COMSOL in the Academic Environment at USNA

Kevin L. McIlhany[1], Reza Malek-Madani[2]
[1]Physics Dept. U.S. Naval Academy, [2]Math Dept. U.S. Naval Academy

Abstract: Academic usage of COMSOL for student use has only begun in the last five years at USNA. Student involvement comes in four types, course-wide usage, focused course related work, student projects and semester-long research projects. A summary of how COMSOL has been successfully used at USNA will be given, showing examples of student work, with topics ranging from acoustics, fluid dynamics, pde solutions, mechanical engineering samples as well as electro-magnetics calculations. In each case, a brief description of the results, difficulties and suggestions will be presented. Overall, using COMSOL in education needs to be addressed for the sake of education itself. How easily do students work with COMSOL? Is COMSOL a substitution for performing calculations in class? How well coupled are textbooks to examples using COMSOL? Are new approaches to teaching PDE's available due to access to solvers, such as COMSOL? Do simplistic models in COMSOL translate to better learning?

Keywords: Education, Students

1. Introduction

COMSOL in the educational environment is in a developmental phase. The program is a leader in the field of computational modeling, yet certain qualities can make a program more desirable to one community over another. In the case of COMSOL, the community which has been targeted in the past has been the finite element modeling groups centered around mechanical engineering, electro-magnetics, and fluid dynamics. These traditional fields have a rigorous set of problems that determine how well a modeling program performs. COMSOL exceeds at the functionality offered by a broad toolset which allows multi-disciplinary studies to be made.

The academic environment differs from research and engineering in significant ways. The goal is the education of students – both new and advanced. This paper will outline the experiences gained from using COMSOL as it has been successfully used in the academic environment. Based on observations made from faculty and students alike, suggestions will be presented which could lead to an "Educational Module" for COMSOL.

1.1 The Academic Environment

COMSOL could be used in a number of formats which are commonly found in math, science and engineering (MSE) courses. Ideally, COMSOL would be the centerpiece of an entire curriculum based on using COMSOL to expose students to the value of modeling and to verify the nascent ideas formed in previous semesters from more traditional, theoretical courses (math, physics, chemistry). Following such a course, using COMSOL as the basis for a senior thesis (undergraduate) or as a tool used as a significant part of a graduate thesis would be an ideal transfer from the textbook, to computer model, to simulation, to validation to end result. All of this would be ideal, yet currently un-realized.

Picking this approach apart, piecewise, reveals where COMSOL's strengths and weaknesses lie at present. Modes that COMSOL could be used are (roughly):

- **a)** Used by faculty as the *centerpiece* of a classes curriculum (semester long)
- **b)** Used by faculty as a *demonstration* of a model discussed in class (briefly or frequently)
- **c)** Used by students as a *module* within a class (short-term)
- **d)** Used by a student as *part* of a research project (short-term)
- **e)** Used as the *centerpiece* for a student research project (semester or multi-semester long)

At present, faculty at USNA are employing COMSOL to varying success as described by methods b), d) and e) and recently c). A full course centered around COMSOL (a) has not been attempted yet, though efforts are underway to build such courses, where COMSOL serves as more than 33% of the course's curriculum.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **OCT 2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**

4. TITLE AND SUBTITLE **COMSOL in the Academic Environment at USNA**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **United States Naval Academy,Physics Department,572 Holloway Rd,Annapolis,MD,21402**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Presented at the 2009 COMSOL Conference Boston, 8-10 Oct, Boston, MA

14. ABSTRACT
Academic usage of COMSOL for student use has only begun in the last five years at USNA. Student involvement comes in four types, course-wide usage, focused course related work, student projects and semester-long research projects. A summary of how COMSOL has been successfully used at USNA will be given, showing examples of student work, with topics ranging from acoustics, fluid dynamics pde solutions, mechanical engineering samples as well as electro-magnetics calculations. In each case, a brief description of the results difficulties and suggestions will be presented. Overall, using COMSOL in education needs to be addressed for the sake of education itself. How easily do students work with COMSOL? Is COMSOL a substitution for performing calculations in class? How well coupled are textbooks to examples using COMSOL? Are new approaches to teaching PDE's available due to access to solvers, such as COMSOL? Do simplistic models in COMSOL translate to better learning?

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**10**	

From a brief survey done by the authors, seven faculty over the last five years have worked with ten students on semester and multi-semester long projects using COMSOL significantly. Additionally, five more faculty use COMSOL, either for research or as beginners. These additional five might convert their experiences into the classroom in the future. Only one course (Computational Physics) currently employs COMSOL for student usage during a four hour sequence. Another course uses COMSOL as a demonstration of oceanographic models. In both cases, the level of exposure is short-term and largely serves to expose students to the possibilities that COMSOL and modeling present.

