Work-in-progress: An approach to engineering literacy emphasizing components, functions, and systems.

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Abstract

All introductory and general education courses benefit from having strong themes that serve to unite course material. Technological and engineering literacy courses that address diverse technological topics without a convincing and fundamental theme risk appearing as impermanent and merely topical in nature. A challenge for engineering literacy courses is the need to include the role of science without leading to the conclusion that engineering is merely applied science. An approach based on components as the core building blocks of engineered systems is able to include scientific principles as embedded in the processes taking place in components, while emphasizing that engineering is the creative use of these capabilities to solve problems. The engineering design process is also an important defining aspect of engineering and merits inclusion in engineering and technological literacy classes. A challenge in promoting engineering literacy based on engineering design occurs due to design being a process or a means by which technology is developed not a product in itself. Students in engineering and technological literacy courses typically are interested in understanding the end result, the hardware, and struggle with a design-centric approach. The design process must involve actual physical material from which designs can be produced. The function-component-system-domain approach helps students to carry out the design process by emphasizing that components providing functions are the elements from which engineering designs are created. Focus on components such as motors, beam, switches, and pumps as building blocks of engineering designs helps to make the design process less abstract and more realizable. This function-components-functions-system-domain (FCSD) perspective has been used in engineering and technological literacy courses at a large state university and a small private college. Results from this pilot testing with these student groups will be presented. In general undergraduates react favorably and are able to understand the fundamentals of this approach to understanding diverse technologies as built around components serving as functional elements that are combined into more complex and capable systems.

Introduction

Technological and engineering literacy courses for non-engineers face a problem in finding organizing principles and course themes that are characteristic of engineering but are also accessible to any undergraduate without extensive prerequisite courses. This work describes a framework for presenting engineering to undergraduates that is based on the component as a central idea characteristic of engineering. Component is this instance means a physical object created to provide a specific function such as a light emitting diode, a heat exchanger, a wing, or an internal combustion engine. This framework depicts engineering as creating technological systems using components to provide a specific capabilities or functions. Components contributing well-defined functions are combined into systems. These systems provide a value or usefulness that exceeds that of individual components. Components are incorporations of natural processes or phenomena. Models or mathematical formulas describing component behavior are developed typically based on the underlying natural phenomena employed in the component. These mathematical models are used to design systems by predicting component and system behavior. The function provided by a particular component can be integrated into different technological systems that might benefit from use of that function. Innovation and evolution of technological systems typically occurs by substitution of an existing component or components with others providing functions better optimized for the purposes of that system. This function-component-system-domain (FCSD) framework can be used as a theme in an engineering literacy or other introductory course. This approach promotes engineering literacy by organizing course material around the underlying structure common to technological systems.

Major Themes

A set of major themes was developed which serve as a framework for describing the engineering of technology. A main goal was to establish a relatively small set of general concepts which can be elaborated upon in greater depth throughout the course and used in the analysis of particular examples. These major themes are summarized below. They are explained in more detail in a later section. The term Function-Component-System-Domain (FCSD) attempts to convey the main focus of the framework.

1.) Technology created for a function accomplished through form.
Technology is created to satisfy needs ad solve problems. The function is the problem to be solved or a need to be satisfied. Function or what a particular object can do, is determined by the form or the physical properties and characteristics of that object. The form of any object can provide a variety of different functions.

2.) Technological systems transform materials, energy, and information.
Technological products are systems that transform inputs into outputs. Inputs and outputs take the form of flows of energy, material, and information.

3.) Function is provided by components combined into systems.
The overall system function is provided by components which combine to form systems. Some components are utilized for the purposes of controlling system behavior. The term subassembly is sometimes used to describe intermediate stages of component groups.

4.) Components utilize physical phenomena.
Components accomplish transformations by utilization of physical phenomena. Transformations and component behavior are frequently expressed in mathematical form. Component interconnection and achievement of system performance requirements are facilitated by te predictive capabilities of mathematics.

