Evidence-based design heuristics for idea generation

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How do product designers create multiple concepts to consider? To address this question, we combine evidence from four empirical studies of design process and outcomes, including award-winning products, multiple concepts for a project by an experienced industrial designer, and concept sets from 48 industrial and engineering designers for a single design problem. This compilation of over 3450 design process outcomes is analyzed to extract concept variations evident across design problems and solutions. The resulting set of patterns, in the form of 77 Design Heuristics, catalog how designers appear to introduce intentional variation into conceptual product designs. These heuristics provide 'cognitive shortcuts' that can help designers generate more, and more varied, candidate concepts to consider in the early phases of design.

Keywords: creativity, conceptual design, design cognition, design tools, innovation

How do designers successfully create novel product concepts? One suggested approach is to first generate a wide range of concepts to consider (Cross, 1994; Liu, Bligh, & Chakrabarti, 2003). This requires the ability to create a large number of concepts that differ from each other so that the set of concepts covers the space of possible designs (Gero, 1990; Goel & Pirolli, 1992; MacLean, Young, Bellotti, & Moran, 1991; Simon, 1981). Logically, the idea generation process benefits from considering as many different concepts as possible (Akin & Lin, 1995; Atman, Chimka, Bursic, & Nachtman, 1999; Brophy, 2001; Liu et al., 2003). However, generating a diverse set of concepts can be challenging because designers tend to fixate on specific design specifications, which leads them to generate more concepts with similar features (Purcell & Gero, 1996; Sio, Kotovsky, & Cagan, 2015). For example, Jansson and Smith (1991) observed designers replicating similar solutions to concepts provided as examples, and even including their flaws. Across studies, designers appear to consider only a small set of related concepts when generating ideas (Ball, Evans, & Dennis, 1994; Chrysikou & Weisberg, 2005; Dong & Sarkar, 2011; Linsey et al., 2010;

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Purcell & Gero, 1996; Sio et al., 2015; Smith, 1998; Viswanathan & Linsey, 2013; Youmans & Arciszewski, 2014).

A number of approaches for facilitating idea generation during the early phases of conceptual design have been proposed (c.f. Clapham, 1997; Shah, Hernandez, & Smith, 2002; Smith, 1998). One approach distills knowledge about specific designs into an intermediate-level knowledge base by constructing composites from multiple examples. In Alexander's *pattern language* (Alexander, Ishikawa, & Silverstein, 1977), and Krippendorf's *design discourses* (2005), patterns common in successful design solutions are identified at a component level, linking the designer to a broad range of helpful guidance from past solutions in a refined form (Alexander et al., 1977). This composite knowledge about design has been referred to as *heuristic* knowledge (Fu, Yang, & Wood, 2015). Heuristics are described as 'mental shortcuts' that capture cognitive strategies that may lead to solutions (though not necessarily the best one) (Nisbett & Ross, 1980), and are ubiquitous in human reasoning (Goldstein et al., 2001). Heuristics capture important features of problem situations and solutions that tend to reoccur in experiences (Clancey, 1985).

In software design, Riel (1996) has described the heuristic approach as 'specific experience-based guidelines' that help developers make good decisions. Lawson (1979) observed architectural students solving puzzles through 'trial and error' heuristic approaches. Lawson (1980) concludes, 'An examination of protocols obtained from such closely observed design sessions reveal that most designers adopt strategies which are heuristic in nature… Heuristic strategies do not so much rely upon theoretical first principles as on experience and rules of thumb' (p. 132). When generating new concepts, designers appear at times to offer intuitive responses derived from 'large pools of experience' (Cross, 2011, p. 10) to make a 'best guess' at a new design. Consider the example in Figure 1, a desk chair that reclines to allow the user to lie beneath (rather than in front of) a computer screen.

In comparing this novel design to prototypical chairs, it is evident that the designer changed the user's direction of access. By moving the access point from in front of the screen to below it, an innovative design results. Further, this strategy, 'change direction of access,' may be a useful heuristic to apply in generating designs for other products. For example, applying the 'change direction of access' heuristic to a trackball controller may suggest side rather than top access, and accommodate thumb control rather than palm movements (see Figure 2). Design heuristics like this one may help designers create more, and more diverse, concepts, thereby increasing the likelihood that an innovative concept will result. Understanding how cognitive processes can be stimulated to generate design ideas may lead to more effective methods and tools to support conceptual design (Jin & Benami, 2010).

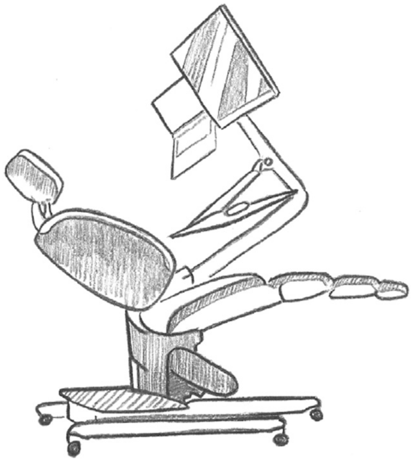


Figure 1 A design released by Altwork (http://altwork.com) positions the user under the workstation

In this paper, we examine evidence for design heuristics in the creation of multiple design concepts. First, we summarize prior research where design heuristics were derived from evidence in the field of product design, including approaches based on analysis of existing products and patents (e.g., Altshuller, 1984; Skiles et al., 2006). Next, we compile results across four research studies to identify a distinct set of heuristics evident in a diverse sample of design solutions. These solutions include an analysis of award-winning products created by many different designers. Uniquely, the present analysis examines design concepts from a professional designer working on a single design problem. In addition, two think-aloud protocol studies of industrial and engineering designers working on a novel design problem are included. These samples add value because they include multiple concepts generated for the same design problem. By considering alternative concepts, it is possible to observe how heuristics are used in the idea generation process, and how they facilitate exploring the space of concepts for a design problem. Compiling patterns observed across varied products, design tasks, and design processes, we identify a new set of 77 design heuristics. Each heuristic is presented with a written description and an example of its application in an existing consumer product. Finally, we discuss issues of the granularity of heuristic descriptions, and the use of heuristics as a concept generation tool for product designers.

