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A functional basis for engineering design: Reconciling and evolving previous efforts

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Abstract In engineering design, all products and artifacts have some intended reason behind their existence: the product or artifact function. Functional modeling provides an abstract, yet direct, method for understanding and representing an overall product or artifact function. Functional modeling also strategically guides design activities such as problem decomposition, physical modeling, product architecting, concept generation, and team organization. A formal function representation is needed to support functional modeling, and a standardized set of function-related terminology leads to repeatable and meaningful results from such a representation. We refer to this representation as a *functional basis*; in this paper, we seek to reconcile and integrate two independent research efforts into a significantly evolved functional basis. These efforts include research from the National Institute of Standards and Technology and two US universities, and their industrial partners. The overall approach for integrating the functional representations and the final results are presented. This approach also provides a mechanism for evaluating whether future revisions are needed to the functional basis and, if so, how to proceed. The integration process is discussed relative to differences, similarities, insights into the representations, and product validation. Based on the results, a more versatile and comprehensive design vocabulary emerges. This vocabulary will greatly enhance and expand the frontiers of research in design repositories, product architecture, design synthesis, and general product modeling.

Keywords Functional modeling, Functional languages, Design representation

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1 Introduction

1.1 Scope

In engineering design, the end goal is the creation of an artifact, product, system, or process that performs a function or functions to fulfill customer need(s). Conceptualizing, defining, or understanding an artifact, product, or system, in terms of function, is a fundamental aspect of engineering design (Pahl and Beitz 1984; Hubka et al. 1988; Ulrich and Eppinger 1995; Ullman 1997; Otto and Wood 2001). Figure 1 illustrates two products with functional labels associated with their physical embodiments. This type of representation provides an abstraction to conceptualize and evolve designs and also applies to many stages of the product or artifact development process: product architecture, concept generation, and physical modeling as examples.

In this paper, we extend the basic understanding of function in engineering design. Specifically, we explore the differences and similarities among two prior efforts to create a functional basis (Little et al. 1997; Szykman et al. 1999a; Stone and Wood 2000). Our hypothesis for this research is that, though developed independently with different immediate goals, these efforts toward understanding function explored the same fundamental issues, and thus should have discernable similarities and complementary and resolvable differences. In addressing this hypothesis, the potential exists to evolve our understanding of functional modeling, and, importantly, to converge to a functional basis that will cover engineering design activities at many scales of product complexity.

In the remainder of this paper, we present the motivation, background, approach, results and conclusions of this research. As specific motivation, we present several immediate and exciting applications for a common functional design vocabulary. As background, we briefly summarize the most recent and independent efforts of the authors (Szykman et al. 1999a; Stone and Wood 2000). The methodology, approach, and specifics of a comparison and resolution effort are then presented. The resulting

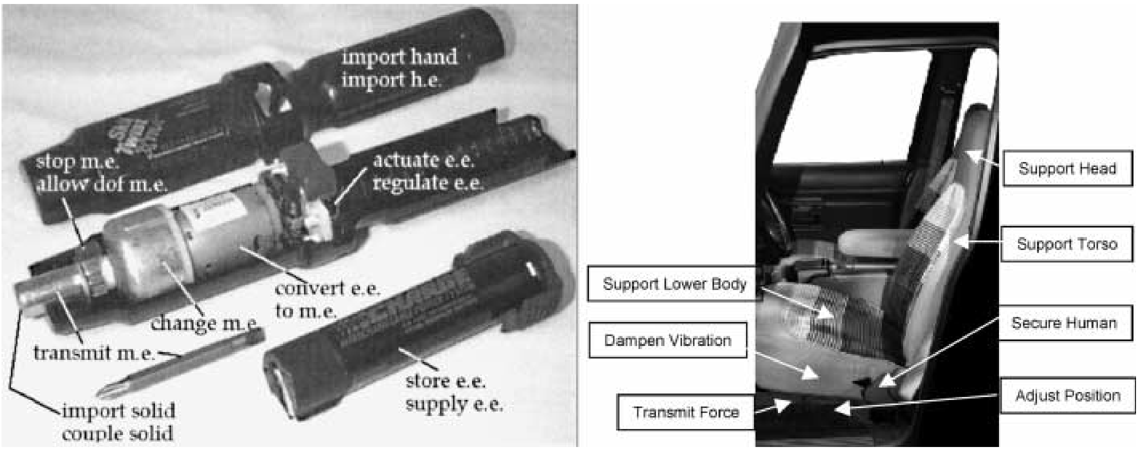


Fig. 1. Example Skil cordless screwdriver and automobile seat with functional labels. (Use of any commercial product or company names in this paper is intended to provide readers with information regarding the implementation of the research described, and does not imply recommendation or endorsement by the authors or their organizations)

functional basis is fully documented, and the paper concludes with insights gained from the research process.

1.2
Motivation and applications

Several factors motivate the creation of a functional basis for mechanical design. What follows are several specific uses for functional modeling. These practical applications serve both as motivation for, and contributions to, the development of a clear and concise functional basis; as the functional basis is used, weaknesses are identified and improvements are made.

1.2.1
Design repository

The NIST Design Repository Project is an ongoing project at the National Institute of Standards and Technology (NIST)<001>[1] that involves research toward providing a technical foundation for the creation of design repositories – repositories of heterogeneous knowledge and data that are designed to support representation, capture, sharing, and reuse of corporate and general design knowledge. The infrastructure being developed consists of formal representations for design artifact knowledge and web-based interfaces for creating repositories.

Through the course of this project, a variety of research issues have arisen that will in the long term affect the way in which design repositories are implemented and used. These issues include:

1. Development of an information-modeling framework to support modeling of engineering artifacts to provide a more comprehensive knowledge representation than traditional CAD systems.
2. Implementation of interfaces for creating, editing, and browsing design repositories that are easy to use and effective in conveying information that is desired.
3. The use of standard representations, when possible, and contribution to long-term standards development where standards currently do not exist (e.g., representation of engineering function).
4. Development of taxonomies of standardized terminology to help provide consistency in, and across, design repositories, as well as to facilitate indexing, search, and retrieval of information from them.

The degree to which these issues have been addressed, to date, varies within the NIST Design Repository Project. However, these issues are all important to the role of design repositories in industry, and ultimately all will have to be resolved by the research community before a successful transition of design repositories into engineering industrial practice is achieved. Other issues, such as security of communications and protection of intellectual property when sharing or exchanging design knowledge, have been recognized but are beyond the scope of this paper.

Within efforts directed toward the development of knowledge representations and vocabularies in this project, there has been a particular focus in the area of engineering function and associated flows. This focus has been driven by requirements articulated at an industry workshop held at NIST, where discussion of the needs associated with representation of engineering function arose in three different breakout sessions. Specific statements indicated (1) a need for representation of function in CAD, in addition to geometry, (2) a need for a fixed representation scheme for modeling function, and (3) a need for a commonly agreed set of functions performed by mechanical systems (Szykman et al. 1998).

1.1.2
Design for Six Sigma with Ford Motor Company

Besides the NIST application, the authors are also working with Ford Motor Company to develop methods for assuring the quality of their products. One such effort is the "Design for Six Sigma" program. The intent of this program is to develop and implement a repeatable process for producing

[1]NIST is a national lab under the US Department of Commerce. It is responsible for identifying standards and emerging technologies as they apply to US commerce.

six-sigma designs with respect to customer needs. An integral component of the program is to create "transfer functions," either analytically or experimentally, that directly measure the customer needs. Functional modeling, as adopted in the program, is a key tool used in the development of these programs. At recent training sessions with engineers across Ford's organization, participants described functional modeling, and associated representations, as a fundamental tool that will greatly assist in the practical implementation of Design for Six Sigma.

1.2.3 General engineering design and product development

The need for formalized representations in function-based design is often overlooked in the literature; however, it is an issue of critical importance for a number of reasons. The first reason is the need to reduce ambiguity at the modeling level. Ambiguities can occur when multiple terms are used to mean the same things, or when the same term is used with multiple meanings. The distillation of a large body of terms into a concise basis does not eliminate this problem entirely, but it significantly lessens its occurrence.

A related issue is that of uniqueness, not at the level of individual terms as with synonyms, but at the concept level. The larger the number of terms there are in a vocabulary, the more different ways there are to model or describe a given design concept. This makes processing of information that has been represented more difficult, whether it be a human trying to interpret information modeled by somebody else, or whether it be algorithms developed for function-based reasoning or design automation. This problem is mitigated by taking a minimalist approach regarding terminology and formal vocabularies. In practice, it is impractical to have a vocabulary that allows all concepts to be modeled in only one unique way because it is the flexibility required for representation of a broad set of concepts that results in multiple ways of expressing the same concept. However, to whatever extent ambiguity problems at the concept level can be reduced, interpreting information that is represented can be made easier.

