REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
27-09-2019	Final Report	20-Jul-2018 - 15-Jul-2019

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Final Report: Advances in Applied Mathematics Conference in memoriam of Professor Saul Abarbanel, Tel Aviv University	W911NF-18-1-0294
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 611102
6. AUTHORS	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES	8. PERFORMING ORGANIZATION REPORT NUMBER
North Carolina State University 2701 Sullivan Drive Admin Srvcs III, Box 7514 Raleigh, NC 27695 -7514	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	ARO
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) 73339-MA-CF.1

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Semyon Tsynkov
UU	UU	UU	UU		19b. TELEPHONE NUMBER 919-515-1877

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

RPPR Final Report
as of 30-Sep-2019

Agency Code:

Proposal Number: 73339MACF **Agreement Number: W911NF-18-1-0294**

INVESTIGATOR(S):

Name: Semyon Victor Tsynkov
Email: stsynkov@ncsu.edu
Phone Number: 9195151877
Principal: Y

Organization: **North Carolina State University**
Address: 2701 Sullivan Drive, Raleigh, NC 276957514
Country: USA

DUNS Number: 042092122 EIN: 566000756
Report Date: 15-Oct-2019 Date Received: 27-Sep-2019
Final Report for Period Beginning 20-Jul-2018 and Ending 15-Jul-2019
Title: Advances in Applied Mathematics Conference in memoriam of Professor Saul Abarbanel, Tel Aviv University
Begin Performance Period: 20-Jul-2018 **End Performance Period:** 15-Jul-2019
Report Term: 0-Other
Submitted By: Semyon Tsynkov Email: stsynkov@ncsu.edu
Phone: (919) 515-1877
Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 0 **STEM Participants:** 0

Major Goals: Advances in Applied Mathematics
International Conference in Memoriam of Professor Saul Abarbanel
Tel Aviv University
December 18 – 20, 2018

The main topic of the Conference is numerical solution of partial differential equations (PDEs). Its primary objective is to review the recent progress in both theory and computation of PDEs that arise from applications of keen practical importance, with particular focus on electromagnetism, acoustics, and fluid mechanics. By bringing together a unique collection of experts in these areas, with backgrounds ranging from analysis to practical implementation, the Conference will promote the exchange of ideas and thus pave the way toward advancing the critical numerical capabilities, such as high order accurate approximations, algorithms with minimal complexity, and projection-based model order reduction. All these capabilities are aimed at drastically improving the efficiency of large-scale computer simulations at the nexus of many modern technologies.

Another central objective of the Conference is to leverage the progress made in designing the advanced computational methods for more traditional areas to move forward the numerical simulation technology in the fields that are very important yet have historically been less exposed to cutting-edge computational mathematics. They may range from imaging to secure communications to space science to quantum physics and the theory of relativity. While from the standpoint of applications these areas are quite diverse, the underlying PDEs often share similar properties. This creates a key opportunity to advance the frontline of scientific research in those areas by introducing modern numerical methods that show superior performance.

Accomplishments: The Conference was a major success. It featured about fifty registered participants and twenty five invited speakers from a number of different countries (USA, Israel, China, UK, Sweden, Switzerland, Germany). It has also included the first award ceremony for the newly established Abarbanel Prize in Applied Mathematics. The talks presented at the Conference accurately reflected on its key objectives. They demonstrated the close interaction between the three central components of the modern scientific inquiry in the field of applied mathematics: theory, computations, and applications. The list of speakers, agenda, and abstracts of all the invited talks are uploaded with this report as a single PDF attachment. The viewgraphs of each invited lecture can be downloaded from the Conference web site (see the Dissemination section of this report).

Training Opportunities: Nothing to Report

Results Dissemination: The Conference has a web site that provides detailed information on all of its relevant aspects: https://stsynkov.math.ncsu.edu/Memorial_Conference/index.html. In particular, from the Agenda section of this web site: https://stsynkov.math.ncsu.edu/Memorial_Conference/agenda.html one can download both abstracts and actual presentation slides for all the invited talks. In addition, the organizers of the conference are currently finalizing a Special Issue of the Journal of Scientific Computing (Springer) that will contain the original papers given at the Conference. Profs Alina Chertock, Adi Ditkowski, Anne Gelb, Sigal Gottlieb, and Semyon Tsynkov serve as guest editors of the Special Issue. It is expected that the Special Issue will be published in 2020.

