The Three Principles of Powered Flight: An Active Learning Approach

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Abstract

A holistic education in aerospace engineering ought to encompass not only aircraft design, but should adequately treat other flight concepts. There are three known fundamental principles of powered flight. Balloons of any kind use the principle of buoyancy. Fixed wing aircraft and rotorcraft are based on airfoil lift. Rockets make use of mass expulsion to generate thrust and change their momentum. We have developed a new approach for introducing sophomores to these principles in *Unified Engineering* in the context of a CDIO (conceive-design-implement-operate) curriculum in Aeronautics and Astronautics. The active learning approach combines traditional lectures with exposure to small hands-on experiments. The artifacts used to investigate these flight principles are helium balloons, balsa wood gliders and water rockets, respectively. The first learning objective is derived from a desire for knowledge integration of traditional aerospace engineering disciplines: dynamics, fluid mechanics, materials & structures, signal & systems and thermodynamics & propulsion. A second set of learning objectives centers around skills required by successful engineers, such as technical communications, modeling, experimentation and estimation under uncertainty. Our initial experiences are positive and suggest improved learning by mutual reinforcement of theory and practice. Student motivation and understanding of key concepts appear to be enhanced, relative to a traditional lecture-only format. Further refinement and more quantitative assessment of learning success are ongoing efforts.

1. Introduction

Traditional curricula in Aeronautical Engineering have focused almost exclusively on aircraft design. This has led to a strong emphasis on the traditional disciplines of aerodynamics, structures and controls. One may hypothesize that this is rooted in the historical importance of the aeronautical industry after World War II and the expansion of civil and military aviation in

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the 1950's and 1960's. Only with the advent of spaceflight in the 1960's and 1970's were many aeronautical departments encouraged to incorporate other domains into their learning objectives and course offerings. Today's situation in aerospace engineering shows a heterogeneous mix of applications. Commercial airliners use GPS satellites for navigation. High altitude balloons are used for monitoring and studying layers of the upper atmosphere. Unmanned aerial vehicles (UAVs) transmit high bandwidth imagery and telemetry data via communications satellites back to the ground. Rotorcraft fulfill various military and civilian missions such as rescue and resupply. This has fundamental implications for teaching the basic principles of flight.

If one considers the multitude of aerospace vehicles: piston and jet aircraft, rotorcraft, balloons, gliders, missiles, boosters, UAVs and satellites, one comes to the conclusion that there are only three known fundamental principles of powered flight: *Buoyancy, Airfoil Lift and Mass Expulsion*. Figure 1 shows these three principles along with the major vertical forces acting on each body (horizontal forces not shown). This paper discusses how undergraduate engineering students can effectively be introduced to these principles by means of an active learning approach, combining lectures and hands-on experiences.

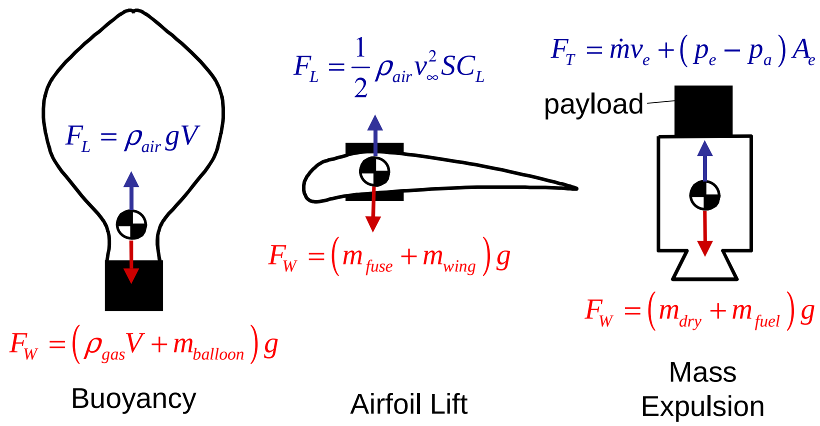


Fig.1 Three principles of powered flight – showing vertical forces only

Nomenclature

F_L	lift force [N]	g	gravitational acceleration [ms^{-2}]
F_W	weight force [N]	ρ_{air}	air density [kgm^{-3}]
F_D	drag force [N]	V	volume [m^3]
F_T	thrust force (rocket) [N]	ρ_{gas}	gas density, e.g. He [kgm^{-3}]
$m_{balloon}$	empty balloon mass [kg]	v_∞	freestream velocity [ms^{-1}]
S	airfoil reference area [m^2]	C_L	coefficient of lift [-]
m_{fuse}	fuselage mass [kg]	m_{wing}	wing mass [kg]
$\dot{m}$	mass flow rate [kgs^{-1}]	v_e	nozzle exit velocity [ms^{-1}]
p_e	nozzle exit pressure [Pa]	p_a	ambient pressure [Pa]
A_e	area of exit nozzle [m^2]	m_{dry}, m_{fuel}	rocket dry and fuel mass [kg]

2. Learning Objectives

Teaching and introducing these principles generically is a multidisciplinary challenge tackled by the systems problems in Unified Engineering [1,5]. The top-level objective of the aerospace systems problems in Unified Engineering[4] at M.I.T. can be summarized as follows:

Students in Unified Engineering will learn how to apply discipline specific knowledge in fluids mechanics, materials & structures, dynamics, signals & systems and thermodynamics to synthesize solutions to problems that typically surface in all lifecycle phases (C-D-I-O) of complex aerospace systems with the help of modeling and experimental techniques and to effectively communicate their results.

