Incorporating Design into Introductory Statics and Strength of Materials Courses

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Abstract

The design of rigid permanent structures, statics, is the most basic of engineering concepts. We believe it is also the place to introduce first year students to design and the broader issues of engineering, and by doing so excite students in all engineering disciplines. We have developed an introductory engineering course based on statics. This course begins by introducing the students to the fundamental physics of statics equilibrium and culminates with the students being able to design a simple structure. To make this course successful we adopted the philosophy "Involve me and I'll not only learn but understand and remember". Such involvement requires emphasizing oral, written, and visual communication. In the beginning of the course, the physical laws are demonstrated by self directed laboratories. During the middle of the course, students optimize a truss using a spreadsheet. The course culminates with a project where the students using a special form of the Tresca Criterion can select a material and its dimensions for a design. This also means they can be introduced to the business consequences of their decision. In this paper we will discuss the evolution of this course during the last three years, the innovative course content, the innovative teaching techniques employed, the dynamics among the instructors, and how we applied what was learned in the Strength of Materials course.

Introduction

Background

First year engineering students typically have no idea of what engineers do, or what engineering is. Therefore there is a need to introduce students to engineering early in their undergraduate experience so that we can: retain good students, allow students to make intelligent choices about their choice of major, and improve the educational experience. The purpose of engineering education is well described by the words of Stephen van Rensselaer, the founder of the first civilian engineering college "...instructing persons, who may choose to apply themselves, in the application of science to the common purposes of life"¹. To effectively apply scientific principles to the common purposes of life, one needs design experience, communication skills, in addition to a sound technical foundation in engineering. Employers have identified the following characteristics as required of successful engineers, strong technical capability, persuasion and communication skills in a variety of media, the ability to lead or work as a team member, and a thorough understanding of the non-technical issues that affect engineering decisions. John Kucharzki - CEO of EG&G, when speaking to the American Society for Engineering Education raised these issues in his 1997 plenary address. He indicated that he as a CEO and potential employer, wants engineers to have the non-technical skills listed above, but does not want technical competence to be sacrificed. This requirement from industry is important to consider in light of recent demands to reduce the number of courses required of engineering students.
Requiring additional courses is not an option, however incorporating these skills into an engineering course is an alternative.

We decided to attempt this in two introductory engineering courses, statics and strength of materials. Our approach as compared to the traditional approach to engineering education is shown below.

Rather than wait until the latter half of the undergraduate experience to allow the students to apply scientific principles we chose to incorporate this experience into the course. Also after having the students apply these principles we chose to expose them to business issues and basic computing skills. Throughout the course communication and teamwork were required. Thus we eliminated making “cubicle” engineers.

Our approach had been advocated by recent findings of the National Science Foundation which found that students are not being served well by typical methods of instruction². Much of this dissatisfaction and disinterest in engineering occurs during the first two years of an engineer’s education when they are exposed to the scientific concepts they will apply during their careers. Ninety percent of engineering majors who switched to a non-engineering major, and seventy five percent who persevered, described the quality of teaching as poor overall. Seniors about to graduate in engineering made it clear their experience in these introductory courses had given them a shaky foundation for higher level work.

The National Science Foundation in a recent call for proposals (Action in Engineering) has
identified several needed changes to address these findings. These include,

1) active project-based learning inside and outside of the classroom,
2) increased student-teacher dialog,
3) horizontal and vertical integration of subject matter,
4) introduction of mathematical and scientific concepts in the context of engineering, and
5) the broad use of information technology.

We used these suggestions to develop an effective learning experience for our students.

The non-traditional cannot be taught in the traditional manner. Typically the introductory science and mathematics course consists of a sequence of lectures combined with a series of assignments and examinations which require little more than rote memorization or repetition. This is not engineering.

Bloom, a noted educational specialist, identified a hierarchy of six educational levels, each higher level being more rewarding than the previous level\(^3\). The typical course experience as described earlier focuses on the lower learning levels and are not appropriate for college students. We feel that college students should perform at the fourth level, Analysis (breaking down a problem into parts and solving it), and by the time they graduate at the fifth level, Synthesis (tying together distinct concepts).