1 Heuristics in product design

How can we identify possible heuristics used in product design? Heuristics are learned from experience within a domain, and tend to be implicit and difficult to verbalize (Nisbett & Ross, 1980). The use of heuristics without conscious access has been documented in studies of experts including firefighters (Klein, 1993), scientists (Baker & Dunbar, 2000) and designers (Yilmaz & Seifert, 2011). However, this tacit knowledge about how to create designs

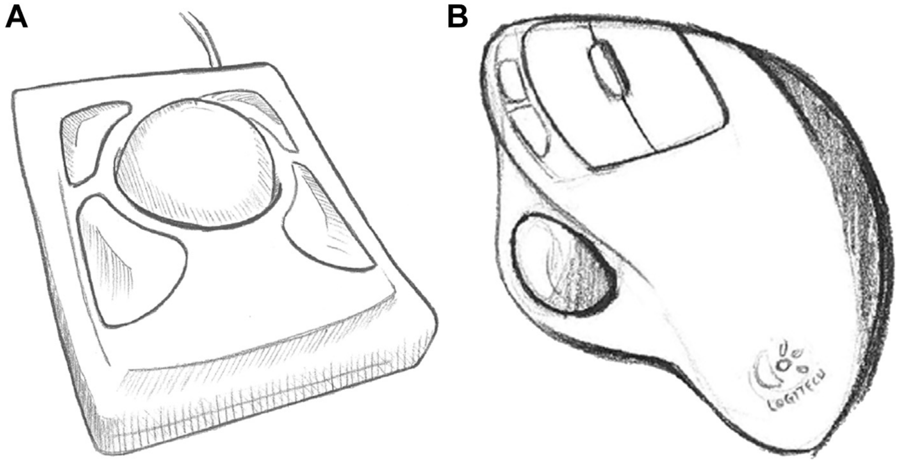


Figure 2 The original version of the Kensington Expert Mouse (www.kensington.com) used a center ball as a trackball, while the newer design by Logitech (www.logitech.com) positions the ball on the right side, under the thumb

may be observable by comparing designers' proposed solutions (Matthews, Wallace, & Blessing, 2000; Yilmaz, Seifert, Daly, & Gonzalez, 2016). Several existing heuristic approaches to idea generation have drawn conclusions based on empirical studies of product concepts (Perez, Linsey, Tsenn, & Glier, 2011) and design patents (Altshuller, 1984).

The theory of 'inventive problem solving' (known as TIPS or TRIZ) (Altshuller, 1984) involved identifying heuristics from successful patents in engineering. The TRIZ analysis focuses on identifying technical contradictions in mechanical engineering designs. For example, Ogot & Okudan (2007) describe a design tradeoff when 'increasing the stiffness of an airplane's wings to reduce vibration during flight (good) increases the weight of the plane (bad)' (p. 111). Altshuller (1984) analyzed thousands of engineering patents and abstracted forty principles, and noted that certain contradictions lend themselves to particular solutions. These were compiled into a contradiction matrix of system features (e.g., speed, weight, measurement accuracy) crossed with typical undesired results to index relevant design principles (Altshuller & Rodman, 1999; Altshuller, 1997, 2005; Orloff, 2003; Savransky, 2000). However, because TRIZ analysis requires the identification of technical tradeoffs first, it is most helpful for designs developed to the point of specific commitments to materials and mechanisms.

Learning to use the TRIZ system requires extensive training, effort and commitment (Ilevbare, Probert, & Phaal, 2013). The terminology and modeling methods are unique to TRIZ, and differ from those found in engineering design (Smith, 2003). However, in a classroom study with first-year engineering students, Ogot and Okudan (2007) trained teams of 4 students to use

TRIZ to generate concepts while other teams used traditional idea generation methods. They found that teams using the TRIZ method produced more unique solutions compared to other teams, along with more feasible concepts. This was replicated in another engineering classroom study where the TRIZ method was found to result in more novelty compared to sketch methods. In a third classroom study, engineering students using TRIZ improved the novelty and variety of concepts generated (Hernandez, Schmidt, & Okudan, 2013; Hernandez, Schmidt, Kremer, & Lin, 2014). Finally, an experimental study with graduate student and professional engineer teams found that TRIZ improved the novelty of solutions with only a ten minute training session (Chulvi, Gonzalez-Cruz, Mulet, & Aguilar-Zambrano, 2013).

Another approach to identifying design heuristics has examined existing products that 'transform,' or change into different configurations or states for use (Skiles et al., 2006). For example, a wooden chair may be designed to transform into a stepladder. Transformer products address each function set independently and at different times, while moving smoothly between states as needed (Weaver, Wood, Crawford, & Jensen, 2010). Based on analyses of 85 past patents, 40 analogies from nature, and 100 existing multistate products, three transformation design principles were extracted (*expand/collapse, expose/cover*, and *fuse/divide*) (Singh et al., 2007, 2009; Skiles et al., 2006; Weaver et al., 2008, 2010). A fourth principle, *reorientation*, was proposed in a later study (Haldaman & Parkinson, 2010). In addition, twenty subordinate 'facilitators' were extracted to support these principles. Example facilitators include using 'generic connections' to allow different modules to perform different functions; 'segmentation,' or dividing a single contiguous part into two or more parts; and 'fold,' or create relative motion between parts or surfaces by hinging, bending, or creasing. A study of engineering students found that encouraging the use of transformation principles and facilitators resulted in the generation of 25% more concepts (Weaver et al., 2009).

Several other studies have analyzed product designs to derive heuristics for idea generation. One study examined 197 award-winning innovative products, and organized the identified design features into categories (Saunders, Seepersad, & Hölttä-Otto, 2011). The thirteen 'innovation characteristics' identified in this analysis include 'additional function,' 'modified size,' 'expanded usage environment,' and 'user interactions.' Another study identified 'consumer variation' heuristics for designing for user differences (Cormier, Literman, & Lewis, 2011). Through an analysis of 31 product lines with 645 product models, 20 heuristics are identified and categorized into function, form, and information and control groups. Examples include, *Utilize (re)configurability when the product architecture is specific to handedness*, *Use system (re)configurability facilitated by modules when desired functionality is decoupled*, and *Utilize materials which have built-in flexibility for aesthetic modification*. Finally, a study of 46 bio-inspired products and systems resulted in six 'scaling principles:' *change energy source, simplify system, change method, combine functions, directly transfer components*, and *change parameters* (Perez et al., 2011).