This is decomposed into measurable outcomes. Students will be able to:

1. Formulate appropriate coupled multi-disciplinary models of engineering systems based on physical laws and principles and identify the underlying assumptions and limitations of those models.
2. Conduct experimental investigations, analyze experimental results, quantify experimental uncertainty and generate simple empirical models.
3. Use physics-based and empirical-experimental models of engineering systems to evaluate proposed designs, conduct trade studies, and generate new design solutions.
4. Understand the role of aerospace engineering in a wider social context including economics, policy, safety, the environment, and ethics among others.
5. Communicate engineering results in written reports[5], using clear organization, proper grammar and diction, and effective use of graphs, engineering drawings, and sketches.

A further decomposition into individual learning objectives is shown in Appendix B. These learning objectives were established as part of the new strategic lifecycle (CDIO) orientation of the department [3,5]. This paper focuses on individual skills and measurable outcomes 1. and 2. from the above list, and to a more limited extent to outcome number 5. This is the focus of the fall semester in Unified Engineering. A team-based Design-Build-Fly (DBF) competition [2] is the focus of the spring semester. The next sections will discuss the assignments and learning activities that are aimed at meeting these learning objectives, with particular emphasis on the three principles of flight.

3. Buoyancy – Helium Balloons

The principle of buoyancy is introduced in two parts by means of common 12" latex balloons that are filled with commercial grade Helium (He). In the *first part* the students are expected to fill three 10-12" diameter latex balloons with helium and release them indoors. The release occurs inside a lecture hall with a ~20' ceiling and is intended to demonstrate relatively repeatable behavior in a quasi-controlled environment, see Figure 2. The *second part* consists of releasing several hundred balloons outdoors where they are subject to random, stochastic

[4] Course numbers 16.010-040, a 48 credit hour sequence of courses.
[5] Oral communications is not an explicit learning objective for Unified Engineering.

disturbances such as temperature and wind fluctuations. The balloons are equipped with stamped return cards such that the student's predictions in terms of flight distance and landing locations can be corroborated by actual returns.

3.1 Helium Balloons – Indoors Release

The indoors release introduces the notion of modeling by requiring the students to theoretically predict the rise time, T, of balloons from floor to ceiling, see Figure 2(a). The students are then asked to implement this model as a simple computer program to predict the trajectories of balloon position and velocity as shown in Figure 2(b). The choice of computing environment is at the student's discretion. Most students have traditionally used the MATLAB environment.

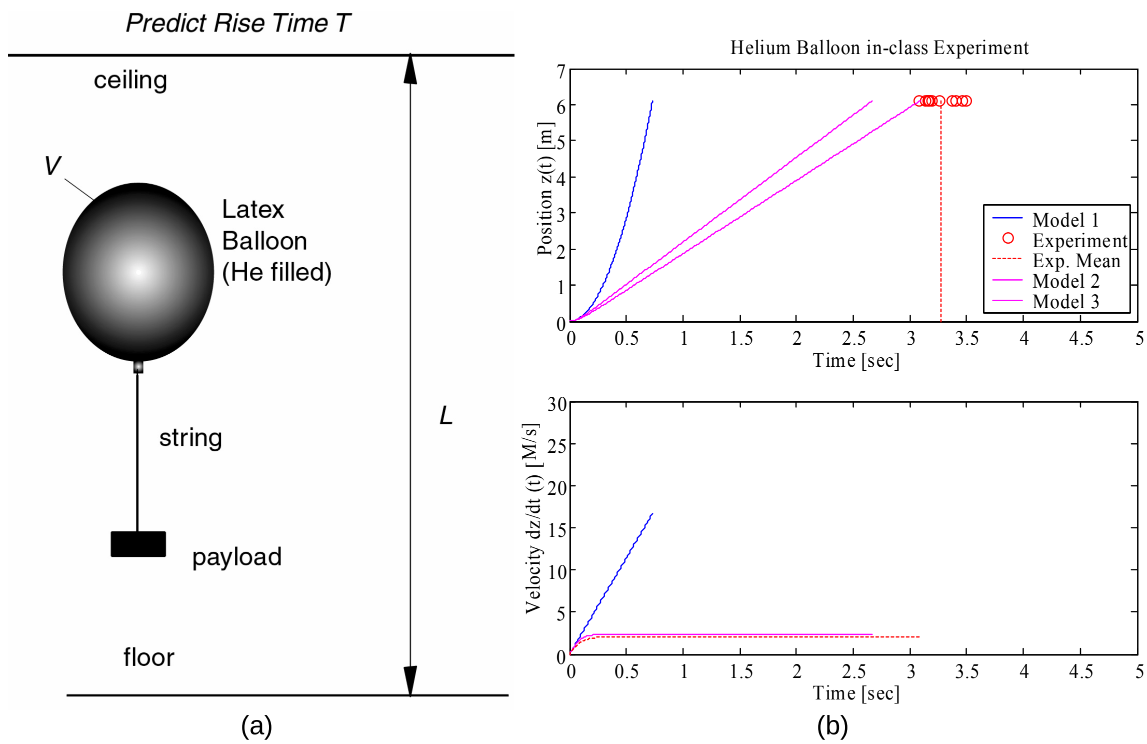


Fig. 2: Helium balloon indoors experiment, (a) Depiction of experimental situation for indoors balloon release, (b) Prediction using a computer program versus experimental data for three models of increasing fidelity. Top plot: vertical position *z(t),* Bottom plot: vertical velocity *dz(t)/dt*.

