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TITLE: Design for Transformation: Theory, Method and Application

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ABSTRACT

Products which transform to reveal new functionality have been a source of fascination and utility for ages. Such products - transformers - have been previously designed employing ad hoc creativity rather than by pursuing any formal design methodology. By incorporating a design methodology and a concept generation tool for transformers, this research not only unearths further utility for these innovative and revolutionary products, but also aids engineers in the design of these devices with dexterity. The success and advantages of transformers result from added functionality while simultaneously using fewer resources and occupying less space. This paper elucidates the foundation of a methodology for the design of such transforming devices. Our basic research on transforming systems involves a combined inductive and deductive approach, uncovering transformation design principles and a novel method for designing transforming products. In the early stages of design, this method employs a unique process to extract customer needs by examining the requirement hierarchy of product usage scenarios. Such an approach broadens the scope of design and aids in identifying opportunities for transforming products while developing process level insights and solutions catering to these needs. During the concept generation phase of design, the method exploits the transformation design principles as a novel tool to complement and expand contemporary concept generation techniques. A unique bicycle accessory which transforms from a lock to a pump and vice versa is provided as an example of the transformational design process.

KEYWORDS: Transformers, Transformation Design Principles; Transformation Design Facilitators; Design for Transformation; Transformation Design Theory; Inductive Research; Deductive Research

1.0 INTRODUCTION

When one is asked about transforming products, what comes to mind may be the mid 80s artistic view of a humanoid robot changing into a land vehicle, air vehicle or dinosaur. Some of these visions of robots were made popular by the television series "Transformers," and their toy counterparts. This concept of a transformer can be a hindrance to the advancement of transformational design, but it does have a first order correlation and exemplifies some essential rules of transformers. Based on our research into transforming systems, we define a transformer as *a system that exhibits a state change in order to facilitate a new functionality or enhance an existing functionality* [1, 2]. A state of a system is defined as *a specific physical configuration in which a system performs a function*. For example the ladder-chair (Fig. 1) has two states: one being

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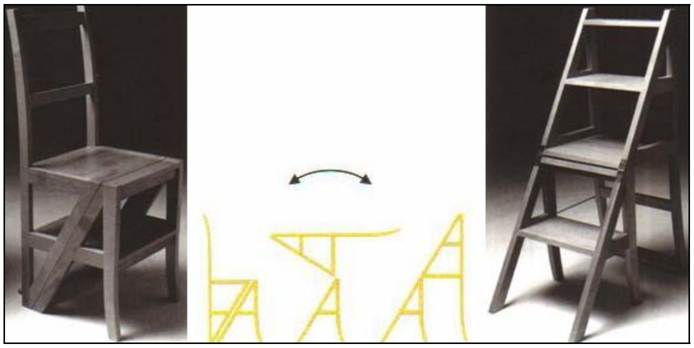
its chair configuration (Fig. 1(a)) and the second state (Fig. 1(c)) is the ladder configuration.



(a) (b) (c)

Figure 1. (a) Chair Configuration; (b) Transformation; (c) Ladder Configuration [3].

Transforming products have a much broader functional repertoire than traditional single state products. Figure 2 is an example of a transforming 6-in-1screwdriver that can change its functionality by changing its head / bit configuration (for example from a “Phillips” head to a straight head). Transformer applications are present in a broad range of product domains from household appliances to applications in unmanned aerial vehicles (UAVs). Figure 3 shows the Switchblade swiveling its wings by approximately sixty degrees before breaking the sound barrier. The claim is that this reconfiguration redistributes shock waves that accumulate in front of a plane at post-mach speeds and induce drag. At sub-sonic speeds, the Switchblade’s wings swivel back so that they are perpendicular to the fuselage like a conventional plane. Work is also being done on transforming or morphing wings [4, 5, 6]; where the wings undergo transformation to provide added functionality into the UAVs such as change in flight characteristics, gust resistant operation, increase in flight time, etc. Transformers can bring advantages through added functionality, use fewer resources, achieve savings in space and time but may also have disadvantages such as more initial time to develop and complexity in their design [1]. It is the role of a transformer design theory to identify when and if transformers should be conceptualized for a given problem, accentuate the advantages, and minimize the disadvantages.

Figure 2. Lock n Load 6-1 screw driver

1.1 Motivation

With an understanding of the potential and impact of transforming devices, we focus on where transformation can be used or proven beneficial. To advance the design process, a basic, consistent method is required to assist in identifying and targeting potential areas for transformation within the design space of a product and in its realm of use. There are, of course, a number of current decision making design tools. However, none of them focus on a strategy to identify potential domains for state change (or transformation) as a solution to needs or requirements of the design [7, 8]. There are various design tools that can be used in different phases of a design process like problem context questions for gathering customer needs [8, 9], quality function deployment (QFD) for identifying important engineering parameters, theory of inventive problem solving (TIPS) [10, 11] to help conceptualize innovative ideas for design conflicts, function structures [12], design structure matrices (DSM) [13] and modular function deployment (MFD) [14] to identify modules in the design of a product and organize product development tasks or teams. These design tools are not specifically suited to address the design of transformers directly. For example they do not explicitly identify different states that could accomplish different functions nor do they even attempt to identify how the system might transform between these different states. These types of questions are the focus of our present work.

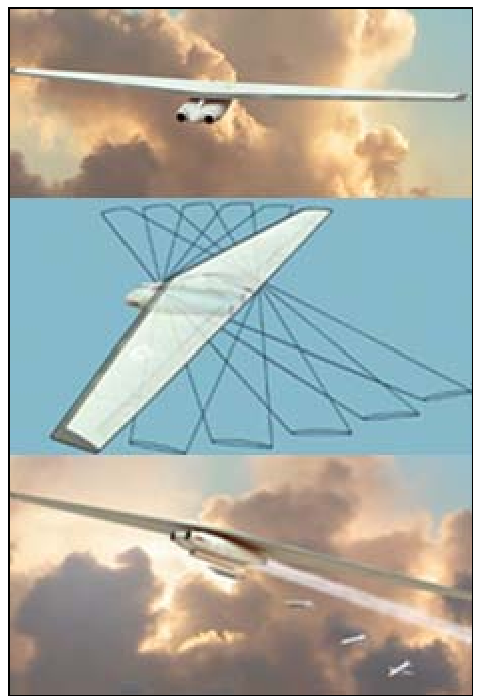


Figure 3. The Unmanned Switchblade Concept under development by Northrop Grumman [4]

The possible design space in the realm of transformers is just beginning to be examined and appreciated. There are examples all around including fixed wing planes that can fly and hover, or structural beams that extend or collapse to new geometries for different purposes. When we consider these examples, there are additional prevalent questions that come to mind. What are the key needs driving the development of such transformers? Why do designers use a singular state for some products or systems, and when should additional states and transformation be considered? The work presented in this paper focuses on understanding and answering these questions by beginning to formulate a detailed methodology for designing such systems. The method outlined in this paper is a work in progress where further research, in the realm of functionality for example, continues to be applied in order to advance the transformational design theory.

