

Ideas to Consider for Chemical Engineering Educators Teaching a New “Old” Course: Freshman and Sophomore Level Courses

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Abstract

So, you are going to teach a core chemical engineering course next term that you have not taught before. It's time to come up with some new ideas to revolutionize that core course in ways that will amaze students and maximize learning, right? Or perhaps the maxim about “an hour in the library is worth a month in the laboratory” might be meaningful in the context of teaching. This paper summarizes the authors' selection of the most effective, innovative approaches reported recently in the literature or discussed at previous conferences for lower-division core courses in chemical engineering, as presented at the 2007 ASEE Summer School for Chemical Engineering Faculty. The challenges associated with particular courses and solutions successfully applied to address those challenges will also be described. Courses covered in this paper include introductory courses for freshmen, material and energy balances, fluid mechanics, introductory thermodynamics, and separations.

Objectives and Motivation

Although teaching is a critical mission of any college or university, today's faculty members are increasingly becoming involved in other scholarly activities. Thus, when teaching a new course, developing a good set of instructional materials can be a challenging, time-consuming task. In this paper we provide a review of some of what we consider the best practices in engineering education, applied to the following courses: freshmen chemical engineering, material and energy balances, fluid mechanics, introductory thermodynamics, and separations. Note that a companion paper which covers the upper-level undergraduate classes in the chemical engineering curriculum is planned for the following year.

The format used for each course is:

- Brief description of typical course content
- Discussion about novel and successful methods used
- Listing of “toughest concepts” for the students (and how to address them)

We note that most of this material was originally presented by the authors at the 2007 ASEE Chemical Engineering Division Summer School in Pullman,

WA¹. This work was originally published (and also presented) at the 2008 ASEE Annual Meeting² as paper number #AC 2008-1147.

Freshman Chemical Engineering Courses

Depending on the school, this course is either a “stand-alone” introduction to chemical engineering or is part of a college-wide introductory course (with a portion devoted to chemical engineering). Ironically, many chemical engineering educators may never have taken this course.

A major goal of the course, as it is a freshman course, should be to cultivate student interest in engineering³ and motivate students to pursue an engineering career. This course can have a wide variety of formats, depending upon the number of credits and objectives of the course for a particular institution. For example, Brigham Young University has a three-credit course which introduces (via an integrated design problem) all of the aspects of the chemical engineering curriculum⁴, while Tennessee Technological University has a one-credit course that focuses more on hands-on experiments and information exchange⁵. Whatever the course, it is important for a department to identify why they have introduced or are teaching such a freshman course and whether (via specific assessment) the goals and objectives of the class are being met, from both the faculty and student standpoint.

In the rest of this section, we briefly highlight (as a resource) some of the novel work available on freshman courses in chemical engineering.

Some best practices that we have used (or discovered) for this course are:

- The use of freshman design projects:
 - Design and economic analysis of a controlled-release nitrogen fertilizer plant⁶
 - Design, build, and test an evaporative cooler⁷
 - Design and build a pilot-scale water treatment plant⁸
 - Analyze and design sneakers with better material properties⁹
- Introduce in-class, hands-on experiments:
 - Melting chocolate and coating cookies¹⁰
 - Electrophoresis and brewing with microreactors¹¹
 - Heat transfer scaling with hot dogs⁵
 - Human respiration process¹²

One overlooked concept in designing this course is to consider the needs of the student *from the student perspective*. Recently, the University of Pittsburgh asked their freshman engineering students to conduct a survey of other first-term freshman engineering students on topics the students felt were important¹³. While the results of the surveys are interesting in their own right, the most useful result is the *types* of surveys the students developed. The top ten types of surveys were as follows:

1. Getting enough sleep?
2. Has high school prepared you for college?
3. Do you feel safe on campus?
4. Any new romantic relationships?
5. Is partying getting in the way of schoolwork?
6. Exercise more or less than in high school?
7. Homesick?
8. Campus food options?
9. Susceptible to doing drugs / alcohol now?
10. Confidence in time management skills?

It is noted that there is nothing about a student's major listed in the top ten. Thus, a freshman engineering course requires a balance between what an instructor knows (or thinks) that a student needs, and what the students think they need. Therefore, while a freshman chemical engineering course must (obviously) contain information about the field of chemical engineering, it should also find ways to address non-chemical engineering related issues as well. Here, ample use of guest speakers in Counseling Services or similar offices on campus should be explored.

