International Workshop on Advanced Micromagnetics

Center for Magnetic Recording Research
University of California, San Diego

May 21-22, 2012
La Jolla, California
Welcome to the International Workshop on Advanced Micromagnetics (IWAM) hosted by the Center for Magnetic Recording (CMRR) at the University of California, San Diego. IWAM is a unique showcase for new and emerging techniques in the micromagnetic analysis of magnetic materials and devices. IWAM brings together leading experts in computational and theoretical Micromagnetics from academia and industry. The format of IWAM, which includes a single oral and poster sessions, is geared towards an informal atmosphere facilitating discussions and collaboration between the participants.

The program includes advanced theoretical models, Multiscale and Multiphysics models, advanced computational models, high-performance numerical techniques, and selected applications of micromagnetic modeling to the study of magnetic materials and devices.

Oral presentations will be of 25-minute talk followed by a 5-minute discussion period. Authors may bring their presentations on their laptop or they may bring a memory stick and use a provided laptop. The dimensions of the poster boards are 6 feet wide and 4 feet high.

IWAM is co-sponsored by IEEE.
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<td><strong>Kayaking Tour</strong></td>
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<td><em>Meeting place: CMRR building, Matthews Lane, 1:45pm</em></td>
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<td>7:45am-8:25am</td>
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| 8:30am-9:00am                              | FDM Micromagnetics Simulation with GPU Computing  
Kenichiro Yamada, *Toshiba Corporation* |
| 9:00am-9:30am                              | MuMax2: Multi-physics Multi-GPU Framework  
Dr. Mykola Dvornik, *DYNAMAT, Ghent University, Belgium* |
| 9:30am-10:00am                            | MicroMagnum: Fast Micromagnetic Simulations  
André Drews, *Universität Hamburg* |
| 10:00am-10:10am                           | Break |
| 10:10am-10:40am                           | Reducing the Time to Create Well-Formed FEM Meshes  
Karl G. Merkley, *Computational Simulation Software, LLC* |
| 10:40am-11:10am                           | GPU Based Micromagnetics for Permanent Magnet Design  
Thomas Schrefl, *St. Poelten University of Applied Science* |
| 11:10am-11:40am                           | (Python) Scripted Micromagnetic Simulations Using Nmag  
Hans Fangohr, *University of Southampton* |
| 11:40am-12:10pm                           | FastMag Micromagnetic Simulator: Computational Models and Massive Parallelization  
Vitaliy Lomakin, *University of California, San Diego* |
| 12:10pm-2:00pm                            | Lunch and Poster session at CMRR |
| 2:00pm-2:30pm                             | Fast, Accurate Computation of the Demagnetization Tensor for Periodic Boundaries  
Michael J. Donahue, *NIST* |
| 2:30pm-3:00pm                             | Tensor Grid Acceleration of the Finite Element Micromagnetics  
Alexander Goncharov, *Hitachi GST* |
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<td>The Fast Multipole Method and Applications to Switching Rates</td>
<td>Pieter B. Visscher, MINT Center, University of Alabama</td>
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<td>3:00pm-</td>
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<td>3:30pm-</td>
<td>Micromagnetic Simulations for Writer Design in Perpendicular Magnetic Recording</td>
<td>Daniel Bai, Western Digital</td>
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<td>4:10pm-</td>
<td>Micromagnetics of Advanced Particulate Tape Media</td>
<td>Pierre-Olivier Jubert, IBM Research</td>
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<td>Hybrid Models for Reader Design</td>
<td>Savas Gider, Western Digital Corporation</td>
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<td>5:10pm-</td>
<td>Analysis of Write Path in Magnetic Recording Using Computational and Analytical Tools</td>
<td>Boris Livshitz, LSI Corporation</td>
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**Tuesday, May 22, 2012**

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<td>8:30am-</td>
<td>mLogic: A Novel STT Device and Circuit Scheme Enabling All Metallic Logic</td>
<td>Jimmy Zhu, Carnegie Mellon University</td>
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<td>9:00am-</td>
<td>Determination of Magnetization Normal Oscillation Modes in Complex Micromagnetic Systems</td>
<td>Massimiliano d’Aquino, Università degli Studi di Napoli “Parthenope” (Italy)</td>
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<td>10:00am-</td>
<td>Simulation of Ultrafast Vortex Dynamics in Magnetic Nanotubes: Cherenkov-Type Spin Wave Radiation and Chiral Symmetry Breaking</td>
<td>Riccardo Hertel, IPCMS – CNRS Strasbourg, France, Forschungszentrum Jülich, Germany</td>
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<td>10:00am-</td>
<td>Plasmon Resonances in Nanoparticles and Magnetization Switching</td>
<td>I. Mayergoyz, University of Maryland</td>
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<td>10:40am-</td>
<td>Quantum dynamics of a nanomagnet driven by spin-polarized current</td>
<td>Lu Sham, University of California, San Diego</td>
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<td>11:00am-</td>
<td>Extending Micromagnetic Theory</td>
<td>Manfred E. Schabes, HGST, a Western Digital company</td>
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<td>11:40am-</td>
<td>Microscopic Theory of Magnetic Interactions and Micromagnetic Simulations</td>
<td>Oleg N. Mryasov, University of Alabama, Tuscaloosa</td>
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<td>12:10pm-</td>
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<td>1:00pm-1:30pm</td>
<td>The Role of Grain Boundaries on the Coercivity of Magnetic Materials</td>
<td>Gino Hrkac, *University of Sheffield, IFW Dresden, St, Poelten University of Applied Science, TU Darmstadt, University of Manchester</td>
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<td>1:30pm-2:00pm</td>
<td>Micromagnetic Energy Minimization for Low-Rank Tensor Magnetization</td>
<td>L. Exl, <em>University of Applied Sciences, St. Pölten, Austria</em></td>
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<td>2:00pm-2:30pm</td>
<td>Kinetic Theory Description of Spin Flipping</td>
<td>Gregory J. Parker, <em>Hitachi GST</em></td>
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<td>2:40pm-3:10pm</td>
<td>Simulation of Heat Assisted Magnetic Recording Using Renormalized Media Cells</td>
<td>Randall H. Victor, <em>MINT, University of Minnesota</em></td>
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<td>3:10pm-3:40pm</td>
<td>Micromagnetic Simulation for Heat Assisted Magnetic Recording Based on Landau-Lifshitz-Bloch Equation</td>
<td>Xi Chen, <em>Seagate Technology</em></td>
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<td>3:40pm-4:10pm</td>
<td>Extended Time and Length Scale Micromagnetics</td>
<td>Dieter Seuss, <em>Vienna University of Technology</em></td>
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<td>4:10pm-4:40pm</td>
<td>Micro-Magnetics and the Statistics of Rare Events</td>
<td>Ned Tabat, <em>Semaphore Scientific</em></td>
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**Wednesday, May 23, Anza Borrego Desert, meeting place: CMRR building, 8:30am - 5pm**
FDM Micromagnetics Simulation with GPU Computing

**Presenter:** Kenichiro Yamada
**Co-authors:** Yoshiyuki Kokojima\(^2\), Masayuki Takagishi\(^2\), Katsuhiko Kou\(^1\), and Akihiko Takeo\(^1\)
**Affiliation:** \(^1\)S&S Products Company, Toshiba Corporation
\(^2\)Corporate R&D Center, Toshiba Corporation

**Abstract:** GPU (Graphics Processing Unit) is one of cutting-edge multi-core parallel processors with reasonable cost. While GPUs are originally designed as 3D graphics accelerators, well-designed software development kit boosts its application fields other than graphics. In scientific computing also, GPUs are increasingly adapted to be used as accelerators\([1][2]\). Unfortunately, software should be re-written and optimized to fully exploit its potential as CPU and GPU have different architecture. In this talk, we will present FDM micromagnetics program with GPU and its result.

The FDM micromagnetics program originally for CPU is re-written and fully optimized for GPU. All calculation is done inside GPU, and CPU is only necessary to input parameters, to control flow, and to output result. Time integration of LLG equation with spin torque by the explicit Runge-Kutta algorithm is parallelized on each cell, and GPU FFT library is used to calculate magnetostatic field. Simulated is a shrunk writer for MAMR (Microwave Assisted Magnetic Recording), including STO (Spin Torque Oscillator) inside write gap. MAMR is one of promising candidates for energy assisted magnetic recording scheme of next generation, boosting capacity of hard disk drives beyond 1Tb/in\(^2\)\([3]\).

