Development of a Simplified Method for Representing Technological Systems for Non-Engineers

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Abstract

A challenge in promoting engineering and technological literacy is the need to convey the major aspects of technological systems to an audience that has a limited pre-existing knowledge of engineering principles. Visual aids such diagrams are helpful in summarizing key features of technological systems and conveying concepts common to all technologies. However in survey courses of modern technology for non-engineers, the methods and conventions used must be consistent across a broad spectrum of common technologies including automobiles, structures such as bridges, and electronics. This work describes the initial development of a set of techniques to describe how technological systems work by focusing on the function structures of technological system. Non-engineers can learn this method in a limited amount of time and a range of technological products can be represented. The method avoids the creation of ad hoc diagrams for each system and is based on the engineering design technique of functional analysis or functional decomposition. This technique is modified to emphasize the description of the functions carried out by existing system components rather than functions to be achieved through the design process. The method utilizes the convention of representing technological systems as transforming specified inputs into expected outputs. Inputs and outputs are treated as flows of material, energy, or information. Icons or representations of form similar to conventional schematic symbols can be utilized to provide visual references and cues. This technique reflects the type of thinking used by engineers; however prerequisite background knowledge or use of extensive mathematics is not required. Initial results from use in a course for non-engineers show an increase in technological and engineering literacy among the pilot audience.

Background

A goal of technological and engineering literacy efforts is to help a non-technical audience develop an understanding of the engineering principles utilized in devices and processes that have become essential to daily life. Engineering literate citizens also appreciate how engineering thinking helps to view all technological systems through a common perspective. Visual aids are useful in conveying key aspects of technological systems. When used in introductory or survey courses for non-engineers, the techniques used to represent common technologies must be applicable across a diverse range of technologies. The gamut of technological literacy topics includes automobiles, electronic devices, and home appliances. Since engineering literacy survey courses often include a wide range of technological systems, there is a need for diagrammatic visual aids for a wide range of technologies.

Rather than establish a static set of visual aids of existing technologies, what is needed is a set of guidelines for creating appropriate visual aids or diagrams for the technological and engineering literacy audience. Any collection of visual depictions will soon be out-of-date. Guidelines can convey the essentials of engineering thinking in a way that is independent of any particular device or process. In this way guidelines, and experience in using them, can help non-engineers to understand high-level concepts that are common to all technologies such as the basic and generally-applicable engineering concept of a system as advocated by the National Academy of...
Engineering in *Technically Speaking* ¹. The potential number of technologies to be represented is effectively limitless so some recommendations for construction of diagrams are needed. In addition, if the guidelines and procedures are accessible to non-engineers they can create their own diagrams and visual aids of technological systems. The ability of non-engineers to develop diagrams is potentially useful as an educational tool.

What types of visual aids are typically useful in technological and engineering literacy applications? Visual aids can be used to convey the appearance of particular technological systems, devices, or components. Visual aids are often used to illustrate or describe how the system works. In other words how the various inputs are transformed by the system into the desired outputs. The inputs can range across a wide scope such as electric current, raw materials, fuel, radio signals, or even automobile traffic. The system outputs include an equally diverse list of potential items such as sound, hot air, video displays, processed materials, or light.

Visual aids are also used to provide a sense of the process within the system through which the inputs become the outputs. Visual aids are often employed to show or illustrate aspects of system operation usually hidden from the user. Visual aids are also used to disaggregate a complex system into smaller subsections or components and identify system parts. Illustrating the processes occurring in the components is often a desired aspect of explaining the operation of a technological system for non-engineers.

The goal technological literacy for all citizens shares many issues in common with efforts to develop a pre-college engineering curriculum. Work in cognitive development and learning science focused on K-12 engineering has identified the importance of system function and behavior of technological artifacts as core organizing concepts that are foundational to the discipline ²,³. The structure-function-behavior framework developed by Gero and others has been used to explain designed physical systems and applied to electrical devices such as an amplifier ⁴,⁵. The effort reported here represents a simplified approximation of these methods in a form which can be learned and applied by non-engineers in a one-semester undergraduate course.

