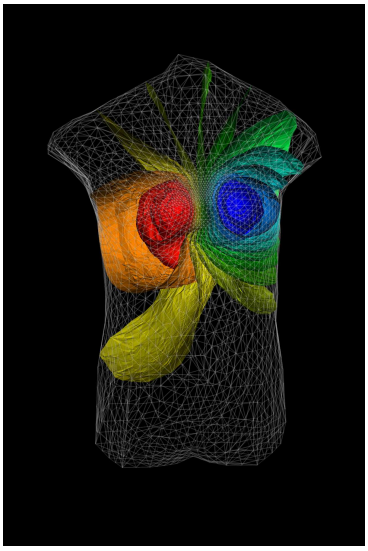
In the Cardiac Computations project, we develop computer models of electrophysiological and mechanical function in the heart, and use these models to study selected biomedical problems. To perform accurate computer simulations of a beating heart, a detailed, complex mathematical model is needed, which gives rise to a series of challenges. First, from a theoretical point of view, it is interesting to derive properties of the solutions. To solve these problems on a computer, one needs stable and fast numerical methods. Additionally, there are challenges related to how such complex systems can be implemented in software in an efficient, yet flexible way. In the project, we have addressed all of these topics, as well as cardiac application-oriented problems. Key application topics within the project focus on both the electrical signal that controls contraction of the heart (termed the cardiac action potential) and the contraction itself (cardiac mechanics). Below, we describe the four main current activities within the project: drug development for cardiac arrhythmias, a new model of atrial myocytes, subcelluar calcium dynamics, and cardiac electro-mechanics.

Mutations of the SCN5A gene can significantly alter the function of cardiac myocyte sodium channels, leading to increased risk of dangerous ventricular arrhythmia, which can decrease cardiac function and even lead to sudden cardiac death. Over the past decade, models of the action potential of wild type and mutant cardiac cells have been developed, as based on measured behavior of membrane ion channels. The effects of drugs on mutant cells have also been incorporated into some of these models. We use such models to predict the effects of theoretical drugs targeting the mutant sodium channel on sodium currents and whole cell action potentials. The aim is to compute advantageous properties of a hypothetical drug by deriving model parameters of the drug action that restores sodium channel function and minimizes the difference between whole cell currents in drugged mutant and wildtype cells.

Investigation of the electrophysiology and pathophysiology of the human atria requires accurate representation of the membrane dynamics of the human atrial myocyte. However, existing models of the human atrial myocyte action potential have not accurately reproduced experimental observations with respect to membrane currents or how the action potential responds to different stimuli frequencies. We have developed a new model of the individual human atrial action potential using newly available experimental data, which ensures accurate representation of cardiac membrane channel processes and accurate reproduction of action potential with respect to measured experiments. The new model constitutes an improved representation of the action potential in the human atrial myocyte, and therefore provides a useful computational tool for future studies involving the human atrium in both health and disease.

In cardiac myocytes, Intracellular calcium links membrane excitation (the action potential) to contraction. Calcium dynamics includes both synchronous oscillations, and nonlinear wave phenomena, both arising from spatially localized stochastic events within the cardiac cell. Three-dimensional cell geometries with realistic spatial distribution of subcellular features have been reconstructed from confocal microscopy of ventricular myocytes. This model provides a computational platform to study intracellular calcium with the ability to interact with experimental measurements of subcellular structures, and will lead to improved understanding of the subcellular calcium dynamics that influence cardiac excitation and contraction in health and disease.

Many questions of scientific and clinical interest can only be studied by considering the coupled electro-mechanical behavior of the heart muscle. Excitation-contraction coupling is mediated by intracellular calcium as noted above, but there also exist feedback mechanisms resulting from tissue deformations and specialized membrane channels activated by mechanical responses.



Cardiac electro-mechanics in CBC has continued its focus on efficient and flexible computational methods for electro-mechanics problems. Although computer simulations of this kind have been performed for a number of years, the complexity, strong linearity and multi-scale nature of the problem still gives rise to a number of computational challenges. Despite this continued focus on methodology, an additional primary focus is currently on the application side on modeling electro-mechanical interactions in the infarcted heart. More details are provided in the article "Featured Research 2009 – Heart Failure".

Inverse Problems

In the Inverse Problems project we investigate, in collaboration with Rikshospitalet University Hospital, the possibilities for improving electrocardiographic (ECG) technology.

The ECG records the electrical activity of the heart on the body surface and is the recommended and most used tool for diagnosing ischemic heart disease, such as infarction and angina pectoris, which is the single most frequent cause of death globally. However, current ECG technology lacks sensitivity, is blind to ischemia in certain regions of the heart, and is largely qualitative. The analysis is based on simple measurements of amplitudes and time intervals that do not reflect the 3D anatomical complexity of the disease.

The aim of our research is to improve the detection capabilities of the ECG and enable 3D imaging of ischemic lesions in the heart through the use of inverse solutions. There are three novel advantageous clinical aspects in our research. First, the inverse

solution is carried all the way into the myocardium, as opposed to standard inverse solutions that compute only the potentials on the outside of the heart. The new approach will provide information about the anatomical position and size of the ischemic lesions. Second, an optimal lead set can be developed by discrete optimization. This will overcome on one side the impracticality of high-density body surface mapping and on the other the lacking sensitivity of the current 12-lead ECG. Third, real-time imaging of the temporal evolution of ischemia can be achieved by carefully designing and optimizing the inverse solver.

We started testing our methods on patients being examined for ischemic heart disease at Rikshospitalet University Hospital in 2008. As part of the clinical evaluation the patients undergo heart MR imaging, angiography and exercise testing with myocardial perfusion scintigraphy. In conjunction with the exercise test we record a 72 lead body surface potential map that together with the MR images form the basis for the inverse procedure. The computed size and location of the lesions will be compared with those from angiography and scintigraphy, and we are currently starting to develop the metrics of the golden standard.

Improved ECG measurements.

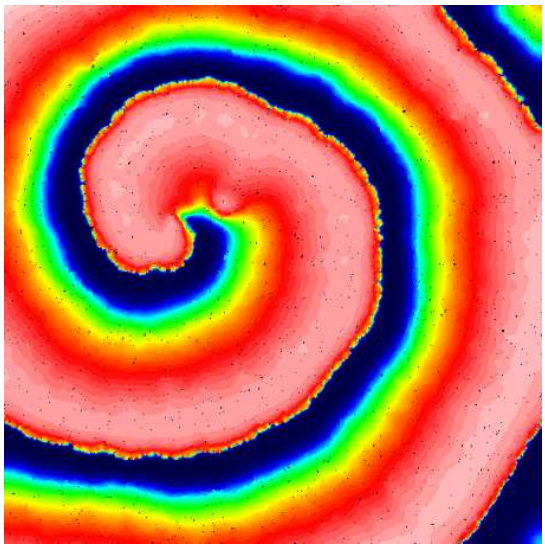
A further research task will be to determine the sensitivity of the results to model assumptions and patient-specific parameters. We are currently expanding the patient recruitment by connecting to the Rikshospitalet branch of a large EU study which will evaluate diagnostic tools for ischemic heart disease. The study will start early in 2010 and Rikshospitalet will recruit about 150 patients over a period of 2 years. This will provide us with enough data to optimize the technology and draw reliable conclusions about its clinical value. Two cardiologists from Rikshospitalet will join the project, completing the competence profile of our research group.

At the end of 2009, we entered a general agreement of collaboration with the US company Heartscape Technologies. This company manufactures an ECG body surface mapping system that specifically targets assessment of myocardial ischemia. Our technology fits perfectly with the business concept, product and know-how of Heartscape Technologies, and we are now negotiating the details of a binding research and knowledge transfer agreement.

Computational Biology

This project is concerned with two different areas in computational biology. The first deals with the dynamics and outcomes of evolutionary processes, the second is concerned with the mechanisms underlying life threatening cardiac arrhythmias. Arrhythmias also constitute a topic in the Cardiac Computations project, but there the main focus is on developing and applying sophisticated numerical models and software, while the present project has its main focus on developing quantitative, human specific models, and on elucidating the biological mechanisms and medical consequences.

The aim of the research on cardiac arrhythmias is to elucidate mechanisms behind cardiac arrhythmias and to identify targetable processes, thus hopefully contributing not only to a better understanding of cardiac arrhythmias but also improving medical prevention and intervention techniques. We focus in our research on the role of two factors influencing arrhythmias: intracellular calcium dynamics and fibrosis (connective tissue formation). Both of these factors receive considerable attention for their potential role in arrhythmogenesis. Calcium has been shown to promote spontaneous, localized electrical activity and has been suggested to lead to wave instability under certain conditions. Fibrotic tissue has been shown to slow down and fragment wave propagation. However, how exactly calcium and fibrotic tissue lead to arrhythmogenesis, and whether similar or different mechanisms are involved remains to be investigated.



The spiral above represents a dangerous, uncontrolled disturbance in the electrical signal in the heart, which can reduce the heart's function and possibly lead to cardiac arrest.

In 2009, a postdoctoral researcher began work investigating the role of fibrosis in arrhythmia dynamics. She has developed detailed bidomain two- and three-dimensional models of human ventricular tissue, incorporating a novel, detailed representation

of fibrotic tissue. The model incorporates both fibroblasts, non-cardiomyocyte cells that can conduct electrical signals but do not actively generate action potentials, and the non-cellular, electrically passive, and non-conducting, extracellular matrix produced by the fibroblasts. In addition, the postdoctoral researcher has finished implementing different fibrotic architectures: diffuse, stringy and patchy, which may arise during different disease states common to fibrosis. We are now performing a large-scale analysis of the effects of bulk fibrotic content, the relationship between fibroblasts and extracellular matrix in fibrosis, and the architecture of fibrosis on arrhythmogenesis and subsequent arrhythmia dynamics. A first article on this study is underway.

The goal of our activity in evolutionary dynamics in the Computational Biology project is to study questions from two main areas of evolutionary biology, speciation and development. For the speciation research a main question is how a single population of a biological specie can give rise to multiple species, given that sexual reproduction should quash any randomly-arising differences in the population. For development the main questions are twofold. First, how is the complex algorithm of development, that produces a patterned, differentiated body plan from a single fertilized egg cell, coded for in the DNA? Second, how did this code evolve and diversify over evolution to give rise to the complexity and diversity of current-day life forms?

Traditionally, mathematical models of evolution that could be solved analytically were used. In these models, individuals consist of a "bag of genes", the composition of which determines their phenotype and fitness to pass along their characteristics. In contrast, we use stochastic individual-based simulation models of evolving populations. Individuals each contain a genome, which specifies a regulatory network of gene interactions. It is the gene expression dynamics, rather than mere gene presence, that determines the individual's phenotype and fitness. Because of the complex interactions in the regulatory gene network, phenotype depends on the genotype.

We published an article demonstrating the evolution of discrete phenotypic differences within a single population of intermixing, mating individuals, something that is not possible in classical more simplistic models. In 2009, a Ph.D. student starting working on extensions of this model. He studied the transition between a polymorphism (a set of different options for a single trait, as in curly or straight hair) within the same specie and the breakup into multiple species. The latter can potentially occur when individuals can evolve to become picky in their mate choice, and only mate with individuals similar to themselves. It turns out that the number of species depends on the complexity of the genetic encoding of this mate choice behaviour. These novel results will soon be ready for publication submission.

In addition, investigation focused on an evolutionary model of development. We find that the evolved developmental processes can be organized both by modular and non-modular network architectures. However, modular architectures are more robust to mutations, development and gene expression noise, and are also more evolvable. This groundbreaking work is one of the first proofs of a connection between modularity, robustness and evolvability in a developmental context. These results will also lead to a new publication in a top international journal.

Computational Geosciences

Since 2005, Simula has had a close collaboration with Statoil[2], addressing computational problems related to oil and gas exploration. The Computational Geosciences (CG) group at Simula conducts research on methodology and software tools needed for new and improved computer-based models of geological and geophysical processes. The challenges in mathematical modeling, numerical methods, and scientific software development in this research are shared with those of the other CBC projects, and from 2008 the group has therefore been part of CBC in order to achieve cross-fertilization and synergy between the "geo" and "bio" applications.

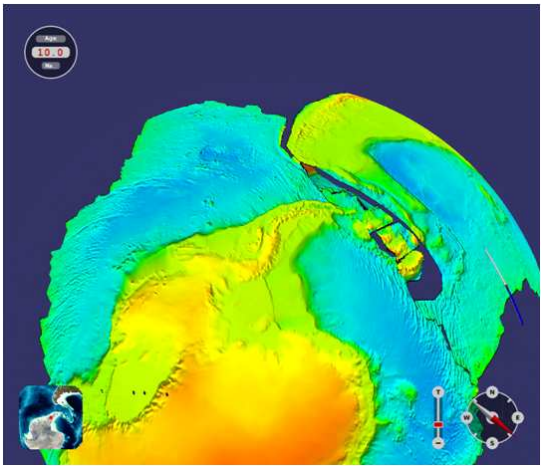
The fundamental research on geoscientific topics is fully funded by Statoil, partly through the Simula School of Research and Innovation's participation as an academic partner in Statoil's VISTA program, and partly through strategic research projects. These basic research activities are paired with the technology development conducted by Simula's commercial subsidiary Kalkulo under contracts with Statoil. In total, the Statoil funding of R&D activities at Simula in 2009 accounted for 12.5 MNOK. The research is conducted in close interaction with senior personnel at Statoil's research centers and in the business unit for global exploration.

Sedimentary basins contain almost all sources of the world's hydrocarbon resources. Understanding the process by which these basins form and are deformed is necessary to improve the efficiency of oil extraction, particularly as the reservoirs become deeper and smaller. Our research activities span three main areas: geodynamic modeling and basin dynamics, numerical methods and algorithms, and calibration and reliability of simulation models.

