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GAUSS: An NSF CSUMS Project at UCF

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***Abstract*—A team of faculty members from mathematics, computer science, and education at the University of Central Florida (UCF) introduces a year-long computational mathematics research and training program based on the successes and experiences of the team in undergraduate research in computer vision and imaging science over the past twenty years. With the year-long training program in computational mathematics using the exciting applications of mathematics in images and videos as motivating examples, it is possible to provide students with a lively environment to acquire a solid background in both mathematical theory and hands-on problem solving skills. Our aim is to make the study of computational mathematics relevant to the real world and to attract students to the field of computational science by exposing them to very exciting applications of mathematics. The project restructures and improves the current curriculum in computational mathematics track at UCF, making impact on a wide range of students.**

I. Overview

NSF's CSUMS program. The goal of Computational Science Training for Undergraduates in the Mathematical Sciences (CSUMS) is to enhance computational aspects of the education and training of undergraduate students in the mathematical sciences – mathematics and statistics – and to better prepare these students to pursue careers and graduate study in fields that require integrated strengths in computation and the mathematical sciences. The core of the activity is long-term research experiences for cohorts of at least six undergraduates. Projects must focus on research topics that require interplay between computation and mathematics or statistics. They should expose students to contemporary mathematics, statistics, and computation, addressed with modern research tools and methods. That is, projects must be genuine research experiences rather than rehearsals of research methods. Interdisciplinary projects are encouraged, and appropriate mentorship from the disciplines involved is welcomed. In addition, it is expected that projects will strengthen the research and education capacity, infrastructure, and culture of the participating institutions. To this end, NSF welcomes projects that create models for education in the mathematical sciences and influence the direction of academic programs for a broad range of students. CSUMS is a joint effort of the Education and Human Resources (EHR) and the Mathematical and Physical Sciences (MPS) directorates at the National Science Foundation (NSF). For information, see [1].

CSUMS at UCF. Our CSUMS program is code-named GAUSS. It starts in the spring semester with a research seminar and two courses that prepare students in numerical methods and mathematical modeling for research. Then, in an intensive summer component, the students immerse themselves in a research project. In the fall semester they continue to conduct research and take two more required classes in advanced computer vision and advanced mathematical modeling. In the follow-up spring semester, the students submit their research for publication, finish an undergraduate honors thesis, and get training in graduate career advancement issues. In addition, participants attend professional conferences, which gives them a chance to present their research and to meet known researchers in the field, who may serve as their role models. To broaden the students' perspective, there are field trips to technology companies in the Orlando area such as Lockheed-Martin, Harris, and Boeing. Finally in order to promote interaction amongst the students and faculty, we organize several social events including dinners with distinguished speakers visiting the campus, and parties for graduating Ph.D. students, etc.

Our goals and our team. The objective of our GAUSS project is to develop a rigorous one-year enhanced research experience in computational theory and practice for undergraduates in mathematical sciences through carefully designed course work and guided research projects and activities. We envision that, after the year-long training program, our students will acquire the knowledge in theoretical foundation of numerical methods as well as the extensive programming skills that make them ready to work or study in any fields that require both mathematical theory and computation. Our confidence is built on the extensive experience of the participating faculty mentors in successfully directing a large number of undergraduates research for almost two decades [2], [22], advising undergraduate Honors in the Major theses, developing and teaching interdisciplinary honors seminars, and the dedicated, interdisciplinary team work spirit that pervades our group. In addition, it is a common myth in math undergraduate circles that mathematics is not applied to real-world problems. To clearly dispel this misconception, our team includes an applied mathematician from industry who actively demonstrates the life of a real-world practicing industrial mathematician.

Why computer vision and imaging science? Computer vi-

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sion and imaging science are ideal for illustrating to mathematics majors the issues in computational sciences because their applications are intuitive and visual. They provide a suitable platform for undergraduate students to see how sophisticated computational mathematics works in offering and improving solutions to real world problems.