True to COMSOL's nature, the faculty involved span the following departments: math, physics, mechanical engineering, electrical engineering and systems engineering. Typical stories from these faculty begin with COMSOL being enthusiastically used as part of their research. Inevitably, COMSOL is compared to existing software in each of their fields and found to be a unique approach, seen as an extensive tool with more capability than most know how to fully use. As the faculty become familiar with COMSOL, the question looms, "Can I use this (COMSOL) with my class?".

2. Winning the Hearts and Minds – Well, Mainly the Minds

How can COMSOL be more successfully *brought* into the classroom? The heart of academic development is driven by faculty interest. Literally, as the authorities in their respective fields, the faculty bring to the university the knowledge and relevant topics of the fields in which they specialize. COMSOL has certainly caught the interest of many faculty. The question remains, what needs to be done in order to help a faculty member decide to move their experiences with COMSOL in their offices/lab into the classroom?

2.1 Ease of Understanding and Use

A strength and simultaneously a weakness of COMSOL is its breadth. Even though multi-disciplinary studies have been in academia for 10+ years, faculty in universities are slowly moving in this direction, and only for certain specialties, where the need is over-whelming. As such, most faculty members are experts in their fields and pseudo-experts in neighboring fields and just plain neophytes in other fields. When building a model, one tends to start in the field of study where one is most comfortable, then slowly add components that are more distant from ones level of expertise. At least in practice, this is the hope. Starting out blindly building a model seems like a path to frustration.

This suggest that the first users of COMSOL that require an education are the experts themselves! As soon as one branches out from the comfort zone afforded by years of experience, you become a student again. As faculty members become more and more comfortable with the results produced by COMSOL, they will be more likely to bring that experience into the class.

As a testing bed, working with one or two students at a time on a project long enough to give the students time to become competent users themselves serves as a buffer zone to the classroom. The current class at USNA using COMSOL as a short module typically is a smaller class (five students on average). These students tend to be well-motivated and advanced. Full classroom participation (24 students), where the course is mandatory, brings students with varying talent and motivation to the scene. When this happens, the social dynamic of the classroom changes entirely, leaving little room for faculty error in the eyes of their students. This is the basis for any reluctance faculty have to bringing new material into a class. When education works well, it's great. When conditions are less than optimal, even just a little, students' attention can wander and the impact of the lesson is compromised. By keeping students exposure to COMSOL limited, much of these concerns can be eliminated. Alternatively, by fully exposing small groups (1-4) of students to COMSOL over at least a semester, the chances for success is greatly enhanced. At USNA, after five years of using COMSOL with a growing number of faculty, we are slowly stepping out of the small groups level and into the full course level. This process still has years of development to go in order to become a standard part of the educational experience – based on the reasons given above.

2.2 Typical Research Project

As most of the examples of success at USNA have focused on research projects, a typical breakdown of a semester is given below:

a) Introduction to the problem (2 weeks)
b) Introduction to software (2 weeks)
c) Project begins (really)
d) Debugging initial model within COMSOL (2 weeks)

e) Questioning the model results (1 week)
f) Re-design of models (2 weeks)
g) The Grind (remainder of semester)
h) Presentation of results (talk/paper/poster) (1-2 weeks)

Semesters at USNA are 16 weeks long, so over half of the semester (9 weeks) is spent getting the students to the point where serious work can begin. The quanta of students feedback tends to be two weeks. This length of time is what is needed for a student to find time to experiment with the model both on paper and on the computer and then "get back" to the faculty with any questions or insight. Despite appearances, this is a fairly aggressive schedule for an undergraduate student. For a graduate student, the tendency is to push them in the deep end and then tell them to swim. Luckily, COMSOL offers excellent tutorial sessions around the country, which helps alleviate more advanced problems that students and faculty come across.

From experience with COMSOL, once a problem has been properly cast, usually at the level that an expert can understand the issues, COMSOL technical support has been superb. When dealing with educational issues, most students do not know how to pose problems well, so they ask questions of a very different nature. As faculty, we need to ensure that we can answer their questions, no matter how ill-posed. This requires of the faculty, enough knowledge of COMSOL that they can discern between a problem the software has with a models' ill-posedness versus a simple bug/typo. Finally, as faculty, one needs to be able to assess the results from a model for its educational impact. Cool graphs simply don't cut it. The results must be meaningful and easy to interpret in order for both students and faculty alike to understand and evaluate.

3. Examples of Student/Faculty Output

A brief description and figure will be shown for several projects which have had significant COMSOL usage.

3.1 Chesapeake Bay Normal Mode Analysis (NMA) – 3 Semesters Long

The first project started as far back as Femlab v3.2 by calculating the eigenmodes of the Chesapeake Bay. This single project continues to present day and is nearing completion (calculating a power spectra versus time for organic structures). For COMSOL, this project is a simple 2D eigenvalue problem. Due to the complex nature of the boundary, COMSOL was compared against a home-grown finite-difference code. For Dirichlet boundaries, agreement of eigenvalues with COMSOL was within 3%. For the Neumann modes, the disagreement was a high as 20%. In this case, COMSOL was deferred to, however, no cross check has been attempted against different code. Figure 1a) shows mode 98 for the Dirichlet boundary conditions – leading to modes exhibiting vorticities. The difficulty in using the normal modes calculated lies in how to integrate the limited data set generated from buoys and tidal gauges around the Bay. How many are needed for a complete set? For a complete description, see COMSOL 2005.