**Course Structure**

Statics is the most fundamental of the engineering courses. Because the scientific and mathematical principles are not difficult, it is a course where a student can be introduced to engineering practice early in their career. This exposure was continued in the more advanced strength of materials course.

Our original goals were ambitious. In addition to statics, we hoped to introduce the following material into the course.

**Linear Algebra** - Due to reductions in the number of courses it was not possible to require a semester of linear algebra. Also we felt that students typically learned this subject so late in their undergraduate careers that they did not see its purpose. We planned to integrate linear algebra into these two courses.

**CAD** - Because we believed in context based learning, we felt that the students could learn CAD while drawing increasingly complicated static structures.

**Communication** - We felt it was necessary to require various forms of written, oral and visual communication throughout the course.

**Office Suite Use** - Students cannot be assumed to have a working knowledge of a word processing, spreadsheet, presentation suite. Yet such skills are required in industry. Therefore we chose to expose the students to this.

**Programming** - A programming course was not required of our students. Therefore, we planned on teaching programming in the context of the introductory course. We had chosen to use the
Visual Basic programming language as it would enable the students to write a Windows based program, and most macro languages were based on Visual Basic.

Business - Engineering students need a sense of business. The sponsors of the engineering school made this clear, and we tried to expose the students to business issues.

To meet these challenges we designed a statics course with the following “novel” features.

1) Assignments which required analysis and explanation.
2) A series of open ended laboratory assignments.
3) A series of computer assignments to complement the laboratory investigations and allow the students to master the programs in an Office Suite in discrete steps.
4) Design projects which required programming, consideration of non-technical issues, and two different communication styles.
5) Linear algebra techniques for solving simultaneous systems of equations.

The same philosophy was used in the second-year strength of materials course except that there were no laboratory experiments and linear algebra was used to rotate coordinate systems and identify principle stresses.

In both courses interactive learning techniques and more frequent testing were used to enhance the course experience.

The Courses

Statics (The Introduction to Engineering Practice)
As indicated in Figure 2, the course involved exposing the students to scientific principles, having the students apply these principles, and then looking at the broader context of engineering.

Phase 1 Fundamentals - explores the basic relationships required in statics; vector manipulation, 2-D force equilibrium, 3-D force equilibrium, and moments. Four self-directed laboratory assignments were used to illustrate these concepts. To complete these assignments the students had to use computer drawing tools, word processors, and spreadsheets.

As one of the most “concrete” sciences, it is disappointing that many statics courses lack a laboratory component. We believe that the laboratory exercises should be structured to reinforce the material presented in class, not as cookbook exercises, which are typically boring but in conjunction with the scientific learning cycle. In the real world, engineers will conduct experiments where the solution is not known ahead of time. Thus, it is not surprising that laboratory experiments appear to be more effective when the solution is not known ahead of time. In a self-directed laboratory the students become involved in the experimental process, they are not simply following directions. Such involvement makes the learning process more successful. These laboratory exercises are integrated into the class experience, typically the lab experiment is used as a demonstration. Then, after introductory remarks, and perhaps a practice problem, the students are given a hypothesis, a piece of equipment, and asked to conduct an
experiment. They decide what data to take, they decide how to write the report, they answer speculative questions, thus demonstrating any insight they have gained from the experiment.

The laboratory assignments served four purposes; 1) to physically demonstrate the concepts introduced in class, 2) to teach the students how to use a personal computer Office Suite by requiring increasingly complicated documents, 3) to expose the students to the linear algebra required to solve systems of linear equations and 4) to teach the students how to prepare a technical report. To complete these laboratories the students were given little more than an apparatus and a hypothesis. The students had to set up a spreadsheet to compare their experimental findings with their hypothesis. The spreadsheet tables, appropriate equations, and drawings had to be incorporated into a single document.

Many of the students have never been challenged in this manner, and a set of laboratory guidelines was made available on-line. The laboratory activities are described below.

Figure 3: Apparatus for Vector Addition Laboratory.

Figure 4: Apparatus for 2-D Equilibrium Experiment.

Figure 5: 3-D Equilibrium Apparatus.

Figure 6: Apparatus for Moment Experiment.
Lab 1 - Vector Addition: A block of wood, constrained so it could only move in one direction, and thus show summation in one direction and cancellation in the other.