In addition to the pedagogical reasons, as an important area of computational sciences, computer vision, and imaging science in general, demands new computational mathematics and algorithms to deal with the ever growing need of intelligent tools for processing and understanding of the various kinds of images and videos due to the phenomenal progress made in the scale and manufacturability of imaging sensors over the past two decades.

The economic impact of this field is substantial: imaging science enables and empowers industries like defense, aerospace, homeland security, health care, bio-medical, space exploration, digital records, communications, transportation, manufacturing, agricultural research, entertainment and arts. Further technological breakthroughs in imaging science will enable new industries, not even conceived today.

A typical GAUSS student's work load. GAUSS is a five-year project. Each year, ten undergraduate (sophomore or junior) students are selected to participate in an intensive year-long training in computational mathematics with an integrated research component in computer vision and imaging science. The program starts in January and continues through December. Typically, during the first semester (January through April), a student takes five courses and one seminar (one-hour) course specially designed to introduce computer vision and imaging science content. The second semester, the summer (May through mid-August), is a full-time immersion in research. During the first three weeks of the summer, the topics from the seminar are dealt with in depth, and students are provided sufficient background to begin to undertake a research project that requires computational mathematics (mostly in calculus of variation, numerical linear algebra, numerical optimization, and numerical solutions of PDEs). Each student needs to choose a research topic/direction by the end of the fifth week of the summer. After choosing a research topic, each student is assigned to two faculty advisors: one main advisor from Math, another from Computer Science. The advisors guide the research of each student in all the stages. There are three milestones (stages): 1. research proposal (presented to the advisors by the eighth summer week, to describe the background and outline possible solution); 2. defense (presented to the advisory faculty around the middle of the third semester which runs from mid-August through mid-December, to present new results); 3. publication (write a first draft of a research report by the end of the third semester, advisors recommend an appropriate publication venue depending on the significance of the research results; each student then polishes this paper for submission and writes an undergraduate honors thesis based on the research (the writing will be completed during the follow-up semester). Both the thesis and the polishing of the paper occur during a fourth semester (without NSF support but most will be supported through other funded projects) which is not part of the twelve months, but which ensures that the student does not cease involvement in research and publication activities after the twelve months with the GAUSS project.

II. Details of Activities

A. Course Descriptions

Our existing curriculum in computational mathematics provides an ample opportunity for students to acquire knowledge in applied mathematics and computer sciences. However, without the exciting and understandable motivating examples, it is hard for students to see the connection between the theory and real world application problems. GAUSS develops new courses as well as update existing courses. In the required course work in GAUSS, students acquire a solid foundation in the theory and practice of programming, mathematical modeling and simulation, and numerical algorithms. They also master elements of computer vision and imaging science. These courses prepare students to understand recent research papers on their chosen research topics.

Numerical Methods for Computational Sciences This is a new course to replace an existing course *Numerical Calculus*. It serves as the introduction to numerical analysis in GAUSS. Covering the traditional topics and error analysis, this course puts emphasis on the modern research tools and methods in numerical computation. In particular, iterative method for solving linear systems, eigenvalue problem, singular-value decomposition, finite-difference scheme, and interpolation and approximation of functions are discussed. This course uses Matlab and C. In addition to the topics mentioned above, some key ideas of parallel computation in a shared memory environment and in a distributed memory paradigm are introduced through the introduction of adaptive quadrature and matrix multiplication.

Mathematical Modeling, I This is the updated and restructured version of an existing course *Mathematical Modeling*. We add more computational components and emphasize issues and practical problems in computational mathematics. Students are trained in (1) the procedures and strategies on how to transform a real world problem into a mathematical one, (2) how to analyze the problem numerically and analytically, and (3) how to find a solution numerically and analytically. The course serves as a platform for students to see various applications of mathematics in image analysis, bio-imaging, bioinformatics, finance, and telecommunication. The course uses discrete models and be based on difference equations.