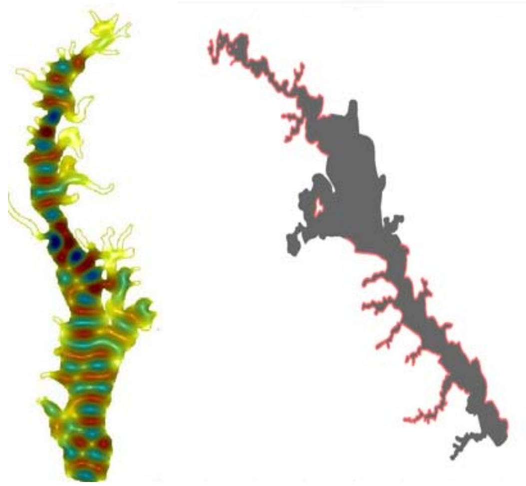

Figure 1. Eigenmodes of the Chesapeake Bay (mode 98). On the right, the mesh for the Severn River.

A follow-up study has begun of the normal modes of tributaries to the Chesapeake Bay, in this case, the Severn river. Linking the flow from tributaries to larger bodies of water is the point of interest. In each case, how modes couple will be studied.

3.2 Violin Eigenmodes – 1 Semester Long

The problem of eignemodes was again studied on the violin. In this case, data was readily available by scattering a Laser Doppler Vibrometer (LDV) off the back of a violin plate. About 100 locations were used to record the intensity of vibration as a frequency sweep was initiated using a speaker nearby. The violin resonates at specific frequencies with complex spatial modes called "Chladni patterns". A comparison to COMSOL eigenmodes was made. Ideally, a dispersion relation can be extracted by matching the model output with the data. Figure 2) shows the initial picture used to input the border which was used to calculate the eigenmodes.

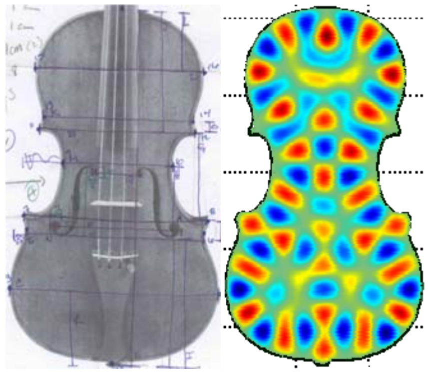

Figure 2. A picture (left) used to input the border of a violin into COMSOL, where the eigenmodes were then calculated (right).

3.3 Superconductivity – Electric Potential – Portion of 1 Semester Long Project

As part of a larger project, a geometric correction was calculated due to the solder joints on a thin metal film. By modeling the electric potential with current passing through wires, the resistance due to the presence of the solder joints can be calculated as a deviation from the potential without the joints.

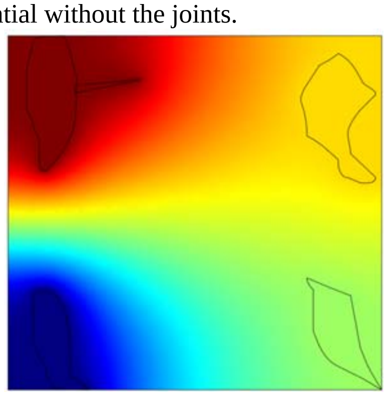

Figure 3. Superconducting plate with solder joints indicated.

3.3 Gas Electron Multiplier (GEM) - 1 Semester Long Project

Two conducting plates are separated by an insulator. A third conducting plate is located beneath the two. High voltage (2kV) is placed across the upper two plates. By drilling holes of a particular shape, a strong electric field can be made. In the presence of a gas, when high-energy particles pass by, the gas becomes ionized. Suddenly aware of the electric field, the free electrons begin to cascade from the upper plate through the holes to the lower plate. As they accelerate, they have enough energy to ionize more of the gas, which causes a cascade of charge accelerating through the gaps in the plates. The lower plate forms an image charge, which is then detected.

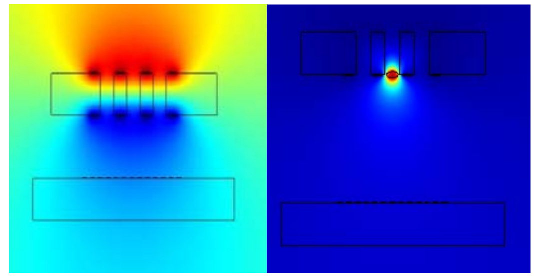

Figure 4. Gaseous Electron Magnification (GEM) detector design. The left figure shows the electric field calculated and the right shows the electron density at one point in time.