2.0 OBJECTIVE

The goal of this paper is primarily to introduce a developing methodology for design engineers to use in the advancement of mechanical transforming devices. The development of a methodological approach for identifying transformations in a device is based on a hierarchical view on system usage scenarios, respective customer needs, and high level solutions relating to the needs.

This paper first evaluates the motivation for this research including a brief description of the research approach, followed by a description of transformational principles and facilitators that are a driving force for this methodology. The paper then moves step-by-step through the current iteration of the method in detail and concludes with an example application.

2.1 Research Approach

The research approach followed a unique combination of an inductive approach and subsequent deductive reasoning to validate the theory [1]. This combined approach, at a high level, is shown in Figure 4. The inductive approach is a bottom-up approach where existing transforming systems, in nature, patents and products, were studied to derive governing transformation design heuristics now termed "transformation principles and facilitators". The deductive approach, which is a top to bottom approach, was then applied to finally categorize these principles and proved to be valuable in creating a method for analyzing product requirements and identifying transformation.

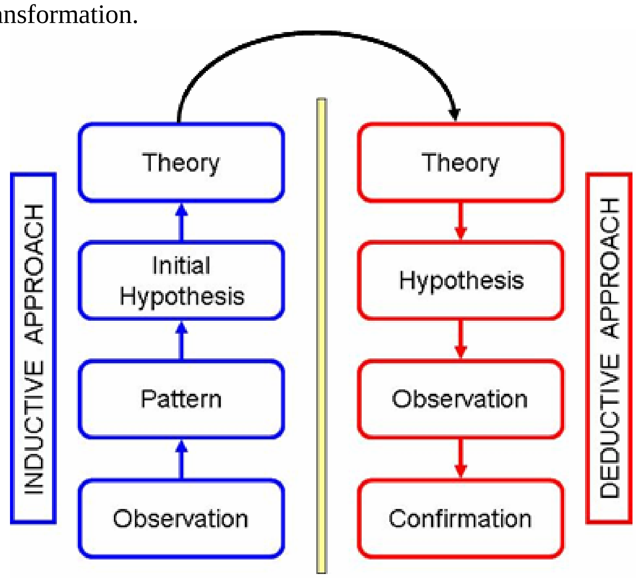


Figure 4. Research Approach – Inductive with Deductive

2.2 Transformation Principles and Facilitators

As a result of our initial research [1, 2, 6, 15] we created a list of governing transformation heuristics. These guidelines help embody transformation in a design. These design guidelines have been categorized and defined as transformation principles and transformation facilitators (see Appendix A).

Transformation Principle

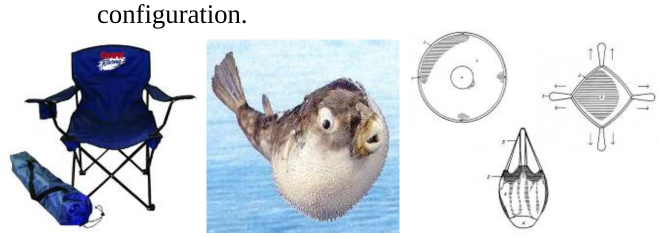
A Transformation Principle is a generalized directive to bring about a certain type of mechanical transformation. A transformation principle is a guideline that, when embodied, singly creates a transformation.

Transformation Facilitators

A Transformation Facilitator is a design architect that helps or aids in creating mechanical transformation. Transformation Facilitators aid in the design for transformation, but their implementation does not create transformation singly.

Through our research approach as described above, three (and only three) fundamental transformation principles, which represent transformation potential in the mechanical domain, are: *"Expand/Collapse"*, *"Expose/Cover"* and *"Fuse/Divide"*. Subordinate to these three principles are the transformation facilitators. The hierarchical relationship between principle and facilitator exists because principles describe what causes transformation while facilitators describe what makes the transformation function correctly. This category was established through the deductive research process involved in our approach. The three transformation principles are described below.

- *Transformation Principle #1: Expand/Collapse – Change physical dimensions of an object to bring about an increase/decrease in occupied volume primarily along an axis, in a plane or in three dimensions.* Collapsible or deployable structures are capable of automatically varying their shape from a compact, packaged configuration to an expanded, operational configuration. In Figure 5: (a) the portable sports chair expands for sitting and collapses for storage or portability; (b) the puffer fish expands its body to ward off and escape predators; and (c) the bag in this patent expands from a towel to a tote bag configuration.



(a) (b) (c)

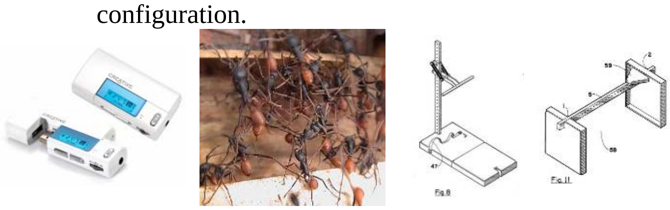
Figure 5. Examples of "EXPAND/COLLAPSE" [16-18]

- *Transformation Principle #2: Expose/Cover – Expose a new surface to alter functionality.* This principle is a directive for changing the surface of a device or its parts so as to alter the primary function of the device. This alteration can be brought about by different types of part-to-part interaction of the device and/or the form of the device itself. In Figure 6: (a) the chair rotates and exposes new surfaces to become a step ladder; (b) the Day-Blooming Water Lily opens during the day to expose its interior, and closes at night; (c) the keyboard in this patent folds out to reveal the operational surface.

(a) (b) (c)

Figure 6. Examples "EXPOSE/COVER" [19–21]

- *Transformation Principle #3: Fuse/Divide - Make single-functional device become two or more devices, at least one of which has its own distinct functionality defined by the state of the transformer, or vice versa.* A functional device divides into two or more parts where at least one of the parts has a distinct primary function. Two or more parts with distinct or similar primary functions can fuse/join to form a new device with a distinct primary function. In Figure 7: (a) the product shown is an audio player which also functions as a USB flash drive or a memory stick. It connects to a power source module making the audio player portable; (b) Army ants join their bodies to form a bridge for the rest of the colony; (c) the patented device shown has its parts divide from functioning as a platform for human interface to form two separate supports for the second exercise equipment configuration.

