Using Space Travel to Teach Engineering to Liberal Arts Majors

Roger Chapman Burk
Department of Systems Engineering
United States Military Academy, West Point, NY

Abstract

This paper describes the author's experience developing and delivering a new course for non-engineers at a top-ranking national university. It covers the educational philosophy behind the course, how it was designed, and the results of teaching it. The core idea was to use the natural fascination of space travel as a vehicle to help non-engineering students learn basic engineering principles and have fun doing it. The course was interdisciplinary, including lectures on relevant science, literature, and history, as well as on rockets, orbits, launches, re-entries, spacecraft subsystems, and human factors. The focus was on what would be needed for routine interplanetary and interstellar manned spaceflight, but we also covered the important considerations for current space operations. The intent was that at the end, the students would not be in a position to start designing a space ship, but they would understand why they are designed the way they are. The author found that this course was excellent for its purpose. It excited interest in students otherwise uninterested in engineering. The variety of topics demonstrated a wide selection of engineering methods and concepts, and also provided variety and kept interest alive. Weekly computer labs used orbit simulations that provided beautiful and absorbing visualizations, and also gave experience in mission design. As a final integrative experience, teams of students quantitatively evaluated space travel proposals and presented their results to the rest of the class. The students enjoyed the class and came out of it with a much more sophisticated understanding of space flight and of engineering in general. Reservations and difficulties include: finding qualified lecturers for the diverse set of topics; integrating their presentations into a coherent whole; and a lingering question how well such a course would work with a less gifted set of students.

Introduction

The purpose of this paper is to convey and reflect on the author's experience developing and delivering a course on engineering for non-engineers, with the hope of finding better ways to teach engineering topics to students who usually learn very little about them. The course was innovative in three areas: gave a quantitative understanding of engineering design to liberal arts majors, it based on solving an interesting engineering problem rather than on the basics of any engineering discipline, and it was interdisciplinary, including excursions into history, literature, science, ecology, and philosophy. The problem area was that of manned space flight, which was chosen because of its inherent fascination for many people, because it provided opportunities to touch on a wide variety of engineering topics, and because of the author's background in the subject. The author found that this approach did succeed in attracting a variety of students who otherwise would learn little of engineering, and in engaging them in the subject and giving them a basic quantitative understanding of some aspects of the subject. Of course, the approach was not without its difficulties, including the problem of integrating very diverse material. On the whole, the author found that the approach worked well and recommends it for further development.

The rest of this paper is in five parts: (1) An account of how and why the course was developed and its educational goals; (2) The design of the course, including the syllabus; (3) Observations on the types of students who took the course; (4) The students' assessment of the course; (5) The instructor's experience, assessment, and recommendations for using this course or a similar one to teach engineering to non-engineers.

1. Genesis and Educational Goals of the Course

The primary motivation for the course was the instructor's experiences with students taking a "core engineering sequence" at the U.S. Military Academy at West Point. West Point students (cadets) can major academically in their choice of a wide variety of subjects, including engineering, economics, and science, but also including history, management, leadership, foreign language, literature, and other non-quantitative subjects. However, they are all required to take a broad core curriculum that includes physics, chemistry, calculus, and statistics, as well as (for those not actually majoring in engineering) a core engineering sequence of three upper-division courses that introduce an engineering discipline such as civil, mechanical, environmental, nuclear, or systems engineering. The author interacted with students taking the third course in the systems engineering sequence; he acted as a surrogate client for several group projects. In conversation with these students, he found that they considered the sequence dry and uninteresting. They saw little point in learning the foundations of an engineering discipline that they were never going to apply. They did not have the perspective to understand the importance of the basic logical structures they were taught, and they did not understand the usefulness of the modeling techniques. The integrative group project in the third course was often too simple to really require the systems engineering techniques they were taught. On the other hand, the problem had to be simple because the students did not have the skills to tackle a complex problem. The author found in one case in which a group was introduced to a problem that was clearly beyond them, and then given some basic modeling techniques to address its basic features, their level of interest increased markedly. Meanwhile, the author was advising a team of engineering majors working on a capstone project for NASA's Marshall Space Flight Center and investigating the logistical requirements for a Moon base. The author observed that the excitement and romance of space flight really caught the imagination of these engineering students, and he got about twice the work from very busy cadets than he normally got from a capstone team. These two experiences led the author to think that a course that was problem-based rather than discipline-based, and linked to a naturally fascinating subject like space travel, might be a better vehicle for teaching engineering to engineers than existing West Point three-course engineering sequence.

