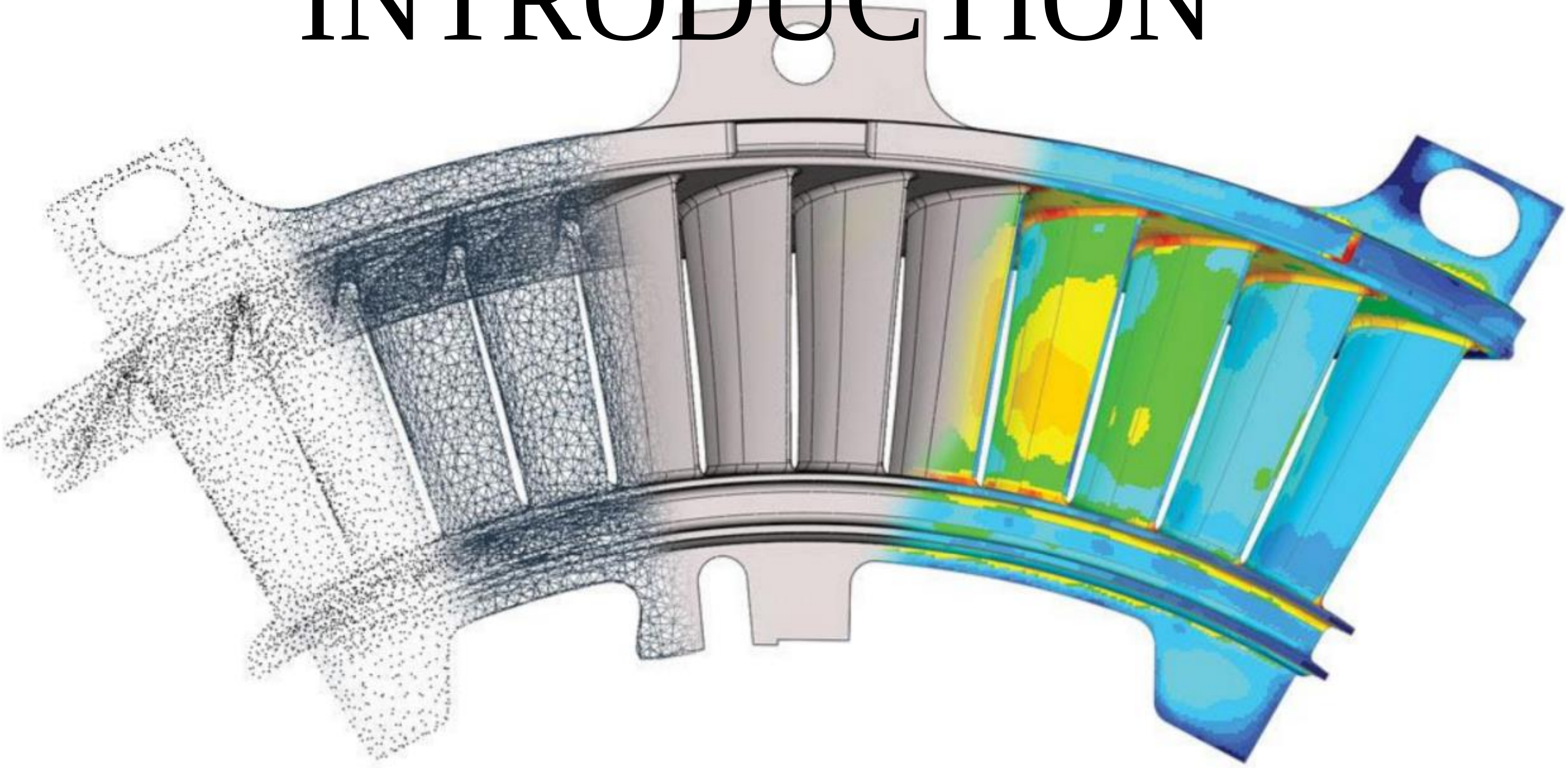
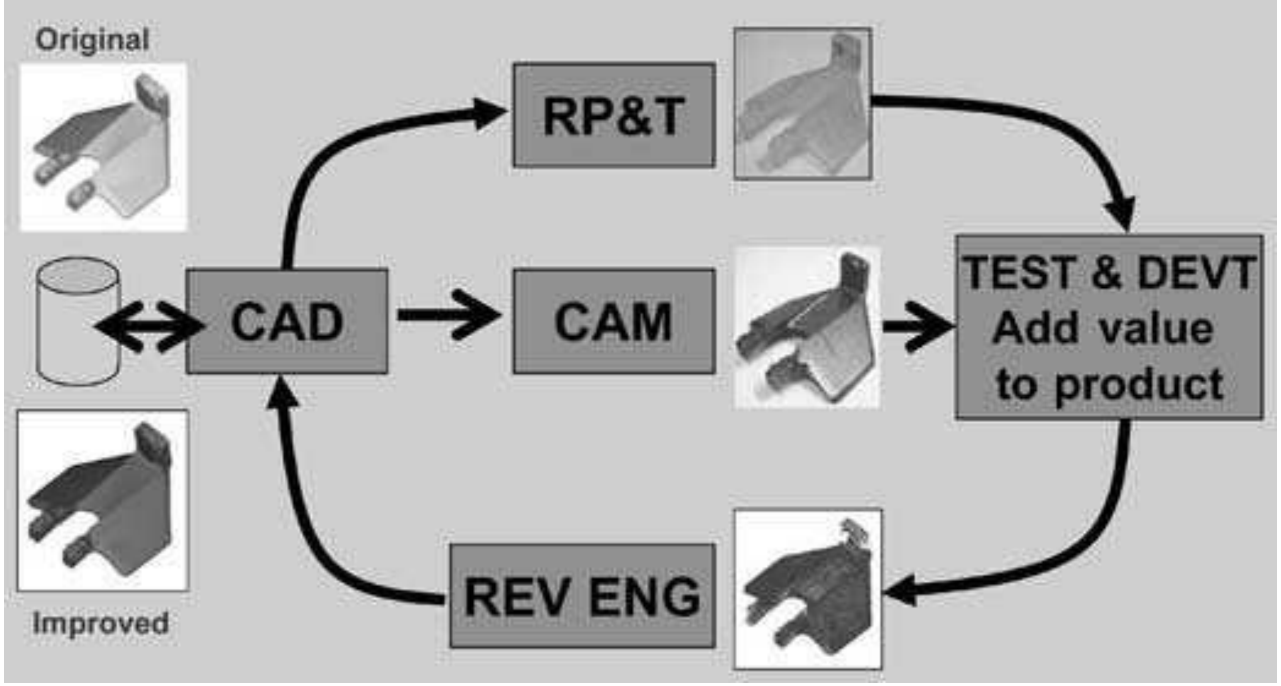
REVERSE ENGINEERING
CHAPTER 1
INTRODUCTION



What Is Reverse Engineering?

