Reverse Engineering

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Khul Ja Sim-Sim
Forward Engineering

Concept $\rightarrow$ Engineering a product $\rightarrow$ Product

Reverse Engineering

Product $\rightarrow$ Reverse Engineering $\rightarrow$ Concept
Reverse Engineering

“Examining competitive or similar or prior products in great detail by dissecting them or literally taking them apart.”

- Dym & Little

“How does it do that?”

“Why would you want to do that?”
Why Reverse Engineering?

“Sometimes, the best way to advance is in reverse,”  By Eldad Eilam
What is a Product?

In general, the **product** is defined as

- a “thing produced by labor or effort” or

- the “result of an act or a process”

**Example:** Fan, Computers, Software, Pen, Clock, Bottle etc.
Who make product?

- Entrepreneurs
- Engineers
- Designers
- Students
- ...

Why make product?

- Earn money
- Get recognition
- Social service
- Personal satisfaction
- ...
- …
Startup company by IIT students

• Company name: IdeaForge
• NETRA is a completely autonomous Unmanned Aerial Vehicle – for Intelligence, Surveillance and Reconnaissance of moving and fixed targets.
• NETRA streams you real time video of the target area with spotless clarity.
• Helped Nepal during Earthquake, saved many life
• Initially struggled, lots of failure in designs

Unmanned aerial vehicles are the best way to access risky terrain, especially cracked buildings during an earthquake. Here rescue officials are inspecting a ramshackled building in the 2015 Nepal earthquake. Image: ideaForge
If you want to design a bird like machine, you have to study the bird first
Reverse Engineering

Gain insight into our own design problem by looking at how other people have addressed the same issues.

Restrictions:
- Expensive designs
- Protected by copyrights and patents
- May be the competitor’s design
- Design may not work very well
- Design may be copied, difficult to copy knowledge
Reasons for reverse engineering

- Interfacing
- Obsolescence
- Bug fixing
- Military or commercial espionage
- Competitive technical intelligence
- Saving money (Value Engineering)
- Creation of unlicensed/unapproved duplicates
- Software modernization
Reasons for reverse engineering a part or product:

1. The original manufacturer of a product no longer produces a product
2. There is inadequate documentation of the original design
3. The original manufacturer no longer exists, but a customer needs the product
4. The original design documentation has been lost or never existed
5. Some bad features of a product need to be designed out. For example, excessive wear might indicate where a product should be improved
6. To strengthen the good features of a product based on long-term usage of the product
7. To analyze the good and bad features of competitors' product
8. To explore new avenues to improve product performance and features
9. To gain competitive benchmarking methods to understand competitor's products and develop better products
10. The original CAD model is not sufficient to support modifications or current manufacturing methods
11. The original supplier is unable or unwilling to provide additional parts
12. The original equipment manufacturers are either unwilling or unable to supply replacement parts, or demand inflated costs for sole-source parts
13. To update obsolete materials or antiquated manufacturing processes with more current, less-expensive technologies
Reverse Engineering for military applications

World war II: Jerry can

- British and American forces noticed that the Germans had gasoline cans with an excellent design.

- They reverse-engineered copies of those cans
Reverse Engineering for military applications

World war II: Panzerschreck

• The Germans captured an American Bazooka during World War II, and reverse engineered it to create the larger Panzerschreck.
• See how the need of mask removed in improved design

Original design: American

Improved design: German
Reverse Engineering for military applications

World war II: Tupolev Tu-4

- Three American B-29 bombers on missions over Japan were forced to land in the USSR.
- The Soviets, who did not have a similar strategic bomber, decided to copy the B-29.
- Within a few years, they had developed the Tu-4, a near-perfect copy.
Reverse Engineering for military applications

World war II: K-13/R-3S missile

- Soviet reverse-engineered copy of the AIM-9 Sidewinder, was made possible after a Taiwanese AIM-9B hit a Chinese MiG-17 without exploding. The missile became lodged within the airframe, and the pilot returned to base with what Russian scientists would describe as a university course in missile development.