In addition to what has been discussed above, other ideas in freshman chemical engineering courses exist as well. Roberts discusses a course that focuses on, among other areas, communication skills¹⁴. Worcester Polytechnic Institute looks to mix writing with first-year engineering in a course taught shared by a ChE faculty and Writing faculty member¹⁴. Vanderbilt University describes a course where students are introduced to chemical engineering by "using examples from cutting-edge research to illustrate fundamental concepts"¹⁶. At Youngstown State University, they are demonstrating combustion principles to chemical engineering (and non-chemical engineering) students using a potato cannon¹⁷.

Trouble spots for this course include:

- Most students do not know what chemical engineers do – one idea is to have teams of like minded students investigate where Chemical Engineers work in a particular field. Each team will present this information to the rest of the class at the end of the semester. Also, The Sloan Career Cornerstone Center¹⁸ has short "Day in the Life" interviews of various young chemical engineers in a wide variety of industries that is quite informative at emphasizing the diversity of career options accessible for B.S. chemical engineering graduates.
- Most students only have a vague idea as to why they are taking math – one idea is to have upperclassmen come into the class and tell them how they are using math in their courses. In fact, using upperclassman as much as possible during the semester is a good idea as it indoctrinates the students easier into the program.

- Many students struggle with the transition from high school – one idea is to use upper-class peer mentors or speakers from on-campus who can discuss student-relevant issues. Having students conduct their own surveys, as discussed in a previous section of this work, might identify the most important issues for your students.

Material and Energy Balances

This course may also be called the “Stoichiometry” or “Process Principles” course by faculty. Students may refer to it as “The Cut Course,” or by even less flattering names. This course poses a unique challenge in many chemical engineering curricula since it requires students to think at a higher level than in previous courses. A typical course will cover: units and dimensions, properties, measurements, phase equilibria, material balances, energy balances (nonreactive and reactive systems), and combined mass and energy balances. The course should prepare students to apply conservation laws to process simulation as the first source of modeling equations. The course is the foundation for the rest of the curriculum—it is all about planting seeds for the future!

Trouble spots for this course include:

- Reluctance to show work. Students should be required from the start to show clean, detailed solutions even on the easiest problems assigned earlier in the class. Significant point deductions for deviations early in the course help train students to clearly communicate with their problem solving¹⁹.
- Reluctance to apply rigorous methods to simple problems. The grader must pay attention to the method and not just the final answer. Requiring students to start from the general material balance even on problems that can be solved intuitively will aid students in solving more complex problems later in the course.
- Misunderstandings about density / specific volume and g_c . Repetition, drills, quizzes, and clear examples help to clear up some of these common misunderstandings. Warning students that these can be challenging issues may help a few pay more attention. Keeping a reference page at the beginning of their notebook or in the cover of the textbook with notes on these and other key subjects can also help.
- Trouble with thermodynamic diagrams. Students will not grasp these diagrams without working with them. One approach is using online interactive tutorials. Another effective approach is to bring copies of charts (even if they are in the text) for students to use in working problems either with the instructor, or better still, in small groups. They will only learn how to use these charts if they practice using the diagrams.
- Reluctance to apply rigorous methods to simple problems. Yes, this problem is significant enough to mention twice.
- Integration of “old” material into subsequent chapters. Student are going to tend to compartmentalize knowledge from each chapter (or each

homework assignment, each exam, etc.) and not internalize the concepts into their problem-solving repertoire. Blending lectures in a manner that bridges the chapter divide, using problems that draw extensively on previous topics, and even giving quizzes on material covered earlier in the course can help develop anchors to key elements in a course as they move on to new topics.