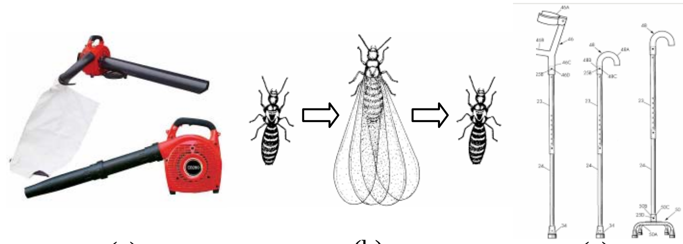


(a) (b) (c)

Figure 7. Examples "FUSE/DIVIDE" [22-24]

While singly embodying a Transformation Principle can create a transforming product, Transformation Facilitators aid in the design of transformers, but their implementation does not create transformation alone. An example of a Transformation Facilitator is *"Common Core Structure"*:

- *Common Core Structure - Compose devices with a core structure that remains the same, while the periphery reconfigures to alter the function of the device.* In essence a reconfigurable device can consist of a core structure that basically is the main support structure that allows for aligning/positioning different peripheral parts or systems. In Figure 8: (a) the leaf blower's working organ shown here remains the same while the usable implements change the device operation from a blower to a vacuum; (b) the reproductive termite begins life as a crawling insect, then grows wings to leave the colony, and sheds its wings to take the roll of king or queen of a new colony; (c) the cane system changes functionality depending on its attachments.



(a) (b) (c)

Figure 8. Examples "COMMON CORE STRUCTURE" [25-27]

2.3 Pilot Results of Transformational Principles and Facilitators

The transformation principles and facilitators aid in the design for mechanical transformation. These guidelines, when embodied, help solve design problems by creating a certain type of transformation thereby acting as a new tool for designers. Using this new tool, a number of transformer concepts were generated and are listed below. These ideas were generated with a blank canvas and the transformational principles and facilitators acting as the sole motivation.

- Water rocket ←→ Squirt gun
- Raincoat ←→ Umbrella
- Hose sprayer ←→ Lawn/garden sprinkler
- Fishing rod handle ←→ Rod stand
- Toaster ←→ Electric griddle ←→Cooking top
- Water-sensitive roof shingles converting to gutters
- Skis ←→ Snowboard
- Hairdryer ←→ Curling iron ←→ Hair straightener
- Headphones → Speaker
- Cooler ←→ Picnic table

These principles and facilitators were also used as design guidelines in a graduate level design course. The students used mind mapping [8] with transformation principles and facilitators to come up with innovative concepts. One such result is shown in Figure 9. With these innovative and unique results, the set of transformational principles and facilitators have been deployed as a design tool, which will be discussed in Section 3.4.1. The principles and facilitators serve as an invaluable tool to generate concepts that harness the potential of transformation in the mechanical domain.

Another question integral to successful design of transforming systems yet lingers – when do we need a transforming system? Transforming systems are time-dependent in that one state and its function cannot be used simultaneously with the other state(s) and function(s). In other words, transformation should not be pursued if both configurations are needed at the same time. Through the inductive approach of studying existing transforming systems and by hypothesizing results of induction, the following indicators hold true in transformational systems. Systems which appear to be "ripe" for implementation as transformers are:

- ❖ Systems needing packaging for portability and deployment
- ❖ Multiple systems allowing consolidation into one system for convenience
- ❖ Multiple systems having dissimilar configurations sharing common material and/or energy flow

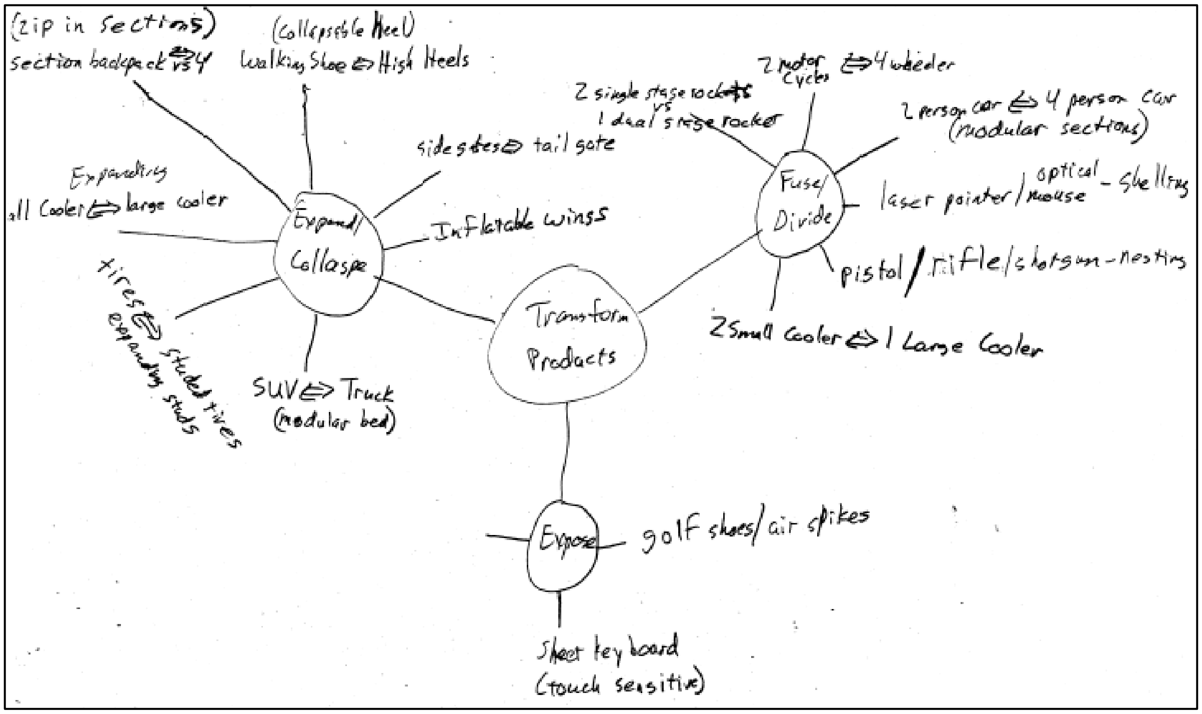


Figure 9. Example Mind Map from Pilot Study with Graduate Student Participants

These indicators give a first indication of when transformation may be beneficial. Current research is being conducted to demonstrate a correlation between the transformation indicators and the functionality of a device. The main point of these indicators is that while the savings in volume, weight, and portability may be the most obvious advantage of transformers, there exist usage situations where a functional metamorphosis is the best candidate solution to a design problem. The indicators are a first step to analytically determine these situations. Although the principles, facilitators and indicators discussed so far provide new understanding for the development of transforming systems, additional detail is needed to guide designers in the pursuit of transformation solutions to their design problems. This additional detail is provided in our Transformational Methodology.