Engineering is the process of designing, manufacturing, assembling, and maintaining products and systems. There are two types of engineering, ***forward engineering*** and ***reverse engineering***. Forward engineering is the traditional process of moving from high-level abstractions and logical designs to the physical implementation of a system. In some situations, there may be a physical part/ product without any technical details, such as drawings, bills-of-material, or without engineering data. The process of duplicating an existing part, subassembly, or product, without drawings, documentation, or a computer model is known as ***reverse engineering***. ***Reverse engineering*** is also defined as the process of obtaining a geometric CAD model from 3-D points acquired by scanning/ digitizing existing parts/products.

In today's intensely competitive global market, product enterprises are constantly seeking new ways to shorten lead times for new product developments that meet all customer expectations. In general, product enterprise has invested in CADCAM, rapid prototyping, and a range of new technologies that provide business benefits. Reverse engineering (RE) is now considered one of the technologies that provide business benefits in shortening the product development cycle. The figure below depicts how RE allows the possibilities of closing the loop between what is "as designed" and what is "actually manufactured".



Reverse engineering is now widely used in numerous applications, such as manufacturing, industrial design, and jewelry design and reproduction For example, when a new car is launched on the market, competing manufacturers may buy one and disassemble it to learn how it was built and how it works. In software engineering, good source code is often a variation of other good source code. In some situations, such as automotive styling, designers give shape to their ideas by using clay, plaster, wood, or foam rubber, but a CAD model is needed to manufacture the part. As products become more organic in shape, designing in CAD becomes more challenging and there is no guarantee that the CAD representation will replicate the sculpted model exactly.

Why Use Reverse Engineering?

Following are some of the reasons for using reverse engineering:

- The original manufacturer no longer exists, but a customer needs the product, *e.g.*, aircraft spares required typically after an aircraft has been in service for several years.
- The original manufacturer of a product no longer produces the product, *e.g.*, the original product has become obsolete.
- The original product design documentation has been lost or never existed.
- Creating data to refurbish or manufacture a part for which there are no CAD data, or for which the data have become obsolete or lost.
- Inspection and/or Quality Control–Comparing a fabricated part to its CAD description or to a standard item.
- Some bad features of a product need to be eliminated *e.g.*, excessive wear might indicate where a product should be improved.
- Strengthening the good features of a product based on long-term usage.

Why Use Reverse Engineering? (Cont.)

- Analyzing the good and bad features of competitors' products.
- Exploring new avenues to improve product performance and features.
- Creating 3-D data from a model or sculpture for animation in games and movies.
- Creating 3-D data from an individual, model or sculpture to create, scale, or reproduce artwork.
- Architectural and construction documentation and measurement.
- Fitting clothing or footwear to individuals and determining the anthropometry of a population.
- Generating data to create dental or surgical prosthetics, tissue engineered body parts, or for surgical planning.
- Documentation and reproduction of crime scenes.

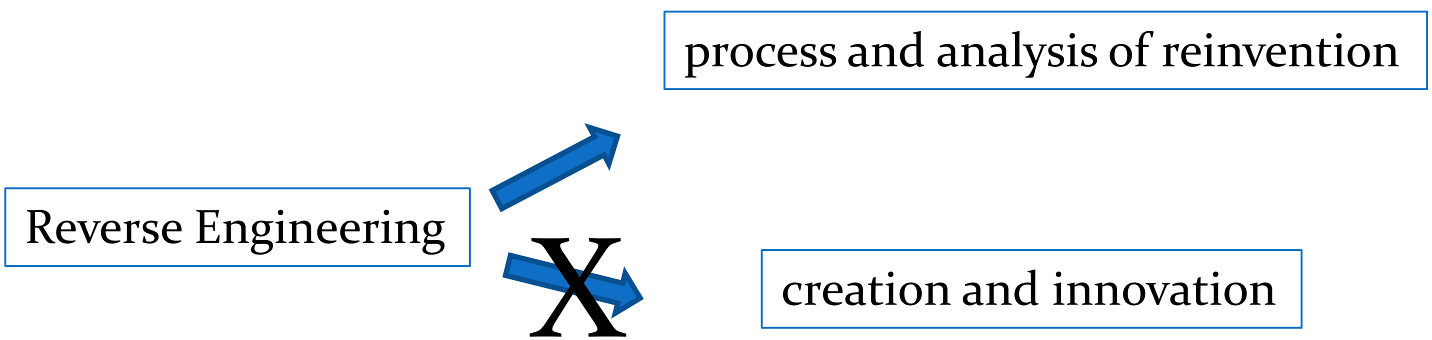
The above list is not exhaustive and there are many more reasons for using reverse engineering, than documented above.

Reverse engineering has been used to study and replicate previously made parts for years. Modern technology makes this replication easier, and the evolving industry makes it more acceptable today. Legally, reverse engineering is deemed as "***a fair and honest means of starting with the known product and working backwards to divine the process which aided in its development or manufacture***" (U.S. Supreme Court, 1974).

Reverse engineering is a practice of invention based on knowledge and data acquired from earlier work. It incorporates appropriate engineering standards and multiple realistic constraints. The part produced through reverse engineering should be in compliance with the requirements contained in applicable program criteria. To accomplish a successful reverse engineering project requires broad knowledge in multiple disciplines. Reverse engineering requirements can be summarized as follows;

1. Applying knowledge of mathematics, engineering, and science in data analysis and interpretation,
2. Using techniques, instruments, and tools in reverse engineering applications,
3. Conducting appropriate experiments and tests to obtain the necessary data in reverse engineering,
4. Identifying, formulating, and solving issues related to reverse engineering,
5. Understanding legal and ethical responsibilities pertinent to reverse engineering,
6. Assessing and evaluating documents and fostering attainment of objectives of a reverse engineering project.

Several professional organizations have provided the definitions of reverse engineering from their perspectives. The Society of Manufacturing Engineers (SME) states that the practice of reverse engineering "starting with a finished product or process and working backward in logical fashion to discover the underlying new technology" (Francis, 1988).



The Military Handbook (MILHDBK-115 A) defines reverse engineering in a broader perspective to include the product’s economic value as “the process of duplicating an item functionally and dimensionally by physically examining and measuring existing parts to develop the technical data (physical and material characteristics) required for competitive procurement” (MIL-HDBK-115A, 2006).