The author arranged to spend his sabbatical year at Princeton University, whose Center for Innovation in Engineering Education (CIEE) includes in its mission teaching engineering to non-engineers, so that he could try out this idea. He received support from both the CIEE and from Princeton's Department of Mechanical and Aerospace Engineering (MAE) to work on it, as well as from his home department at USMA. He outlined the course in cooperation with a member of the MAE faculty, who however left Princeton before the course was delivered. The core idea of the course was to use the natural fascination of space travel as a vehicle to help non-engineering students learn basic engineering principles and have fun doing it. It was based on the idea that a non-specialist can get a lot of insight from basic quantitative relationships without having to go into all the details that a professionally-trained engineer would. At the end, the student would not be in a position to start designing a space ship, but he or she should be able to understand why they are designed the way they are. The title of the course was "Faster and Higher: The Romance and Reality of Space Flight." The objectives of the course were as follows:

1. Impart a basic knowledge of the capabilities and limitations of scientific inquiry and technological development.
2. Provide an understanding of the relationship between romantic or visionary ideas of space flight and its practical realities.
3. Provide a practical quantitative understanding of the basic scientific and engineering principles of space flight and the limitations they impose.
4. Develop the analytical tools and skills necessary to evaluate ideas for space flight and distinguish among the imaginary, the possible, and the practical.
5. Provide an understanding of how to make the tradeoffs involved in engineering design of a complex system.

6. Develop general college-level intellectual skills: clear thinking, orderly reasoning, good verbal and written communication, intellectual curiosity, disciplined problem-solving, self-confidence, perseverance, etc.

The course was also designed to meet a Princeton distribution requirement in “Science and Technology,” which meant that it had to include a laboratory component. All Princeton students are required to take two “S&T” courses. This was an additional incentive for liberal arts students to take the course. The required preparation for the class was limited to algebra, a little calculus, and good high-school science. It was open to all class years. Engineering students were welcome on the grounds that their knowledge would enrich the class; they were expected to find the technical approach elementary but would get a comprehensive overview of the space flight problem. They were limited to no more than 25% of the available seats.

2. Course Design

The catalog description of the course was:

> This is an introductory aerospace engineering course for non-engineers. It gives an elementary technical understanding of what it takes to explore and operate in outer space. We will cover the history of space flight, the space environment, rockets, orbits, launches, re-entries, spacecraft subsystems, and human factors. Students will work with the technical tradeoffs in space mission design in weekly computer labs. Guest lecturers from the engineering and scientific communities will present case studies. Towards the end of the course students will lead critical evaluations of realistic science fiction and visionary non-fiction.

The structure of the course started with a review of ideas about space travel found in realistic science fiction literature and visionary non-fiction such as O’Neill’s proposals for space colonies in *The High Frontier* (Anchor Books, Garden City, NY, 1982). This would be the hook for capturing interest. A set of lectures on the space environment followed. Then came the bulk of the course, covering the various technologies involved in space travel and the constraints they impose. Much of it was on basic orbital dynamics, to give an understanding of the velocities needed for space travel, and on the physics of rocket propulsion and the ideal rocket equation to convey the practical difficulties of achieving those velocities. Launch and re-entry problems were only touched on because of their analytical complexity, but the students were asked to do a simply numerical integration of a re-entry trajectory using Excel. Other lectures described the major engineering considerations of spacecraft subsystems: structures, electrical power, attitude control, guidance and navigation, communication, environmental control and life support, and thermal control. One lecture covered spacecraft system integration, and another covered mission operations. For an integrative experience, the students were put in teams and asked to use the methods they had learned to quantitatively analyze some idea for space travel of their own choice taken from imaginative or technical literature. The teams presented their results to the rest of the class in final meetings of the course.