The FDM micromagnetics program with GPU provides x60 acceleration compared with single CPU. Even simulation is done under single-precision floating point accuracy, reasonable result is obtained. Stable STO oscillation under gap field and sufficient microwave field for MAMR are confirmed, even there is interaction between write pole and STO. This effort offers a new approach to achieve large scale micromagnetic simulation, like MAMR writers.

**References:**

**Bio:** Kenichiro Yamada received his M.Sc. degree in chemistry from University of Tokyo (Japan) in 1995. In 1995-2006, he joined Fujitsu Ltd. In 1998-2001, he stayed at Materials Science and Engineering at Stanford University. He joined Toshiba Corporation in 2006. His research interests include micromagnetic simulation and design of read heads and write heads for hard disk drives.
**MuMax2: Multi-physics Multi-GPU Framework**

**Presenter:** Dr. Mykola Dvornik

**Coauthors:** Dr. Arne Vansteenkiste, Dr. Ben Van de Wiele, and Prof. Bartel Van Wayenberge

**Affiliation:**
- **a** DYNAMAT, Department of Solid State Science, Ghent University, Belgium
- **b** EELAB, Department of Electrical energy, systems and automation, Ghent University, Belgium

**Abstract:** Computation demands of modern micromagnetic problems grow enormously. This includes applications of the emerging fields of magnonics, high-density data-storage, ultrafast magnetization dynamics and spintronics. Furthermore, multi-physics approach is necessary to describe hybrid dynamics of magnetic sub-lattices with various others subsystems of the solid state. In general, modern micromagnetic infrastructures do not fit into the aforementioned requirements.

We present a vastly improved state-of-the-art cross-platform finite difference solver, MuMax2, which employs computational power of all Graphics Processing Units (GPUs) available in the node. When properly treated, GPUs guarantee supercomputer-like performance in desktop-level systems, giving the possibilities to solve multi-scale multi-physics problems on reasonable timescales (including atomistic scale simulations). The main downside of GPUs is complex memory hierarchy and limited throughput of the GPUCPU and GPUGPU data transfers. The asynchronous architecture of MuMax2 with memory recycling eliminates these problems, to ensure maximum computational performance. The MuMax2 framework has a modular structure, and so it is easily extensible by means of additional modules. The current modules tree offers a unique opportunity to solve both Maxwell and Landau-Lifshitz equations simultaneously at finite temperature. The spin-transfer torque is also one of the main features of MuMax2, to satisfy computational needs of spintronics. Furthermore, longitudinal magnetization dynamics, typically seen in ultrafast magnetization dynamics, is included by means of relatively novel Baryakhtar equations. The framework has been validated by set of micromagnetic problems defined by NIST’s μMAG group, Standard Problem no. 5 as proposed by M. Najafi et al. and calculation of magnonic dispersion.

**Bio:** I have a master degree in theoretical physics from Donetsk National University, Ukraine. Followed by PhD and Associate Research Fellow position in University of Exeter, UK focused on computational magnonics. Currently, I am a member of DYNAMAT group of Ghent University, Belgium with the main aim to extend the functionality of the MuMax framework to fulfill novel micromagnetic problems.
MicroMagnum: Fast Micromagnetic Simulations

Presenter: André Drews$^{1,2}$
Co-authors: Gunnar Selke$^1$, Benjamin Krüger$^3$ Claas Abert$^2$
Affiliation: $^1$Arbeitsbereich Technische Informatik Systeme, Vogt-Kölln-Straße 30, 22527 Hamburg.
$^2$Institut für Angewandte Physik, Universität Hamburg, Jungiusstraße 11, 20335 Hamburg.
$^3$Institut für Theoretische Physik, Universität Hamburg, Jungiusstraße 9, 20355 Hamburg.

Abstract: In recent years computing on Graphics Processing units (GPU) entered the field of micromagnetic simulations [1], [2], [3]. On GPU the stray field can be computed massively in parallel. The fast finite-difference micromagnetic simulation tool MicroMagnum [4] is presented. It runs on CPU as well as on GPU. MicroMagnum achieves a speed-up of up to two orders of magnitude in comparison to computations on CPU. The speed-up increases with increasing sample size which makes it capable to use element sizes like in experiment. The demagnetization field is implemented using the Demagnetization tensor method by Newell [5] as well as the scalar potential method [6]. The demagnetization field computation only needs single precision accuracy. Calculating the exchange field with the finite difference method results in a summation of large values with small deviations. In case of e.g. a relaxation towards the energy minimum of a magnetic configuration the exchange field computation requires double precision accuracy. A Micromagnetic module, an Oersted field module, and a Current path module are implemented in MicroMagnum. For the Oersted field computation an Oersted field tensor method is used, while for the current paths the poisson equation is solved. Currently, the current path module only runs on CPU. To perform selfconsistent simulations all modules can be connected. Further modules can be easily inserted in MicroMagnum due to its modular architecture. Current- and magnetic field induced nonlinear vortex gyration in permalloy squares is investigated using MicroMagnum. For large core displacements the shape of the trajectory of nonlinear gyration approaches the shape of the samples. For an increase of the thickness of the squares the resonance frequency turns from higher to lower values. The total potential of gyration is a sum of the exchange energy and the demagnetization energy. In the nonlinear regime the demagnetization energy increases smaller than a parabola in the corners of the squares while at the edges it is larger than a parabola. The exchange energy isotropically increases stronger than a parabola. For an increasing thickness the influence of the demagnetization energy exceeds the influence of the exchange energy which influences vortex gyration by a transition from a blue to a red shift of the gyration frequency [7].


Bio:
Diploma Degree in Astrophysics (2006).
Ph. D. in Micromagnetic simulations (2009).
Postdoc and group leader of the simulation division around the simulator MicroMagnum.
Reducing the Time to Create Well-Formed All Hexahedral Meshes

Presenter: Karl G. Merkley
Affiliation: Computational Simulation Software, LLC

Abstract: Previous studies have shown that the majority of time consumed in performing a complex analysis is spent in creating an accurate model. Common problems include dirty, trivial, and non-watertight geometries. Accuracy in some applications may also be affected by element type. Creating all hexahedral meshes requires additional decomposition to allow well-formed hexahedral elements to be created. This presentation demonstrates techniques for cleaning up geometry and creating all-hexahedral, hex-dominant and all-tetrahedral meshes using Cubit, a meshing toolkit developed over the last twenty years at Sandia National Laboratories, various universities, and commercial entities. It compares the number of cells and faces created for each of these cases and demonstrates that an all-hexahedral mesh creates the most efficient analysis model.
GPU Based Micromagnetics for Permanent Magnet design

Presenter: Thomas Schrefl
Co-authors: Alexander Luger, Lukas Exl, Simon Bance, Harald Oezelt
Affiliation: St. Poelten University of Applied Sciences

Abstract: Permanent magnets are essential for green technologies such as hybrid vehicles and wind turbines. The key properties to be computed with micromagnetic simulations are the hysteresis loop and first order reversal curves. These properties result from the interplay between the intrinsic magnetic properties and the microstructure of the magnet. A fine computational grid is required, in order to take into account grain morphology, intergranular phases, and surface defects. For these large scale simulations we need effective algorithms. Fast magnetization dynamics is not relevant for permanent magnets. Therefore we can apply energy minimization techniques. In the early days of numerical micromagnetics, Viallix and co-workers applied a modified conjugate gradient method, in order to minimize the micromagnetic energy [1]. They propose to search for the update of the magnetization vectors, \( \mathbf{m} \), within in the tangential plane to the pervious magnetization configuration \( \mathbf{m}_0 \). Thus search directions that violate the non-linear constraint \( |\mathbf{m}| = 1 \) are excluded. Numerically such a scheme has advantages: Instead of a non-linear optimization problem, we have to solve a quadratic optimization problem with a linear constraint \( (\mathbf{m} \cdot \mathbf{m}_0) \). For such type of problems efficient algorithms based on preconditioned conjugate gradients have been published [2]. We developed a hybrid CPU/GPU algorithm for effective energy minimization of the micromagnetic energy using OpenCL. The method is applied to compute first order reversal curves of various types of permanent magnets.