Mathematical Modeling, II This new course on mathematical modeling treats more advanced problems at a higher level. Based on the discrete models in the first course, this course treats (1) continuous models using differential equations, and (2) statistical and probabilistic models. The main applications include video analysis, optimization and optimal control, mathematical biology, and fluid mechanics. The course is project oriented. It prepares students for different research fields in applied and computational mathematics.

Weekly One-Hour Seminar This will include presentations by the faculty mentors on various research topics. The students repeat the material in more depth during the first three summer weeks. The seminar also includes introduction to many current mathematical and computational tools from image analysis, pattern recognition and machine learning, statistical computing, bio-imaging, and numerical optimization. All these topics are presented with numerous applications from real world problems.

Advanced Computer Vision In this new research topics course, recent computer vision papers are discussed. Students report on their assigned research papers with short summaries on the good and week points, old and new ideas, etc. More importantly, students are required to implement two papers, to reproduce the numerical results given in the papers, which requires an extensive programming experience of building *complete* systems that combine many different program components. This is a course that transforms GAUSS students from novice programmers to experts.

B. Sample Research Projects

This section briefly outlines some example research projects for GAUSS participants.

Based on the various research backgrounds of 9 faulty mentors from mathematics and computer science, our GAUSS project has the luxury to allow students choose from a large pool of research problems. Faculty mentors present the research projects in seminars and students have the freedom in selecting among these projects that best fit their ability and interests rather than have one assigned to them. This approach has proven successful with our past experience working with undergraduate students.

1) Distributed Compressive Imaging: We investigate the most recently developed techniques of sparse recovery (also referred to as compressive sampling) and its applications. Mathematically, a finite digital signal or image is equivalent to a vector in a finite dimensional space. It is a common task to recover a vector $\mathbf{x} \in \mathbb{R}^d$ from a number of its linear measurements in the form of linear filters: $y_1 = \mathbf{a}_1^T \cdot \mathbf{x}$, $y_2 = \mathbf{a}_2^T \cdot \mathbf{x}, \cdots, y_k = \mathbf{a}_k^T \cdot \mathbf{x}$ where $\cdot$ denotes the inner product operation. When the dimension d is bigger than the number of observations k, in general, it is not possible to uniquely determine $\mathbf{x}$ from its observations $\mathbf{y}$. During the past few years, *sparse* recovery has been shown possible to recover the *sparsest* signals uniquely by using the l^1 linear and convex programming techniques ([7]-[14]).

One GAUSS participant, Chris Huff, studied the problem of using the sparse recovery idea in compressive imaging for distributed imaging sensors. Distributed Compressive Imaging offers joint image compression/reconstruction from imaging sensors which have overlapping fields-of-view. When viewed as a composite image sampling mechanism, a network of imaging sensors need only to transmit dramatically less data than current technologies while maintaining or surpassing image reconstruction quality of the underlying scene. Numerical experiments were designed and performed to emulate the scenario where 25 cameras are taking independent samples of sometimes overlapping regions of the same scene. It is also assumed that there is no communication between the cameras and none of the cameras samples the full region of interest. Under the constraint that only a limited numbers can be transmitted by each camera, he demonstrated that the distributed compressive sampling/imaging outperform the traditional compression and reconstruction method. He will present his research result at the forth coming Annual meeting of SIAM in June.

2) The tracking and counting of mitochondria: Two students, Devina Shiwlochan and Tyler Gomez, worked on the problem of couting and tracking mitochondria as posed to us by researchers ([4]-[6]) from the UCF College of Medicine. The difficulties lie in the low quality of the image sequences. They applied the standard methods in image analysis like edge detection and components labeling as well as the recent idea based on diffusion maps ([15]-[17]) to count the mitochondria in asingle image and used Hough transform and the level sets method (see, c.f., [3], [21]) to track the mitochondria in a sequence of images. A Matlab routine will be handed to the College of Madicine by the end of the spring semester. The methods and algorithms have been tried on synthetic image sequences and showed acceptable performance. A future research task will be to improve the method for the real mitochondria data set.

