AC 2010-1062: USING FUNCTIONAL ANALYSIS AS A FRAMEWORK FOR UNDERSTANDING TECHNOLOGY

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Using Functional Analysis as a Framework for Understanding Technology

Abstract

While engineers bear responsibility for promoting the general understanding of technology, the means through which this may be accomplished is not well-established. In this work the technique of functional analysis or functional decomposition is adopted as a framework for explaining technological products and systems. Functional analysis is a method used in systems engineering and product design. The overall function of a technical system is accomplished through a series of interacting subfunctions attributed to specific components. The system function is to transform specified inputs into expected outputs. Inputs and outputs are treated as flows of either: material, energy, or information. Each of the engineering disciplines uses the principles of functional analysis in development of their specific technological domains. For example, in broad terms, chemical engineering treats transformation of materials, mechanical engineering treats transformations of energy, while electronics is concerned with flow of information. Each discipline has specialized methods and techniques that are applied to specific hardware components that carry out well-characterized subfunctions. Functional analysis or functional thinking is then recognized as one of the characteristics of the engineering habit of mind or modes of engineering thinking. This technique is well-suited to explaining engineering to a non-engineering audience. The method reflects the type of thinking used by engineers. A prerequisite background knowledge or use of extensive mathematics is not required. The systems perspective is inherent in the technique, underlying scientific principles used in specific components can be incorporated, and there is an evident connection to the engineering design process. The technique is applicable to a wide-variety of technological systems and devices and the method applies to past, present, and emerging technologies. Functional analysis can be taught by any engineering faculty member and helps novice engineers build a knowledge base of components and devices that provide common functions. By drawing attention to the process of function substitution, innovation is readily highlighted. The following discussion includes results from using functional analysis in an introduction to engineering course and with non-engineers in a general education engineering course.

Introduction

"Capable and confident participants in our technologically-dependent society must know something about engineering," states the National Academy of Engineering (NAE) in *Changing the Conversation: Messages for Improving Public Understanding of Engineering.*[1] In *Technically Speaking: Why All Americans Need to Know More about Technology*, the NAE stresses the value of being knowledgeable about technology in the twenty-first century.[2] Technological literacy is defined in *Tech Tally*[3] as "an understanding of technology at a level that enables effective functioning in a modern technological society."

Technology in this case is broadly defined as the efforts and products of the various fields of engineering. Technology encompasses any modification of the natural world to fulfill human needs and wants. Technology includes not only engineered products and systems but also the knowledge and processes needed to create, produce, and maintain those products.

Engineering is the profession that bears primary responsibility for creating, developing, and producing the technology that defines our way of life. If engineers see that it is imperative that the non-engineering public understand engineering and technology, then it follows that engineers should bear a significant responsibility for educating and informing the non-engineering public about these issues. While this responsibility is apparent, and even readily acknowledged by engineers, the means and methods through which engineering should communicate technical information to the non-engineering audience are not well-developed. This paper proposes a method derived from an engineering way of thinking that can provide a consistent framework for describing and explaining technology to non-engineers.

Problem Statement

The field of engineering lacks a general framework or a prescribed formal approach to describe and explain technological devices and systems. The individual engineering fields such as civil, chemical, electrical, and mechanical engineering have discipline-specific methods and techniques used to develop specific types of technology. The engineering disciplines share a common perspective on technology. This perspective has been largely implicit rather than explicitly identified and articulated. Discerning the perspective on technology that is unique to engineering is an important element of the engineering body of knowledge. An elaboration of the common view of technology shared by engineers and identification of ways of engineering thinking, is needed to make implicit perspectives explicit.

There is also a need for engineers of all types to be able to explain the technological products of engineering to a general audience. This explanation should describe technology using a way of thinking or a perspective that is uniquely engineering. Engineering must identify its own distinctive understanding of technology and use it when explaining technology to those who are not engineers.

The unique perspectives that identify an engineering world view should be accessible to interested non-engineers. As in any other field the generally accessibility of these major ideas does not imply that the general audience should then readily grasp the specific details of all types of specialized analytical methods. Any engineer should be able to articulate the basic characteristics of engineering thinking and use it as a means to explain technology to the non-engineering public.

Background: Describing Engineering and Technology to a General Audience

It is possible to identify several approaches that currently exist to explain engineering and technology to a non-engineering audience. One approach emphasizes an understanding of the scientific principles put to use in a particular device or component. Another approach focuses on an ability to apply the engineering design process as equivalent to understanding technology. A third approach eschews formal engineering or scientific methodologies and instead aims to explain how things work to the non-technically trained public by using everyday vocabulary, exceptional quality graphics and other visual aids.

Engineering Design Process

Design is frequently recognized as one of the defining characteristics of the discipline of engineering.[4-6] Since the engineering design process is viewed as a distinct activity from the hypothesis testing that characterizes the scientific method, this leads to an equating of understanding technology with being able to carry out the engineering design process.