5.) System employ diverse interacting phenomena.
Most technological systems utilize a wide and diverse range of phenomena. Although components may utilize different phenomena they interact through exchanging the same type of energy, material, or information flow.

6.) Component functions transfer across systems.
Components can be employed to provide the same subfunction in systems with dissimilar overall function. Component variations offer a range of features around the same core function and principle.

7.) Systems become components and systems are sociotechnical.
There is no absolute or inherent distinction between a system and a component. A technological system can be considered as a component in different system. Boundaries of technological system are arbitrary to the extent that they depend on the intent of a particular analysis. Technological systems encompass social and cultural interactions they are sociotechnical in nature.

8.) System design creates component ensembles with emergent properties.
The utility or usefulness of systems exceeding that of individual components. Technological system design envisions combinations of components to achieve desired overall system function. Subproblems or subfunctions are solved by components of the system. Component parameters can be adjusted in accordance with system performance, desired features, and requirements of the intracomponent interactions. The design process frequently uses representations of both the function and form of the system. Compromise between competing objectives is characteristics of technological system design.

9.) Technological system domains are groups of related systems.
Engineering design domains exist around collections of related systems. Systems within a domain typically provide the same overall function in diverse applications. Frequently utilized common components and a set of core underlying principles characterize domains.

10.) Technological systems evolve.
Substitution at the component level is a frequent mechanism by which tchnological systems frequently evolve over time. Other modes of change include the combination or merging of separate components into integral structures, optimization of particular features, proliferation of added subfunctions, and substitution of component with different operating principles.

Background Motivation of Major Themes

The major themes derive from a number of sources that address aspects of the nature of engineering and the features found in common across engineering disciplines. The role of engineering to solve problems and satisfy needs has been widely discussed, representative sources include National Academy of Engineering publications *Technically Speaking*[1] and *Changing the Conversation*[2].

The central nature of the relationship between form and function in the creation of technological artifacts is well-established. A fundamental step in engineering is the ability to envision abstract function and manipulate physical reality to provide desired function. Illustrative analyses include work by Alexander[3] discussing the concept of function as an abstraction or a generalized description of a needed transformation rather than a specific physical object or component. Akiyama[4] emphasized the utility of abstract product function as inherit in discussion of form defining product value. More recently, Vermaas and Houkes approach the fundamental nature of the form and function relationship in the definition of technological artifacts[5,6].

The description of technological products as systems that transform inputs into outputs in the form of flows of materials, energy, and information emerged from efforts to analyze the engineering design process. This view began to appear widely in the 1970s and was well-articulated by authors Hubka and Eder[7] along with Pahl and Beitz[8]. Overall system function is provided by components which combine to form systems. This generic systems view of technology continues to form the basic structure for envisioning the products of engineering as seen in treatments of the engineering design process by Otto and Wood[9], and Ulrich and Eppinger[10].

The recognition that components in technological systems accomplish transformations by the application of physical phenomena is widely recognized, and some recent physical science textbooks call attention to this as a way to motivate study of science. Of particular note Bloomfield has developed a physics course based on technological devices entitled: *How Things Work: The Physics of Everyday Life*[11]. A similar emphasis on phenomena appearing in modern technology is found in Snyder, *The Extraordinary Chemistry of Ordinary Things*[12]. The view that explanations of component behavior can be described using mathematics is deeply embedded in modern physical science. Works clarifying the foundations of these beliefs and practices include Park[13] and Bakker and Clark[14].

Similarly, the principle that components can be used to provide the same subfunction in systems with different overall function and component behavior is often expressed mathematically is most readily perceived in works that summarize information frequently needed by engineers working in particular disciplines. For example handbooks for mechanical, chemical and civil engineers highlight system components and descriptive formulas[15-17]. The parameterization of components to address variations in system requirements is also treated in these approaches.