In accordance with the Princeton academic calendar, the course was presented in two 80-minute lectures per week for twelve weeks. The titles and contents of the 24 lessons are shown in the following table, which shows both the variety of topics covered and their inherent interest for most people.

Syllabus

Block I: History of Space Flight	**1. Romance** History of science fiction, particularly realistic or “hard” SF. Mythology. Newton’s realization that terrestrial physics also applies to the heavens. Jules Verne. The pulps. The realism of Clarke, Asimov, Heinlein, Harrison, Card, and others. The fantasy alternative. This is to hook students interested in literature.
	2. Reality: Science, War, and Business Pioneers of rocketry—Tsiolkovsky, Goddard, and Oberth. The interplanetary societies. Von Braun’s *Collier’s* pictorial articles. The Space Race—Mercury, Gemini, Apollo. The denouement: Skylab, STS, ISS. New societies—L5, National Space Society. NASA’s Space Exploration Initiative (1990-91) and Vision for Space Exploration (2004-??). Utility of space for national defense, scientific exploration, and commercial exploitation (communications, earth resources, thrill rides, etc.). Interplay of the impulse from romance and the check from reality. This is to hook students interested in history.
Block II: Space Environment	**3. Into the Void** The scale of the Solar System and of interplanetary space. Vastness and emptiness. Atmosphere and altitude. The “no-fly zone” between the lowest sustainable orbit and the highest possible aerodynamic flight. Micrometeoroid and debris dangers. This block should hook students interested in science.
	4. The Radiation Will Nearly Kill You First of two lessons on why outer space is dangerous and uncomfortable for humans. Solar radiation. Heating and cooling effects. The solar constant. Dangers from the quiet sun, solar flares, and galactic cosmic rays. Van Allen belts. Shielding requirements.
	5. Only the Hope of Dying Will Keep You Alive Other reasons to avoid space travel. Crushing from acceleration. Space sickness (“everything leaves by the nearest exit”). Bone deterioration. Confinement, isolation, and overwork. Beneficial effects of men in space—pattern recognition, adaptation, inventiveness. Deleterious effects of men in space—carelessness; mass; low duty cycle; contaminants; vibration; huge overhead for life support, quality of life, and assured return. This illuminates the engineering tradeoffs between manned and unmanned systems.
	6. What's There for Us? Based on our reconnaissance of the Solar System so far, just rocky deserts. Is it really worth it to go there? Are there any resources worth going there for? Eventually, can we move heavy industry and power generation there, and turn Earth into a garden? There is a hook here for students interested in sustainability. This was a guest lecture delivered by a planetary scientist.