Bio: Thomas Schrefl started his work in micromagnetics with the simulation of exchange spring permanent magnets during his PhD at Vienna University of Technology and the Max Planck Institute of Metal Physics, Stuttgart. He worked with IBM on parallel micromagnetics solvers. He received the START-Award of the Austrian Government for “Advanced numerical micromagnetics”. Currently he is Professor at St. Poelten University of Applied Sciences.
(Python) Scripted Micromagnetic Simulations Using Nmag

Presenter: Hans Fangohr
Co-authors: M Franchin, D. Chernyshenko, M. Albert, W. Wang, M. Beg, MA Bisotti, Fischbacher, G Bordignon.
Affiliation: University of Southampton

Abstract: We introduce the micromagnetic simulation package Nmag [1] which is available as open source. Nmag is based on a finite-element discretization of space, and can be controlled through the popular Python language. We describe and critically review the multi-physics design and implementation decisions, and summarize some of our experiences of using Nmag in a variety of research problems. This work has received funding from the Engineering and Physical Sciences Research Council (EPSRC) UK (DTC EP/ G03690X/1) and from the European Community’s Seventh Framework Programme (FP7/2007-2013) under grant agreement no. 233552 (DYNAMAG project).

Figure: (a) magnetization in a Nickel disk (diameter 100 nano meter, height 20 nanometre) sampled on regular grid for visualization, (b) a domain wall in cylindrical nanowire is stuck in front of barrier realised by local anisotropy, (c) magnetization in a magnetic Ni shell grown on top of an Ag pyramid, (d) selected results from 5th micro-magnetic standard problem [2].


Bio: Hans Fangohr is a computational scientist and Professor of Computational Modelling at the University of Southampton in the Faculty of Engineering. He received his undergraduate degree in physics from the University of Hamburg (Germany) and completed his PhD studies in the department of Electronics and Computer Science of the University of Southampton. His research interests are computer simulations of physical processes and materials, visualization and management of data, effective simulation research, and in particular multi-physics and multi-scale simulations of nanoscale systems and devices. In addition to the Nmag software, his group has contributed higher order anisotropy extension modules to OOMMF, the conversion to VTK file format tool ovf2vtk to allow 3d simulation of OOMMF results, and some mesh conversion utilities to Magpar.
FastMag Micromagnetic Simulator: Computational Models and Massive Parallelization

**Presenter:** Vitaliy Lomakin  
**Co-authors:** R. Chang, M. Lubarda, M. V. Escobar, Shaojing Li, S. Fu, J. E. Martin, M. Kuteifan, D. Gabay, C. T. Dinh, Matthew K. Hu  
**Affiliation:** Center for Magnetic Recording Research, Dept. of ECE, University of California, San Diego

**Abstract:** Magnetic materials and devices are an inherent part of a host of physical and engineering systems. Micromagnetic simulations have a significant predictive power and are important for our ability to analyze and design such systems. We present our recent work on the development of high-performance micromagnetic and electromagnetic simulators as well as their use for applications in magnetic material and device analysis and design. In particular, we demonstrate a high-performance fast magnetic simulator framework (FastMag), which includes high-performance solvers for Landau-Lifshitz-Gilbert (LLG) type equations, coupled LLG-Maxwell’s solvers including Eddy currents, and minimization solvers implementing the nudged elastic band method for energy barrier computations. The performance of these simulators is based on efficient discretization methods with tetrahedral/ hexahedral/Voronoi meshing, fast methods for computing effective magnetic fields, efficient methods for non-linear time integrations, and massive parallelization on single/multi-CPU and single/multi-GPU computing systems. Examples of using the developed simulators for applications in magnetic recording, magnetic memories, magnetic processing, and microwave magnetic materials are presented.

**Bio:** Vitaliy Lomakin received his M.S. in Electrical Engineering from Kharkov National University in 1996 and Ph.D. in Electrical Engineering from Tel Aviv University in 2003. From 2002 to 2005 he was a Postdoctoral Associate and Visiting Assistant Professor in the Department of Electrical and Computer Engineering, University of Illinois at Urbana Champaign. He joined the Department of Electrical and Computer Engineering at the University of California, San Diego in 2005, where he currently holds the position of Associate Professor and serves as an Associate Director of the Center for Magnetic Recording Research. His research interests include Computational Micromagnetics/Nanomagnetics, Computational Electromagnetics, the micromagnetic analysis and design of magnetic nanostructures and devices, and the electromagnetic analysis and design of photonic and microwave structures.
**Fast, Accurate Computation of the Demagnetization Tensor for Periodic Boundaries**

**Presenter:** Michael J Donahue  
**Affiliation:** National Institute of Standards and Technology

**Abstract:** This talk details a technique for computing the demagnetization interaction tensor in finite difference micromagnetics with periodic boundaries. This approach supports rectangular discretization cells and uses high order approximations to improve the accuracy and speed of the computation of the tensor.

Given an analytic formula for the average stray field \( H \) in one cell arising from a uniform magnetization \( M \) in a second cell at offset \( r \), say \( H = N(r)M \), then the average field in the first cell arising from a periodic array of cells is simply

\[
H = \sum_{k=-\infty}^{+\infty} N(r + kp)M = N^{pbc}M
\]

where \( p \) is the vector representing the offset between successive periods. Once computed, \( N^{pbc} \) can be used inside a micromagnetic program in exactly the same manner (and speed) as the non-periodic tensor \( N \). In particular, \( N^{pbc}M \) is amenable to evaluation via FFT if the discretization is on a regular grid.

There are two practical problems—the analytic formula for \( N \) are numerically inaccurate at large offsets, and the convergence of the infinite sum is not especially fast, so some method of quickly approximating the tail of the sum is necessary. To solve these problems, the sum is decomposed into three ranges, near-field (small \( |k| \)), mid-field (intermediate \( |k| \)), and far-field (large \( |k| \)). The analytic formulae are used directly in the near-field regime. In the mid-field, the analytic formulae are replaced with asymptotic approximations that are both accurate (error \( O(1/R^{11}), R = |r + kp| \)) and quick to compute. One complication is that the pre-factor to the error in the asymptotic approximation grows sharply with the aspect ratio of the discretization cell, but this can be tamed via an embedded (optionally recursive) computation on subcells having smaller aspect ratios. In the far-field, the tail sum is replaced with an integral approximation having error \( O(1/R^6) \).

**Bio:** Michael Donahue is a mathematician in the Applied and Computational Mathematics Division at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland, where he does research on micromagnetics and leads development of the OOMMF public domain micromagnetics package. Prior to joining NIST, he held a joint postdoctoral research position with the University of Minnesota and Siemens Corporate Research on artificial neural networks and computer vision. Dr. Donahue holds PhDs in mathematics and engineering from The Ohio State University, and has authored over 50 journal publications.
Tensor Grid Acceleration of the Finite Element Micromagnetics

**Presenter:** Alexander Goncharov  
**Affiliation:** HGST San Jose Research Center, San Jose, CA, 95135, USA.

**Abstract:** The accurate simulation of the magnetization dynamics in ferromagnetic bodies requires a fine discretization on a level comparable to the exchange length (5~10 nm). Hence, the practical simulations of the magnetic writers or readers require huge computational effort for calculation of the magnetostatic field. Tensor product grids are very attractive candidates for fast potential evaluation by computing convolution using FFT. But actual shapes of magnetic bodies are better approximated by nonstructural meshes. To combine advantages of both methods we use precorrected FFT method described in Ref. 1 combined with a Kronecker approximation of the 1/R kernel on the regular grid. Use of a low rank approximation of the kernel is beneficial for two practical reasons. The super-linear compression of the tensor entries ($O(N^3)$ entries instead of $O(N^3)$), where $N$ is the number of nodes in one dimension, and reduction of the convolution order for potential calculation from 3D to 1D [2]. Computation is performed in 5 stages and can be represented by 5 operators: \( C \) – magnetic charge operator (computes magnetic volume and surface charges at FEM nodes in $O(3n)$), \( P \) – projector operator (projects charges onto the grid in $O(n)$), \( H \) - grid interaction operator (evaluates $1/R$ interaction between point charges in $O(N^3 \log N)$), \( I \) – interpolation operator (interpolates potential from the grid back to FEM nodes in $O(n)$), \( D \) – correction operator (corrects interaction for near neighbors in $O(3n)$). For the FEM mesh with \( n \) nodes, the method has a total complexity of $O(n) + O(N^3 \log N)$. The corrector matrix for the interaction between elements in adjacent cells is assembled by integrating over those elements using analytical formulae (near neighbors) or Gaussian quadratures. If potential is corrected at boundary nodes only, then \( I \) and \( D \) operators have complexities $O(nb)$, where \( nb \) is the number of boundary nodes in the FEM mesh.  
A linear system is then solved on a GPU as a final step in order to find the potential at internal nodes. As a case study, the magnetostatic potential was computed for a reader shield with dimensions 50x25x2 um, discretized with 50 nm tetrahedral cells. The number of FEM nodes and elements were ~5e6 were ~40e6 respectively. The grid dimensions were 1024x512x32. The RAM consumption and evaluation times on Intel Xeon E5620 CPU with GTX580 GPU for each operator presented below. \( C \sim 2.7 \text{ GB}, \ I \sim 1.5 \text{ GB each}, \ H \sim 100 \text{ MB}, \ D \sim 4 \text{ GB} \) (for boundary nodes), \( \text{Astiff} \sim 1 \text{ GB} \) (for internal nodes). The numbers include RAM required to store sparsity patterns of the matrices. Evaluation times were: \( C \sim 0.7 \text{ s}, \ P \sim 0.5 \text{ s}, \ H \sim 0.5 \text{ s} \) (GPU), \( I \sim 0.5 \text{ s}, \ D \sim 1.0 \text{ s} \). The final step required to find a potential at internal nodes took 2.5 seconds.  