An AIM-9E Sidewinder missile on display at the National Air and Space Museum

K-13: Short-range, infrared homing air-to-air missile developed by the Soviet Union
Product (re)design begins with Reverse Engineering Methodology

Investigation, Prediction and Hypothesis

Concrete Experience: Function & Form

Design Models

Design Analysis

Parametric Redesign

Adaptive Redesign

Original Redesign

Reverse Engineering

Modeling & Analysis

Redesign

Adapted from Otto and Wood’s “Reverse Engineering and Redesign Methodology” UT Austin
1. Investigation, Prediction and Hypothesis

- Develop black box model
- Use / Experience product
- List assumed working principles
- Perform economic feasibility of redesign
- State process description or activity diagram
Segment 1:

Selected crash tests
Engines from different automotive companies

Example

XL Super, heavy duty, 95% market share, 15 year old engine
Rubber dampers

- Rubber dampers are provided between the fins to reduce their vibration
- High vibration of fins produces undesirable noise.
- Undesirable noise leads to customer dissatisfaction.
- Proper design of the fins are necessary
- Rubber dampers add extra cost to the vehicle
Two-wheeler engine head

TVS Moped Engine

- Reliable engine: > 15 years in the market
- Holds 95% market share in moped class
- Lakhs of satisfied customers
- 16 dampers on the cylinder head.

If dampers are removed, the new cylinder head should have noise level equal to or better than the existing cylinder head !!!
Radiated noise with and without rubber dampers

Comparison of noise radiated from the engines with and without rubber dampers on the cylinder head at 3150 Hz.
Experimental verification...

- Campbell diagram during gradual acceleration
- Noise levels have spread and are higher in magnitude in the 2nd case

All 16 dampers in place

All 16 dampers removed
Existing cylinder head
Modified cylinder head
It was observed that the new head design may not be feasible from the manufacturing point of view.

2\text{nd} stage cylinder head
Further design changes and analysis

- **Design 1**
  - First mode: 1473 Hz
  - Fifth mode: 2086 Hz

- **Design 2**
  - First mode: 2969 Hz, ~100%
  - Fifth mode: 3633 Hz, ~74%

- **Design 3**
  - First mode: 3462 Hz, ~136%
  - Fifth mode: 4304 Hz, ~106%

- **Design 4**
  - First mode: 4134 Hz, ~181%
  - Fifth mode: 5318 Hz, ~155%
Experimental verification: Campbell diagram

- Similar Campbell diagram in both the cylinder head
- 3rd stage cylinder head can replace the existing cylinder head
Noise level comparison

![Graph showing noise level comparison between Design 1 with rubber dampers and Design 4 without rubber dampers.](image)
Computational Fluid Dynamic analysis
3rd stage cylinder head shows lower temperature on the fins and in the combustion chamber compared to the 1st stage design of the head. This is experimentally verified. 3rd stage design without rubber dampers is implemented on the vehicle for mass production.
Costs and environmental impact

- Among many benefits, few advantages are listed below

1. Rubber damper manufacturing process is eliminated completely; rubber production is harmful to the environment
2. Long term benefits; over a period of time typically after six months of use, rubber dampers properties deteriorates and it becomes brittle due high temperature of the fins. The initial grip between the dampers and fins reduces and finally these dampers come off the engine. The noise radiated from the engine increase again. Hence, putting rubber dampers on engines does not provide long-term benefits,
3. Logistics and inventory reduction; logistics of dampers involves the integration of information, transportation, inventory, warehousing, material handling, and packaging,
4. Man power saving; since rubber dampers are not an integral part of the engine, additional workman are needed to hammer down the rubbers between the fins
5. Part count reduction; rubber dampers are additional parts that needs to put on the engine before integrating on the vehicle and hence increases the number of part count of the engine,
6. Improves engine cooling; rubber dampers restricts the free flow of air around the engines and hence increases the overall engine temperature.
Life cycle cost benefit

- Each rubber damper cost = Rs. 1
- Total cost dampers = 16 x 1 = Rs. 16
- Additional benefit = Rs. 4
- Total saving = Rs \( (16 + 4) = \text{Rs. 20/vehicle} \)
- Sales = 70,000 vehicles/month
- Benefit/month = Rs 20 x 70,000 = 14 Lakh/month
- Benefit/year = 12 x 14 lakh = 1.68 Crore/year
- Life cycle benefit = 10 x 1.68 crore = 16.8 crore
Product life cycle: Competitors upper hand
Example