Block III: What Makes Spacecraft Fly	**7. Orbit Appreciation** Basic orbital motion. Newton's laws. Conservation Laws. Restricted two-body problem in a plane. Constants of the motion. Orbital velocities. Why orbits anyway? What if you let yourself fall? What if you hover?
	8. What's *v*? Orbit description and classification. Classical orbital elements and state vectors. Common mission orbits.
	9. This Is Rocket Science How you achieve those velocities when floating in free space. The ideal rocket equation. Exhaust velocity and specific impulse. Implications for mass fraction. Practical structural limits. Advantages from staging. A peek at rocket motor fluid dynamics. Launch vehicles.
	10. Exotic Propulsion Propulsion other than thermodynamic chemical rockets. Non-chemical rockets: resistojet, nuclear, etc. Non-thermodynamic rockets: ion, plasma, mass driver. Non-rockets: linear accelerators, space elevators, solar sails, etc. Available technology and physical limits. Thrust vs. specific impulse. This was a guest lecture delivered by a MAE faculty member whose research area is electrical propulsion.
	11. Orbital Maneuvers Hohmann transfers. Plane changes. Escape trajectories.
	12. Interplanetary Travel Coplanar patched conics. Dangers from Earth-crossing asteroids (a hook). A mission to 99942 Apophis.
	13. Celestial Billiards The practical difficulties of direct flights to outer planets. Coplanar gravity assist trajectories. Historic banks shots: Mariner 10, Pioneer 11, Voyager II, Cassini-Huygens, Far Horizons.
	14. You Can't Get There from Here Time and distance constraints for non-relativistic interstellar flight. Desperate measures—suspended animation, generation trips. Relativistic rocket equations. The physical limit: exhaust velocity = c. Relativistic time dilation. The implication of Special Relativity that faster-than-light travel of any sort would produce impossible paradoxes of causality. (Hooks for those interested in such philosophicalities.)
	15. Orbit Prediction; Launch Windows Beyond the two-body problem: orbital perturbations. Orbital planes, launch window, orbital inclinations, and initial eastward velocity.
	16. Burn, Baby, Burn! Re-entry trajectories. Numerical integration of reentry through idealized atmosphere on non-rotating planet. Remarks on dealing with heating. Advantages of aerobraking.

Block IV: Spacecraft Systems	**17. Built by the Lowest Bidder** Overview of spacecraft systems engineering. Case study. This was a guest lecture delivered by the principal investigator for a NASA mission under development.
	18. Attitude Adjustment Hour Attitude control—disturbing torques, attitude sensors, passive and active actuators, detumbling. Autonomous orbit determination.
	19. Glow in the Dark Electrical power generation—chemical, solar, nuclear. Power storage. Hooks to terrestrial nuclear power generation. Basic concepts of communication and data handling. Beam width and data rate. Link budgets.
	20. Excrete Today, Drink Tomorrow Environmental control and life support systems. Open and closed loops. Biological input/output mass balance. Hooks to terrestrial environmental issues. Thermal control—thermal inputs; conduction, convection, and radiation; transmissivity, absorptivity, and reflectivity. Basic considerations for structures and mechanisms.
	21. Hello, This Is Mission Control This lesson was devoted to watching s Discovery Channel program on the development of NASA Mission Control during the Mercury, Gemini, and Apollo programs, including the handling of the Apollo 13 flight emergency. The hook was the human drama. This program gave and excellent picture of engineers working together, and also showed the size of the mission control effort required to support manned spaceflight.
Block V: Visions for the Future	**22-24. Visions** Student teams presented their analyses of space travel proposals from science fiction or imaginative non-fiction.

The reader will observe that no opportunity was missed to connect to topics likely to be of interest to liberal arts majors. The reader will also observe that a great deal of material was covered, necessarily very lightly. For each topic, the emphasis was first on conceptual understanding of the major issues and phenomena, and then on quantitative understanding one or two key equations or graphs that played a crucial role in the subject matter. For example, in orbital dynamics the emphasis was on equations relating orbital total mechanical energy, velocity, and radial distance; in rocketry it was the ideal rocket equation formulated to relate mass fraction, exhaust velocity, and final velocity; when discussing micrometeoroids it flux as a function of particle size. The intent was to impart enough quantitative understanding to have insight into an engineering problem without having to know enough to actually do engineering.

The required text was Jerry Jon Sellers, *Understanding Space: An Introduction to Astronautics*, 3rd ed. (New York: McGraw-Hill, 2005). This text was written for a course at the U.S. Air Force Academy that is required of all students, including liberal arts majors. It turned out to be very suitable for this course, and the students generally liked it. Its emphasis was on current military unmanned space operations, rather than on what we'd need for routine interplanetary and interstellar manned spaceflight, but still the overlap in material was substantial, and the level of presentation was good for non-engineering undergraduates. An optional text was Wiley J. Larson and Linda K. Pranke, eds., *Human Spaceflight: Mission Analysis and Design* (New York: McGraw-Hill, 1999), which was at a more technical level.