**Existing Options for Visual Aids**

Materials intending to explain how technological devices work already frequently employ visual aids and diagrams. It is helpful to review some of the existing options for visual aids in technological and engineering literacy. Many of the commonly used types of visual aids have useful features, however each has some drawbacks that are less-than-ideal for use in technological and engineering literacy courses.

**Ad hoc Diagrams**

Many descriptions of technological devices intended for broad audiences employ visual aids. However these representations and diagrams are constructed on an ad hoc or case-by-case basis. The visual aid is created for a particular one-time purpose. This is typical of representations used in newspaper and magazine articles, websites, or promotional materials. Diagrams appearing on the website “How Stuff Works,” are characteristic of these types of diagrams⁶.
Ad hoc visual aids can be highly successful in helping to portray how a particular technological device works for the particular case for which it has been produced. The visual aid can draw attention to the main components, use various types of arrows or color schemes to convey transfer or progression through the system. The level of detail of the illustration can be varied to include features to aid in the recognition or identification of critical components.

Problems with ad hoc visual aids and diagrams arise when generalizing or attempting to explain a different type of technological system. The types of features illustrated, the simplifications made, the color scheme or types of arrows employed in one ad hoc diagram may not be appropriate to promote engineering and technological literacy for a different device. Each ad hoc diagram or visual aid is unique. Each must be produced and interpreted based on whatever self-contained cues are made available to the person interpreting the diagram.

Students using ad hoc visual aids and diagrams to understand how technological systems work develop some transferrable skills; however the process of this skill acquisition is inefficient. Because each visual aid is created using its own conventions and simplifications, each must be interpreted independently of others with which the student may have experience. Over time students will gain experience interpreting and using these ad hoc visual aids but what and how these skills are acquired will be difficult to monitor. Similarly, ad hoc visual aids do not provide any formal guidance about how a student can create his/her own visual aids of unfamiliar systems. Student may gradually learn what effective practices might be in developing visual aids but what is learned will likely be as ad hoc as the visual aids themselves.

Formal Engineering Schematics

Schematic diagrams used in many engineering fields might be considered as a type of visual aid that could be used in technological and engineering literacy applications. Typical examples are electrical circuit schematic diagrams and piping diagrams. Schematics are used to indicate the particular components used in a technological system and to show how the components are interconnected. Schematic diagrams may also include information about the conditions that exist at various points in the system.

As visual aids engineering schematics have several advantages. Schematic include standardized symbols or icons to represent components commonly used in a particular domain of technology. These symbols frequently contain visual cues which indicate aspects of the form or function of a particular component or the underlying principles employed in that device. These schematic diagrams are usually easy to draw and require minimal artistic skill to create. Consistent rules or guidelines exist for creating and interpreting particular types of schematic diagrams such as piping or circuit diagrams. Due to this consistency it is possible for students to develop increased proficiency in both interpreting and creating schematic diagrams with increased exposure and practice. This is the case even if students are starting from very limited backgrounds as is the case in many technological and engineering literacy courses.

While formal engineering schematics have many advantageous attributes, aspects inherent in schematics limit their usefulness in engineering literacy applications. Schematic diagram
conventions are developed for a particular technological domain and do not transpose well across a wide range of technological systems. The quantity being transferred through the system is usually of a limited range of options. For example in electrical schematics the input and output of nearly all components is electric current and only electric current. A similar problem exists in piping schematics. The components icons and symbols available are drawn from a limited range of technological devices such as electrical components or elements of piping systems. Non-engineers can learn the conventions used in creating and interpreting engineering schematics but the opportunity to transfer these abilities to different technological domains is restricted. Since technological and engineering literacy survey courses typically range across several domains, engineering schematic diagrams are not necessarily the best choice for visual aids.

**Form Representations**

Several options for visual aids to help explain technological systems primarily depict the form or appearance of the device. These form representations include photographs, line drawings, 3D CAD renderings, and exploded views. Form representations emphasize the look or visual attributes of a particular object. The drawings of David Macaulay are an exemplary case.