In these different approaches, various design heuristics were identified based on the design evidence considered. These approaches differ in the observed designs, with a focus on transforming (dual function) products in Weaver et al. (2010), award-winning innovative products in Saunders et al. (2011), consumer variation product lines in Cormier et al. (2011), and products at varied scales (in Perez et al., 2011). TRIZ (Altshuller, 2005) stands out for the large number of patents analyzed. However, in all of these approaches, only a final 'winning' concept is considered. The present study also includes a large sample of designs for award-winning consumer products. But uniquely, the present study adds samples of multiple candidate concepts generated by designers for a single design problem. The opportunity to observe the set of candidate concepts generated by a designer for a given problem provides a richer sample of variations among concepts than is captured by final product designs. Observations from a long-term design project by a very experienced designer added hundreds of concepts for a single design problem. The observation of idea generation sessions (rather than solely the 'winning,' final product) provides more evidence about how designers introduce variations in their concept sets through what Lawson (2012) calls 'knowing by doing.' By consolidating results across four empirical studies of concept generation, with varied contexts and more concepts sampled, we hoped to detect a broad array of design heuristics.

2 Method

For the present study, we compiled a larger database from four prior empirical studies (described in Table 1). The goal was to create a larger, rich dataset of design concepts from three different contexts, multiple design problems and multiple designers. The four studies included diverse datasets: (1) award-winning products from a wide range of consumer domains, (2) an expert industrial designer's sequential concept sketches from a two-year solo design project, and (3) a protocol study of engineering designers where student and practicing designers' think-aloud protocols were recorded as they worked on a novel product design task. A fourth study (4) replicated the think-aloud protocol study with industrial designers in order to compare concepts from the two design disciplines.

The process for extracting a design heuristic from award-winning product was as follows: For observed design concepts, major elements and key features of each concept were analyzed for functionality, form, and user-interaction features. A content analysis of the needs, design criteria, functions, and the design solution was performed for each concept. Then, potential heuristics were

Table 1 Separate empirical studies of design concepts included in the cumulative database

Study	*Research question*	*Data collection*	*Source*
Study 1. *Product Analysis*	What are the strategies that successful designers use to create novel products?	400 award-winning products from a diverse range of design domains.	Yilmaz, Seifert et al. (2016).
Study 2. *Case Study*	How does an experienced designer add variation to concepts within a single long-term design problem?	218 sequential concepts created by an expert industrial designer over two years for a single design project (a universal access bath within an existing home).	Yilmaz and Seifert (2011).
Study 3. *Protocol Analysis*	How do different designers create concepts within a single novel design task?	Think-aloud protocols from 36 engineers at varying levels of expertise as they designed a novel product (a portable solar oven) in a 25-min session, with a total of 179 concepts generated.	Daly, Yilmaz et al. (2012).
Study 4. *Protocol Analysis*	How does Design Heuristic use differ among designers from different design disciplines?	Think-aloud protocols from 12 industrial designers at varying levels of expertise working with the problem (in Study 3) for a total of 68 concepts generated.	Yilmaz, Daly et al. (2015).

hypothesized and design criteria for their application were identified. Other concepts in the dataset with the same design features were compared in order to explore commonalities in candidate heuristics. Finally, a heuristic would be defined at a level of generality that applied to multiple products, but was still specific to the observed design solution. For example, one heuristic was described as the ‘hollowing out’ of material, such as a brush handle with its mass reduced by using a hollow cylinder for a handle. This kept the heuristic’s description as close as possible to the observed concepts; for example, different heuristics captured reducing material through flattening or folding. This extraction approach catalogs more specific innovations while ensuring the heuristics are general enough to fit several different observed concepts. Singh and colleagues (2009) describe a similar extraction method in their analysis of transforming products.

The product images in Figure 3 illustrate the process of extracting a heuristic from two of the 400 award-winning products included in the study. The first image shows a new product — a paint roller — where a commonly used mechanism in ballpoint pens (the ink storage and roller) is *applied in a new context* to solve the problem of delivering wall paint touchups. This heuristic also appears in the second image as a brush repurposed as a desk organizer design. The heuristics extracted identify independent components of the design, and are not exhaustive, such that other features of these designs might serve to identify other possible heuristics. In the first image, a second heuristic is also observable; namely, *Synthesize Functions*, where both paint storage and applicator are combined in the design. In this way, observed concepts sometimes provided evidence of multiple heuristics.

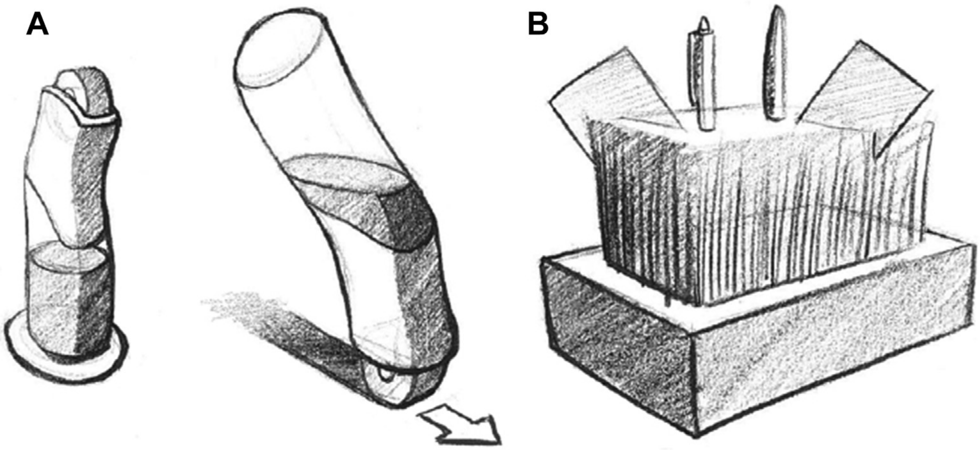


Figure 3 Example designs exhibiting the design heuristic, Apply existing mechanism in new way. *On the left, the Rubbermaid Paint Buddy is a touch-up paint roller with onboard paint storage with a mechanism similar to ballpoint pens (http://www.idsa.org/awards/idea/computer-equipment/rubbermaid-paint-buddy). On the right, a desk organizer for pens and cards makes use of brush bristles to catch and hold these objects (http://ideasmodern.com/ideas/playful-pencil-organizer-pratonzolo/)*

This extraction method for identifying design heuristics in existing products was applied to the design concepts in the remaining three studies (Daly, Christian, Yilmaz, Seifert, & Gonzalez, 2012; Daly, Yilmaz, Christian, Seifert, & Gonzalez, 2012; Yilmaz & Seifert, 2011; Yilmaz, Seifert et al., 2016). Study 2 provided 218 concepts created by a single, very experienced industrial designer over a two-year period (Yilmaz & Seifert, 2011). The design problem was to create a universal access bathroom to be installed in private homes. The designer worked on a large paper scroll to preserve his concepts as they were created. By examining sequential concepts, transitions between candidate concepts were evident. Across this set of designs, we observed that the same specific heuristics appeared repeatedly in this designer's work. For example, one heuristic addressed a change in how the functions of the product were controlled. In this example concept, the designer arranged components around the same central structure (a plumbing tube) (see Figure 4). This strategy was then observed in other designs, leading to a proposed heuristic, *Align components around the center*. This concept also suggests other heuristics, *allowing the user to reorient* the product according to their height, and *repeat* design elements.