3. TRANSFORMATION METHODOLOGY

Within the context of the guidelines for transformation given above, the desire to incorporate a methodological approach emerges. This section describes such an approach.

3.1 Hierarchical Approach to Design

The conventional approach in defining a problem and gathering needs and requirements has been reconditioned. The hierarchical approach (Fig. 10) explained in this section takes the current problem or need and creates an abstract problem scenario, or a *Generalized Scenario.* From this scenario, predicted or anticipated uses of the system, *Objectives*, are extracted. *Customer Needs* are then gathered from each objective to create a comprehensive list of needs for the *Generalized Scenario.* From this list of needs, high process order solutions are created. These are termed as *Capabilities* and give a first level insight of effective solutions to the needs relating to *Objectives* and to the *Generalized Scenario*. This type of an approach not only helps capture various possible present or future needs during the design of a system but can also help designers at a managerial level decide the outcome of their design by scrutinizing a bigger picture of the problem. The following sections will help explain this hierarchy.

3.1.1 Understanding Generalized Scenario

Generalized Scenario – Abstract statement describing the over-arching extent of the problem. For example, “a system for surveying and defending a large open area” may be used as a generalized scenario. The idea of creating a generalized scenario is to take a step back, analyze a problem and enter the space of possible uses (current or future) of the system being designed. Stating a general scenario in context of a specific usage of the system not only captures that usage but helps in anticipating and predicting other existing or nonexistent uses of the system. This not only helps gather *Objectives* for the system but makes a designer anticipate and think about non-obvious needs and future needs.

3.1.2 Creating Objectives

Objective - An anticipated event or sequence of events projecting the plan or possibilities of use of a system in the context of the generalized scenario. For example "survey pipeline in the desert,” “interrogate prison inmates in specified perimeter,” and “defend designated area of thick foliage” could be objectives for the previously stated generalized scenario. *Objectives* are more specific descriptions of what the system must do, but are not a fully-refined list of *Customer Needs*; they broadly define what the system must do in the context of the *Generalized Scenario.*

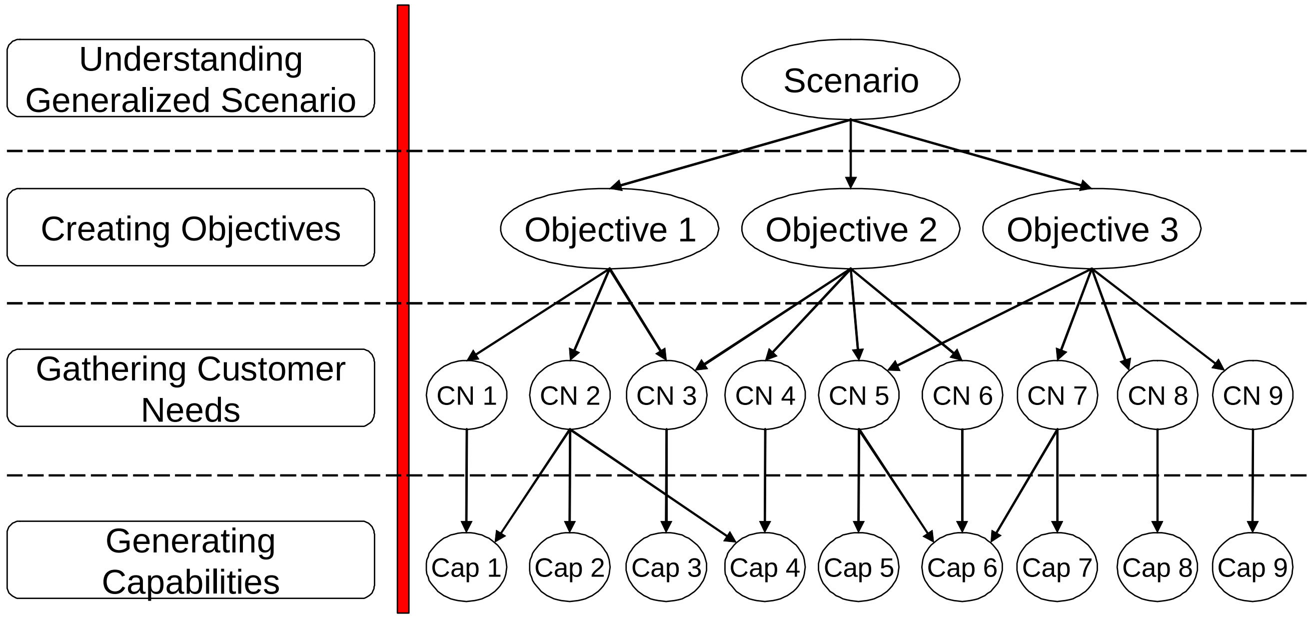


Figure 10. Hierarchical Approach Flowchart

3.1.3 Gathering Customer Needs

Customer need - Requirement of the system stated in the context of an objective. There are general categories in which customer needs can be grouped to understand their differences. For example a need could be "survey area stealthily" or "travel through different weather conditions." By gathering needs for each objective individually, a more comprehensive set of needs is created that now captures most of the needs of the possibilities of the system expressed in the objectives and generalized scenario. The next step is to generate solutions to these needs that are not form-specific, maintaining abstraction. These abstract (not form-specific) solutions (identified as "capabilities" below) aid in developing the widest design space of form-specific solutions in the later stages of the design process.

3.1.4 Generating Capabilities

Capability - A high-order process-oriented task enabling a customer need or set of customer needs. This task is not form or technique specific. For example, given the customer need above "survey area stealthily," a possible capability may be "hover." We can then embody this capability into the system by allowing for the system to hover using gases, rotors, jet engines, magnetic levitation, etc. A single capability may or may not relate to more than one customer need. In this case "hover" does relate to the needs of "survey area stealthily" and "travel through different weather conditions." However a capability like "perch" relates to "survey area stealthily" and not to "travel through different weather conditions," as "perch" isn't catering to the need of traveling.