Systems engineering approaches to complex technological devices emphasize how one technological system can become a component in another system[18-19]. These overviews of systems engineering methods also stress the need to consider that technological system boundaries are arbitrary and depend upon the intent of a particular analysis.

The description of the engineering design process itself is well-represented in engineering textbooks intended for an introduction to engineering that are not discipline-specific[20-22]. These approaches stress how analysis methods allow component parameters to be adjusted in accordance with desired features and system performance. Introductory treatments of design also help convey the utility of different types of representations of technological systems. Procedural guidelines to facilitate compromise between competing objectives are described.

Similar to descriptions of the basic engineering design process, a large body of work address the evolution of technology. The major ideas utilized in our current work attempt to include the main features of particular relevance. Overviews of the modes of change include merging of separate components into integral structures, optimization of component features, proliferation of added subfunctions, and substitution of component operating principles as described by Basalla[23].

Function-Component-System-Domain Perspective

The major themes which describe engineering outlined above are extended to include essential characteristics of technological systems. The emphasis is on the component as the element of function used by the engineer to create systems. Around this central idea supporting information is developed. This section provides a summary of each main theme in the Function-Component-System-Domain perspective.

1.) Technology created for a function accomplished through form.
Technology exists to provide for human needs and solve problems. Technology is engineered with some utility, purpose or function in mind. Technology has a function. It is expected to accomplish something, solve a problem, or meet a need. Technology changes the physical circumstances and conditions in which people live. In widest terms, this function is to cause some change in conditions, to transform some set of inputs into a set of outputs. Form describes the material properties and physical parameters of an object. Functions are the actions that can be carried out through a particular form. Functions are expressed as combinations of verbs and nouns.

2.) Technological systems transform energy, materials and information.
System describes any technological device without regard to size or complexity. Technological systems are one type of system. In general a system is a group of objects, forming a network, to achieve a common purpose. A system is identified by the use of a boundary, real or imagined, that encompasses or encloses the system separating it from everything else in its environment. The system is connected to or interacts with its environment through inputs and outputs that are identified at the system boundary. The system function is identified by the transformation of inputs into outputs. Flows into and out of a technological system can be classified as material, energy, or information.

3.) System function is provided by components which combine to form systems
The overall function of a technological system is divided into a network of subfunctions occurring within the system. The subfunctions are the subproblems or subtasks which when combined solve the main problem. The arrangement of interconnected subfunctions is called the function structure or function architecture. A technological system accomplishes its overall function by means of its constituent parts or components. Components are the physical elements that embody the subfunction transformations. Components solve subproblems within a system. Components interact with other components. The interaction of two components requires the exchange of the same type of material, energy, or information between those componets. Some components or combinations of components may have the function of controlling system behavior or operation. In some instances the terms assembly or subassembly may be used to describe combinations of components that accomplish well-defined functions but do not appear as a completed system.

The allocation of overall system function to specific subfunctions, the choice of specific components assigned to particular subfunctions, and the exchanges of materials, energy, and information between components are not unique. Typically a variety of potential arrangements may be able to achieve a given overall system function.

Through an assemblage of components, a technological system is able to provide a function or utility that is not possible for any single component to accomplish. The creative combination of components produces a result that exceeds the usefulness of the individual parts.

4.) Components are based on physical phenomena
Although components are created by people to provide a specific function in a technological system, all technology is actually part of the natural world thus the behavior of components is determined by natural phenomena. Components utilize natural phenomena in carrying out functions within technological systems. Although technology is made by humans, its behavior is governed by the same laws of nature that apply to the natural or non-human made world. Science uncovers and clarifies the behavior of the natural world. The engineering sciences are those with particular relevance to the behavior of technological components and systems. The action or behavior of components is often described mathematically. Mathematical models or formula describing component behavior can be based on the physical principles responsible for the characteristics of that component, empirical characterizations, or combinations of theoretical and experimental results. The predictive capabilities of mathematical models facilitate component selection, interconnection, and the achievement of desired performance.