The focus of the work on geodynamic modeling and basin dynamics is on understanding plate driving forces, mantle convection and mantle-induced vertical basin movements, as well as to model the sedimentary processes forming basins. Last year, we formed kinematic reconstructions of the Tonga region, one of the most seismically active regions in the world. Here the Tonga trench is moving eastward as the Pacific plate collapses into the Earth's interior. By approximating the Earth's surface and interior as a highly viscous fluid over very long timescales, we can calculate how a subducting slab moves once it enters the Earth's interior and then estimate the resulting subsidence on the surface due to the sinking slab. Quantifying this subsidence is important in determining the effect it might have on hydrocarbon formation in basins that move over the slab, such as the Taranaki Basin off the North Island of New Zealand.

In 2009, we created a model describing the motion of small plates in the Scotia Sea region. The region separates Antarctica and South America and the timing of its formation has implications for regional and global climate. Regional climate controls the amount and types of sediment entering basins and the presence of the circum-Antarctic current has had a profound impact on the amount of bio-mass trapped in sedimentary layers at the Eocene-Oligocene boundary, particularly in the Southern Atlantic. In the near future, we hope to understand the basin at a multi-physics level, incorporating the mantle, tectonics, sedimentary processes and climate into the picture. We envisage that this will add to the ability of geologists to interpret the availability and location of potential hydrocarbon sources in particular regions.

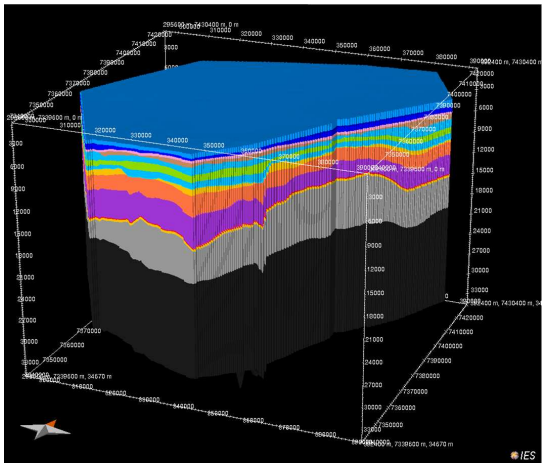
[2]The collaboration started with the oil and gas division of Hydro, and continued after the merger between Statoil and Hydro in 2007, resulting in the company StatoilHydro. The name changed to just Statoil in 2009.



The geology of a basin is formed by thousands of single events over several million years, influencing domains that span tens of kilometers laterally. The accumulate effect of a large number of events on the deposition of sediments can be modeled as a system of diffusion processes, which allow efficient numerical investigations over larger spans of time and space. Alternatively, one can model the detailed physics of individual events by expensive simulations covering very short time intervals and limited computational domains. We investigate both approaches.

Turbidity currents released by large underwater avalanches of sand and mud constitute a single geological event resulting in structures known as turbidites. Stratigraphic records from deep water regions show regularly proof of such flows, often constituting the basis of petroleum reservoirs (the Ormen Lange gas field outside mid Norway being one example). Proper understanding of these sediment bodies and their history is therefore an important aspect of oil and gas exploration. To gain such understanding, we have over the last two years developed a novel simulation framework for sand-laden fluid flow, in which the mass transport is modeled in a hybrid continuum-particle fashion. The particle nature of this approach allows close connection between observable physical properties and the model parameters. By "lumping" particles together in a continuum fashion, high computational efficiency can be obtained compared to the standard method of tracking individual particles. This new framework can model convection and diffusion in addition to dispersion, which is hard to model correctly by classical continuum methods. The first paper on the novel simulation framework was accepted by the end of 2009 in a prestigeous computational physics journal, while additional papers with highly promising results are in progress. There is still a way to go, nevertheless, before this type of method can be used for real turbidity currents. However, already now the method is highly relevant for calculating transport of nutrients in blood flow and also transport of simple areosols in air.

Modeling geodynamic processes requires efficient numerical methods and large-scale high-performance computing so that sufficient model complexity and spatial and temporal resolution can be achieved. One complex process is that of the internal deformation of sedimentary basins. Such basins are composed of numerous layers of rock, often with huge differences in physical parameters. These differences sometimes cause numerical methods for linear system solution to diverge or converge slowly. We conduct research on preconditioners for linear system solvers which can handle large jumps in physical parameters. Special focus is on coupled problems involving both fluid flow and elastic deformations. The first paper on this research was submitted in 2009, and further work investigates the performance of mixed finite element methods for this type of problems. The mathematical model and numerical methods from the present study will be further investigated in a new Ph.D. project about cerebrospinal fluid flow and elastic deformations within the spinal chord, related to cyst formation and the Chiari I malformation. This is a major topic in the Biomedical Flows and Structure project.



We started in 2009 an initiative to look into uncertainty quantification, which is important in all numerical models where there is lack of knowledge of input data. This is particularly the common case in our medical and geoscientific applications. The committee which performed the evaluation of Simula in 2009 also pointed out the importance of uncertainty quantification as a future research topic.

As mentioned, averaged models of diffusion type can explain the depositional history of a sedimentary basin. Although such models are currently in use by sedimentologists and geomorphologists to simulate the process of sedimentary deposition, the impact of the models has been quite limited. This fact is mainly due to the difficulty for geologists to estimate values of the diffusion coefficients entering the models. The uncertainty in these coefficients leads to an unknown overall uncertainty in the simulations. We try to attack estimation of diffusion coefficients from two different angles: (i) by estimating parameters from observed present-day data, using techniques adopted from the Inverse Problems project, and (ii) by representing the uncertain coefficients as stochastic quantities and then computing the overall uncertainty in simulations.

In the latter stochastic approach, one assigns probability distributions for the uncertain parameters. Using the probabilistic collocation method (PCM) one can compute the expectation and variance of the response of the model from a series of deterministic simulations. Since the deterministic simulations just involve the original non-stochastic simulator (in this case the commercial code Dionisos), PCM is a non-intrusive method that can be used for a wide range of problems. Toward the end of 2009, PCM was also applied to electromechanical simulations in the heart. The application of PCM for depositional modeling showed promise and involved real field data from the Ebro basin in Spain.

Stochastic simulation remains an important part of CBC's research. In 2009 we established a close collaboration with Texas A&M University and the Stochastic Mechanics Group at the Zachry Department of Civil Engineering, in order to further strengthen our expertise in this field.

Featured Research 2009: Finite Element Software

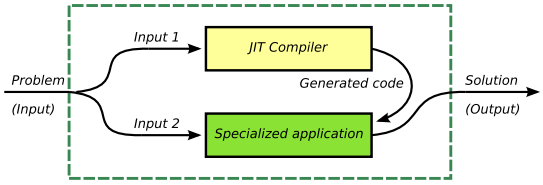
FEniCS is a program package offering a leading software technology for solving finite element problems in an easy way. CBC is heavily involved in the development of FEniCS, and this article describes the history, philosophy and usage of FEniCS, as well as features and future plans.

The FEniCS project was initiated at the University of Chicago in 2003 as a collaborative project towards the development of a mathematical framework and software for automated solution of differential equations. The initial version of FEniCS consisted of DOLFIN, a C++ finite element library developed at Chalmers University of Technology by Anders Logg and Johan Hoffman, and FIAT, a Python finite element module developed at the University of Chicago by Robert C. Kirby. Since then, FEniCS has grown considerably and includes close to 20 different software components. Figure **??** displays the most important components and their relations. DOLFIN and FIAT remain two of the core components of FEniCS, with DOLFIN providing the main C++/Python interface to FEniCS and FIAT implementing the finite element backend. FEniCS has been documented in a large number of journal publications and has started to attract a substantial user base. The latter is indicated by approximately 1000 monthly downloads by users from more than 70 countries around the world.

FEniCS is developed in collaboration between a number of research institutions and universities, which include (in order of appearance) University of Chicago, Argonne National Laboratory, Delft University of Technology, Royal Institute of Technology KTH, Simula Research Laboratory, Texas Tech University and University of Cambridge. Around 15-20 active developers spread out across these institutions are working constantly on improving the software. At present, Anders Logg at CBC and Garth Wells at the University of Cambridge are the principal designers, developers, and maintainers of FEniCS. The success of FEniCS is very much due to the enormous efforts and enthusiasm put into the project by these two researchers. After the first official release of FEniCS in 2010 we hope that the group of active developers can increase significantly over the coming years.

FEniCS is based on a new paradigm for scientific computing which enables users to specify a problem with little effort and solve the problem with high efficiency. In addition, FEniCS aim at providing tools for automatically ensuring a level of reliability of the computed results. Successful combination of generality, simplicity, efficiency, and reliability has so far been extremely difficult to obtain in software for partial differential equations (see [10] for a thorough discussion). FEniCS is a pioneering project in this respect and has consequently attracted widespread interest.

Generality and efficiency are normally viewed as contradictory goals, but FEniCS combines the two in a novel way through *automated code generation*. From a high-level specification of a differential equation (in Python), FEniCS automatically generates efficient low-level code (in C++) for solving the differential equation. This allows a user to specify a differential equation or, more precisely, a variational problem in a notation very close to the mathematical notation. A just-in-time (JIT) compiler translates this specification to a problem-specific, very efficient C++ code.



FEniCS solves differential equations by automatic code generation.

As an example on the user-friendliness of FEniCS, consider the variational formulation of Stokes equations for viscous flow: Find u in V such that

$$a(v, u) = L(v)$$

for all v in V, where

$$\begin{aligned} a &= (\operatorname{grad} v, \operatorname{grad} u) - (\operatorname{div} v, p) + (q, \operatorname{div} u), \\ L &= (v, f). \end{aligned}$$

The corresponding implementation, expressed in Python and our Unified Form Language (UFL), reads

```
a = (grad(v), grad(u)) - (div(v), p) + (q, div(u))
L = (v, f)
```

The reader should examine the close correspondence between the code and the mathematics. This means that it is very easy to add a new term in a partial differential equation, or add a new equation. FEniCS is therefore ideal for problems with novel models not being available in other types of software, or in situations where experimenting with different models is important. Since the user's program is in Python, it becomes very easy to couple the solution process with visualization, data analysis, report generation, and use of other programs.

To provide an impression of how a researcher can quickly solve a new problem with FEniCS, we provide an example of large elastic deformations of a cube. A ready-made general solver CBC.Twist for large-strain elasticity problems already exists on top of FEniCS, so the researcher can simply provide the problem-specific data, such as the mesh, the boundary conditions, and material parameters to compute how the cube is deformed. The code looks as follows:

```
from cbc.twist import *

class Twist(StaticHyperelasticity):

    def mesh(self):
        return UnitCube(8, 8, 8)

    def dirichlet_conditions(self):
        clamp = Expression(("0.0", "0.0", "0.0"))
        twist = Expression(("0.0",
        "y0+(x[1]-y0)*cos(a)-(x[2]-z0)*sin(a)-x[1]",
        "z0+(x[1]-y0)*sin(a)+(x[2]-z0)*cos(a)-x[2]"))
        twist.y0 = 0.5
        twist.z0 = 0.5
        twist.a = pi/3
        return clamp, twist

    def dirichlet_boundaries(self):
        left = "x[0] == 0.0"
        right = "x[0] == 1.0"
        return left, right

    def body_force(self):
        B = Expression(("0.0", "0.0", "0.0"))
```

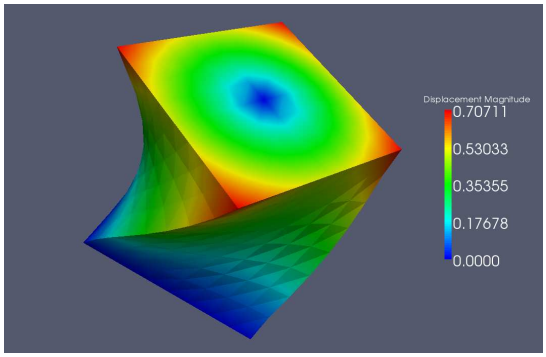
```
        return B

    def material_model(self):
        mu      = 3.8461
        lmbda   = 5.7692
        material = StVenantKirchhoff([mu, lmbda])
        return material

    def __str__(self):
        return "Hyperelastic cube twisted 60 degrees"

# Setup and solve problem
twist = Twist()
u = twist.solve()
plot(u, title="Twisted cube", mode="displacement")
```

Here is the resulting twisted cube:



Many important contributions to the FEniCS project were made in 2009, which was our most productive year ever. We organized one major workshop and two small workshops; many new components and features were added to FEniCS; we moved to a new development platform; and FEniCS was accepted into the Debian GNU/Linux operating system. More details on these results can be found under the Computational Middleware project.

Together with Springer we are working on a book project to summarize the state of FEniCS. The book will discuss the theoretical foundations of FEniCS, function as a reference for users, and showcase interesting applications built with FEniCS. The tentative title for the book is *Automated Scientific Computing*. A large portion of the planned chapters have already been submitted and we expect the remaining chapters to be submitted in 2010.

Finally, we describe some of the important issues to address in the near future. The year 2010 will be an important year for FEniCS as we expect to release the first stable version of DOLFIN (version 1.0) after eight years of development. Ideally, we can make a coordinated release of DOLFIN 1.0 and the FEniCS book. This will mark an important milestone in the development of FEniCS. At this point, FEniCS will take the step from being a project targeted mainly at developers and enthusiasts, to a software system that can be promoted to a much wider audience. As part of this effort, we plan to provide simple one-click installation directly from the FEniCS web page. A prototype implementation of this is already available as part of Dorsal and will be integrated with the FEniCS web page in 2010.

Recent years have seen a large number of new additions to the FEniCS project, both in terms of new components and new features added to existing components. Next year, it will therefore be important to consolidate the current software base, track down bugs and smooth any rough edges. We also plan to focus on improving the efficiency of FEniCS, which includes refinement of our current implementation of parallel computing and a possible extension to GPUs. Another important focus in 2010 will be the further development of the MeshBuilder code into a graphical, user-friendly preprocessor for defining finite element domains for advanced applications.