The wide range of accessible materials available about the engineering design process helps to promote design as synonymous with engineering. Engineering for K-12 students emphasizes application of engineering design methods.[7] Design is a common focus in introduction to engineering courses for first-year undergraduates.[8-11]

Design offers several advantages when introducing engineering to non-engineers. The process is relatively accessible at a variety of levels and it emphasizes the creation of physical objects to solve problems. Design projects are active and engage students. The activity can use a wide variety of materials ranging from simple to complex. The engineering design methodology does not rely on mathematical procedures or extensive background knowledge and is therefore usable by K-12 students or non-engineers without prerequisite study. Once learned, engineering design methods can be used as a general problem solving skill for a wide variety of problems. Engineering can advocate design as a practical skill to acquire regardless of an individual's intended profession.

These advantages not withstanding, being able to carry out an engineering design process is not equivalent to understanding technology and engineering. Engineering design is a *process* that is used to develop new technology. Understanding the *process* does not necessarily explain the *products*. Understanding engineering requires a familiarity with the design process but the *process* evaporates once the technological artifacts are created. A means is needed for understanding technology that can be used to analyze and comprehend existing technology.

Another drawback of exclusive emphasis on the design process is engineering design must utilize and integrate new technology with the abundant variety of existing technology. The design process itself provides little guidance on a systematic means of developing a familiarity with the wide array of actual items from which engineering designs must be created. This is a notable problem with beginning engineering students. It is difficult for students to conduct an engineering design process without an understanding what potential technological elements exist from which that design might be composed.

The Science Principles of Modern Technology

Recently a number of science textbooks have been developed that highlight the underlying science principles at work in technological products. These are intended primarily for the general education of non-science and non-engineering students. For example, Bloomfield has developed a physics course and textbook entitled *How Things Work: The Physics of Everyday Life.*[12] This book uses examples from familiar technology to illustrate principles of physics. Physics books by Wilson,[13] Trefil and Hazen,[14] and Hewitt, [15] also draw heavily on examples from technology. This approach of technologically-themed and application-oriented science courses for non-science majors stands in distinct contrast to earlier classic works such as *Physics for the Inquiring Mind*[16] and *Physics for Poets,*[17] which avoided technological applications and emphasized philosophical questions and natural phenomena.

These approaches offer several advantages for helping the non-engineer understand modern technology. One strength is that most do not assume extensive prior knowledge of physics. Basic principles are described using verbal and visual explanations rather than mathematics. Using familiar technology as the setting for explaining a particular scientific principle effectively engages students' prior knowledge. Connection to prior knowledge is an important element of effective learning.[18] Also, given the extent to which technology surrounds and permeates modern life, it is possible that students are more likely to have prior experience with a particular technological device than a comparable example of the scientific principle from the natural world.

While science materials centered on technology may be accessible to the general audience, explanations of technology that are limited to the scientific principles at work remain an incomplete understanding of technology. In some limited number of cases, there may be a single scientific principle that characterizes a particular technology. In these instances it may be that grasping the relevant scientific principle is equivalent to understanding the technology. It is more often the case that a given technological device incorporates a wide range of scientific principles often from distinct areas of science. The assemblage of scientific principles used in a given device is not likely to form a set that is conceptually coherent in the usually recognized progression of ideas within a single scientific discipline. A set of examples that best illustrates important principles of science is not likely to be the same best set of examples illustrating the key principles of engineering. Additionally, explanations of the scientific principles at work in a technological device do not usually include the system nature of technology that is a central feature of most engineered products.

These science-based approaches to understanding technology view technology with the same perspective with which they view the natural world: as preexisting phenomena to be deciphered. The approach to understanding technology that is centered on the underlying science principles at work in a particular device will struggle to address the importance of the social context or any other aspects of the decision-making process underlying the particular form taken by a technological product. Science has been described as the discovery or study of what already exists in nature.[19] Explaining science principles in the context of technology is primarily about science and not about engineering.

Popular "How Things Work" Materials

One approach to understanding technology is to make use of the materials that already exist in the popular media on technological topics. These works are intended for a general audience of curious and interested individuals and assume no prior knowledge of science, engineering or mathematics. Explanations are based on verbal descriptions and visual aids. These usually include descriptions of underlying scientific and engineering principles. Some examples of these include the extensive website "How Stuff Works[20]" and related book,[21] as well as the popular book by David Macaulay "The Way Things Work.[22]"

Websites are just the most recent embodiment of efforts to explain technology to a general audience. In any given era, efforts were made to explain how things work for the general public. Some of these are encyclopedic,[23] while others focus on a small range of technological devices or products.[24]

It is interesting to note that these materials make liberal use of visual aids and tend to utilize whatever was the current state-of-the art for conveying visual information. Currently this is video and animation. In the past these were books printed in high quality color. In times that were dominated by text-only publications, the "how things work books" were distinguished by widespread use of illustrations and line drawings.[25] Using the best available technology to engage the visual senses of the audience has served to capture the interest of the general public. This emphasis on visual representations in the popular media imply that visually-oriented representations may be useful in helping a non-engineering audience understand how things work.