A third reason for developing a functional basis is that it increases the uniformity of information within functional models. This uniformity will facilitate the exchange of function information among distributed researchers and developers, and will greatly simplify the task of indexing and retrieving information for the purposes of function-based searches and query capabilities.

Several other justifications exist for formal representations of function for engineering design. These include increasing the expressiveness of designers for exploring and communicating designs, creating early and repeatable physical models of products at a high-level of abstraction, decomposing design problems into realizable sub-problems, systematically searching for analogies to solve design problems, and synthesizing designs with computable formulations (Antonsson and Cagan 2001). These justifications underscore the expanding frontiers offered by the continued development of a functional basis.

2 Background and related work

2.1 Functional modeling research

The functional basis research draws its inspiration from prior work in Value Engineering dating back to the 1940s (Miles 1972; Akiyama 1991; VAI 1993). Value Engineering assigns a fraction of the product's cost to each of the elemental functions describing the overall product function to redesign high-cost functions to reduce manufacturing cost. Active verb–object descriptions are given for different product domains to describe a product's function, though no single comprehensive list exists.

Other researchers have recognized the importance of a common vocabulary for broader issues of design. To accurately archive and retrieve helicopter failure information, Collins et al. (1976) develop a list of 105 unique descriptions of mechanical function. Here, the mechanical function descriptions are limited to helicopter systems, do not utilize any classification scheme nor do they discriminate between function and flow.

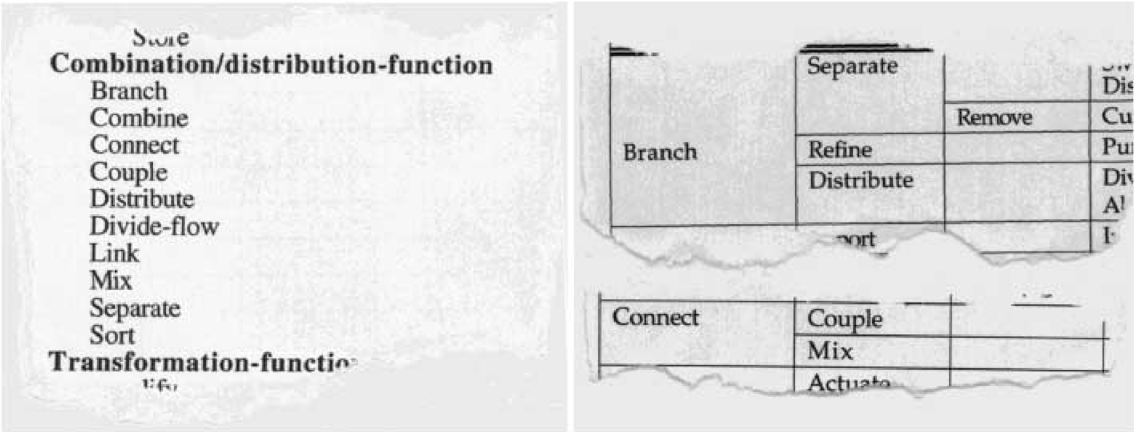
In modern, systematic, function-based design methodologies, the search for a consistent functional vocabulary is motivated by the related needs of a clear stopping point in the functional modeling process and a consistent level of functional detail. Pahl and Beitz (1984) list five generally valid functions and three types of flows at a very high level of abstraction. Hundal (1990) formulates six function classes with more specific functions in each class, but does not exhaustively list mechanical design functions. Another approach uses the 20 subsystem representations from living systems theory to represent mechanical design functions (Koch et al. 1994). Kirschman and Fadel (1998) propose four basic mechanical functions groups, but vary from the standard verb–object sub-function description popular with most methodologies. A further review of function classification is found in Hubka and Eder (2001).

In a separate development, Soviet Union researchers created the Theory of Inventive Problem Solving (TIPS), which describes all mechanical design with a set of 30 functional descriptions (Altshuller 1984). The TIPS work represents a credible source owing to its study of over 2 million patents to formulate its theory and the functional descriptions. Malmqvist et al. (1996) compare TIPS with the Pahl and Beitz methodology and note that the detailed vocabulary of TIPS would benefit from a more carefully structured class hierarchy using the Pahl and Beitz functions at the highest level.

More recently, the authors of this paper have worked on two independent research efforts to develop a consistent functional vocabulary which are reviewed next.

2.2 The NIST research effort

In 1999, as part of work involving the development of a generic representation for product knowledge, researchers at NIST undertook an effort to develop generic taxonomies of engineering functions and associated flows (Szykman et al. 1999a). In this context, a taxonomy is a hierarchical classification of terms. The intent of these taxonomies of



(a) NIST Function Flow Representation (partial) (b) Functional Basis (partial)

Fig. 2. Excerpts (partial listings) of the NIST and Functional Basis Representations

terms was to provide a classification of types that would be associated with various knowledge entities (which can be thought of as data structures) within the product knowledge representation. In addition to engineering functions and associated flows, other knowledge entities include artifacts, behaviors, forms, and others (Szykman et al. 2001).

This paper focuses on that portion of the NIST research that involved the concepts of function and flow. The aim of that work was to generate taxonomies that are as atomic as possible, yet generic enough to allow modeling of a broad variety of engineering artifacts. An excerpt of the NIST function taxonomy is shown in Fig. 2a. The representation was developed to provide an infrastructure to facilitate the capture and exchange of function information, among researchers at present, and eventually in industry by contributing to interoperability between design systems, be they commercial or developed internally within a company.

The organization of the NIST flow taxonomy follows a traditional approach set forth by Pahl and Beitz (1984), whereby flows are divided into material, energy and signal flows. It is important to note that the categorizations used in the taxonomies are not unique, but are rather a matter of convenience. The organization of the taxonomy is a particular instance of a view of the terminology it contains. For example, the flow taxonomy is broken down by domain (mechanical, electrical, thermal, etc.), each having various terms hierarchically below them. However, an alternative categorization could have organized them by the mapping of variable types across domains. The importance is placed on the content of the taxonomy rather than the specific approach to organizing the terms.

An extensive review of the literature (over 40 articles from researchers across four continents) yielded a large body of function- and flow-based terminology within the context of engineering function. From these bodies of terminology, an extensive list of functions and related flows was extracted. The lists of functions and flows were then distilled into considerably smaller ones by removing synonyms, by eliminating functions that were specializations of more generic functions, and by eliminating flows that were specializations of more generic types of flows. The lists of functions and flows were then categorized hierarchically and organized into taxonomies. The taxonomies developed at NIST contain over 130 functions and over 100 flows. Additional details regarding the process of developing these taxonomies are presented in (Szykman et al. 1999a), as are the full function and flow taxonomies themselves.

2.3
The functional basis effort

The functional basis research grew out of various researchers' needs to describe and compare products functionally, and to create a formal function representation that would advance design methods and lead to repeatable models.

To describe a product's functionality, an extension to the Pahl and Beitz function structure approach was developed. However, different researchers would represent the same product's functionality with a different set of terms, making design communication, modeling, and computation difficult. To alleviate this problem, Little et al. (1997) first proposed a function and flow representation as part of a product comparison method (refer to Fig. 2b). This representation was developed empirically through the study of over 100 products. The flow set adopted the Pahl and Beitz flows of material, energy, and signal as their highest level and further specified them into two more detailed categorizations. The function set built on the previous work of Value Analysis and later Pahl and Beitz-inspired functional categorizations to include eight function classes. As with the flow set, the function classes were further broken down into two more detailed levels. The function and flow sets were eventually given the name *functional basis*. The choice of the word *basis* was motivated by the authors' desire to associate the qualities of a mathematical basis – linear independence and spanning the space – with a functional vocabulary of design.