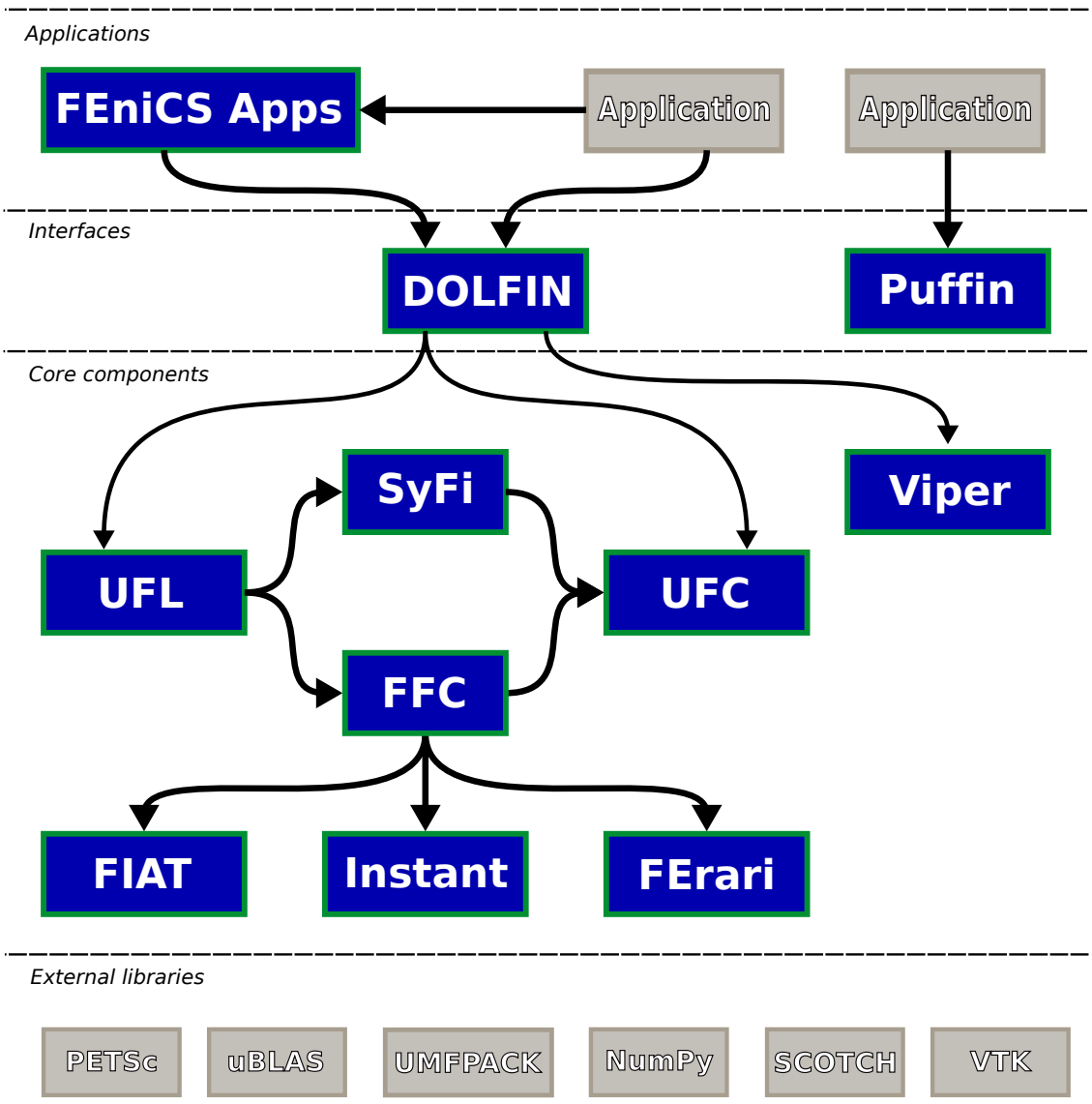


Figure 1: *FEniCS software map. UFL is a Python tool for defining the PDE problem to be solved. This definition is translated to efficient UFC-compliant C++ code by either of the components SyFi or FFC. The resulting code is linked with the DOLFIN library and other external libraries (like PETSc for linear system solution). Viper is a component for visualization of the solution of the PDEs and derived quantities. FFC applies FIAT as finite element library, Instant for coupling C++ and Python, and FErari to optimize finite element computations. A FEniCS application is a Python program using UFL to specify the problem to be solved. A FEniCS application can also be programmed in C++. Puffin is a minimalistic version of DOLFIN and FIAT implemented in Matlab.*

Featured Research 2009: Mechanics of Heart Failure

The Cardiac Computations project (see previous project description) has been involved in computational cardiac electro-mechanics for several years. The main emphasis has been on computational tools in the form of numerical methods and software for solving the complex non-linear PDE systems that describe the electro-mechanical interactions. This activity has led to the development of a purpose-specific cardiac electro-mechanics simulator implemented in Diffpack, and has inspired and funded the development of UFL, which is a new form language in the FEniCS system (see the detailed description in the section on the Computational Middleware project, and the previous Featured Research section).

The heart is an electro-mechanical pump, whose function is can be described by cellular biophysical models, Maxwell's laws of electromagnetics, and the fundamental laws of continuum mechanics. Although these three components are all well studied and established physical models, coupling them together leads to a highly complex system of non-linear ordinary differential equations (ODEs) and partial differential equations (PDEs):

$$\frac{\partial s}{\partial t} = f(v, s, \lambda), \qquad x \in H(t), \tag{1}$$

$$\frac{\partial v}{\partial t} + I_{ion}(v, s, \lambda) = \nabla \cdot (M_i \nabla v) + \nabla \cdot (M_i \nabla u_e), \quad x \in H(t), \tag{2}$$

$$\nabla \cdot ((M_i + M_e)\nabla u_e) = -\nabla \cdot (M_i \nabla v), \quad x \in H(t), \tag{3}$$

$$\nabla \cdot (FS) = 0, \qquad x \in H(0). \tag{4}$$

Here (1) is a system of ODEs describing the dynamics of a cellular state vector s, typically containing ionic concentrations and membrane gate variables. Furthermore, (2)-(3) is the so-called bidomain model, which describes the tissue electrical activity in terms of the membrane potential v and the extracellular potential u_e. Intracellular and extracellular tissue conductivities are denoted M_i and M_e, respectively, while $I_{ion}(v, s, \lambda)$ is a non-linear function describing ionic flux across the cell membrane. Finally, (4) is a Lagrangian formulation of Cauchy's equation of motion, where inertia terms and body forces have been neglected. The equations are coupled with the constitutive relations

$$S = S^p + S^a, \tag{5}$$

$$S^p = \frac{\partial \Psi}{\partial E}, \tag{6}$$

$$S^a = JF^{-1}\sigma^a(s, \lambda, \dot{\lambda})F^{-T}, \tag{7}$$

where S is the second Piola-Kirchoff stress tensor, which is split into a passive elastic part S^p and a part S^a resulting from active muscle contraction. Furthermore, Ψ is a given strain energy function, E is the Green-Lagrange strain tensor, F and J are the deformation gradient and its determinant, λ and $\dot{\lambda}$ are the muscle fiber stretch ratio and its time derivative, and σ^a is the active Cauchy stress.[3]. The equations must also be complemented with appropriate boundary conditions, taking into account the dynamic nature of pulsatile blood flow.

The Cardiac Computations project has for many years done research on solvers for the complex system given by (1)-(7). Currently, the most efficient and robust methods are based on operator splitting techniques that separate the system into smaller and more manageable parts, followed by finite element discretization of both the bidomain equations and the non-linear elasticity equations. Multigrid methods are employed for the bidomain equations, and the multilevel structure is also utilized for efficient handling of the multiple spatial and temporal scales in the problem. The research focus is now on applying the computer model to investigate problems of significant clinical importance, to be described in more detail below.

Heart failure (HF) is a rapidly growing health problem in the industrialized world, which is associated with dramatic reductions in quality of life for the affected patients. HF is currently the most common cause for hospitalization in both Europe and the US, and is associated with health care costs of approximately USD 35 billion in the US alone. HF may have many causes, including myocardial infarction, hypertension, genetic disorders, valve defects and heart muscle diseases. An ageing population and increased survival rate for acute myocardial infarction are factors contributing to the increased occurrence of heart failure.

In spite of large research efforts and considerable progress, many fundamental questions related to HF remain unresolved. For instance, the condition is characterized by a progressive loss of pump function, which is commonly described as a downward spiral where the failing heart struggles to keep up with the metabolic demands of the body, only to overload itself and further reduce function. The mechanisms underlying this gradual loss of function are only partly understood.

Some HF related questions are directly linked to clinical practice and therapy. For instance, better understanding of the pathological remodeling and consequent loss of function can lead to improved pharmacological therapy. Another treatment that has proven effective for HF is the use of advanced pacemaker technology to correct poorly synchronized heart contraction, which is often associated with HF. The treatment, known as cardiac resynchronization therapy (CRT), is highly effective for large groups of patients. However, about 30% of patients selected for CRT show no improvement. Given the invasive character and high cost associated with CRT, improving the current selection criteria is a subject of substantial interest and research, and this is also in focus at CBC.

Current selection of CRT patients is mainly based on a low ejection fraction (indicating poor pumping function), and a visual inspection of the curves from the ECG recording, typically identification of a widened so-called QRS complex (>120 ms). The QRS complex is the electrical signal which results from the activation of the ventricles, and its width corresponds to the time it takes for the electrical activation pulse to travel through the entire heart muscle. A wide QRS therefore indicates a delayed activation of some parts of the heart, which leads to poorly synchronized contraction and low pump function. CRT involves implanting a pacemaker with two leads placed on opposite sides of the ventricles. The electrical pulses from these pacemaker leads activate the surrounding tissue, and may compensate for the blocked or slowed conduction from the heart's own pacemaker. Why some patients with widened QRS still do not respond to CRT is largely a

[3] For an introduction to heart electrophysiology modeling, see for instance Sundnes et al, *Computing the Electrical Activity in the Heart*, Springer, 2006. An introduction to soft tissue continuum mechanics can be found in for instance Holzapfel, *Nonlinear solid mechanics. A continuum approach for engineering*, Wiley 2006.

mystery, and indicates the high complexity of the cardiac electro-mechanical coupling. Other diagnostic tools based on echo imaging have been proposed, but these have yet to demonstrate any improvement over the standard technique.

Through 2009 the cardiac electro-mechanics staff has developed and validated dynamic electro-mechanics simulations of failing ovine hearts. The simulations are based on the model equations given above, and geometries extracted from MR images provided by collaborators at UC San Francisco. The MR images are also used for validation of the model, by matching computed strain values with estimates from tagged MRI. The simulations may give new insight into the relevance of dynamic stresses and strains in post MI HF, as well as the role of mechano-electric feedback in rhythm disturbances following a heart attack.

As described in a popular science article in Apollon[4], CBC has recently entered a collaboration with the Heart and Lung Clinic at Oslo University Hospital. The goal for the collaboration is to use electro-mechanical simulations to improve our understanding of heart failure in general, and un-synchronized contraction in particular, with the aim of improving the current success rate of CRT and other HF therapies. This collaboration currently forms a core component of a proposal for a Center for Research-based Innovation (SFI) from the Research Council of Norway. The proposed center will integrate advanced electro-mechanical simulations with conventional diagnostic tools such as ultrasound and ECG, to develop new technologies for cardiological diagnosis and intervention.

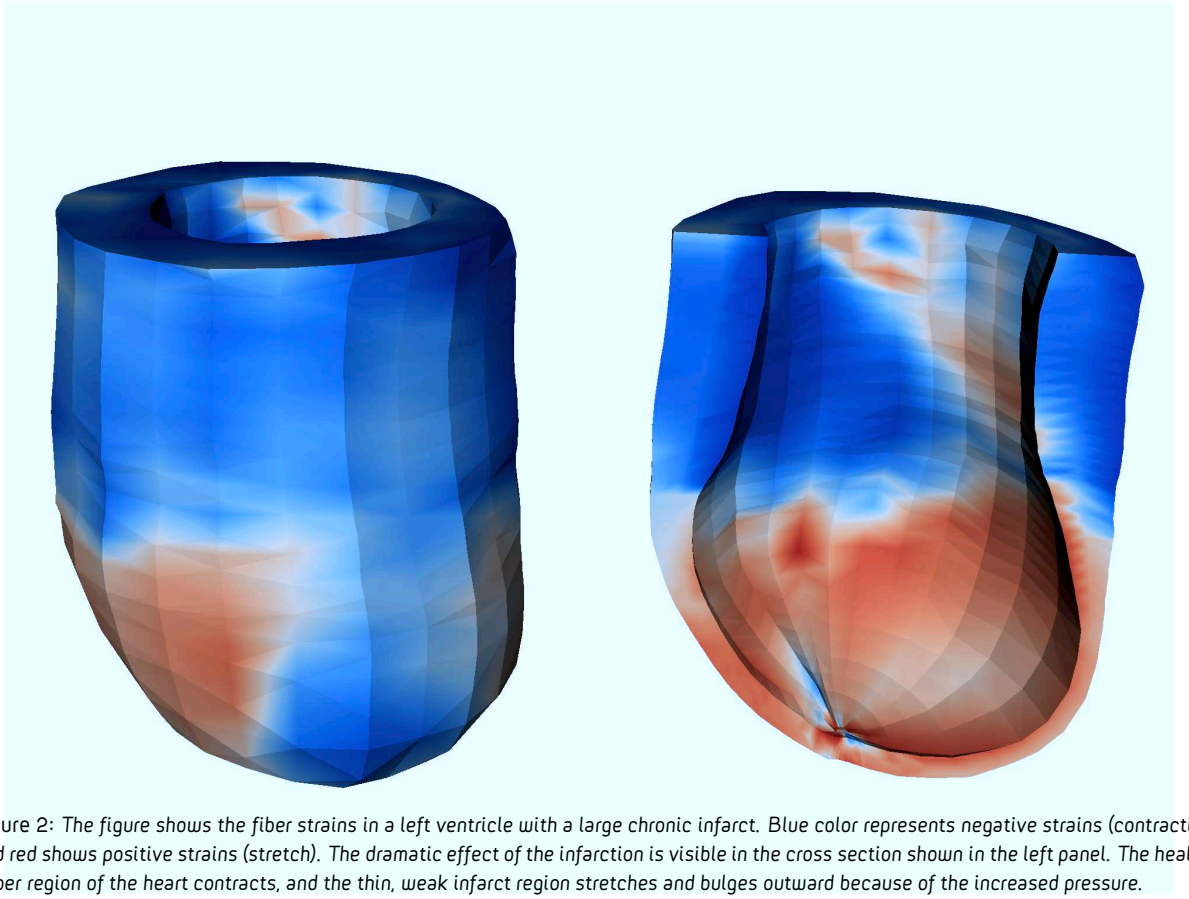


Figure 2: *The figure shows the fiber strains in a left ventricle with a large chronic infarct. Blue color represents negative strains (contraction) and red shows positive strains (stretch). The dramatic effect of the infarction is visible in the cross section shown in the left panel. The healthy upper region of the heart contracts, and the thin, weak infarct region stretches and bulges outward because of the increased pressure.*