The concepts collected from Studies 3 and 4 involved a 'think aloud' protocol (Dorst & Cross, 2001; Ericsson & Simon, 1993) of engineering and industrial designers' process while creating solutions for a novel product problem (the design of a solar oven for use in an outdoor setting). Forty-eight designers generated 247 different concepts for this single design problem. For example, one of the designers generated a concept for a portable backpack container that allowed cooking using sunlight (see Figure 5).

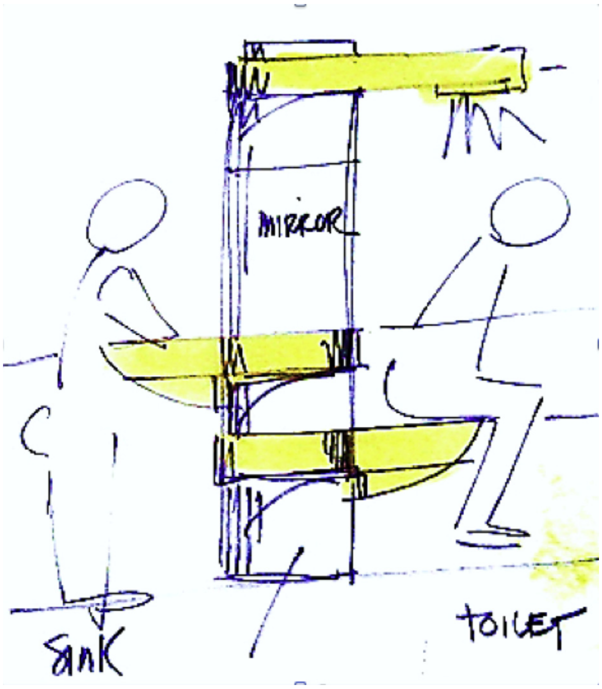


Figure 4 Example concept combining the heuristics Align components around center, Allow user to reorient, *and* Repeat. *(Courtesy of Allen Samuels, Industrial Designer.)*

Next, three independent coders with advanced degrees (one with an M.F.A. in industrial design, one with a Ph.D. in engineering education, and one a senior student in mechanical engineering) worked as a team to examine each concept in the collected database. The coders considered each concept both individually and in its concept set sequence for evidence of heuristic use. The three coders worked collaboratively to refine heuristic definitions, and all decisions about identified heuristics were argued to consensus. Because the coders worked as a team during the extensive analysis, no measure of reliability was possible. The collaborative identification of heuristic use across these observed concepts occurred over a period of six weeks.

3 *Results*

The analysis of this combined sample of 3457 products and design concepts across four empirical studies resulted in the observation of 77 distinct design heuristics. Each of the identified heuristics was observed in at least four different concepts across the sample datasets. These heuristics addressed design goals such as adding functionality, using fewer resources, saving space, providing visual consistency, and forming new relationships among design elements. The 77 Design Heuristics are shown in Figure 6. This set of 77 Design Heuristics includes only those necessary to account for the data in these four studies. Each Design Heuristic is described, and illustrated with a commercial product where the heuristic is evident.

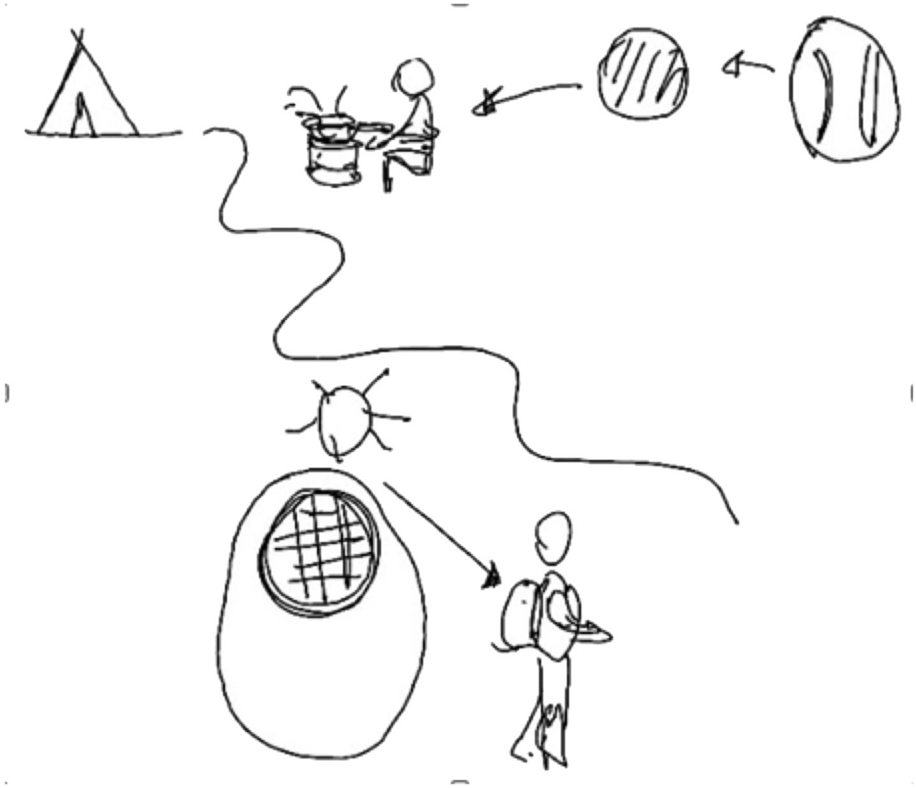
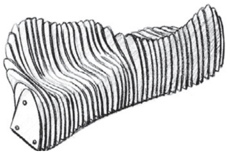


Figure 5 A concept for a solar oven generated by a designer using an Attach product to user *heuristic, along with an* Add functions *heuristic. The industrial designer described a context in which the user was a hiker, and designed an integrated backpack with a heating element and pot attached to it. This would allow the user to warm food throughout the day while traveling*

The observations supporting this set of 77 Design Heuristics (capitalized when referring to heuristics from this set) are shown in Table 2. An important feature of this compilation of heuristics across studies is that each heuristic was observed multiple times (at least four) in different products and product concepts, and all were observed in solutions from more than one designer. The sole exception is *expose interior*, which was observed only one concept (in Study 4) but included because it is well known (e.g., watches or clocks) and may facilitate the goal of considering a variety of candidate concepts.

