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Connecting Theory to Applications Through Simulations Using Industry-Standard Tools

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Rajesh Bhaskaran is the Swanson Director of Engineering Simulation in the Sibley School of Mechanical and Aerospace Engineering at Cornell University. His work seeks to promote the democratization of simulation through effective integration of industry-standard simulation software into engineering education. His vision is to create a new paradigm in engineering education by combining two disruptive technologies – simulations and online learning. He has helped introduce Ansys-based simulations into 17 Cornell engineering courses.

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Introduction

The vision undergirding this work is two-fold. The first is the democratization of simulation whereby every engineer is able to use industry-standard and other simulation tools effectively for analyzing and developing designs. The second is to pioneer a new paradigm in engineering education by combining simulation and online learning technologies to promote problem-based and project-based learning grounded in practical applications.

Democratization of simulation will enable design engineers and other non-specialists to leverage the power of simulation earlier in the design cycle leading to better products. There are two elements to help students learn how to apply simulation tools to solve engineering problems such as predicting the fluid dynamic forces on an object or optimizing the geometry of a part in a structure such as a wind turbine blade. First, students need to learn the requisite skills to navigate the software interface. This is the easy part since this can be done through self-paced videos which can be assigned as homework. In fact, students now can easily find online videos to learn specific aspects of the interface of most engineering software packages. Second, the educational ecosystem needs to better prepare non-specialists to combine the art of design with the science of simulation. It is not necessary for non-specialists to learn the details of the relevant math and physics since the simulation tool takes care of the nitty-gritty. However, it is vital for them to develop a deep conceptual understanding of the underlying fundamentals to avoid "garbage in, garbage out."

An oft-heard complaint from engineering students is that they are unable to see how the theory that they are learning is connected to practical applications. Simulation can help bridge the gap between theory and applications since it connects to both CAD and fundamental theory which usually are taught as different realms. A general framework to do this bridging -- using problem-based learning – has been developed and implemented in over a dozen Cornell engineering courses using industry-standard Ansys simulation software. This framework can be used with any engineering simulation tool.

Applications for which we have developed online learning modules using this framework include pressure vessel static behavior, wind turbine blade buckling, turbine vibration as well as turbulent flow over a car and an airplane. These applications have been developed with input from engineers at Ansys Inc. to ensure industry relevance. A couple of sample applications are shown in Figures 1 and 2. One can see from the figures that the geometries considered are realistic which in our experience can help students connect with the material since they can readily see the practical relevance. We describe below the framework, just-in-time problem-based learning based on it, implementation through online learning modules and assessment results showing the impact on student learning.

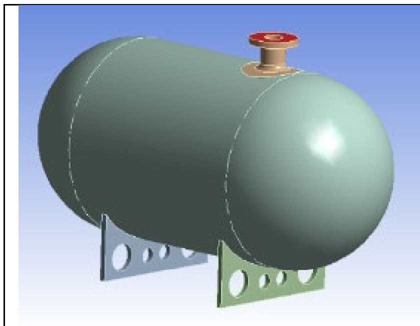

Figure 1: Pressure vessel example for learning static structural analysis using 3D elasticity theory.

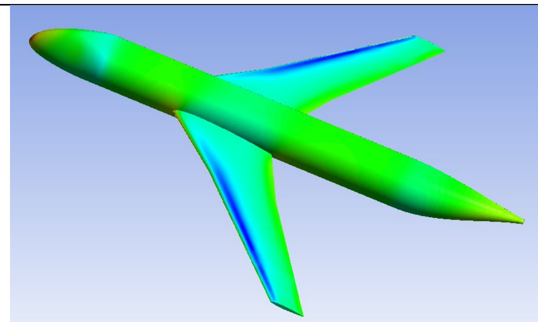

Figure 2: Airplane example for learning compressible fluid flow analysis by solving the Navier-Stokes equations.

What's Inside the Black Box

Any sophisticated simulation tool appears as a black box to the user who gives it inputs such as geometry, mesh, material properties and boundary conditions. The tool in turn provides outputs such as displacement, stresses and factor of safety in solid mechanics and velocity, pressure, temperature and shear stress in thermo-fluids. If the user doesn't understand key elements of what's inside the black box, this process looks like "garbage in, garbage out." These key elements have been identified and systematized using a backwards-design approach [1] by looking at the solution procedures for several examples from different subject areas. These key elements are organized into the framework shown in Figure 3. We refer to this as the black box framework.