Engine Oil consumption measurement

Dipstick

Drain cap
# Engine Oil consumption measurement methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drain &amp; measure</td>
<td>• Simple and economical</td>
<td>• Error in measurement</td>
</tr>
<tr>
<td></td>
<td>• No complicated equipment required</td>
<td>• Approx 25 hrs to run</td>
</tr>
<tr>
<td></td>
<td>• No skilled labor required</td>
<td>• Impossible to drain all oil practically</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Increase in viscosity due to degradation increases time of drain</td>
</tr>
<tr>
<td>Tracer Radioactive Sulfur</td>
<td>• Measurement time – order of minutes</td>
<td>• Very costly equipment and special handling procedures for radioactive material</td>
</tr>
<tr>
<td></td>
<td>• Transient effects can be measured</td>
<td>• Secondary measurements and calibration of air and fuel flow</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Oil deposited on piston, valves, and exhaust after treatment devices not accounted for in final measurement</td>
</tr>
<tr>
<td>Smart Oil Consumption Meter</td>
<td>• Level sensor to gauge level of oil in crankcase</td>
<td>• Accuracy of level sensor is of concern</td>
</tr>
<tr>
<td></td>
<td>• Measurement time of the order of hours</td>
<td>• Requires addition of new oil</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Suitable for diesel engines</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Transient effects cannot be measured</td>
</tr>
<tr>
<td>New Method</td>
<td>• Cheap to build and use</td>
<td>• Accuracy of the scale</td>
</tr>
<tr>
<td></td>
<td>• Portable</td>
<td>• Vibrations need to be handled better</td>
</tr>
<tr>
<td></td>
<td>• Run time of the order of hours</td>
<td>• Leakages have to be monitored</td>
</tr>
<tr>
<td></td>
<td>• Pump flow characteristics can be studied</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Addition of new oil not required</td>
<td></td>
</tr>
</tbody>
</table>

Comparison of various oil consumption measurement techniques.
Example: Engine oil measurement

1. Investigation, Prediction and Hypothesis
Example: Engine oil measurement

Calibration and measurement
Reverse Engineering Methodology

2. Concrete Experience: Function and Form

- Plan and execute product disassembly
- Group defined systems and components together
- Experiment with product components
- Develop free body diagrams
- Identify function sharing and compatibility
- Transform to engineering specs and metrics
Car Assembly Plant
3. Design Models

- Identify actual physical principles
- Constantly consider the customer
- Create engineering models and metric ranges
- Alternatively or concurrently build prototype to test parameters
- Ethical issues
- IPR issues
Reverse Engineering Methodology

4. Design Analysis

- Calibrate model
- Create engineering analysis, simulation or optimization
- Create experiment and testing procedures
Reverse Engineering Methodology

5. Parametric Redesign

- Optimize design parameters
- Perform sensitivity analysis and tolerance design
- Build and test prototype

Parametric design  Prototypes testing
Reverse Engineering Methodology

6. Adaptive Redesign
   - Recommend new subsystems
   - Search for inventive solutions
   - Analyze force flows and component combinations
   - Build and test prototype
Reverse Engineering Methodology

7. Original Redesign
   – Develop new functional structure
   – Choose alternatives
   – Verify design concepts
   – Build and test prototype
System Level Design

- Reverse Engineering requires understanding the product or design as a system or set of systems that work and interact together.

- This concept is known as System Level Design.
System Level Design

System = Components + Connections

- Components
  - Physical - pick-up, measure, draw on CAD
  - Functional - flowcharts, difficult to define

- Connections
  - Fundamental - intended design
  - Incidental - created by physical proximity of components (vibration, heat transfer, etc.)
System Level Design

System Unit

Monitor

Mouse

Keyboard

Peripheral device bay (system disk drive, CD-ROM drive, floppy disk drive)

Disk drive cage

Fan cage (two fans)

System board

Expansion card (typical, in slot on system board)

I/O Connectors (on I/O panel)

Fan

Power supply

Processor (one or two)
Approaches to reverse engineering

- **Black Box Analysis**
  - Analyzing a running product by probing it with various inputs and outputs

- **White (or Glass) Box Analysis**
  - Analyzing and understanding sub-system components
  - Connections between components

- **Gray Box Analysis**
  - A combination
System and sub-systems

Black box analysis

Glass box analysis
System Level Design

Develop **black box** model avoiding bias.