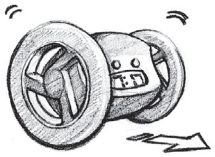
Only seven heuristics were observed in just one of the four studies. The frequency of observation for each heuristic in the compiled dataset ranged from 4 to 274, indicating high variation in frequency of use. Only 12% of the observed instances of Design Heuristic use occurred in Study 1 (product analysis), but over half of the Design Heuristics (39) were observed in that particular study. Across the four studies (analyzed sequentially), the number of new heuristics identified decreased from 39 to 25 to 5 to 1. Even though the design problem and setting changed with each study, a great number of

ADD LEVELS 1
Identify different levels of the product's function, and add a series of gradual changes to the design elements to facilitate those levels. This can increase functional options and unify form relationships.



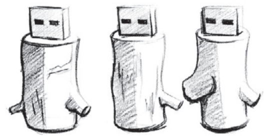
TOPOGRAFI
Jonas Wannfors
This bench provides a variety of seat shapes achieve through gradual changes of an initial form.

ADD MOTION 2
Add motion as part of the product's function. This can improve function, change user interaction, or add playfulness.



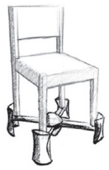
CLOCKY
Nanda Home Inc.
This alarm clock can jump off a table and roll along the floor while ringing.

ADD NATURAL FEATURES 3
Explore relationships between the product and nature. This can help achieve the product's function or improve aesthetics.



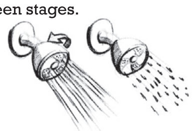
WOODEN MEMORY STICKS
Oooms
These USB flash memory sticks are encased in handpicked branches.

ADD TO EXISTING PRODUCT 4
Use an existing item as part of the product's function. Consider physically attaching components, creating a system, or defining relationships between objects. This can reduce material and cost, or improve efficiency.



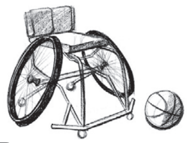
KABOOST
Kaboost Corp.
This product attaches to any dining chair to turn it into a high chair for children. Using spring-loaded arms, it can securely hold any size chair.

ADJUST FUNCTION THROUGH MOVEMENT 5
Allow the user to adjust stages or degrees of function by moving the product or its parts. Consider applying different types of motion and control mechanisms. This can give flexibility to the user through the transitions created between stages.



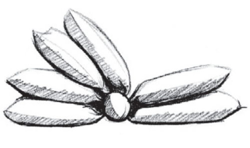
ORIGINAL SHOWER MASSAGE
Waterpik
This shower head has four different modes to alter the way the water is released. The user switches through modes by rotating the head.

ADJUST FUNCTIONS FOR SPECIFIC USERS 6
Design the functions of the product with target user characteristics in mind (e.g., age, gender, education, occupancy, ability). This can improve product performance, and increase comfort and safety.



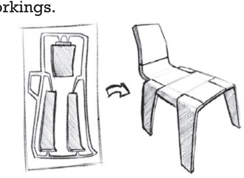
TOP END
Paul Schulte
This wheelchair is designed for handicapped basketball players. It has few fasteners (which can loosen), and minimal weight for speed.

ALIGN COMPONENTS AROUND CENTER 7
Create a central component and arrange other components around it. This can unify the product's functions and appearance.



MANDACARU FLIP OVER
Baba Vacaro
This lounge chair is made of multiple cushions that can rotate around a central cushion, allowing the user to choose the seating angle.

ALLOW USER TO ASSEMBLE 8
Make the user part of product creation by providing individual parts for assembly. This can decrease shipping costs and help users understand the product's inner workings.



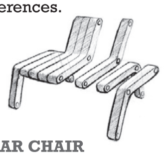
KIT
Arik Grinberg
After purchase, the user assembles this chair by snapping the pieces out of the frames and attaching them together through snap joints.

ALLOW USER TO CUSTOMIZE 9
Give the user customizable options to best fit their needs and preferences. The final product is developed for each user based on their choices. This can provide the user with a sense of ownership and functional awareness.

CONTESSA
Giugiaro Design
This chair offers customizable options such as an attachable headrest and different seat and back materials.

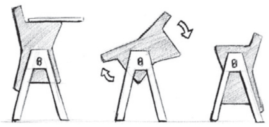
Figure 6 The 77 Design Heuristics identified across four studies of award-winning product designs, a solo professional design project, and protocol studies of engineers and industrial designers working on a novel problem. Each is illustrated with a description and an example consumer product where the Design Heuristic is evident. (Courtesy of Design Heuristics, Inc.)

ALLOW USER TO REARRANGE 10
Define form relationships among components to make various arrangements possible through reconfiguration of connected, separate, or detachable pieces. This can allow the user to change the arrangement of components to suit changing needs and preferences.



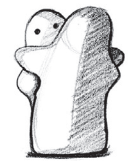
MODULAR CHAIR
Takumi Yoshida
This seat is made of a one-piece component that can rearranged and snapped together to form either a chair or bench.

ALLOW USER TO REORIENT 11
Allow the user to flip the whole product or its parts vertically or horizontally. This can create different orientations that can perform different functions.



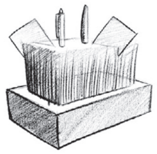
HI LO KIDS CHAIR
Age Design
This product provides three seating options. By turning the chair seat upside down, a baby seat becomes a toddler seat, or at an angle, a recliner.

ANIMATE 12
Give lifelike qualities to the product by replicating human or animal features and gestural forms. This can make the product more approachable and recognizable, or convey emotion.