5.) Most technology relies on a diverse collection of phenomena
Typically the complete operation of technological systems includes a diverse range of components employing a wide range of physical principles. Physical phenomena are classified in a particular logical order by science. A technological system however is not confined to only use phenomena from one specific area of science. Most technology employs a disparate range of phenomena. Technological systems usually have a critical set of components that are responsible for the primary aspects of operation or transformation of inputs to outputs. Not all phenomena and effects are of the same significance in establishing the functional behavior of the technology. Some technological systems have useful capabilities and features that are not involved with what is perceived as the primary function of the system. Components in a system may utilize markedly different underlying principles and still interact with each another provided they share a common flow of the same material, energy, or information.

6.) Components providing functions used in other systems with or without adaptation.
A major characteristic of the creation of technology is the use of the same component to carry out the same function in different technological systems. A component represents a solved problem. The association between a particular component and a particular function is a central activity in the engineering design process. The need for a particular subfunction appears in a variety of technological systems. The same component can be used to provide this subfunction. The component can also be modified or altered to more appropriately suit the conditions of a particular system. Families of components exist offering features suited for diverse situations but providing the same primary function. The physical principle or phenomenon at work in the component family remains the same.

7.) Component system boundary is arbitrary.
In the structure of technology there is no absolute distinction between a component and a system. What is considered as a component in one situation can be viewed as a system composed of separate components in another. Similarly a system can be viewed as a component if the individual constituent elements are ignored and only the overall transformation of inputs to outputs is considered. The designation of system or component is dependent upon the objectives of a particular analysis. The outputs of one system frequently serve as some of the inputs to one or more other systems. This illustrates the interdependent nature of systems. Extending the technological system boundary emphasizes that technological systems interact with social, economic, cultural, and political systems. The term sociotechnical system describes a system encompassing technological and social elements.

8.) The engineering design process creates ensembles of components into systems function.
Engineering is the creative process of developing a physical object or technological system that improves the quality of life by solving problems and meeting human needs and wants. The engineering design process creates these technological systems transforming available inputs into the desired outputs. The engineer must work with the components available that might be relevant to the solution of the problem. The design process therefore requires a familiarity with the capabilities of components, the problems they solve, and the subfunctions they provide. The design process establishes the system function structure and the choice of physical components to accomplish the necessary transformations in the system. Component parameters and features are selected and modified to meet specific system performance requirements. The capabilities of interacting components are matched where inputs and outputs are in common. Creating technological systems involves representations of system form and function. Social and cultural needs and preferences influence system requirements and therefore shape the function and form of the system.

9.) Technological domains exist around collections of related components.
As technology evolves, design domains develop which are based around a set of components and physical principles. Often these components share, or are derived from, a related set of physical principles. Engineers will frequently work within a particular domain and develop expertise in utilizing the families of components to create systems within the domain to meet specific functions. These domains usually come into being around specific types of products or related applications and problems to be solved. Systems within a domain consist of both components and function structures that are common in the domain as well as components unique to particular systems providing functionality characteristic of that system.

10.) Technological system change typically occurs at the component level.
The evolution or progression of technological systems share common characteristics. One is the progression from modular to integral function structures. Newly created systems must utilize the components available. Over time as grouping of components become stabilized into commonly used subsystems, these grouping can be produced in a single unit into which formerly individual components are integrated into a complete assembly. This leads to reductions in cost and size but renders the individual components no longer accessible. Other aspects of the evolution are the

optimization of components to increase performance, a proliferation of variations of a basic system, and the addition of subsystems to extend capabilities.

Implementation and Evaluation

The FCSD approach has been used in technological and engineering literacy courses at our institutions. Student groups have included non-engineering students enrolled in courses which are used to satisfy a general education requirements as well as introduction to engineeing.