Form representations are very useful and most explanations of technological devices in engineering literacy applications benefit from employing some of these visual aids. Form representations are successful in showing spatial relationships between the parts of a system. These types of images also aid in recognition of particular components due to characteristic form features. Photographs are easy to obtain using digital cameras or online sources. Similarly, 3D CAD images of components are readily accessible through internet searching.

Images of form are useful in describing how a system works when the system transfer forces. Forces are transferred through structural elements. Therefore images showing structural features can be interpreted as load bearing or load transferring elements.

While useful for recognition and spatial location of parts, form representations have some drawbacks. Form depictions struggle to convey an idea of what is being transformed or transferred through a particular component. Exploded views are time consuming to create and would be difficult for novices to produce. Photographs can provide excessive information or distracting details which inhibit grasping of the primary intent of using the image. Form representations are excellent for depicting static features but are not well-suited for showing underling processes or changes taking place on a continuous basis. Producing useful drawings requires a combination of talent, interest, training, and practice that is beyond the range of what is likely to be possible to accomplish in a engineering and technological literacy course for non-engineers.

**Requirements for Visual Representation Method**

In survey courses of modern technology for non-engineer, the methods and conventions used must be consistent across a broad spectrum of common technologies including automobiles, structures such as bridges, and electronics. Some general requirements needed for visual aids used in technological and engineering literacy courses are listed in Table 1. The primary use of
these visual aids is to help to convey how the technology works. An overall goal is to combine the intuitive, flexible, and self-explanatory nature of ad hoc diagrams with the efficiencies derived from a degree of standardization and consistency as is characteristic of engineering schematics. Form images and depictions of appearance are useful in helping students to recognize and identify aspects of technological devices. Most people, including non-engineers are visual learners; therefore the option of including some renderings of the appearance of the technological system is desirable.

Table 1: Requirements for Visual Aids for Technological and Engineering Literacy.

<table>
<thead>
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<th>Requirement</th>
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<tr>
<td>Can apply to any technology and applicable across broad range of technological systems.</td>
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<tr>
<td>Promote understanding of component applications across different systems.</td>
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<td>Can contain aspects visual appearance or form features if desired.</td>
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<td>Depict differing levels or layers of detail if desired.</td>
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<td>Non-engineers can quickly learn to interpret the diagram.</td>
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<td>Non-engineers can learn to create or draw the diagram with some practice.</td>
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<td>Diagrams can be rendered in black and white and created using a pencil.</td>
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<td>General-purpose computerized drawing applications can be used if desired but not required.</td>
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<tr>
<td>Color can be used if desired but is not essential.</td>
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<td>Includes some flexibility for customization around common standards.</td>
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<tr>
<td>Interpretation is generally intuitive with minimal instructions (like ad hoc diagrams)</td>
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Overview of Method

A set of guidelines has been developed for creating visual descriptions of technological systems for use in technological and engineering literacy applications. Visual aids prepared using this format are largely able to meet the requirements that have been outlined regarding the needs of technological and engineering literacy visual aids. The diagram format is based on the technique of functional analysis frequently used as a formal design methodology in engineering product development. The technique is modified to include additions helpful in describing existing technological systems as opposed to creating new designs. Some aspects of development have been described in an earlier work.

Functional Analysis

Since functional analysis serves as the basis of the technique reported here, a brief summary of functional analysis is included. Functional analysis is a method used in engineering design to develop an abstract or functional description of the way in which a component, system or process accomplishes an intended goal or purpose. Functional analysis is used in the engineering design process to help identify particular transformations that must take place in the product. The benefit of functional analysis is a focus on the abstract “what” is to be accomplished rather than the “how” or specific means employed.

When using functional analysis methods, any human-made technological artifact is considered as a technological system regardless of its degree of complexity. The technological system is then viewed as transforming 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. Figure 1
illustrates the basic functional analysis or “black-box” representation of a technological system. A dotted-line box is used to indicate the system boundary. The boundary may correspond to actual physical boundaries or may represent imaginary boundaries similar to property or political boundaries in the context of land.