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Other (specify)
Participant: Matania Ben-Artzi
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Other (specify)
Participant: Alina Chertock
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Other (specify)
Participant: Adi Ditkowski
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Other (specify)
Participant: Wai Sun Don
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Other (specify)
Participant: Gadi Fibich

Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Other (specify)
Participant: Dalia Fishelov
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Other (specify)
Participant: Dan Givoli
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Other (specify)
Participant: Moshe Goldberg
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Other (specify)
Participant: Sigal Gottlieb
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Other (specify)
Participant: Thomas Hagstrom
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Other (specify)

Participant: Isaac Harari
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Other (specify)
Participant: Jan Hesthaven
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Other (specify)
Participant: Gunilla Kreiss
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Other (specify)
Participant: Alexander Kurganov
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Other (specify)
Participant: David Levin
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Other (specify)
Participant: Doron Levy
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Other (specify)
Participant: Jennifer Ryan
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Other (specify)
Participant: Michael Sever
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Other (specify)
Participant: David Sidilkover
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Other (specify)
Participant: Mark Sussman
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Other (specify)
Participant: Shlomo Taasan
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Other (specify)
Participant: Eitan Tadmor
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Other (specify)
Participant: Hillel Tal-Ezer
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: PD/PI
Participant: Semyon Tsynkov
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Other (specify)
Participant: Eli Turkel
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Home

Organizers and contacts

Agenda

Registration

Invited speakers

Travel info

Publication info

Download conference poster

International Conference *Advances in Applied Mathematics* in memoriam of Professor Saul Abarbanel, Tel Aviv University, December 18 - 20, 2018

Invited speakers

- Matania Ben-Artzi, The Hebrew University of Jerusalem, Israel
- Alina Chertock, North Carolina State University, USA
- Adi Ditkowski, Tel Aviv University, Israel
- Wai Sun Don, Ocean University of China
- Gadi Fibich, Tel Aviv University, Israel
- Dalia Fishelov, Afeka Tel Aviv Academic College for Engineering and Tel Aviv University, Israel
- Dan Givoli, The Technion, Israel
- Moshe Goldberg, The Technion, Israel
- Sigal Gottlieb, University of Massachusetts, USA
- Thomas Hagstrom, Southern Methodist University, USA
- Isaac Harari, Tel Aviv University, Israel
- Jan Hesthaven, Ecole Polytechnique Fédérale de Lausanne, Switzerland
- Gunilla Kreiss, Uppsala University, Sweden
- Alexander Kurganov, Southern University of Science and Technology, China and Tulane University, USA
- David Levin, Tel Aviv University, Israel
- Doron Levy, University of Maryland, USA
- Jennifer Ryan, University of East Anglia, UK and Heinrich Heine University, Duesseldorf, Germany
- Michael Sever, The Hebrew University of Jerusalem, Israel
- David Sidilkover, Soreq Research Center, Israel
- Mark Sussman, Florida State University, USA
- Shlomo Taasan, Carnegie-Mellon University, USA
- Eitan Tadmor, University of Maryland, USA
- Hillel Tal-Ezer, The Academic College of Tel Aviv — Yaffo, Israel
- Semyon Tsynkov, North Carolina State University, USA
- Eli Turkel, Tel Aviv University, Israel

Advances in Applied Mathematics, International Conference in Memoriam of Prof Saul Abarbanel