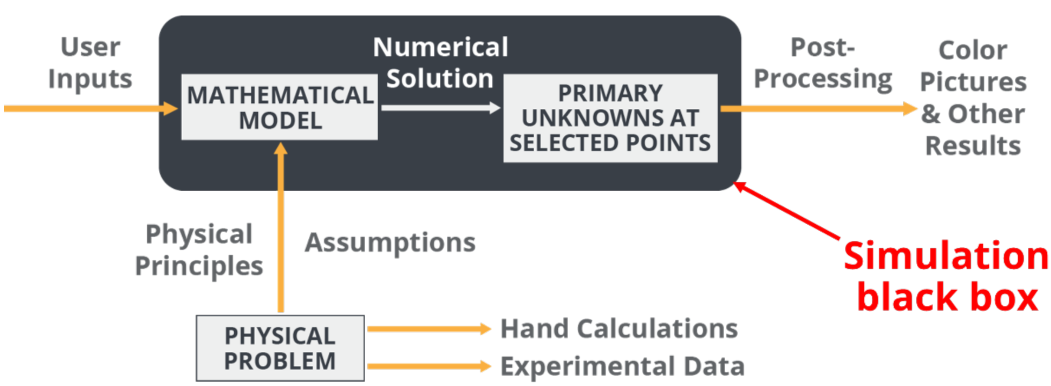

Figure 3:Key elements of the black box framework used to help students connect steps in the simulation software to underlying theoretical concepts.

The first element of the black box framework is the mathematical model of the physical problem being considered. In most of the applications considered, the mathematical model is a boundary value problem -- governing equations defined in a domain and boundary conditions defined at the edges of the domain. Other types of mathematical models encountered include initial value problems for time-varying applications, eigenvalue problems such as for determining the natural frequencies of vibration and minimization problems such as in optimization. So the most fundamental aspect of the simulation that the student needs to know is the mathematical model (or model for short); for instance, the governing equations, domain and boundary conditions as well as the chain of reasoning and assumptions used to develop the model.

The second element of the black box framework is the numerical solution of the model to obtain the primary unknowns at selected points (which are marked by creating a mesh as discussed later). The student needs to know the numerical solution strategy used to solve the model and how to minimize the numerical errors introduced. Here, it is necessary to cover only the big ideas such as discretization and interpolation since the details are taken care of by the simulation tool. A common source of confusion is conflation of the model and the numerical solution strategy used to solve it. Our framework helps overcome this by clearly distinguishing between these two aspects which are separate elements in Figure 3.

The framework's third element is post-processing where one obtains relevant results from the primary unknowns at selected points. For instance, the results might be displacement/stress contours and factor of safety in solid mechanics and velocity/pressure/temperature contours and drag coefficient in thermo-fluids. The student needs to know the high-level procedures used by the tool to develop these results from the primary unknowns at selected points through interpolation and differentiation. Again, it is necessary to cover only the big ideas since the tool takes care of the details. The visualization of results can be highly effective in helping students develop physical intuition while also connecting the underlying theory to CAD models of practical applications.

The fourth and final element of the framework consists of hand calculations and experimental data. Hand calculations can be performed by simplifying the mathematical model or by using a different, much simpler model with more restrictive assumptions. The simulation results can be checked against the hand calculations to verify results. Experimental data for validation of the simulation results might be available from the literature for some applications or when used in a lab course. The four elements described encapsulate key aspects of how an expert would approach simulations. Thus, when students learn to identify and describe these four elements of the framework for many applications, they are moving along the spectrum from novice to expert thinking [2]. This can help them move beyond "garbage in, garbage out" as discussed later.

Just-in-time Problem Based Learning

Below we describe how the above black box framework leads to a uniform solution process that connects theory to applications across applications and subject areas. This process helps students repeatedly practice the same expert-like approach to simulations across courses, helping to internalize it and carry it forth into their careers. We begin with a problem statement where we describe the geometry, material properties and boundary conditions as well as the desired outputs such as the displacement field and factor of safety in solid mechanics. The problem can involve a simple geometry with an analytical solution such as a bar in extension or a realistic geometry such as those shown in Figures 1 and 2.

The first step in the solution process is labeled as Pre-analysis as shown in Figure 4 and is performed before getting into the software. The first part of Pre-analysis is to use physical reasoning and assumptions to build a mathematical model, which in most cases is a boundary value problem -- governing equations defined in a domain and boundary conditions defined at the edges of the domain as discussed previously. The second part is to review the numerical solution strategy used to solve the model and how to minimize the numerical errors introduced. Here, it is necessary to cover only the big ideas such as discretization and interpolation since the details are taken care of by the simulation tool. The third part is to perform hand calculations to predict expected results and also review any relevant experimental data.