The system interacts with its environment (which may include other system) via inputs and outputs. Input and outputs, sometimes termed flows, are identified at the system boundaries. These 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. Three different arrow types are used to indicate each of the three categories of flows. A thick solid line is used for materials. A thin line indicates energy. Information shown using an dotted-line arrow.

![Diagram](image)

**Figure 1:** Basic Functional Analysis Representation of a Technical System.

![Diagram](image)

**Figure 2:** Illustration of a Hypothetical Device Subfunction Structure.
The overall function of the device, or technological system, is accomplished via subtasks or subfunctions. 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.

The technique of functional analysis provides a majority of the foundation and conventions needed for technological literacy visual aids describing how things work. Functional analysis views a technological device as a system of components that transfer and transform material, energy, and information in the process of accomplishing the overall function or purpose of that technology. The approach is consistent with the goal of illustrating that engineered products utilize combinations of pre-existing components to provide specific portions or subfunctions in the overall operation of the device.

Standard functional analysis for product design is not entirely suitable for creating visual aids in technological and engineering literacy courses. The technique is primarily a design aid for creating new systems. Form depictions are deliberately excluded to reduce bias in the designers thought process. The primary goal is to identify functions needed rather than illustrate specific components used. For explaining existing technology a clearer connection between components of the artifact and functions performed is needed.

Component Function Maps

The purpose of the visual aids or diagrams developed under the current work is to explain how technological devices work by focusing on the systems nature of most technological devices and the central role of components in providing needed capabilities. Most technological devices, processes, or artifacts are combinations of components that interact with one another and, as a collective, provide the overall functionality of the technology. The goal of these visual aids is to make evident and describe technology as a collaboration of individual parts. This approach also divides the problem of understanding a complex device into smaller pieces or subproblems centered around the action of the components.

The goal of the visual aids developed here is deliberately not to depict the underlying physical process or phenomenon taking place in a specific component or part of the system. The underlying science at work in one section of a technological system is important in understanding how something works. However, visual aids to illustrate particular physical processes of nature are considered as a separate challenge from the goal of this work which is to describe the overall process taking place. An example of a visual aid illustrating a scientific principle would be something like a drawing showing dots representing electrons moving in a wire as a representation of electric current. Most technological device operation involves a number of different scientific principles. So a collection of these scientific principle illustrations would be needed. The goal here is to focus on the operation and interaction of the ensemble rather than only the specific principles of a particular component. The closest analogy would be engineering schematic diagrams which are successful in depicting an entire system and illustrating which components interact with one another.
The approach to creating the diagram is to use most of the conventions of functional analysis but substitute specific components in place of abstract function. Functional analysis identifies abstract functions or tasks to be achieved in a yet-to-be built design. Describing how a system works is a similar task but the emphasis is on describing an existing design using the components as centers of attention.

Components are depicted as shown in the generic representation for a component in Figure 3. It is intended that component depiction should be straightforward. Components are represented by boxes which may include icons or simplified drawing of the component. It is helpful to include the component function with the component. Major inputs and output represented by appropriate arrows are shown entering and leaving the component. Some judgment may be exercised in determining the inputs and outputs are those most relevant to system operation.