Stone et al. (2000a, 2000b) and Stone and Wood (1999) applied and evolved the functional basis as part of a method to identify modular product architectures. Here the basis gave functional models a common vocabulary and identified a stopping point for decomposition by

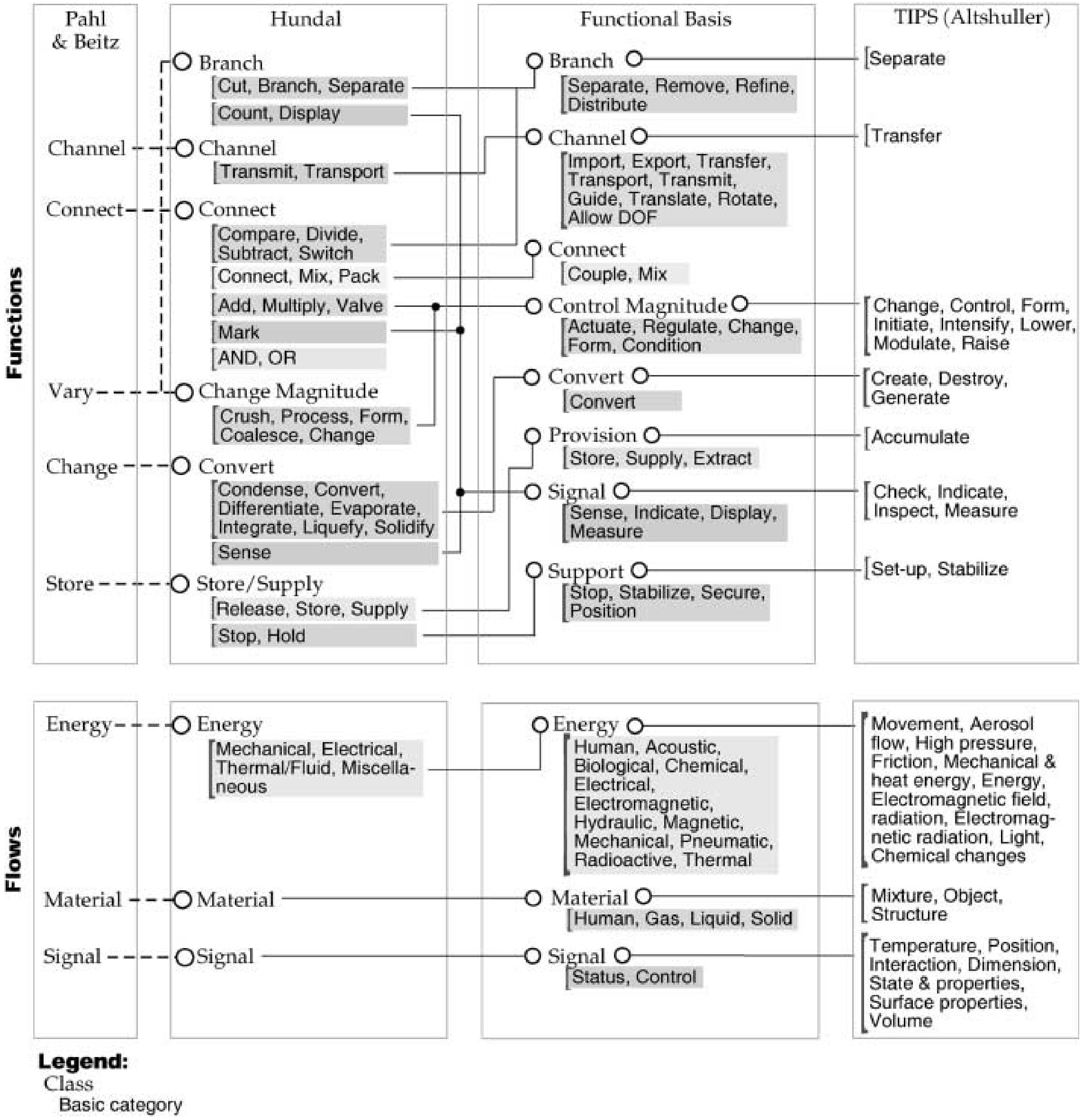


Fig. 3. Comparison of earlier function representations with the functional basis

specifying that function and flow words be chosen from a certain level. Definitions for the flow set were first introduced in this work as well (Stone 1997). McAdams et al. (1999) applied the functional basis to product similarity computations. Later, the basis was used as part of a design-by-analogy method (McAdams and Wood 2000) and a functional tolerancing method (McAdams and Wood 1999). The functional basis, complete with definitions for functions and flows, was presented by Stone and Wood (1999, 2000) after reviewing over 30 articles from researchers on four continents. In addition, a study demonstrating the functional basis' ability to improve repeatability of functional models among different designers was conducted (Kurfman et al. 2000).

To date, the functional basis is founded on empirical studies of over 100 existing and original products representing a broad variety of intended use. (Figure 3 shows a past comparison with the general research field.) This foundation has greatly assisted the development of a number of design methods and solutions to industry design problems. Each new research endeavor adds to existing knowledge and enables this work to converge toward a more complete and defendable result. The research described in the following section demonstrates a significant step towards this convergence. Through the cooperative and critical integration of two independent efforts, an important evolution of the functional basis is obtained. The positioning of the research among NIST, two universities, and industrial collaborators provides a conduit for its immediate application in practice.

3 Reconciliation of the NIST taxonomy and the functional basis

Examination of the two functional vocabularies reveals a high degree of similarity (excerpts in Fig. 2). Both research

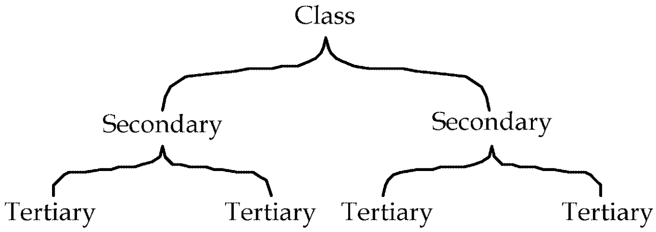


Fig. 4. The hierarchical relationship between levels of specification in the functional basis

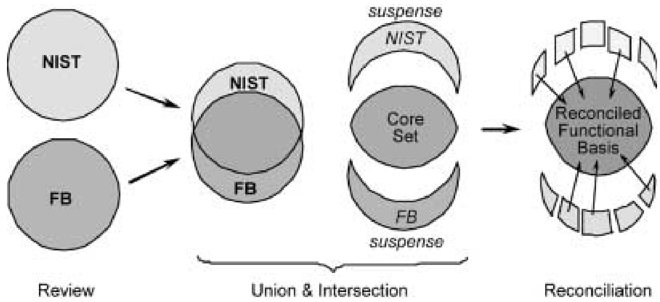


Fig. 5. Specific approach followed to reconcile the two functional vocabularies

efforts independently attempt to derive a standard list of functions and flows that completely describe the electro-mechanical design space. In order to meet those goals, the authors agreed to take a critical look at both vocabularies and to reconcile and integrate the differences.

3.1 General approach

The intent of the integrated functional basis is that the set of terms at a given level should provide complete coverage of all concepts within that category. For example, it should be possible to classify any flow into material or signal or energy, and it should be possible to classify any solid material into object, particulate, composite, or aggregate.

During the reconciliation process, a new term is added when it is necessary to do so in order to provide coverage to some area that is not currently fully covered. A new term should appear at the highest level possible such that the new terms and existing terms at that level provide as complete coverage as possible for the category under which the terms appear. This idea is illustrated in Fig. 4. The new term must also be mutually exclusive with other terms at that level. If the term is not mutually exclusive but instead overlaps to some degree with a term at that level, then the following categorization algorithm is employed:

1. The new term might be a subset of the existing term it overlaps with, and would therefore be bumped down to the next lower level.
2. The new term might be a superset of the existing term it overlaps with, in which case the new term might replace the existing term and the existing term would be bumped down to the next lower level.
3. The new term might be similar enough to an existing term that it might be categorized as a comparable term (synonym) rather than entering the basis as a new item.

For example, the NIST flow taxonomy did not include "Biological Energy" in its original formulation. It was clear where this flow type would enter the representation. It would not go at the top level, because we do not expect to classify all flows into material OR signal OR energy OR biological energy. Biological energy is a subset of Energy. We would expect to classify all energy flows into Human OR Acoustic OR Biological OR [...]. So it is inserted at the second level of representation.

By developing functional models at varying levels of granularity or refinement, different levels of specification are possible. These different levels of functional specification are important for several reasons. In the design of new products, the customer needs, and thus functional requirements, are more difficult to ascertain than in a redesign or evolutionary design effort. In general, ambiguous customer needs result in the use of higher-level functions. More specific customer needs lead to the use of more specific types of functions. As in all modeling efforts in design, models should provide sufficient precision to give designers the information necessary to make a design specification, analysis, or decision.