Problem Specification

1. Pre-analysis
2. Geometry
3. Mesh
4. Mathematical Model Setup
5. Numerical Solution
6. Post-Processing
7. Verification + Validation

Figure 4: The structured solution process used in our problem-based learning approach. The Pre-analysis and Verification & Validation steps are key for connecting relevant theory to the software inputs/outputs.

Following Pre-Analysis, we move to Ansys or another tool and specify the mathematical model with the domain being defined through a CAD geometry which can be provided. Next, we obtain the numerical solution to the model in the tool using a mesh, a process that is highly automated. The numerical solution yields the primary unknowns at discrete points marked by the mesh. This sets the stage for post-processing where we obtain relevant results from the primary unknowns.

The order of steps in the tool to implement this process is as follows with the numbers referring to step number:

2. **Geometry**: Specify/import the CAD geometry to define the domain
3. **Mesh**: Generate a mesh by dividing the domain into elements or cells
4. **Mathematical Model Setup**: Specify the model, for instance, the governing equations and boundary conditions at the edges of the domain
5. **Numerical Solution**: Obtain the numerical solution on the mesh to determine the primary unknowns at selected points (nodes or cell centers) marked by the mesh
6. **Post-processing**: Post-process the results to obtain relevant quantities from primary unknowns at selected points
7. **Verification and validation**: Check the results through a systematic procedure as described below

Verification and validation have specific meanings even though they are often used interchangeably in common practice [3]. Verification looks at whether we solved the model right whereas validation looks at whether we solved the right model. Verification involves the following three main components which follow from the corresponding components in the Pre-analysis step.

1. The first component involves checking if the results are consistent with the mathematical model from the Pre-analysis step. For instance, one can check if equilibrium or conservation is satisfied if those are the physical principles used to develop the model. One can also check if the results at the boundary are consistent with the boundary conditions.
2. The second component involves assessing whether the level of numerical errors considered in Pre-analysis are acceptable. A basic aspect of this is a mesh refinement study. For nonlinear problems as in CFD, one would also need to assess whether linearization errors have been reduced sufficiently through iterations.
3. The third component involves comparison of software results with hand calculations from the Pre-analysis step.

Thus, the Pre-Analysis step forms the basis for Verification and Validation. As the student works through the above seven-step solution process for an application, they are making sense of the software inputs and outputs by connecting with the underlying theory in context. In other words, the simulation connects the relevant theory to the application. This can be thought of as just-in-time, problem-based learning. There is evidence in the literature that problem-based learning is more effective than conventional topic-based learning in engineering [4]. The just-in-time aspect refers to the fact that we cover the relevant theory at a high level in the context of the solution process. The focus in covering the theory is on helping students develop a deep conceptual understanding of the big ideas, without getting bogged down in the details since these are taken care of by the software.

Implementation through Online Learning Modules

This structured set of steps, from problem specification to Pre-Analysis to V&V has been implemented through online learning modules in around 30 examples -- involving both simple and complex geometries -- in multiple courses as well as a massive open online course or MOOC at edX.org. The MOOC -- entitled "A hands-on introduction to engineering simulations" – is one of the most popular free online engineering courses with an enrollment exceeding 300,000 from 173 countries. Assessment and student evaluation results show that this approach helps students connect theory to practice while also developing an expert-like approach to simulations.

Two courses in which the intervention has been extensive are *MAE 4721/5720 Advanced Applications of Finite Element Analysis using Ansys* and *MAE 5230 Intermediate Fluid Dynamics*. Here, we'll focus the discussion on MAE 4721/5720 -- taught concurrently at senior and MEng levels – since the course is built on our approach. This course covers 1D/2D/3D elasticity, beam and shell theory for slender and thin-walled structures, buckling and modal analysis for vibration from an applications perspective, with the software used being *Ansys Mechanical* which is an industry standard. The examples used to cover these application areas are a bar in extension, a simple beam, pressure vessel, wind turbine blade buckling and turbine disk vibration. The pressure vessel example is shown in Figure 1.

The bar in extension problem, which can be reduced to 1D, is used to cover the big ideas in finite element analysis: discretization, interpolation, derivation of algebraic equations through the weak form, post-processing and numerical error assessment and reduction. Students derive and solve the relevant 1D boundary value problem using the finite element method both by hand and using Ansys via the seven-step solution process. This allows them to compare the two approaches and develop a deep conceptual understanding of foundational ideas.