**Bio:** Alexander Goncharov received his MSc Degree in Physics from the Moscow State University, Russia in 2000 and PhD degree from the University of Southampton, UK in 2005. He worked as a postdoctoral research associate at the University of Sheffield, UK from 2006 to 2010, where he was undertaking research in the magnetic recording and numerical micromagnetism. In 2010 Alexander joined Hitachi GST research lab in San Jose, CA. His research interests include computational micromagnetics, recording physics, advanced numerical algorithms for fast potential calculations and GPGPU computing.
The Fast Multipole Method and Applications to Switching Rates

Presenter: Pieter B. Visscher  
Affiliation: University of Alabama, Tuscaloosa, AL

Abstract: I will give a short introduction to the Fast Multipole method (FMM) for the calculation of magnetostatic fields, in the context of a maximally simple binary-tree implementation (JMMM 322 (2010) p. 275), with emphasis on understanding why it is an O(N) algorithm. Essentially this is because the magnetostatic field is calculated by traversing the tree, and for each (field) cell (“this” cell) in the tree only fields from nearby source cells of the same size (i.e., the same level in the tree) need be dealt with. The larger source cells are dealt with by this cell’s ancestors (higher in the tree), and the smaller ones are dealt with by this cell’s descendants (lower in the tree). The number of like-sized nearby cells does not scale upward with N. If we enlarge N by enlarging the system (expanding the tree upward) the added cells are larger or distant; if we enlarge N by refining the grid (expanding the tree downward), the added cells are smaller. Thus the computational labor per cell is independent of N, and the total labor is O(N).

This method is applicable to either finite element (tetrahedral-cell) or “finite-difference” (more precisely finite volume, rectangular cell) micromagnetics. In either case, it requires knowing magnetostatic kernels describing interactions between very nearby cells. To simulate a periodic system, we also require kernels describing the potential of a cored-dipole-array; I will describe an iterative method for calculating these.

Application to the calculation of low-dimensionality energy landscapes (see figure) and switching rates will be briefly described. It is convenient to describe the energy as a function of various moments (dipole, quadrupole, vortex, etc.) and their conjugate fields (uniform, gradient, vortex, etc.).

Bio: Pieter Visscher received a BA in Physics from Harvard College in 1967, and a PhD in Solid State Physics from UC Berkeley with Leo Falicov. He held several temporary positions including a postdoc with Harry Suhl at UCSD (1973-75) before moving to the University of Alabama in 1978. He has worked on renormalization group theory of fluid dynamics, colloid dynamics, and most recently micromagnetics and magnetization dynamics.
Micromagnetic Simulations for Writer Design in Perpendicular Magnetic Recording

Presenter: Daniel Bai  
Co-author: Zhanjie Li  
Affiliation: Western Digital Corporation

Abstract: Finite element modeling (FEM) has played an essential role in the design of magnetic write heads for hard disk drives. It has been successful in handling complicated geometries in the writer and predicting the head field with good accuracy. However, as the head design becomes even more sophisticated to enable high track density and linear density as well as high data rate in today’s perpendicular magnetic recording (PMR), it has become more critical to rely on micromagnetic modeling, in particular for those areas where traditional magnetic FEM packages are incapable of. In this talk we will review some applications of micromagnetic modeling in modern PMR writer design in an industry environment. The software we used is FEMME, and the head we studied is a fully wrap-around shielded (FWAS) PMR writer. The entire head is meshed with various mesh sizes in different areas, depending on the type of problems. Specifically, we will review three areas of applications: 1) Transient field dynamics; 2) Side field characteristics; 3) Degauss processes. Although certain tradeoffs in mesh size have to be made in order for the simulation time to be acceptable, we have found the results consistent with the expectations from the underlying physics. Moreover, in multiple cases we have achieved reasonable correlation between the FEMME results and the empirical data for performance differentiation and design optimization, even though the exact domain configurations in the non-critical areas (such as in the yoke or areas far away from the writer pole tip) are not necessarily physical, as a result of intentional chosen large mesh sizes.

Despite the encouraging results, significant challenges and opportunities are ahead for micromagnetic modeling in writer design applications. Further enhancement of capabilities of handling much larger number of elements is most desired, as it will allow finer discretization and provide results closer to physical reality.

Bio: Dr. Daniel Bai is currently the Director for Advanced Writer Design at Western Digital. His areas of research interest include magnetic nano-devices, FEM and micromagnetic modeling, magnetization dynamics etc. Dr. Bai has co-authored over 30 journal publications in the field of magnetics, and a co-inventor of over 40 issued or pending patents. He received his B.S. and M.S. degrees in Physics from Peking University, and M.S. and Ph.D. degrees in Electrical and Computer Engineering from Carnegie Mellon University.
Micromagnetics of Advanced Particulate Tape Media

Presenter: Pierre-Olivier Jubert
Affiliation: IBM Research - Almaden, San Jose, CA 95120 USA

Abstract: “Magnetic tape storage is the technology of choice for backup and archive applications and, with the explosion of the volume of digital data created each year, the need for such cost-effective archival solution will continue to persist. Nonoriented particulate barium ferrite media has just been introduced in commercial tape drives providing a recording capacity of 4 TB per tape cartridge. Using finer barium ferrite particles and orienting the particles out-of-plane have allowed recording demonstrations of up to 29.5 Gb/in\(^2\), a 10x increase in areal density compared to the commercial products. To predict the performance limits of this particulate media technology, it is essential to understand and quantify how the different particle and media parameters affect the signal-to-noise ratio. To that purpose, we have conducted micromagnetic modeling studies. First, it was necessary to develop a packing algorithm that reproduces the structure of nonoriented and oriented particulate media. Then, recording simulations were performed on a Blue Gene/L supercomputer using a modified version of the parallel micromagnetic solver Magpar. The results were compared with analytical recording models. I will present the outcome of this study, which compares very well with experimental findings and provides us with means to design future particulate media and to predict the density limits of this medium technology.”

Bio: Pierre-Olivier Jubert is a Research Staff Member at IBM Research - Almaden in San Jose, California. He received his PhD from the University of Grenoble in 2001, in the field of epitaxial growth and magnetism of nanoparticles. He then joined the IBM Zurich Research Laboratory as a Postdoctoral Fellow, working on magnetism in nanoscale systems and particularly on spin-torque induced magnetic domain wall motion. He joined the “Advanced Storage Concepts group” at IBM Almaden in 2005, focusing on magnetic recording physics and tape storage applications.
Abstract: The geometry of a magnetic recording head ranges over orders of magnitude, from the nanometer scale of layers in the sensor stack to the micron scale of the shields. This presents a challenge for a model that must encompass the physics at all these scales, especially for future designs that may incorporate side shields. Since the mesh must not exceed the exchange length, a full micromagnetic model of the reader and shields may not be practical for the exploration of large design spaces. An alternative is a hybrid model that allows regions to be defined as either magnetostatic (Maxwell equations) or micromagnetic (LLG equations). We use a hybrid finite element code (SpinFlow3D) to study a dual free layer sensor with side shields. A dual free layer or “trilayer” sensor was proposed originally to enable a thinner read gap and to allow the integration of side shields. Previous studies also found an improvement in signal-to-noise ratio due to cancellation between the two free layers. We find that the performance depends strongly on the stripe height (SH) to track width (TW) ratio. In addition to the transverse field from the rear bias, longitudinal stabilization is required. A negative interlayer coupling helps stabilization, but can be realized only in GMR devices presently. A side shield can provide stabilization in the presence of positive interlayer coupling as in TMR devices. The noise properties are simulated in the frequency domain by an eigenmode solver in conjunction with the hybrid magnetostatic/micromagnetic solver. Like the signal, the noise depends strongly on the SH/TW ratio. Also, the side shields can change the eigenmodes of the coupled dual free layer sensor and modify the noise cancellation.