Date	Tuesday, Dec 18	Wednesday, Dec 19	Thursday, Dec 20
Time			
9:00am	Opening by Rector	Eli Turkel	Jan Hesthaven
9:30am	Eitan Tadmor	David Levin	Adi Ditkowski
10:00am	Matania Ben–Artzi	Semyon Tsynkov	Jennifer Ryan
10:30am	Coffee break	Coffee break	Coffee break
11:00am	Alina Chertock	Thomas Hagstrom	Gadi Fibich
11:30am	Alexander Kurganov	Dan Givoli	Wai Sun Don
12:00pm	Lunch break	Lunch break	Lunch break
12:30pm	Lunch break	Lunch break	Lunch break
1:00pm	Lunch break	Lunch break	Lunch break
1:30pm	Doron Levy	Gunilla Kreiss	Isaac Harari
2:00pm	Shlomo Ta'asan	Sigal Gottlieb	Mark Sussman
2:30pm	Coffee break	Moshe Goldberg	Coffee break
3:00pm	Michael Sever	Coffee break (3:00 - 3:20)	David Sidilkover
3:30pm	Hillel Tal-Ezer	Abrabanel Prize Award Ceremony and Talk by Winner (3:20 - 4:00)	Dalia Fishelov
4:00pm	Adjourn for the day	Memorial session	Meeting adjourn
4:30pm		Memorial session	
5:00pm		Break	
5:30pm		Break	
6:00pm		Break	
6:30pm		Memorial Dinner	
7:00pm		Memorial Dinner	
7:30pm		Memorial Dinner	
8:00pm		Memorial Dinner	

Eitan Tadmor
University of Maryland

Emergent behavior in collective dynamics

A fascinating aspect in collective dynamics is self-organization: ants form colonies, birds flock, mobile networks coordinate a rendezvous and human crowds reach a consensus. We will overview recent results on the large-time, large-crowd collective behavior, driven by different "rules of engagement". In particular, we address the question how short-range interactions lead, over time, to the emergence of long-range patterns.

Matania Ben-Artzi

The Hebrew University of Jerusalem

Conservation laws on the sphere: From Shallow-Water to Burgers

One of the best known models for atmospheric flow is that of the "Shallow-Water" system (on the sphere). It is a complicated system of nonlinear hyperbolic equations, involving material discontinuities, shocks and other wave patterns. The first part of this talk is devoted to a Lagrangian derivation of the system.

In the second part a scalar conservation law is introduced. It is the "geometric" equivalent of the famous Burgers equation. The theory of existence and uniqueness is stated (uniqueness is implied by a suitable version of the entropy condition). The proofs (not discussed in detail in this talk) use a combination of dissipative estimates and Young measures. Some numerical results are presented, showing a very rich collection of steady-state solutions, solutions confined to designated domains and more.

(Joint work with J. Falcovitz and Ph. LeFloch).

Alina Chertock
North Carolina State University

Structure preserving numerical methods for hyperbolic system of balance laws

Many physical models, while quite different in nature, can be described by nonlinear hyperbolic systems of conservation and balance laws. The main source of difficulties one comes across when numerically solving these systems is lack of smoothness as solutions of hyperbolic conservation/balance laws may develop very complicated nonlinear wave structures including shocks, rarefaction waves and contact discontinuities. The level of complexity may increase even further when solutions of the hyperbolic system reveal a multiscale character and/or the system includes additional terms such as friction terms, geometrical terms, nonconservative products, etc., which are needed to be taken into account in order to achieve a proper description of the studied physical phenomena. In such cases, it is extremely important to design a numerical method that is not only consistent with the given PDEs, but also preserves certain structural and asymptotic properties of the underlying problem at the discrete level. While a variety of numerical methods for such models have been successfully developed, there are still many open problems, for which the derivation of reliable high-resolution numerical methods still remains to be an extremely challenging task.

In this talk, I will discuss recent advances in the development of two classes of structure preserving numerical methods for nonlinear hyperbolic systems of conservation and balance laws. In particular, I will present (i) well-balanced and positivity preserving numerical schemes, that is, the methods which are capable of exactly preserving some steady-state solutions as well as maintaining the positivity of the numerical quantities when it is required by the physical application, and (ii) asymptotic preserving schemes, which provide accurate and efficient numerical solutions in certain stiff and/or asymptotic regimes of physical interest.