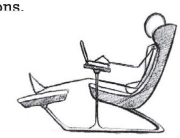
HUG
Alberto Mantilla
These shakers abstract human figures to suggest a "hug."

APPLY EXISTING MECHANISM IN NEW WAY 13
Consider whether existing products or their components can fulfill the desired function. This can facilitate reuse of existing products, make the design process more efficient, and expand the pool of options.



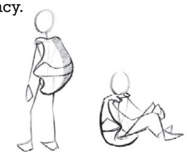
PRATONZOLO
Max Battaglia
This desk organizer uses brush bristles to hold pens, pencils, and business cards.

ATTACH INDEPENDENT FUNCTIONAL COMPONENTS 14
Identify different parts or systems with distinct functions, assign form to each, and add a connection between them. This can increase product efficiency, reduce material, facilitate compactness, and unite separate functions.



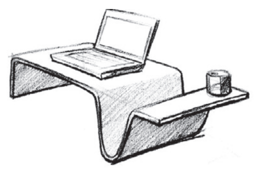
DAYBED
Manuel Saez
This workchair has a footrest and laptop desk attached to the seat, allowing the user to do office work in an ergonomic position.

ATTACH PRODUCT TO USER 15
Design the product around the user by attaching it to the user's body, and redefine how the function is achieved. Consider attachments to a variety of body parts like the head, finger, back, and feet. This can increase product portability and efficiency.



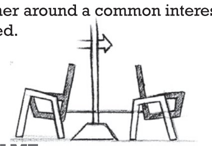
WEAR YOUR CHAIR
Body Beauty
This chair attaches to the user's back to support the body when sitting on the floor.

BEND 16
Form an angular or rounded curve by bending a continuous material, and assign different functions to its surfaces. This can reduce material, improve product uniformity, and create additional functions.



OVERLAP TRAY
Offi
Using a single continuous material, this bent tray and the negative spaces it creates serve a variety of functions.

BUILD USER COMMUNITY 17
Design the product around multiple users. Consider how users can work together to create or operate the product, or how users can interact through the product. This can facilitate product sharing and bring people together around a common interest or need.



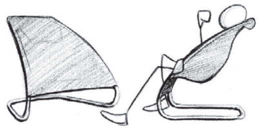
ROCK ME
Rachel Boswell
These two benches are attached through the lattice using metal rods. They are forced to swing together, making each sitter aware of the other's presence.

CHANGE DIRECTION OF ACCESS 18
Give the user customizable options to best fit their needs and preferences. The final product is developed for each user based on their choices. This can provide the user with a sense of ownership and functional awareness.

TRACKBALL M570
Logitech
This computer mouse changed the way it is used by allowing the user to navigate by rolling a track ball with his or her thumb.

Figure 6 (continued).

CHANGE FLEXIBILITY 19
Alter the typical or expected flexibility of the product's material. This can affect durability, collapsibility, function, and adjustability of the product.

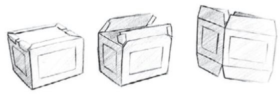


FIT
Christine Ludeke
The seat of this chair is made of a woven material that stretches in places to fit the user.

CHANGE GEOMETRY 20
Alter the typical or expected geometric form of the product or its components while maintaining function. This can redefine user interactions, make the product more intuitive, and suggest new product functions.

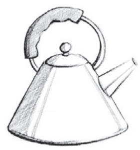
CHAIR
Michael Wolk
These chair legs are designed to be triangular instead of rectangular, creating a unified look with the seat.

CHANGE PRODUCT LIFETIME 21
Consider the assumed lifetime of a product (or its parts) and alter the number of times it can be used. For example, replace disposable components with reusable ones, or vice versa. This can optimize material use, allow environmentally friendly material use, and decrease waste.



TREPAC
Essential
This reusable shipping container is designed to replace single-use cardboard boxes.

CHANGE SURFACE PROPERTIES 22
Highlight areas where the user interfaces with the product or components by using different colors, textures, materials, or forms. This can improve existing function, and improve usability, safety, and comfort.

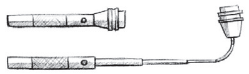


ALESSI TEAPOT
Michael Graves
The material on the handle of this tea pot gives it a distinctive look, showing the user where to grasp the pot.

COMPARTMENTALIZE 23
Divide the product into distinct compartments, or add a new compartment. This can separate distinct or complimentary product functions, or create an organizational scheme for multiple functions.

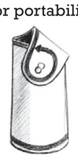
BOOKSEAT
Fishbol Design Atelier
This chair has storage compartments that can be used for books and magazines.

CONTEXTUALIZE 24
Envision the details of how and where the product will be used, and fit the product to this context. Alternatively, redesign a product to function in a new context. This can specialize the product for target user groups and environments.



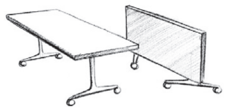
EXTENDABLE MAGNETIC FLASHLIGHT
Tundra Specialties
This flashlight is designed with a magnet and extendable arm for mechanical work in hard to reach places.

CONVERT 2-D MATERIAL TO 3-D OBJECT 25
Create a three-dimensional object by manipulating two-dimensional materials through bends, twists, creases, or joints. This can reduce costs, allow user assembly, or be reversed for portability and compactness.



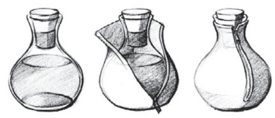
COCA-COLA REFRESH
fuseproject
This recycling bin is created by rolling a recycled sheet of plastic. It can be unrolled to make transportation and storage easier.

CONVERT FOR SECOND FUNCTION 26
Create multiple stable states of the product, where each state defines a separate function. Transitions between these states can be achieved through rearranging, reorienting, and attaching or detaching components. This can allow multiple functions to be incorporated into one product.



AKIRA TABLES
Coalesse Vecta
This table features a folding top that can flip up or down, making it useful as a room divider.

COVER OR WRAP 27
Overlay a cover, form a shell, or wrap the surface of the product or its parts with another material. This can affect customizability, multifunctionality, durability, and safety.



TEASHIRT
Eva Solo
This fabric cover keeps the tea hot, accentuates the sleek lines of the glass jar, and protects the user's hands.

*Figure 6 (*continued*)*.

CREATE SERVICE 28
Alter the typical or expected flexibility of the product's material. This can affect durability, collapsibility, function, and adjustability of the product.

SA YL
Yves Behar
This chair comes with a 12 year warranty. If broken, a certified repairman will repair the chair on-site, free of charge.