Some best practices and useful tools that we have used (or discovered) for this course are:

- Emphasize importance of communication in problem solving¹⁹. Requiring students to submit a solution or two that meets corporate standards can be a useful exercise in developing students' communication skills. Overuse of such a requirement can distract from the problem-solving objectives, so use sparingly.
- Teaching by analogy²⁰. Using simple analogies for explaining confusing topics like mass / mole fractions, steady-state, specific volume, saturated air, and others can help students grasp topics that might elude them from lecture and reading alone. Analogies provide a link between what the student already knows and what you are trying to teach them.
- Mass and energy balances on the human body²¹. In this module students are asked to measure flows and compositions using a medical gas analyzer while exercising and at rest. They then apply several ChE fundamental principles (ideal gas law, partial pressure, stoichiometry, relative humidity, heat of reaction, work, efficiency, and process simulation) to analyze their results.
- Starting the unit operations early in the curriculum²². The equipment is already in the laboratory, so why not use it within the material and energy balance course? This allows for introduction of measurement, application of conservation laws, and an introduction of the fundamentals of design. Any time students can apply knowledge to a real task, they will learn better.
- Incorporating programming with templates²³. Programming is an effective way of teaching students numerical methods. The problem with programming is that it often has significant overhead (input/output, user interface, etc.) that has nothing to do with the objectives of an assignment. Using templates, or "almost finished" programs lacking only the numerical method code, enables students to focus on implementing the numerical method and concentrate on the learning objectives for the assignment.
- Student-centered teaching²⁴⁻²⁶. This reference provides a host of suggestions for the material and energy balance course, including: developing a well-structured team approach to homework, posting homework answers (but not solutions), giving open book exams, and developing clear objectives and exam study guides to aid in student learning.
- Psychrometric chart applet²⁷. This applet allows the user to calculate properties of humidified air, and helps students understand how to use the

psychrometric chart. It also frees up valuable lecture time when assigned to students to study on their own and then assessed through in-class active learning exercises.

- Richard Felder's Resources in Science and Engineering Education Website²⁸. This is a popular site containing a link to the stoichiometry course taught by the textbook²⁹ author. The site also contains links to Excel tutorials³⁰. Furthermore, there are many links to information on using active learning in your courses.
- Graph paper website³¹. Assuming you still expect students to learn fundamentals of graphing like use of logarithmic axes, these papers will come in handy.

Fluid Mechanics

Fluid mechanics has an interesting history within Chemical Engineering programs³². It developed from steam and gas technology for industrial chemistry and chemical engineering needs. From this evolved Unit Operations, which helped make chemical engineering a unique field. Meanwhile, fundamental studies in fluid mechanics were quite popular (and remain so) in the literature. This research work became integrated into the chemical engineering curriculum mostly due to the *Transport Phenomena* text³³.

Trouble spots for this course include:

- Students may possess weak math skills. Instructors can develop handouts to step students through difficult solution processes (such as solving differential equations). Have them practice with in-class problems and homework before testing them.
- Difficulty in connecting highly theoretical content to real industrial applications – if there is an internet connected computer and projector in the classroom, instructors can use online and/or laboratory demonstrations to make a strong connection. This connection can also help students with their following classes.
- Students often do not know order-of-magnitude values for pressure drops, velocities, Reynolds numbers, etc. The teacher can provide them with general values on a handout they can paste in the front of their textbook
- Students struggle with when to eliminate terms in the governing equations. If they are provided with handouts to step them through difficult solution processes (such as solving differential equations), they will be prepared for more advanced homework and exam questions.

One major advantage of teaching a course in fluid mechanics is the visualization that could be easily brought into this course. Some best practices that we have used (or discovered) for achieving this in the fluids course are:

- Ford's paper on "Water Day"³⁴ developed several observation stations so that students can visualize continuity, the Bernoulli equation, conservation

of linear momentum, the vena contracta effect, and relative and absolute velocities.