These popular "how things work" materials are commendable in generally including an overall or complete system view of the technology. Explanations encompass the entire operation of the device rather than a single component. Some present practical relevant information relating to the operation, repair, or maintenance of the technology.[26] Historical background information is often included.[22]

Despite the accessibility and visual nature of the popular "how things work" materials, a significant shortcoming can be indentified. In striving to be accessible to a general audience the works are little informed by the methodologies of the engineering disciplines actually responsible for creating, developing, and improving these technologies. In being self-contained, the readers of these materials are also insulated from the possibility of being led through any gateways to more sophisticated levels of understanding. This insulation protects the general reader from being overwhelmed by complex explanations and discipline-specific vocabulary. At the same time it deprives the general reader of an opportunity to gain the more in-depth understanding of the technology that a thoughtful connection with actual engineering principles could provide. The "how things work" materials both start and end at a general level. No knowledge of engineering is *required* but also no knowledge of engineering is *acquired* either.

Characteristics of a Framework for Explaining How Things Work

Development of an easily-used framework or approach for understanding technology would help to promote technological literacy. Since engineering is the profession whose primary purpose is the creation of new technology, this framework should reflect a characteristically engineering way of thinking. Engineers must use some ways of thinking or habits of mind that are unique to the discipline. The framework for understanding technology might be found in the question "What does it mean to think like an engineer, and what or how do engineers think about technology?" The goal is to make it possible to understand technology by thinking like an engineer.

At the same time, the framework or organizational principle should not be specific to a particular device. The framework should provide knowledge that is transferrable or applicable to understanding any technology. The framework should help the non-engineering audience develop knowledge of some key ideas of engineering that contribute to the development of technological products.

Organizational Framework Based on Functional Analysis

Functional analysis can provide a framework for explaining technology. The methods of functional analysis were developed for creating new technological devices and systems.[27] However, separated from the design task, functional analysis can be used as a framework or way of thinking for understanding already existing technology. Functional analysis is often employed in the context of engineering product development[28,29] and systems engineering.[30-32] Functional analysis describes the abstract purpose or role of any part of an engineering product.[27] Because the emphasis is on abstract utility, functional analysis, or thinking in terms of function, is independent of any specific technology.

Thinking Like an Engineer = Thinking in Terms of Function

Using functional analysis to explain how technology works is comparable to stating that one aspect of engineering thinking is thinking in terms of function. Engineers think about the function or purpose which is accomplished by a particular physical object or form. In other words, engineers think about how things work by understanding the role of each component.

Examples from the various engineering disciplines and products support the suggestion that a characteristic of engineering is thinking in terms of function. Systems engineering and product design both utilize functional analysis as a central technique. Systems engineering emphasizes the development and management of extremely complex technological products such as defense systems that can be large in extent in both space and time. Functional analysis as a primary tool in systems engineering design takes the form of the functional flow block diagram.[30-32] In contrast, product development is typically oriented toward development and improvement of new and existing technological devices. The focus is often on small inexpensive products utilized by millions of individual mass-market consumers.[28-29] Product development efforts employ functional analysis as a perspective and technique in the design process. In both systems engineering and product development applications the same basic functional analysis ideas are applied to develop technology of vastly different degrees of scale, complexity, and cost.

Examples of thinking in terms of function can be identified in each of the major engineering fields even though the specific products are notably different. Electrical engineering relies on specific components which provide well-defined functions with specific capabilities which are utilized in differing specific circuit applications. The mechanical engineering field of machine design is based on use of functional components such as gears, cams, and bearings, each of which provide a specific function in a particular class of technological products.[33] Similarly, the diverse products of civil engineering utilize the functional design elements characteristic of civil infrastructure.[34] The chemical engineering concepts of unit operations and unit processes serve as functional elements for creating material transformation processes.[35]

Basic Principles of Functional Analysis

Functional analysis considers any human-made technological artifact as a technical system regardless of its degree of complexity.[27] The technical system then transforms a specific set of inputs into outputs. The system may have different modes of operation which may be characterized by a different set of inputs and outputs. The extent of the technical system is defined by the system boundary. The system boundary defines the location at which the system connects with its environment and where the inputs and outputs are identified.[28,36] The system boundary does not have to correspond to a physical boundary; it may be an imaginary surface defining the extent of a system. Figure 1 illustrates the basic functional analysis or “black-box” representation of a technical system.