**Figure 3:** General Format for Representation of a Component.

An example of the representation of a particular component is illustrated in Figure 4. An electric motor is represented. The function of an electric motor is to convert electrical energy into mechanical energy. This mechanical energy may be used for various purposes in the innumerable systems that utilize electric motors. The primary input is electrical energy and the major output is mechanical energy. Other outputs are produced the importance of which will vary with the specific motor used and the system in which it is utilized. Electric motors can also produce heat and vibration as shown in the Figure. Vibration here is considered as a type of motion or kinetic energy. Various types of information are available which in this case help to describe the condition or operating status of the motor. Most motors produce some type of noise and information describing the operating status of the motor might include the motor speed measured, for example, in revolutions per minute. In general the potential amount of information produced by a component is probably limitless (temperature, input current, torque as a function of speed) but not all of this is of significance in every application of the motor. The example illustrates that analysis of a particular system is not entirely automatic and some degree of judgment is required.
It is important to note that some simplification is useful in considering the function and behavior of components. Focus on the primary function and major component inputs and outputs is advantageous when introducing non-engineers to technology. Most components have considerable numbers of variations and actual selection of a particular model for use in a particular application can be a complex process. However there is a benefit from utilizing a hierarchy of detail when working with non-engineers.

![Electric Motor Diagram]

**Figure 4:** Depiction of an Electric Motor.

An advantage of this approach is the non-engineering students can develop a repertoire of components with which they are familiar. Students can draw on their set of familiar components when analyzing unfamiliar systems. For example, an electric motor is nearly always used to supply mechanical energy in a particular system. If an electric motor is identified as part of a system, the known function can be assumed. Development of this working knowledge of common components is one dimension of achieving technological and engineering literacy. Familiar components provide known functions in unfamiliar systems.

Using this basic way of representing components, a diagram of a technological system can be constructed. To convey how the system works, the diagram should include the characteristics listed in Table 2. These features convey what is needed to describe how something works.

The diagram should differentiate between the technological system and its environment. It should be possible to see what is part of the system and what is not. The boundary between system and non-system should be indicated. This may seem like a trivial issue in some cases. For example in the case of a home appliance like a blender, the constituents of the system are readily differentiated from a space in which the appliance is located. However in the case of a distributed technological system of large extent, like an electrical utility, a clear indication of what is considered as part of the system and what is external to the system and part of a different system is an important issue.
Table 2: Features Included to Convey Technological System Operation.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
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<tbody>
<tr>
<td>1. Indicate the extent of the system or the system boundary.</td>
<td>The visual aid should indicate the interaction of the technological system and its surroundings.</td>
</tr>
<tr>
<td>2. Indicate the interaction of the system with its surroundings showing what is entering and leaving the system.</td>
<td>Items entering the system from other sources should be indicated. Things exiting the system should be depicted. The nature of these entities transported into and out of the system can vary over a diverse range such as electric current, materials, and radio signals.</td>
</tr>
<tr>
<td>3. Show major transformation taking place in the system of inputs to outputs.</td>
<td>The major system components should be included and the inputs and outputs of each component illustrated. It is important to balance between excessive detail obscuring major features and too little information. On the order of 10 components (5-15) might be considered appropriate for most systems. The diagram should be amenable to different levels of detail. If desired it should be possible to include additional components or higher resolution of system elements.</td>
</tr>
<tr>
<td>4. Include major system components.</td>
<td>The diagram should convey the interaction between the components. The direction of component interactions should be indicated. The diagram should convey the most important or most critical operations within the system that are responsible for accomplishing the transformation of the system inputs into the outputs.</td>
</tr>
<tr>
<td>5. Convey component function, show the inputs and outputs of specific components.</td>
<td>The visual aid should show or be able to depict different operating modes or phases of operation for specific technological systems. In many instances, the technology operates as an on-going process. Time dependence should be included.</td>
</tr>
<tr>
<td>6. Accommodate appropriate number of components (in range of 5-15).</td>
<td>Conservation principles are useful in describing system behaviors. For example conservation of mass and conservation of energy are helpful ideas in tracking changes taking place in entities within a system. Application of conservation principles is a useful check to determine if some aspect of operation has been overlooked. The visual aid therefore should be amendable to interpreting if relevant conservation principles are satisfied by the system.</td>
</tr>
<tr>
<td>7. Amenable to different levels of detail.</td>
<td></td>
</tr>
<tr>
<td>8. Convey interaction between particular components. Indicate direction of transfers within the network or system.</td>
<td></td>
</tr>
<tr>
<td>9. Describe the most important or most critical interactions responsible for system operation.</td>
<td></td>
</tr>
<tr>
<td>10. Describe different modes of operation of the same system if appropriate.</td>
<td></td>
</tr>
<tr>
<td>11. Represent conservation principles in describing system operation (Such as conservation of energy as energy changes from electrical energy to heat)</td>
<td></td>
</tr>
<tr>
<td>12. Show how the condition or status of the system can be determined or interpreted. (Information such as temperature used by controls or the user to evaluate conditions)</td>
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In addition to identifying major components and conveying the interaction between particular components, the visual aid should provide information of the state or status at different points in the system. For example this information might be temperatures or rates of flow of liquid into and out of particular components. The visual aid should include some way of providing these types of system status information.