Some readings from this text were assigned for certain topics. For a few more esoteric topics (e.g. relativity) other readings were used.

The course required weekly labs that involved the use of orbit simulator Satellite Toolkit by AGI to illustrate concepts from the week's lectures and to solve simple design problems. The powerful graphical capabilities of this tool showed beautiful spinning planets and circling spacecraft. It was the perfect accompaniment to the material. AGI provided free educational licenses for the course.

Grading was as follows:

Take Home Midterm Exam	15%
Take Home Final Exam	30%
Weekly Lab Reports	30%
Weekly Problem Sets	15%
Group "Vision" presentation	10%

(Groups were assigned so as to distribute talents and backgrounds. Peer evaluations were solicited in order to mitigate freeloading.)

3. Students

The course was designed to be accessible to a freshman liberal arts major, but only a small minority of the students who elected the course met that description. Thirty-five students registered for the course, of which 30 completed a background survey. There were 6 freshmen, 4 sophomores, 8 juniors, 9 seniors, 1 graduate student, and 3 community auditors. There were 6 majoring in liberal arts, 6 in physical sciences or math, 7 in engineering, and 8 in social sciences.

When surveyed on their reasons for taking the course, the responses included:

- To satisfy a distribution requirement(14/35)
- Interest in the subject (24/35)
- Interest in science fiction (2/35)
- For fun (3/35)
- Other memorable reasons:
  - Space travel is "exotic" – "incredibly intriguing" – "the coolest" – "mysteriously fascinating" – "awesome"
  - I would "enjoy it instead of getting stressed out"
  - I'm a Star Trek fan
  - Reminds me of Discovery Channel
  - I liked the "Mission: Space" ride at Epcot
  - "Who's not fascinated by space flight?"

When surveyed on what they hoped to get out of the class, the responses included:

- Knowledge of the technology of space flight (20/35)
- Knowledge of the history of space flight (5/35)
- Ability to project the future of space flight (4/35)
- Comparison of science fiction with reality (4/35)
- Other memorable things:
  - What happened to the momentum of the space program in the 60s?
  - When will we walk on Mars? Will we ever live on the Moon? Will civilian spaceflight become common?
  - Do we have the technology to do what we dream up?
  - Whether all those cool things in the movies are possible
  - "All kinds of cool stuff"

It seemed that the expectations of the students aligned well with the design and intentions of the course. The connection to science fiction turned out to matter less than was expected: only a few of the students confessed to being real fans, and in the final group projects it didn't seem that any group used the assignment to analyze a favorite work. On the other hand, interest in the practicalities of space flight was prominent.

4. Students' Course Assessment

Surveys indicated that the students enjoyed the course and felt that they learned a lot. Fourteen students returned a survey; thirteen of them indicated that they felt the pace of the course was about right, despite the large quantity of diverse material that was covered. For a question asking what they liked about the class, the responses included:

- Interesting material (5)
- Introduction to science & engineering
- Learning dynamics without getting bogged down in intense details
- Application to real missions
- Less quantitative lectures
- Labs (4)
- Good organization

It is notable that 5/14 (36%) singled out the interesting material, and 4/14 (29%) singled out the sometimes time-consuming labs. It seemed that the strategy of building on the natural fascination of space travel and assigning labs with dynamic orbital simulations worked well.

When surveyed on how helpful the different instructional methods were to their learning, the students responded as follows:

	Extremely	Very	Somewhat	Little	Not at All
Professor's classroom instruction	6	5	3	0	0
STK Labs	2	7	7	0	0
Textbook readings	4	5	7	0	0
Working problems	6	7	1	0	0

It seems that all instructional methods worked reasonable well and contributed to student learning.

Informal discussions with the students also indicated that they enjoyed the course and felt that they learned a lot.