Lab 2 - 2-D Force Equilibrium: A mass was supported with two cables as shown in Figure 2, and the students were to predict the tension in each cable.

Lab 3 - 3-D Equilibrium: The students were given an upright pole held into place by three cables. They were to adjust the tension of the cables until the pole was vertical and check their results.

Lab 4 - Moments: A very unstable structure as shown in Figure 3, was built. This structure consisted of an upright column (1.5 in)², 4 ft. high which had either two or three moment arms (4 ft. long) The students would hang weights on the arms, and determine if the moments balanced mathematically when the structure did not tip over.

The National Science Foundation has called for teaching mathematics and science in the context of engineering. One statics text introduces linear algebra, but then unfortunately does not use it consistently throughout the rest of the text. Thus, the students are not convinced of its usefulness. We had planned to use the laboratory experiment and Excel to teach some linear algebra techniques. Matrix addition was covered in the first lab, Gaussian elimination in the second, Cramer’s rule and determinants in the third, and inverses and matrix multiplication in the fourth. Each laboratory assignment also required increased use of an Office Suite. All graphs, tables, equations and data were required to be in a single word processor file appropriately formatted. The drawing and graphing became more demanding each week.

We felt it was inappropriate to assign a large number of “one-step” drill problems. This is not representative of tasks which the students will encounter in the real world. A recent review article based on twenty-five years of studies, concludes that merely presenting drill problems in class and requiring the students to do large numbers of them for homework is not effective. We selected the homework problems from the most challenging problems within each chapter of the text. These were collected and corrected. To make the homework assignments a worthwhile learning experience we did not emphasize getting the correct answer, with a minimum number of calculations. The students were required to learn and master a method of solution. Every assigned homework problem and every test question was a multi-step problem. This required the students to work at the “Analysis” level.

This required involving the students in their own learning on a magnitude not typically seen in introductory courses. Our model of the ideal learning cycle is shown in Figure 7. Note the relative importance of experience and feedback as opposed to passive learning. For two years this course was taught in a studio mode, like courses in Calculus, Physics, and Materials Chemistry, where the lecture, laboratory and problem solving sessions are combined into a single holistic session.
learning experience. Mid-term examinations were replaced by weekly tests to increase the amount of feedback.

One form of feedback was to develop a set of homework solutions that taught solution strategy. Simply demonstrating the correct solution to these problems, in the form of mathematical equations, on the board or in homework solutions will not work. The student needs to learn the thought process as well as the method of solution. Photocopying the solutions provided to the instructor, and making them available to the student, is not sufficient. Using the funding provided through the Teaching Excellence Grant we established a website where the solutions to approximately three years of homework problems are solved in a step-by-step basis, these solutions include narrative, which is key to teaching the student to develop an effective problem solving strategy.

Phase 2 Engineering Applications - requires the students to build on the fundamentals as they explore the in depth analysis of many common structures. This is engineering, the application of science to benefit mankind. This is done in two stages, 1) support reactions, and 2) internal reactions (trusses and structures). The students are required to complete a design project which requires the preliminary analysis of a structure, alternative design, and the development of a spreadsheet module to analyze this system. This is presented in visual and written form.

During the second part of the course the students learned about internal and external reactions, this phase of the course culminated in a design project. One of the eight possible projects is shown in Figure 4. The students must conduct a preliminary analysis of the structure where they determine the support reactions and internal loads. They then must evaluate at least five design changes and make a recommendation.

<table>
<thead>
<tr>
<th>Assignment</th>
<th>Investigate the following design changes.</th>
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<tbody>
<tr>
<td>1) Changing the height of the bridge,</td>
<td></td>
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<tr>
<td>2) Changing width of the central member,</td>
<td></td>
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<tr>
<td>3) Changing the vertical position of the leftmost pin.</td>
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</tbody>
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Your report must discuss the implications of these design changes as they apply to

1) The performance of the structure |
2) The necessary material requirements. |
3) The benefit to the manufacturer needs to be discussed |

The project is presented as a poster and a 3-5 pg. technical paper. In their paper the students were required to explain their analysis. They were told that saying “the program predicted”, or “the equations say” is not acceptable. It was possible to expose the students to the design process, because in the first part of the course they a) learned the math and science fundamentals,
b) were required to ask “what-if” as part of the lab exercises and tests, c) were exposed to spreadsheets, presentation graphics and word processing in the first part of the course.