This problem forces the students to derive the equations of motion of a helium balloon, whereby $z(t)$ is the time depended variable. They write a computer program that attempts to predict the behavior of the system (rise time from floor to ceiling), given certain system attributes (volume, helium density, frontal area, balloon shape) and environmental attributes (density of the air, height of classroom). While the system attributes can be considered as independent variables (over which a designer has control), the environmental attributes must be considered as fixed parameters (over which the designer has no control). This is often the first time that sophomores are presented with such a distinction. This is also used to show the effect of increasing model fidelity by gradual removal of simplifying assumptions. The first generation model, labeled "Model 1" in Figure 2(b), is given to the students at the outset and erroneously neglects drag, thus significantly underpredicting rise time. The students are expected to detect and correct this deficiency. The resulting second generation model yields a nonlinear second order ordinary differential equation of the form:

$$\alpha\ddot{z} + \beta\dot{z}^2 + \gamma = 0 \text{ , where } \alpha, \beta, \gamma \text{ are } \textit{constants}.$$

This presents the students with a significant challenge, since a closed form solution is not known. Hence, they recognize that a finite difference integration scheme will yield the desired result:

Time dependent acceleration: $a(t) = m_{tot}^{-1} \cdot \left[-\frac{1}{2}\rho_{air} C_D A v(t) + (\rho_{air} - \rho_{He}) V g - m_b g \right]$

Time dependent velocity: $v(t) = v(t - \Delta t) + a(t - \Delta t) \cdot \Delta t$

Time dependent position: $z(t) = z(t - \Delta t) + v(t - \Delta t)\Delta t + \frac{1}{2} a(t - \Delta t)\Delta t^2$

We refer to the earlier nomenclature for an explanation of the variables. This problem achieves several goals at once. First it demonstrates the principle of buoyancy in a practical fashion. Next, it forces the students to find the equation of motion and solve it using a computer program. Thirdly, it stimulates critical reasoning by comparing experimental data (rise times obtained with stop watches) versus theoretical predictions. Many students were humbled by this seemingly trivial experiment, when their initial rise time estimates were off by more than 20%. Gradually they were able to identify sources of modeling error such as the drag coefficient, C_D, or the helium balloon volume, V. Even though the rise times for the same balloon generally exhibited a coefficient of variation, $C = 100\% \cdot \sigma_T / \mu_T$, on the order of 2-5%, this was presented to the students as a "deterministic" situation with no important random parameters.

3.2 Helium Balloons - Outdoors Release

The next step was to release 244 helium balloons outdoors (class size was 70 students) with stamped return cards attached. In this problem the students were asked to create a crude model of how the helium balloons behave outdoors and how the environment affects their behavior, leading to a stochastic (random) response. Since not all students have a background in probability and statistics at this point, we didn't expect them to work with probability density functions (pdf). Rather they were allowed to work with estimated +/- % upper and lower bounds around mean values. This was a first introduction to estimation and qualitative analysis (2.1.3) as well as analysis with uncertainty (2.1.4), see Appendix B.

The key considerations the students had to take into account here were:

- Estimation of equilibrium or helium balloon burst altitude
- Estimation of helium leak rate and time aloft
- Winds aloft direction and speed
- Estimation of the percentage of mailed returns

The helium balloons that were released had an average volume of $V = 0.0119$ [m^3], see Figure 3. This allowed obtaining an estimate of the equilibrium altitude as: $z(V = 11.9 \text{ [lt]}) \approx 5196 \text{ [m]}$ +/-

1000 [m]. An interesting study about outdoors releases of latex helium balloons was previously compiled [3] and used to compare the class results.