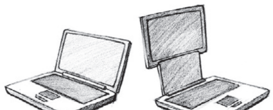
CREATE SYSTEM 29
Identify the core product functions and define a multi-stage process to achieve the overall goal. Separate the stages to organize functional steps, build a complex function, and increase efficiency.

WET JET
Swiffer
This floor cleaner system dispenses cleaning fluid onto a disposable cloth while in use, making mopping easier for the user.

DIVIDE CONTINUOUS SURFACE 30
Divide single, continuous parts or surfaces into two or more elements or functions. Independent parts can be repeated or reconfigured, and replaced with new materials. This can offer options to the user, distinguish multiple functions, allow partial replacement, and improve product performance.

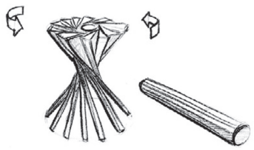
SNAP CHAIR
Karim Rashid
This chair is divided into two separate components that can be swapped for different colors and designs.

ELEVATE OR LOWER 31
Raise or lower the entire product or its parts. This can increase ease of use, improve ergonomics, and suggest additional functions.



DREAMCOM 10
Dreamcom
With a vertically adjustable screen, this laptop gives greater comfort while working.

EXPAND OR COLLAPSE 32
Allow the volume or area of the product or its parts to get larger or smaller. Consider the use of fluids, inflatables, flexible materials, and complex joints. This can improve portability and storage options, and allow adjustability.



ONE SHOT
Materialise.MGX
This stool can be collapsed into a staff by twisting, providing compactness for storage.

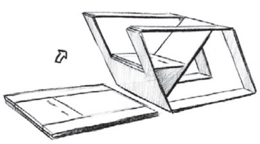
EXPOSE INTERIOR 33
Reveal the inner components of the product by partially or entirely removing the outer surface, or making it transparent or translucent. This can affect users' understanding of the product's function.

ALTIPLANO SQUELETTE
Piaget Watches
This watch's inner mechanism is revealed through a transparent surface to give it a unique aesthetic quality.

EXTEND SURFACE 34
Identify all surfaces in the product and lengthen or widen one or more of these surfaces. This can enhance function, add adjustability, or add new functions.

SENZ XL
Senz Umbrellas
Due to its asymmetric design, this umbrella automatically positions itself in the wind, making it comfortable and easy to use.

FLATTEN 35
Compress the product to a flat surface by removing connections or deflating it, or using flexible materials or joints. This can improve portability, durability, and compactness.



FOLDING
Brainstream Design
This chair uses a parallelogram geometry that can be folded flat when not in use.

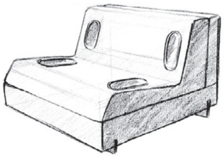
FOLD 36
Hinge, bend, or crease the product's parts or surfaces. This can improve compactness for packaging and storage.

NEPTUNE
Ernest Race
This chair can be folded up when not in use. When unfolded, the chair uses straps to hold the seat in position.

Figure 6 (continued).

HOLLOW OUT 37

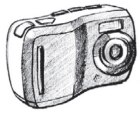
Identify product volumes and remove a portion of that volume to create a cavity (without impacting structural integrity). This can improve the product's fit to the user, other products, or its environment.



DECOMPRESSION SPACE
Matali Crasset
This chair has cavities that provide space for the user's elbows and hands.

IMPOSE HIERARCHY ON FUNCTIONS 38

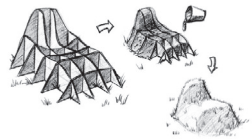
Present the functions of the product in a set order to assist in using the product. Make the steps for each function clear; for example, access to the second function only occurs after the first. This can increase safety, make the product more intuitive, and guide the user through the product's functions.



EASYSHARE ONE
Kodak
After a picture is taken, this camera can print the picture or send it to others.

INCORPORATE ENVIRONMENT 39

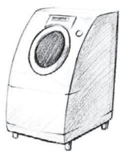
Use the surrounding environment (living or artificial) to perform a part of the product's function or serve as a product component. This can reduce material, create uniformity with the environment, and increase environmental awareness.



LAWN CHAIR+COUCH
Earth Furniture
By building a structure, filling it with dirt, and planting grass, this seating becomes part of its environment.

INCORPORATE USER INPUT 40

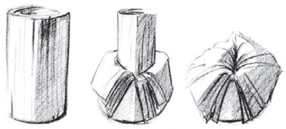
Identify product functions that are adjustable and allow users to make those changes through an interface control, using buttons, sliders, levers, dials, touch screens, etc. This can make the product adjustable to the user's needs.



WASHER/DRYER COMBO
Panasonic
This unit performs both washing and drying clothes through user-selected functions and settings.

LAYER 41

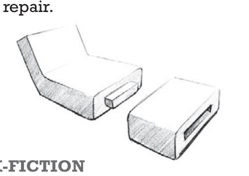
Build the product through a series of layers of similar or different materials. Different layers can provide a variety of functions and interest.



THE CABBAGE CHAIR
Nendo
This chair is handmade from rolls of waste-paper, which are peeled away to reveal functional, organic sculptures.

MAKE COMPONENTS ATTACHABLE/DETACHABLE 42

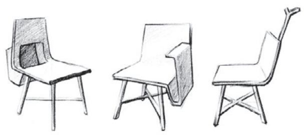
Separate parts of a product, and develop ways these parts can be joined and separated, such as with fasteners or interlocking pieces. This can provide product flexibility and make the product easy to clean, carry, and repair.



SEX-FICTION
Diego Fortunato and Gabriel Fontanilo
This lounge chair uses male and female connectors to attach individual pieces.

MAKE MULTIFUNCTIONAL 43

Identify a secondary, complimentary function for the product, and create a new form to accomplish both functions. This can reduce material, increase efficiency, and facilitate compactness.



FAMILY
Kaman Tung
This set of cafe chairs has compartments for storage of purses, coats, and other belongings.

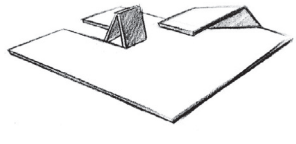
MAKE PRODUCT RECYCLABLE 44

Explore the use of recyclable materials within the product Additionally, consider ways the products can be returned to manufacturers for recycling. This can help reduce waste, lower cost, and preserve natural resources.