[4] *http://www.apollon.uio.no/vis/art/2009_2/artikler/hjerte*

Education and Outreach

The Simula School (SSRI)

Being hosted by Simula Research Laboratory, CBC has access to a well-developed infrastructure for education of new researchers through doctoral and postdoctoral studies. In particular, all Ph.D. students and postdoctoral fellows at CBC are affiliated with the Simula School of Research and Innovation (SSRI), which is the organizational instrument for all levels of education at Simula Research Laboratory. This ensures a professional framework for our Ph.D. students and postdocs with respect to their research and career development. The added value of our association with SSRI consists of enhanced support in supervision, mentoring and recruitment, as well as special courses on presenting science and on entrepreneurship. These activities are described in more detail next.

The aim of the Simula School is to educate highly qualified researchers within the research fields of Simula, as an attractive resource for academia, industry, and the society at large. In addition to the traditional researcher education, management development programs and career guidance at postdoctoral level are key elements of the School's activities. The Simula School encourages and assists the students in establishing close connections with industry as a result of exchange programs and international collaboration. Through specific initiatives and activities the School will ensure the necessary academic and social conditions to allow the students to focus on their work and conduct their research effectively.

The School is organized as a limited company co-owned by Simula Research Laboratory (56%), Statoil (21%), Bærum Municipality (14%), Telenor (7%), SINTEF (1%), and The Norwegian Computing Center (1%).

During 2009, the Simula School has focused on two specific initiatives designed to enhance the competence of the students and postdoctoral fellows in research dissemination and in innovation and commercialization. The annual course on Communicating Research in Science, which is co-developed with Pennsylvania State University, was offered as a national workshop. The event was realized by generous funding from the large industrial companies Statoil and Telenor, and was also sponsored by the University of Oslo, IT Fornebu and the Norwegian Defense Research Establishment (FFI). The course treated four topics: effective scientific presentations, writing of papers, writing of grant proposals, and outreach of research to the public. The feedback from the participants has been unanimously positive, and a series of surveys measuring the effect and quality of the teaching has documented statistically significant improvements of the participants' communications skills. These results have been presented at two major educational conferences.

Complementing the communication course, the Simula School has collaborated with Simula Innovation in order to give a course on Innovation and Entrepreneurship. In this course, the students combined lectures with work on business cases based on their own research. The final results included several proposals that will be considered for further development in Simula Innovation.

In collaboration with Simula's Basic Research unit, the School has co-arranged a seminar discussing the nature of research, based on Richard Hamming's famous lecture "You and Your Research" (*http://tinyurl.com/8hbdv*). An important part of the School's role is to facilitate excellent scientific supervision. As part of this work, the school has arranged a seminar for the Simula personnel involved in supervision of Ph.D. students, targeting topics concerning progression of Ph.D. studies, gender issues, and a multi-cultural working environment.

This year the School entered into a 5-year agreement with Statoil, which in total will provide 20 million NOK for Ph.D. and postdoctoral research projects in computational geosciences. The agreement is part of Statoil's Academia Programme, and the academic research sponsored by the company is part of CBC.

The Simula School has also continued its collaboration with Valler Upper Secondary School. This initiative will provide a basis for the development of further cooperation between upper secondary schools and Simula. The collaboration with upper secondary schools is an important part of a long-term promotion of science and technology, and in particular information and communication technology, as a career path for young people.

The results obtained in the first two years of the School's existence were assessed in the 2009 evaluation of Simula Research Laboratory, conducted by the Research Council of Norway. The committee clearly expressed that it "strongly supports the creation and continued implementation of SSRI as a core educational component of Simula". Moreover, the committee stated that

> *SSRI could well grow to become a national resource for science education and take on a role as a coordinating center across several universities. Such opportunities should be explored and strengthened.*

To unleash this ambitious potential, the School plans to actively use the advice offered in the scientific evaluation report as an important element in upcoming strategic decisions.

Python for Scientific Computations

CBC continued in 2009 its efforts with bringing Python-based software development technology out to the national and international computational science community of students and researchers. More details about this activity is described in the annual report of 2008. Our general impression is that the interest in Python-based tools for scientific computations is rapidly growing year by year, and that our competence and experience with the subject are widely acknowledged.

We work further with developing the introductory programming course for science students (INF1100) at the University of Oslo. The annual report of 2007 has more detailed about this popular course. The book written for the course, "A Primer on Scientific Programming with Python", by Hans Petter Langtangen, was published by Springer in August 2009. This multi-disciplinary book aims at teaching computer programming as a powerful technique to solve mathematical problems arising in diverse fields such as physics, biology, and finance. There is already quite some interest in adopting the book for courses at other universities.

Scientific Software to the World

The most important outreach project at CBC is probably the FEniCS software suite, which is described in detail under the heading "Featured Research 2009 – Finite Element Software" previously in this report. CBC researchers and collaborators spent much efforts in 2009 on writing chapters to the upcoming book about FEniCS. This production of documentation also led to quite some work with redesigning interfaces in FEniCS in order to increase the user friendliness. We expect the launch of the book together with the first official release of FEniCS in 2010 to be a major event in the history of CBC that will attract widespread attention in the international computational science community.

Linux (or formerly Unix) has been, and probably will be, the dominating operating system for large-scale, high-performance computing. Therefore, distributing scientific software via the most important Linux channels is a key strategy for widespread use. The popularity of Ubuntu Linux has increased greatly in recent years, mostly due to its user friendliness. Ubuntu applies Debian packages for distributing software, and it is demanding, but correspondingly awarding, to get software accepted in Debian. We are happy to announce that a number of packages from the software development activity at CBC were accepted in the official Debian release in 2009. So far the packages SciTools, Swiginac, and all of the FEniCS components are found in standard unstable Debian (SciTools was also included in RedHat Linux). This way of distributing software enables people around the world to install our packages with a simple click or command on any computer with a Debian-based Linux operating system.

The simple installation scheme is also accessible on the Windows and Mac platforms by running Ubuntu in a separate window using the VirtualBox software. Our software packages are of course available on native Windows and Mac operating systems as well, but the installation is not as trivial as with Debian-based systems.

University Teaching

Almost all senior CBC researchers are involved with university teaching. The Simula staff lecture at the University of Oslo, Department of Informatics. Our collaborating Biomechanics Division at NTNU gives courses at the Department of Structural Engineering at NTNU, collaborators at FFI have created courses in fluid mechanics at the University of Oslo, and CBC associates in San Diego are involved with teaching computer science courses at the University of California at San Diego.

CBC teachers take particular interest in the *Computers in Science Education* (CSE) project at the University of Oslo (see *http://tinyurl.com/yjeksn2*). The goal of this project is to introduce numerical programming and simulation in all relevant science courses at all education levels. That is, CSE is a computational science reform that aims at implementing computer simulations in existing courses, rather than doing this in a new separate "Coomputational Science" student program, which is the common approach elsewhere. Furthermore, CSE aims at introducing programming and simulation from day one (through the course INF1100 mentioned above) and not wait until the master or Ph.D. level as is usual elsewhere.

The CSE project has received quite some international recognition as one of the very few successful attempts to modernize existing science education in a substantial way. So far, about a dozen of science courses have undergone a major modernization, building on the new numerical knowledge that the students gain in the first semester. This modernization also has three important pedagogical aspects: 1) programming is an effective tool for increasing the *understanding*[5]; 2) numerical solutions move the attention from lengthy algebra to a focus on problem formulation and interpretation of solutions, i.e., physical understanding; and 3) computer simulations allow more realistic and inspiring problems to be studied, and give students insight into current research problems. For CBC the CSE project is about bringing the tools and working habits of our research to students. Hopefully, this modern approach can improve recruitment and draw attention to the subjects we are dealing with in the center.

It is worth mentioning that the minister of research and higher education in Norway, Tora Aasland, requested a presentation of the CSE project and its visions in August 2009. This meeting, which also featured the rector and other leaders at the University of Oslo, identified the CSE project as a clear candidate for the upcoming Centers of Excellent Education. Unfortunately, the financial support for such centers seems to be substantially postponed at the time of this writing.

[5]To cite one of Norway's two greatest contributors to computer science, Kristen Nygaard: "Programming is understanding".

Appendix

In the appendices below, we use several abbreviations:

ADM	The Administration unit at Simula
BFS	Biomedical Flows and Structures (CBC project)
CB	Computational Biology (CBC project)
CBC	Center for Biomedical Computing
CC	Cardiac Computations (CBC project)
CG	Computational Geosciences (CBC project)
CM	Computational Middleware (CBC project)
F	Female
FFI	Norwegian Defence Research Establishment
HOST	Simula Research Laboratory (SRL)
IP	Inverse Problems (CBC project)
M	Male
NTNU	Norwegian University of Science and Technology
RCN	Research Council of Norway
RFS	Robust Flow Solvers (CBC project)
SRL	Simula Research Laboratory (CBC host institution)
SSRI	Simula School of Research and Innovation
UCy	University of Cyprus
UiO	University of Oslo
UMB	Norwegian University of Life Sciences
UmU	Umeå University
UW	University of Wisconsin

Staff

Senior scientists 2009: 28 people, 13.8 man-years

Name	Gender	Period	CBC share	Project	Funding
Achim Schroll	M	01.01.2008-31.12.2010	20%	CG	SSRI
Anders Logg	M	01.04.2007-31.12.2011	100%	CM/RFS	HOST
Andrew D. McCulloch	M	01.04.2007-30.06.2010	10%	BFS/CC	50% RCN grant 162730, 50% CBC
Are Magnus Bruaset	M	01.01.2008-31.03.2017	50%	CG	SSRI
Aslak Tveito	M	01.08.2007-31.03.2017	25%	CC	HOST
B. Anders Pettersson Reif	M	01.01.2008-31.12.2012	30%	CBC@FFI/UCy	FFI/Ucy
Bjørn Fredrik Nielsen	M	01.08.2007-31.03.2017	100%	IP	HOST
Bjørn H. Skallerud	M	24.05.2007-31.03.2017	50%	CBC@NTNU	NTNU
Carl Erik Wasberg	M	01.01.2008-31.12.2012	20%	CBC@FFI/UCy	FFI/UCy
Geir K. Pedersen	M	01.01.2008-30.06.2009	10%	BFS	CBC
Glenn Terje Lines	M	01.08.2007-31.03.2017	100%	CC	HOST
Hans Petter Langtangen	M	01.04.2007-31.03.2017	100%	CM/BFS/CG	HOST
Harald Osnes	M	01.08.2007-31.12.2009	40%	CC	50% CBC + 50% UiO
Joakim Sundnes	M	01.04.2007-31.03.2017	50%	CC	HOST
Kenneth H. Karlsen	M	01.01.2008-31.12.2009	10%	BFS/CC	CBC
Kent-Andre Mardal	M	01.04.2007-31.03.2017	100%	BFS/CM/RFS	CBC
Kirsten ten Tusscher	F	10.06.2008-31.05.2011	93%	CB	HOST
Leif Rune Hellevik	M	24.05.2007-31.03.2017	45%	CBC@NTNU	NTNU
Mats G. Larson	M	01.04.2007-31.05.2010	40%	RFS	50% CBC + 50% UmU
Mikael Mortensen	M	01.01.2008-31.12.2012	90%	CBC@FFI/UCy	FFI/UCy
Ola Skavhaug	M	01.04.2007-31.03.2017	95%	CM/CC	HOST
Per Grøttum	M	01.08.2007-31.12.2010	20%	IP	HOST
Scott Baden	M	11.06.2007-10.06.2010	20%	CM	CBC
Stavros Kassinos	M	01.01.2008-31.12.2012	10%	CBC@FFI/UCy	FFI/UCy
Svein Linge	M	01.04.2007-30.06.2010	20%	BFS	CBC
Victor Haughton	M	15.06.2008-14.06.2011	20%	BFS	70% UW + 30% CBC
Xing Cai	M	01.04.2007-31.03.2017	100%	CC/CM/CG	HOST
Øyvind Andreassen	M	01.01.2008-31.12.2012	10%	CBC@FFI/UCy	FFI/UCY