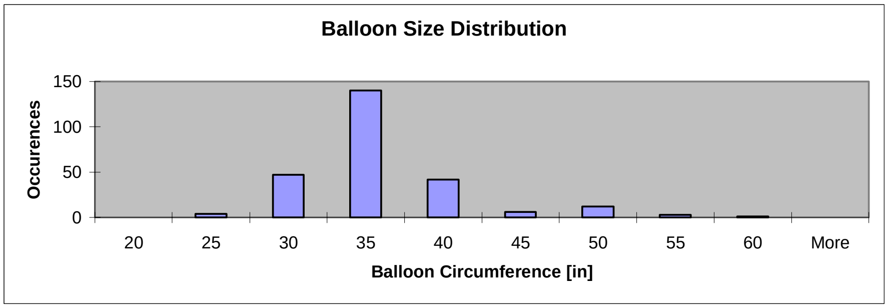


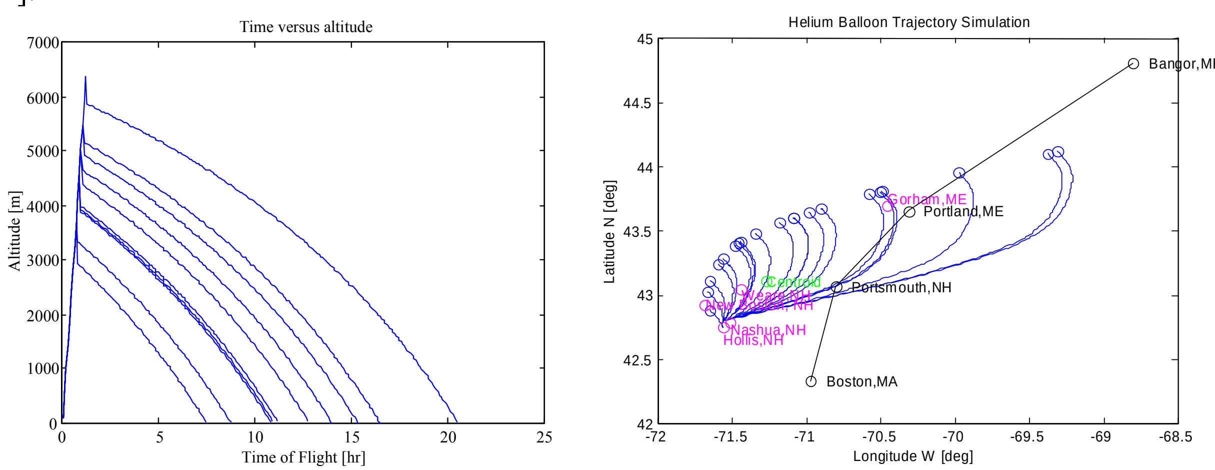
Fig. 3: Student helium balloon circumference histogram

The incoming misconception of most students was that all balloons were identical and that, if released at the same time, there would be no differences in how the environment affects them. Therefore, they should land at exactly the same place as a tight cluster. The students learned from experience and analysis that this is not true, a sharp contrast to the indoors experiment.

The day and location of the balloon release was as follows:

Location: Hollis, NH – Lat 42.751 N – Lon 71.56 W – Date: October 9, 2002

The outdoors helium balloon release was recreated for the students using a Monte-Carlo simulation. The altitude trajectories of the balloons (sample of 10 shown) as a function of time are shown in Figure 4(a). The balloons rise rapidly within 30-60 minutes to their equilibrium altitude. Because of the volume variations the equilibrium altitude ranged from ca. 3000-6000 [m].



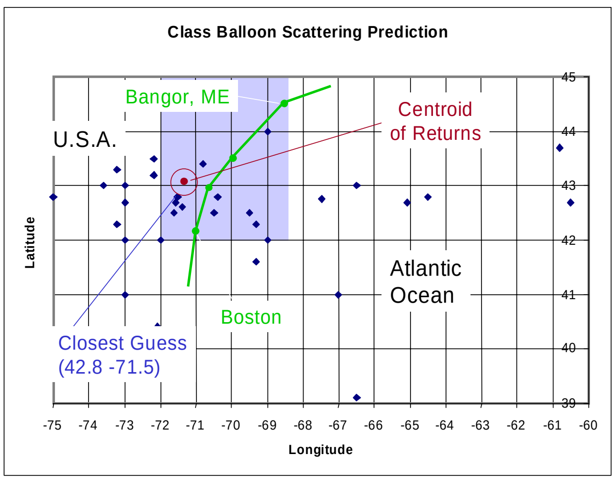
(a) (b)

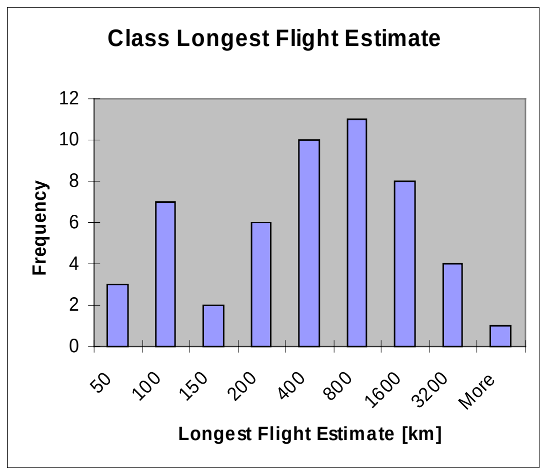
Fig. 4: Outdoors balloon release experiment: (a) Vertical flight profile simulation, (b) horizontal ballon trajectory estimates. Circles with city names show actual returns.

Since helium is constantly leaking from the balloons at a rate of roughly 0.4 lt/hour they gradually sink back to Earth. The larger balloons generally float longer. The expected landing sites are shown in blue circles in Figure 4(b). The New England shoreline with some important port cities is also shown. We received 3 actual returns as of October 30, 2002, see the circles in Figure 4(b). The return locations were:

Nashua, NH:	-71.515 W	42.782 N
Weare, NH:	-71.44 W	43.05 N
Gorham, ME:	-70.46 W	43.70 N

An interesting, but challenging exercise for the students was to predict the expected balloon landing sites. This has been done in Figure 4(b). The plot shows Hollis, NH (-71.56W, 42.751N) as the common departure point. The returns for Weare, NH and Gorham, ME are explained quite well by this model, although the exact winds aloft and flight times might have varied somewhat. Figure 5(a) shows the student estimates of the centroid of returns. As expected the scatter of student responses is much larger than in the indoors experiment. This suggests that fast "back-of-the-envelope" calculations remain challenging at this early stage of their engineering education.





(a) (b)

Fig. 5 (a) Balloon scattering centroid estimates, (b) Longest flight estimates

This was confirmed when they were asked to estimate the longest balloon flight distance. The longest flight distance based on the returns is 138 [km], whereas most students estimated significantly longer flights, cf. Figure 5(b). This problem clearly illustrated to the students that a system can behave in a predictable manner in one environment (indoors classroom) and in a stochastic manner in a different environment, when subject to random external disturbances. As before the students had to carry out modeling, but in addition had to resort to back-of the envelope calculations and estimates under uncertainty. It was extremely motivating for the students to receive actual returns from the field. Those students who had sent the three returned cards decided to send thank-you packages to the individuals who had found their balloons.