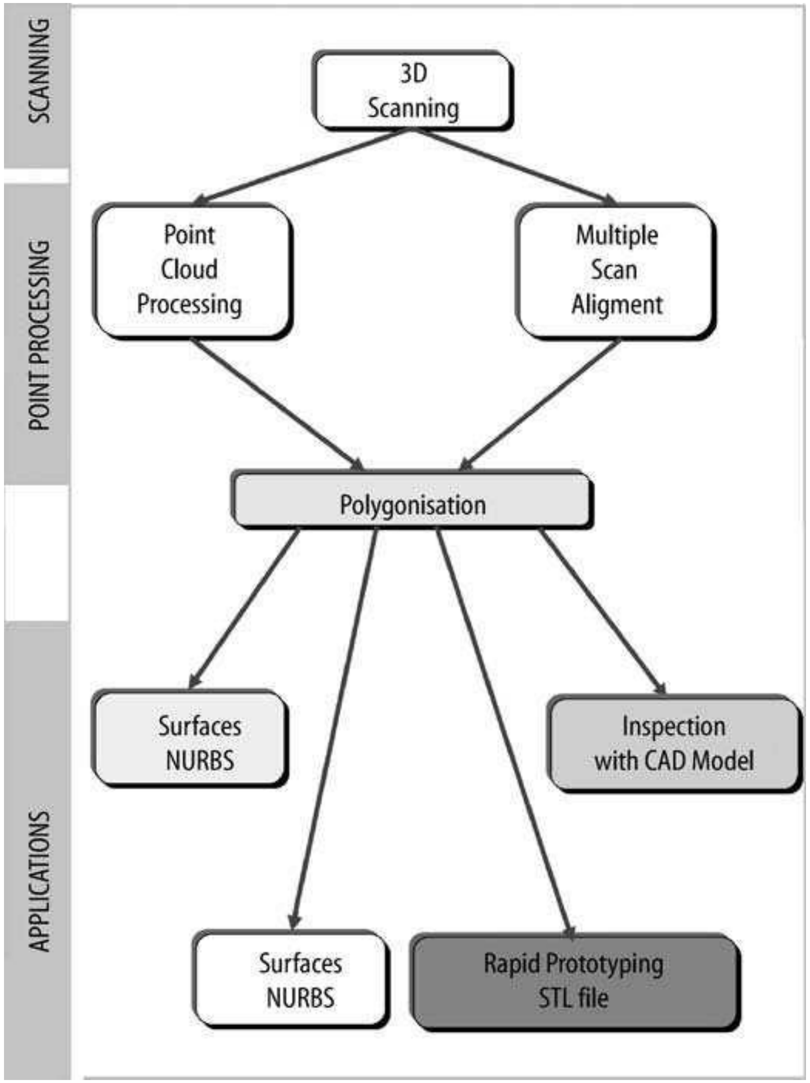
This definition casts light on the primary driving force of reverse engineering:

competitiveness.

Reverse Engineering–The Generic Process

The generic process of reverse engineering is a three-phase process as depicted in figure. The three phases are scanning, point processing, and application-specific geometric model development. Reverse engineering strategy must consider the following:

- Reason for reverse engineering a part
- Number of parts to be scanned–single or multiple
- Part size–large or small
- Part complexity–simple or complex
- Part material–hard or soft
- Part finish–shiny or dull
- Part geometry–organic or prismatic and internal or external
- Accuracy required–linear or volumetric



Historical Background

1. Industrial Evolution

The impact of reverse engineering on today's industry is beyond just introducing less expensive products and stimulating more competition. It also plays a significant role in promoting industrial evolution. The life cycle of a new invention usually lasted for centuries in ancient times. It took thousands of years to invent the electric light bulb for the replacement of the lantern. Both industry and society accepted this slow pace. However, the average life cycle of modern inventions is much shorter. It has only taken a few decades for the invention of the digital camera to replace the film camera and instant camera. This has led to a swift evolution of the photo industry. To accommodate this rapid rate of reinvention of modern machinery and instruments, reverse engineering provides a high-tech tool to speed up the reinvention process for future industrial evolution.

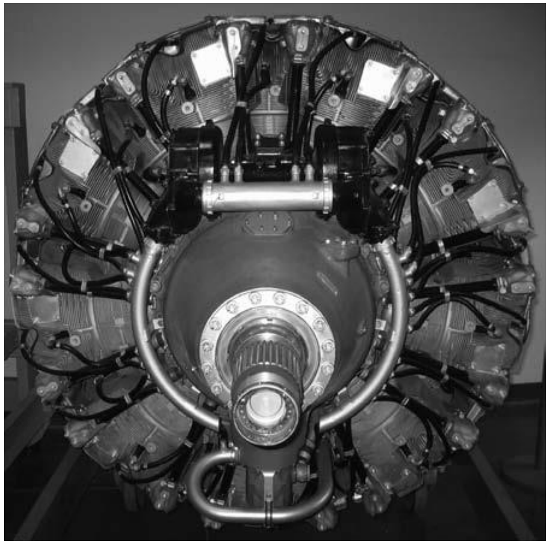
Reverse engineering plays a significant role in the aviation industry primarily because of the following reasons: maturity of the industry, advancement of modern technologies, and market demands. From the dawn of the aviation industry in the early 1900s to its hardware maturity with the development of jet aircraft in the 1950s, the aviation industry revolutionized the modes of transportation in about 50 years.

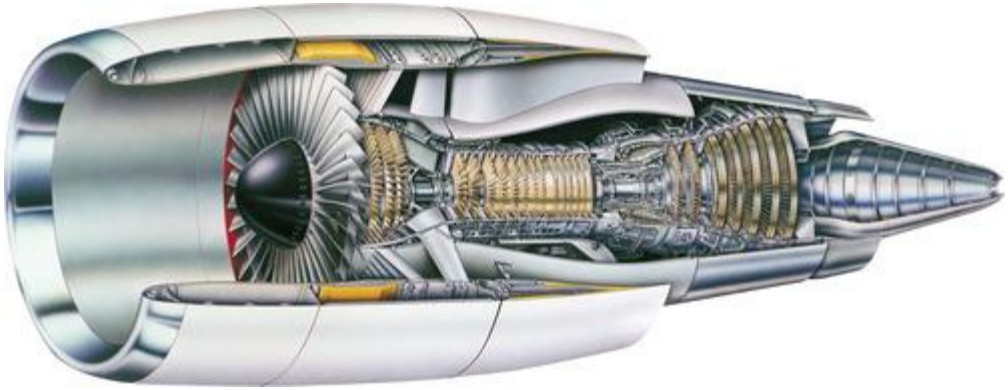
(a)

(b)

The early airport is unpaved and looks like a bus stop in the countryside (as shown in Figure 1.1a, also posted at the Automotive Hall of Fame in Dearborn, Michigan). It is a sharp contrast to today’s openfield, paved-runway airport vested with modern technologies, as shown in Figure 1.1b.

A similar analogy is also found in the aircraft engine and airframe. Figure 1.2 shows an early radial reciprocal aircraft engine that could generate a thrust up to 2,500 horsepower. It is exhibited in the New England Air Museum, Windsor Locks, Connecticut. An advanced turbine engine can generate a thrust of more than 100,000 horsepower today. However, this revolution of the flying machine has slowed down significantly since the invention of the jet engine. The fundamental principles of propulsion and aerodynamics have not changed for decades. Despite that the flight and air traffic control systems have continuously made striking advances with the integration of computer technology into the twenty-first century, the basic hardware designs of jet engine and airframe structures remain virtually the same.