Inputs and outputs are classified in three categories: energy, materials, or information. Energy and materials have the usual meaning from physical science. Information is described as signals, data, or energy with a decision-making purpose. In functional analysis, forces are sometimes considered using the same perspective as energy. Forces can be visualized as flowing through a system as they are transferred from one component to the next.[36-40]

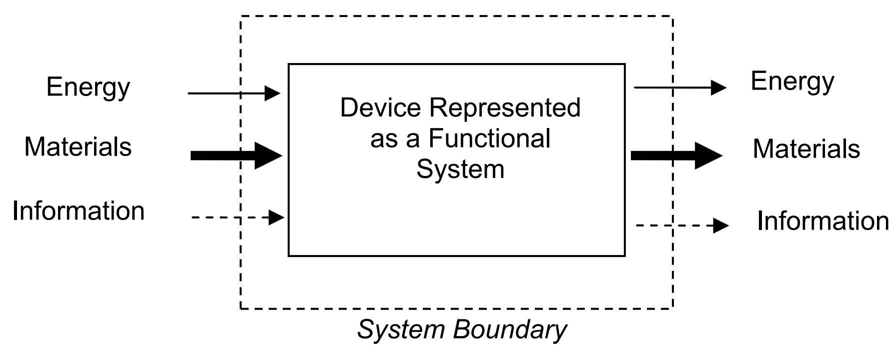

Figure 1: Basic Functional Analysis Representation

The overall function of the device, or technical system, is accomplished via subtasks or subfunctions. These subfunctions are expressed as verb-noun pairs. Examples are transmit-torque or actuate-electricity. Some physical component or collection of components carries out each subfunction. Figure 2 illustrates a hypothetical subfunction structure. Subfunctions are responsible for transforming some subset of the inputs into a subset of the outputs. Intermediate inputs and outputs which are internal to the system may be produced.

As a specific example, Figure 3 shows a functional analysis representation of a hair dryer. One input is material in the form of air which enters the system at the air intake. Energy is also an input which enters the system as an electric current via the cord. The electric motor converts electric current into torque (or electrical energy into kinetic energy) which rotates a fan. The fan pressurizes the air creating flow over the heating coils. Electric current is converted into sensible heat by the heating coils. This heat energy is then transferred to the air. The heated air is an output of the system. Information is output in the form of noise which indicates that the dryer is operating as does the temperature of the output air stream. Heat is also transferred to the dryer housing.

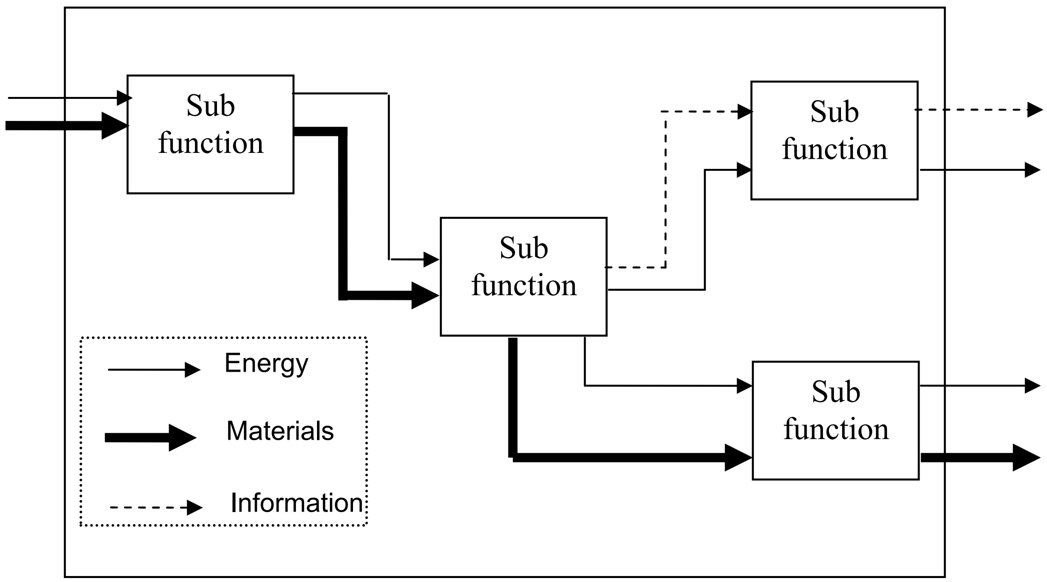

Figure 2: Illustration of a Hypothetical Device Subfunction Structure

The functional analysis representation is a description of how the system works. The intent of the functional analysis representation is to describe the major or most significant components that contribute to the transformation of inputs to outputs. The analysis can be conducted to progressively finer levels of detail. It is also the case that more than one variation of the functional analysis diagram can be constructed for a particular technical system. The purpose is not to represent a detailed physically accurate representation of the components, or to include every electrical or mechanical interconnection within the system. The emphasis is on the major steps in the progression from system inputs to expected outputs.