Postdoctoral candidates 2009: 15 people, 11.2 man-years

Name	Gender	Period	CBC share	Project	Funding
Alf Emil Løvgren	M	01.04.2007-31.10.2009	100%	RFS/BFS	CBC
Anders Helgeland	M	01.01.2009-31.12.2009	25%	CBC@FFI/UCy	FFI/UCy
Dimokratis Gregoriadis	M	01.01.2008-31.12.2010	50%	CBC@FFI/UCy	FFI/UCy
Harikrishnan Radkakrishnan	M	01.01.2008-31.12.2010	50%	CBC@FFI/UCy	FFI/UCy
Harish Narayanan	M	24.06.2008-23.06.2010	100%	RFS	RCN YFF grant 180450/V30
Johan Elon Hake	M	02.11.2009-31.12.2010	20%	CC/CM	HOST
Marie Rognes	F	02.06.2009-31.12.2012	100%	RFS	RCN YFF grant 180450/V30
Molly Maleckar	F	01.01.2009-31.12.2012	100%	CB	CBC
Murat Tutkun	M	03.10.2008-03.10.2012	100%	CBC@FFI/UCy	CBC
Ola Marius Lysaker	M	01.10.2008-31.04.2010	100%	IP	HOST
Pan Li	M	15.08.2008-10.06.2009	100%	CC	SRL in kind
Robert Artebrant	M	01.10.2007-01.03.2010	100%	CC	SSRI
Samuel Wall	M	26.05.2008-25.05.2012	100%	CC	HOST
Stuart Clark	M	01.01.2008-31.03.2011	100%	CG	SSRI
Victorien Prot	M	01.09.2008-31.08.2010	100%	CBC@NTNU	CBC

Ph.D. students 2009: 18 people, 13.7 man-years

Name	Gender	Period	CBC share	Project	Funding
Andre Massing	M	01.04.2009-31.03.2012	100%	RFS	RCN YFF grant 180450/V30
Aron Wahlberg	M	08.09.2009-07.09.2012	100%	RFS	RCN YFF grant 180450/V30
Martin S. Alnæs	M	01.08.2007-31.07.2009	100%	CC	RCN YFF grant 162730
Marie Rognes	F	01.01.2009-02.06.2009	100%	RFS	RCN YFF grant 180450/V30
Kristoffer Selim	M	01.01.2008-31.12.2010	100%	RFS	RCN YFF grant 180450/V30
Didem Unat	F	11.09.2007-10.09.2011	100%	CM	CBC
Joachim Berdal Haga	M	01.01.2008-06.06.2010	100%	CG	SSRI
Johan Elon Hake	M	01.08.2007-01.10.2009	100%	CC/CM	HOST
Jonathan Feinberg	M	15.08.2009-14.08.2013	100%	CG	SSRI
Kristian Valen Senstad	M	21.05.2008-20.05.2011	100%	BFS/RFS	SSRI
Oddrun Myklebust	F	15.08.2008-26.01.2009	100%	BFS	SSRI
Omal al-Khayat	M	01.01.2008-31.03.2010	100%	CG	SSRI
Paul Roger Leinan	M	10.09.2007-10.09.2011	100%	BFS	NTNU
Rolv Erlend Bredesen	M	01.04.2007-13.03.2011	92%	CM	90% UiO + 10% CBC
Sigrid Kaarstad Dahl	F	15.08.2008-14.08.2011	100%	CBC@NTNU	92% SSRI and 8% CBC
Sune Hansborg Pettersen	M	01.01.2009-12.06.2009	100%	CBC@NTNU	NTNU
Tim Dorscheidt	M	01.11.2008-01.11.2011	100%	CB	CBC
Wenjie Wei	M	01.10.2008-01.10.2011	100%	CM	SSRI

Technical and administrative staff 2009: 11 people, 4.1 man-years

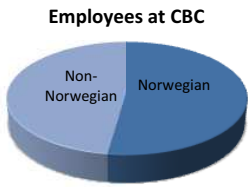
Name	Gender	Period	CBC share	Project	Funding
Anders Helgeland	M	01.06.2007-31.12.2009	20%	BFS	CBC
Emma Wingstedt	F	01.01.2008-31.12.2012	20%	CBC@FFI/UCy	FFI/UCy
Hannibal Fossum	M	10.08.2010-31.12.2010	13%	CBC@FFI/UCy	FFI
Hege Johnsrud	F	01.04.2007-31.03.2017	5%	ADM	HOST
Ilmar Wilbers	M	01.03.2009-30.06.2009	100%	CM	HOST
Johannes Hofaker Ring	M	01.01.2008-31.03.2017	100%	CM	CBC
Rainer Nerlich	M	05.10.2009-04.10.2010	100%	CG	SSRI
Susanne Hentschel	F	01.01.2009-31.08.2009	100%	BFS	SSRI
Tom David Atkinson	M	01.05.2007-31.03.2017	100%	ADM	CBC
Tor Gillberg	M	15.09.2009-28.02.2010	100%	CG	SSRI
Wenche Angel	F	01.04.2007-31.03.2017	10%	ADM	HOST

Guest researchers 2009: 2 people, 1.5 man-years

Name	Gender	Period	CBC share	Project	Funding
Hans Ekkehard Plesser	M	01.02.2009-01.02.2010	100%		UMB
Ralph Lorentzen	M	01.01.2008-31.12.2009	60%	CG	HOST

Development of staff (no. of individuals/man-years)

Position	2007	2008	2009
Senior scientists	19/7.1	28/13.4	28 /13.8
Post docs	8/4.1	17/8.8	14/10.1
Ph.D. students	7/3.2	16/11.3	18/13.7
Technical and administrative	10/3.5	12/5.8	11/4.1
Guest researchers	0/0	2/0.7	2/1.5



Accounting and Budget

Below, we present the main figures regarding the CBC budget and funding. The operating revenues and expenses represent the funding and cost that we control our selves. The income in kind and operating expenses in kind presents representative figures from activities (people) within the CBC project, but with the funding and costs outside of CBC's books. By further expanding the cope of CBC and establishing collaboration with The Norwegian Defence Research Establishment, the University of Cyprus and the Computational Geosciences project financed by Statoil through Simula School of Research and Innovation the SFF grant from the Research Counsil of Norway now representsless than 25 % of the total funding of CBC activities, instead of the approximately 65 % that was originally intended in our proposal.

Operating Revenues	Note	Account 2008	Budget 2009	Account 2009	Budget 2010
RCN CoE founding		7,500	8,160	8,160	8,180
Allocation from earlier years		1,478	-117	-117	-1390
Host - Simula Research Laboratory		9,639	9,651	9,349	8,502
Other income RCN	1	4,131	3,915	3,475	3,358
Other income	2	16		516	500
Sum operating revenues		22,764	21,609	21,383	19,150
Income in kind:					
SSRI	3	5,842	5,760	6,763	6,000
NTNU	4	1,131	1,320	1,913	2,000
University of Oslo	5	792	960	893	1600
University of Umeå	6	152	160	160	160
Host – Simula Research Laboratory	7	636	1,000	1,000	500
FFI and University of Cyprus	8	2,032		2,640	2,000
Norwegian University of Life Sciences	9			733	67
Sum income in kind		10,585	9,200	14,102	12,327
Total income		33,349	30,809	35,485	31,477

Operating Expenses	Note	Account 2008	Budget 2009	Account 2009	Budget 2010
Cost of labour		16,330	16,000	17,287	14,305
Indirect costs	10	3,255	4,060	3,938	3,095
Outsourcing of R&D services		866			200
Other operating expenses	11	2,430	3,300	1,548	1,550
Sum operating expenses		22,881	23,360	22,773	19,150
Operating expenses in kind:					
Cost of labour		7,622	6,440	10,151	8,629
Indirect costs	10	1,905	1,840	2,545	2,465
Other operating expenses	11	1,058	920	1,406	1,233
Sum operating expenses in kind		10,585	9,200	14,102	12,327
Total operating expenses		33,466	36,875	36,365	31,477
Year end allocation		-117	-1,751	-1,390	0

Note 1: Other income RCN (= 3,475):
162730: YFF - Computing the mechanics of the heart (= 700)
180450: YFF - Automation of Error Control with Application to Fluid-Structure Interaction in Biomedicine (= 2,775)

Note 2: Other income:
University Hospital of Northern Norway (= 516).

Note 3: Simula Research Laboratory's subsidiary Simula School of Research and Innovation (SSRI) is responsible for all educational activities in Simula Research Laboratory. The Simula School has financed the work of two post docs (S. Clark and R. Artebrant) parts of the year, 0,7 researchers (A. Schroll and A. M. Bruaset) and five Ph.D. students all year (O. Al-Khayat, J. B. Haga, K. V. Sendstad, S. K. Dahl and W. Wei), and one Ph.D. student (J. Feinberg) for half a year, and two research trainees for parts of the year (S. Hentschel and R. Nerlich).

Note 4: Contributions in kind from the Norwegian University of Science and Technology (NTNU) (= 1,913): NTNU has financed in kind a total of 0,95 man-years of senior scientists (Prof. B. Skallerud and Prof. L. R. Hellevik), and the equivalence of 1.44 man-years of Ph.D. students (P. R. Leinan and S. Hansborg Pettersen).

Note 5 Contributions in kind from the University of Oslo (= 893):
One Ph.D. student (R. E. Bredesen) and part-time funding of researcher (H. Osnes).

Note 6: Contributions in kind from the University of Umeå (= 160):
Part time funding of one senior scientist (Prof. M. Larson)

Note 7: Contributions in kind from the host – Simula Research Laboratory (= 1,000):
Funding of one part-time senior scientist (Prof. A. Tveito), two postdocs (P. Li and R. Artebrant) as well as administrtive services.

Note 8: Contribution in kind from the Norwegian Defence Research Establishment (FFI) and University of Cyprus (= 2,640):
1.60 man-years of senior scientists (shared between B. A. P. Reif, C. E. Wasberg, M. Mortensen, S. Kassinos and Ø. Andreassen), 1.25 man-year of post doc positions (D. Gregoriadis, H. Radhakrishnan, A. Helgeland), and 0,45 man-years of technical staff (A. Helgeland, H. Fossum and E. Wingstedt).

Note 9: Contributions in kind from the Norwegian University of Life Sciences:
Funding of full-time guest senior scientist (H. E. Plesser).

Note 10: Indirect costs cover the expenses of offices and infrastructure for all employees.

Note 11: Other operating expenses include the cost of scientific equipment, travelling, workshops, seminars, and visitors.

Collaboration partners

Title	Name	Affiliation	Country	Project
Prof.	G. Holzapfel	Graz University of Technology, also KTH (Stockholm)	Austria	CBC@NTNU
Dr.	G. Sommer	Graz University of Technology	Austria	CBC@NTNU
Mr.	J. Degroote	Ghent University	Belgium	CBC@NTNU
Prof.	J. Vierendeels	Ghent University	Belgium	CBC@NTNU
Mr.	S. Annerel	Ghent University	Belgium	CBC@NTNU
Prof.	R. W. Dos Santos	Federal University of Juiz de Fora	Brazil	CC
Dr.	W. Giles	University of Calgary	Canada	CB
Prof.	R. J. Spiteri	University of Saskatchewan	Canada	CC
Prof.	W. Chen	Hohai University	China	CM
Prof.	Y. Maday	University Pierre et Marie Curie	France	RFS
Prof.	H.-P. Bunge	Ludwig-Maximilian University	Germany	CG
Prof.	U. Ruede	University of Erlangen	Germany	CG
Prof.	M. Burger	University of Münster	Germany	IP
Dr.	B. Erdmann	Zuse Institute Berlin	Germany	CC
Prof.	P. Deuflhard	Zuse Institute Berlin	Germany	CC
Dr.	R. Roitzsch	Zuse Institute Berlin	Germany	CC
Dr.	L. Antiga	Mario Negri Institute	Italy	BFS
Dr.	B. Verheij	University of Groningen	The Netherlands	CB
Prof.	D. G. M. Beersma	University of Groningen	The Netherlands	CB
Dr.	C. Soeller	University of Aukland	New Zealand	CM
Prof.	M. Cannell	University of Aukland	New Zealand	CM
Prof.	R. Winther	University of Oslo	Norway	BFS
Dr.	S. Glimsdal	Norwegian Geotechnical Institute	Norway	CM
Prof.	E. Rønqvist	Norwegian University of Science and Technology	Norway	RFS
Prof.	O. M. Sejerstedt	Oslo University Hospital	Norway	CC
Mr.	W. Louch	Oslo University Hospital	Norway	CC
Prof.	A. Malthe-Sørenssen	University of Oslo	Norway	CM
Dr.	A. Stray-Pedersen	Rettsmedisinsk Institutt	Norway	BFS
Dr.	S. Bakke	Rikshospitalet University Hospital	Norway	BFS
Prof.	R. Haaverstad	St. Olav Hospital, Trondheim	Norway	BFS
Dr.	A. Thurmond	Statoil	Norway	CG
Dr.	J. Skogseid	Statoil	Norway	CG
Dr.	T. Løseth	Statoil	Norway	CG
Dr.	T. O. Sømme	University of Bergen	Norway	CG
Dr.	B. Høyland	University of Oslo	Norway	CM
Mr.	J. Nilsen	University of Oslo	Norway	CM
Dr.	J. Isaksen	University Hospital of North Norway	Norway	BFS
Prof.	T. Ingebrigtsen	University Hospital of North Norway	Norway	BFS
Dr.	S. Deparis	EPFL Lausanne	Switzerland	RFS
Mr.	K. Oelgaard	TU Delft	The Netherlands	RFS
Dr.	A. V. Panfilov	Utrecht University	The Netherlands	CB
Prof.	P. Hogeweg	Utrecht University	The Netherlands	CB
Dr.	G. N. Wells	University of Cambridge	United Kingdom	CM, RFS
Prof.	A. Holden	University of Leeds	United Kingdom	CM
Dr.	M. G. Knepley	University of Chicago	USA	CM
Prof.	Y. Maday	Brown University	USA	RFS
Dr.	N. Trayanova	Johns Hopkins University	USA	CB
Dr.	J. Zhu Kentucky	Geological Survey	USA	CG
Ms.	H. C. Bender	Missouri University of Science and Technology	USA	CG
Prof.	M. G. Abdelsalam	Missouri University of Science and Technology	USA	CG
Prof.	R. C. Kirby	Texas Tech University	USA	CM
Prof.	J. T.-C.Yeh	University of Arizona	USA	CM
Dr.	S. Narayanan	University of California, San Diego	USA	CB
Ms.	C. A. Micek	University of Minnesota, School of Mathematics	USA	RFS
Prof.	D. N. Arnold	University of Minnesota, School of Mathematics	USA	RFS
Prof.	M. C. Calderer	University of Minnesota, School of Mathematics	USA	RFS
Prof.	C. Strother	University of Wisconsin, Madison	USA	BFS
Dr.	J. Jiang	University of Wisconsin, Madison	USA	BFS
Dr.	O. Wieben	University of Wisconsin, Madison	USA	BFS
Dr.	P. Turski	University of Wisconsin, Madison	USA	BFS
Dr.	P. Li	Washington University, St. Louis	USA	CG
Prof.	William George	Chalmers Institute of Technology	Sweden	CBC@FFI/UCy

Publications

CBC only reports publications where a significant part of the research has been funded by CBC. By this we mean that at least one of the authors of the reported publications must have his/her main affiliation with CBC, and has contributed to the publication as laid out in Simula's publication guidelines: *http://simula.no/research/publication-guidelines*.