Alexander Kurganov
Southern University of Science and Technology, China, and Tulane University, USA

Central-Upwind Schemes for Shallow Water Models

In the first part of the talk, I will describe a general framework for designing finite-volume methods (both upwind and central) for hyperbolic systems of conservation laws. I will focus on Riemann-problem-solver-free non-oscillatory central schemes and, in particular, on central-upwind schemes that belong to the class of central schemes, but has some upwind features that help to reduce the amount of numerical diffusion typically present in staggered central schemes such as, for example, the first-order Lax-Friedrichs and second-order Nessyahu-Tadmor scheme.

In the second part of the talk, I will discuss how central-upwind schemes can be extended to hyperbolic systems of balance laws, such as the Saint-Venant system and related shallow water models. One of the main difficulties in this extension is preserving a delicate balance between the flux and source terms. This is especially important in many practical situations, in which the solutions to be captured are (relatively) small perturbations of steady-state solutions. Other crucial points are preserving positivity of the computed water depth (and/or other quantities, which are supposed to remain nonnegative) and treatment of nonconservative products appearing in, for example, the classical Saint-Venant system in the case of discontinuous bottom topography or generically nonconservative multilayer shallow water equations. I will present a general approach of designing highly accurate and robust central-upwind schemes and illustrate their performance on a number of shallow water models.

Shlomo Ta’asan
Carnegie Mellon University

Challenges in Modeling Polycrystalline Materials

Polycrystalline materials, such as steel, aluminum and copper, are ubiquitous in most technological applications. Their use can be found in small devices such as smartphones, as well as in much larger machines; cars, ships and airplanes. These materials exhibit complex response to thermal and mechanical loading that is mostly due to defects, their nucleation and evolution. Changes in defect content affect material response to further loading and is the source of nonlinear behavior. Understanding the variety of defects and their interactions is essential for accurate prediction at the macroscopic scale.

In this talk we discuss measure theoretic approach for modeling such materials and we focus on dislocations and twinning. We propose a variational formulation in new spaces of parameterized measures, allowing for a natural description of microstructures at small scales. Entropy plays an important role in this formulation. Evolution equations are obtained by minimizing free energy of the system in an appropriate metric.

Doron Levy
University of Maryland

Modeling the chemotherapy-induced selection of drug-resistant traits during tumor growth

The emergence of drug-resistance is a major challenge in chemotherapy. In this talk we will present our recent mathematical models for describing the dynamics of drug-resistance in solid tumors. Our models follow the dynamics of the tumor, assuming that the cancer cell population depends on a phenotype variable that corresponds to the resistance level to a cytotoxic drug. We incorporate the dynamics of nutrients and two different types of drugs: a cytotoxic drug, which directly impacts the death rate of the cancer cells, and a cytostatic drug that reduces the proliferation rate. Through analysis and simulations, we study the impact of spatial and phenotypic heterogeneity on the tumor growth under chemotherapy. We demonstrate that heterogeneous cancer cells may emerge due to the selection dynamics of the environment. Our models predict that under certain conditions, multiple resistant traits emerge at different locations within the tumor. We show that a higher dosage of the cytotoxic drug may delay a relapse, yet, when this happens, a more resistant trait emerges. Moreover, we estimate the expansion rate of the tumor boundary as well as the time of relapse, in terms of the resistance trait, the level of the nutrient, and the drug concentration. Finally, we propose an efficient drug schedule aiming at minimizing the growth rate of the most resistant trait. By combining the cytotoxic and cytostatic drugs, we demonstrate that the resistant cells can be eliminated.

Michael Sever
The Hebrew University

A source of uncertainty in computed discontinuous flows

Some recent results suggest that particularly in higher dimensions, admissible weak solutions of systems of conservation laws are in short supply. In particular, convincing empirical results may be compatible with boundary data insufficient to uniquely determine such a solution. A method is described for a posteriori computational investigation of this question.