3.2 State Extraction

The purpose of the product hierarchy is to equip the design engineer with a plethora of information pertaining to the essentials of the design (expressed in the objectives and customer needs) along with general means to satisfy these needs (expressed in the capabilities). Not only does this process force the designer to contemplate the nature of the design problem, this process causes engineers to put their thoughts, insights, and creative avenues into tangible form. The cohesion of this information represents usage knowledge—one of the greatest tools a design engineer can possess.

As with any design problem, the final goal is to provide a quality product that satisfies the comprehensive list of needs expressed by the customer. The first step in materializing a product from the process outlined thus far is state extraction. The development of states directly corresponds to the previously generated set of capabilities. Inasmuch as states spawn from capabilities, a state can also be considered as a specific physical embodiment of a capability. As an example, the capability *fly* has several states, including propeller-driven airplane, jet airplane, helicopter, rocket, ornithopter, and flying saucer.

Rehashing the design process to this point, the engineer has started with a general scenario, from which objectives were created. For each objective, customer needs are gathered, representing the requirements for successful execution of the objective. Next, capabilities stem from the needs as high level process solutions to carry out the respective needs. And from the capabilities, we are now left with states, or more specific and physical forms of a capability. The next step in the transformational design method is to assemble and process all the information we have developed about the design problem to uncover the best possible manner to accomplish the scenario.

3.3 Transformation Route of Design

The steps outlined thus far simply provide a systematic mode of obtaining as much knowledge as possible regarding the design problem. With this in mind, the designer must take a step back and reexamine the big picture.

In an ideal situation, a product satisfies the entirety of objectives and customer needs. However, products rarely accomplish this. It is common, for example, to have conflicting customer needs. In the context of automobiles, for example, customers want high performance ratings yet also high fuel efficiency. While the need for high performance does not necessarily oppose high fuel efficiency, it is actually at the state level where the conflict resides. Elaborating on the automotive example, a high performance automobile usually has a rather large engine supported by a large frame. On the other hand, a fuel efficient car normally contains a smaller engine, and a smaller lighter frame. The results of such conflicts often result in a compromise where neither one of the needs is satisfied holistically but each need is satisfied only partially, yet still sufficiently. The goal of any design engineer, however, is not just to sufficiently satisfy the wants of the customer but to completely and absolutely satisfy the customer.

The ability to solve the totality of customer needs, even the conflicting or contradicting needs, is somewhat of a paradigm shift from conventional design theory. Transformers may provide some new insight and solutions here. The purpose of a transformational product is to be able to execute an objective requiring or dependent upon a certain state and then transform to a different state in order to fulfill a different objective. Referring back to the previously outlined hierarchical breakdown of product usage, the designer should explore transformation when encountering the situation where different objectives requiring independent states are necessary to carry out the general scenario. This heuristic for transformation is general. Its implementation is left to the creativity and subjectivity of the design engineer.

Currently, there is no systematic tool to quantitatively show the relationships between the steps in the transformational design process (Generalized Scenario → Objectives → Customer Needs → Capabilities → States). In a previous publication, we reported some progress in using a "design matrix" approach to describe the relationships between these steps. We are continuing this research and plan to report those results in future publications.

3.4 Concept Generation for Transformation

With the development of a scenario, objectives and customer needs of the design problem to capabilities and state extraction, concept generation techniques discussed in this section help in further embodying transformation. To aid the generation of transforming concepts, we employ the use of transformation design principles and facilitators in the form of cards. While conventional concept generation techniques can assist in the development of a transforming product, the transformation principles and facilitators act as a specialized tool to enable efficient contrivance of transformers. Existing concept generation methods such as mind mapping and brain writing can also be used in conjunction with these principles to generate ideas for transformation. These tools and techniques are discussed below.

3.4.1 Transformation Cards: T-Cards

We have created a set of "T-cards" to be used in the concept generation process. Each card shows one of the transformation principles or facilitators along with examples of how the principle/facilitator is embodied. This deployment brings the design principles and facilitators to the designer in a simple yet creative environment. The transformation cards are 4"x6" and coded with color and geometric shapes (Fig. 11). The color and geometric codes relate a principle to its facilitators. This relationship / taxonomy exist because certain facilitators have been found to aid a certain type of transformation captured by a transformation principle. For example a facilitator as *Shared Power Transmission* does not facilitate the principle *Expand/Collapse* in its embodiment, but it will facilitate the principle embodiment *Fuse/Divide* (Fig. 11).

The transformation cards are used in two primary ways for concept generation. First, the cards can be used in a sequential manner. For example one transformation principle is selected and different combinations of transformation facilitators under that principle are considered to apply a form of transformation. This approach can also be used backwards starting with a facilitator. Using the geometrical and color codes this facilitator is linked to other facilitators, and ultimately linked to a principle to generate a transformation solution. For example consider the problem of storing a Micro Unmanned Aerial Vehicle (MAV). Historically, MAVs were stored in either a disassembled state that required a series of assembly operations or in an assembled state that required a relatively large space. The wing usually requires the greatest storage volume per unit mass of the plane and therefore presents the greatest challenge when attempting to reduce its stored volume. Air Force Research Labs have developed the Tactical MAV (TACMAV) [28] which addresses this problem by building the wings from flexible carbon fiber so that the wings can be rolled into a container for ease of storage and portability. The 50 cm long TACMAV (53 cm wing span) uses *flexible* (*Material Flexibility facilitator)* wings which can be *rolled* (*Roll/Wrap/Coil facilitator*) around its fuselage allowing it to *collapse* (*Expand/Collapse principle*) and be stored in a 13 cm diameter tube carried in a soldier's backpack. When pulled out of the tube, the folded wings automatically snap into place (*Furcation facilitator*). Figure 12 shows how the cards can capture this embodiment.