Publications from people with part time positions at CBC are generally not counted, unless the research is particularly relevant for a CBC project. Such exceptions from the main rule are few, and must in all cases be approved by the director of the center.

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[129] **S. K. Dahl**. Fluid-Structure Interaction Simulation of Mitral Valve Dynamics in a Subject-Specific Geometry During Diastolic Filling. Invited talk at the MI-Lab seminar; Cardiac imaging and LV mechanics, Trondheim, Norway, November 10 2009.

[130] **S. K. Dahl**. Fluid Structure Interaction with a User Defined Subroutine. Invited talk at Fluent Users Group at SINTEF/NTNU, June 3 2009.

[131] **V. Haughton**. MRI Research and Techniques for CSF Flow. ASAP's Chiari & Syringomyelia Conference: Quest for Understanding, Sheraton Madison Hotel, Madison, Wisconsin, USA, July 15–18 2009.

[132] **V. Haughton**. CSF Flow in the Chiari I Malformation Evaluated with PC MR and Computation Flow Design. Nordic Society of Neuroradiology, Hurtigruten, Norway, September 10 2009.

[133] **V. Haughton**. Imaging Evaluation of the Chiari I Malformation. Meeting and symposium of the American Syringomyelia Alliance Project, San Francisco, California, USA, 2009.

[134] **H. P. Langtangen**. Experience with Merging Mathematics, Numerical Methods, Physics and Programming From Day One. Invited talk at Telemark College, Engineering Faculty, Porsgrunn, Norway, October 2009.

[135] **H. P. Langtangen**. Techniques for Achieving High Performance in Numerical Python Codes. Invited talk at Telemark College, Engineering Faculty, Porsgrunn, Norway, February 2009.

[136] **H. P. Langtangen**. Experience with Python in a Major Educational Reform. Minisymposium talk at the SIAM Conference on Computational Science and Engineering, March, Miami, USA, 2009.

[137] **H. P. Langtangen**. Modeling and Simulation. Invited talk at a Tekna Labor Union seminar, November 2009.

[138] **H. P. Langtangen**. Python as an Important Tool in a Major Science Education Reform. Invited talk at Telemark College, Engineering Faculty, Porsgrunn, Norway, February 2009.

[139] **S. Linge**, **A. E. Løvgren**, **K.-A. Mardal**, **V. Haughton**, and **H. P. Langtangen**. Cerebrospinal Fluid Flow Investigations with Modelling and Simulation. Invited talk at The Chiari Institute, New York, USA, January 14 2009.

[140] **S. Linge**, **A. E. Løvgren**, **K.-A. Mardal**, **V. Haughton**, and **H. P. Langtangen**. Simulating Normal and Abnormal CSF Flow with Idealized Geometries. Talk, seminar on cerebrospinal fluid flow, University of Wisconsin, USA, January 16 2009.

[141] **S. Linge**, **A. E. Løvgren**, **K.-A. Mardal**, **V. Haughton**, and **H. P. Langtangen**. Tonsilar Herniation - How Is the CSF Flow Influenced? Invited talk at Rikshospitalet University Hospital, Oslo, Norway, June 5 2009.

[142] F. V. Lionetti, **A. D. McCulloch**, and **S. B. Baden**. GPU Accelerated Solvers for ODEs Describing Cardiac Membrane Equations. Poster at the GPU Technology Conference, San Jose, California, USA, October 2009.

[143] F. V. Lionetti, **A. D. McCulloch**, and **S. B. Baden**. GPU Accelerated Electrophysiology Simulations. Poster at the 2009 ACM/IEEE Conference on Supercomputing (SC 2009), Portland, Oregon, USA, November 2009.

[144] **A. Logg**. FEniCS: Automated Computing. Talk at Workshop on Computational Fluid Dynamics, Simula Research Laboratory, Oslo, Norway, May 4 2009.

[145] **A. Logg**. Automatic Code Generation and the FEniCS Project. Talk at Opportunities and Challenges in Computational Geodynamics, Caltech, USA, Mars 30 2009.

[146] **A. Logg**. Automated Finite Element Discretization. Invited talk at the Workshop on Compatible and Innovative Discretizations for Partial Differential Equations – Algorithms, Analysis and Implementation, Norwegian Academy of Science and Letters, Oslo, Norway, June 18 2009.

[147] **A. Logg**. Parallel Data Structures and Algorithms in DOLFIN. Talk at High-Performance Computing Workshop, Simula Research Laboratory, Oslo, June 16 2009.

[148] **A. Logg**. DOLFIN: Automated Finite Element Computing. Talk at ENUMATH'09, Uppsala, July 3 2009.

[149] **A. E. Løvgren**, Y. Maday, E. Rønquist, and S. Deparis. Real-Time Flow Simulation. Invited talk at The Chiari Institute, New York, USA, January 14 2009.

[150] **A. E. Løvgren**, Y. Maday, E. Rønquist, and S. Deparis. Real-Time Computation of CSF Flow. Invited talk at a seminar for cerebrospinal fluid flow, University of Wisconsin, Madison, USA, January 16 2009.

[151] **A. E. Løvgren**, Y. Maday, and E. Rønquist. The Reduced Basis Element Method: Offline-Online Decomposition in the Nonconforming, Nonaffine Case. Invited talk at the Reduced Basis Function minisymposium at ICOSAHOM'09, NTNU, Trondheim, Norway, June 22–26 2009.

[152] **A. E. Løvgren**, Y. Maday, and E. Rønquist. The Spectral Element Method Used to Assess the Quality of a Deformed Mesh. Talk at ICOSAHOM'09, NTNU, Trondheim, Norway, June 22–26 2009.

[153] **A. E. Løvgren** and S. Deparis. Stabilized Reduced Basis Approximation of the Navier-Stokes Equations in Deformed Domains. Contributed talk at the workshop on Model Reduction of Parametrized Systems, Münster, Germany, September 16–18 2009.

[154] **K.-A. Mardal**, **A. Helgeland**, **S. Hentschel**, **H. P. Langtangen**, **A. Logg**, **S. Linge**, **A. E. Løvgren**, and **K. Valen-Sendstad**. Some Biomedical Applications at Simula. Talk at the Workshop on Computational Biology, organized by CBC and the Norwegian University of Life Sciences, Oslo, Norway, 2009.

[155] **K.-A. Mardal**, **S. Hentschel**, **A. Logg**, and **K. Valen-Sendstad**. Cerebral Blood Flow. Invited talk at Telemark College, Engineering Faculty, Porsgrunn, Norway, October 2009.

[156] **K.-A. Mardal**, **S. Hentschel**, **A. Helgeland**, **H. P. Langtangen**, **S. Linge**, **A. E. Løvgren**, **A. Logg**, and **K. Valen-Sendstad**. Patient-Specific Simulations of Stroke and Syringomyelia. Talk at Advisory Commitee Meeting for FFI project P1112 "Aerosols: Dispersion, Transport and Consequences", Kjeller, Norway, November 3 2009.

[157] **K.-A. Mardal**, **V. Haughton**, **S. Hentschel**, **H. P. Langtangen**, **S. Linge**, **A. E. Løvgren**, and **K. Valen-Sendstad**. CSF Flow Modelling. Invited talk at the CSR Flow Research Conference, University of Wisconsin, USA, November 9 2009.

[158] **K.-A. Mardal**, **S. Hentschel**, **A. Logg**, and **K. Valen-Sendstad**. Patient-Specific Hemodynamics in FEniCS. Invited talk at the minisymposium on Computational Vascular and Cardiovascular Mechanics at the 10th US National Congress on Computational Mechanics, July 16–19 2009.

[159] **K.-A. Mardal**, **A. Logg**, **S. Hentschel**, **O. C. Myklebust**, and **K. Valen-Sendstad**. Patient-Specific Hemodynamics in FEniCS. Talk at the FEniCS'09 Conference, Oslo, Norway, 2009.

[160] **B. F. Nielsen**, **O. M. Lysaker**, **P. Grøttum**, K. Haugaa, J. G. Fjeld, and A. Abildgaard. The Inverse Ischemia Problem; Mathematical Models and Validation. Talk at the Applied Inverse Problems conference, Vienna, Austria, 2009.

[161] **B. F. Nielsen** and **K.-A. Mardal**. An Operator Theoretical Approach to Preconditioning Optimality Systems. Talk at the Applied Inverse Problems conference, Vienna, Austria, 2009.

[162] **B. F. Nielsen**. Recent Contributions to the Inverse Problem of Electrocardiography. Organization of a minisymposium at the Applied Inverse Problems conference, Vienna, Austria, 2009.

[163] **B. F. Nielsen**, **O. M. Lysaker**, **P. Grøttum**, **A. Tveito**, K. Haugaa, A. Abildgaard, J. G. Fjeld, and M. Burger. Modelling, Mathematical Properties and Validation of the Inverse Ischemia Problem. Invited talk at the workshop Bidomain 2009, University of Graz, Austria, 2009.

[164] **M. E. Rognes**. Mixed Finite Element Methods for Linear Viscoelasticity. Invited talk at the Workshop on Compatible and innovative discretizations for Partial Differential Equations – Algorithms, Analysis and Implementation, Norwegian Academy of Science and Letters, Oslo, Norway, June 18 2009.

[165] **M. E. Rognes**. Efficient Assembly of $H(\mathrm{div})$ and $H(\mathrm{curl})$ Conforming Variational Forms. Talk at ICOSAHOM'09, NTNU, Trondheim, Norway, 2009.

[166] **M. E. Rognes**. Automated Error Control – Current Status and Future Ambitions. Simula Seminar, September 24 2009.

[167] **B. H. Skallerud**. Tissue Fiber Families in the Mitral Valve - Constitutive Modelling Numerical Analysis and Potential Clinical Application. Invited keynote talk at the 22nd Nordic Seminar on Computational Mechanics, Aalborg, Denmark, October 22–23 2009.

[168] **B. H. Skallerud** and **V. E. Prot**. Alternative Elasticity Modeling Approaches for Mitral Valve Analysis: Consequences for Stress and Deformation Prediction. Talk at the 22nd Nordic Seminar on Computational Mechanics, Aalborg, Denmark, October 22–23 2009.

[169] **H. Osnes**, **S. R. Clark**, and **J. Sundnes**. Uncertainty Analysis of the Mechanics of the Heart. Talk at the 22nd Nordic Seminar on Computational Mechanics, Aalborg, Denmark, October 22–23 2009.

[170] **J. Sundnes**, **S. Wall**, and **H. Osnes**. Computer Modeling of Cardiac Electro-Mechanics - Models and Numerical Methods. Talk at the Cardiac Modeling Seminar, Simula Research Laboratory, Oslo, Norway, 2009.

[171] **J. Sundnes**. Multiscale Models of Physiological Systems. Guest lecture in the course "Bioinformatics for Molecular Biology", University of Oslo, Norway, 2009.

[172] **J. Sundnes**, **S. Wall**, and **H. Osnes**. Simulation of Strongly Coupled Electro-Mechanics in an Infarcted Left Ventricle. Invited talk at the workshop Bidomain 2009, University of Graz, Austria, 2009.

[173] **D. Unat** and **S. B. Baden**. Optimizations of Common Scientific Kernels on GPU. Poster presented at the Early Adopters PhD Workshop: Building the Next Generation of Application Scientists, Supercomputing Conference 2009, Portland, OR, USA, 2009.

[174] **K. Valen-Sendstad**, **K.-A. Mardal**, and **A. Logg**. Simulation Methodology for Bioflows. Talk at Advisory Commitee Meeting for FFI project P1112 "Aerosols: Dispersion, Transport and Consequences", Kjeller, Norway, May 5 2009.

[175] **W. Wei**, **S. R. Clark**, **X. Cai**, and **A. M. Bruaset**. Parallel Simulation of Dual Lithology Sedimentation. Poster presented at the NOTUR 2009 conference, Trondheim, Norway, May 18–20 2009.

[176] **S. K. Dahl**, J. Vierendeels, J. Degroote, S. Annerel, **B. H. Skallerud**, and L. R. Hellevik. Implicit Interaction of Two Rigid Mitral Leaflets in a Partitioned Fluid-Structure Approach. Talk at MekIT'09: Fifth National Conference on Computational Mechanics, Trondheim, Norway, May 26–27 2009.

[177] **H. E. Fossum** and **B. A. Pettersson Reif**. A Comparison of RANS Turbulence Models for Simulation of Flow in the Human Respiratory System. Talk at MekIT'09: Fifth National Conference on Computational Mechanics, Trondheim, Norway, May 26–27.

[178] **J. B. Haga**, **H. P. Langtangen**, **B. F. Nielsen**, and **H. Osnes**. On the Performance of an Algebraic Multigrid Preconditioner for the Pressure Equation with Highly Discontinuous Media. Talk at MekIT'09: Fifth National Conference on Computational Mechanics, Trondheim, Norway, May 26–27.

