

Reverse Engineering

INTRODUCTION

The study of engineered objects can lead to important insights about design and, specifically, the design process. Reverse engineering involves the methodic disassembly and re-assembly of a device, taking care to document, test, analyze and report on the study of its function¹.

Whereas the mystery artifact challenge is a capsule introduction to reverse engineering of assigned artifacts, the reverse-engineering project is open-ended, requiring students to choose an engineered device and perform a broad and detailed study of the factors and constraints that dictated its final form. For teams working effectively and efficiently (with members respecting and understanding each others' talents), the reverse-engineering project can provide an interesting, valuable experience and a challenge to integrate and apply one's ever-growing skills. The process of reverse engineering a well-designed product can uncover a wealth of subtle innovations that can lead to a lasting respect and wonder about seemingly "simple" objects. Often, a superficial simplicity prevents us from appreciating elegant design features.

PROJECT LEARNING GOALS

The reverse engineering project learning objectives are quite broad. They are to:

- ◆ Document design
- ◆ Analyze design
- ◆ Learn about design by example
- ◆ Design and execute quantitative tests
- ◆ Discover design principles by understanding the design attributes producing its functions

1. Stanford University [1] offers a mechanical dissection course based upon this concept.

- ♦ Analyze device users
- ♦ Create an advertisement or television commercial (being sensitive to the elements of a product marketed for a specific audience)
- ♦ Design for manufacturing
- ♦ Create packaging for customers
- ♦ Improve design, making enhancements
- ♦ Think green: can it be redesigned to be more environmentally friendly?
- ♦ Design universally: can it be redesigned to be accessible to all people?
- ♦ Reinforce lessons learned from course design experiences
- ♦ Apply tools, techniques and team methodologies developed during courses

Responding to the project challenges will provide a range of valuable experiences. The fact that the objects usually represent evolutionary designs means that an object in its present form is not only analyzed, but that the dynamics which cause design changes with time are also studied. Additionally, the need for testing and analyzing challenges teams to invent methods for study, within the constraints of time and available resources.

Reverse engineering brings to bear the skills of analysis and the design of investigative approaches. Methodological testing, documentation, data retrieval, spread sheet use, graphical representation and creative design are equally important. This is accomplished in a framework of sensitivity to manufacturing and marketing factors.

CHOOSING PROJECT DEVICES

The fact that the choice of the object to be reverse engineered is open-ended encourages responses to a natural curiosity about an artifact. If this project immediately follows a “forward” engineering project, team members should be sensitive to design issues (problems, challenges and solutions). In this exercise, teams ask and answer their own questions.

Typically, the project starts with a simple question: How does this work? This leads to an ensemble of other questions and challenges to which responses are needed. These questions include:

- ♦ How will the team perform the investigation?
- ♦ What constraints have to be dealt with in analyzing the artifact?
- ♦ What plan will best unravel the artifact's function and design features?
- ♦ What types of plots or graphical displays will best communicate discoveries about the object's function?
- ♦ How was it manufactured?
- ♦ What is the consumer population?
- ♦ Are design improvements possible?
- ♦ What kind of an ad or commercial will be suited for the object?

If the team feels comfortable with the challenge of responding to these questions, then the object is probably suitable for reverse engineering. The following sections provide some examples of past reverse-engineered devices and also make specific suggestions about potential objects.

Another approach to choosing an object is to first define the reverse-engineering goals and methodology. Some teams decide that they want to exercise a particular approach and then choose a suitable object. For example, teams may consider any of the following:

- ◆ Non-destructive dissection
- ◆ Destructive dissection
- ◆ Destructive dissection and creation of a metamorph²
- ◆ Analysis and testing

Examples of devices involving non-destructive dissection include an expensive tennis racquet or a pitot (pronounced pea-toe) tube. In the case of the tennis racquet, the critical components are exposed, and the challenge is to develop a reliable testing methodology. Similarly, the details of a pitot tube are easily documented without dissection, but there is a need to analyze and test.

There is a wealth of surrounding opportunity to discover devices. It is important to find an object that is intriguing to help ensure that reverse-engineering experiences are fun and rewarding. Many places are overflowing with great objects to reverse engineer and provide inspiration. These include:

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| ◆ Dorm rooms | ◆ Electronic stores |
| ◆ Automobiles | ◆ Second-hand stores |
| ◆ Universities | ◆ Garage sales |
| ◆ Army surplus stores | ◆ Toy stores |
| ◆ Hardware stores | |

A continuous stream of new, innovative toys appear on store shelves, many of which are very sophisticated. Often, these toys provide feedback loops and decision-making sub-components that are quite interesting to study.

EXAMPLES OF REVERSE-ENGINEERED DEVICES

Examples of reverse-engineering projects include a great variety of devices, of which some were quite complex (e.g., a portable CD player). Others, however, at first seemed quite simple (e.g., a fly swatter), yet turned out to be very interesting. The listing below indicates the range of objects that can be studied and disciplines that can be represented.