5. Instructor's Course Assessment and Recommendations

The instructor found that teaching the course was very demanding because of the diversity of material, not all of which he was expert in. Arranging guest lectures consumed much time, though the guests were always cooperative, helpful, and eager to teach. Nevertheless, the course was always fun to teach. A diligent graduate assistant took up the grading load for labs and problem sets, and also did much individual work with the students.

The course was extremely successful in teaching engineering principles to non-engineers. Starting with the romance of space flight and using many STK simulations captured their interest and imagination. Student learning was excellent overall. The final average class score was 92% (excluding one outlier case of catastrophic fecklessness). The final course grades included six A+'s, 9 A's, and 6 A-'s. Princeton has a grading guideline recommending no more than 40% A+/A/A-, but in fairness to the students the instructor could not meet that guideline because of the high quality of their work.

The author believes that a course like this is excellent for teaching non-engineers about engineering. The problem area does excite interest in a significant proportion of students otherwise uninterested in engineering. The wide range of topics provides variety and keeps interest alive. There are links to non-engineering topics that many liberal arts students find interesting: science fiction literature (Lesson 1), the political history of space exploration (Lesson 2), solar system astronomy (lessons 3, 4, and 6), nuclear power (19), ecology (20), and even philosophy and the implications of causality (Lesson 14). STK provided stunning, beautiful, and absorbing visualizations that both delighted the students and boosted understanding. The different topics also showed a wide selection of engineering methods. Keplerian astrodynamics (lessons 7, 8, 11, 12, 13) and the ideal rocket equation (Lesson 9) give important practical results with closed-form algebraic equations. The discussion of ideal and real rockets (Lesson 9) conveys the practicalities of making real systems that follow theoretical behavior. The lesson on atmospheric re-entry (16) uses Excel-based numerical integration and touches on thermodynamics. The video shown in Lesson 21 showed the human side of engineers at work. Towards the end of the course many students commented on how much they had learned and how interesting they found the course. The instructor believes that indeed all or most of the students will have a much more sophisticated understanding of space flight and of engineering in general.

Space flight was a suitable vehicle for this course, but other similar problem areas would probably work just as well. For instance, a similar course could be built around the problem of designing a helicopter, a submarine, or a military tank.

There are two reservations in this recommendation. Careful consideration should be given to the difficulties of organizing an interdisciplinary course like this, and to the special qualities of Princeton students as the initial test group.

Interdisciplinary courses are hard to teach because professors concentrate in single disciplines and it takes extra effort, tolerance of discomfort, and acceptance of teaching from a lesser command of the material to cross disciplinary lines. Cooperative teaching and guest lecturing can mitigate this problem to some extent, but the author found it difficult to integrate the different presenters into a common vision of what the course was designed to accomplish. Each lecturer tended inevitably to concentrate on his own area of passion, which might be the geological history of planetary surfaces, or the detection of extra-solar terrestrial planet, or something else different from space travel per se. The author had a certain advantage in this course because it built on his own interdisciplinary master’s degree. It might be more difficult for another instructor. Ideally a course like this should be taught by a team with backgrounds in all the relevant disciplines.

This course was successful at Princeton, but Princeton students are an exceptional group. When surveyed, only one of 33 students admitted to any real difficulty with math. The great majority were quite comfortable with calculus. This might not be true of a diverse group including many liberal arts and social science majors at another school. These students were very willing to work hard and showed great intellectual curiosity. A course like this needs to be carefully calibrated to the abilities of the students.

Despite these reservations, the author feels that this approach is a good one for teaching engineering to non-engineers. Properly delivered, it will convey the essentials of engineering to a diverse classroom and give them a quantitative appreciation of what engineers do, how the do it, and what it means for their lives.

Biographical Information

Dr. Burk has taught Systems Engineering at West Point since 2000. He served in the Air Force in space operations and analysis, including being the Director of the Graduate Space Operations program at the Air Force Institute of Technology (AFIT). After retiring in 1995, he worked in industry for five years, mainly in space systems engineering, before coming to West Point. He has an MS in Space Operations from AFIT and a PhD in Operations Research is from the University of North Carolina at Chapel Hill.