An advantage of using the functional analysis approach is the ability to illustrate that engineered products utilize combinations of pre-existing components to provide specific portions or subfunctions in the overall operation of the device. The major components of the hair dryer include the cord, switch, electric motor, fan blades and heater. The components provide well-defined functions which are also utilized in other devices to carry out similar functions. Through this approach, the non-engineer or even the novice engineer in an introduction to engineering course, can begin to develop a working vocabulary of components that provide frequently used functions. This is the essence of engineering and also avoids reinventing the wheel.

Components providing subfunctions can be described in terms of the underlying scientific principles of their operation and the mathematical expressions that describe their performance. Variations on these components that are optimized for a different set of requirements, such as the many variations on the electric motor, can be introduced. Standardized components enter naturally into the discussion.

Each of the engineering disciplines uses the principles of functional analysis in development of their specific technological domains. For example, in broad terms, chemical engineering treats transformation of materials. Electrical engineering is primarily concerned with flows of electrical energy and information in the form of electric current. Mechanical engineering frequently considers transformations of energy where there is a change of form of the energy, for example in the many types of heat engines. Civil-structural engineering focuses on directing the flow of forces through a system.

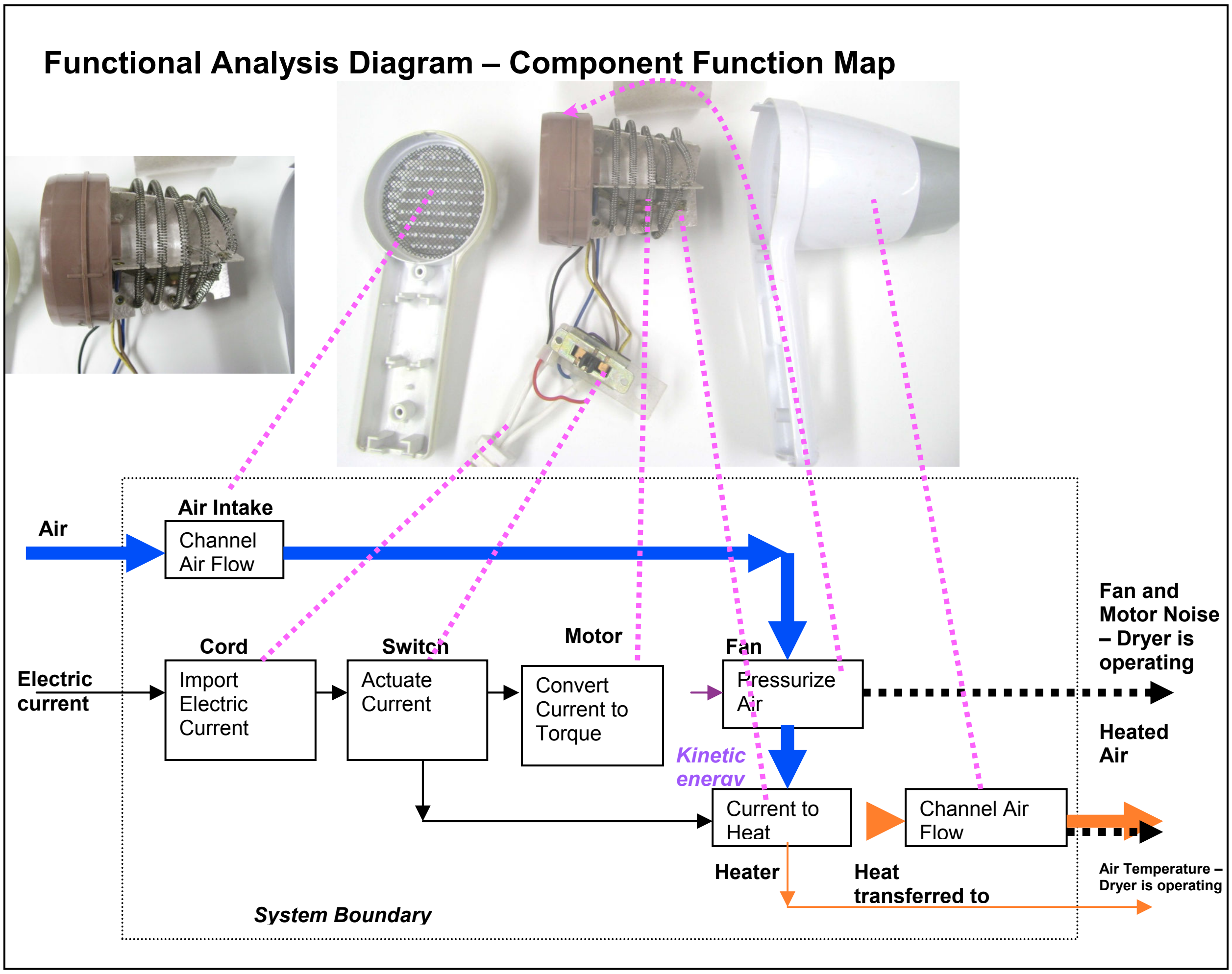

Figure 3: Functional Analysis Description of a Hair Dryer

Functional Analysis Adapted to Explaining How Things Work

A necessary step is the development of an explanation of functional analysis that is accessible to anyone without prerequisite background technical knowledge. A slight shift in emphasis must be made to adapt this technique from a design method to a means of understanding technology. An explanation and set of procedures was developed to adopt this design technique for use as an explanatory tool and to make it possible for non-engineering and beginning engineering students to think in terms of function when explaining how things work.