One type of evaluation that has been conducted is based on student writing assignments and reaction papers. This approach was used to avoid rote memorization quizzes or tests. Students were asked to read and interpret descriptions of some of the main themes outlined above. Initial analysis of responses indicates use of the main themes such as function, form, system definition, and transformation of flows of energy, material, and information is characteristic of student work. More detailed analysis is ongoing.

An approach to evaluation based on the ability of student to apply the design process was used. The approach is structured to emphasize that components carry out subfunctions in support of the overall functioning of a system. Students are asked to design and construct their own version of the technological device. Design process evaluation using the electrodynamic speaker has been developed.

To support students in this process, an explanation is given of how the speaker works in terms of the functions that must be accomplished and the components that supply needed subfunctions. The operation of the speaker was explained in terms of nine key components responsible for transforming the input electrical signal into the sound vibrations output. The function of the component is described and the important design requirements or characteristics of that component are reviewed. Figure 1 shows the form of a typical commercial speaker. The nine key components are summarized in Table 1.

Figure 1: Typical Form of a Commercial Electrodynamic Speaker.

Table 1: Key Component Sub-Functions of an Electrodynamic Speaker.

	Component	Function	Characteristics
1	Fixed Magnet	Push/pull on coil	Very strong magnetic field
2	Coil	Create varying magnet field	Light weight, 8 ohms resistance
3	Coil form	Hold coil wire in place	Light weight , hold coil wire in place
4	Conductive link	Transfer current to coil	Transfer current without hindering coil motion
5	Support structure	Hold components	Sturdy, easy to construct
6	Cone-coil-link	Transfer KE from coil to cone	Light weight, transmit axial force without bending
7	Cone	Transfer KE into Sound energy	Relatively light, able to flex but somewhat stiff
8	Restoring spring	Push/pull on coil opposite fixed magnet	Appropriate stiffness not too stiff but able to exert sufficient force to keep coil in place with respect to the fixed magnet
9	Electrical Connector	Connect to signal source	Secure to prevent accidental pulling or tugging on the coil

The students are then given access to a wide variety of basic materials which can serve as component parts for an electrodynamic speaker. This includes items such as paper plates, cups, cardboard, plastic sheeting, cloth, and construction paper. Each individual student completes his or her own design. Students create designs for each component using basic materials. Some materials are specified. In this first effort, the gage and length of wire to be used in the coil was specified. Also the electrical connector was provided. The supply of basic materials also included a variety of different types of magnets which could be selected by the student to provide a permanent magnetic field. Figure 2 conveys the types of materials provided and the design objective to provide comparable function using other forms.

In completing this process, students were not told about the assignment ahead of time. Also they were restricted to the laboratory without access to the internet. These restrictions were used to prevent students from looking online for the design of a speaker using basic components and then replicating that design. The intent was to require students to think through the design process and to use the idea of “form follows function” to develop a unique design.

Some examples of completed speakers designed and built by students are shown in Figure 3. In the group of 29 students tested all were able to design and build their own speaker. Each speaker was required to produce audible sound when connected to an 0.25W audio amplifier (based on LM386N). The output was generally surprisingly loud and one was measured at 99 dB. The project could be completed in one three hour lab session by most students. While all of the students were successful, some required considerably more coaching or guidance than others. Students were allowed to keep the working speakers and take them home.