Bio: Savas Gider is a Senior Staff Engineer in the read head design group at Western Digital. Previously, he worked on writer and reader design as well as drive integration for 10 years at Hitachi and IBM. He has also worked on mechanical design for MEMS and magnetic design for MRAM. He holds a bachelor’s degree in applied physics from Cornell University and a doctoral degree in physics from the University of California, Santa Barbara.
Analysis of Write Path in Magnetic Recording Using Computational and Analytical Tools

Presenter: Boris Livshitz  
Co-author: Jason S. Goldberg  
Affiliation: LSI Corporation

Abstract: The magnetic storage industry is continuously enhancing areal density and operating with faster data rates. The write path, comprising write and degaussing modes, becomes a challenging part of high-speed magnetic recording due to the nature of the heterogeneous recording system comprising components of different material properties (write driver circuitry, transmission line terminated by coil, magnetic write head and recording media) and spatial scales (from centimeters to nanometers). A computational micromagnetic approach is intensively used to investigate effect of write current wave shaping and recording system design on recording performance on a nanosecond time scale. However, analytical tools are useful in a translation of micromagnetic results to the observed long time-scale in-drive phenomena such as on-track and off-track performance.

The first part of the talk will be a short introduction on write path in magnetic recording. The second part will be dedicated to write mode analysis [1] covering a computational micromagnetic study vs. data rate, write current amplitude and time settings; a comparison of different recording metrics and ways to characterize on-track recording and adjacent track erasure. Finally, a degauss mode study [2] will be elucidated with a detailed discussion on critical parameters affecting reduced remanent magnetization and the benefits to avoiding magnetization pinning in out-of-plane state and erase after write.


Bio: Boris Livshitz received his M.S. degree in EE/physics from St. Petersburg State Polytechnic University, Russia, in 1995, and his Ph.D. degree in EE from Tel Aviv University, Israel, in 2006. He was a Postdoctoral Associate in the UCSD, ECE & CMRR in 2006-2009. From November 2009, Dr. Livshitz is with LSI Corporation, where he is a Senior Engineer in the PreAmp Architecture group responsible for the recording system-electronics interface.

His research interests cover two areas. The first area includes computational micromagnetics, magnetic recording and recording system analysis. The second area of interests includes fast computational algorithms. Recently Dr. Livshitz has been elevated to the grade of IEEE Senior Member.
mLogic: A Novel STT Device and Circuit Scheme Enabling All Metallic Logic

Presenter: Jimmy Zhu  
Co-authors: David Bromberg, Dan Morris, and Larry Pileggi  
Affiliation: Department of Electrical and Computer Engineering Carnegie Mellon University

Abstract: In this talk, we will present a novel STT design, referred to as mCells, a four-terminal device utilizing current driven domain wall motion for switching its resistance states while maintaining electrical isolation between the write and read paths. Novel schemes to connect mCells to enable fanout operation and forming logic gates have been developed to enable all metallic integrated circuits performing digital logic operations without using semiconductor transistors. Because of the nonvolatile nature of the logic states, the driving voltage can be pulsed and the voltage pulses act essentially as the clock, for which we referred to as power-clock or pclock. The Micromagnetic model with the inclusion of spin transfer torque effect has been developed to simulate current driven domain wall motion in perpendicularly magnetized multilayer structure. The talk will focus on the state switching characteristics and the dynamics of current driven domain wall motion in magnetic thin films. Both analytical analysis and simulation results will be presented. The associated instantaneous speed variation during the current driven domain wall motion and impact on device design will be discussed.


Bio: Jian-Gang (Jimmy) Zhu is the ABB Professor of electrical and computer engineering at Carnegie Mellon University and the director of the Data Storage Systems Center. He received his his Ph.D. in Physics from University of California at San Diego in 1989. Prior come to Carnegie Mellon in 1997, he had been a faculty in the Department of Electrical Engineering at University of Minnesota since 1990. Some of the awards that he received include the McKnight Land Grant Professorship from University of Minnesota in 1992, the NSF Presidential Young Investigator Award in 1993, the R&D Magazine Top 100 Invention Award in 1996, and most recently, IEEE Magnetic Society Achievement Award in 2011. He was IEEE Magnetic Society Distinguished Lecturer in 2004. He has published over 290 refereed journal papers along with six book chapters and has given over 70 invited papers at various major international conferences. He holds 16 U.S. patents. As a university professor, he has graduated 38 Ph.D. and many more M.S. students. He is a Fellow of IEEE.
Determination of Magnetization Normal Oscillation Modes in Complex Micromagnetic Systems

Presenter: Massimiliano d’Aquino  
Affiliation: Dipartimento per le Tecnologie, Università degli Studi di Napoli “Parthenope”, 80143 Napoli (Italy)

Abstract: The study of the normal oscillation modes of ferromagnetic nano-particle systems is a fundamental issue for its applications to the analysis of magnetization dynamics under microwave applied fields[1, 2] and thermal fluctuations[5]. The normal oscillation problem was theoretically analyzed by W.F. Brown and Aharoni [1, 3] with analytical techniques limited to particles of special shapes (spheres, ellipsoids) for the case of saturated equilibrium configurations. Recently, considerable research has been focused on numerical computations of normal modes for particles with generic shapes[4] and on experimental observations involving spatially non uniform equilibrium magnetization configurations[5].

In this work, a general formulation of this problem is presented[6]. The small oscillation modes in complex micromagnetic systems around an equilibrium are numerically evaluated in the frequency domain by using a novel formulation of the linearized Landau-Lifshitz-Gilbert (LLG) equation as a generalized eigenvalue problem for suitable self-adjoint operators connected to the micromagnetic effective field, which naturally preserves the main physical properties of the problem. It is shown that the discrete approximation of the eigenvalue problem obtained either by finite difference or finite element methods has a structure which preserves relevant properties of the continuum formulation. This approach has several advantages with respect to time-domain techniques and can be implemented by using the classical exchange and magnetostatic operators implemented in both finite differences and finite elements micromagnetic codes.


Bio: Massimiliano d’Aquino was born in Naples (Italy) in 1977. He received the Laurea and Ph.D. degree in Electrical Engineering from the University of Naples “Federico II” in 2001 and 2004, respectively. In 2003, he has joined, as visiting Ph.D student, the Magnetic Materials and Micromagnetics group at the Vienna University of Technology. From 2006, he is ‘researcher’ (assistant professor) of Electrical Engineering with the Department of Technology and the Engineering Faculty of the University of Naples “Parthenope”. In 2010, he won a public selection in Politecnico di Torino and got the national habilitation for the position of Associate Professor of Electrical Engineering. His research interests are in micromagnetics and magnetization dynamics, mathematical models of hysteresis and electrodynamics of materials. He is reviewer of many international journals in the area of electrical engineering and applied physics (IEEE Trans. Magn., J. Appl. Phys., Phys. Rev. B, J. Comput. Phys. Physica B, ...). He is co-author of about 60 scientific papers in peer-reviewed international journals (detailed publication list at http://wpage.unina.it/mdaquino/). He has participated as coordinator and/or researcher in several national and international research projects. He has given many invited and contributed talks in several international scientific conferences (Intermag, Magnetism and Magnetic Materials, Hysteresis and icromagnetic Modeling, Joint European Magnetic Symposia) on magnetism and magnetic materials. He has served as guest editor of IEEE Transations on Magnetics and Journal of Applied Physics and is currently in the Editorical Review board of IEEE Magnetics Letters. He has been member of the program/organizing committee (MMM 55, HMM 2007, HMM 2011), session chairman of several international conferences. Currently, he teaches Elettrotecnica (circuit theory and electromagnetism) at the Engineering Faculty of the University of Naples “Parthenope”.
Simulation of Ultrafast Vortex Dynamics in Magnetic Nanotubes: Cherenkov-Type Spin Wave Radiation and Chiral Symmetry Breaking

Presenter: Riccardo Hertel
Co-authors: Christian Andreas, Ming Yan, Attila Kakay
Affiliation: IPCMS – CNRS Strasbourg, France
Forschungszentrum Jülich, Germany

Abstract: Magnetic vortices in nanostructures display highly non-trivial dynamic properties. The scientific aesthetics of these properties and their potential for applications in nanotechnology have triggered increasing interest in this field of research. So far, magnetic vortex dynamics has been studied mostly in thin-film nanostructures. By means of GPU-accelerated finite-element simulations we found that changes in the geometry may reveal surprising aspects: Field-driven vortex-type domain walls in ferromagnetic nanotubes display very unusual properties, i.e., a chiral symmetry breaking [1] and the occurrence of super-stable domain walls [2].