The two original functional vocabularies differ in the naming schemes employed for the levels of specification. Stone and Wood offer a class/basic/flow-restricted (functions) or sub-basic (flow) level identification scheme. In contrast, Szykman et al. do not name the levels to avoid differentiating between the significance of terms at different levels. In both vocabularies, the distinction between the levels has largely the same intent. Therefore, in the reconciled basis we label the three levels (in descending order) as class (or primary), secondary and tertiary. Note that we retained the top-level categorization of *class* that is commonly used in functional modeling literature, but also recognize that this usage of the word *class* is different from that in other fields. As the level number increases, so does the specification of the level. The tertiary level, for example, provides a more specific function and definition than the class or secondary levels, leading to specific technologies or physical principles.

In the previous functional basis efforts, the secondary level is referred to as basic. The secondary functions are intended to be used in the majority of engineering design as well as impart a mathematical connotation of a basis to the second level of functional decomposition. In other words, the basic functions are the smallest functional set spanning the functional space while remaining practical for use. Recognition and inclusion of the tertiary level of functions alters this view. Thus the classification for both functions and flows is unified and presented here as class, secondary, and tertiary.

3.2 Specific approach

Our specific approach to reconciling the two functional vocabularies followed a three-step algorithm consisting of review, union, and reconciliation steps. The approach is shown schematically in Fig. 5 and the steps are described below.

- Step 1: Review. The latest versions of the functional basis (Stone and Wood 2000) and the NIST function and flow taxonomies (Szykman et al. 1999a) are reviewed, and definitions for each of the function and flow terms are formulated (within a product design context).
- Step 2: *Union and intersection*. The union of the two vocabularies is generated, creating a combined list of terms. Those terms that fall in the intersection of the two sets form a core set of terms that are common to both. This unioning process is carried out at each level of the two vocabularies (functions and flows). At this point, a check is made to ensure that the core function and flow terms do not overlap in meaning at each level. The function and flow words that emerge in the difference of the two sets are temporarily placed in a holding category termed "suspense." Here suspense is used in the bookkeeping sense to indicate a term that is set aside for further review before it is accepted or rejected to the reconciled functional basis.
- Step 3: Reconciliation. Using the definitions, each suspense word is initially evaluated at the level it occupied in its original vocabulary. There are two possibilities: (1) If the suspense term is mutually exclusive (i.e., the definition is different from the other words' meanings at that level), then it is added to the reconciled functional basis at that level. (2) If the meaning of the suspense term overlaps with other words at that level, the categorization algorithm of Sect. 3.1 is applied to find its proper location.

In all cases, the comparison is carried out with respect to product examples. Specifically, we judge a function term's suitability based on whether or not it describes an operation that a product or device carries out on a flow. This ensures that the reconciled functional basis will consist of only *device functions*, as opposed to *user functions*. For instance, a coffee maker (the device) *imports* the flow of water while a person (the user) *pours* water into the coffee maker.

4 Results

A review of Szykman et al. yields three class (primary) flows and six class (primary) functions, whereas Stone and Wood yields three class (primary) flows and eight class (primary) functions. On the surface, the two works appear very similar. However, the differences emerge in the number of secondary and tertiary categories. Tables 1 and 2 detail the number of initial secondary and tertiary terms in the two lists of flow (Table 1) and function (Table 2) representations and compare it with the reconciled count. In the two tables, the NIST taxonomies are denoted by NT, the Stone and Wood functional basis is denoted by FB, and the reconciled functional basis is denoted by RFB. As can be seen in Table 2, in some instances one category in the NIST taxonomy corresponded to two separate categories in the original and reconciled function bases.

In general, the NIST function and flow terms at the lowest level are more detailed than the lowest level of the functional basis. The secondary level of the functional basis function set proved to be complete, in the sense of spanning a broad set of concepts and remaining non-repetitive, while the NIST taxonomy had more complete secondary flows in terms of material. Through the process of integration, definitions for each representation were compared. Additions to the functional basis resulted in new or evolved definitions. Overlapping flows and functions created integrated definitions or simple refinements.

The reconciled functional basis, resulting from the comparison and combination of the two vocabularies, is shown in Tables 3, 4, 5. The reconciled flow set in Table 3 still contains three class (primary) flows: material, signal and energy. The material level has five further specified secondary categories with an expanded list of tertiary categories. The signal class has two further specified secondary categories with an expanded list of tertiary categories. The energy class has 13 further specified secondary categories with an expanded list of tertiary categories. Table 4 is a more specific breakdown of the energy class. To achieve more detail when specifying product infor-

Table 1. Level comparisons between the NIST taxonomy, the functional basis, and the reconciled functional basis flow set

Class (Primary)	Secondary	Tertiary
Material (NT)	8	20
Material (FB)	4	0
Material (RFB)	6	11
Energy (NT)	11	7
Energy (FB)	12	5
Energy (RFB)	12	4
Signal (NT)	3	4
Signal (FB)	2	5
Signal (RFB)	2	7

Table 2. Level comparisons between the NIST taxonomy, the functional basis, and the reconciled functional basis function set

Class (Primary)	Secondary	Tertiary
Usage-function (NT)	3	0
Provide (FB)	3	0
Provision (RFB)	2	2
Combination/distribution-function (NT)	10	0
Branch (FB)	4	0
Connect (FB)	2	0
Branch (RFB)	3	5
Connect (RFB)	2	3
Transformation-function (NT)	10	0
Convert (FB)	1	0
Convert (RFB)	1	0
Conveyance-function (NT)	13	0
Channel (FB)	4	0
Channel (RFB)	4	5
Signal/Control-function (NT)	32	0
Signal (FB)	4	0
Control Magnitude (FB)	3	0
Signal (RFB)	3	4
Control magnitude (RFB)	4	8
Assembly-function (NT)	21	0
Support (FB)	4	0
Support (RFB)	3	0

Table 3. Functional basis reconciled flow set

Class (Primary)	Secondary	Tertiary	Correspondents
Material	Human		Hand, foot, head
	Gas		Homogeneous
	Liquid		Incompressible, compressible, homogeneous
	Solid	Object	Rigid-body, elastic-body, widget
		Particulate	
		Composite	
	Plasma		
	Mixture	Gas–gas	
		Liquid–liquid	
		Solid–solid	Aggregate
		Solid–liquid	
		Liquid–gas	
		Solid–gas	
		Solid–liquid–gas	
		Colloidal	Aerosol
Signal	Status	Auditory	Tone, word
		Olfactory	
		Tactile	Temperature, pressure, roughness
		Taste	
		Visual	Position, displacement
	Control	Analog	Oscillatory
		Discrete	Binary
Energy	Human		
	Acoustic		
	Biological		
	Chemical		
	Electrical		
	Electromagnetic	Optical	
		Solar	
	Hydraulic		
	Magnetic		
	Mechanical	Rotational	
		Translational	
	Pneumatic		
	Radioactive/Nuclear		
	Thermal		

Overall increasing degree of specification from left to right

Table 4. Power conjugate complements for the energy class of flows

Class (Primary)	Secondary	Tertiary	Power conjugate complements	
			Effort analogy	Flow analogy
Energy			Effort	Flow
	Human		Force	Velocity
	Acoustic		Pressure	Particle velocity
	Biological		Pressure	Volumetric flow
	Chemical		Affinity	Reaction rate
	Electrical		Electromotive force	Current
	Electromagnetic		Effort	Flow
		Optical	Intensity	Velocity
		Solar	Intensity	Velocity
	Hydraulic		Pressure	Volumetric flow
	Magnetic		Magnetomotive force	Magnetic flux rate
	Mechanical		Effort	Flow
		Rotational	Torque	Angular velocity
		Translational	Force	Linear velocity
	Pneumatic		Pressure	Mass flow
	Radioactive/Nuclear		Intensity	Decay rate
	Thermal		Temperature	Heat flow