The term “Component Function Map” was selected to describe these diagrams. These diagrams focus on identifying key components and showing the function or purpose of the component in a particular system. Identifying components is a central aspect of this process. The term map is used since maps depict connections and explain how to get from one location to another. These diagrams show how the system inputs become the outputs when moving from one location to another in the system. Maps represent reality at a reduced level of detail. Maps are not photographs but rather are created to show the details most important for a particular purpose. Different maps can show the same region at differing degrees of detail, similarly component function maps can be more or less detailed depending on needs. Similarly these diagrams are not intended to show every detail of how a particular technological device looks but rather provide an overview of the main aspects of how the technology works.

**Component Function Map Construction Guidelines**

A set of guidelines was prepared for non-engineering students to use when creating component function maps to describe the workings of a particular technological device. These form a step-by-step procedure which can be useful in helping students to make progress on a complex task. The guidelines are summarized in Table 3.

In explaining the process to non-engineering students it is emphasized that these diagrams are more like an essay than a mathematics problem. There is more than one way to convey how the system works. Since the creator of the diagram is selecting from a near infinite number of potential details, there is an element of judgment involved. Some details may be different in different people’s diagrams just like two people may use different sentences to describe the same event. However the meaning should be the same. An essay uses words and phrases to create sentences and paragraphs that convey meaning or tell a story. The component function map uses the conventions of flow of materials, energy, and information to tell the “story” of how the system works.

**Examples of Student Outcomes**

Several examples of student-generated diagrams are included in Figures 5-9. In all cases these were produced by non-engineering students enrolled in a general education technological and engineering literacy course. The students produced these diagrams independently as an assignment to analyze a device that had not been already studied in the class. The students are engaging previously unfamiliar devices and working at the “Analysis” or fourth level of the six levels of Bloom’s taxonomy. This assignment culminated a series of assignments introducing guidelines for analyzing unfamiliar systems and creating diagrams including a variety of practice assignments.
Table 3: Component Function Map Construction Guidelines.

- If the system has several modes of operation, decide the operating mode that will be analyzed.
- Identify the overall system function. What is the main purpose of the system?
- Establish the system boundary. What is the boundary between the system and the rest of the world?
- Identify the main system inputs and outputs. While these may seem obvious, if the net inputs and output are not correct, the rest of the diagram will not be correct.
- Determine the major components to be included.
  - A recommended goal is to identify the 5-15 most important components. This is an approximate number not an absolute restriction. Sometimes more than 15 might be appropriate, however fewer than 5 may not provide enough detail to be informative.
  - Identify components that are common to similar systems (if you know them). Is there anything that known about these common components that should be included in the diagram?
  - Identify those components that provide unique or important characteristic functionality for that particular system. What is their contribution that is particularly important for the overall function of this system?
- Identify interactions between components and determine the direction or “flow” of an interaction. Consider each component individually and determine with what other components each component directly interacts.
  - Verify that each component has at least one input and output.
  - Classify the inputs and outputs or interactions as: material, energy, information.
  - Create a draft component function map. Edit arrows so they are of the appropriate type (thick line = material, thin line = energy, dotted line = information)
- Apply conservation principles to the system
  - Materials: Are all materials accounted for? Is material conserved? Where does everything entering go to inside the system? What flows in must flow out or be stored somewhere. What flows out must originate someplace.
  - Energy: Are all energy flows accounted for? Where does all the energy go to / come from? Are all the necessary flows of energy needed by components indicated? Is energy conserved? Where does the energy come from, go to?
- Analyze information in the system
  - Information: Are sufficient information flows included so that the status of the system can be determined?
  - Is there sufficient information to determine if the system is actually functioning as expected? If a robot were being programmed to observe the system, what would you tell the robot to look for to determine if the system was operating correctly?
- Balance sufficient detail vs. overly cluttered. The goal is clarity in conveying how the system works. It is important to show enough detail to be informative and non-trivial, however excessive amounts of detail appear cluttered and obscure the meaning.
- Revise the draft and create a final version.
Figure 5 is an analysis of the dishwasher. This work is notable as a generally accurate depiction of a relatively large number of components with complex and non-linear interactions between these components. The student has been able to show the distribution of energy and basic control signals in the dishwasher. The multiple paths of water are carefully tracked. Also the student has made an effort to arrange the diagram with inputs entering from the left and outputs exiting the system to the right.