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2. A metamorph is a melding of the essences of two distinct objects to create an object with new or enhanced functions [2]. For example, destructive dissection of a “weed whacker” and a lawn mower could lead to a combined system that would trim difficult edges evenly while the lawn was being cut, eliminating the need for a two-stage process.

- ♦ Frisbee
- ♦ Aluminum can
- ♦ Wind-up toy robot
- ♦ Disposable camera
- ♦ Stapler
- ♦ Climbing rope
- ♦ Coffee maker
- ♦ Thermos
- ♦ Harmonica
- ♦ Golf ball dimples (comparative study)
- ♦ Speed reducing geared motor
- ♦ Etch-a-Sketch toy
- ♦ Light bulb
- ♦ Carabiners (comparative study)
- ♦ Hovercraft
- ♦ Lock and key
- ♦ Ski binding
- ♦ Water gun
- ♦ Lighter
- ♦ Match
- ♦ Bicycle light system
- ♦ Audio speakers
- ♦ Shop vac
- ♦ Electric and battery-powered pencil sharpeners
- ♦ Running shoes (Nike vs. Reebok comparative study)
- ♦ Shock absorber
- ♦ Bouncing balls (comparative study)
- ♦ Velcro vs. zipper (comparative study)
- ♦ Alarm clock

An interesting exercise is to sit in a familiar room and look around analytically. How many objects are interesting, but have puzzling functionality? This is an opportunity to reverse engineer an object and satisfy one's curiosity at the same time.

PROJECT EXERCISE PROCESS

Usually, five two-hour lab periods are available for the reverse-engineering project. Past teams have produced excellent reverse-engineering projects working within this block of time.

During one class meeting, student teams propose the object that they wish to reverse engineer. Discussions involving the instructor, TAs and teams address issues concerning the proposed device (e.g., safety, practicality, timeliness, resources required, etc.). Usually the proposed reverse-engineering project is accepted, and only occasionally is an alternate proposal requested.

Once the project goal is defined, teams usually purchase the device; however, donations of objects frequently occur (especially when non-destructive dissection is involved). Next, teams submit a one-page reverse-engineering plan and begin analysis.

At the completion of the exercise, teams make a presentation of their results, show their video commercial or ad, and submit their report. Teams are encouraged—and many elect—to construct a poster to summarize their work.

PREVIOUS PROJECTS

A book by H. Petroski [3], *Invention by Design*, reviews several simple objects from a reverse engineering perspective. The design history of the simple paper clip emphasizes that when engi-

neers study an object, they tend to see the imperfections and also potential design improvements and solutions to problems. There have been several hundred patents issued for bent wire paper clips during the past century. The author challenges readers to reverse engineer a Gem paper clip, design an improved clip, and objectively measure the gripping forces.

A second object studied by Petroski is the pencil. He points out that often it is the analysis of design failures or limitations that leads to improved products. Such a failure analysis study based upon reverse engineering of a spectrum of manufactured pencils led to significant design improvements.

The zipper is another object reviewed. Its design history is developed, including the discovery of Velcro by the Swiss inventor George de Mestral and the development of resealable plastic bags. This book also covers aluminum cans, the 777 aircraft and a variety of structures.

The National Transportation Safety Board has teams available to be dispatched at a moment's notice to the scene of a transportation accident. These teams apply a reverse engineering approach to work backwards from the evidence at a crash site to determine the cause. Numerous design weaknesses uncovered in this way have helped make transportation systems safer. Similarly, forensic atmospheric science is used to analyze the aftermath of destructive severe weather events (e.g., hurricanes and tornadoes) to estimate the magnitude and structure of the wind fields causing damage. These analyses have led to improved building codes to help mitigate future damage.

The following examples of methods and findings from previous student projects may serve to guide team design approaches.

Aluminum Can

Procedure	Results/Conclusions
Measured dimensions, weight, flow rates (wide mouth, narrow mouth), force (required to open) and load (to deform and to explode). The deformation force defines the critical axial buckling load.	<ul style="list-style-type: none"> ◆ Requires 550 to 600 pounds to deform. ◆ Requires 725 to 790 pounds to explode. ◆ Wide mouth takes 8.3 seconds to empty. ◆ Narrow mouth takes 13.6 seconds to empty. ◆ Ease of recycling is a big advantage. ◆ 617 cans can be stacked high without damaging the bottom can. This is important for storage and shipping.

The Match

Procedure	Results/Conclusions
Studied history. Measured the burn time of matches of different lengths as a function of angle, the critical angle to hold a match in the wind (a fan was used) and the striking force and match angle (an air track was used).	<ul style="list-style-type: none"> ◆ Held horizontally, a short match burned about 1.7 inches in 30 seconds. ◆ Held at 45°, a short match burned about 1.4 inches in 12 seconds. ◆ In wind, it is best to point a match straight down. ◆ The best striking angle was between 35 - 40° from the surface.