Table 5. Functional basis reconciled function set

Class (Primary)	Secondary	Tertiary	Correspondents
Branch	Separate		Isolate, sever, disjoin
		Divide	Detach, *isolate*, release, sort, split, disconnect, subtract
		Extract	Refine, filter, purify, percolate, strain, *clear*
		Remove	Cut, drill, lathe, polish, sand
	Distribute		Diffuse, dispel, disperse, dissipate, diverge, scatter
Channel	Import		Form entrance, *allow*, input, *capture*
	Export		Dispose, eject, *emit*, empty, *remove*, destroy, eliminate
	Transfer		Carry, deliver
		Transport	Advance, lift, move
		Transmit	Conduct, convey
	Guide		Direct, shift, steer, straighten, switch
		Translate	Move, relocate
		Rotate	Spin, turn
		Allow DOF	*Constrain*, unfasten, unlock
Connect	Couple		Associate, connect
		Join	Assemble, fasten
		Link	Attach
	Mix		Add, blend, coalesce, combine, pack
Control	Actuate		Enable, initiate, start, turn-on
	Regulate		Control, equalize, limit, maintain
		Increase	*Allow*, open
		Decrease	Close, delay, interrupt
Magnitude	Change		Adjust, modulate, *clear*, demodulate, invert, normalize, rectify, reset, scale, vary, modify
		Increment	Amplify, enhance, magnify, multiply
		Decrement	Attenuate, dampen, reduce
		Shape	Compact, compress, crush, pierce, deform, form
		Condition	Prepare, adapt, treat
	Stop		End, halt, pause, interrupt, restrain
		Prevent	Disable, turn-off
		Inhibit	Shield, insulate, protect, resist
Convert	Convert		Condense, create, decode, differentiate, digitize, encode, evaporate, generate, integrate, liquefy, *process*, solidify, transform
Provision	Store		Accumulate
		Contain	*Capture*, enclose
		Collect	Absorb, consume, fill, reserve
	Supply		Provide, replenish, retrieve
Signal	Sense		Feel, determine
		Detect	Discern, perceive, recognize
		Measure	Identify, *locate*
	Indicate		Announce, show, denote, record, register
		Track	Mark, time
		Display	*Emit*, expose, select
	Process		Compare, calculate, check
Support	Stabilize		Steady
	Secure		*Constrain*, hold, place, fix
	Position		Align, *locate*, orient

Overall increasing degree of specification from left to right

mation, the power conjugate complements of effort and flow can be used.

The reconciled function set in Table 5 has been modified from having categories of class, basic, and flow restricted (in the original functional basis) to class (primary), secondary, tertiary, and Correspondents. The column labeled as "Correspondents" is provided as an aid for mapping from terms that are not in the reconciled functional basis to terms that are. In other words, the terms rigid-body, elastic-body or widget in some other representation would all be mapped to the term *object* in a representation built upon the reconciled functional basis. The words contained within the Correspondents category are merely a means of comparison and are not considered to be a fourth level of terms in the reconciled functional basis. The italicized words in Table 5 are repeated correspondents. For example, *allow* is a correspondent for both the secondary functions import and regulate. The combined function set now contains eight class (primary) categories with an expanded list of secondary categories and the creation of new tertiary categories. The eight secondary categories are branch, channel, connect, control magnitude, convert, provision, signal, and support. Clear definitions have been developed for all flow and function categories (see Appendices A and B). An illustrative example for each term is also included for clarity.

5 Usage and validation of earlier efforts

5.1 Discussion of usage

Both of the earlier efforts (the NIST taxonomies and the original functional basis) were not developed solely as an information-organizing exercise, but to actively support manual and software-based applications of functional modeling methods. Since these initial efforts emerged from projects that addressed different engineering design issues and evolved separately, they both were involved with different modes of usage. This section describes how the reconciled functional basis fits within the context of the two different approaches to using vocabularies for functional modeling.

The reconciled functional basis is flexible enough to form functional descriptions that follow the standard *verb–object* format as well as other formats. In the case of the Pahl and Beitz verb–object format, a function term occupies the verb spot, while a flow term fills the object spot. Other formats are possible as long as the function and flow terms are expressed correctly at the desired level of specification. Specifically, a function term can be selected from any of the three levels, depending on the specification desired. Flow terms may be formed at all levels as well. A class (primary) flow is simply the class term, such as *material*. A secondary flow is described by a secondary term plus a class term. For example, *human energy* is a secondary flow. Tertiary flows are described by a tertiary term plus a class term. An example is the flow *auditory signal*.

If additional energy flow specification is needed at the level of performance variables, then power conjugate complements may be used. Power conjugates are part of a system modeling technique known as bond graphs (or multi-port elements) where the connection between system elements is represented by power flow. The power flow consists of two conjugates – the effort and flow variables – with their product equaling power. A list of power conjugate complements for the energy flow category is given in Table 4. Here the flow description is formed by a secondary or tertiary term plus a power conjugate term. A more specific description of human energy used by a product such as a power screwdriver is *human force*. A few special cases exist where complements stand alone in describing a flow. Stand-alone power conjugate complements are denoted by a gray background in Table 4. Taking an engine, for example, we may be interested in the *torque* produced by the engine instead of the more cumbersome rotational torque.

The degree of specification depends on the type of design and customer needs. Using a more general flow description produces a generic function structure and a wider range of concept variants. However, if customer needs dictate concreteness in flows, then an increasingly specific level is more valuable.

The NIST work in developing taxonomies was part of a larger effort aimed at developing a standardized representation of function. The work was done in order to enable the implementation of software tools that support functional modeling, and to provide a common basis for the exchange of function-based information among individuals or teams involved in distributed collaborative product development. The need for a standardized representation of function was motivated in part by industry needs (as described in Sect. 1.2), and also by a desire to provide a common basis for exchange of information associated with product function, in an attempt to reduce costly interoperability problems in next-generation product development tools.

The NIST research set forth an initial specification for a standardized representation of engineering artifact function. This includes schemata (information models) for representation of function and associated flows, as well as an initial attempt at developing taxonomies of functions and flows. These taxonomies had been developed in order to support the standardized representation and to provide a basis for knowledge indexing and retrieval, allowing better access to information for the purpose of design reuse. Additional information regarding representation and associated schemata for representing function and flow can be found in (Szykman et al. 1999a).

Since computational design knowledge is typically stored in some kind of database rather than in plain text files, the generic schemata and taxonomies introduced in Szykman et al. (1999a) may not be best-suited for exchange of information between software systems. To address this issue, mappings of the generic function representation models into the Extensible Markup Language (XML) were developed (Szykman et al. 1999b). The XML specification imposes guidelines on how to structure a document (in this case function data), how to represent schemata, how to make references, etc., providing advantages over, say, a plain text file format for artifact function models. Subsequent research within the NIST Design Repository Project has led to a more expanded representation for product knowledge. This work extends beyond function and flow to also include representation of artifacts and their form, physical decompositions, capture of the mappings between physical structures, functions, and flows, as well as various kinds of relationships among these entities. This product knowledge representation is described in greater detail in (Szykman et al. 2001).

5.2 Supporting cases and validation

A number of research and industrial partnership efforts are under way to support our research on the functional basis. Two examples are a NIST Design Repository Project and a new program at Ford Motor Company.

NIST researchers have been validating work under the NIST Design Repository Project both at the interface development level and the knowledge representation level by modeling existing artifacts using prototype interfaces and a web-based communications architecture. The artifacts modeled at NIST include several power tools (e.g., a power drill, a detail sander, an electric saw), an ultrahigh vacuum artifact transport system,[2] and the new encasements for the Charters of Freedom.[3]

Ford Motor Company has also participated in recent efforts to implement the functional basis. A new program in Design for Six Sigma uses the functional basis as a method of developing critical and repeatable "transfer functions" to create robust designs. Functional modeling has been received with great enthusiasm, and the results show that the functional basis can model the large-scale systems developed by Ford.

6 Conclusions

In engineering design, functional modeling provides a direct method for understanding and representing an overall artifact function without reliance on physical structure. In practice, to achieve repeatable and meaningful results from functional modeling, a formal functional representation is needed. This paper represents the reconciliation of two independent efforts to create such formal representations of function.

Both of these efforts were initiated and progressed independently, but were founded on common assumptions. Both groups believed that:

- It was possible to identify a comprehensive set of functions and flows that could be used to model engineering artifacts, products and systems,
- Each of these sets of terms could be distilled to a more fundamental set that would ideally (as it was refined and validated) lead to a minimal set of terms that did not overlap, and yet provided complete coverage of the space of designed products.
- Identifying these sets of terms would be very valuable to engineers, both by providing a basis to support the use of more formal design methods by people, and to support the development of computer-aided software tools developed for use during conceptual design.

Examining some statistics that came out of the reconciliation effort provides revealing insights as to the validity of these assumptions. One would expect that if there were a fundamental set of functions and flows, two unrelated efforts would begin to converge to the same sets. On the other hand, if there were not one fundamental set of flows but many alternative sets, two independent efforts would more likely converge to different sets. At the gross level, one can examine the independently developed sets of functions and flows (Stone and Wood 2000; Szykman et al. 1999a) and note that there is a high degree of similarity at the top levels of the hierarchies. One can also do a more detailed comparison by examining the commonality between the reconciled functional basis and the earlier works.