3.3 Acoustic Detection of Landmines – 3 Semesters Long Project

In cooperation with the Army, USNA has studied landmine detection from the back-scatter of acoustic waves. A loud speaker system is placed on a cart at a height of six feet. Sound waves ensonify the ground in front of the cart. A Laser Doppler Vibrometer (LDV) directs a laser beam at a location in front of the cart. Ground vibrations are measured by the LDV. If a landmine is buried near the surface, a resonance can be detected from the LDV response. Establishing proper boundary conditions far from the source was essential to modeling this problem well. The source is approximated by a delta function.

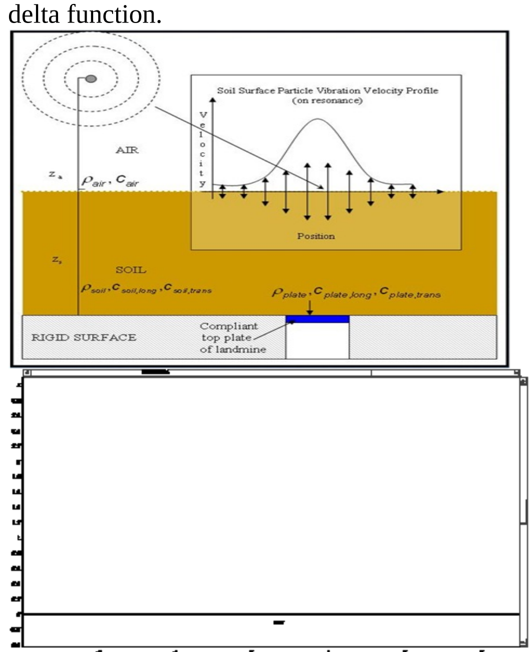

Figure 5. Acoustic Detection of Landmines – modeled as a point source (delta function) 2 meters above the ground near a buried landmine.

A LDV is used to indicate a resonance in the ground (porus media).

3.3 Acoustic Imaging of Scattering Centers – 2 Semester Long Project

COMSOL is used to model a plane wave formed from multiple speakers embedded in a wall. The sound is ultrasonic, at 40kHz, which corresponds to a wavelength of 0.86cm. For scattering centers of 1cm in size, diffraction will cause the plane wavefront to deform as it approaches the far wall, 30cm from the speaker wall. The far wall is instrumented with ultrasonic receivers. Data is collected by a National Instruments digital I/O acquisition card. The arrival times relative to the time of the start of the wave is recorded. The differing arrival times correlate to the deformed wavefront, which correlates to the position of the scattering center. Using the results from COMSOL, the arrival times and center's location are used to train a neural network to accurately return the position of a scattering center, given the arrival times of the receivers. By increasing the number of scattering centers from 1 up to 30, a complex structure like a human hand can be modeled as a "blob" of spherical scattering centers. The experiment should be able to acoustically image the human hand.

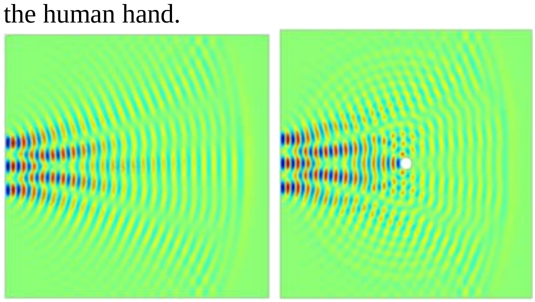

Figure 6. Acoustic Scattering Decomposition – in analogy to electron scattering, the diffraction pattern from ultrasonic waves off of hard scattering centers is used to determine position information.

3.3 Ocean Modeling – 2 Semesters Long Project

Various projects have used COMSOL to demonstrate fundamental models used in oceanography, such as the Stommel model as well as cavity driven flows.

In each of these smaller cases, one student was initiated to COMSOL over a semester-long project and given a simple real-world example to model. The purpose of the exercise was to provide instruction to the student into the output of FEA techniques, as they will be more and more often exposed to model and simulated data in the future. Once these one on one student projects were complete, they serve a different purpose.

From an academic perspective, in each of these cases, the usage of COMSOL was mainly for demonstrating a principle to the students for a larger oceanography class. In this case, COMSOL excels, as the expertise is in the hands of the instructor, yet an academic concept is illustrated via numerics/graphics. So, in the end, a few advanced students are taught to use COMSOL and work with the instructor to build a simple model. As a result, a larger group of students can later take advantage of the model as a teaching aid. Furthermore, telling the students that this model was built by a fellow student is important as it encourages them to reach for harder projects. Exposure to peer projects ups the standard for everyone.