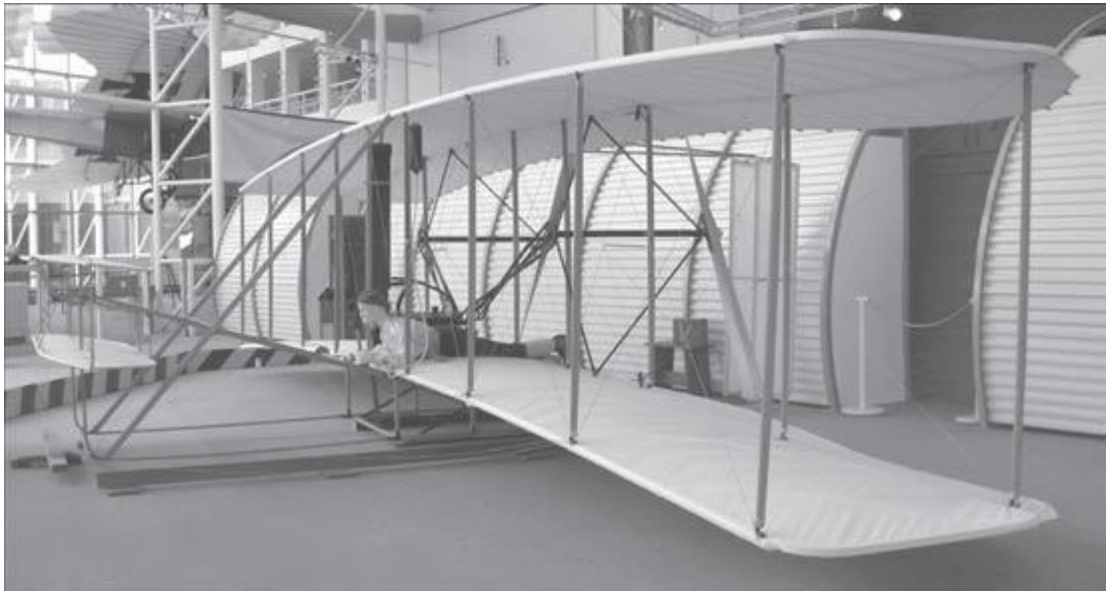
The maturity of the aviation industry, hardware in particular, gradually shifted the gravity of this industry from a technology-driven to an economic-driven business. This shift provides a potential market for reverse engineering.

During the same period, the advancement of modern metrology introduced many new tools for precision measurements of geometric form and accurate analysis of material composition and process. The fact that the aviation industry is a safety industry subject to rigorous regulations further augments the role of reverse engineering in this industry because certification requirements lead to an inevitable boost in part costs. Consequently, the market demands the least expensive certificated spare parts that are best provided by reverse engineering.

Similarly, great potentials of reverse engineering exist in the medical device field.

2. Reinvention of Engineering Marvels from Nature

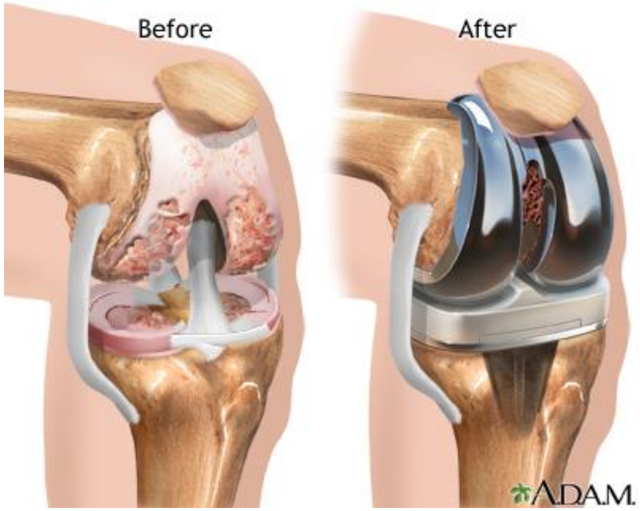
Many modern machines were invented with inspiration from nature, or reinvented through reverse engineering based on what was observed in nature. The airplane is one of the most noticeable examples. The first self-powered airplane invented by the Wright brothers was designed partially based on their observations, and imitations of flying birds. Figure 1.3a shows the maneuver and movement of flying birds. Figure 1.3b is a photo of the model plane that carried Orville Wright at the beach in Kitty Hawk, North Carolina, in his historical first flight on December 17, 1903. This model plane is exhibited in the Museum of Flight in Seattle, Washington. The first flight lasted about 1 minute and over a distance of approximately 260 m (~850 ft). Today, the cruise altitude of a commercial jet is about 10,000 m (~33,000 ft). However, the altitude of the first flight was about the same altitude of the flying birds.



The Wright bothers tried to reinvent a manmade “bird” by reverse engineering the functionality of a flying creature in nature. A century later, we find ourselves still far behind when it comes to catching the maneuverability of most birds, bats, or even bugs. A hawk moth can easily put up an aerial show flying up, down, sideways, and backwards with rapid acceleration or deceleration.

Bats are capable of agile flight, rolling 180°, and changing directions in less than half a wingspan length; today’s aerospace engineers can only dream of an airplane being so maneuverable. Various lengthy mathematic formulas with complex scientific variables and parameters are introduced to decode these myths. Nonetheless, today even the most intelligent aerospace engineers can only wish they could design a flying machine that remotely resembles these features. Reverse engineering is the key for scientists and engineers to deconstruct the basic skills of flying animals and reinvent the next-generation aircraft with better maneuverability and stability.

The human body is a beautiful piece of engineering work in nature. Reverse engineering is the most effective way to reinvent the component parts of this engineering marvel due to lack of the original design data. The production of an artificial knee for implementation in the medical field is a good example. It also reflects one of the major purposes of reverse engineering: replacing the original part. The reinvention process of an artificial knee highlights the key elements of typical reverse engineering practice. It requires accurate dimensional measurement and proper material for suitability and durability. It is also very critical for the substitute new part to meet the performance requirements and demonstrate system compatibility with the surrounding original parts.



3. Reverse Engineering in Modern Industries

The distinction between an OEM* and a supplier has been blurred in recent years in today's dynamic and competitive global market. The three major OEMs for aircraft engines—General Electric (GE), Pratt & Whitney (PW), and Rolls Royce (RR)—all just manufactured approximately one-quarter of the components in their respective brand engines. The identities of both the OEM and supplier are disappearing. On February 15, 2006, Pratt & Whitney launched its Global Material Solutions (GMS) program, a new business that will provide CFM56 engine operators with new spare engine parts through the Federal Aviation Administration (FAA) Parts Manufacturer Approval (PMA) and Supplemental Type Certificate (STC) processes. CFM56 is an aircraft engine manufactured through the cooperation of GE in the United States and Snecma Moteurs of France; PMA parts are those developed by companies other than the OEM, and are approved by the FAA based on either identicality or test and computation. The GMS program made Pratt & Whitney the first engine OEM to produce PMA/STC parts by reverse engineering for its rival products, GE engines. Upon the establishment of PW's GMS program, United Airlines immediately signed on as a prospective customer, with a potential long-term parts agreement for its fleet of ninety-eight CFM56-3-powered Boeing 737 aircraft. It brings the application of reverse engineering to a new era.