Functional Analysis Procedure / Component Function Maps

The term "Component Function Map" was developed to emphasize key elements of the approach. The focus is on identifying the key components of the technical system and identifying the function of those components in transforming the inputs into the outputs. The final product is a diagram or map showing the route or path the inputs follow through various components in becoming the outputs of the system. As in other types of maps, some judgment or selectivity is implied determining what portion of physical reality to include. An effort was also made to evoke the idea of a concept map[41] in particular the sense of individual choice that is implied in developing such maps. An important point is that explaining how something works is necessarily a selective process. Every single individual component is not of equal significance in transforming the system inputs into the outputs. Like a written essay, functional analysis requires selectivity and judgment on the part of the creator. As such it can also be classified at the synthesis level of Bloom's taxonomy[42] indicating a high degree of cognitive engagement. It is also emphasized that a component function map is not intended to depict the appearance of the technical system, but rather how it works or the more abstract function of the component. Other than the guidelines listed below creative interpretations or individual adaptations are encouraged.

Simplified Functional Analysis Procedure / Component Function Maps

1. Establish the system boundary.
2. Identify overall function and flows in/out.
3. Determine major components function and flows.
    Recognize common components or core technologies.
    Identify components performing subfunctions unique to that system.
4. Arrange sub-functions matching inputs and outputs of material, energy, and information.
5. Create visual representations to illustrate operation.

Background Preparation for Students

It is not likely that non-engineers or even beginning engineering students would be able to functionally analyze an unfamiliar technical system without some assistance to develop a mastery of appropriate background material. A basic procedure has been developed. A particular technological domain or category of related technical systems is selected for study. The most common or characteristic subfunctions of that domain are identified. These might be called the core technologies of the domain. These individual characteristic subfunctions or core technologies are analyzed. This includes underlying principles of operation, inputs, outputs, and operating characteristics. A functional analysis is carried out on a representative technical system based on these core technologies. As an assessment method, students create functional analysis diagrams of unfamiliar technological systems within the domain.

Summary of Student Prior Preparation

1. Identify a technological domain or category of related technical systems.
2. Identify shared characteristic components or core technologies.
3. Analyze core technologies: principles of operation, inputs and outputs, models.
4. Carry out functional analysis of selected representative technical systems.
5. Demonstrate mastery by analyzing unfamiliar technological systems within the domain.

Example: How Home Appliances Work

Some work has been carried out on the use of functional analysis to promote the ability of non-engineering students and students in introduction to engineering to explain how things work.[43-44] Non-engineering majors were enrolled in a class called "Science and Technology of Everyday Life" at Hope College. The engineering majors were enrolled in Introduction to Engineering. The method described for promoting thinking in terms of function and creating functional analysis diagrams was developed and used with these groups.

The use of functional analysis to explain how things work was implemented in a section of each course under the topic of home appliances. Course work included a treatment of several key components used in home appliances. These were the electric motor, electric heaters, gears, and fans. This selection of components was guided by results reported by Otto and Wood[28] who described the frequency of common subfunctions in consumer appliances. A representative functional analysis of the hair dryer was carried out as a class exercise.

The non-engineering students and introduction to engineering students were then asked to carry out a functional analysis of a device that had not been previously addressed in the course. They had not studied the device before but where able to analyze and describe how it works by creating component function maps. Figures 4 and 5 show results produced by two different non-engineering students. In the first example, the student used standard boxes and arrow styles for flows of material, energy, and information. In the second, the student chose to embellish the arrow styles and create more visually interesting representations for the subfunctions. These results are an encouraging initial indication that this technique could be a successful framework for explaining how things work.

In creating the component function maps, it was found helpful to emphasize the need to both identify the components providing a generic function common to home appliances, as well as components that are unique to that particular device. In other words, if the technical system was a blender, what components does a blender use that are found in other devices? Conversely, what components provide the unique or characteristic functionality of blenders that distinguish blenders from other appliances?