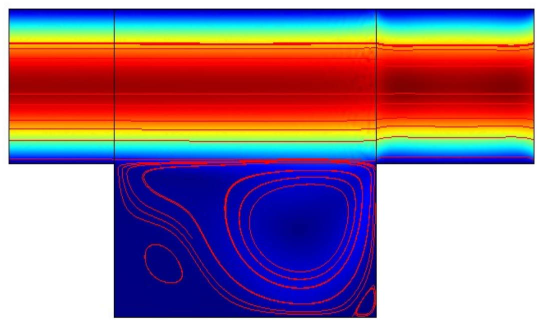

Figure 7. Cavity Driven Flow, where flow through the upper channel drives a cell in the lower cavity.

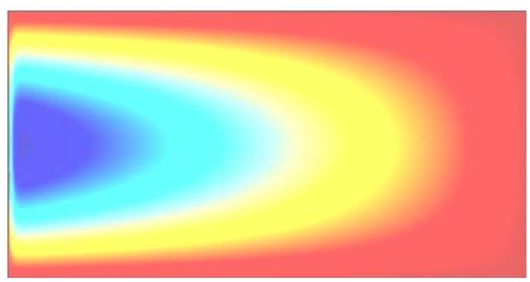

Figure 8. Stommel model of ocean currents. As the Earth rotates from west to east, the fluid resists due to inertia and appears to flow onto the eastern shows. Coupled with Coreolis forces, a convective cell is formed which is identified as the Atlantic Gulf Stream.

Other teacher/student projects at present at USNA not discussed in this paper include:

- Electro-mechanical "inchworm"
- Adhesive sandwich
- Severn river - eigenmodes

- Chesapeake Bay flow (3D)
- Micro-fluidic mixing - pressure driven
- Micro-fludic mixing - lid driven flow

4. Need for an "Educational Module" within COMSOL

Based on interactions with students as well as the logistics of classroom teaching, several things could be done to improve COMSOL and gear it towards education. If all of these suggestions were to be implemented at once, it would comprise enough changes to be considered a full module, and "Educational Module". In outline form, the module would provide the following changes/functionality:

- Re-introduce COMSOL *printed* manuals
- A user interface geared towards student use
- Place numerical limits within COMSOL to guarantee textbook solutions
- Presentation of results made specific for student use and teacher evaluation (assessment oriented)
- Educational model library of classic problems which align to a curriculum
- "Quizzing" capability to allow student based self-assessment as well as instructor generated classroom assessment.
- Ease of organic modeling – to help visualize the transition from Platonic solids (the abstract world) to the real world (organic)
- Addition of the "E" button – which cuts down the standard COMSOL interface to a much simplified interface with limited modeling options and specific output modes leading to faster execution overall.
- At least one book focusing on teaching COMSOL to undergraduates – hopefully more will follow.

4.1 Student's View

Each suggestion listed above stems from common problems faced in the classroom when presenting COMSOL to a class. Not to appear too critical, once indoctrinated to COMSOL, student reactions vary, but are generally very positive. The high learning curve pays off in the end. Typical reactions of students to COMSOL (I'm paraphrasing here):

- It's the greatest thing since sliced bread!
- It *SOLVES* my homework.
- Wow, this is hard.
- *What* does this do/mean?

Part of the reasons for reactions like this stem from understanding the environment that students find themselves in today. For instance, students today know computers well and have high expectations of their performance – any activity needs to be fast while booting up and fast in returning output. Further, students eventually need to be able to "close the loop" and be able to assess the validity of their own work in order for them to have a lasting and positive impression of COMSOL. Finally, once they have achieved some proficiency, students like to bring their own experiences to a project, so make this process easy (organic modeling). The abstract world of Platonic solids – although easy to teach with, does not resemble the world as seen through the eyes of children. They are presented with a vibrant, living, breathing planet. It takes years for scientists and engineers to acclimate to seeing the world abstractly. By introducing better modeling tools for "organic modeling", COMSOL could easily capture students imagination and help promote long-term interest in using the product as well as a new perspective towards looking at nature through equations and numerics. For excellent examples of organic modeling, consider the entertainment industries heavy investment in computer graphics and modeling. Packages such as Maya, Zbrush, Mudbox and others excel at this type of modeling. A simple "blob" modeler would be a major step towards this goal within COMSOL.

4.2 Faculty's View

From the perspective of a teacher, several obstacles immediately present themselves when teaching and using COMSOL. First and most important, students lose confidence in faculty performance when things do not immediately work properly. The infamous scrambling to get the program to do what we ask of it ("I got it, I got it, hold on…"), leads students to think that if it doesn't *seamlessly* work for the teacher, how it can it possibly be expected to work for them. Establishing student confidence in the teacher is essential for long-term usage of COMSOL in the academic sector. Consider whether a teacher will continue to teach using COMSOL if – after a bad semester of interactions – the ultimate goal is to instruct and *know* that students have learned new things by the end of the semester.