**OEM-Original Equipment Manufacturer*

The reverse engineering endeavor, such as reinventing PMA/STC parts, usually is market driven. From 1996 to 2006, more than half the new aircraft with 100 or more passengers were powered by CFM engines. The introduction of CFM engine spare parts produced by reverse engineering for the repair and replacement of worn-out components will have significant economic impact on the aviation industry and its customers, who will have more options in their maintenance programs.

Advancements in technology have dramatically changed the landscape of reverse engineering. In the 1970s, to reverse engineer a single-crystal high pressure turbine (HPT) blade was a challenge due to the need to decode highly guarded industry proprietary information. In the 2000s, reverse engineering a single-crystal HPT blade might be just a textbook exercise. Not only have technical innovations changed the reverse engineering process, but the practice itself is also more widely accepted.

To obtain precise geometric information for the aftermarket automobile parts, many companies also resort to the technology of digital scanning and reverse engineering. United Covers, Inc. is an automobile aftermarket manufacturer. It provides a variety of auto parts, including spoilers, running boards, fenders, and wheel covers. The company is not always able to take advantage of the OEM CAD data, partially because the as-built parts are often slightly different from the CAD data. As a result, real-life data acquisition is required to produce a high-quality replicate part to satisfy customers' expectations. Eventually United Covers contracted with 3DScanCo, a company specializing in 3D scanning and reverse engineering, to help it obtain accurate CAD data and modeling.

The genuine parts manufactured by reverse engineering have been used in automobile repairs and maintenance for years. In contrast to the PMA parts that are certificated by the U.S. federal government, the reverse engineered automotive parts are certified by the industry itself. The Certified Automotive Parts Association (CAPA) was established in 1987. This nonprofit organization develops and oversees a test program ensuring the suitability and quality of automotive parts to meet the standards for fit, form, and function in terms of component materials and corrosion resistance. CAPA encourages price and quality competition in the marketplace so that customer expenses are reduced while still maintaining part quality. It provides consumers with an objective method for evaluating the quality of certified parts and their functional equivalency to similar parts manufactured by automotive companies.

One of the widely cited reverse engineering examples in the military is the Soviet Tupolve Tu-4 (Bull) bomber. During World War II, three battle-damaged U.S. B-29 Superfortress bombers made emergency landings in then Soviet Union territory after missions to Japan. Most airplanes can be distinguished from one another by their respective characteristics. However, the similarity between the general characteristics of the U.S. B-29 Superfortress bomber and the Soviet Tupolev Tu-4 bomber, illustrated in Figure 1.4a and b.

(a) B-29 Superfortress bomber. (b) Tupolev Tu-4 bomber. (Reprinted from Oldfield, R., http://www.airliners.net/photo/Russia—Air/Tupolev-Tu-4/1297549/&sid=53544687ba303b72094370 7110073baf.)

Table 1.1 has led many people to believe that the Tupolev Tu-4 was a replica of the B-29 Superfortress.

TABLE 1.1

Characteristics of the B-29 and the Tu-4

Characteristics	B-29 (Model 345)	Tu-4
Maiden flight	September 21, 1942	May 19, 1947
Wingspan	43.1 m (141 ft 3 in.)	43 m (141 ft)
Length	30.18 m (99 ft)	30.18 m (99 ft)
Height	8.46 m (27 ft 9 in.)	8.46 m (27 ft 9 in.)
Cruising speed	220 mph (190 knots, 350 km/h)	220 mph (190 knots, 350 km/h)
Service ceiling	10,241 m (33,600 ft)	11,200 m (36,750 ft)
Power for takeoff	2,200 HP	2,200 HP

Source: National Museum of the U.S. Air Force, Boeing B-29 fact sheets, http://www.national-museum.af.mil/factsheets/factsheet.asp?fsID=2527; Wikipedia, Tupolev Tu-4, http://en.wikipedia.org/wiki/Tupolev_Tu-4 (accessed September 25, 2009).

Note: mph = miles per hour, HP = horsepower.

It is also widely believed that the U.S. fighter F-86 was reverse engineered for modification from a defected Mikoyan-Gurevich MiG-15 fighter during the Korean War. An F-86F (on loan from the National Museum of the U.S. Air Force) and a MiG-15 aircraft are exhibited in the New England Air Museum, as shown in Figure 1.5a and b. The F-86F was first introduced in 1951.

It was a variant of the original North American Sabre, and later evolved into an all-weather jet interceptor and fighter. The F-86F aircraft was powered by a General Electric J47 turbojet engine that was exhibited in front of the aircraft.

The MiG-15 fighter first flew in 1947. It was a superior fighter and extensively used during the Korean War. The exhibited MiG-15 fighter was manufactured under license by the People’s Republic of China and later obtained by the New England Air Museum in 1990.

The general characteristics of the MiG-15b is that debuted in early 1950 and the F-86F-30 are compared in Table 1.2.

TABLE 1.2

Characteristics of MiG-15 and F-86F-30

Characteristics	MiG-15bis	F-86F-30
Wingspan	10.06 m (33 ft 0.75 in.)	11.91 m (39 ft 1 in.)
Length	11.05 m (36 ft 3 in.)	11.27 m (37 ft)
Height	3.4 m (11 ft 2 in.)	4.26 m (14 ft)
Cruising speed	947 kph (589 mph)	826 kph (513 mph)
Maximum speed	1,075 kph (668 mph) at sea level	1,107 kph (688 mph) at sea level
Service ceiling	15,514 m (50,900 ft)	14,630 m (48,000 ft)

Source: Swinhart, E., The Mikoyan-Murevich MiG-15, Aviation History On-line Museum, http://www.aviation-history.com/mikoyan/mig15.html, and North American F-86 Sabre Aviation History On-line Museum, http://www.aviation-history.com/north-american/f86.html (accessed September 25, 2009).

Note: kph = kilometers per hour, mph = miles per hour.

A successful reverse engineering program requires great attention to the miniature details and accuracy of all measurements, in addition to a thorough understanding of the functionality of the original part. Not all reverse engineering projects are successful. For example, a reproduction of the 1903 Wright Flyer fell into a puddle after attempting flight on December 15, 2003, at the 100th anniversary of the feat of powered flight. This ill-fated flight attempt brought out another risk factor in reverse engineering. Even though we might have produced a seemingly identical replica of the original part, the operability of the reverse engineered part also depends on the operating environment, such as wind speed in this case, and system compatibility in more sophisticated operations.