- Incorporate high school outreach into the course
 - Using pressure concepts³⁵
 - Using a tank-tube viscometer experiment³⁶
- Use unit operations and/or research laboratories
 - Unique experiments have been developed by Fan³⁷ who discusses flow surrounding a bubble, two phase theory, flow segregation, phenomena of bubble wake dynamics, and computational fluid dynamics of particulate systems).
 - Particle technology is a field which offers a large number of simple experiments that can be brought into the classroom³⁸. These include wet powder systems (single-particle settling, hindered and lamella settling, sedimentation and flocculation, interparticle force effects on colloidal suspension rheology, wetting behavior of dry powders, and granulation coalescence behavior) and dry particle systems (hopper flow, consolidation effects of powder flow, particle dilation, wall friction, segregation during hopper flow, vibrational segregation, fluidization, and flow improvement due to powder agglomeration). There is also a CD³⁹ and website⁴⁰ available with additional powder technology education information.
 - Golter et al.⁴¹ have developed a methodology to teach students fluid mechanics and heat transfer inductively. Many of their modules are see-through to aid in visualization. These include Reynolds dye/flow-through clear pipe, pressure drop through fittings and valves, flowmeters (Venturi, orifice, and Pitot tube), extended surface heat exchangers, kettle boiler / steam condenser, 1-2 shell and tube heat exchanger, fluidized bed (compressed air through sand), and a double-pipe heat exchanger.
 - Wright et al.⁴² introduced bioseparations through a three-part laboratory experiment. This includes bed expansion characterization under fluidization conditions, tracer studies, and protein adsorption studies.
 - Other experimental unit operations that could be demonstrated include agitation and aeration⁴³, solid/liquid and liquid/liquid mixing⁴⁴, and compressible flow analysis⁴⁵.
- Use fluid mechanics videos from the web
 - Most notably is the “Fluid Mechanics” video series starring Prof. Hunter Rouse of the University of Iowa. These videos are available online at the Iowa website⁴⁶. General topics include the introduction to the study of fluid motion; experimental principles of flows; characteristics of the laminar and turbulent flows; fluid motion in a gravitational field; form drag, lift, and propulsion; and effects of fluid compressibility.
 - There is also the “National Committee for Fluid Mechanics Film Series⁴⁷” with sample topics: aerodynamic generation of a sound,

cavitation, channel flow of a compressible fluid, deformation of a continuous media, Eulerian Lagrangian description, and flow instabilities.

- Use commercially available software
 - Computational Fluid Dynamics (CFD) case studies in the fluids course⁴⁸ and for fluid-particle flow⁴⁹
 - COMSOL modules for fluid dynamics and heat and mass transfer applied to fuel cells⁵⁰
 - Use of Mathematica⁵¹ to analyze non-Newtonian flow systems

Introductory Thermodynamics

This course is normally the first of two thermodynamics courses where fundamental thermodynamics concepts are introduced (1st and 2nd Law of Thermodynamics) while solution properties are normally not discussed. Processes and equipment are emphasized, including various thermodynamic cycles and the analysis of their components (turbines, compressors, throttling valves, etc.) The course enrollment can also contain non chemical engineering students, so the instructor must also be aware of issues that mechanical or civil engineers may encounter in their careers.

German Physicist Arnold Sommerfeld said it best when discussing the topic of thermodynamics:

Thermodynamics is a funny subject. The first time you go through it, you don't understand it at all. The second time you go through it, you think you understand it, except for one or two small points. The third time you go through it, you know you don't understand it, but by that time you are so used to it, it doesn't bother you any more

The subject of thermodynamics can be confusing due to a number of issues, but most notably the lack of an intuitive feel for certain integral concepts, such as entropy, internal energy, fugacity, chemical potential, etc. Recently one of us observed, in research involving student-prepared study guides, that entropy and the 2nd Law of Thermodynamics are the most confusing topics. In fact, students did not put much information, if at all, on their study guides for these two topics not because they were comfortable with them, but because they had a poor understanding of the topic. This manifested itself in exam scores on problems with these concepts⁵².

One way to connect this concept to students is through unique, non-lecture methods. Kyle discusses the mystique of entropy, applied to a wide range of fields including cosmology, time, life, and art⁵³. Muller integrates 2nd law concepts into common life experiences and economic theories⁵⁴. Foley presents a view of entropy as a quality of energy degraded⁵⁵. There are also newer

thermodynamic terms that are gaining in popularity, including exergy (maximum work done by a system which brings it into equilibrium with a reservoir) and emergy (the cost of a process or product in solar energy equivalents).

Another problem that students face with thermodynamics is the strong importance placed on the use of differential calculus concepts. While students have normally been exposed to all of these concepts in their Calculus sequence, the act of placing it in a thermodynamic context often proves a significant barrier. Working with $F=F(x,y)$ is, seemingly, different than working with $P=P(T,v)$. Accordingly, the thermodynamics instructor has two options. The first involves re-teaching the fundamental concepts of differential, partial derivatives, meaning of integrals, etc. within the thermodynamics course. The second is to work with the people who are teaching students these math concepts, which are Mathematics Faculty members. If chemical engineering (or any engineering) faculty were to work with Calculus instructors to provide context to some of the math they are learning, this would mitigate the need for the remedial work when they arrive in the classes that depend on this knowledge.