From a presentation point of view, faculty should be able to discuss the program without having to look at it. The workflow is important not only from a productivity perspective, it is a simple logistical issue. Lecturing while rigidly tied to a computer is difficult. Consider how COMSOL accomplishes this within its own mini-course presentations. Typically, a speaker is at the front of the room, while at least one more consultant is "floating" around the room assisting lost users. For most of us, it is just the students and me (no helper). The procedural issues of running COMSOL should involve as few steps as possible to get to an answer for instructional purposes. The interface should be intuitive for learning. As of 2009, when teaching a computational class, most faculty project their screen. Projectors today are still largely run at resolutions of 1280x1024 on screens typically 6-8 feet wide. This suggests that the projected interface should be presentable using LARGER FONT menus – easy to read from the back of the class.

Finally, if only to have something heavy to throw from time to time, **bring back the printed documentation**. While learning, being able to simultaneously look at a book while quickly looking at the screen for comparison, allows for quick clarification by the students when a question arises. Being able to reference the book allows the teacher to assign reading and helps reduce the laziness that students occasionally present by asking trivial or stupid questions that the book clearly can answer should they decide to read (yes! there are stupid questions). The COMSOL help system is extensive, but difficult to find precisely what you want if you do not know the terminology (and most students have not yet learned the vocabulary). An educationally based introduction to COMSOL would be a self-contained text with step-by-step instructions covering 15-20 classic examples showing the output as seen in common texts from other courses (like a differential equations or statics course).

4.3 Assessment

Assessment is the current buzzword in the educational research community and it is working its way from K-12 up to and beyond the undergraduate level. Being able to assess an answer for its correctness is a time-honored pursuit in education. Most of COMSOL's current user-base are experts in their respective fields and are already able to assess when COMSOL presents a correct (plausible) answer versus numerical garbage. Students cannot do this themselves. By presenting the textbook cases and modeling them using COMSOL, students and teachers alike can develop the self-assessment skills they will need to move onto harder projects.

At it's heart, assessment from the point of view of using COMSOL should allow *faculty to lead students through a model. When finished, ask them to predict a new answer and trivially have them demonstrate that prediction. If it fails to match prediction, the reasons* ***why it failed*** *should be easy for the faculty to interpret.* To this end, model outputs should be presentable in a familiar format – like graph paper. Model outputs should be easy to manipulate – sliders, knobs and buttons for various parameters could be created, not the convoluted tree-menu system currently employed in COMSOL v4.

Quizzes are a common tool for assessment. Faculty should be able to create windows for annotations, where they ask questions. For a specific parameter, define a region where the correct answer should lie. Asking a student to predict the answer could be as simple as having them place a slider at a location for a given variable, then have the "Quiz" mark how close they are to the correct answer. Collecting quiz results would follow. Used in this manner, COMSOL serves several purposes. First, COMSOL is used as a modeler of problems. Once the model is finished, COMSOL now serves as a simulation of the model. Students provide new inputs, COMSOL provides new answers. The feedback loop of seeing a proper answer from COMSOL then followed by a proper guess from the student for a slightly different parameter gives the student confidence and hopefully "closes the loop" within the mental framework that is being developed in the students brain. Keep in mind, this is a new paradigm to learning, beyond the textbook. Computers today are just becoming fast enough to have true model/simulation based learning take place. For most of the expert user-base of COMSOL, this idea has taken us most of our professional careers to develop, as we patiently waited for the technology to gain speed. Imagine how our students might be able to envision new problems and solutions should they develop this skill earlier in their careers rather than later. **That** is the reason to pursue the "Education Module" within COMSOL. It isn't about teaching, or even learning, it is about creating new students with a genuinely different perspective than the one we had 10 years ago.

Of course, this new approach is coupled to an ancient fear that as we improve our technology, our children will become idiots. Clearly, calculators poisoned my generation as I never enjoyed using a slide-rule. This next generation will be able to enjoy programs like COMSOL that – once properly set-up – can simply solve textbook problems that used to take one week in graduate school. It is incumbent on the academic sector to make sure that they don't miss the point and also understand the tools they are using. Just to be clear, how many readers of this paper fully understand the inner workings our their favorite calculator? The chips? The CPU? Don't judge the new generation too quickly.

4.4 The Educational Module

Putting the above suggestions into one pot leads to the creation of a new “Educational Module”. The implementation of this could be as simple a having an “E” button located somewhere in the interface. In this manner, experts can simply ignore it or not even install it. For teachers, simply fire up COMSOL and press the “E”.