Owing to their extraordinary stability, vortex domain walls in nanotubes can propagate smoothly at ultrafast velocities. When driven by moderate fields of a few mT, they move at speeds as high as 1000 m/s without encountering the usual instabilities which occur already at much lower velocities for any other type of domain wall known so far. The velocity of these superstable walls may even exceed the speed of spin waves, thereby causing an effect reminiscent to the Cherenkov radiation, i.e., the spontaneous emission of spin waves. By means of systematic simulations, this effect has been studied in detail, making it possible to explain its physical origin and to provide clear predictions for observations of this phenomenon.


Bio: Riccardo Hertel obtained his PhD in physics in 1999 at the University of Stuttgart, and his Habilitation in 2005 at the University of Halle-Wittenberg. His field of expertise is the simulation of magnetic nanostructures and dynamic magnetization processes using the finite-element method. In the past six years he has lead a Young Investigator Group in Jülich, has been a physics lecturer at the University of Duisburg-Essen and has recently moved to Strasbourg, France, as a Scientific Director.
Plasmon Resonances in Nanoparticles and Magnetization Switching

Presenter: I. Mayergoyz
Affiliation: ECE Department & UMIACS, University of Maryland

Abstract: Metallic (silver and gold) nanoparticles exhibit plasmon resonances when two conditions are satisfied: 1) the dielectric permittivity of nanoparticle is negative and 2) the free-space wavelength of incident optical radiation is large in comparison with nanoparticle dimensions. The plasmon resonances result in very powerful nanoscale localized sources of light that are very attractive for HAMR and all-optical modes of magnetic recording. The modal analysis of plasmon resonances will be discussed. This analysis can be mathematically framed as an eigenvalue problem for specific boundary integral equations. The issues of coupling of specific plasmon modes to incident optical radiation as well as time-dynamics of excitation and dephasing of plasmon modes in nanoparticles and apertures will be outlined as well.

In applications to magnetic recording, plasmon resonances are important for localized media heating which facilitates magnetization switching. This raises the issue of magnetization dynamics at close to the Curie temperature when the magnetization magnitude is not conserved. A new approach to such magnetization dynamics which is based on the description of thermal bath effects by a jump-noise stochastic process will be discussed and the appropriate generalization of the Landau-Lifshitz equation will be presented.

Bio: Prof. Mayergoyz received his Master and Ph.D. degrees in the former Soviet Union where he worked as a senior research scientist in the Institute of Cybernetics of Ukranian Academy of Sciences before his emigration to the United States. On his arrival to the United States in 1980, he became a full professor of the Electrical and Computer Engineering Department of University of Maryland, College Park. For many years, he served as a consultant for the Research and Development Center of General Electric Company and has been selected as a visiting research fellow of this center. He has authored and coauthored 11 books and over 350 scientific papers. He is a Fellow of IEEE (1988), Visiting Research Fellow of GE Research and Development Center (1988), Distinguished Lecturer of the IEEE Magnetics Society (1994), Distinguished Scholar-Teacher of University of Maryland, College Park (1994) and a recipient of Outstanding Teacher Award of College of Engineering (1987). In 2009, he received the Achievement Award of the Institute of Electrical and Electronics Engineers (IEEE) Magnetics Society, the highest award given by the society. He has served on numerous IEEE committees, editorial boards of scientific journals and as the Editor of Academic Press-Elsevier Electromagnetism series.
Quantum Dynamics of a Nanomagnet Driven by Spin-Polarized Current

Presenter: Lu J. Sham  
Co-author: Yong Wang  
Affiliation: Center for Advanced Nanoscience and Department of Physics, University of California San Diego

Abstract: A quantum treatment of magnetization dynamics of a nanomagnet may be needed as the magnet is scaled down in size or as the magnet interacts with quantum objects, or for the first-principles source of noise. We have made a modest beginning of such a study with a simple model keeping the magnetic state as a rigid macro-spin state. The spin torque transfer, as a sequence of scatterings of each electron spin with the macro-spin state of magnetization, gives in each encounter a probability distribution of the magnetization recoil state associated with each outgoing state of the electron. This picture provides a natural Monte Carlo process for simulation of the dynamics in which the dice throwing is determined by quantum mechanics. It also provides a quantum derivation of the master equation for the dynamics and diffusion. The computed results of the quantum trajectory of the magnetization contain the average motion tending in the large spin limit to the semiclassical results of spin transfer torque. The very act of scattering produces a quantum correlated state of the current electron and the magnet which gives rise to a quantum noise, evident in the fluctuations of the magnetization dynamics. The theory provides the transfer of charge noise and spin noise in the current to the magnetization dynamics and vice versa. We are working on the microscopic dissipation effects while the magnetization is in motion. We are also interested in better modeling of the quantum magnetization state and in understanding the quantum limit to the scaling down of the nanomagnet.


Bio: A condensed matter theorist currently interested in spintronics and in quantum information processing of semiconductor quantum dots. Professor of Physics, Member, NAS and Academia Sinica; Fellow, APS, OSA, and AAAS.
Extending Micromagnetic Theory

Presenter: Manfred E. Schabes
Affiliation: HGST, a Western Digital company, San Jose Research Center

Abstract: The design and fabrication of magnetic nanostructures is at the center of a wide range of technologies, including high-resolution magnetic sensors, recording media for ultra-high bit densities, and tunable oscillators with frequencies in the microwave regime. Accordingly, the scope of micromagnetic simulations has expanded significantly over the last two and a half decades, marshalling, at times, the best of numerical analysis and the best of supercomputing. Robust and detailed calculations of magnetic properties are possible with good spatial resolution for certain classes of questions. However, challenges remain for connecting the mesoscopic realm of a micromagnetic description to the atomistic domain. The physics of these challenges is of great technological interest, since the performance of nanostructured materials and devices has become increasingly dependent on critical features involving atomistic length scales. For instance, interfaces and grain boundaries play an important role in nanostructured magnetic media for ultra-high-density data storage. In this presentation, I will first discuss the treatment of interfacial interactions within the framework of classical micromagnetic theory, and then develop extensions of the theory by examining calculations using density functional theory. I will propose methods to connect atomistic calculations with the continuum methods of classical micromagnetics.

Bio: Dr. Manfred E. Schabes is a Research Staff Member at HGST, a Western Digital company. He received a Dipl. Ing. degree in physics (1982) from the Technical University of Vienna, Austria, an M.S. in physics (1984) from the University of Texas, Arlington, where he was a Fulbright scholar, and a Ph.D. in physics (1989) from the University of California, San Diego. Dr. Schabes has worked on magnetic data storage technology at Honeywell (1989-1991), Komag (1991-1997), IBM Research (1997-2003), Hitachi GST (2003-2012), and currently studies advanced nanostructured media at the San Jose Research Center of HGST. His micromagnetic theory of non-uniform magnetization reversal processes was first to predict the magnetic configurational anisotropy of magnetic nanostructures and also introduced the enumeration of non-uniform micromagnetic states. In 2002 he received an IBM Outstanding Technical Achievement Award for his contributions to the invention of Antiferromagnetically Coupled (AFC) magnetic recording media. He has published over 50 papers and one book chapter and holds multiple patents related to magnetic data storage technology.
Abstract: In this presentation we focus on two examples of microscopic theory of magnetic interactions impacting micromagnetic simulations. In the first example we focus on temperature dependence of magnetic anisotropy. We focus on two specific material systems with unusual temperature dependence of effective anisotropy constant $K_{\text{eff}}(T)$: (i) 3d-5d (L1$_0$ FePt, m-DO$_{19}$ Fe$_3$Pt) and (ii) MnBi. We use ab-initio calculations (DFT-LDA and beyond (GW)) to parameterize magnetic interactions and construct relevant effective spin Hamiltonians. These effective spin Hamiltonians used to analyze experimental data to extract relevant anisotropy constants needed for micromagnetic simulations. In particular, in the case (ii) we show that higher order anisotropy constants ($K_2, K_3$) need to be taken into account to describe both temperature dependence and magnetic response of this class of materials. In the second example we consider micromagnetic exchange stiffness ($A$) tensor which in the principal axis representation characterized by $A_{||}$ and $A_{\perp}$ elements. We used constrained density functional theory to parameterize $A_{||}$ and $A_{\perp}$ elements of exchange stiffness tensor for two cases: (i) layered L1$_0$ FePt and (ii) hexagonal symmetry hcp Co. In both cases we use micromagnetic simulations to determine impact of realistic micromagnetic exchange tensor on magnetic response of nanostructures made of these materials. In our calculations we compare two cases for in-plane and perpendicular exchange constants: (a) $A_{||} = A_{\perp}$ and (b) $A_{||} = 0$. $A_{\perp}$ and find that the athermal coercive force for 30x30 nm bilayer rectangular dots differs for these two cases. Further, we find that the magnetization switching changes from curling mode in the case (a) to the vortex formation in the case (b). We also find that these differences in magnetization switching become more pronounced if interface exchange between hard and soft layers is increased to the bulk value.