Projects need to be carefully identified so that by completing the project both the subject matter is reinforced and the students can successfully go through the design phase. Many of the projects are therefore somewhat constrained and artificial. There are some students and faculty who are not comfortable with this. For example, when designing a truss at this level the students cannot account for bending or buckling - and some of their conclusions would not work in the real world. This needs to be pointed out to the students and discussed, if such projects are chosen.

It was noted that the instructors must spend time in class explaining how to a) create a poster, b) prepare a technical report, and c) prepare an oral presentation. The reports were excellent, and the students were able to explain their results as we had hoped.

The students enjoyed the design project. Many said it was the best part of the course. During the Spring 1998 semester students were allowed to pick one of eight projects. During the next two terms we limited this to four trusses, in order to ensure that all required the same amount of work. The students taking the course during the Summer of 1999, were given the same project, shown in Figure 8. The project needs to be sufficiently challenging that students are not guaranteed completion. Comments by other faculty attending the poster session were positive. The students were required to think on their feet. Their comments of others work was constructive. There was some concern about certain team members not pulling their weight. This was addressed in two ways. First the students performance on tests, homework, and the final far outweighed the percentage assigned to the project. Second, in some cases instructor intervention was required.

Phase 3 Broader Context of Engineering - requires the students to write a user friendly Windows based program to analyze a frame or machine. This program will also allow the user to make business decisions. In addition to programming fundamentals, the students are introduced to elements of micro economics, net present value, fixed and variable costs, and supply and demand. Their program will allow them to make a “bid” which satisfies their client and company. A sample project is shown below.
Write a user friendly Windows program which will, through the use of individual forms, which will,
determine the performance of a structure based on design,
generate a parts list for the structure which estimates the parts cost by searching a parts database),
estimates potential sales, and potential profit if one sells the product,
and prepares a summary for your supervisor which includes all pertinent details for a three-year project.

In addition to demonstrating the program, you will be graded on the soundness of your business decision.

This project includes materials selection. Because the students learn about shear forces and bending moments it is possible to introduce them to an artificial concept called “effective force”. This will allow them to identify a suitable material based on strength (F/A) and dimension (A). Identifying the maximum normal stress from the maximum bending moment, and the maximum shear stress based on the shear force, one can apply the Tresca Criterion and determine the following formulae for simple geometries.

For a square cross-section,

\[ F_{eff} = \sqrt{\left( \frac{6M}{w} \right)^2 + \frac{9}{4} V^2} \]

and for a cylinder,

\[ F_{eff} = \sqrt{\left( \frac{4M}{r} \right)^2 + \frac{9}{4} V^2} \]

this adds a component of reality to the project as students can identify a material.

The evolution of microcomputers now means that users can buy programs to do what they require. This means that while during the 1980's many high schools taught computer programming, these high schools will now probably focus on computer use. Engineers, however require some knowledge of computer programming. We feel that computer programming, like other science concepts can be more effectively taught to engineering students, if done in the context of engineering, as suggested by the National Science Foundation². We chose to Visual Basic as it allows the students to write a Windows program, which is the operating system they are most familiar with. It introduces them to the Basic programming language which is the basis
for most macro languages used in Office Suites.

The following programming skills were covered, formulas, if-then-else structures, looping, subroutines, data arrays, records and files. To make this work team problems have been prepared which require the students to write programs in class, these team problems are the basis of a set of homework assignments which are structured so that the students write some of the routines for their second project as part of the homework.

The third form of the second project was used to perform a business analysis on the machine (the students were provided with initial data). To prepare the students for writing the program the following business concepts are briefly introduced.

Time value of money: This is the metric by which the value of the potential project will be judged.

Identification of costs: For the project they need to consider sales, marketing, parts, labor and overhead; they are free to vary sales, marketing, labor (by reducing labor time) and parts (by improving the design).

Supply and demand shifters: as changing performance and price will change sales, the students are given the basics for “estimating” the effects of changing sales price and performance. They are asked to justify there assumptions.