Hillel Tal-Ezer
Tel Aviv University

Computing function of a matrix times a vector via Newton interpolation approach

Krylov algorithms are widely used for approximating the vector $w=f(A)v$. The main advantage of the Krylov approach stems from the fact that no a priori knowledge of the domain of eigenvalues is needed. On the other hand, its drawback lies in the need to store all the vectors spanning the approximation space. In this talk we would like to present a new algorithm which overcomes this drawback. The algorithm is based on approximating the function $f(z)$ by Newton interpolation polynomial. The optimal interpolating points are computed by the algorithm using Leja approach. Hence, as in the Krylov case, no a priori knowledge of the domain of eigenvalues is needed. High accuracy is achieved with only few vectors stored. Applying the new algorithm for general, linear time dependent PDEs will be described.

Eli Turkel
Tel Aviv University

Obstacle location and identification using Time Reversal and Machine Learning

The inverse problem of obstacle location and identification has been studied using many approaches. We have developed an algorithm based on time reversal for the acoustic wave equation to locate the position of an obstacle even in the presence of partial and noisy information. We propose methods for using the latest machine learning algorithms to get improved predictions for hard obstacles in a homogeneous environment. We present promising results and several options for further development.

Semyon Tsynkov
North Carolina State University

Synthetic aperture imaging through a turbulent ionosphere

We will discuss an intriguing recent finding that pertains to the imaging of the surface of the Earth by spaceborne synthetic aperture radars (SAR). SAR is a coherent imaging technology that uses microwaves for reconstructing ground reflectivity as a function of spatial coordinates.

Ionospheric turbulence brings an additional dimension into the SAR analysis; this new dimension accounts for randomness. The overall error now has two components, deterministic and stochastic. They are fundamentally different. The stochastic component becomes larger as the synthetic aperture gets smaller compared to the outer scale of turbulence. Then, why in the ultimate case of very short apertures it appears that the stochastic error can be completely disregarded?

We will outline an approach to answering this question and identify the outstanding issues that require future attention.

David Levin
Tel Aviv University

Some ideas in multivariate approximation

I will demonstrate the construction of an algorithm for scattered data multivariate approximation using the desired properties of the resulting approximant. Evaluating the approximant is done by checking the same properties used for deriving the algorithm and not by applying the algorithm to some test functions. The result is a quasi-interpolation approximation, also known as the Moving Least-Squares approximation (MLS). Two applications of MLS will be presented:
1. Approximation of non-smooth multivariate functions from scattered data.
2. Approximation of a low dimensional manifold from noisy scattered data in high dimension.

Thomas Hagstrom
Southern Methodist University

Hermite Methods for Waves

We discuss a class of numerical methods for hyperbolic systems based on Hermite-Birkhoff interpolation. The methods are high-order in both space and time, stable for any time step satisfying the physical CFL constraint independent of order, and admit highly localized evolution algorithms. We will outline their analysis, which is built around a remarkable projection property of the interpolation operators, and which has recently been extended to highly efficient leap-frog formulations. We will also demonstrate their practical performance, in particular their ability to effectively leverage many-core platforms such as GPUs.

Dan Givoli
Technion

Absorbing Boundary Condition for Anisotropic Elasticity

We discuss the design of absorbing boundary conditions (ABCs) in general. Then we propose new forms of low-order ABCs for time-dependent elastic waves in anisotropic media. We prove the energy-stability of the proposed ABC, even in the presence of so-called inverse modes. We discuss the incorporation of the ABC in a standard finite element scheme. We optimize the free parameters in the ABC based on energy-flux reflection coefficients. We present some numerical examples, and mention future extensions.

Gunilla Kreiss
Uppsala University

Cut Finite Element methods and immersed boundary Finite Difference methods

Much effort has been directed towards constructing stable and high order accurate finite difference methods that can solve time-dependent PDEs on a computational grid that does not align with the boundary. We are particularly interested in methods that fit in the Summation-By-Parts framework, and will specialize to second order wave equations. There are recent advances in creating stable, immersed finite element methods for solving partial differential equations using the Cut Fem approach, see [1]. In particular, when applied to the wave equation small cuts do not lead to correspondingly severe time step limitations, [2]. The methodology involves imposing boundary conditions weakly and adding special stabilization at cut elements. In this talk we shall explore the connection between finite difference methods and these Cut Fem methods.