Of the 42 terms in the reconciled flow set (Table 3), 34 are present in the NIST function taxonomy as either exact matches or equivalent terms. A significant portion of this discrepancy can be attributed to the fact that the earlier NIST work considered the human as being "outside of the system," resulting in the absence of the Human terms and all of the terms associated with human senses (i.e., Auditory, Olfactory, Tactile, Taste, Visual). Other than the human and human-related terms, there are only two terms in the new flow set that did not appear in the earlier NIST work. Similarly, 27 of the terms in the reconciled flow set appear in the original functional basis work. Of the 53 terms in the reconciled function set (Table 5), 46 are present in the NIST function taxonomy as exact matches or equivalent terms; in the original functional basis work, 47 of them are present.

From this perspective, it can be seen that the terms in the reconciled function and flow sets were covered by both sets of earlier work to a significant degree. Among the more significant differences between the two earlier efforts themselves (as opposed to the reconciled basis and earlier work) was the size of the sets of terms, the NIST taxonomies being considerably larger than the original functional basis. This is primarily due to a fundamental difference in approach; the NIST effort attempted to provide a comprehensive list of function and flow terms used by engineers, whereas the original and reconciled functional basis attempt to minimize terms. Many of the terms that were originally in the NIST taxonomies are now listed among the correspondents. Thus, while these terms are not counted when tallying the total number of fundamental function and flow terms in the reconciled basis, the breadth of terminology used by engineers and information about the relationships between terminology and the fundamental sets of terms, is still preserved.

There are a number of important contributions of this research. By combining these two function vocabularies, we have evolved our understanding of functional modeling and created a taxonomy that supports engineering design at many scales. Also, the rigorous review of the previous function taxonomies has sharpened the distinctions between the function and flow terms.

Another important contribution, and the key goal of this paper, is the evolved definitions included in the appendices. These definitions result from a number of empirical studies over a wide range of existing and original products, a number of person-years of effort, and independent research efforts. The formality of the reconciled functional basis facilitates engineering design education in both university and industry settings. Functional models are more easily reviewed for either similarity or correctness. Also, they can be developed at different levels of precision, offering enough abstraction for original design problems and enough detail for redesign or documentation of existing products.

Though additional research at a basic level would be likely to contribute to the functional taxonomy presented here, we see the next evolution of the reconciled functional basis to occur through usage. The reconciled functional

[2]The NIST Artifact Transport System was designed and built at NIST in order to transport atomically accurate specimens created in a molecular beam epitaxy laboratory to a scanning tunnel microscope laboratory across the NIST campus, where metrologists verify atomic-scale measurements.

[3]These encasements were designed and fabricated in a collaboration between the National Archives and several operating units at NIST to house the Charters of Freedom – the Declaration of Independence, the Constitution, and the Bill of Rights.

basis offers a foundation for design repositories, support for new knowledge-based design methods such as design by analogy, design for manufacturing and product architecture, and a teaching tool for design education and training. As it is used in these endeavors, we expect the reconciled functional basis to slowly evolve and mature. Thus, one of the important results of the research presented here is a process for adding new terms to the reconciled functional basis.

Appendix A: Flow definitions

1 Material

a. Human
All or part of a person who crosses the device boundary. *Example*: Most coffee makers require the flow of a *human hand* to actuate (or start) the electricity and thus heat the water.

b. Gas
Any collection of molecules characterized by random motion and the absence of bonds between the molecules. *Example*: An oscillating fan moves air by rotating blades. The air is transformed as *gas* flow.

c. Liquid
A readily flowing fluid, specifically having its molecules moving freely with respect to each other but, because of cohesive forces, not expanding indefinitely. *Example*: The flow of water through a coffee maker is a *liquid*.

d. Solid
Any object with mass having a definite, firm shape. *Example*: The flow of sandpaper into a hand sander is transformed into a *solid* entering the sander.

i. *Object*. Material that can be seen or touched that occupies space. *Example*: The box of scrap paper for recycling is represented as the flow *object*.
ii. *Particulate*. Substance containing minute separate particles. *Example*: Granular sugar and powdered paint are *particulates*.
iii. *Composite*. Solid material composed of two or more substances having different physical characteristics and in which each substance retains its identity while contributing desirable properties to the whole unit. Any class of high-strength, lightweight engineering materials consisting of various combinations of alloys, plastics, and ceramics. *Example*: Materials such as wood, fiberglass combined with metals, ceramics, glasses, or polymers together are considered a *composite*. Kevlar cloth combined with paper honeycomb by means of a resin is considered a *composite*.

e. Plasma
A collection of charged particles that is electrically neutral exhibiting some properties of a gas, but differing from a gas in being a good conductor of electricity and in being affected by a magnetic field. *Example*: Plasma cutting focuses an intense beam of ionized air, known as *plasma*, produced by an electric arc, which melts the material to be cut.

f. Mixture
A substance containing two or more components which are not in fixed proportions, do not lose their individual characteristics and can be separated by physical means. *Example*: Expected precipitation for this evening is a *mixture* of rain, sleet, and snow.

i. *Liquid–liquid*. A readily flowing combination of two or more fluids, specifically having its molecules moving freely with respect to each other, but because of cohesive forces, not expanding indefinitely. *Example*: Machine oil and gasoline is a common *liquid–liquid* mixture used in yard maintenance machines.
ii. *Gas–gas*. A collection of molecules containing two or more components, which are characterized by random motion and the absence of bonds between the molecules. *Example*: The mixture of argon and carbon dioxide, a *gas-gas* flow, is commonly used in welding.
iii. *Solid–solid*. A combination of two or more objects with mass having a definite, firm shape. *Example*: Pebbles, sand, gravel, and slag can be used to form concrete, mortar, or plaster. After it cures, concrete is a *solid–solid*.
iv. *Solid–liquid*. A combination of two or more components containing at least one solid and one liquid. *Example*: Iced tea is a *solid–liquid* mixture of ice (solid), water (liquid), and tea grounds (solid).
v. *Solid–gas*. A combination of two or more components containing at least one solid and one gas. *Example*: Fog is a *solid–gas* mixture of frozen ice particles (solid) in air (gas).
vi. *Liquid–gas*. A combination of two or more components containing at least one liquid and one gas. *Example*: Carbonated drinks are *liquid–gas* mixtures of flavored syrup (liquid), purified water (liquid), and carbon dioxide (gas).
vii. *Solid–liquid–gas*. A combination or three or more components containing at least one each of a solid, liquid, and gas. *Example*: In a cup of soda and ice cubes, the cup contains the *solid–liquid–gas* flow.
viii. *Colloidal*. A solid, liquid, or gaseous substance made up of very small, insoluble non-diffusible particles that remain in suspension in a surrounding solid, liquid, or gaseous medium of a different matter. *Example*: Aerosols, smoke, and mist can all be considered *colloids*. Mist is a combination of very fine water droplets suspended in air.

2 Energy

a. Generic Complements
i. *Effort*. Any component of energy used to accomplish an intended purpose.

ii. *Flow*. Any component of energy causing the intended object to move or run freely.

b. Human
Work performed by a person on a device. *Example*: An automobile requires the flow of *human energy* to steer and accelerate the vehicle.

i. *Force*. Human effort that is input to the system without regard for the required motion. *Example*: *Human force* is needed to actuate the trigger of a toy gun.
ii. *Velocity*. Activity requiring movement of all or part of the body through a prescribed path. *Example*: The track pad on a laptop computer receives the flow of *human velocity* to control the cursor.

c. Acoustic
Work performed in the production and transmission of sound. *Example*: The motor of a power drill generates the flow of *acoustic energy* in addition to the torque.

i. *Pressure*. The pressure field of the sound waves. *Example*: A condenser microphone has a diaphragm, which vibrates in response to *acoustic pressure*. This vibration changes the capacitance of the diaphragm, thus superimposing an alternating voltage on the direct voltage applied to the circuit.
ii. *Particle velocity*. The speed at which sound waves travel through a conducting medium. *Example*: Sonar devices rely on the flow of *acoustic particle velocity* to determine the range of an object.

d. Biological
Work produced by or connected with plants or animals. *Example*: In poultry houses, grain is fed to chickens, which is then converted into *biological energy*.

i. *Pressure*. The pressure field exerted by a compressed biological fluid. *Example*: The high concentration of sugars and salts inside a cell causes the entry, via osmosis, of water into the vacuole, which in turn expands the vacuole and generates a hydrostatic *biological pressure*, called turgor, that presses the cell membrane against the cell wall. Turgor is the cause of rigidity in living plant tissue.

ii. *Volumetric flow*. The kinetic energy of molecules in a biological fluid flow. *Example*: Increased metabolic activity of tissues such as muscles or the intestine automatically induces increased *volumetric flow* of blood through the dilated vessels.