Figure 6 shows one student’s analysis of a mixer. This example is characteristic of the level of accomplishment achieved by most students. The major components are identified. The function of each component is included. The transformation of energy and materials in the device are recognized and labeled.

The diagram shown in Figure 7 is a student analysis of a vacuum cleaner. This example is distinguished by considerable effort devoted to including drawings of each component. In this case the student deviated from the conventions for the designation of materials, energy and information, substituting colored arrows for each flow. It is not uncommon for the non-engineers to re-interpret some of the recommended procedures. This can result in both positive and negative outcomes. This example also illustrates how the emphasis on identification of components can help to provide a framework for students who might tend to gravitate toward more form aspects of technological system (how it looks) compared to the underlying functions and interactions of the components (how it works).

An analysis of an automobile exhaust and fuel and air system produced by a non-engineer is shown in Figure 8. There are a few small oversights in the diagram but in general this is a good overview of the major components of these systems. This is a good example of the usefulness of including a brief description of the function of each component. This student has elected to color-code the components to identify the subsystem to which each belongs.

Each of these examples provides some evidence that the non-engineers were able to analyze and comprehend the basic operation of these technological systems. Production of these diagrams appears to be an effective and efficient means for these non-engineers to both develop and demonstrate the extent of their knowledge. It is useful for the students to prepare written descriptions of this same information, but generally the written text follows the creation of the diagram. Also, in terms of assessment, less time is needed by the instructor to review a diagram compared to written descriptions.

The benefit of a well-defined set of guidelines for creating diagrams for assessment of learning gains is demonstrated in Figure 9. Diagrams produced by two different students are depicted. The students were asked to explain how a bread machine works. Additional details related to this particular assignment are described below. The work of Student 1 conveys an adequate understanding of the internal structure and operations of a bread machine. While not flawless, the diagram identifies the major components, indicates how electrical energy is utilized in the
Figure 5: Analysis of a Dishwasher by a Non-Engineer.
Figure 6: Component Function Map of a Kitchen Mixer by a Non-Engineer.
Figure 7: Student Diagram of a Vacuum Cleaner Including Physical Representations.
Figure 8: Student Diagram of Automobile Fuel and Air and Exhaust System Including Descriptions of Component Functions.
Student 1 – Diagram conveys adequate understanding of device internal operations.

Student 2 – Weak comprehension of bread machine structure.

**Figure 9**: Examples of Component Function Diagrams Explaining the Workings of a Bread Machine Made by Two Different Students.
device, includes information used to discern the status of the system, and depicts an appropriate sequence of subfunctions within the system.

In contrast to the sense of understanding conveyed by Student 1, the diagram produced by Student 2 conveys a weak comprehension of the structure of this device. The student does identify some of the major components; however the diagram shows an inappropriate linear sequence of operations without an indication the internal parallel arrangement of components. Intermediate interactions are unlabeled. The overall purpose of the device is not shown. This example helps to illustrate how these component function maps can aid both non-engineering students in communicating their knowledge of technology, and faculty in assessing this understanding.