A new interface opens. Immediately noticeable is much fewer options are available. The screen is formatted to work properly with a 1280x1024 window. The fonts are large enough to be clearly seen from 30' away from a 6' projected screen. The interface is streamlined to present the workflow clearly – similar to COMSOL v3.5, where the Model/Physics/Mesh/Solve/Evaluate sequence is returned in button form. Under modeling, focus on 2D platonic solids, free-hand drawing of boundaries as well as introduce a “blob” modeler. Also, provide the ability to import a jpeg/pdf image and extract the edges to provide an outline for a geometric structure. When modeling in 3D, take cues from the entertainment industry, and provide a 4-window layout (x-y, y-z, z-x, perspective) as well as provide building constructs similar to products like Sketch-Up, Maya or AutoCAD. An extensive library of pre-built models would include all of the Platonic solids, combinations of Platonic solids of varying complexity (think snow-flakes or jewelry) as well as pre-built common items like swing-sets, car tires, house (simple), stick figure (mannequin). Finally, add a few complex models into the library, such as anatomically correct humans (censored or not).

For the Physics section, limit the number of options so that COMSOL can always find a solution. By limiting the equation set and boundary condition enough, numerical stability could be guaranteed. This provides a streamlined modeler that cannot fail and should be significantly faster due to the limited solution set available. Similarly, limit the solution choices to the best known techniques. It is important to expose the students to which techniques are being employed, but not overwhelm them with so many choices that they cannot possibly choose at that early stage in their learning. In this manner, they can develop their vocabulary about how a model was solved and which techniques are used, allowing them future opportunities to learn the specifics of a particular technique and try it in the full version of COMSOL.

For the Results section, a clear presentation of a model's answer should not challenge the user – both student and teacher alike – to properly interpret the result. Projections in x-y, y-z, z-x simultaneously with gridlines in the background, make the results an approximation to graph paper, something familiar to students. Data visualization takes years to mature within professionals. At the outset of learning, students need to be able to grasp what they are seeing so that they can evaluate its correctness trivially. Each model provided in the library could have a set of pre-built answers that the instructor can lead the students through, so that as simply as possible, the student can watch a model be solved and presented with a reasonable, correct answer. Then, as the students vary parameters of the model (which should be very limited), they can try to predict the model behavior and gain trust in the result/technique/concept.

Throughout the entire “E” module, the presentation of parameters can be streamlined as they should be a limited set by design. In this case, each parameter could be set using a slider interface. Figures 9 and 10 illustrate the proposed sliders. This slider has many features useful for teaching. Set points at each end can be adjusted to set the minimum and maximum values allowed. Further set-points could be allowed between the min/max points, which further breakdown the allowed domain of the parameter. An “answer” slider could be made which represents some metric used by the model. As a type of quiz for the student, they could be asked to click on the slider *where* they think the answer will lie and then run the simulation.

Figure 9. A slider for use in setting parameters, with the green set-point indicating the minimal value and the red set-point the maximal value.

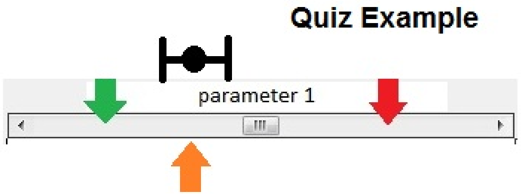

Figure 10. A "Quiz" slider, where the student indicates their answer by placing the orange marker where they predict the answer lies. After entering an answer, the slider presents the correct answer and its range.

5. Statistical Assessment within COMSOL

For advanced classes, once familiarity with using COMSOL has been established, the harder issue of understanding modeling systematic errors can addressed. Version 4 has made great strides towards this end, but more can be done. Consider a model with 5 main parameters that can vary. A parametric study can be done, however, even scanning each parameter over a course set of 10 values would result in 10^5 different configurations of the model, and would take COMSOL a *while* to finish. Furthermore, simply obtaining model outputs are not enough, assessment of model outputs is essential and not being taught at present. Often model results need to be “Monte Carloed” (MC) in order to establish the full statistical data set needed for error bars to be properly assigned. As part of the “E” module suggestions, a new slider has been proposed which impose limits on the domain of that particular parameter. Why not expand the sliders capability by adding a “Monte Carlo” aspect to it?

Specifically, while right-clicking a parameters slider, one of the options could be “Monte Carlo” (MC). Once selected, a small screen pops up above the slider. In that screen, the user can draw (with a mouse) a distribution function, which represents the statistical distribution being sought for the values of that parameter. Using either a rejection method or an inverse functional approach, the slider now can generate a set of values for that parameter. Once the MC is initiated, COMSOL first generates a set of values based off of the distribution drawn, then proceeds to solve the model much like batch jobs of old. This process most likely would take hours if the model is complex, but for simplistic student models, this could go quickly (~1-2 minutes). Once the slider has been selected for use by the MC, the slider itself sets the number of values to be generated in the histogram. Figure 11 illustrates the proposed MC slider.