Fly Swatter

Procedure	Results/Conclusions
Conducted comparative tests of a variety of fly swatters. Measured the pressures on an impact surface from a “swat” (used a sensitive pressure gage connected to a hole in a flat plate).	<ul style="list-style-type: none"> ◆ The larger swatters and the ones with a few smaller or no holes produce the largest air pressure changes and will actually warn a fly before swatting. ◆ It is better to use a smaller swatter with a porous surface.

Horner Harmonica

Procedure	Results/Conclusions
Studied history. Measured frequencies of blowholes in which a spectrum analyzer was used. Measured the minimum pressure required to produce a clear note (used a simple U-tube water manometer).	<ul style="list-style-type: none"> ◆ Frequency is inversely proportional to the length of the metal strips. ◆ The low- and high-frequency notes require the most pressure. ◆ The range of pressures required is from 1 to 2.5 inches of water.

The Toaster

Procedure	Results/Conclusions
Dissected object and measured dimensions. Measured temperature and time at each setting. Measured electrical resistance.	<ul style="list-style-type: none"> ◆ The time for toasting ranges with settings from 20 to 34 seconds, if the toaster is cooled between tests. ◆ The time for toasting ranges with settings from 4.7 to 11.7 seconds, if the toaster is <i>not</i> cooled between tests. Hence, for a quick response, let the toaster go through a heat cycle before initially toasting. ◆ The toast compartments taper in width from top to bottom. The team theorized that this permits smaller, thicker items to be toasted without falling to the bottom of the toaster.

An additional reverse-engineering project, a comparative study of the “sweet spots” of tennis racquets, comes to mind because of the elegant simplicity of the test method. Video film was taken of tennis balls (marked with chalk) dropped from a fixed height. The heights of the ball bounces after impact on the tennis racquets were measured as a function of the impact position. A three-dimensional plot of the data vividly displayed the forms of the very complex sweet spots of the tennis racquets.

STUDENT PROJECT PRODUCTS

The products for the reverse-engineering project include a number of required elements. Although many of these products should be contained in the final report, team notebooks should contain sufficient detail and background to answer questions that may arise. Include the following elements or answers to questions:

- ◆ Documentation of background, including:
 - Areas of use and a characterization of typical users.
 - Where did it come from?
 - Was there an evolution with time? Were there distinct transitions of form or use?
- ◆ Description of the typical function.
- ◆ Summary of any documentation provided.
- ◆ A definition of goals and methodology.
- ◆ Documentation of the test methodology created.
- ◆ Documentation of systematic analysis, including:
 - A list of major components.
 - Definition of the dissection sequence (if required).
 - Description of interactions between components.
 - Summary of working guesses concerning functions.
 - Summary of equations or physical processes that determine the function.
- ◆ Documentation of procedures.
- ◆ Summary of results and recommendations.
- ◆ Identification of a market and marketing approach.
- ◆ Creation of an advertisement or a User’s Manual.

PRESENTATION AND REPORT

Teams turn in a final report at the time of the presentation. The suggested following outline covers the key topic areas. The report should contain a combination of drawings and photos covering key functions.

Reverse Engineering Project Report

1. *Background:* Describe what need the device fulfills. Give a brief history of the design. Include any accompanying literature as an appendix.
2. *Project Goals:* List the goals for performing the reverse-engineering study; i.e., what will be learned from the study?
3. *Test and Analysis Procedures:* Describe the procedures used to address the above goals. How was the device and its components evaluated? Document test data obtained.
4. *Dissection Details:* Describe (using drawings, photos and/or video where appropriate) the key components and how they function.
5. *Results:* Describe what was learned about this device's design and functionality. Provide suggestions for changes that would improve its function or make it more cost effective to produce. Provide suggestions for any changes that would make it "greener" or more universally available.
6. *Marketing:* Include either an advertisement (in print) or a video or radio commercial, marketing this artifact to an identified target group of potential customers.

Ad or Commercial

Typically, examples of past student advertisements or commercials are shown to introduce a reverse-engineering exercise. Although most teams produce television commercials, others create radio ads or flyers. The key to the creation of a successful ad—regardless of its medium—is to have a good understanding of the product, as well as the intended market. With this knowledge, marketing efforts can appeal to the desires of consumers, emphasizing the strengths of the product. The ability to communicate effectively with marketing experts in a company can be critical to the success or failure of a product and is an important skill for engineers to nurture. In the ad presentation, include a clear definition of the target customer population and an assessment of the desired product characteristics.

REFERENCES

1. Sheppard, S.D., *Mechanical Dissection: An Experience in How Things Work*, Proceedings, Engineering Education Curriculum Innovation and Integration, January 6-10, 1992, Santa Barbara, CA.
2. Sheppard, S.D., *Personnel Communication*, 1993.
3. Petroski, H., *Invention by Design: How Engineers Get from Thought to Thing*, Harvard University Press, 242 pp, 1996.