The diagrams created by the two students depicted in Figure 9 were part of a larger pre and post test conducted with a class of 29 non-engineering students. The results provide some indication that the routine use and creation of component function maps might help non-engineers to understand modern technology and to communicate this understanding.

The students involved were enrolled in the Science and Technology of Everyday Life course at Hope College. This course is intended for students from non-technical majors and includes students from music, management, fine arts, and pre-service education students. An objective of the course is to develop an understanding of both the engineering aspects of how various technological devices work, and a familiarity with the major principles of science in operation. The course focuses on the wide variety of technology used in everyday life. The course topics were selected to represent the technologies most frequently encountered in everyday life and were based partly on the results of surveys of student interests. Course emphasis includes an elaboration of the general nature of technological systems.

On the first day of class students were asked to answer the question: “How does a bread machine work?” This part of the exercise was done immediately at the start of the first class and was repeated at the end of last class fourteen weeks later. A total of 29 students participated in the exercise. Student responses were evaluated using the criteria shown in Table 4. The scores were allocated on the basis of a maximum of 100 points. It is important to note that the bread machine itself was not studied during the course. The course did include disassembly by the students of some home appliances but not the bread machine. The intent of the exercise was to gain an idea of the ability of the non-engineers to analyze a slightly novel system.

<table>
<thead>
<tr>
<th>Table 4: Outline of Criteria Used For Evaluating Technological System Descriptions.</th>
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</thead>
<tbody>
<tr>
<td>1. Overall function of the system noted</td>
</tr>
<tr>
<td>2. Identification of major components identified.</td>
</tr>
<tr>
<td>3. Major inputs and outputs required to accomplish desired function listed.</td>
</tr>
<tr>
<td>4. Appropriate sequence of subfunctions determined.</td>
</tr>
<tr>
<td>5. Information used to describe the status of the system recognized.</td>
</tr>
</tbody>
</table>

The average for the group on the pretest was 21/100 with a standard deviation of 9. At the end of the course, the average for the group increased to 76/100 with a standard deviation of 13. It seems reasonable to describe these results as showing a change from an average condition of
being technologically illiterate to a general state of possessing a “passing” or “fair” degree of technological literacy. These limited results do not establish that the use of the component function map diagrams was responsible for this change. However these limited results do show some potential that non-engineering students can use these diagrams to help organize their thinking and communicate their understanding of how technological devices work.

Future Work

Non-engineers have been able to analyze automobile subsystems and consumer appliances with which they were previously unfamiliar. An important next step will be to see if comparable results can be achieved when applied to larger systems composed of multiple complex subsystems. Examples of such systems include: a mass transit system, a chemical processing facility, or fossil-fueled power plant.

Engaging in collaboration with other educators with an interest in explaining technological systems to non-engineers will help to validate and improve these guidelines. Other efforts are directed toward improving and testing rubrics for evaluating diagrams produced by students to allow a larger sample of students can be examined.

Non-engineers in technological and engineering literacy classes frequently express an interest in being able to understand what is wrong when technological devices are not working properly. Component functions maps may be a means by which some degree of problem diagnostics or troubleshooting might be carried out by non-engineers. Work is being pursued in this direction.

Conclusions

Component function maps appear to offer promise as a visual aid used to explain how technological systems transform a given set of inputs into desired outputs. The technique combines the useful features of engineering schematics, form representations, and ad hoc diagrams while avoiding the most troublesome drawbacks of these other types of visual aids. Initial work indicates that non-engineering students are able to learn this method of describing a technological system and can apply it to some novel situations. Because the creation of component function maps requires discernment and analysis, creation of these diagrams can be used to access aspects of higher levels of cognitive engagement on the part of non-engineers. Such methods are beneficial as alternatives to assessment based on questions that can be answered by rote memorization. This initial work shows promising indications that non-engineering students are able to employ this technique to understand how things work.

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Bibliography