As a by-product, Devina also analyzed the diffusion maps methods in the detection of 2D orientation ([17]). Her analysis will explain in theory as why the diffusion maps methos can extract the orientation parameter.

3) Optical rouge waves: Rogue waves, or extreme waves, are large amplitude, anomalous waves ([19]). With the observation of rogue waves in oceanic sea states modeled by the Nonlinear Schrdinger equation (NLS), the natural question is whether they can be observed in other systems modeled by the NLS. Recent physical experiments by Solli et al. ([18]) in 2007-2008 have shown that rogue waves can be observed in optical systems. GAUSS participant, Maria Boak, further studied the properties of optical rogue waves through numerical experiments with a generalized NLS to model various nonlinear fiber systems. The propagation equation she considered is a generalized NLS with added dampening. Here she is considering the anomalous dispersion regime, where the refractive index decreases with increasing wavelength.

4) Nearly structure-preserving algorithms for perturbed multi-Symplectic PDEs: Laura Norena worked on structure-preserving algorithms in the numerical solution of multi-symplectic PDE's. There are many prescribed laws that are preserved for multi-symplectic equations. Her work is to analyze the behavior of equations that do not follow this form. The very well know Preissmann Box scheme ([20]) was used to solve the equation. She compared the Preissmann Box scheme and the splitting method, i.e., composition of flow maps. Linear KdV-Burgers equation was the particular example used for all calculations. This equation follows the multi-symplectic laws only when the parameter $\varepsilon = 0$. The energy relation of the equation has also been analyzed.

5) Optimization of Some Behavioral Portfolio Selection Problems : The paper [25] formulated and studied a general continuous-time behavioral portfolio selection model under Kahneman and Tverskys prospect theory ([26]), featuring S-shaped utility functions and probability distortions. One of the GAUSS students, Leon Guerrero, studied the discrete-time version of the behaviorial portfolio selection model. He used several classes of S-shaped functions and formuklated the problem as a optimization problem. Numerical simulation is used to gain insight as well as for the demonstration of the method.

C. Project Schedule

Orientation

About two weeks before the New Year, students selected for the upcoming twelve month GAUSS project are brought together for a workshop in which they are able to meet all the faculty mentors. Basic rules are laid out. Textbooks, laptop computers, software, and office keys are also distributed.

Spring Semester

All participants will take: (1) Numerical Methods for Computational Sciences and (2) Mathematical Modeling I as part of their regular program of study. All participants also attend the one-hour weekly seminar.

Week 1 – Week 3, Summer Semester

During these three weeks, the faculty mentors and senior personnel provide intensive lectures and tutorials on the details of the common core background for the research topics.

Week 4 – Week 5, Summer Semester

During this period, various possible research projects are discussed. Each participant are asked to select a project. Sufficient background materials are provided to students to ensure a productive and smooth start on their projects. Our proposed research topics are presented so that the students work in teams addressing different components of larger systems.

Week 6 – Week 14, Summer Semester

Throughout these nine weeks, the participants meet their research advisors regularly each week for guidance on their chosen research topic. They prepare a presentation on their progress during the past week. The presentation is about fifteen minutes and sketches out progress made, delays encountered, dead-ends run into, help needed, and plans for the next week. At the end of the presentation, each participant should expect to get feedback comments and assistance from the faculty mentors and any other research advisors, the graduate students assistants, and most importantly from their peers. This management structure facilitates knowledge-sharing, group bonding, and solutions to most practical problems related the research. Also, the peer support factor and the public reporting keep the participants motivated to ensure that they have something to report each week.

By the end of Week 8, they should be prepared to write an outline of their proposed research project. Some participants also possibly have conducted initial analytical analysis, started numerical experiments, and obtained initial results.

Week 9 – Week 14

During these weeks the participants are working hard to make progress on their projects.