Reverse Engineering vs. Machine Design

Engineering design is the process of devising a system, component, or process to satisfy engineering challenges and desired needs. It focuses on creativity and originality. However, reverse engineering focuses on assessment and analysis to reinvent the original parts, complementing realistic constraints with alternative engineering solutions. Reverse engineering has become a standard practice for engineers who need to replicate or repair a worn component when original data or specifications are unavailable.

The reverse engineering technology is also applicable to new designs of old parts. Reverse engineering is a top-down reinvention process, while machine design is a bottom-up creation process. In the reverse engineering process an existing and sometimes worn-out part is measured and analyzed with proper methodology to re-create a design drawing for future production.

In a machine design process, the design drawing is first created from a new idea or innovation, and the production of the part follows. The first step of reverse engineering is measurement and data acquisition of an existing part. This collected information is then analyzed and interpreted. During data acquisition, the engineer should obtain as much relevant information as possible, including available documentation, existing technical data, and nonproprietary drawings. It is also important to identify any missing engineering data as early as possible. A successful reverse engineering practice requires sufficient familiarity and adequate knowledge of the part being reverse engineered.

Although the primary purpose of reverse engineering an OEM part is to imitate the original part and duplicate it, usually the reproduced part is not identical to the original piece. It may be comparable, but it is unlikely to duplicate the identical dimensional tolerances and manufacturing processes. However, reverse engineered parts should resemble OEM parts as much as possible. In the aviation industry, PMA parts are preferred to be the identical twins, whenever possible, to OEM parts to ensure the same functionality and safety. Occasionally the PMA parts intend to integrate some improvement. It is always challenging to determine how much “improvement” is acceptable for a PMA part that is created using reverse engineering.

Parts ManufacturerApproval

Under some circumstances, reverse engineering is one of the few options engineers have to accomplish a task; for example, when the OEM design data are not available but repair to the original part is required, or the original designer is now out of business but more parts are needed.

1. Motivation and Challenge

Another difference between machine design and reverse engineering is their respective economic driving forces. To develop a new innovative part or an improved old part is often the primary motivation in machine design; the market acceptance of this part is yet to be tested. In contrast, the market acceptance of a reverse engineered part has already been proven. In fact, the best candidate for reverse engineering is often determined by the market demand of this part. The challenge for reverse engineering is to reproduce this "same" part with better or equivalent functionality at lower costs.

Due to the unique financial consideration, a successful reverse engineering project often integrates the legal, economic, environmental, and other realistic constraints into consideration early on. For instance, it is advisable before launching a reverse engineering project to be in close consultation with all the stakeholders, including the reverse engineering practitioner, the prospective customer, and the governmental agency that regulates and approves the final product. The prospective customer might have specific market demand on the part that can dictate the project planning, for example, the product quantity and schedule. The regulatory agency might require some specific demonstration to show the part's compliance to certain environmental regulations before its approval, which can affect the product test plan. All these requirements can significantly impact a reverse engineering project, costs in particular.

From time to time reverse engineering faces the following tough challenges to replicate an original part, that usually do not apply to machine design. First, the information might be lost during the part fabrication. For instance, the filler alloy will be consumed during a welding process. The original composition of the filler alloy is theoretically intractable because it is completely melted and usually metallurgically reacted with the base alloy during the welding process. In other words, the original alloy composition information is lost in the process. Second, the data might be altered during the process.

For example, the melting points of lithium and aluminum are approximately 180 and 660°C, respectively. During casting, an Al–Li alloy will be heated up to above 660°C for a period of time. More lithium will evaporate than aluminum during this process. The alloy composition of the final ingot will be different from the original composition of the raw material. The reverse engineering based on the part made of cast ingot has to consider the composition alteration during casting.

Third, the details of intermediate processes might have been destroyed to produce the final product. Analysis can easily confirm that a part is manufactured by forging. However, how many cycles of reheat and what presses are used at each cycle are much more difficult to verify because most the evidence has been destroyed before the final cycle.

Reverse engineering does not duplicate an identical twin to the original part because it is technically impossible. The primary objective of reverse engineering is to reinvent a part that possesses equivalent form, fit, and function of the original part based on engineering analysis of the original part. Reverse engineering is an ultimate art of applied science. It uses scientific data to recreate a piece of art that resembles the original one as much as technically possible. Engineering judgment calls based on the best available data play a much more significant role in reverse engineering than machine design.

Analysis and Verification

It is essential to meet the form, fit, and function requirements, and other design details. In a reverse engineering process, the part’s physical features are determined by measuring its geometric dimensions, and the tolerance has to be verified. Two other key elements in reverse engineering are material identification and processes verification, including material specification conformity. The material properties to be evaluated are contingent on the service environment and expected functional performance. The material properties at room temperature, high temperature, and sometimes even at cryogenic temperatures may be required. It is worth noting that the material property depends not only on its chemical composition, but also on its manufacturing process. It is critical in reverse engineering to verify the manufacturing process to ensure that the reinvented component will meet the functional and performance requirements of the original design.

In light of part performance verification, communication among all stakeholders and documentation of engineering data often are among the most important factors for a successful reverse engineering project. It is advisable to keep all relevant documents and records in order, and get all stakeholders to buy in as early as possible. It is also highly recommended to justify any technical modifications to the part, including alterations to the design.

The following two examples of modification are usually acceptable in reverse engineering:

(1) the use of a new material to substitute an obsolete material that is no longer available, and

(2) using an alternate manufacturing process that is commercially available to substitute an OEM-patented process, provided that they are comparable with each other, and both will produce similar products.

Accreditation

Both professional competence and data reliability are essential to reverse engineering. Engineering judgment is often called upon for the discrepancy between measurements due to instrumental and human inconsistency in reverse engineering practice. To ensure data reliability, all the tests and evaluations should be conducted at accredited laboratories and facilities.

Instead of obtaining accreditations or certifications independently from various organizations, an association can provide a universal certification service acceptable by many regulatory agencies and companies worldwide.

Part Criticality

One of the driving engines propelling the advancement of modern reverse engineering is its ability to provide competitive alternatives to OEM parts. The rigorousness of a reverse engineering project depends on the criticality of the part and cost-benefit consideration. The criticality of a part depends primarily on how it is used in the product.

A fastener such as a bolt will be a less critical component if it is used to assemble a non-load-bearing bracket only for division. However, when a bolt is used with glue to hold a 2-ton concrete ceiling in an underground tunnel, it can be a very critical component.

The fasteners are among the most popular candidates for reverse engineering. It is also estimated that approximately 70% of all mechanical failures are related to fastener failures. Fortunately, most times the failures are not devastating, and proper corrective actions can be taken to avoid further damage.

For example, the utilization of SAE class H11 bolts in aeronautic structures was attributed to a “higher than normal” failure rate due to stress corrosion cracking. FAA Advisory Circular 20-127 discourages the use of H11 bolts in primary aeronautic structures to avoid more incidents.