Graphic representation of the system or object being designed, with inputs shown entering on the left and outputs leaving on the right.

```
Inputs  System  Outputs
```

Black box
System Level Design

Example: Radio

- Power
- RF Signal
- User Choices (Volume, Freq.)

Convert RF Signal To Sound At Desired Level

- Heat & Noise
- Sound
- Status Indications (Volume, Freq.)

RF=radio frequency
System Level Design

Example: Motorcycle

- Price
- Fuel
- User choices

- Mileage
- Comfort
- Sound
- Durability
- ...

...
System Level Design

Continue with the glass box approach.

- Identify sub-systems
  - Electrical
  - Mechanical
  - Task oriented

- Define interactions and flow of forces
  - Intentional
  - Unintentional
  - Wires, signals, material, data, etc.
‘Glass Box’ Example

Ink Jet Printer

Enclosure
- Enclose Printer
- Provide Structural Support
Chassis
- Store Output
- Store Blank Paper
- Paper Tray

Print Cartridge
- Position Cartridge in X-Axis
- "Pick" Paper
Print Mechanism

User Interface Board
- Accept User Inputs
- Display Status

Control Printer
- Communicate with Host

Power Cord and "Brick"
- Supply DC Power
- Command Printer
- Host Driver Software

Logic Board
- Connect to Host
System Level Design

Final Breakdown
For every piece or component of interest, discuss:

1) How was it made
2) Why it was made this way
3) Design issues
4) The material it is made out of
5) Complexity and cost
6) Ergonomic issues
7) Interaction with other components
Reverse Engineering Example

Example Project
Hedge/Bush Trimmer

Hand trimmer

Electrical trimmer
Reverse Engineering Methodology

- Investigation, Prediction and Hypothesis
- Concrete Experience: Function & Form
- Design Models
- Design Analysis
- Parametric Redesign
- Adaptive Redesign
- Original Redesign

Adapted from Otto and Wood’s “Reverse Engineering and Redesign Methodology” UT Austin
Reverse Engineering Example Project

1. Investigation, Prediction and Hypothesis

   Develop Black Box Model
   » Assemble product and conduct a test
   » What goes in? What comes out? (i.e. power, noise, heat, vibration)

![Diagram of Input, Black Box, Output]

- **Input**
  - Electric Power
  - Finger Switch
  - Safety Off

- **Black Box**
  - Hedge Trimmer

- **Output**
  - Noise
  - Blade Movement
  - Vibration, heat
Reverse Engineering Example Project

Conduct a single test of the performance of the product:

- **Record product performance attributes**
  - Shearing speed
    - 3300 strokes/min
    - 5:1 Gear reduction = 16,500 RPM for the motor
Reverse Engineering Example Project

What is the market for this product?

» “Suitable for small shrubbery” – Product Catalog
» Homeowners with small yards and limited budget
» For use only 3-4 times a year

What are the costs associated with this product?

» Design - Manufacturing - Assembly – Packaging
» Resale ($40.00)
Reverse Engineering Example Project

How long will this product last?
» Assumed durability of each component (outdoor use, dirt)
» Availability of replacement parts and service shops

What features does this product have that are important?
» Molded-in cord retainer
» Lock off switch prevents accidental start-up
» Lock on switch for continuous running
» Lightweight design for less fatigue (4.5 lbs.)
Market Research

• I bought my first hedge trimmer at WalMart because it was very inexpensive compared to most other trimmers.

• It has an excellent reputation.

• The 13" seemed a little too small… The 18" seemed heavier.

• I also wanted electric rather than gas because being a busy woman, I had no time to learn about mixing gas.

• Durability: Excellent
• Noise Level: Average
• Purchase Price: $25.00
Market Research...

• While it may be a good trimmer it also has it's downside!