REFERENCES

[1] E. Burman, S. Claus, P. Hansbo, M. G. Larson, A. Massing, CutFEM: Discretizing geometry and partial differential equations, Int. J. Num Meth Eng 104(7),472–501, 2015.

[2] S. Sticko, G. Kreiss, A stabilized Nitsche cut element method for the wave equation, Comput Meth in App Mech and Eng 309, 364–387, 2016.

Sigal Gottlieb
University of Massachusetts Dartmouth

Developing Time Filtering using a General Linear Method Approach

Time filtering has been used to enhance the order of accuracy of given methods. In this work, we should how this is equivalent to generating a general linear method and use this approach to develop and analyze new time-filtering methods.

Moshe Goldberg
Technion

Radii of Elements in Finite-Dimensional Power-Associative Algebras

The purpose of this talk is to introduce a new concept, the *radius* of elements in arbitrary finite-dimensional power-associative algebras over the field of real or complex numbers. It is an extension of the well-known notion of classical spectral radius.

As examples, we shall discuss this new kind of radius in the setting of matrix algebras where it reduces to the spectral radius, and then in the Cayley-Dickson algebras where it is something quite different.

We shall also describe two applications of this new concept which are related, respectively, to the Gelfand formula, and to the stability of norms and subnorms.

Jan Hesthaven
Ecole Polytechnique Federale de Lausanne (EPFL)

Adaptive discontinuous Galerkin method for tsunami modeling and prediction on a global scale

The need to accurately and efficiently predict the impact of earthquake-driven tsunamis requires the development of large scale simulation tools to solve the shallow water equations on a global scale. Such tools can serve as an integral part of tsunami warning system.

In this talk, we present a novel high-order discontinuous Galerkin discretization for the spherical shallow water equations, able to handle wetting/drying and non-conforming, curved meshes in a well-balanced manner. This requires a well-balanced discretization, that cannot rely on exact quadrature, due to the curved mesh. Using the strong form of the discontinuous Galerkin discretization, we achieve a splitting of the well-balanced condition into individual problems for the flux and volume terms and discuss its advantages. More importantly, this approach enables the development of a new method for handling wet/dry transitions which, in contrast to alternative wetting/drying techniques, it is well-balanced and able to handle wetting/drying robustly at any polynomial order, without the introduction of additional physical model assumptions, e.g., viscosity, artificial porosity or cancellation of gravity. The flexibility of the formulation also allows for the use of a fully non-conforming discretization, opening the path to efficient adaptive formulations.

We illustrate the properties of the scheme through a series of simple one-dimensional tests and analyze the properties of our scheme. To validate the method for the simulation of large-scale tsunami events on the rotating sphere, we perform numerical simulations of several historical large scale events and compare our results to real-world data. By considering both static and dynamic earthquake models, we demonstrate that the method is able to predict arrival times and wave amplitudes accurately, even over long distances.

This work has been done with in collaboration with B Bonev (EPFL, CH), F. Giraldo (NPS, US), M. Hajihassanpour (Sharif, Iran), and M. A. Kopera (UC Santa Cruz, US).

Adi Ditkowski
Tel Aviv University

Error inhibiting schemes for differential equations

Typically, when semi-discrete approximations to time-dependent partial differential equations (PDE) or schemes for ordinary differential equation (ODE) are constructed they are derived such that they are stable and have a specified truncation error Te. Under these conditions, the Lax-Richtmyer equivalence theorem assures that the scheme converges and that the error is, at most, of the order of Te.

In most cases, the error is in indeed of the order of Te. We demonstrate that schemes can be constructed, whose truncation errors are Te, however, the actual errors are much smaller. This error reduction is made by constructing the schemes such that they inhibit the accumulation of the local errors; therefore, they are called Error Inhibiting Schemes (EIS).