4. Airfoil Lift – Balsa Gliders

In this problem the students were introduced to the principle of airfoil lift and were asked to conceptualize and design a simple hand-launched balsa wood glider. The following functional requirements were given:

Functional Requirements: Design a balsa wood glider that will be hand-launched indoors from a height of ca. 4 [m] by a human into horizontal flight. The balsa glider should have a minimum glide path angle, fly straight and achieve maximum flight duration from the time of release until it first hits the ground. The glider should possess good pitch, roll and yaw stability and not stall during flight. The glider should possess enough strength to bear its own weight and withstand the impact of at least 10 landings.

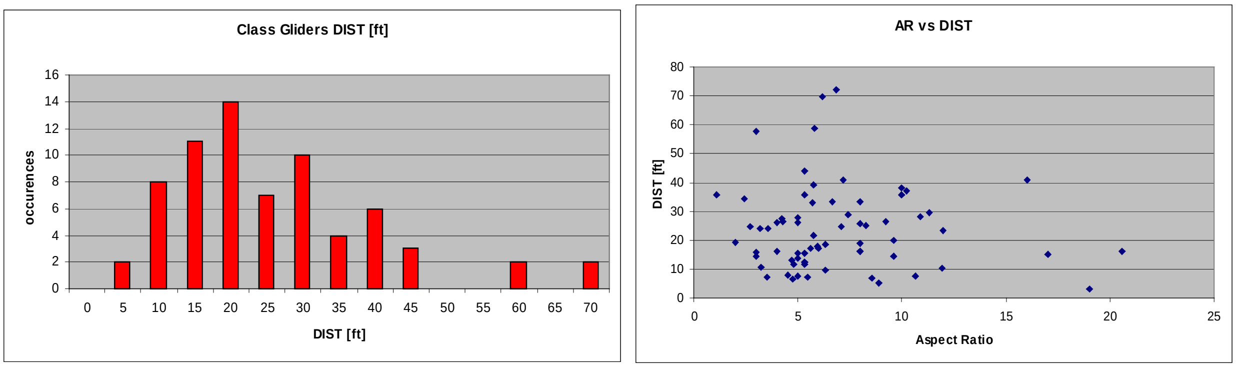
Constraints:
- The balsa glider must be constructed from balsa wood and glue (no more)
- The balsa glider will be launched by hand (no starting/launch device)
- The completed, assembled glider must fit within a 16” x 16” x 6” box
- Parts manufacture and assembly should take no longer than 90 min

We encouraged students not to copy existing designs, but to allow their own creativity to be expressed. Figure 6 shows a sample of three (out of 70) design concepts that resulted.

Fig. 6: Balsa Wood glider design concepts: flying wing, monoplane, delta wing (from left to right)

We incorporated learning objectives in technical, written communications into this exercise. One student would generate the concept, design the glider and create engineering blueprints and assembly instructions. This, along with a professional cover letter, was then assembled into a “build-to-kit”, similar to a package that would be handed to a supplier in industry. A second, randomly chosen student would then pick up the instructions kit and manufacture and test fly the glider according to the instructions of the kit. To round out the exercise, the student who manufactured the glider would provide a detailed technical email as feedback to the builder. The email was graded by the department’s writing instructor based on criteria for professional, technical correspondence.

Each of the 70 gliders was test flown and the time of flight in [sec] and the distance flown [ft] were recorded, see Figure 7(a). As was observed in previous years there often appear to be a small number of designs that dominate the rest of the class in terms of performance. The students were also presented with plots of their design variable choices such as aspect ratio, *AR*, versus distance and were asked to comment. Figure 7(b) shows the aspect ratio versus distance, and as expected, it appears that aspect ratios in the range 5-10 were most successful. The students were asked to explain this data and generate a hypothesis for the large amount of scatter in the data.



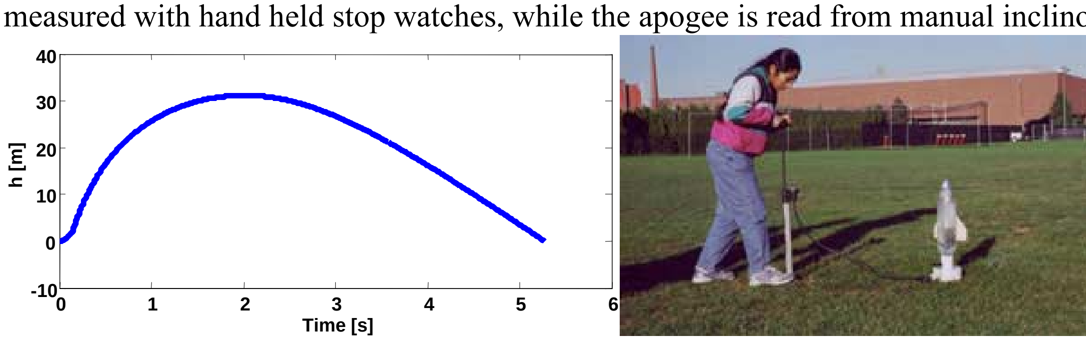
(a) (b)

Fig. 7: (a) Histogram of distance flown for 70 gliders, (b) Distances versus Aspect Ratio – a commercially available balsa glider was flown as a reference and achieved an average distance of 35 [ft].