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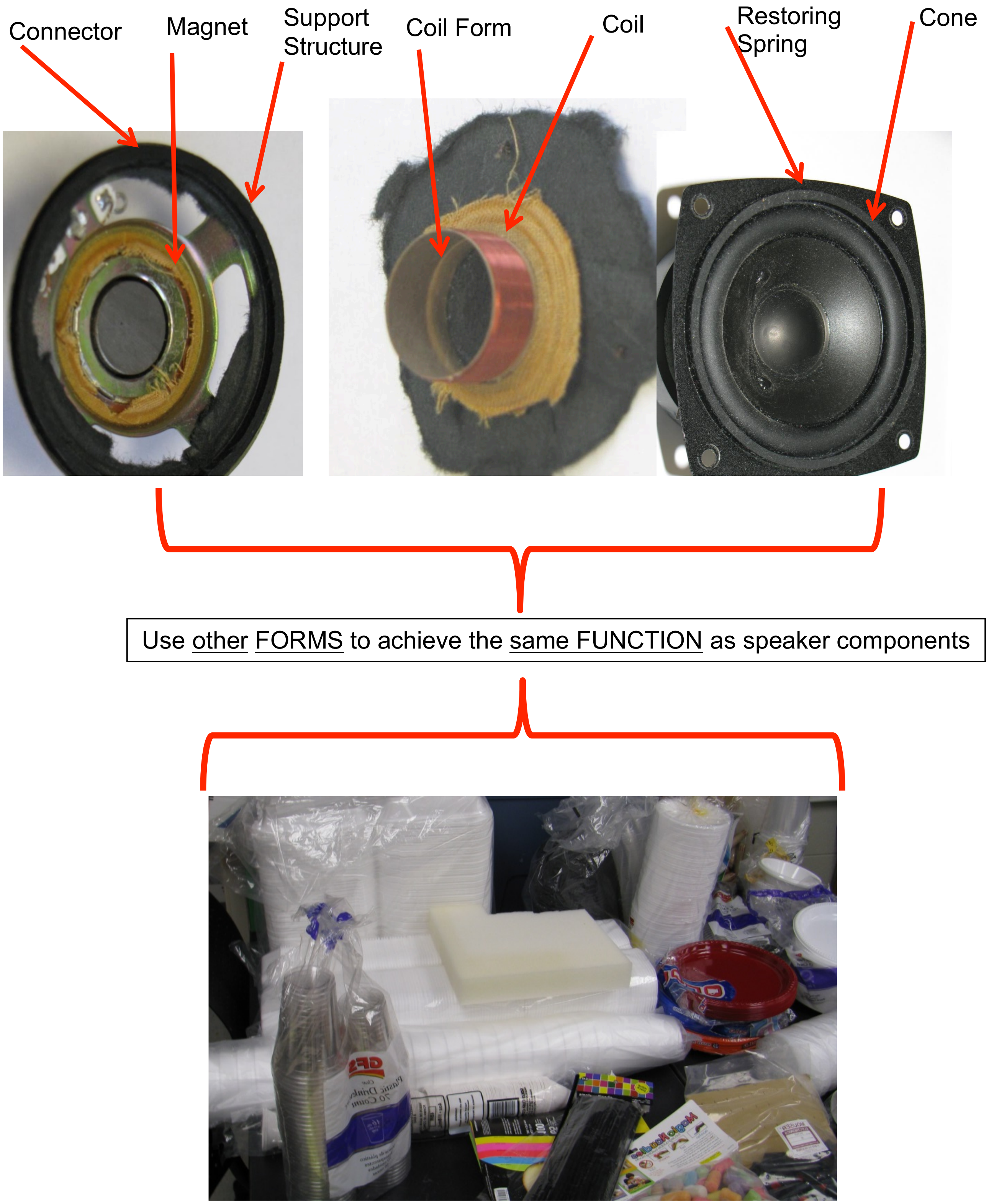

Figure 2: Summary of the Design Problem and the Some of the Basic Materials Provided

Figure 3: Examples of Working Simple Speakers Designed and Built by Students.

Conclusions

The Function-Component-System-Domain (FCSD) was developed as a framework for an introduction to engineering based on the underlying structure common to all technological systems. The approach emphasizes that components provide specific capabilities or functions and are combined using the design process into technological systems. Initial results of this work-in-progress are encouraging. The FCSD framework has been used in engineering literacy and introductory courses. In preliminary studies students are able to articulate main concepts and conduct a design project following an FCSD approach.

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