Jennifer Ryan
University of East Anglia & Heinrich Heine University

Utilizing Geometry of Smoothness-Increasing-Accuracy-Conserving (SIAC) filters for reduced errors

Smoothness-Increasing Accuracy-Conserving (SIAC) filters for Discontinuous Galerkin (DG) methods are designed to increase the smoothness and improve the convergence rate of the DG solution form p+1 to 2p+1 through post-processing. However, introducing these filters can be challenging for multi-dimensional data since a tensor product filter grows in support size as the field dimension increases [(3p+2)*h]^d, where p + the polynomial order and d is the dimension. This becomes computationally prohibitive as the dimension increases. An alternative approach is to utilize a one-dimensional univariate filter. In this talk we introduce the Line SIAC filter and explore how the orientation, structure and filter size affect the order of accuracy and global errors. We show how line filtering preserves the properties of traditional tensor product filtering, including smoothness and improvement in the convergence rate, given an appropriate rotation. Furthermore, numerical experiments are included, exhibiting how these filters achieve the same accuracy at significantly lower computational costs.

Gadi Fibich
Tel Aviv University

A Spline-Based Approach to Uncertainty Quantification with Applications to Density Estimation

Uncertainties and noise are prevalent in mathematical models in all branches of science. Because of the randomness, the calculation of the deterministic value of a quantity of interest is replaced by the calculation of its moments (e.g., mean and standard deviation) and, ideally, its Probability Density Function (PDF). Standard approaches to these tasks are either statistical, such as Kernel Density Estimators (KDE), and spectral methods such as the gPC. We present a novel spline-based, non-intrusive algorithm for uncertainty quantification. This method outperforms existing methods, which are often vastly inefficient for PDF estimation. Furthermore, although standard methods such as gPC approximate moments with spectral accuracy, the spline-based method approximates moments more accurately given small sample sizes. Thus, when each solution of the underlying model is computationally expensive, the spline-based model can be a more efficient choice for moment-approximation as well. The spline-based method can also approximate non-smooth quantities of interest, which is often prohibitive in spectral stochastic methods. We present application of our algorithm to nonlinear optics and computational fluid dynamics.

Wai Sun Don
Ocean University of China

Space-Time Adaptive Hybrid WENO-Compact Finite Difference Scheme for Hyperbolic Conservation Laws with High Order Shock Detectors

A high order/resolution space-time adaptive hybrid scheme that conjugates a nonlinear WENO finite difference scheme and a linear compact finite difference scheme will be described. The hybrid scheme takes advantages of the sharp essentially non-oscillatory capturing of shocks and high gradients of the WENO reconstruction procedure while reducing the inherent strong dissipation, and high resolution and non-dissipative nature of the compact scheme for efficient capturing of small scale structures. By treating the solution frozen in time as an image at each third order explicit TVD Runge-Kutta step, high order shock detection algorithms such as the polynomial based multi-resolution analysis by Harten, and non-polynomial based radial basis function analysis will be presented. Their performances in terms of accuracy, efficiency and robustness will be illustrated via several benchmark shocked flows, such as the one-dimensional shock-density wave interaction, two-dimensional classical Riemann initial value problem and the Mach 10 double Mach reflection problem.

Isaac Harari
Tel Aviv University

Spectral Performance of Nitsche's Method

Relaxing admissibility requirements (such as kinematic boundary and interface conditions) provides added flexibility in computation by accommodating non-conforming meshes (unaligned with geometric features) and non-interpolatory approximations. Such formulations that are based on Nitsche's approach to enforce surface constraints weakly, which shares features with stabilized methods, combine conceptual simplicity and computational efficiency with robust performance. The basic workings of the method are well understood, in terms of a bound on the parameter. However, its spectral behavior has not been explored in depth.

The dimension of the solution space in Nitsche's method is larger than in the corresponding standard formulation. Consequently, in addition to the physical eigenpairs which approximate the exact ones, as in the standard formulation, Nitsche's method gives rise to mesh-dependent complementary pairs associated with weak enforcement of boundary or interface constraints. The dependence of the eigenvalues on the Nitsche parameter is related to a boundary quotient of the eigenfunctions (reminiscent of the Rayleigh quotient). The boundary quotient proves to be useful for separating the two types of solutions.