The main benefits of this exercise were to introduce sophomores to the concept of airfoil lift. They soon recognized that successful flight requires more than choosing the correct aspect ratio or wing area. Issues of weights and balance and stability and control were apparent during flight tests. A secondary benefit was the introduction to the area of technical communications and the need for succinct, clear and understandable engineering blueprints and assembly instructions.

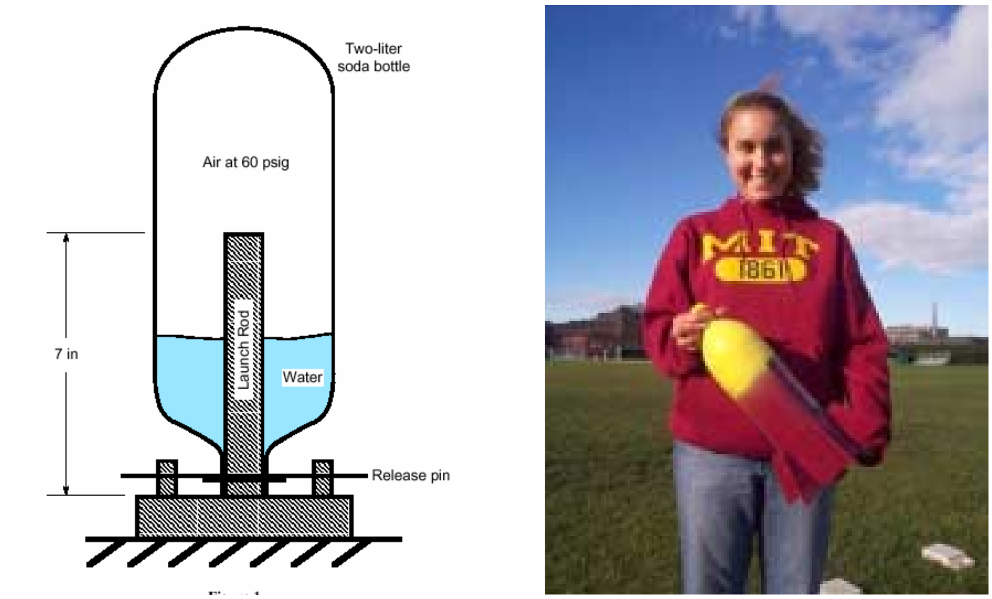
5. Mass Expulsion – Water Rockets

The principle of mass expulsion was introduced with water bottle rockets. These rockets are made inexpensively using standard 2-liter plastic soda bottles, see Figure 9(a). They are filled with ca. 30-50% of water and pressurized up to 60 [psi] as shown in Figure 8(b). After the release pin is pulled, the compressed air forces the water out of the nozzle, accelerating the bottle upward. Before launching, the students are required to model the underlying thermodynamics as well as the kinematics of the problem. The thermodynamics are modeled in four phases including isothermal compression and adiabatic expansion, see Figure 10. The goal is to predict the flight trajectory in terms of altitude versus time, see Figure 8(a). The experimental verification in the field consists of total flight time and apogee measurements. The flight time is measured with hand held stop watches, while the apogee is read from manual inclinometers.



(a) (b)

Fig.8 (a) Prediction of vertical flight trajectory, (b) Student during rocket pressurization



(a) (b)

Fig 9: (a) Schematic of water bottle rocket, (b) Student redesigned rocket – blending arts and engineering