e. Chemical
Work resulting from the reactions by which substances are produced from or converted into other substances. *Example*: A battery converts the flow of *chemical energy* into electrical energy.

i. *Affinity*. The force with which atoms are held together in chemical bonds. Affinity is proportional to the chemical potential of a compound's constituent species. *Example*: An internal combustion engine transforms the chemical *affinity* of the gas into a mechanical force.
ii. *Reaction rate*. The speed or velocity at which chemical reactants produce products. Reaction rate is proportional to the mole rate of the constituent species. *Example*: Special coatings on automobile panels stop the *chemical reaction rate* of the metal with the environment.

f. Electrical
Work resulting from the flow of electrons from a negative to a positive source. *Example*: A power belt sander imports a flow of *electrical energy* (electricity, for convenience) from a wall outlet and transforms it into a rotation.

i. *Electromotive force*. Potential difference across the positive and negative sources. *Example*: Household electrical receptacles provide a flow of *electromotive force* of approximately 110 V.
ii. *Current*. The flow or rate of flow of electric charge in a conductor or medium between two points having a difference in potential. *Example*: Circuit breakers trip when the *current* exceeds a specified limit.

g. Electromagnetic
Energy that is propagated through free space or through a material medium in the form of electromagnetic waves (Britannica Online, 1997). It has both wave and particle-like properties. *Example*: Solar panels convert the flow *electromagnetic energy* into electricity.

i. *Generic Complements*

   1. *Effort*. Any component of electromagnetic energy used to accomplish an intended purpose.
   2. *Flow*. Any component of electromagnetic energy causing the intended object to move or run freely.

ii. *Optical*. Work associated with the nature and properties of light and vision. Also, a special case of solar energy (see solar). *Example*: A car visor refines the flow of *optical energy* that its passengers receive.

   1. *Intensity*. The amount of optical energy per unit area. *Example*: Tinted windows reduce the *optical intensity* of the entering light.
   2. *Velocity*. The speed of light in its conducting medium. *Example*: NASA developed and tested a trajectory control sensor (TCS) for the space shuttle to calculate the distance between the payload bay and a satellite. It relied on the constancy of the *optical velocity* flow to calculate distance from time of flight measurements of a reflected laser.

iii. *Solar*. Work produced by or coming from the sun. *Example*: Solar panels collect the flow of *solar energy* and transform it into electricity.

   1. *Intensity*. The amount of solar energy per unit area. *Example*: A cloudy day reduces the *solar intensity* available to solar panels for conversion to electricity.
   2. *Velocity*. The speed of light in free space. *Example*: Unlike most energy flows, *solar velocity* is a well-known constant.

h. Hydraulic
Work that results from the movement and force of a liquid, including hydrostatic forces. *Example*: Hydroelectric dams generate electricity by harnessing the *hydraulic energy* in the water that passes through the turbines.

i. *Pressure*. The pressure field exerted by a compressed liquid. *Example*: A hydraulic jack uses the flow *hydraulic pressure* to lift heavy objects.
ii. *Volumetric flow*. The movement of fluid molecules. *Example*: A water meter measures the *volumetric flow* of water without a significant pressure drop in the line.

i. Magnetic
Work resulting from materials that have the property of attracting other like materials, whether that quality is naturally occurring or electrically induced. *Example*: The *magnetic energy* of a magnetic lock is the flow that keeps it secured to the iron-based structure.

i. *Magnetomotive force*. The driving force which sets up the magnetic flux inside a core. Magnetomotive force is directly proportional to the current in the coil surrounding the core. *Example*: In a magnetic door lock, a change in *magnetomotive force* (brought about by a change in electrical current) allows the lock to disengage and the door to open.
ii. *Magnetic flux rate*. Flux is the magnetic displacement variable in a core induced by the flow of current through a coil. The magnetic flow variable is the time rate of change of the flux. The voltage across a magnetic coil is directly proportional to the time rate of change of magnetic flux. *Example*: A magnetic relay is a transducer that senses the time rate of change of *magnetic flux* when the relay arm moves.

j. Mechanical
Energy associated with the moving parts of a machine or the strain energy associated with a loading state of an object. *Example*: An elevator converts electrical or hydraulic energy into mechanical energy.

i. *Generic Complements*.
   1. *Effort*. Any component of mechanical energy used to accomplish an intended purpose.
   2. *Flow*. Any component of mechanical energy causing the intended object to move or run freely.

ii. *Rotational energy*. Energy that results from a rotation or a virtual rotation. *Example*: Customers are primarily concerned with the flow of *rotational energy* from a power screwdriver.
   1. *Torque*. Pertaining to the moment that produces or tends to produce rotation. *Example*: In a power screwdriver, electricity is converted into rotational energy. The more specific flow is *torque*, based on the primary customer need to insert screws easily, not quickly.
   2. *Angular velocity*. Pertaining to the orientation or the magnitude of the time rate of change of angular position about a specified axis. *Example*: A centrifuge is used to separate out liquids of different densities from a mixture. The primary flow it produces is that of *angular velocity*, since the rate of rotation about an axis is the main concern.

iii. *Translational energy*. Energy flow generated or required by a translation or a virtual translation. *Example*: A child's toy, such as a projectile launcher, transmits *translational energy* to the projectile to propel it away.
   1. *Force*. The action that produces or attempts to produce a translation. *Example*: In a tensile testing machine, the primary flow of interest is that of a *force* which produces a stress in the test specimen.
   2. *Linear velocity*. Motion that can be described by three component directions. *Example*: An elevator car uses the flow of *linear velocity* to move between floors.

k. Pneumatic
Work resulting from a compressed gas flow or pressure source. *Example*: A BB gun relies on the flow of *pneumatic energy* (from compressed air) to propel the projectile (BB).

i. *Pressure*. The pressure field exerted by a compressed gas. *Example*: Certain cylinders rely on the flow of *pneumatic pressure* to move a piston or support a force.
ii. *Mass flow*. The kinetic energy of molecules in a gas flow. *Example*: The *mass flow* of air is the flow that transmits the thermal energy of a hair dryer to damp hair.

l. Radioactive (Nuclear)
Work resulting from or produced by particles or rays, such as alpha, beta and gamma rays, by the spontaneous disintegration of atomic nuclei. *Example*: Nuclear reactors produce a flow of *radioactive energy* which heats water into steam and then drives electricity generating turbines.

i. *Intensity*. The amount of radioactive particles per unit area. *Example*: Concrete is an effective radioactive shielding material, reducing the *radioactive intensity* in proportion to its thickness.
ii. *Decay rate*. The rate of emission of radioactive particles from a substance. *Example*: The *decay rate* of carbon provides a method to date prehistoric objects.

m. Thermal
A form of energy that is transferred between bodies as a result of their temperature difference. *Example*: A coffee maker converts the flow of electricity into the flow of *thermal energy*, which it transmits to the water. Note: A pseudo bond graph approach is used here. The true effort and flow variables are temperature and the time rate of change of entropy. However, a more practical pseudo-flow of heat rate is chosen here.

i. *Temperature*. The degree of heat of a body. *Example*: A coffee maker brings the *temperature* of the water to boiling in order to siphon the water from the holding tank to the filter basket.

ii. *Heat rate*. (Note: this is a pseudo-flow.) The time rate of change of heat energy of a body. *Example*: Fins on a motor casing increase the flow *heat rate* from the motor by conduction (through the fin), convection (to the air) and radiation (to the environment).

3 Signal

a. Status
A condition of some system, as in information about the state of the system. *Example*: Automobiles often measure the engine water temperature and send a *status signal* to the driver via a temperature gage.

i. *Auditory*. A condition of some system as displayed by a sound. *Example*: Pilots receive an *auditory signal*, often the words "pull up," when their aircraft reaches a dangerously low altitude.
ii. *Olfactory*. A condition of some system as related by the sense of smell or particulate count. *Example*: Carbon monoxide detectors receive an *olfactory signa*l from the environment and monitor it for high levels of CO.
iii. *Tactile*. A condition of some system as perceived by touch or direct contact. *Example*: A pager delivers a *tactile signal* to its user through vibration.
iv. *Taste*. A condition of some dissolved substance as perceived by the sense of taste. *Example*: In an electric wok, the *taste signal* from the human chef is used to determine when to turn off the wok.
v. *Visual*. A condition of some system as displayed by some image. *Example*: A power screwdriver provides a *visual signal* of its direction through the display of arrows on the switch.

b. Control
A command sent to an instrument or apparatus to regulate a mechanism. *Example*: An airplane pilot sends a *control signal* to the elevators through movement of the yoke. The yoke movement is transformed into an electrical signal, sent through wiring to the elevator, and then transformed back into a physical elevator deflection.

i. *Analog*. A control signal sent by direct, continuous, measurable, variable physical quantities. *Example*: Turning the volume knob on a radio sends an *analog signal* to increase or decrease the sound level.
ii. *Discrete*. A control signal sent by separate, distinct, unrelated or discontinuous quantities. *Example*: A computer sends *discrete signals* to the hard disk controller during read/write operations.