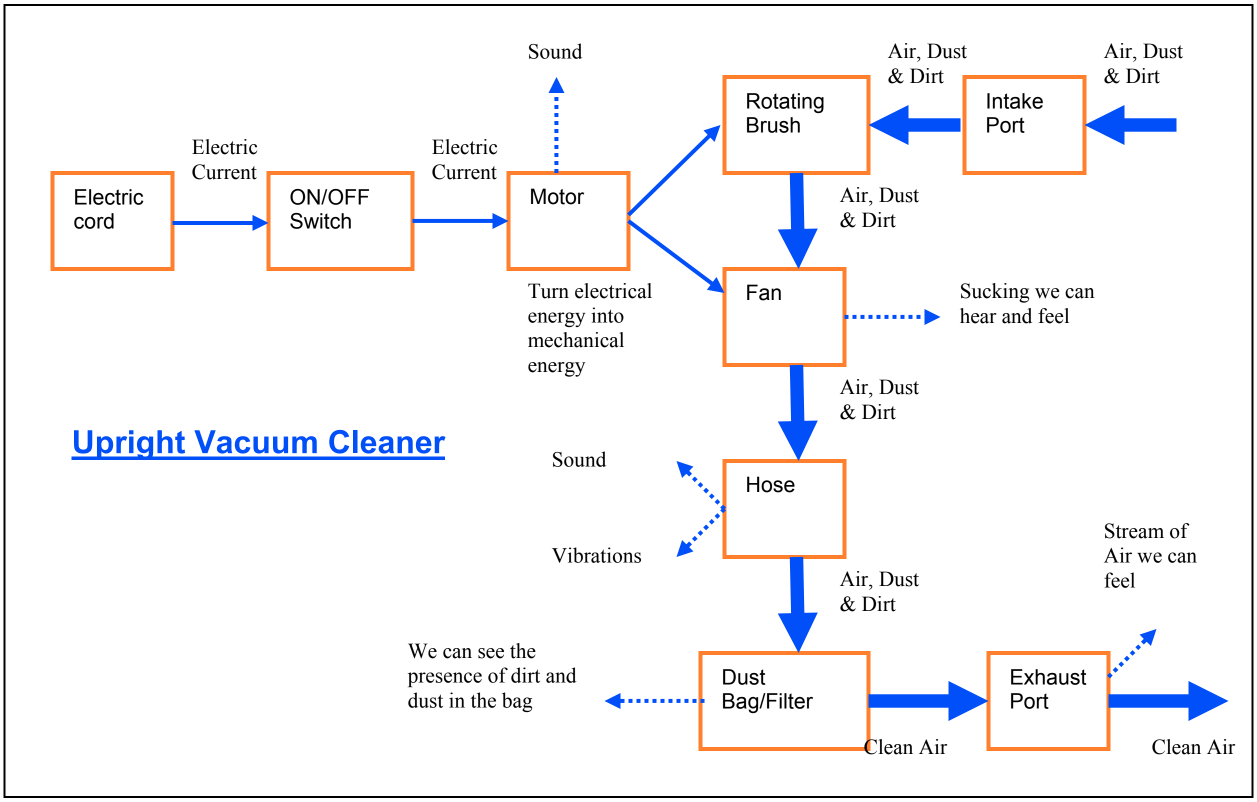

Figure 4: Example of Student-Generated Component Function Map of a Vacuum Cleaner.

Benefits of Functional Thinking

In using functional analysis, or thinking in terms of function, as a framework or method to describe how things work from an engineering perspective, a number of benefits are realized. These can be summarized as:

Characteristic of Engineering Thinking
The method reflects an approach or method of understanding technology that is characteristic of engineering. The method reflects the processes actually used by practicing engineers in understanding and designing technology.

Systems Perspective
Functional analysis approach incorporates a systems perspective in describing technology.

Generic to All Engineering Disciplines
Functional analysis can be used to describe the products of any of the engineering disciplines. Functional thinking is not exclusive to one field. It is a general engineering approach.