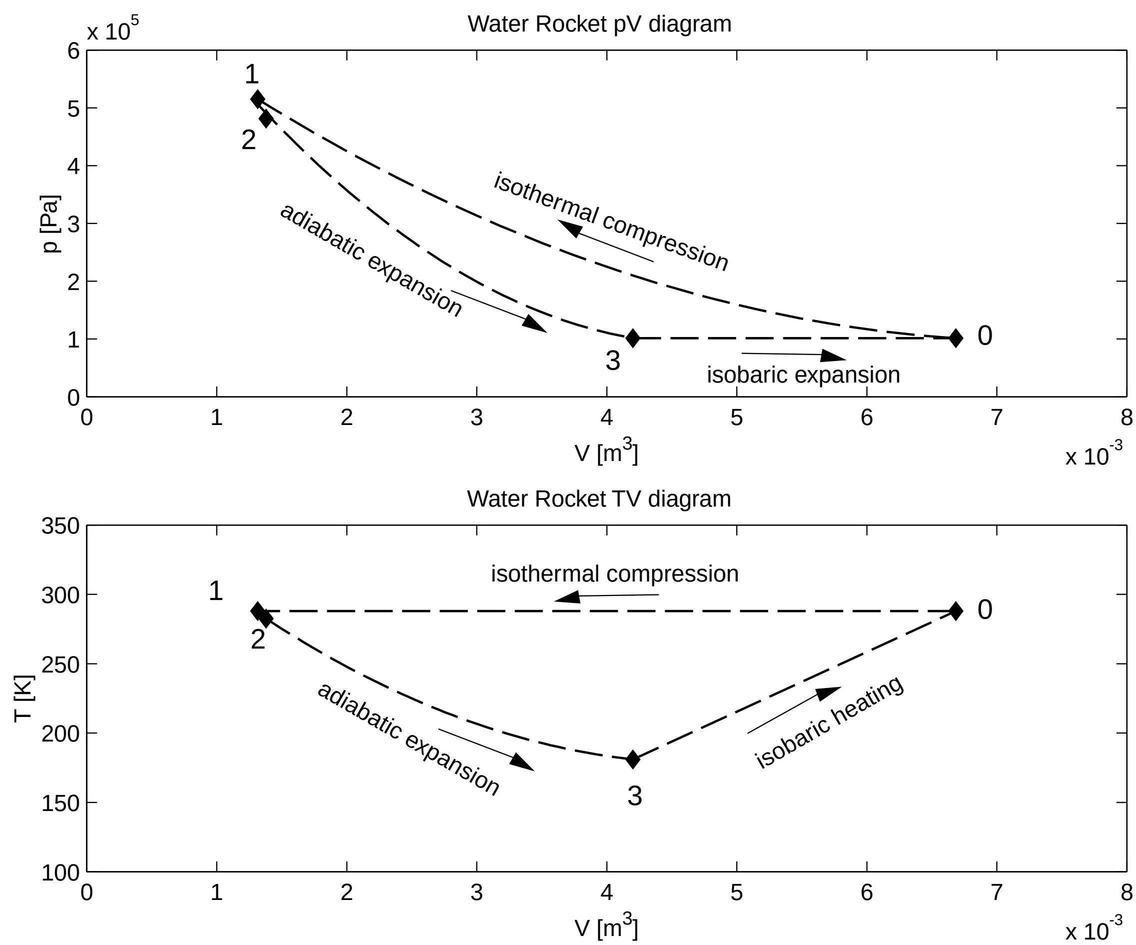
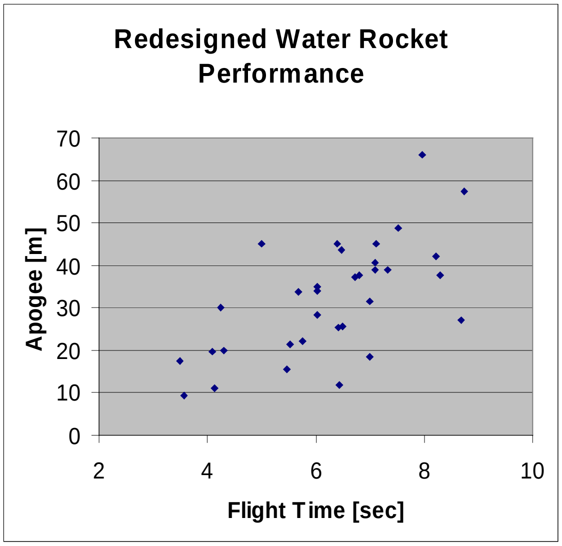


Fig. 10 Water bottle rocket p-V and T-V diagrams



After launching unmodified bottles and recording their baseline flight performance, the students have the opportunity to redesign their water rockets using nose cones for drag reduction and fins for improved flight stability. This is done in a relatively informal way and has proven to be a popular first introduction to design in anticipation of the spring design competition, see reference [2]. Figure 9(b) shows an example of a redesigned water bottle rocket presented by a Unified Engineering student, while Figure 10 shows a scatter plot of recorded apogees and flight times for the entire class. The highest recorded altitude was 66 [m]. Also here, there were a few outstanding rockets that clearly stood out.

Fig 10: Apogee height versus flight time for student water rockets

6. Conclusions

This paper presents a new method for introducing the three principles of powered flight - buoyancy, airfoil lift and mass expulsion - using a combination of lectures and small practical experiments. The artifacts are helium balloons, balsa wood gliders and water rockets, respectively. For each of these exercises the students were asked to create an apriori mathematical model that would predict the flight behavior of the system. The systems were subsequently built and tested. Substantial learning and insight occurs when initial predictions and experimental results are compared. Students are generally humbled by what appear to be trivial problems at first. It turns out that parametric and non-parametric modeling errors as well as unmodeled environmental influences can be significant factors in real flight situations.
For each exercise we compiled and analyzed a database of student artifacts and flights to obtain quantitative data on system variables, modeling assumptions and flight performances. This data was shared freely. Presenting problems in such an active learning format enabled us to address secondary learning objectives such as technical communications, system modeling and qualitative estimation. Despite the absence of formal quantitative assessments for these systems problems, we are confident that student learning is increased by such a combined theoretical hands-on approach. The positive feedback we have received so far compels us to further refine this approach in the coming years. Samples of initial student feedback are shown in Appendix A.

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Selected Student Feedback — Appendix A

(collected anonymously from the end-of-semester online survey)

"It's cool to be exposed to many different engineering disciplines over the course of the semester. The lab where we had to develop a flight model for the water rockets was very interesting and instructive"

"The systems problems were most valuable. Though they take much longer …compared to problem sets, they integrate the various topics and allow us to apply our knowledge".

"I enjoyed the more hands-on labs, such as the gliders and the water rockets."

"I love the balance of lectures/problem sets, and hands on labs/design/building."

"Overall, the primary frustration with the systems problems has been that a relatively small fraction of time is spent learning engineering concept, while a relatively large fraction of time is spent debugging and making up for equipment limitations. That being said, the systems problems force students to learn much more about practical engineering (especially modeling!) than other more theoretical parts of the course."

CDIO Design for Unified Engineering

Appendix B

Teach: (implies *Introduce*)

Really try to get students to learn new material

Learning objective is to advance at least one cognitive level (e.g. knowledge → comprehension, comprehension → application)

- Typically 1 or more hours of dedicated lecture/discussion/laboratory time are spent on this topic
- Assignments/exercises/projects/homework are specifically linked to this topic. Assessed in a formal manner.