Bio:
Dr. Oleg N. Mryasov is an Associate Professor of Physics. He received his doctoral degree in Solid State Physics from Russian Academy of Sciences in 1993 and performed postdoctoral research from 1993 to 1999 at Northwestern University, IL. From 1999-2001 Dr. Mryasov held joint appointment of Research Engineer/Technical Staff at UC, Berkeley and Sandia National Laboratories. He joined Seagate Research Center, Seagate Technologies LLC, Pittsburgh, PA in 2001 as Research Staff Member and has been later promoted to Principal Research Engineer. His research has been focused on fundamentals of relativistic and quantum effects such as anisotropy, exchange and multifunctional properties such as magnetism-transport, magnetism-optics, magnetism-ferroelectricity in solids. His fundamental research was applied to search for a novel materials and design solutions for data storage and information processing applications, fundamentals of recording media and transducer.

Dr. Mryasov joined the University of Alabama faculty in 2009. His research focuses on the microscopic theory of fundamental magnetic interactions (magnetic anisotropy, exchange coupling) in metals, intermetallics and metal insulator hetero-structures, spin dependent transport in artificially layered nanostructures including high-spin-polarization materials (Heusler alloys) and magnetic tunneling junctions based on ordinary and multi-functional oxides. Dr. Mryasov research interests include fundamentals of large magnetic anisotropy materials, multi-scale models of static and dynamic properties of nano-magnets, theory of extended lattice defects, fundamentals of multi-functional materials such as transparent-conductors, magnetic semiconductors and ferroelectric materials.

Dr. Mryasov has authored and coauthored more than 80 scholarly papers, one book chapter and 4 US patents.
The Role of Grain Boundaries on the Coercivity of Magnetic Materials

Presenter: Gino Hrkac1
Co-authors: Lalita Saharan1, Tom Woodcock2, Thomas Schrefl3, Oliver Gutfleisch4, Chris Morrison5 and Thomas Thomson5
Affiliation: University of Sheffield, IFW Dresden, St Poelten University of Applied Science, TU Darmstadt and University of Manchester5

Abstract: In this work we investigate the microscopic origin of the coercivity of sintered magnets. To understand the interaction of multiple grains in real Nd2Fe14B sintered magnets we carry out high-resolution transmission electron microscopy (HR-TEM) in order to image grain boundaries (GB) in commercially available materials. We then use the crystallographic orientation relationships, determined from these images, as input for solid-state lattice minimization calculations of Nd2Fe14B structures with different interface compositions (NdOx / Nd2Fe14B and Nd2O3 / Nd2Fe14B) and crystallographic orientations. The strain acting on the atomistic positions near the grain interface is computed and from that, a change in the total magnetic anisotropy is calculated. Solid-state lattice minimization calculations show that close to a grain boundary the magnetocrystalline anisotropy is reduced as compared to its bulk value. The anisotropy profile gained from solid-state lattice minimization calculations is used as an input parameter in micromagnetic simulations and compared with experiments. It is shown that the localized change of the anisotropy close to the boundaries is one of the dominating factors for the reduced coercivity found in experiments.

But grain boundaries also play a role in nano-magnets such as ones used in magnetic recording media grains such as CoCrPt. A combined micromagnetic and nudged elastic band method was used to investigate the utility of a one-grain model (with/without GB) in describing the switching field of CoCrPt media as a function of applied field angle at finite temperatures. The effect of grain diameter, attempt frequency and thermal activation on the switching field were investigated. The results of the simulations show good agreement with VSM measurements on well segregated, single layer CoCrPt-SiOx recording media and demonstrate that thermal activation and grain boundaries can modify the Stoner-Wohlfarth angle dependency of the switching field by reducing the depth of the minimum that occurs at 45 degrees.

Bio: He completed his PhD in the Department of Solid State Physics, Vienna University of Technology in 2005, studying eddy current effects in magnetic nanomaterials and their influence on high frequency magnetisation behaviour. 2005 He joined the Department of engineering Materials at the University of Sheffield. He was developing a finite element model to treat non linear magnetisation dynamics to investigate high frequency switching and spin torque effects in magnetic nano pillars and magnetic Tunnel Junction systems. He has published over 54 papers, given 14 invited talks and over 20 contributed conference talks. He is member of the American physical society, a Royal society University research fellow and will join the University of Exeter as an associate Professor in August 2012.
His main research area is computational and theoretical magnetism, and especially the development of a numerical model to investigate and predict the behaviour of magnetic spin valve systems and the effect of eddy currents in nano-scale materials. In particular he is working on the theoretical and numerical description of spin electronic devices on a length scale ranging from the computation of the local spin current density and magnetization dynamics with a sub-nm resolution in micron size devices (magnetic nano pillars and Magnetic Tunnel Junctions).
A prominent example for his work is the theoretical explanation of the angular dependency of phase locking phenomena in point contacted spin valves and His work on the simulation of spin current induced magnetization dynamics that explained the low frequency oscillations found in point contact devices that were explained by vortex oscillations.
His latest research includes ab initio simulations of atomic structures, solid state molecular dynamics for the simulation of the transition of amorphous to crystalline grain boundaries in NdFeB magnets within the framework of an industrial funded project on permanent magnets (European-Japanese consortium).
Micromagnetic Energy Minimization for Low-Rank Tensor Magnetization

Presenters: L. Exl, T. Schre
Affiliation: University of Applied Sciences, Department of Technology, A-3100 St. Pölten, Austria

Abstract: A tensor grid algorithm for the minimization of the micromagnetic energy is presented. Based on the method of multipliers [1] this approach allows the treatment of the micromagnetic side constraint in a tensor-structured framework [2] by introducing a constraint function \( p \), but also offers a competitive alternative to well-established approaches in numerical micromagnetics for non-tensor-structured considerations. The energy minimization is done by solving a sequence of unconstrained optimization problems, where the objective is given by an augmented Lagrangian function

\[
L_\mu(m, \lambda) = e_{\text{tot}}(m) - \lambda p(m) + \mu \Phi(p(m)).
\]

(1)

Since energy components and their gradients can be computed efficiently for low-rank tensor magnetization (e.g. Tucker tensors) [3], the algorithm shows sub-linear complexity with respect to the grid size in terms of costs per iteration [4], if the magnetization is sufficiently well compressed. Thus, tensor structured minimization techniques allow solving large-scale three-dimensional problems on low-cost computers. An example is the computation of hysteresis of permanent magnets with several million unknowns. Apart from that, the ill-conditioning of the unconstrained subproblems usually arising in penalty-like methods is overcome by the multiplier iteration, leading to

\[
\|m^* - m_j\| \leq M |\lambda^* - \lambda_j| \mu_j, \quad \mu_j > \mu.
\]

(2)

as an estimate of the convergence to the constrained minimizer \( m^* \).

We compare with results of the Standard Problem No.3 posed by the \( \mu \)MAG micromagnetic modeling activity group at the National Institute of Standards and Technology (NIST) [5].

References

Bio: Lukas Sebastian Exl (27)
Lukas S. Exl graduated from the Vienna University of Technology in 2010 with a M.Sc. in mathematics in the sciences. He is researcher and lecturer at the University of Applied Sciences St. Poelten and participating researcher in the ViCoM project part 'Multi-scale simulations of magnetic nanostructures' led by Dieter Suess. Within the scope of his doctoral thesis he works on tensorgrid methods for micromagnetic simulations supervised by Thomas Schrefl.
Kinetic Theory Description of Spin Flipping

**Presenter:** Gregory J Parker (1)  
**Co-author:** W Nick G Hitchon (2)  
**Affiliation:** (1) HGST, (2) ECE Dept., UW-Madison  
**Abstract:** Calculation of the time until a magnetic moment can escape from a potential well is addressed. A detailed micromagnetic simulation is employed to generate the parameters for a continuity equation which describes (in terms of diffusion coefficient, mobility and similar quantities) the probability density for the magnetic moment, as a function of its energy. Direct micromagnetic integration is computationally too expensive by many orders of magnitude, and even direct solution of the continuity equation by standard methods is made difficult by the very large gradients of density with respect to energy. Consequently, we have examined semi-analytic solutions of the equation for the probability density, which attempt to avoid numerical problems with the solution. The approach can be extended to multiple interacting magnetic moments by, for example, kinetic Monte Carlo algorithms to follow the long time behavior of the magnetic moments in the presence of thermal fluctuations and externally applied fields. Theory and results will be presented.