We then move on to 3D elasticity -- a modeling approach used extensively in static structural analysis -- which is covered through the pressure vessel example. We begin by covering the necessary concepts such as extension of 1D elasticity theory and the associated finite element solution approach to 2D and 3D. We then go through the structured solution process spanning Pre-analysis, Ansys implementation and Verification and Validation. Students learn the solution process through short online lecture videos which are 5-10 minutes in length. The videos that cover concepts such as the chain of reasoning used to build the mathematical model are followed by *check your understanding* (CYU) multiple-choice questions. Students need to watch a short video and answer the associated CYU question which presents them with four expert-like statements about the concepts covered in the video. One of these statements is incorrect and students have to identify that. In the process of answering CYU questions, students are evaluating the correctness of expert-like statements which helps them move along the spectrum from novice to expert thinking.

Students are given two attempts to answer each CYU question. If they get their first attempt wrong, they have the option of reviewing the lecture material in the associated video before trying again. Each video has an associated searchable and clickable transcript. This makes it easy for students to find and review relevant lecture material in the videos as they are working on assessments. This is in contrast to in-class lectures where students have to recall the material from memory.

By the time the learner has watched a lecture video that is about 10 minutes long, their working memory is saturated. That is the reason to chunk the material into short videos. The CYU question following a short video is an opportunity for the learner to immediately apply the concepts covered in the video and move the knowledge gained from their working memory to long-term memory. The learning experience is active throughout: students are watching a video and immediately applying the knowledge via the following CYU question or following along in the simulation software (Ansys).

Once students have completed the structured solution process for an example problem such as the pressure vessel by following the videos, they need to solve a challenge problem such as a 3D beam using the same process but without videos to guide them. So they have to apply the knowledge gained from the example problem to solve the challenge problem. They can return to the videos as necessary and consolidate the knowledge in their long-term memory. Students go through the videos and complete the associated CYU questions or Ansys exercises for example problems outside of class and solve the challenge problems in groups in class. Thus, we leverage the lecture videos to flip the classroom. The teaching model described in this section is illustrated in Figure 5.

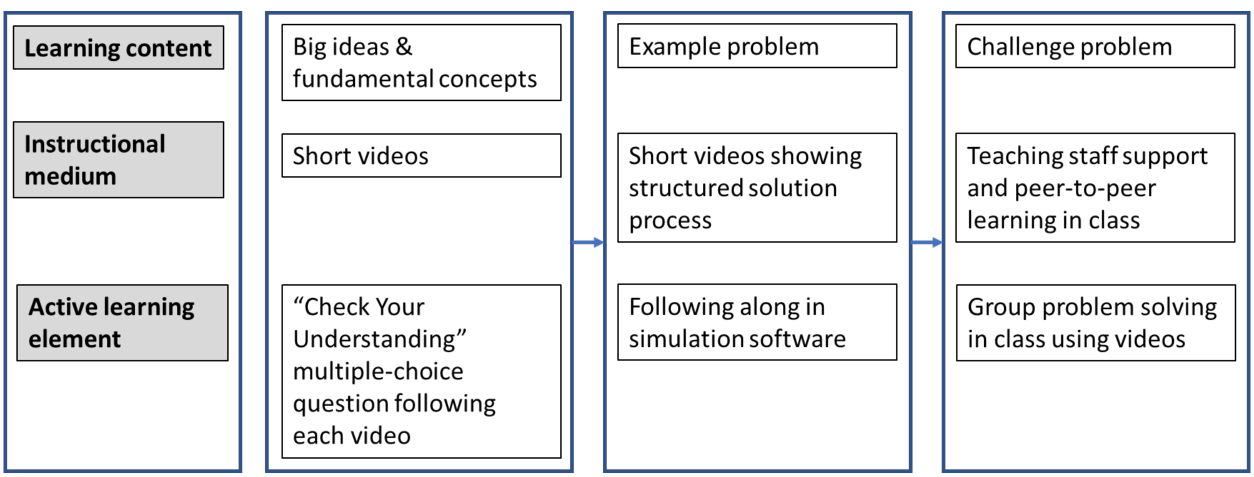

Figure 5: Illustration of teaching model.

Assessment Results and Student Response

Assessment type	Total no. of questions	Average	Standard deviation	Findings
Multiple-choice "Check Your Understanding" (CYU) questions following videos	67	93%	4%	Students were successful in immediately applying the knowledge in the videos
Four "Challenge problems"	76	97%	2%	Students were able to adapt the knowledge and structured solution process from an example problem to solve a challenge problem

Table 1: Assessment results from MAE 4721/5720 during the Spring 2024 semester.