By interspersing statics, and business with programming the students are given programming assignments which are immediately relevant and time to debug their programs.

**Strength of Materials (Design for Mechanical Engineers)**

Although material selection was simplified for freshman, it is possible for sophomores to select materials for a given application and do some design. This course was taught with the philosophy that the innovative learning techniques used in statics had to be applied or all was for naught.

The emphasis on linear algebra was continued. Students were shown how a coordinate system could be rotated using matrix multiplication. Rather than using Mohr’s Circle to identify principal stresses and strains, the students were introduced to eigenvalues and eigenvectors. This approach provided a real world application for a very abstract concept.

Students were required to reexamine the projects they had completed in the statics course. Rather than using the “effective force” formulae given to them in statics, they were able to perform a real stress analysis accounting for torsion, bending and shear. When reexamining the truss students could account for deflection and buckling of beams. No new business concepts, or computer programming techniques were introduced in this course but the students used “software” they had written the previous year.

The involvement of students in the learning process, was key. As shown in Figure 7, we believe that constant feedback is important. Each class began with a problem, the students were required to enter into a journal. This problem was usually a simple application of the reading assignment.
Following a discussion of the solution of this problem - the class period focused on elaboration, and implications of the results of the calculations.

Discussion

Assessment of Course Effectiveness
A detailed assessment, based upon the handout describing the recent workshop at Rose-Hullman, as distributed at the 1998 ASEE conference was conducted.

- First, four to five broad goals were identified, based on the course description. The course description was rewritten to tell the students what they could expect to do as a result of taking the course.
- Based on these goals a list of 12 objectives was developed, which are similar to the material found in course descriptions in many college catalogs.
- Specific metrics, based on the activities listed in the course syllabus were identified to measure these objectives. This included graded performance records (histograms of individual test questions), student comments on course objectives and general survey responses.
- The information in the course portfolio was used to measure the success of these objectives and then the course goals, and identify appropriate action.
- Finally an evaluation of the course was prepared based on the measurements. This evaluation is similar to a reflective memo, which has been suggested as the second step of the assessment process.

Incorporation of Active Learning into Courses
As shown in Figure 7 we believe that if students are to successfully perform at the Analysis Level of Bloom’s taxonomy, which we feel is vital to the course experience, many opportunities for experience and feedback are required. Longer class sessions are required if in class problem solving is to take place, however if the instructor is uncomfortable with this approach and reverts to lecture the classroom experience is less effective than the traditional approach. The assessment of the course sections where interactive learning was adopted showed that it was successful, if not necessary to the success of the course. Some instructors preferred to require additional homework problems, easier ones. These were what the students would have done in class as in-class problems. Regardless, if the students are to be able to do the more difficult problems, they must practice with easier problems.

Each of the experimental apparatus were constructed quickly using hand tools and stock lumber. Students, who were used to more sophisticated equipment from laboratories in other courses did not like the “rough” look of the labs. They were particularly uncomfortable with the experimental error guaranteed by using this equipment. In spite of this many students found the labs enjoyable, and “less Mickey-Mouse” than those in other courses. As the term progressed, students were observed questioning their data and calibrating the scales, without instruction. The writing and computer proficiency of the students improved as a result of these exercises.

Replacing mid-terms with weekly tests was successful. As evidenced by grades and student evaluations (quantitative and qualitative), the students problem solving ability and analytical skills improved. Students said they liked the weekly tests, as they said they were unlikely to fall behind.
A decision needs to be made in the beginning as to the scope of discretion each faculty member will have to the extent they adopt interactive studio approach. This method is neither appropriate for every student, nor every faculty member. Allowing such discretion allows for students and faculty to match learning styles, and for innovative ideas to be attempted, evaluated and if successful adopted. By having faculty reviewing each other’s classes, and jointly reviewing evaluations, innovative ideas can be accepted through “buy-in” rather than mandate. If the mandate approach is taken, the team members may become alienated from one another and the project will fail. Additionally, the resources available to faculty must be considered. When first learning this method faculty need at least twice as much time to learn and become convinced of the new techniques.