[179] **S. H. Pettersen**, A. Aamodt, O. A. Foss, and **B. H. Skallerud**. Subject Specific Finite Element Analysis of a Callus Distraction - a Preliminary Study. Talk at MekIT'09: Fifth National Conference on Computational Mechanics, Trondheim, Norway, May 26–27.

[180] **K. Selim** and **A. Logg**. Simulating Heart Valve Dynamics in FEniCS. Talk at MekIT'09: Fifth National Conference on Computational Mechanics, Trondheim, Norway, May 26–27.

[181] **M. Tutkun**, **B. A. Pettersson Reif**, P. B. V. Johansson, **Ø. Andreassen**, and J. Werne. Low Order Dynamical System Modelling of Stratified Shear Turbulence. Talk at MekIT'09: Fifth National Conference on Computational Mechanics, Trondheim, Norway, May 26–27.

[182] **K. Valen-Sendstad**, **M. Mortensen**, **H. P. Langtangen**, **B. A. Pettersson Reif**, and **K.-A. Mardal**. Implementing a $k-\epsilon$ Turbulence Model in the FEniCS Finite Element Programming Environment. Talk at MekIT'09: Fifth National Conference on Computational Mechanics, Trondheim, Norway, May 26–27.

[183] M. Vartdal and **B. A. Pettersson Reif**. Numerical Modeling of Aerosol Dispersion Inside a Rotating Aerosol Chamber. Talk at MekIT'09: Fifth National Conference on Computational Mechanics, Trondheim, Norway, May 26–27.

[184] T. Vik and **B. A. Pettersson Reif**. Numerical Simulation of the Evaporation From a Liquid Pool Beneath a Turbulent Boundary Layer. Talk at MekIT'09: Fifth National Conference on Computational Mechanics, Trondheim, Norway, May 26–27.

[185] **I. Wilbers**, **H. P. Langtangen**, and Å. Ødegard. Using Cython to Speed Up Numerical Python Programs. Talk at MekIT'09: Fifth National Conference on Computational Mechanics, Trondheim, Norway, May 26–27.

[186] **E. M. M. Wingstedt** and **B. A. Pettersson Reif**. CFD Modeling of Pollutant Dispersion in an Idealized Urban Area. Talk at MekIT'09: Fifth National Conference on Computational Mechanics, Trondheim, Norway, May 26–27.

[187] **H. E. Plesser**, K. Austvoll, and E. Nordlie. Simulation and Visualization of the Early Visual System Using PyNEST and ConnPlotter. Talk at the Kongsberg Vision Meeting, The Norwegian Association of Optometrists, Norway, 2009.

[188] H. Lindekleiv and **K. Valen-Sendstad**. Sex Differences in Intracranial Bifurcation Geometry and Blood Flow Velocity Result in Stronger Hemodynamic Forces Upon the Female Vessel Wall. Talk at the Nordic Society of Neuroradiology Meeting, 2009.

Conferences, Workshops and Seminars

We have used the following rule of thumb to make a distinction between conferences, workshops, and seminars:

Conference: A formal event over several days, with at least 50 participants. It may include one or more workshops, seminars and poster sessions.

Workshop: A formal event, containing several talks organized in sessions.

Seminar: A less formal meeting between researchers which includes one or more talks with discussions.

In addition to organizing two joint conferences with a couple of other Norwegian Centers of Excellence (*CIPR* and *CMA*), CBC hosted 11 workshops, 6 seminars, and 12 talks in 2009, with a total number of 170 presentations and more than 630 participants.

CBC Workshop on Simulating Normal and Abnormal CSF Flow with Idealized Geometries - January 16, 2009

Svein Linge and Alf Emil Løvgren from CBC were invited to organize a workshop at the University of Wisconsin, Madison, USA. The topic of the workshop was computer simulations of cerebrospinal fluid (CSF) flow to obtain a better understanding of the Chiari I malformation and the associated formation of cysts in the spinal chord. The medical group in Madison is internationally highly recognized and collaborates with CBC on CSF flow.

Total number of participants: 26
Total number of guests outside of CBC: 23
Number of different nationalities represented: 4
Total number of speakers: 2
Total number of talks: 2

CBC Workshop on Heart Modeling - February 26, 2009

The purpose of this workshop was to present the current status and challenges in the Inverse Problem project.

Total number of participants: 17
Total number of guests outside of CBC: 3
Number of different nationalities represented: 5
Total number of speakers: 6
Total number of talks: 6

CBC Workshop on Ultrasound Imaging of Cardiac Activity - March 23, 2009

Professor Matthew O'Donnell from University of Washington, who is a leading scientist in ultrasound imaging, visited CBC and a workshop was organized to communicate cutting edge research on imaging of the heart.

Total number of participants: 17
Total number of guests outside of CBC: 11
Number of different nationalities represented: 6
Total number of speakers: 1
Total number of talks: 2

CBC Workshop on Current Issues and Activities in the Robust Flow Solvers Project - April 23, 2009

The workshop featured contributions from most of the researchers in the Robust Flow Solver project. The purpose was to document status and provide a forum for critical discussion of results and future plans.

Total number of participants: 9
Total number of guests outside of CBC: 0
Number of different nationalities represented: 4
Total number of speakers: 9
Total number of talks: 9

CBC Workshop on Aerosols: Dispersion, Transport and Effects - May 4-5, 2009

This workshop concerned simulation of flows with small droplets or solid particles (aerosols), a topic of great relevance to, e.g., drug inhalation, spreading of the swine flu, bioterror attacks, and effects of pollution. The first day, at Simula, featured technical in-depth talks on mathematical modeling, numerical methods, and discussion of results from case studies. The second day, at FFI, contained presentations of the main results to the advisory committee for this project. The advisory committee has members from the Norwegian Armed Forces, the Norwegian Ministry of Defense, Ullevål University Hospital, CBC, University of Oslo, Norwegian University of Science and Technology, and the University of Cyprus.

Total number of participants: 30
Total number of guests outside of CBC: 10
Number of different nationalities represented: 6
Total number of speakers: 11
Total number of talks: 17

CBC Seminar on Fluid Mechanics - May 29, 2009

The purpose of this seminar was to present some challenges in fluid mechanics related to biomedical flows of relevance to CBC. Researchers from FFI and Simula discussed how to approach the challenges and further strengthen the collaboration between the research groups. The topic of an upcoming Ph.D. position was

also discussed.

Total number of participants: 7
Number of different nationalities represented: 3
Total number of speakers: 2
Total number of talks: 2

CBC, CIPR and CMA Conference on Scale Space and Variational Methods in Computer Vision (SSVM'09) - June 1-5, 2009

This biannual conference series is a merger of the Scale Space conferences and the Variational Level Set Methods conference. The aim is to bring together two different communities with common research interests: the one on scale space analysis and the one on variational, geometric and level set methods and their applications in image interpretation and understanding.

Total number of participants: 101
Total number of guests outside of CBC: 100
Number of different nationalities represented: 22
Total number of talks: 25

CBC Seminar on Stability, Consistency, and Convergence: Modern Variations on a Classical Theme - June 10, 2009

Prof. Douglas N. Arnold, the current president of SIAM, visited Simula and gave a presentation where he reviewed key elements in numerical computing and showed how these could be generalized to make classically hard problems tractable.

Total number of participants: 29
Total number of guests outside of CBC: 4
Number of different nationalities represented: 6
Total number of speakers: 1
Total number of talks: 1

FEniCS'09: The Annual FEniCS Workshop - June 11-12, 2009

CBC hosted the fourth FEniCS workshop on June 11-12, 2009. This is an annual workshop bringing together FEniCS developers and users. The talks presented the latest achievements in FEniCS, successful applications, future demands, and the status of other similar packages. Notable speakers included Scott Baden (UCSD), Johan Hoffman (KTH), Michael Holst (UCSD), Claes Johnson (KTH), Robert C. Kirby (Texas Tech), Mirko Maraldi (University of Bologna), Christophe Prud'homme (Universite de Grenoble), Garth N. Wells (University of Cambridge) and Ragnar Winther (Center of Mathematics for Applications (CMA), University of Oslo).

Total number of participants: 38
Total number of guests outside of CBC: 26
Number of different nationalities represented: 17
Total number of speakers: 18
Total number of talks: 18

CBC Workshop on High-Performance Computing - June 16, 2009

The recent wide accessibility of multicore-based parallel hardware provides new possibilities for doing high-performance scientific computing. This one-day workshop addressed issues such as state-of-the-art parallel hardware, parallel programming techniques, and new scientific applications.

Total number of participants: 17
Total number of guests outside of CBC: 7
Number of different nationalities represented: 4
Total number of speakers: 8
Total number of talks: 7

CBC and CMA Conference on Compatible and Innovative Discretizations for Partial Differential Equations - June 17-19, 2009

The numerical solution of partial differential equations is a fundamental task in science and engineering. Recent research has focused on so-called "compatible discretization techniques", defined as those discretization methods that inherit or mimic fundamental properties of the PDE such as topology, conservation, symmetries, and positivity structures and maximum principles. Although this research has established a firm framework for the analysis of discrete PDE problems, most developers and users of scientific software for the numerical solution of PDEs employ simple and less robust methods. With this workshop the aim was to bring together researchers on the theoretical aspects of numerical methods and scientists focusing on simulations and software development.

Total number of participants: 32
Total number of guests outside of CBC: 26
Total number of speakers: 19
Total number of talks: 19

CBC Seminar on Shock Waves in the Body - June 25, 2009

As a part of a visit by Professor Randall LeVeque from the University of Washington, we organized a seminar with a talk "Algorithms for Shock Wave Propagation in Tissue, Bones and Kidney Stones".

Total number of participants: 20
Total number of guests outside of CBC: 3
Number of different nationalities represented: 4
Total number of speakers: 1
Total number of talks: 1

CBC/UMB Workshop on Computational Biology - September 16, 2009

CBC and the computational systems biology groups at the Norwegian University of Life Sciences (UMB) have a significant potential for closer collaboration. We share common interests regarding computational methods and have complementary strengths. The purpose of this workshop was two-fold: to present the research at CBC and UMB, and to bring researchers from the institutions together and identify potential collaborations.

Total number of participants: 24
Total number of guests outside of CBC: 12
Number of different nationalities represented: 4
Total number of speakers: 19
Total number of talks: 19

CBC Seminar on Gender Equality - September 17, 2009

CBC wants to raise gender awareness among the employees and together with Simula find a strategy and action plan for further developing gender equality in our organization. This seminar featured a talk and a following forum for discussion.

Total number of participants: 29
Total number of guests outside of CBC: 0
Number of different nationalities represented: 6
Total number of speakers: 1
Total number of talks: 1

CBC Seminar on Python for Interactive, Large-scale Biomedical Computing - September 23, 2009

CBC has a decade of experience with Python for scientific computing. A Norwegian Center for Research Based Innovation (SFI), Statistics for Innovation, with researchers from the Norwegian Computing Centre, Department of Informatics, and others, works on a comprehensive system for genome analysis, implemented in Python. The experience with Python for large-scale biomedical computing from this project and the unsolved efficiency issues are of interest to the scientific Python programmers at CBC. A one-day seminar was set up to exchange ideas between the two groups and discuss possible ways of collaborating on biomedical computations.

Total number of participants: 7
Total number of guests outside of CBC: 3
Number of different nationalities represented: 2
Total number of talks: 1

CBC Workshop on Modeling Active and Passive Cardiac Mechanics - October 21, 2009

This workshop presented the current status and the challenges in modeling tissue with active and passive stress, followed by discussions on the direction of future work and a closer collaboration with the Biomechanics Division at NTNU and the researchers working on active stress in the heart tissue and stochastic uncertainty quantification at Simula. The discussions concluded with three specific problems for further collaboration between NTNU and Simula researchers.

Total number of participants: 7
Total number of guests outside of CBC: 1
Number of different nationalities represented: 3
Total number of speakers: 5
Total number of talks: 4

CBC Workshop on Engineering Methods in Medicine - October 30, 2009

To increase the awareness of the potential of using engineering methods of analysis in biomechanical problems, Telemark University College and CBC arranged a common workshop on this topic at the Faculty of Engineering, Telemark University College, in Porsgrunn. The talks covered problem settings, methods, and results from several CBC projects.

Total number of participants: 15
Total number of guests outside of CBC: 10
Number of different nationalities represented: 3
Total number of speakers:4
Total number of talks: 4

CBC Workshop on Calcium Dynamics in Cardiac Myocytes - November 3, 2009

Contraction of muscular heart cells (myocytes) are triggered by electrical signals, but the intra cellular carrier of this signal is calcium ions. The topic of the workshop was on this intra cellular calcium signaling. Specifically, the focus was on the early phase of the process, called the calcium induced calcium release, where a small influx of ions triggers a much larger release from internal compartments. Both the phenomenon itself and the modeling of it was discussed.

Total number of participants: 13
Total number of guests outside of CBC: 9
Number of different nationalities represented: 7
Total number of speakers: 4
Total number of talks: 3

CBC Workshop on Aerosols: Dispersion, Transport and Effects - November 3-4, 2009

This workshop had the same format as the workshop with the identical title, held on May 4-5. We refer to the description of the latter for details on the organization and purpose.

Day 1: Total number of participants: 21
Total number of guests outside of CBC: 12
Total number of speakers: 7

Total number of talks: 7

Day 2:
Total number of participants: 17
Number of different nationalities represented: 5

Total number of speakers: 7
Total number of talks: 6

Other Activities

Media Appearances

1) NRK TV: 04.10.09 "Newton" Professor Bjørn Skallerud participated in the main theme of the program, addressing "why things bounce". Different objects were tried out with respect to bouncing, such as tennis and golf balls, person on a trampoline etc. As the program addresses science for children, the scope was to give a playful and simplistic explanation on elasticity and energy balance laws. Skallerud did his own performance on the trampoline.
http://www1.nrk.no/nett-tv/klipp/555781.