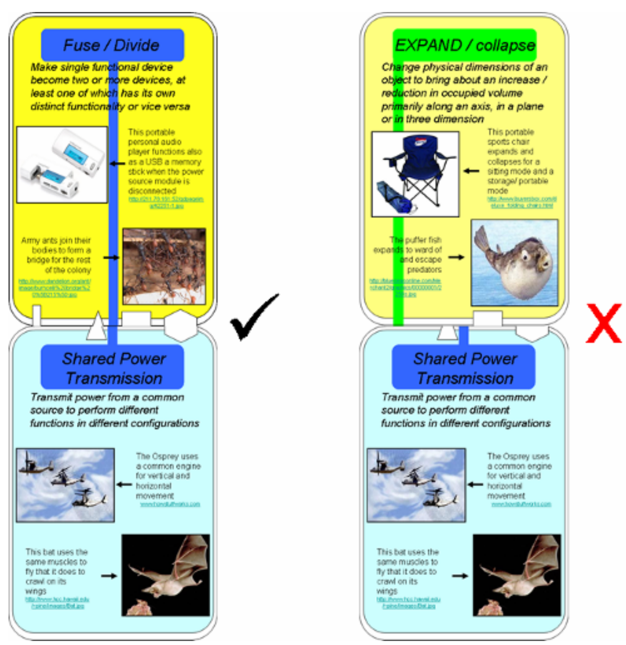


Figure 11. Using the Color and Geometrical Codes in the Transformation Cards

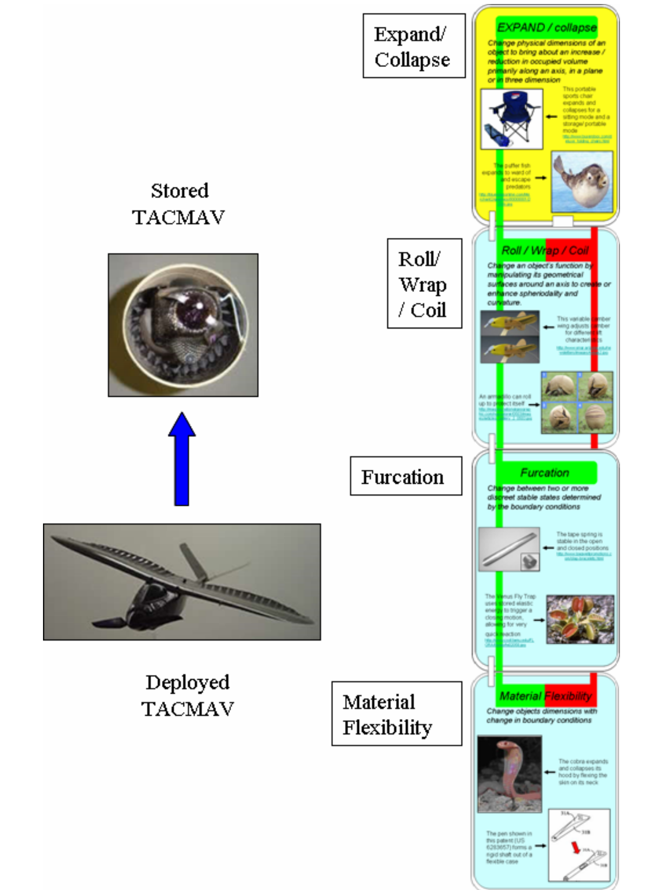


Figure 12. How the T-Cards Capture the Design Embodiment of the TACMAV

3.4.2 Design by Analogy

Another way to use the cards for concept generation is to facilitate design by analogy. Analogy is defined as "a similarity between like features of two things, on which a comparison may be based." Concept generation often involves use of analogy in an implicit fashion. Research shows that a more explicit version of this may be helpful [29]. Very little is known about specifically how analogies should be incorporated into the concept generation process in order to maximize production of innovative solutions. The design principles governing transformation help generate a form-specific solution to the design problem requiring transformation at a systems level. The use of T-cards is one way of using analogies. All the cards are laid out in front of the designer(s) which sparks new ideas by creating an atmosphere of analogies that the designer can pick at random and extract analogous solutions. The designer can randomly select card(s) and then apply the hierarchical approach described above to create more transformation embodiments. Similar to how the transformation principles and facilitators were created (inductive process), analogies can be found in biology: Micro & cellular level, zoology, plant biology, human anatomy and associated mechanics; physics: State changes, quantum mechanics, relativity, classical mechanics; chemistry; current systems: patent searches, consumer products, manufacturing systems and techniques etc.

3.4.3 Mind mapping

Mind mapping is an effective way of recording the results of a brainstorming session as it happens by memory [8]. Mind mapping in this context is used with the transformation principles and facilitators. The three transformation principles act as starting points for generating concepts. The designer creates ideas in these three principle realms using the facilitators.

4. APPLICATION OF THE TRANSFORMATIONAL DESIGN METHOD

In order to demonstrate the effectiveness of the proposed methodology, graduate students applied the technique to develop a cycling accessory. First, the students decided on a general scenario: Take a day-long trip/commute on a bicycle. Then the students developed five objectives based upon the general activity of riding a bike: Secure the bike, perform maintenance, transport cargo, ride in different environments, and carry personal items. The objectives do not directly pertain to the act of riding a bike but are important supporting processes that are common occurrences corresponding to the overall cycling activity.

The second step of the design involved the students generating a comprehensive list of customer needs for each objective. In order to successfully execute the objective to *secure the bike*, the students expressed that the device had to exhibit the following qualities: *Tamper-resistant, weather-resistant, and have quick and easy locking and unlocking procedures*, etc. To successfully complete the objective to *perform maintenance*, the device needed the following traits: *Store tools on bike, know the tire pressure, and exert minimal human effort*, etc. An abundance of needs for each objective were developed but only a portion is provided in this paper. Refer to Figure 13 for a condensed version of the methodology results.

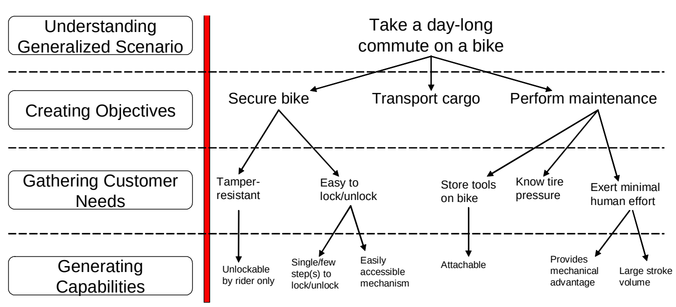


Figure 13. Hierarchical Approach Applied to a Scenario

Subsequent to building a list of customer needs, the graduate students produced capabilities for each need. To effectively generate capabilities, the students contemplated ways to accommodate or solve each need. Another way to describe a capability is a manner to facilitate a particular need. For example, the graduate students listed the capabilities of *single/few step(s) to unlock/lock* and *easily accessible locking mechanism* and others not mentioned here to solve or accommodate the customer need of *lock the bike*. The next step involves analyzing the lists of objectives, customer needs, and capabilities to unveil insights regarding the design.