Other new ideas associated with this course include:

- Incorporation of biological concepts in addition to traditional chemical engineering examples. For example, Haynie⁵⁶ describe the irreversible increase in entropy involved in how a grasshopper jumps. Additional problems are available in this area as part of the Bioengineering Educational Materials Bank⁵⁷.
- Development of a Personalized Class Binder⁵⁸ which requires students to put class notes, handouts, in-class problems, quizzes, exams, and homework into a binder. The binder is graded at various points during the semester. Students are also required to rewrite the notes neatly for inclusion in the binder and to show reworked exams, quizzes and homework. Finally, the binder will include brief biographies of the scientists mentioned in the course which goes towards humanizing the subject matter.
- Creative Expression Day, where students make visible posters that can be placed above the chalkboard which contains various concepts or formulas important for the course. Students can then easily “view” this information during the whole semester.
- Extensive use of NIST WebBook for data to perform any of a number of comparisons of involving polar and nonpolar substances⁵⁹.

Do note that many articles in the journal *Chemical Engineering Education* have been written on thermodynamics problems, especially in the “Class and Home Problems” section. Some notable ones include a powerful example on energy consumption relating the 2nd Law by Fan and co-workers⁶⁰, an open-ended design estimation problem from Lombardo⁶¹, and the description of an experimental vapor-liquid equilibria laboratory at the University of Delaware⁶².

Trouble spots for this course include:

- Second law of thermodynamics. One idea is to use the statistical nature of entropy as an introduction as well as the work of Foley⁵⁵ and Fan⁶⁰.
- Translating concepts of mathematics into this course. Rather than assume knowledge of differentials, partial derivatives, etc., spend some time to remind students of these concepts.

Equilibrium-Staged Separations

This course typically combines steady state material and energy balances with phase equilibrium to form the student's first experience with equipment design. Students apply equilibrium relationships to the design of staged separations equipment. Typical operations include flashes, cascades, absorption, stripping, binary distillation, and extraction. This course may also cover rate-based processes such as membranes, adsorption, and ion exchange.

Graphical methods are used to learn conceptual relationships and for order-of-magnitude design. Analytical methods are then used as rigorous design tools and provide a foundation for simulation.

Trouble spots for this course can include:

- Reluctance to show work; Reluctance to apply rigorous methods to simple problems; Trouble with thermodynamic diagrams. These are problems encountered in earlier courses and have been discussed in the Material and Energy Balances portion of the paper.
- Looking for "answers" instead of trends. Students often fail to see that the point of solving model equations (outside of homework and exams) is not to find a particular number. Models are always approximations or subject to other forms of error. The real value of models is in simulation to determine answers to questions like "What happens if my flow rates vary +/- 50%" or "What would be the effect of a malfunctioning thermocouple?"
- Expecting rigor in graphical approximate solutions. You will need to constantly remind and reinforce the fact that assumptions are being made throughout the course. Some of the assumptions may not be significant (equimolar counter diffusion for a binary distillation with similar substances) or may change the character of the entire separation (use of inappropriate thermodynamic models).
- Disconnect between theory and simulators. If students do not learn how to use a process simulator for separations as they learn theory, they will have difficulty reconciling the terminology used in their text and the input fields in the simulator. Fostering that connection throughout the course makes use of simulators more effective.

Some best practices that we have used (or discovered) for this course are:

- Ask the experts. Sometimes we do not teach the courses for which we have the most relevant experience. Both Chemical Engineering Progress⁶³

and Chemical Engineering Magazine⁶⁴ routinely publish relevant articles on separations applications on a regular basis. They are written at a level that students can often understand better than their textbook.