T¹ = Primary Teach = larger commitment of time & importance
T² = Secondary Teach = smaller commitment of time & importance

Introduce:

- Touch on or briefly expose the students to this topic
- No specific learning objective of knowledge retention is linked to this topic
- Typically less than one hour of dedicated lecture/discussion/laboratory time is spent on this topic
- No assignments/exercises/projects/homework are specifically linked to this topic
- This topic would probably not be assessed on a test or other evaluation instrument

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2.1 Engineering Reasoning and Problem Solving	**T¹**	**T²**	**I**
2.1.1 (4.4) Problem Identification and Formulation			●
2.1.2 (4.3) Modeling			●
2.1.3 (4.0) Estimation and Qualitative Analysis			●
2.1.4 (3.7) Analysis with Uncertainty			●
2.1.5 (3.8) Solution and Recommendation			
2.2 Experimentation and Knowledge Discovery	**T¹**	**T²**	**I**
2.2.1 (3.4) Hypothesis Formulation			
2.2.2 (3.0) Survey of Print and ElectronicLiterature			●
2.2.3 (3.6) Experimental Inquiry			●
2.2.4 (3.3) Hypothesis Test, and Defense		●	
2.3 System Thinking	**T¹**	**T²**	**I**
2.3.1 (2.9) Thinking Holistically			●
2.3.2 (2.6) Emergence and Interactions in Systems			●
2.3.3 (2.7) Prioritization and Focus			●
2.3.4 (2.9) Tradeoffs, Judgement, Balance in Res.			●
2.4 Personal Skills and Attitudes	**T¹**	**T²**	**I**
2.4.1 (3.4) Initiative and willingness to take risks			●
2.4.2 (3.4) Perseverance and flexibility			
2.4.3 (3.6) Creative Thinking			●
2.4.4 (3.8) Critical Thinking			●
2.4.5 (3.4) Awareness of one's personal knowledge, skills and attitudes		●	
2.4.6 (3.1) Curiosity and lifelong learning			
2.4.7 (3.4) Time and resource management		●	
2.5 Professional Skills and Attitudes	**T¹**	**T²**	**I**
2.5.1 (3.7) Professional ethics, integrity, responsibility & accountability			●
2.5.2 (2.7) Professional behavior			
2.5.3 (2.7) Proactively planning for one's career			
2.5.4 (2.9) Staying current on World of Engineer			
3.1 Teamwork	**T¹**	**T²**	**I**
3.1.1 (3.4) Forming Effective Teams			●
3.1.2 (4.0) Team Operation	●		
3.1.3 (2.7) Team Growth and Evolution		●	
3.1.4 (3.4) Leadership			●
3.1.5 (3.0) Technical Teaming			●
3.2 Communication	**T¹**	**T²**	**I**
3.2.1 (3.5) Communication Strategy			●
3.2.2 (3.8) Communication Structure		●	
3.2.3 (3.9) Written Communication		●	
3.2.4 (3.1) Electronic/Multimedia Communication			●
3.2.5 (3.4) Graphical Communication		●	
3.2.6 (4.1) Oral Presentation and Interpersonal Communication			●

4.1 External And Societal Context	**T¹**	**T²**	**I**
4.1.1 (2.2) Roles and Responsibility of Engineers			●
4.1.2 (2.5) The Impact of Engineering on Society			●
4.1.3 (1.7) Society's Regulation of Engineering			●
4.1.4 (1.4) The Historical and Cultural Context			
4.1.5 (2.2) Contemporary Issues and Values			
4.1.6 (2.1) Developing a Global Perspective			
4.2 Enterprise And Business Context	**T¹**	**T²**	**I**
4.2.1 (1.6) Appreciating Different Enterprise Cultures			
4.2.2 (2.2) Enterprise Strategy, Goals and Planning			
4.2.3 (1.8) Technical Entrepreneurship			
4.2.4 (1.8) Working Successfully in Organizations			
4.3 Conceiving and Engineering Systems	**T¹**	**T²**	**I**
4.3.1 (3.2) Setting System Goals and Requirements			●
4.3.2 (3.2) Defining Function, Concept and Architecture			●
4.3.3 (3.1) Modeling of System and Ensuring Goals Can Be Met			
4.3.4 (3.0) Development Project Management		●	
4.4 Designing	**T¹**	**T²**	**I**
4.4.1 (3.9) The Design Process	●		
4.4.2 (2.9) The Design Process Phasing and Approaches			●
4.4.3 (3.4) Utilization of Knowledge in Design		●	
4.4.4 (3.4) Disciplinary Design		●	
4.4.5 (3.4) Multidisciplinary Design			●
4.4.6 (3.5) Multi-objective Design			●
4.5 Implementing	**T¹**	**T²**	**I**
4.5.1 (2.3) Designing the Implementation Process			
4.5.2 (2.1) Hardware Manufacturing Process			●
4.5.3 (2.4) Software Implementing Process	●		
4.5.4 (2.4) Hardware Software Integration		●	
4.5.5 (2.7) Test, Verification, Validation and Certification			●
4.5.6 (2.0) Implementation Management			
4.6 Operating	**T¹**	**T²**	**I**
4.6.1 (2.6) Designing and Optimizing Operations			●
4.6.2 (2.2) Training and Operations		●	
4.6.3 (2.4) Supporting the System Lifecycle			
4.6.4 (2.4) System Improvement and Evolution			●
4.6.5 (1.5) Disposal and Life-End Issues			
4.6.6 (2.3) Operations Management			