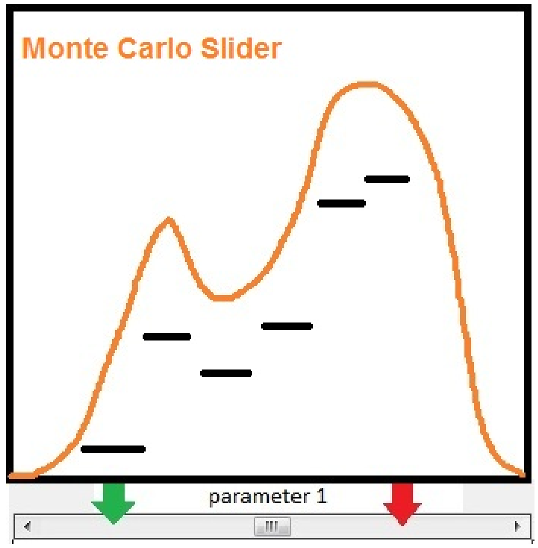

Figure 11. The proposed Monte Carlo (MC) slider. A drawn distribution indicates the set of values obtained, and the slider now represents the population of the sample.

Adding more variables to the MC is simple, simply right-click and select. However, a second choice becomes available, once more than one variable is generated by the MC. The choice is whether to couple the distributions together or not. For two distributions (parameters), there are multiple ways to meaningfully couple them, including, simple addition, multiplication, convolution (both additive and multiplicative) as well as creating a generalized probability distribution f(x,y) based on the values of the two parameters. As more parameters are added to the MC, the batch time clearly goes up. Also, some thought needs to go into how the multiple distributions interact. The rejection method is sometimes employed where a condition is set by when a member of the statistical set is either accepted or rejected based on a constraint in the system.

Although clearly adding complexity to the simulation process, what is gained is far more valuable and worth the additional effort. Once the batch set of simulations is complete, a screen showing multiple cross-sectional views of the metrics of simulation clearly expose where the model sensitivity is in the parameter space. This is the golden goose sought after in many projects. For classes advanced enough, a further Kolmogorov-Smirnov test could be employed to examine the models sensitivity quantitatively. Further analysis using Principle Component Analysis (PCA) or other techniques could prove useful. This feature alone could require a new module to be created, the "Monte Carlo" module, which would couple nicely to the Optimization module.

6. Conclusions

This paper was presented at the 2009 COMSOL conference in Boston. At the time of writing, version 4 was not available and the authors held-off submission as several issues brought up in version 4 appear to address some of the suggestions of this paper. With one year passing since version 4 was released (now at v4.1), the need for the "E" module is still apparent. Luckily, many of the features introduced in version 4 will facilitate the building of the "E" module, however, some in-house coding will also be necessary.

Unfortunately, some of these suggestions do not appear to be viable after version 3.5a. For instance, students do not like to work between two different programs. For them, running two programs in conjunction seems inefficient and cumbersome. Although it is just a suggestion (wish) at this point, make COMSOL a one-stop shop for all of these "E" needs – make sure that no other programs are necessary to learn as students view this as bad. Add basic image processing so that organic structures are easy to import. If possible, add sound input (for FFT) and output (based on power spectrum) capability (thank you v4!). If possible, allow the user interface to be user-definable (thank you v4!). This would allow user created "themes" that can be loaded to create different interfaces. Allow for a user creatable presentation mode (like a powerpoint slideshow) taking the user through a module. This also allows students to present their answer to the class without having to go outside to Powerpoint or some other program.

5.1 Should COMSOL invest in Education?

I am biased. I teach at a great school with outstanding students. Still, a casual glance at the news these days is telling a new story about society. More and more decisions are made based on modeling/simulations (more than engineering – social and political policy making as well). Our students *deserve* the education they **need** to be a part of that process. The issue at stake is nothing short of developing a new mind-set (user base) towards PDEs and modeling. This is a current and pressing issue in education driven by the technology of today. If we do not advance our students using all of the tools available, who will?

The job market is sensitive to this issue as well. Students who learn a specific program find transitioning to the workplace easier if they support that software (Ideas, Solidworks, Ansys, RealFlow, COMSOL…) As more students graduate with COMSOL experience, they might *drive* the need for industry to support **their** skill set. Many problems have been solved historically by in-house code, which can now be solved with COMSOL. Students today will become the project leaders of tomorrow and they may show the older generation a better/easier way to a solution.

6. Education and COMSOL at USNA

In summary, to date at USNA, we have enjoyed success translating faculty driven research into student involved research using COMSOL. We have found that the longer the engagement, the better COMSOL is appreciated by the students. In the classroom, COMSOL is used to demonstrate models that are discussed in the text. **No** class has fully integrated COMSOL as part of its curriculum yet. The biggest success has been a small class and a two week "crash course" using COMSOL. A small group of able students have learned to pose problems well in terms of how COMSOL can address them.

7. References

1. Assorted professors, Private Communications (2005-2009)

8. Acknowledgements

Professors Burkhadrt, Cimpoiasu, Firebaugh, Malek-Madani, Mcilhany, Radice, Witt, contributed to the broader process of using COMSOL in one form or another at USNA and we thank you.