For this application, the graduate students looked at the totality of information gained from the list of objectives, needs, and capabilities then subjectively chose the most relevant needs and capabilities to determine the objectives most likely to facilitate a transformational design solution. These objectives were *secure bike* and *perform maintenance.*

By considering these two objectives along with the key customer needs and capabilities, they derived two states (a single state per objective). The first state, a U-shaped bike lock, relates to the objective to *secure the bike*. The customer needs of *easy to lock/unlock, tamper-resistant, weather-resistant, stored on bike easily,* and others further directed the concept generation. Lastly, the capabilities of *waterproof, unlockable by rider only, attachable, single/few step(s) to lock/unlock,* and others further guided the students in state visualization. The second state, a hand-actuated air pump, relates to the objective to *perform maintenance*. The customer needs of *store tools on bike, know tire pressure, exert minimal human effort, nozzle should fit valve easily, stores on bike easily,* and others assisted concept generation. Further, the capabilities of *indicate exact pressure, large stroke volume, provides mechanical advantage, flexible nozzle,* and others further directed us in the extraction of this state.

With the two separate states known, the next thought process was to determine whether transformation should be pursued. The two objectives require separate states that are not used simultaneously, hinting that transformation is a promising avenue. Furthermore, this application fits the convenience transformation axiom in that the two systems having individual configurations allow consolidation into one system for convenience. After reaching this key milestone in the transformation design process, we began the detailed concept generation process.

Transformation cards developed for this phase of design were used in two ways to generate concepts. In one concept generation activity design by analogy was used where the principle and facilitator cards were spread out to inspire analogous transformation solutions. Some concepts, as a result of this activity are shown in Figure 14.

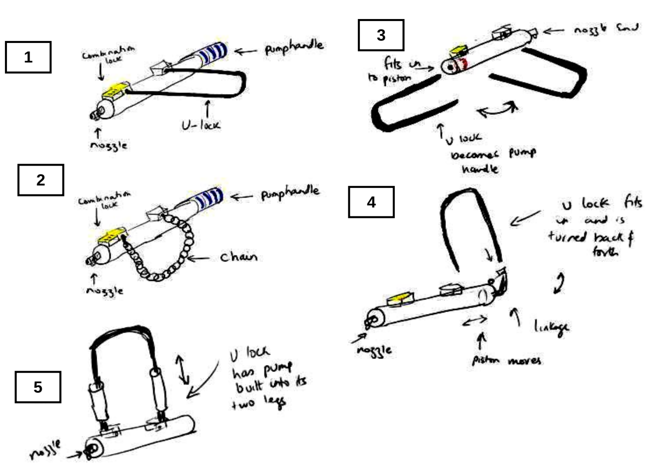


Figure 14. Concepts from Design by Analogy Using Transformation Principles and Facilitators

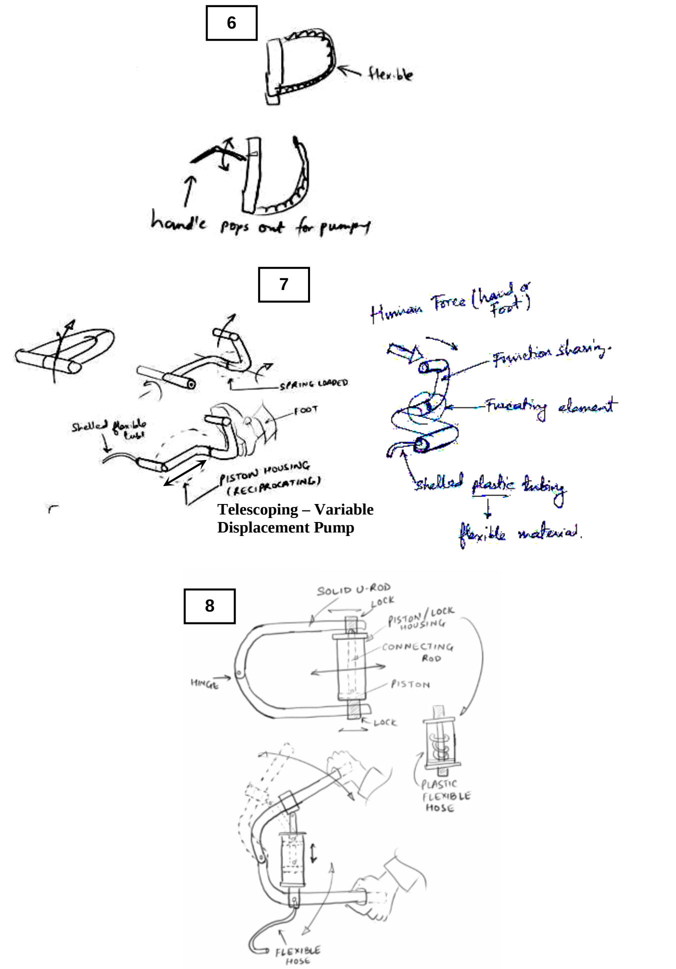
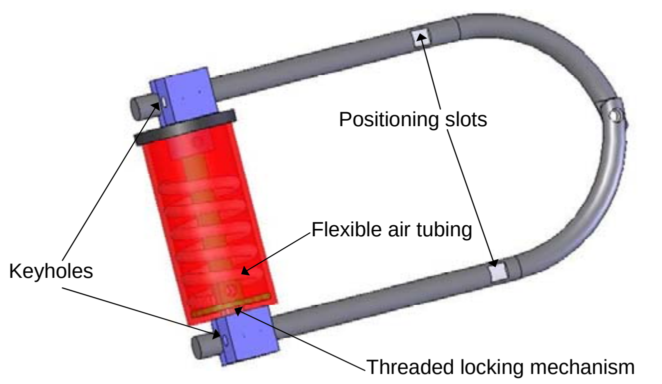


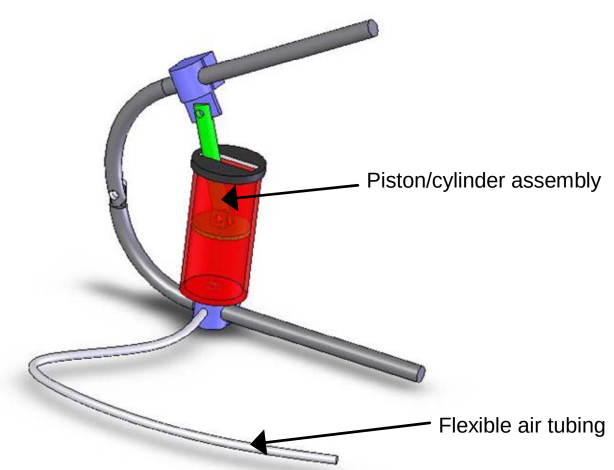
Figure 15. Concepts from Using the T-Cards Activity

A second concept generation activity was carried out where the embedded relationship between principles and facilitators, as dictated by the codes in the T-cards, were used. This activity produced concepts already captured in the design by analogy exercise but also yielded some unique and non-obvious concepts not seen from the previous technique (Fig. 15). Concept 8, which was generated from using the T-Card activity, embodies a simple and novel transformation solution. Although one can argue in favor of the other conceptual designs for simplicity the motive here is to push the envelope of innovation by incorporating transformation. As T-Cards capture a sequential approach in using the transformation principles, where certain facilitators aid different principles to create transformation, the activity provided more insights by generating various combinations of transformation embodiments.