Appendix B: Function definitions
Note that certain functions are limited to operate on certain types of flows. This restriction is typically given in the function definition and applies to all functions at sub-levels of the given function.

1 Branch
To cause a flow (material, energy, signal) to no longer be joined or mixed.

a. Separate
To isolate a flow (material, energy, signal) into distinct components. The separated components are distinct from the flow before separation, as well as each other. *Example*: A glass prism *separates* light into different wavelength components to produce a rainbow.

i. *Divide*. To separate a flow. *Example*: A vending machine divides the solid form of coins into appropriate denominations.
ii. *Extract*. To draw, or forcibly pull out, a flow. *Example*: A vacuum cleaner *extracts* debris from the imported mixture and exports clean air to the environment.
iii. *Remove*. To take away a part of a flow from its prefixed place. *Example*: A sander *removes* small pieces of the wood surface to smooth the wood.

b. Distribute
To cause a flow (material, energy, signal) to break up. The individual bits are similar to each other and the undistributed flow. *Example*: An atomizer *distributes* (or sprays) hair-styling liquids over the head to hold the hair in the desired style.

2 Channel
To cause a flow (material, energy, signal) to move from one location to another location.

a. Import
To bring in a flow (material, energy, signal) from outside the system boundary. *Example*: A physical opening at the top of a blender pitcher *imports* a solid (food) into the system. Also, a handle on the blender pitcher imports a human hand.

b. Export
To send a flow (material, energy, signal) outside the system boundary. *Example*: Pouring blended food out of a standard blender pitcher *exports* liquid from the system. The opening at the top of the blender is a solution to the export sub-function.

c. Transfer
To shift, or convey, a flow (material, energy, signal) from one place to another.

i. *Transport*. To move a material from one place to another. *Example*: A coffee maker *transports* liquid (water) from its reservoir through its heating chamber and then to the filter basket.
ii. *Transmit*. To move an energy from one place to another. *Example*: In a hand-held power sander, the housing of the sander *transmits* human force to the object being sanded.

d. Guide
To direct the course of a flow (material, energy, signal) along a specific path. *Example*: A domestic HVAC system *guides* gas (air) around the house to the correct locations via a set of ducts.

i. *Translate*. To fix the movement of a flow by a device into one linear direction. *Example*: In an assembly line, a conveyor belt *translates* partially completed products from one assembly station to another.
ii. *Rotate*. To fix the movement of a flow by a device around one axis. *Example*: A computer disk drive *rotates* the magnetic disks around an axis so that the head can read data.
iii. *Allow degree of freedom (DOF)*. To control the movement of a flow by a force external to the device into one or more directions. *Example*: To provide easy trunk access and close appropriately, trunk lids need to move along a specific degree of freedom. A four bar linkage *allows a rotational DOF* for the trunk lid.

3 Connect

To bring two or more flows (material, energy, signal) together.

a. Couple

To join or bring together flows (material, energy, signal) such that the members are still distinguishable from each other. *Example*: A standard pencil couples an eraser and a writing shaft. The coupling is performed using a metal sleeve that is crimped to the eraser and the shaft.

i. *Join*. To couple flows together in a predetermined manner. *Example*: A ratchet *joins* a socket on its square shaft interface.
ii. *Link*. To couple flows together by means of an intermediary flow. *Example*: A turnbuckle *links* two ends of a steering cable together.

b. Mix

To combine two flows (material, energy, signal) into a single, uniform homogeneous mass. *Example*: A shaker *mixes* a paint base and its dyes to form a homogeneous liquid.

4 Control magnitude

To alter or govern the size or amplitude of a flow (material, energy, signal).

a. Actuate

To commence the flow of energy, signal, or material in response to an imported control signal. *Example*: A circuit switch *actuates* the flow of electrical energy and turns on a light bulb.

b. Regulate

To adjust the flow of energy, signal, or material in response to a control signal, such as a characteristic of a flow. *Example*: Turning the valves *regulates* the flow rate of the liquid flowing from a faucet.

i. *Increase*. To enlarge a flow in response to a control signal. *Example*: Opening the valve of a faucet further *increases* the flow of water.
ii. *Decrease*. To reduce a flow in response to a control signal. *Example*: Closing the value further *decreases* the flow of propane to the gas grill.

c. Change

To adjust the flow of energy, signal, or material in a predetermined and fixed manner. *Example*: In a hand-held drill, a variable resistor *changes* the electrical energy flow to the motor, thus changing the speed at which the drill turns.

i. *Increment*. To enlarge a flow in a predetermined and fixed manner. *Example*: A magnifying glass *increments* the visual signal (i.e., the print) from a paper document.
ii. *Decrement*. To reduce a flow in a predetermined and fixed manner. *Example*: The gear train of a power screwdriver *decrements* the flow of rotational energy.
iii. *Shape*. To mold or form a flow. *Example*: In the auto industry, large presses *shape* sheet metal into contoured surfaces that become fenders, hoods and trunks.
iv. *Condition*. To render a flow appropriate for the desired use. *Example*: To prevent damage to electrical equipment, a surge protector *conditions* electrical energy by excluding spikes and noise (usually through capacitors) from the energy path.

d. Stop

To cease, or prevent, the transfer of a flow (material, energy, signal). *Example*: A reflective coating on a window *stops* the transmission of UV radiation through a window.

i. *Prevent*. To keep a flow from happening. *Example*: A submerged gate on a dam wall *prevents* water from flowing to the other side.
ii. *Inhibit*. To significantly restrain a flow, though a portion of the flow continues to be transferred. *Example*: The structures of space vehicles *inhibits* the flow of radiation to protect crew and cargo.

5 Convert

To change from one form of a flow (material, energy, signal) to another. For completeness, any type of flow conversion is valid. In practice, conversions such as convert electricity to torque will be more common than convert solid to optical energy. *Example*: An electrical motor *converts* electricity to rotational energy.

6 Provision

To accumulate or provide a material or energy flow.

a. Store

To accumulate a flow. *Example*: A DC electrical battery *stores* the energy in a flashlight.

i. *Contain*. To keep a flow within limits. *Example*: A vacuum bag *contains* debris vacuumed from a house.
ii. *Collect*. To bring a flow together into one place. *Example*: Solar panels *collect* UV sun rays to power small mechanisms.

b. Supply

To provide a flow from storage. *Example*: In a flashlight, the battery *supplies* energy to the bulb.

7
Signal

To provide information on a material, energy, or signal flow as an output signal flow. The information providing flow passes through the function unchanged.

a. Sense

To perceive, or become aware, of a flow. *Example*: An audiocassette machine *senses* if the end of the tape has been reached.

i. *Detect*. To discover information about a flow. *Example*: A gauge on the top of a gas cylinder *detects* proper pressure ranges.
ii. *Measure*. To determine the magnitude of a flow. *Example*: An analog thermostat *measures* temperature through a bimetallic strip.

b. Indicate

To make something known to the user about a flow. *Example*: A small window in the water container of a coffee maker *indicates* the level of water in the machine.

i. *Track*. To observe and record data from a flow. *Example*: By *tracking* the performance of batteries, the low efficiency point can be determined.
ii. *Display*. To reveal something about a flow to the mind or eye. *Example*: The *xyz*-coordinate display on a vertical milling machine *displays* the precise location of the cutting tool.

c. Process

To submit information to a particular treatment or method having a set number of operations or steps. *Example*: A computer *processes* a login request signal before allowing a user access to its facilities.

8
Support

To firmly fix a material into a defined location, or secure an energy or signal into a specific course.

a. Stabilize

To prevent a flow from changing course or location. *Example*: On a typical canister vacuum, the center of gravity is placed at a low elevation to *stabilize* the vacuum when it is pulled by the hose.

b. Secure

To firmly fix a flow path. *Example*: On a bicycling glove, a Velcro strap *secures* the human hand in the correct place.

c. Position

To place a flow (material, energy, signal) into a specific location or orientation. *Example*: The coin slot on a soda machine *positions* the coin to begin the coin evaluation and transportation procedure.

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