The precision and tolerance required to reverse engineer a part are often determined by the criticality of the part. From operation safety point of view, the criticality of a part is determined by checking the impact of safety if the part fails. A critical aeronautic part is deemed a part that, if failed, omitted, or nonconforming, may cause significantly degraded airworthiness of the product during takeoff, flight, or landing. However, in different fields and services the definition of criticality varies significantly. When analyzing a load-bearing critical component, the critical strength varies from tension, compression, torsion to fatigue or creep when it is subject to different types of load. The service environment also plays an important role in determining the essential characteristics of the part. High-temperature properties such as creep and oxidation resistance are the determining factors for a turbine blade operating in a high-temperature gas generator. The tensile strength is critical for a static load-bearing component, and also used to determine if a turbine disk will burst out at high rotating speed. However, for a part subject to cyclic stress, such as the automobile axle, fatigue strength is more relevant than the tensile strength. The corrosion resistance becomes a key material property for a part used in the marine industry. In other words, the critical property for a critical part in reverse engineering depends on its functionality and operating condition. For a critical part, higher-dimensional accuracy and tighter tolerance along with higher evaluation costs are expected, and it can become prohibitively expensive for a reverse engineering project.

To best meet the form, fit, and function compliance, and maximize the exchangeability, many commercial parts commonly used in industries, many of them are standardized by individual companies, government agencies, professional societies, or trade associations. Reverse engineering rarely applies to these standard parts because they are readily available on the shelf, and therefore lack financial sensitivity. However, a standard part set by one organization is not always a standard part according to the criteria of another organization.

Beyond standardization and globalization, technology advancement definitely has made it easier to reinvent the OEM part with little knowledge of original design details. More and more high-quality spare parts are manufactured through reverse engineering to substitute OEM counterparts at a competitive price.

Applications of Reverse Engineering

Reverse engineering is a multidisciplinary generic science and virtually can be applied to every field universally. The primary applications of reverse engineering are either to re-create a mirror image of the original part, decode the mechanism of a function, or retrace the events of what happened. It is widely used in software and information technology industries, from software code development to Internet network security. It is also used to reconstruct the events just before and immediately after accidents in the aviation, automobile, and other transportation industries. Forensic science is another area where reverse engineering is used to help resolve the myth. Other fields, such as medical systems, architecture and civil engineering, shipbuilding, and art galleries, also find a lot of reverse engineering applications. In this aspect the utilization of reverse engineering is beyond just reproducing mechanical components. It is used in prototype production for new design and repairs for used parts as well. Thousands of parts are reinvented every year using reverse engineering to satisfy the aftermarket demands that are worth billions of dollars.

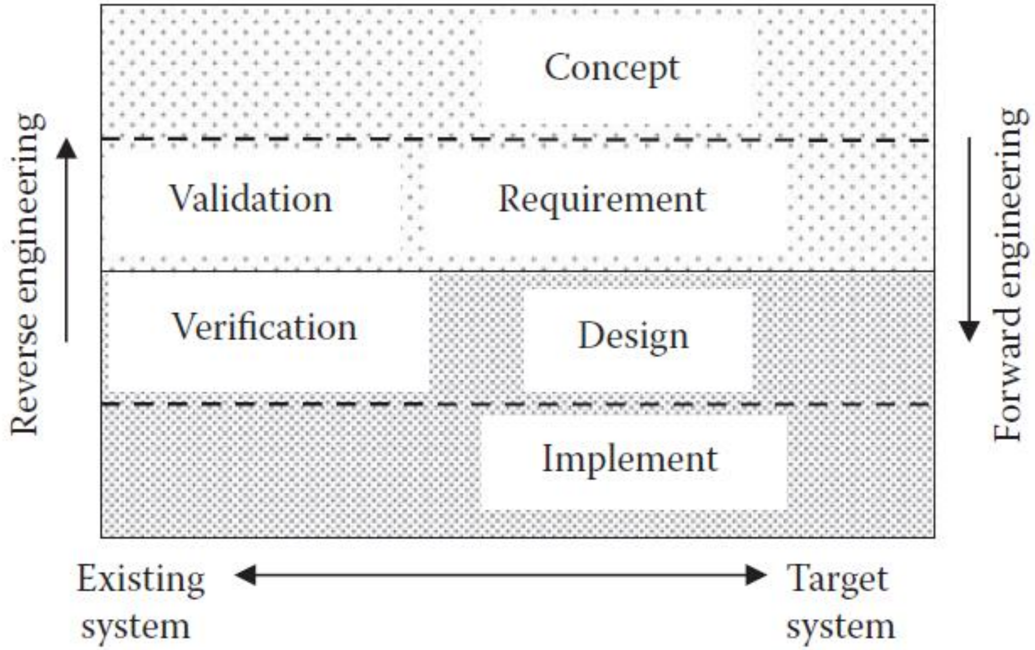
The invention of digital technology has fundamentally revolutionized reverse engineering. Compared to the aviation and automobile industries, the applications of digitalized reverse engineering in the life science and medical device industries have faced more challenges and advanced at a more moderate pace. This is partially attributable to human organs' delicate function and unique geometric form. The rigorous regulatory requirements in life science also demand a thorough test before any reverse engineered medical device can be put into production. The fact that we have yet to fully understand the engineering originality of the human body has put reverse engineering in a unique place in the life science and medical device industries, particularly in implementing artificial parts into the human body. The lack of original design drawing often makes reverse engineering one of the few options to rebuild the best replacement part, such as a spinal implement. Applying scanned images with finite element analysis in reverse engineering helps engineers in precisely modeling customized parts that best fit individual patients.

The applications of reverse engineering in software and information technology, in the life science and medical device industries, are a significant part in the overall reverse engineering applications.

Software Reverse Engineering

Software reverse engineering is defined as “the process of analyzing a subject system to create representations of the system at a higher level of abstraction” (Chikofsky and Cross, 1990, p. 13). Abstraction is a concept or idea without affiliation with any specific instance. In software development, the higher abstraction levels typically deal with concept and requirement, while the lower levels accentuate design and implementation. Generally speaking, reverse engineering performs transformations from a lower abstraction level to a higher one, restructuring transformations within the same abstraction level; while forward engineering performs transformations from a higher abstraction level to a lower one.

Several levels of abstraction are labeled in Figure 1.6, which illustrates the building blocks in software development. A standard software development model can be represented as a waterfall, starting with concept at the top, then requirement, followed by design, and finally implement. The requirement and design levels are separated by a validation vs. verification division. The reverse engineering process moves upward, analyzing the implementation of the existing system, extracting the design details, recapturing the requirements, and facilitating the original concept.



Level of abstraction of software development.

Reverse engineering will, step-by-step, represent the system at a gradually higher level of abstraction, from implement level through design, requirement, and finally reaching the concept level. The key objectives of reverse engineering are to recover the information, extract the artifacts, and synthesize higher abstractions. Reverse engineering will not change the software functionality or alter the system. Any alteration is made only at the completion of reverse engineering in a reengineering process. Reverse engineering builds the foundation that can be used by the subsequent forward engineering to complete the software maintenance or revision, when applied. The software forward engineering process is similar to the typical software code development process. Any refinement will only be made in the forward engineering process to reach the goals of the target system.