- Bring in the history of the field⁶⁵. Separations have been performed for millennia. The earliest recorded use of distillation dates back to 50 B.C.; it was used in the 12th century for ethanol processing; and in the 16th century was widely used for perfumes, vinegars, and oils. Occasionally interrupting terribly interesting technical lectures with historical anecdotes can renew student interest in a lecture while giving them perspective on their current course of study.
- Use literature from industrial suppliers⁶⁶. Many manufacturers and distributors of industrial equipment have useful applications papers describing not only their equipment in particular but general concepts as well. A web search will easily find vendor articles like “Factors Affecting Distillation Column Operation”, “Evaporator Handbook” and “Liquid-Liquid Coalescer Design Manual”. These are also written at a very accessible technical level.
- Wankat’s “Why, What How?” approach. Establish why you’re teaching something (economics, core of chemical engineering), what exactly you’re teaching (equilibrium staged separations), and then teach it using best pedagogical practices (lecture with simulation labs, inductively structuring the course, using both graphical and then analytical methods, and then reinforcing with laboratory exercises and design projects)⁶⁷. This process should lead to a deeper understanding of the subject.
- Levels of understanding⁶⁸. Dahm combines Wankat’s approach with Haile’s Special Hierarchy of understanding to give a specific possible formulation of the levels of understanding in teaching separations.
- Separations using spreadsheets⁶⁹. Working with students to develop an analytical approach to graphical separations on a spreadsheet forces a connection between the graphical methodology and the theoretical underpinnings. Automating shortcut separations develops an understanding of what is required to be known in what order.
- Use of commercial simulation⁷⁰. Use of commercial simulators in the classroom enables a range of inductive exercises to be incorporated into a course. Instead of performing time-consuming laboratory exercises (which do have an esteemed place in the course) to explore a piece of equipment, experiments can be performed virtually with the simulator, enabling students to observe results and draw conclusions. When the theory is later discussed, students have a framework of understanding whereby they can assimilate the salient points of the discussion.

Use of Active Learning

Studies have shown⁷¹⁻⁷⁵ that students typically learn best in an active mode; however, engineering is usually taught as lectures. The use of active learning is underscored in teaching textbooks⁷¹⁻⁷² and those intended for the new professor⁷³ as well as in numerous conference proceedings and engineering education archival publications and conference proceedings. A good listing of references are presented by Smith⁷⁴ and by Dyrud⁷⁵.

A great deal of information on improving student-teacher interaction through active learning is presented at the National Effective Teaching Institute (NETI)⁷⁶ and the Excellence in Engineering Education (ExcEEd)⁷⁷ workshops. One former attendee and active learning advocate is Ken Reid who highlighted the positive experiences in his classroom⁷⁸, and summarized simple ways that faculty can increase active and collaborative learning in their lectures and within the laboratory⁷⁹.

Improving student motivation may also improve learning, as was recently illustrated by Newell who developed a game based on the reality television show "Survivor" within a material and energy balance course⁸⁰. Newell referenced the student motivation classifications of Biggs and Moore⁸¹:

1. Intrinsic – learning because of a desire to learn
 2. Social – learning to please others
 3. Achievement – learning to enhance one's position
 4. Instrumental – learning to gain long-term rewards
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- Think-pair-share – think for 1-2 minutes, talk with neighbor for 1-2 minutes, then share answers with the rest of the class)
 - Poll the audience – with a show of hands, colored notecards, or clickers
 - Minute paper – the students write down 1-2 ways to do something, then the instructor solicits answers from the students. This is also a good way to get anonymous feedback on the course content, what the "muddiest" point of a lecture is, etc.
 - Engineering Education articles from Rich Felder²⁸ – this site highlights recent teaching methods that have been proven to improve student learning
 - Use of Quiz Shows - Within the chemical engineering education literature, a popular way to use active learning within the classroom is through quiz shows such as "Jeopardy" or "Trivial Pursuit"⁸², "Hollywood Squares"⁸³, and professor-created games such as "Green Square Manufacturing,"⁸⁴ "True Blue Titanium Game,"⁸⁵, "Chemical Engineering Balderdash,"⁸⁵ and the "Transport Cup."⁸⁶ Although these games usually only address the knowledge or comprehension component of Bloom's taxonomy⁸⁷, these games certainly address the social and achievement components of Biggs

and Moore. Newell⁸⁰ found that the “Survivor” game addressed all four motivation categories and improved student learning.

Conclusions

This paper has described some of the best practices for use in the following lower level chemical engineering courses: freshman chemical engineering, material and energy balances, fluid mechanics, introductory thermodynamics, and separations. For copies of the presentation slides from the Summer School, contact one of the authors.

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