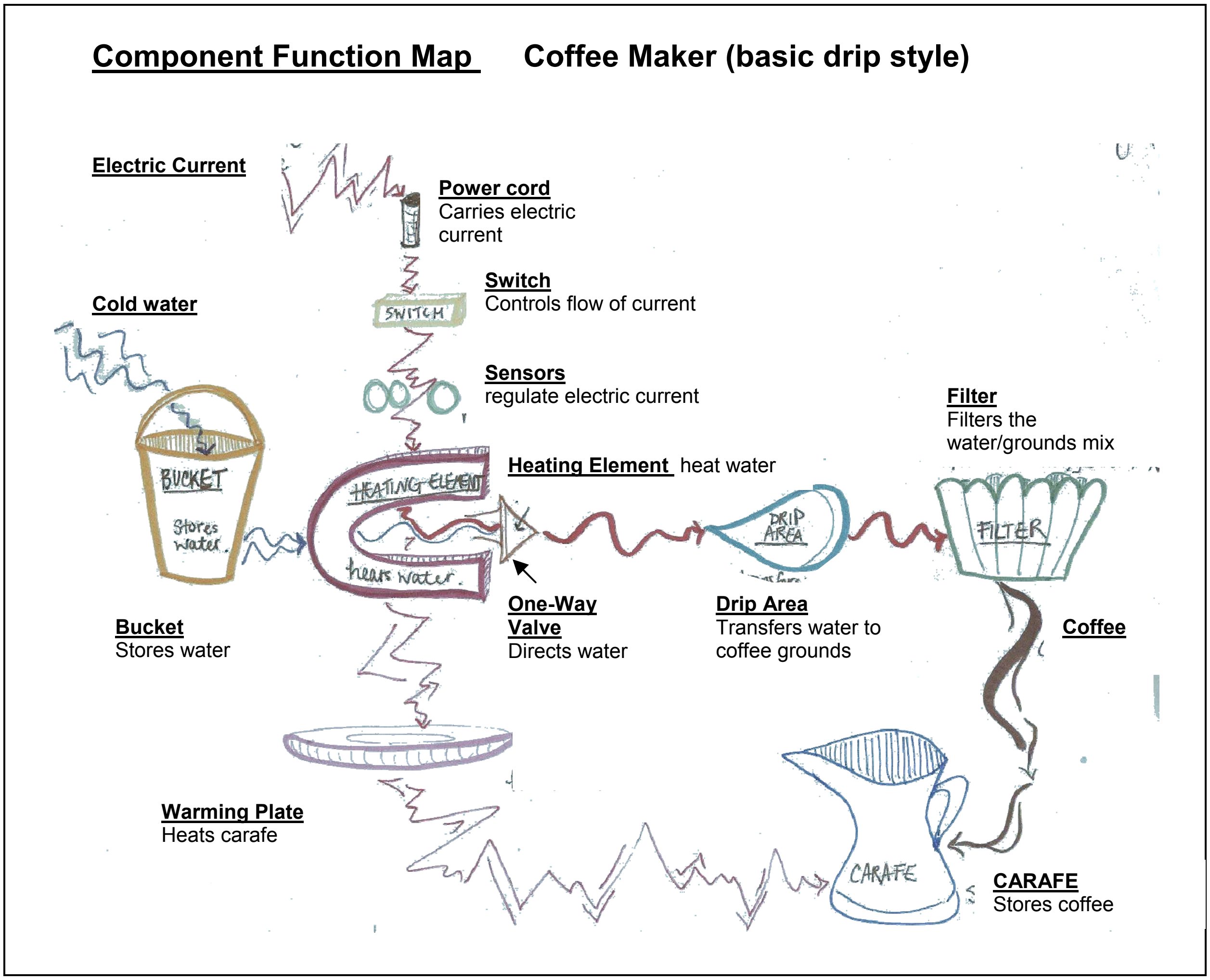

Figure 5: Example of Student-Generated Component Function Map of a Coffeemaker.

No Prerequisite Knowledge
When used to describe engineering to a general audience, elaborate prerequisite knowledge is not needed to understand the approach. It is a largely self-contained framework that would be accessible to any student.

Supports Engineering Design Process
The method is consistent with and merges naturally into the engineering design process.

Applicable to Any Technological Product
The framework can be used to describe any technological product that is the outcome of the engineering process. It is flexible in describing the size, scale, extent or complexity of the product.

Taught by All Engineers
This approach is something that all engineers might find familiar and could be taught by faculty from any engineering discipline.

Applies to Evolving Technologies
Functional analysis is not a static technique but can be applied to the constantly changing nature of technology. Description of the evolving state-of-the-art should be accessible with this framework.

Builds Engineering Component Vocabulary
The functional analysis approach helps non-engineers and novice engineering students acquire a vocabulary or knowledge base of existing components that provide useful functions.

Inclusion of Science Principles and Mathematics
It is possible, if desired, to include relevant scientific principles and the use of mathematics in describing component subfunctions that reflects modern engineering practice.

Highlights Innovation
Innovation in product design is frequently achieved through improving existing or creating new subfunctions. Innovation can be merged naturally with engineering education using the structure and vocabulary provided by functional analysis.

Current Work

Current efforts are directed toward developing materials and examples for other technological domains. Other work seeks to develop rubrics for helping to evaluate functional analysis diagrams so a larger sample of students can be examined. Attention is also being directed toward developing assessments to characterize the ability of students to use the framework to understand technical systems with which they have no prior familiarity.

Conclusions

The technique of functional analysis provides a definition for one aspect of what it means to think like an engineer. Functional analysis highlights the role of components which provide subfunctions which can be manipulated, modified, and adapted to a particular design problem. Important devices such as the electric motor can be introduced to novice engineers and non-engineers in the context of providing commonly needed subfunctions. The method is not restricted to any one engineering discipline and can be used to understand the workings of a wide variety of technical systems. Initial work shows promising indications that non-engineering students are able to use this technique to think in terms of functions or think like an engineer when attempting to understand how things work.

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