Incorporation of Linear Algebra
We believe that linear algebra is best taught in the context of engineering, that it can be incorporated into basic mechanical engineering classes, and that a late exposure is not in the students best interests. However, our assessment results show that it was not very successful. The students are still not completely comfortable with linear algebra. The lack of a text which uses this approach is a major problem. Students need to see its usefulness or they will become disillusioned and learn nothing. The amount of work required to prepare resources by which the students would learn linear algebra in the context of statics and strength of materials is beyond the scope of any one instructor or team of instructors with a normal academic load. We feel that a completely new text would have to be developed in addition to significantly revising the course. Broad discussion on this matter is needed to determine if such effort is justified.

Incorporation of Computer Usage
Our assessment results show that the students did learn how to use an Office Suite and that their spreadsheet proficiency made the design projects more successful. This does require that the instructor demonstrate how to use the various programs, especially the spreadsheet, in an Office Suite to the students as part of the classroom experience.

The Visual Basic Programming has been the most challenging portion of the course. We have expanded the time devoted to the topic and changed the delivery method. More time is needed for the students to work in class on programming assignments and less lecturing is needed. Despite our best efforts, the assessment results show that more exposure to computer programming is needed, and we feel that it is best done outside of a course such as this. The amount of time for students to learn how to program cannot be underestimated. Teaching programming in the context of engineering increased student interest in programming and we feel this shows that the instructors of an engineering computer course should communicate with those teaching engineering courses and develop a set of relevant projects.

The spreadsheet is sufficient for all calculations required in these courses and more emphasis on spreadsheets is appropriate.

Incorporation of Non-Technical Skills
The communication skills of students improved throughout each term, as evidenced by grades and student evaluations. At the same time they became more proficient with word-processing and presentation graphics software. The results of our assessment indicate that giving the students multiple opportunities to communicate is necessary. Although it is impossible to
measure directly, we feel that requiring the students to communicate their knowledge involves them in the learning process and makes learning more effective. We found that by requiring the presentations before the papers were due, the students listened to each other, and in many cases prepared better papers. It was noted that instructors did have to spend time in class explaining how to a) create a poster, b) prepare a technical report, and c) make an oral presentation.

The students did like the exposure to business, however some students and faculty thought the limited number of topics meant that one could not address business successfully. This is true, the business decisions available to the students in a project like this are very limited, primarily to reducing cost of parts, and possibly labor through a reduction in assembly costs and increasing market share by lowering price or improving the product. Incorporating business into the second project was moderately successful. Comments from students indicate that due to the challenge (and thus the amount of time dedicated) of writing a computer program the students did not understand that the program is part of the project, and it is how they use the program to make a business decision which is important. Using a spreadsheet should alleviate this problem. We do believe that making students think about business issues is important, and that an initial exposure will excite the students about taking courses in business during their undergraduate career.

Incorporation of Design
We feel the best way to teach design is to give the students numerous design experiences. The course assessment shows that this improves the student’s education. Many students have said this was the best part of the course.

Projects have to be identified so that completing the project both reinforces the subject matter and can be successfully completed given the knowledge of the students. This often means constraining the project, which makes them artificial. Not all faculty are comfortable with this, and it is imperative that the students know to what extent they have been constrained.

While two projects require more work, and some elimination of subject matter, it does allow the student to learn from a mistake. We feel that this is important.

Conclusion
Design has been successfully incorporated into two introductory courses for mechanical engineering students. This has enhanced the student learning experience. By incorporating design into the course we were also able to include communication, computer skills and business issues in the subject matter and teach them in the context of engineering. Attempts to incorporate linear algebra and computer programming were not successful, however our findings indicate that it is possible to improve the teaching of these subjects, and that future projects to address these issues are warranted.

Teaching a non-traditional course required examining and incorporating non-traditional teaching techniques to involve students in the learning process. These include self-directed laboratories, in-class problem solving, and increased feedback. Such cannot be mandated and immediately adopted, but that faculty can learn from each other.

A course such as this can be described as fragile. Planning, cooperation and a commitment from
the university is required. More time is required to get the better results, we feel that the ratio of positive effect to time exceeds that of a traditional course, but a university level commitment is required for the increased time to be made available.

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Bibliographic Information


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