2) NRK P2: 17.06.09: "Verdt å vite" A radio interview about the research done at CBC, with a particular focus on our simulations of the electrical activity of the heart, and the possible medical insights and benefits this research are contributing to.
http://www.nrk.no/programmer/sider/verdt_aa_vite/

3) Computerworld; 09.06.2009: "Slik skal hjerter reddes av IT" An article describing CBCs effort on simulating the hearts electrical activity, and the possible medical insights and benefits this research are contributing to.
http://www.idg.no/computerworld/article135519.ece

4) Apollon; 09.06.2009: "Simulerer elektrisk feil i hjertet" An article describing CBCs effort on simulating the hearts electrical activity, and the possible medical insights and benefits this research are contributing to.
http://www.apollon.uio.no/vis/art/2009_2/artikler/hjerte

5) Apollon; 02.06.2009: "Verdensledende i moderne realfagsundervisning" By integrating numerical methods and computer simulations already in the beginners course in mathematics, physics and informatics, UiO has taken the lead in modern science education. The courses have been developed by researchers at the Centers of Excellence: Center for Biomedical Computing (CBC), Physics of Geological Processes (PGP) and Center of Mathematics for Applications (CMA) in coorporation with the Faculty of Mathematics and Natural Science at the University of Oslo.
http://www.apollon.uio.no/vis/art/2009_2/artikler/undervisning

6) Dagbladet; 28.05.2009: "Ønsker mer informasjon for å forebygge shaken baby syndrome" An article about the collaborative research CBC (Simula) and SINTEF are doing in regards to look into damages done to infants and babies as a result of violence.
http://www.dagbladet.no/2009/05/27/nyheter/barnemishandling/politikk/barnevern/sykehus/6430393/

7) Computerworld; 01.04.2009: "Ønsker Google-Python velkommen" An interview with the director of CBC in regards to Google's announcement of their goal to make "Google-Python" 5 times quicker than "CPython".
http://www.idg.no/computerworld/article127632.ece

Refereeing Activities

During 2009, employees at CBC have refereed manuscripts for:

- A*Star
- Acta Biomateriala
- Advances in Water Resources
- American Association for the Advancement of Science
- American Heart Association
- American Journal of Physiology
- American Journal of Physiology - Regulatory, Integrative and Comparative Physiology
- Annals of Biomedical Engineering
- ASME Journal of Fluids Engineering
- Biophysical Journal
- Biomechanics and Modeling in Mechanobiology
- BIT Numerical Mathematics
- Cardiovascular Research
- Cell
- Cellular and Molecular Bioengineering
- Cellular and Molecular Biomechanics
- Circulation
- Circulation Research
- Computer Methods in Biomechanics and Biomedical Engineering
- Engineering Applications of Computational Fluid Mechanics
- Experimental Physiology
- Flow, Turbulence and Combustion
- Heart Rhythm
- IEEE Transactions on Visualization and Computer Graphics
- International Journal of Applied Mechanics
- International Journal of Solids and Structures
- International Conference on Spectral and High-Order Methods (ICOSAHOM)
- International Journal of Heat and Fluid Flow
- International Journal of Numerical Methods in Fluids
- Journal of Biomechanical Engineering
- Journal of Biomechanics
- Journal of Cellular and Molecular Cardiology

- Journal of Fluid Mechanics
- Journal of the American College of Cardiology
- Mechanics of Advanced Materials and Structures
- Medical Engineering and Physics
- Molecular Systems Biology
- National Institutes of Health
- National Science Foundation
- Nature Biotechnology
- New Zealand Foundation for Research Science and Technology
- Physics of Fluids
- Physiological Measurement
- PLoS Computational Biology
- Progress in Biophysics and Molecular Biology
- SIAM Journal on Scientific Computing
- Software: Practice and Experience
- Surface Coatings and Technology
- Systems and Synthetic Biology
- The Royal Society (London)

Committee Work and Recognition

- **A. McCulloch:** Jacobs School Distinguished Scholar (2009-2014)
- **A. Tveito:** Member of the National Biomedical Computation Resource – Resource Advisory Committee (NBCR RAC) in the United States, *http://www.nbcr.net/*
- **H. P. Langtangen:** Member of the scientific committee for Basic Research Projects in Engineering and Information Technology ("FRITEK"), Research Council of Norway

Editorial Boards

Employees of the center are on the following editorial boards:

V. Haughton:
1. American Journal of Neuroradiology
2. Neuroradiology

K. H. Karlsen:
1. Advances in Applied Mathematics and Mechanics
2. Advances in Numerical Analysis
3. Journal of Hyperbolic Differential Equations
4. Networks and Heterogeneous Media
5. SIAM Journal on Numerical Analysis

H. P. Langtangen:
1. Advances in Water Resources
2. BIT Numerical Mathematics
3. International Journal of Applied Mathematics & Computational Sciences
4. International Journal of Computational Science and Engineering
5. International Journal of Oceans and Oceanography
6. Mathematical Modelling and Applied Computing
7. Journal of Computational Science
8. SIAM Journal on Scientific Computing

A. McCulloch:
1. American Journal of Physiology: Heart & Circulatory Physiology
2. Cellular and Molecular Bioengineering
3. Computer Methods in Biomechanics and Biomedical Engineering
4. Drug Discovery Today: Disease Models
5. Experimental Physiology
6. Medical and Biological Engineering and Computing
7. PLoS Computational Biology
8. Synthetic and Systems Biology

B. A. P. Reif:
1. International Journal of Heat and Fluid Flow, Elsevier Science

B. Skallerud:
1. International Journal of Applied Mechanics

J. Sundnes:
1. Simulation modeling practice and theory, International Journal of the Federation of European Simulation Societies (EUROSIM)

A. Tveito:
1. Computing and Visualization in Science
2. SIAM Journal on Scientific Computing

Conference Committees

1. **S. Baden:** 15th International Euro-Par Conference, Delft, The Netherlands, August 25-28, 2009
2. **B. A. P. Reif and S. Kassinos:** 6th International Symposium on Turbulence and Shear Flow Phenomena, Seoul, June 22-26, 2009
3. **B. A. P. Reif and H. P. Langtangen:** Fifth National Conference on Computational Mechanics, Trondheim, May 26-27, 2009
4. **B. Skallerud:** (editor) Fifth National Conference on Computational Mechanics, Trondheim, May 26-27, 2009

Organization of Minisymposia and Workshops at Conferences

1. **H. P. Langtangen**, R. LeVeque (Univ. of Washington), and F. Perez (Univ. of California at Berkeley): Three minisymposia on Python for Scientific Computing at the SIAM Conference on Computational Science and Engineering, March 2-6, Miami, USA.
2. M. Cannataro (Univ. of Catanzaro, Italy), R. Weber dos Santos (Fed. Univ. of Juiz de Fora, Brazil), and **J. Sundnes**: Workshop on Bioinformatics' Challenges to Computer Science: Bioinformatics Tools and Biomedical Modeling at the International Conference on Computational Science, May 25-27, Baton Rouge, USA.
3. **A. Logg**: Minisymposium on Finite Element Software Development at the ENUMATH 2009 conference, June 29 - July 3, Uppsala, Sweden.
4. **B. F. Nielsen**: Minisymposium on Recent Contributions to the Inverse Problem of Electrocardiography at the Applied Inverse Problems conference, July 20-24, Vienna, Austria.

5. **B. F. Nielsen** and M. Burger (Univ. of Münster): Minisymposium on Preconditioning of Inverse Problems at the Applied Inverse Problems conference, July 20-24, Vienna, Austria.

Released software packages

In 2009, SciTools, Swiginac and all of the FEniCS software packages were included in the Debian GNU/Linux operating system. We also introduced parallel computing in DOLFIN 0.9.3, and the new UFL form language that extends the capabilities of FEniCS to handle complex nonlinear problems.

In addition, the following software projects were developed significantly:

- DOLFIN 0.9
- FFC 0.6, 0.7
- UFC 1.2
- UFL 0.2, 0.3, 0.4
- SyFi 0.6

List of International Guests in 2009

In 2009 CBC had 49 international guests from 18 different countries. Norwegian visitors are not listed, but count more than 35.

Period	Name	Affiliation	Nationality
December 3	Prof. Carlos Pfeiffer	University of Monterrey, Department of Computer Sciences	Mexican
November 3	Dr. Liren Li	Computational Physiology, University of Oxford	Chinese
November 3	Dr. Steven Niederer	St John's College, University of Oxford	New Zealand
November 2-3	Dr. Martin Falcke	Mathematical Cell Physiology, Max-Delbrück-Centrum für Molekulare Medizin	
November 2-3	Dr. William Louch	Institute for Experimental Medical Research, Oslo University Hospital UllevÃ¥l	Canadian
November 2-3	Prof. Nic Smith	Oxford University Computing Laboratory	British
October 19	Prof. Xue Anke	President of Hangzhou Dianzi University, China	Chinese
October 19	Dr. Xu Hong	Hangzhou Dianzi University	Chinese
October 19	Prof. Du Hongwen	Deputy Dean of School of Finance Economics of Hangzhou Dianzi University, China	Chinese
October 19	Prof. Li Lihua	School of Automation of Hangzhou Dianzi University, China	Chinese
October 19	Dr. Ji Zhengguo	School of Automation of Hangzhou Dianzi University, China	Chinese
October 12	Fredrik Andersson	Chalmers	Swedish
September 16	Dr. Henrik LindÃ©n	Dept. of Mathematical Sciences and Technology, Norwegian University of Life Sciences	Swedish
September 16	Dr. Tom Tetzlaff	IMT, Norwegian University of Life Sciences	German
September 14	Dr. Patrick Turski	Dep. of Radiology, University of Wisconsin	American
September 11	Prof. David Gilbert	Brunel University	British
June 25	Prof. Randall LeVeque	University of Washington, Seattle	American
June 12 - 13	Maraldi Mirko	University of Bologna	Italian
June 11-19	Prof. Robert Kirby	Texas Tech	American
June 11-13, Sept. 31 - Oct. 1	Dr. Christophe Prud'homme	University of Grenoble	French
June 11-12	Rodrigo Vilela de Abreu	KTH (Royal Institute of Technology, Swededn)	Brazilian
June 11-12	Carella Alfredo	NTNU	Argentinian
June 11-12	Dr. Ian Donaldson	Biotechnology Centre of Oslo, University of Oslo	Canadian
June 11-12	Peter Fick	Delft University of Technology	Dutch
June 11-12	Prof. Johan Hoffman	KTH (Royal Institute of Technology, Swededn)	Swedish
June 11-12	Prof. Michael Holst	University of California, San Diego	American
June 11-12	Dr. Johan Jansson	KTH (Royal Institute of Technology, Swededn)	Swedish
June 11-12	Nicklas Jansson	KTH (Royal Institute of Technology, Swededn)	Swedish
June 11-12	Prof. Claes Johnsson	KTH (Royal Institute of Technology, Swededn)	Sweden
June 11-12	Nazarov Murtazo	KTH (Royal Institute of Technology, Swededn)	Tajikistan
June 11-12	Jeannette Spüler	KTH (Royal Institute of Technology, Swededn)	Swiss
June 11-12	Aron Wahlberg	LTH (Lund University, Technical Faculty, Sweden)	Swedish
June 11-12	Dr. Shawn Walker	New York University, Courant Institute	American
June 11	Dr. Sulie Motshevich	Brunel University (UK)	British
June 10-19	Andy Terrel	University of Chicago	American
June 10-13	Peter Brune	University of Chicago	American
June 10-13	Mehdi Nikbakht	Delft University of Technology	Iranian
June 10-12	Dr. Garth Wells	University of Cambridge	Australian
June 10-12	Kristian Ølgaard	Delft University of Technology	Danish
June 10	Prof. Douglas Arnold	School of Mathematics, University of Minnesota	American
May 19-27	Yuan Jiang	University of Karlsruhe (TH), Karlsruhe, Germany	Chinese
May 1- July 1	Megan Lewis	University of Saskatchewan, Cananda	Canada
April 15	Dr. Rikkert Keldermann	Utrecht University	Dutch
March 23	Ann Blomberg	Dept. of Informatics, University of Oslo	Swedish
March 23	Jean-Francois Gelly	GE Vingmed Ultrasound	French
March 23	Iben Holfart	Tech. University of Denmark	Danish
March 23	Prof. Matthew O'Donnel	University of Washington	American
February 26 - 27	Prof. Olaf Dössel	University of Karlsruhe	German
February 2009 - February 2010	Dr. Hans E. Plesser	Dept. of Mathematical Sciences and Technology, Norwegian University of Life Sciences	German

Quotes from the 2009 Simula Evaluation

The Scientific Computing department has maintained its high level of visibility, increased its activity and impact, and developed extensive collaborations with outside partners, including major industrial partners. The department is excellent in every aspect.

The Evaluation Committee was extremely impressed by the breadth and depth of the research activities in the department, and by the clear evidence being presented, that the rapid expansion of the department over just a few years had not resulted in any dilution of the quality and quantity of the research. This is a clear sign of a strong scientific base of active and involved researchers, supported in the process by a well-qualified group of scientific leaders with a clear vision.

The potential impact on Norwegian industry and research is substantial through the important education of computational scientists, and by lifting the international visibility of the quality of Norwegian led science.

The Evaluation Committee is impressed by the exceptionally high scientific production, including books (6), journal papers (84), and high-level conference contributions (44), as well as the dedication to many other scientific ativities such as teaching and advising of students, memberships of editorial committees (10), and the development of close research-based industrial partnerships and collaborations.

The Evaluation Committee was impressed with the strong interaction between the individual projects.

Visiting address: Martin Linges v. 17, 1364 Fornebu
Mailing address: P.O.Box 134, 1325 Lysaker, Norway
Phone: +47 67 82 82 00, fax: +47 67 82 82 01
Email: post@simula.no
Org.#: 984 648 855