Numerical studies show that, for the most part, the complementary values exhibit essentially linear growth with the parameter, whereas the eigenvalues are virtually constant, in line with the values of the corresponding boundary quotients. This behavior sheds light on the role of the stabilization parameter in attaining coercivity for the Nitsche method. Veering behavior, typical of parameterized systems, is observed, but does not impair the performance of the method. The spectrum of a reduced system obtained by algebraic elimination contains only physical eigenpairs, and is free of veering. The favorable features of the reduced system warrant its use in the solution of boundary-value problems.

To date, incompatible discretizations are rarely used for eigenvalue problems in engineering applications, possibly due to the potential presence of the mesh-dependent complementary pairs. Removing the added degrees of freedom on the boundaries addressed by the Nitsche approach by Irons-Guyan reduction is a relatively inexpensive procedure that preserves the essential structure of the underlying formulation, and yields a system that contains only eigenpairs. As such, the spectrum is virtually insensitive to stabilization beyond the threshold required for coercivity, preserving the conditioning of the standard formulation. Being free of the complementary eigenpairs, the Irons-Guyan reduced Nitsche formulation of the eigenvalue problem may be solved by any conventional eigenvalue solver. This procedure facilitates the use of Nitsche's method for formulating eigenvalue problems, and justifies its use in explicit dynamics.

Mark Sussman
Florida State University

A hierarchical block structured space-time spectral element method for simulating complex multiphase flows

A new parallelized hierarchical space-time spectral element method has been developed for simulating multiphase compressible or incompressible flows in which the bulk regions of one or more of the fluids can be complex. Such flows occur in the study of ocean currents, atomization and spray in combustion engines, and bubbly flows. In our previous work in simulating multiphase flows on a hierarchical block structured adaptive grid (Jemison et al 2014), the level of efficiency of dynamic adaptive mesh refinement had to be decreased because the numerical solution on coarse levels was overly damped, resulting in incorrect feedback on multiphase interface(s), or retarding naturally occurring nonlinear flow phenomena. We shall present original work in which the solution in spectral elements spanning a single material is represented with space-time spectral accuracy (Pei, Sussman, Hussaini JSC, 2018). The discretization in multimaterial (>1 material) elements is the same as in our previous work. Our present hierarchical adaptive mesh strategy is to prescribe the highest order spectral elements on the coarse adaptive levels, and progressively reduce the order on finer levels. A relatively easy to implement multigrid preconditioned BiCGSTAB (MGPBiCG) algorithm has been developed for the variable density projection equation on our new hierarchical adaptive spectral element grid. The efficiency of the MGPBiCG solver is comparable to that of the lower order MGPCG counterpart.

David Sidilkover
Soreq Nuclear Research Center

A relationship between the Shock-Capturing and Vorticity Confinement methods

Shock-Capturing methods are a general class of techniques for computing compressible flows with shock waves. Vorticity Confinement methods aim at enhancing the resolution of vortical structures by numerical methods. Despite the fact that these two approaches were developed for entirely different purposes, there appears to be a deep commonality between the two.

In this presentation we shall explore this commonality and present novel multidimensional extensions of the TVD and finite difference ENO/WENO methods for the compressible flow equations, which can be viewed as a unification of the Shock-Capturing and Vorticity Confinement methodologies. This is because it acquires capabilities of the both by means of a single mechanism. The performance of the new methods will be illustrated by numerical experiments.

Dalia Fishelov
Afeka Tel Aviv Academic College of Engineering

An embedded Cartesian scheme for the Navier-Stokes equations

In this talk the two-dimensional Navier-Stokes system in stream function formulation is considered.

We describe a fourth-order compact scheme for regular domains in 2D. We then proceed to irregular domains. First, the irregular domain is embedded in a Cartesian grid. Then, an interpolating polynomial is built for regular elements inside the domain as well as for irregular elements near the boundary.

A compact high-order scheme is then constructed for the Navier-Stokes equations by applying the differential operators involved in the Navier-Stokes equations to the interpolating polynomial.

Numerical results will be presented for various irregular domains. A particular attention is devoted to flows in elliptical domains. In the case of the ellipse, we also demonstrate the ability of the scheme for computations of the eigenvalues and the eigenfunctions of the biharmonic problem on the ellipse.

Joint work with Matania Ben-Artzi and Jean-Pierre Croisille.