Table 1 above presents some assessment results and associated findings from MAE 4721/5720 *Advanced Applications of Finite Element Analysis using Ansys* during the Spring 2024 semester. There were a total of 30 students enrolled in the class. It is reasonable to conclude from the above assessments results that the vast majority of students had learned to use an expert-like approach to create practical simulations for structural analysis.

We present in Table 2 some results from the student survey conducted at the end of the course. Ten students completed the survey. Since the sample size is small, the conclusions indicated in the Findings column are preliminary. In the future, we will provide points to students for completing the survey to increase the response rate and develop more definitive conclusions.

Survey Question	Score	Findings
How valuable were outside of class-time resources (e.g., readings, videos, online content, course notes) in building your understanding? 1. Minimal value 2. Occasional value 3. Moderate value 4. Significant value 5. Very valuable, well worth the time spent on them	4.5	The videos & CYU questions -- the main outside-of-class resources --were of significant value to students.
Did the course structure and organization facilitate your learning? 1. Very disorganized, significantly hindered my learning 2. Somewhat disorganized 3. Adequately organized 4. Well organized	4.8	Students found our structured problem-based learning approach using an industry-standard simulation tool significantly enhanced their learning.

5. Very well organized and structured, significantly enhanced my learning		
This course challenged me to synthesize ideas, think critically about the content, and apply the material to unfamiliar topics and problems. 1. Not at all 2. Occasionally 3. Every few classes 4. Many classes and assignments 5. Nearly every class and assignment	4.3	Many classes and assignments helped students learn to think like an expert (synthesizing ideas, applying material to unfamiliar topics and problems, etc.).
Overall, how does this course compare with other comparable technical courses you've taken at Cornell? 1 = Poorly, not educational 5 = Excellently, extremely educational	4.8	Students found this course built on problem-based learning, simulations and online content much more educational than other comparable technical courses at Cornell.

Table 2: Some student survey results for MAE 4721/5720 from the Spring 2024 semester.

Student comments were all positive; some selected comments follow.

- I found that the assignments were very useful in learning how to apply skills in Ansys, but also how it all relates to the finite element theory. This helps to better frame how to approach problems. I have found this super useful in personal projects, and I was able to apply the skills that I was learning on projects I am working on now, not even having to wait a semester.
- The best organized class at Cornell. So easy to follow and every class is motivating and interesting to attend.

Conclusion

We have described a framework for connecting theory to applications in engineering courses using simulations. The framework leads to a problem-based learning approach where the same structured solution process can be used for different applications using simple or complex geometries and physics. For each application or problem, the first step is to use physical reasoning and assumptions to build a mathematical model. The second step is to review the numerical solution strategy used to solve the model and how to minimize the numerical errors introduced. Here, it is necessary to cover only the big ideas such as discretization and interpolation since the details are taken care of by the simulation tool. The third step is to perform hand calculations to predict expected results. These three steps comprise what is labeled as the “Pre-Analysis” stage.

Following Pre-Analysis, we move to Ansys or another tool and specify the mathematical model with the domain being defined through a CAD model which can be provided. Next, we obtain the numerical solution to the model in the tool using a mesh, a process that is highly automated.

The numerical solution yields the primary unknowns at discrete points marked by the mesh. This sets the stage for post-processing where we obtain relevant results from the primary unknowns. The visualization of results can be highly effective in helping students develop physical intuition while also connecting the underlying theory to CAD models of practical applications.

The final step is verification and validation (V&V) where we undertake a systematic process to check the results. This structured solution process, from problem specification to Pre-Analysis to V&V, has been implemented in around 30 examples -- involving both simple and complex geometries -- in courses. The implementation is through online learning modules which are organized around short videos and associated "check your understanding" questions to make the learning active. We have presented assessment and student evaluation results to show that our approach helps students connect theory to practice while also developing an expert-like approach to simulations.

This material is freely available to the community through a massive open online course (MOOC) at edX.org and through the Ansys Innovation Courses platform. It is also available through paid certificate programs offered by eCornell for working professionals on finite element analysis and computational fluid dynamics. The paid versions include personal support to the learner from a course facilitator. We are interested in exploring opportunities to work with faculty in deploying our online learning modules at other universities and also to help them develop content for their courses using our approach. An open issue that warrants collaboration for further development is the integration of AI technologies such as generative design into this framework and paradigm.

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