**Bio:** G.J. Parker has a Ph.D. and B.S. in physics from the UW-Madison. He has worked at Lawrence Livermore National Laboratory, Seagate Research, General Electric Global Research and now at HGST on large computer simulations and model reduction for applications including plasma processing, lighting, magnetic recording, reverse osmosis, liquid sodium batteries, fuel cells, photonic crystals and field emission. He has 15 patents and over 40 papers.
Simulation of Heat Assisted Magnetic Recording using Renormalized Media Cells

Presenter: Randall H. Victora  
Co-author: Pin-Wei Huang  
Affiliation: MINT, Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis, MN 55444

Abstract: Heat Assisted Magnetic Recording (HAMR) is widely regarded to have good potential for transitioning magnetic recording to densities beyond 1 TBits/Inch$^2$. The technology uses a near field optical spot to heat the recording layer to a temperature near the Curie temperature where high anisotropy materials have a diminished switching field and thus can be written. Once cooled, the high anisotropy returns and protects the small grains from thermally induced switching (superparamagnetism).

This high temperature writing introduces new physics. In particular, large fluctuations of magnetization, anisotropy, and exchange are expected: this will introduce jitter and DC noise into the recording process. In principle, recording could be simulated by including every atom, but the computational demands would be enormous. Instead, we take advantage of the long term correlation of spin fluctuations near the Curie temperature to group neighboring spins in blocks, small enough to include the physics, yet large enough to allow treatment of the large number of grains inherent to a recording simulation.

The talk will begin with predictions for the anisotropy fluctuations, including their spectral content. Renormalized values for magnetization, exchange, anisotropy, and damping are numerically derived for incorporation in these spin blocks. A recording simulation, written in CUDA for use on a Graphical Processing Unit, is used to predict bit patterns and jitter as a function of recording velocity, applied field, and the physical characteristics of the optical spot.


Bio: Randall Victora earned B.S. degrees in Physics and Math at the Massachusetts Institute of Technology in 1980 and received his Ph.D. in Physics from U.C. Berkeley in 1985. Upon graduation, Dr. Victora joined Kodak Research Laboratories, where he worked on the theory and simulation of magnetic materials, particularly for magnetic and optical storage. In 1998, he joined the Department of Electrical and Computer Engineering at the University of Minnesota, where he is now a Professor and Director of the Center for Micromagnetics and Information Technology (MINT). He is known for his work on Superlattice Perpendicular Recording Media and Exchange Coupled Composite media, both of which earned Technical Achievement Awards of the Information Storage Industry Consortium (previously NSIC). Professor Victora served as the General Chairman of the 50th annual MMM Conference and as the President of the IEEE Magnetics Society in 2009 and 2010. He is a Fellow of the American Physical Society and a Fellow of the IEEE.
Micromagnetic Simulation for Heat Assisted Magnetic Recording Based on Landau-Lifshitz-Bloch Equation

Presenter: Xi Chen  
Co-authors: Thomas Roscamp, Roy Chantrell, Ganping Ju  
Affiliation: Seagate Technology

Abstract: A realistic description of magneto-dynamics at elevated temperature presents a significant challenge from both fundamental and application perspective. It is particularly important for the development of heat assisted recording (HAMR). Conventional approach based on Landau-Lifshitz-Gilbert (LLG) equation is no longer adequate at high temperature where anisotropy and magnetization strongly depend on the temperature. The Landau-Lifshitz-Bloch (LLB) equation provides a more realistic approach. By including the dynamics in the longitudinal direction, LLB allows magnetization and anisotropy change magnitude self-consistently. Non-trivial phenomena such as linear reversal can also be captured by LLB.

In this talk, we discuss our recent work on micromagnetic simulation for HAMR based on LLB equation, with emphasis on the recording medium. In order to grasp the underlying physics, we first developed a non-interacting spin model obeying stochastic LLB dynamics. This simple model allows us to gain insight on the interesting switching behavior near Curie temperature and the thermal dynamic noise caused by the rapid cooling process. The LLB equation is also implemented on a micromagnetic recording model. Using the realistic model, various parameters such as temperature gradient, head field strength and angle, damping parameters etc. are varied in order to study how they affect the recording performance, as measured by transition jitter and write width. The results provide valuable guidance for the medium and head design of HAMR.

Bio: Xi Chen is working for Seagate specializing on building micromagnetic models and using them to study the magnetic recording media in the context of perpendicular recording and heat assisted recording. He obtained his PhD in physics in 2010 from the University of Minnesota, where he carried out theoretical research in spin transport nanostructures and spin transfer torque. He received his BS from the University of Science and Technology of China in 2005, also in physics.
Extended Time and Length Scale Micromagnetics

Presenter: Dieter Suess
Co-authors: Christoph Vogler, Florian Bruckner, Christoph Dellago
Affiliation: Vienna University of Technology, Institute of Solid State Physics, Vienna, Austria

Abstract: Various applications ranging from spintronic devices, giant magnetoresistance (GMR) sensors, and magnetic storage devices, include magnetic parts on very different length scales. The involved time scales ranges from the picosecond regime (internal precessional frequency) to years in order to predict the thermal stability of magnetic structures. Within this work we present state of the art methods to bridge the length scales of standard micromagnetic simulations to macroscopic feature size (mm) and extend the time scales to years.

Using the Landau-Lifshitz-Gilbert equation (LLG) constrains the maximum element size to the exchange length. Hence, it is not possible to simulate macroscopic parts with a pure micromagnetic approach. To bridge the length scale we will present a hybrid solver, where micromagnetic parts are coupled to macroscopic magnets which are described by Maxwell’s equations using the experimentally obtained material law. Results of magnetic recording heads, where macroscopic shields are simulated using Maxwell equations and the media is simulated using LLG will be presented.

To bridge the time scale gap we developed a technique consisting of a combination of a nudged elastic band (NEB) method, which is part of our finite element micromagnetic package FEMME, and a statistical method to simulate rare events called “Forward Flux Sampling” (FFS). Forward flux sampling uses a series of interfaces between the initial and final states to calculate the average lifetime of a magnetic state and to generate transition paths for rare events in equilibrium or nonequilibrium systems with stochastic dynamics. In between the interfaces Langevin micromagnetic simulations are performed. Using this technique we present calculations of the lifetime of magnetic structures of various shapes which are thermally stable and not directly accessible by standard Langevin simulations. The developed method successfully predicts the rare event switching periods.

Bio: Dieter Suess born 1975 in Vienna is Dozent, equivalent to Associate Professor in Institute of Solid State Physics, Vienna University of Technology. He is an author of 121 scientific papers (H-index 19) and 9 book chapters, holder of 9 patents on magnetic technologies and CEO of SuessCo, which develops and distributes the commercial micromagnetic software FEMME. The focus of his research ranges from the design of functional magnetic nanostructures for magnetic recording to experiments of magnetic sensors. FEMME, the micromagnetic solver developed with Prof. Thomas Schrefl over the last decade, is used by the major companies in the recording industry (Western Digital, Seagate, Hitachi, Samsung). The detailed prediction of the functional behavior of novel nanostructures led to practical applications for data storage and magneto-electronics as for example exchange spring media and graded media for perpendicular recording. Dr. Suess gave 24 invited and plenary talks at major international conferences within the last 5 years.
Abstract: In this work we propose a framework for analyzing the behavior of stochastic processes in magnetic systems, demonstrating its capabilities with a specific application: on-track erasure caused by residual flux from a magnetic write head. The basic physics of such phenomenon is that the existence of metastable states in the system results in a finite probability for the write head to exhibit a long-lived (ms) remnant magnetic moment. Determining how application of external fields, sample's geometry, and starting conditions affect that probability is of practical interest. A well documented approach is to utilize deterministic models, studying magnetization dynamics as a function of time over short (ns) timescale and extrapolating that to the relevant time scales. We show that such analyses reveal only the fundamental relaxation processes in the system and are often inadequate for capturing the relevant physics or reproducing the experimental results. In this work, a combination of micro-magnetics and statistical methods are used instead to build a phenomenological model which enables a more predictive analysis of the system.

Bio: Ned Tabat is the managing director at Semaphore Scientific, Inc. Prior to Semaphore, Ned worked at Seagate Technology’s Recording Head Operations, the University of Wisconsin-Madison, and Bell Laboratories/Bellcore. He holds BS, MS, and PhD degrees in Electrical Engineering and Physics from the University of Illinois at Urbana-Champaign.
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