• The second problem is that since it is electric and you use it outside, you run the risk of being electrocuted! Remember most people doing lawn work are also running sprinklers to water the lawn. *I have had good friends killed simply by using these trimmers on wet grass.*

• Over all this tool does a great job of trimming but the hazards to your personal safety far out weigh the pros of this tool.
Patent Search on Hedge Trimmers

After completing a search on the U.S. Patent and Trademark website:

http://www.uspto.gov

Power Driven Hedge Trimmer

Hedge Trimmer with Combination Shearing and Sawing Blade Assembly
Function and Form

2. Concrete Experience: Function and Form

- Carefully begin Disassembly
- Document steps and components with photographs, sketches or video
Hedge Trimmer Sub-Systems and Interactions

- Group defined systems and subsystems together.
Motor

- 120 V - 8 Amp Motor
- 350 RPM
- Why not batteries?
- How important is size, speed?
- Was weight a consideration?
Switch

- Safety lock allows trigger action.
- Is this a regulatory requirement?
- Ergonomic issues of size and lever force
- What type of spring mechanism is used?
Switch

Sketch of Switch
Blades

- How fast do the blades need to move? Force?
- Are the blades sharp?
- What are the blades made of?
- Can we replace the blades?

Excavator
Transmission

Input gear from motor

Output gear

Blades

Pin for upper blade

Pin for lower blade

Slot for upper blade

Slot for lower blade
Case

- How was the case made?
- Was the case designed to be esthetically pleasing?
- Why isn’t the case made out of metal?
- What sort of costs are involved in the manufacturing of this case?
Feature List

- Switch - Plastic Injection Molded
- Gear – Die Cast Steel
- Case – Plastic Injection Molded
- Handle – Plastic Injection Molded
- Guard – Plastic Injection Molded
Reassemble Product
Engineering Specifications

Transforming to engineering specifications

**Example - Motor-Blade Kinematics**

Helical gears

Number of teeth: input = 4
output = 60

Motor speed = 22800 rpm

Output speed $= \frac{4}{60} \omega_{in} = \frac{1}{15} (22800 \text{ rpm})$

= 1520 rpm = 159 rad/s

Maximum blade speed $= 1 \text{ m/s}$
Engineering Specifications

Transforming to engineering specifications

Input gear from motor

\[ T_{in} - T_1 = I_1 \dot{\omega} \]

\[ T_1 = F_t \frac{d_1}{2} \]

\[ T_2 = F_t \frac{d_2}{2} \]

Output gear to blades

\[ T_2 - F_1 r_1 - F_2 r_2 = I_2 \dot{\omega}_2 \]

\[ F_1 = m_1 \left( r_1 \dot{\omega}_2 \sin \phi - r_1 \omega_1^2 \cos \phi \right) \]

\[ F_2 = m_2 \left( - r_2 \dot{\omega}_2 \sin \phi + r_2 \omega_2^2 \cos \phi \right) \]
3. Design Models

- Identify actual physical principles
- Create engineering models and metric ranges
- Alternatively or concurrently build prototype to test parameters
Design Analysis

4. Design Analysis

- Calibrate model
- Create engineering analysis, simulation or optimization
- Create experiment and testing procedures
Parametric Redesign

5. Parametric Redesign

- Optimize design parameters
- Perform sensitivity analysis and tolerance design
- Build and test prototype
Adaptive Redesign

6. Adaptive Redesign
   – Recommends new subsystems
   – Searches for inventive solutions
   – Analyzes force flows and component combinations
   – Builds and tests prototype
Environmental Impact
Environmental Impact

To determine the environmental impact of the existing design evaluate each step of the Product Life Cycle

- Pre-production
- Manufacturing Process
- Product Life
- The After Life
Pre-production

- Replaceability of natural resources
- Availability of an alternative resource
- Energy required to obtain
- Energy to process
- Amount of waste created during processing
- Waste disposal method
Manufacturing Process

- Energy to produce
- Waste created during production
- Type of waste - solvents, emissions?
- Reuse of in-process material waste?
- Material yield
Product Life

- Energy consumption
- Waste production
- Length of product life
The After Life

- Reuse
- Recycle - design for disassembly?
- Neither - harmful pollutants?

Think: Reuse vs. Recycle
Summary

Reverse engineering

• Tool to understand current design solutions and technology
• Use dissection, experimentation and analysis
• Save time and gain insight on current design challenges and solutions
Products

- Printer/Scanner
- Electric fan
- Steam iron
- Television set
- Laptop
- Desktop computer
- Microwave Oven
- Air Conditioner
- Refrigerator
- Mobile
- Tea & Coffee maker
Groups

• Make groups consisting of 6 members
• Members: 2 ME, 2 SC & 2 EE
• Max. 3 girls students in group
Evaluation

- Quality of documentation
- Product knowledge
- Disassembly and assembly
- Presentation
- Viva voce