There are two commonly acknowledged aspects of software reverse engineering. First, it is a coding process to rewrite a source code that is either not accessible or not available in the field of software development. In this case, great caution has to be taken to avoid potential infringement of any proprietary information or intellectual properties. Second, it is a decoding process to dissolve (or debug) an intrusion in the software security arena. In this aspect, reverse engineering plays an increasingly important role in modern information technology.

Software reverse engineering is a backward process starting with a known functionality to produce a code that can deliver or dissolve this given functionality. There are many potential applications of software reverse engineering. One is to provide an open and fair use option for the maintenance and revision of the ever-growing large volume of software by reengineering, both reverse and forward (Boehm, 1979). Reverse engineering is the first leg of software reengineering. The essential tasks in software reverse engineering are to understand the structure and behavior of the legacy software code, and to process and redescribe the information on an abstract level.

As illustrated in Figure 1.6, there are two primary activities, validation and verification, during a typical software code development and in the subsequent software life cycle. A software code development usually starts with the establishment of the requirement baseline. This refers to the requirement specifications, which are developed and validated during the plan and requirement phase, accepted by the customer and developer at the plan and requirement review as the basis for the software development contract, and formally change controlled thereafter. The subsequent verification activities involve the comparison between the requirement baseline and the successive refinement descending from it, such as the product design and coding, in order to keep the refinement consistent with the requirement baseline.

Thus, the verification activities begin in the product design phase and conclude with the acceptance test. They do not lead to changes in the requirement baseline—only to changes in refinements descending from it. In the context of validation and verification of software code development, software reverse engineering usually will get involved with the following activities (Freerisks, 2004):

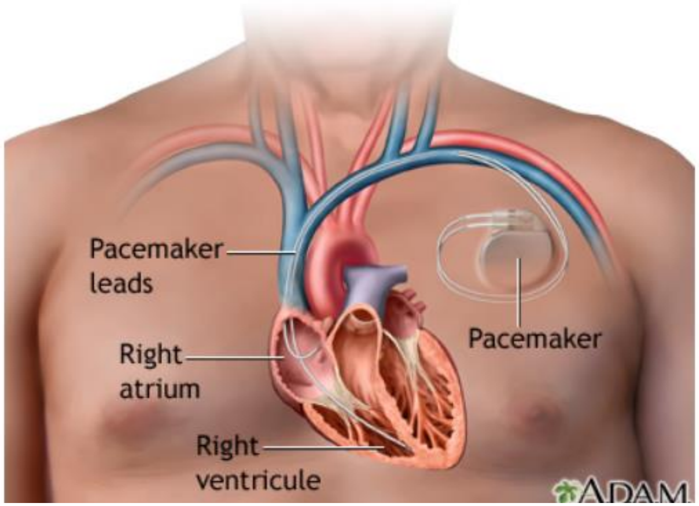
- Determining the user demand
- Realization of software-related improvements
- Restoring technical aspects
- Restoring user-level aspects
- Mapping the user-level aspects on the technical aspects
- Software integration
- System integration
- Reintroduction of the system
- Finding software items that can be reused

Software reverse engineering defines the system architecture with the elements of the generic product structure, and identifies the technical requirements for the overall system. In the end, software reverse engineering will generate sufficient data on system interfaces among various units, and provide an integration plan containing the regulations governing the technical aspects for the assembly of the system. Software reverse engineering usually also identifies the user requirements and the application environment.

Applications of Reverse Engineering in the Life Science and Medical Device Industries

The physiological characteristics of living cells, human organs, and the interactions among them form the baseline requirements for reverse engineering in life science and medical devices. Some success has been reported from time to time in identifying the biological components of the control systems and their interactions. However, a fully comprehensive understanding of the complex network of the interacting human body is still beyond today's science and modern technology. In fact, engineers and scientists often work in the reverse direction with the belief that between the observed body behaviors and the biological elements there must underlie the mechanisms that can reproduce these biological functions. This is the typical reverse engineering approach, similar to trying to figure out how a complex piece of electromechanical equipment works without having access to the original design documentation.

To reverse engineer a medical device, engineers first have to identify the materials that are used for this part and their characteristics, then the part geometric form has to be precisely measured, and the manufacturing process has to be verified. Also, more frequently than most other industries, a medical device is operated with sophisticated software for proper function. The operating software has to be fully decoded. For example, the software compatibility of a reverse engineered implantable cardiac pacemaker is one of the most critical elements of the device. In another example, to reverse engineer a blood glucose monitoring device that can be used to measure the glucose level of a diabetes patient, compatible software is a mandatory requirement for the proper transfer of the test results to a computer, and any communication between this meter and the host computer.



Reverse engineering is used in several medical fields: dentistry, hearing aids, artificial knees, and heart (Fu, 2008). Two medical models produced by prototyping are shown in Figure 1.7, including a dental model that illustrates a detailed teeth configuration. The different and unique shape of each individual's teeth configuration provides an excellent application opportunity of reverse engineering in orthodontics. The three-dimensional high resolution scanner used in reverse engineering can be utilized to accurately measure and model the dental impression of a patient's upper and lower arches. Based on the input digital data, advanced computer-aided manufacturing processes can build customized orthodontic devices for individual patients. Modern computer graphics technology also allows the close examination of teeth movement during follow-ups and the necessary adjustment, if required. Traditional braces with wires and brackets are no longer needed. The application of reverse engineering offers a less expensive and more comfortable treatment in orthodontics. It is worth noting that this new treatment is possible only because of the recent advancement of the modern digital process and computer technology.

High-tech computer hardware, sophisticated software, feature-rich laser scanners, advanced digital processes, and rapid prototype manufacturing have also made more effective applications of reverse engineering to other medical devices, such as the hearing aid, possible since the early 2000s. The digital technology processes sound mathematically, bit by bit, in binary code, and provides a much cleaner, crisper, and more stable sound than that from analog processing. It offers better overall performance and is relatively easy to update, modify, and revise, thereby providing superior consumer satisfaction in hearing aids. The further growth of reverse engineering applications in this field is mostly dependent on technology evolution to make the wireless hearing aid smaller, more sophisticated, and more efficient, while easier to manufacture and at lower cost.

The applications of reverse engineering to orthopedics, such as the knee, hip, or spine implantation, are very challenging, partially due to the complex motions of the knees, hips, or spine. A proper function of these implants manufactured by reverse engineering requires them to sustain multiaxial statistic stresses and various modes of dynamic loads. They are also expected to have sufficient wear and impact resistance. Several institutes, such as ASTM International, originally known as American Society for Testing and Materials, have published various standards on the testing of these implants. Medical devices, biomedical materials, and orthopedic implants are usually thoroughly tested to satisfy the rigorous regulatory requirements.