Fall Semester

By this time, participants should have some preliminary research results. The weekly seminar is used to reinforce their knowledge and provide a chance to report their research status in order to improve their research results. All GAUSS students are required to take (1) Advanced Computer Vision and (2) Mathematical Modeling II. During this semester, the GAUSS student also proceeds to write up a draft of a research paper. The end of this semester marks the official end of GAUSS, but the student continues in the following ("follow-up") semester to polish the paper for submission and to write a honors thesis (without NSF support).

D. Poster Presentation

In the required follow-up semester, each participant prepares a conference-style poster from their most recent presentation, and participates in the University-wide Undergraduate Research Symposium, to which dignitaries and local industry leaders are invited as judges to select the best research work done by a undergraduate student.

Last year, five students participated in the NSF funded Cha Cha Day conference for undergraduate and graduate students in Applied Mathematics by presenting their research projects in posters during the conference.

E. Distinguished Speaker Series

UCF conducts a Distinguished Speaker Series in both Mathematics and Computer Vision, as part of its commitment to excellence. As part of this series, world-class researchers speak at UCF each year, and spend two days on campus. All GAUSS participants are invited to meet with the speakers in an informal discussion session where the GAUSS participants are free to ask seek advices on their research.

In the spring of 2009, as the first distinguished speaker, Dr. R.R. Coifman of Yale University visited us and spent a whole day with GAUSS participants, making suggestions and providing advice to each student. Dr. D. Geman of Johns Hopkins also visited us and, in addition to the regular talk, he also gave a "career talk", using his own life experience as a student and as a researcher to inspire the students to strive for excellence in their study and research.

F. Professional Development

Attendance at professional meetings gives undergraduates exposure to well-known researchers in the field, provides an opportunity to see polished and less-polished research presentations, and allows students to assimilate the latest research results. All of the GAUSS participants attend at least one professional meeting to present their research results. In addition, important research findings will be submitted for publication.

Last May, all GAUSS participants are taken to the International Conference on Computer Vision and Pattern Recognition (CVPR 2009) in Miami, FL. This is one of the highest level international conference in computer vision. All students, as observers, participated in lectures, workshops, and poster sessions.

In the August, five students attended the three days National CSUMS Conference held at St. Paul, MN. Each of the five students gave a twenty minuets presentations to share their research experience with students from other CSUMS programs. These are all their first professional presentation! Due to their intensive training in the summer's seminars, all of our students earned praise from other students and faculty and they realized that the hard work in the summer research paid off.

G. Social Events

Our motto is: *if you work hard, then you must play even harder.* To ensure that this message is not lost in the midst of all the scholarly activity, we have included many social activities including lunches with the faculty mentors, field trips, and dinner parties for any graduating Ph.D. students from Mathematics and the Computer Vision Lab. These social events also provide the faculty mentors the venues to continue mentoring in non-scholarly aspects of the profession.

III. Concluding Remarks

We have described the details about GAUSS, the NSF CSUMS program at UCF. Our GAUSS project has a cohort of 10 participants per year. The key distinctive elements of our approach are (1) to have a full year training in carefully designed course work so that the participants can master the mathematical and computational fundamentals, (2) to engage each participant in a meaningful research project integrated into the year-long program, (3) to present each participant with several possible project topics, so that they can feel they have chosen a project which is most interesting to them, (4) to immerse the participants in the general research environment essentially as if they were graduate students, and (5) to develop the participants' skills in communicating scientific ideas in writing and oral presentations through writing journal papers for publication, giving routine seminar presentations, and presenting at the professional meetings.

As we are preparing this article, we have just worked on the GAUSS project for a little over one year. We are in the process of finishing the assessment and we plan to report our findings in the near future. One thing we are doing differently this year is that we are presenting research topics in the spring seminars to expose students to research as early as possible. In this way, (i) we can adapt our courses toward students' research areas by treating the necessary background materials in Math Modeling I and Numerical Methods courses, and (ii) students will have more time to work on their research. We have found that students were eager to select their research topics and this involvement in research helps them be more motivated and focused in their studies.

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