All three principles *Expose/Cover, Fuse/Divide* and *Expand/Collapse* proved to be extremely helpful in generating this concept. A solid model of the transforming bike lock and tire pump is shown in Figure 16. Under the principle of *expand/collapse*, the facilitators *wrap/fold* and *material flexibility* lead to the use of a flexible hose that could be wrapped for storage. Further, it was thought that the wrapped hose could be stored in the device by incorporating the *shelling* facilitator. This facilitator also falls under the *expose/cover* principle. The *expose/cover* principle suggested exposing an unused space in which the hose can be stored in the lock configuration. See Figure 16 for a graphic of the hose in its stored and in-use configurations. The principle of *fuse/divide,* with relation to the *segmentation* and *function sharing* facilitators, aided the students in converting the U-section of the lock into pumping handles and as a means for guiding the reciprocating motion of the pump. An analogy to the way the device is used in its pump configurations is a pair of pruning shears. The location of the pumping mechanism is housed inside the end component that is integrated with the locking mechanism. To develop this idea, the students simultaneously applied the *shelling* and *function sharing* facilitators.



(a)

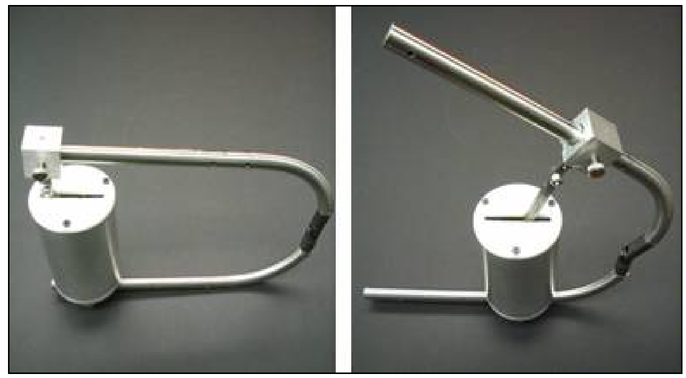


(b)

Figure 16. Solid Model of Transforming (a) Bike Lock and (b) Pump

This device will successfully accomplish the objectives of *secure the bike from theft* and *perform maintenance* by embodying such a design. For example, to accommodate the capabilities of *large stroke volume* and *provide mechanical advantage*, the piston-cylinder assembly is adjustable along the length of the U-section. This allows for variation in stroke volume and also in moment arm length.

The design (Figure 16) was pursued through to the prototyping phase. The first fully-functional prototype (Figure 17) demonstrates the feasibility and manufacturability of the design. For ease of manufacturing, most components were specified to correlate to available common stock sizes. The cylinder was constructed of aluminum tubing. The U-section is constructed of stainless steel rod. The remaining components were constructed of aluminum and steel, besides the piston and top cap, which were created with high density polyethylene and Teflon, respectively. For this prototype, commercial detents secure the chamber assembly in each configuration. The next iteration would involve optimizing the chamber dimensions to fine tune the pressure and volume capabilities, along with further developing the locking mechanism and jointed section for maximum security.



(a) (b)

Figure 17. “Pulock” Alpha Prototype (a) Lock Mode; (b) Pump Mode

5. CONCLUSION

Transforming products have tremendous potential benefit in a wide array of applications. The benefit comes from their ability to change state and facilitate new functionality; all within a single system. This research has developed a theory of transformation encapsulated in a set of transformation principles and facilitators. These form a basis from which a transformational design methodology is developed. The ultimate goal is to have a repeatable method to not only reveal the opportunity for transformational devices but also to deploy the theory and physically embody transforming products that have abilities unparalleled by any other product architecture. This paper presents the developments in the current progression of the transformation design theory by describing a renewed approach for generating and analyzing system usage scenarios, objectives, customer needs, and capabilities. The method provides an avenue for developing transforming systems. The initial stages of the method are followed by concept generation techniques that use the transformation design principles and facilitators.

For such a methodology to be widely accepted and repeatable the framework of the methodology may be refined for consistency, simplicity and accuracy when applied to a wide variety of design problems. The next major area of emphasis lies in device functionality. Further, mathematical tools for transformational analysis, state extraction, and more concept generation tools and techniques are currently being explored. These future improvements will help us to consistently design and embody new innovative products using transformational solutions.

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Appendix A

Principles	Expand/Collapse	Change physical dimensions of an object to bring about an increase/decrease in occupied volume primarily along an axis, in a plane or in three dimensions
	Expose/Cover	Expose/Cover a new surface to alter functionality
	Fuse/Divide	Make single functional device become two or more devices, at least one of which has its own distinct functionality defined by the state of the transformer or vice versa
Facilitators	Common core structure	Compose devices with a core structure that remains the same, while the periphery reconfigures to alter the function of the device
	Composite	Form a single part with distinct functionality from two or more non functional parts
	Conform with Structural Interfaces	Statically or dynamically constrain the motion of a component using structural interfaces
	Enclosure	Manipulate object in two or three dimensions in order to enclose a three dimensional space
	Flip	Perform separate functions based on orientation of the object
	Function Sharing	Perform two or more discrete functions
	Furcation	Change between two or more discrete stable states determined by boundary conditions
	Generic Connections	Employ internal or external connections (structural, power) that can be used by different modules to perform different functions or perform the same function in a different way
	Interchangeable transmissions	Use multiple transmissions to produce different motions
	Material Flexibility	Change object dimensions with change in boundary conditions
	Modularity	Localize related functions utilizing common signal, material, and force flows into subsystems (modules) which are easily integrated into the device and may be interchangeable
	Nesting	Place an object inside another object wholly or partially wherein the internal geometry of the containing object is similar to the external geometry of the contained object
	Segmentation	Divide single contiguous part into two or more parts
	Shared Power Transmission	Transmit power from a common source to perform different functions in different configurations
	Shelling	Embed functional element in a device which performs a different function