MIRRA
Herman Miller
This office chair is 96% recyclable and can be easily disassembled.

MERGE SURFACES 45

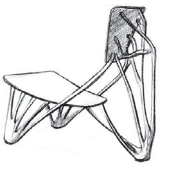
Identify relationships between components and join their contours to create a new form. This can create product unity and reduce material.



LAND PEEL
Shin Yamashita
This floormat can be folded up into a variety of furniture settings, making use of the ground to reduce the need for additional support.

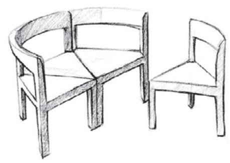
*Figure 6 (*continued*).*

MIMIC NATURAL MECHANISMS 46
Imitate naturally occurring processes, mechanisms, or systems. This can provide efficiency and proven effectiveness.



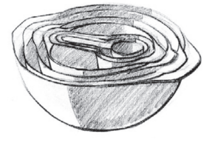
BONE CHAIR
Joris Laarman
This chair's design takes inspiration from the way human bones grow by reinforcing areas under higher stress.

MIRROR OR ARRAY 47
Reflect or repeat elements across a central axis or point of symmetry. This can help distribute force, reduce manufacturing cost, and improve aesthetics.



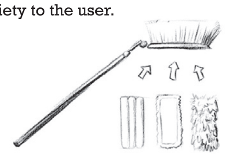
DAIDAI
Mikko Paakkanen
These chairs are formed like pieces of a pie arrayed around a central point.

NEST 48
Fit one object within another by matching the inner form of the containing object to the outer form of the contained object. This can increase compactness and create product unity.



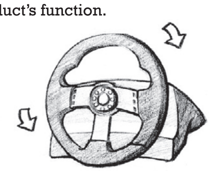
NEST 8
Joseph Joseph
These different sized bowls and accessories are nested inside each other for compact storage.

OFFER OPTIONAL COMPONENTS 49
Provide extra components for the user to swap. Consider whether they will be purchased separately or included with the product, and where they will be stored when not in use. This can provide flexibility in function or offer variety to the user.



QUANTUM REACH
CrowleyJones
This cleaning tool offers three functions by allowing the user to attach different heads.

PROVIDE SENSORY FEEDBACK 50
Return perceptual (e.g., tactile, aural, visual) feedback to the user to guide use. This can reduce errors, confirm actions, and inform the user of the product's function.

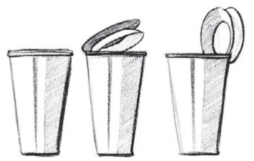


G27 RACING WHEEL
Logitech
This gaming racing wheel is equipped with a force-feedback response system, allowing the user to feel vibrations and steering resistance.

RECONFIGURE 51
Identify relationships between functional components and change their configurations. This can accommodate a new type of use, or allow the product to function differently.

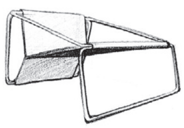
FORCE 5*RANS*
RANS
This bicycle is reconfigured so the pedals are above and in front of the steering column. This allows the user to sit in a reclined position.

REDEFINE JOINTS 52
Identify the ways the product parts are connected and modify that connection by removing, covering, or changing the orientation of joints. This can improve visual consistency and increase safety.



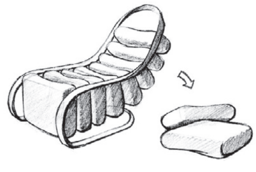
BALANCE ACT
Eva Solo
Because there are no fasteners, this trash can lid can be opened from all sides by gently lifting the edge.

REDUCE MATERIAL 53
Remove material from the product by eliminating unnecessary components, reducing volume, or redesigning the product in ways that are more efficient. This can decrease product weight, reduce material cost, allow use in new spaces or with different products, and change aesthetics.



SP
Khodi Feiz
By taking advantage of material properties, this chair is made sturdy and rigid with minimal material.

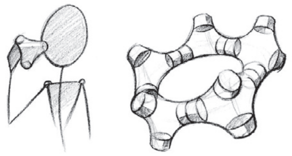
REPEAT 54
Copy components or products. This can enhance function, allow for multiple simultaneous functions, evenly distribute load, and decrease manufacturing costs.



SHAIR
Jie Jyun Lyu
Repeated cushions are aligned on this frame to form a single seat. Removed from this frame, they provide multiple seats.

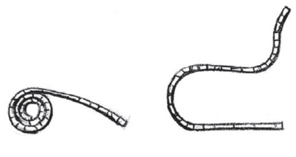
*Figure 6 (*continued*).*

REPURPOSE PACKAGING 55
Create a product in which its packaging can be converted into another product after use. This can reduce waste and offer additional functions to the user.



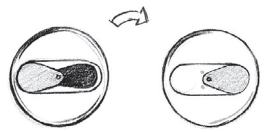
Y-WATER
Yves Behar
These Y-shaped bottles turn into a toy after use. They can be attached to each other in various configurations to make interesting sculptural forms.

ROLL 56
Roll a part or the entire product around a center point or a supporting surface. This can make the product more compact.



MIESROLO
Uros Vitas
This chair is made of slats of wood and a synthetic elastomer. It can be rolled up for easy storage.

ROTATE 57
Revolve a component or multiple components of the product about a pivot point or axis, or allow the user to do so. This can provide product flexibility, or adjust or change product function.



STOPENER
*Bum Joon Lee and Seung Hwan Shin*Bum
This lid rotates to both open and close the can.

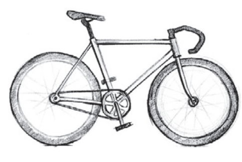
SCALE UP OR DOWN 58
Increase or decrease any of the physical dimensions of the product or its parts. This can introduce a new function, alter the existing functions, and create options for different users.

X+X=1.5
Michal Pickel Sagi and Tami Pampanel
This chair is made of two identical chairs, where one is scaled down and attached to the leg of the other.

SEPARATE FUNCTIONS 59
Identify different functional components of a product and separate them into individual forms. This can change user interaction, make the product more accessible, or allow easier replacement of individual components.

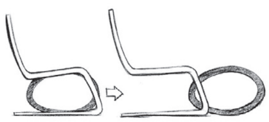
TABLE CHAIR
Richard Hutten
This chair is made of a stool and a backrest that each stand alone.

SIMPLIFY 60
Remove unnecessary complexity from the product. This can reduce manufacturing costs and material waste, or make the product more intuitive.



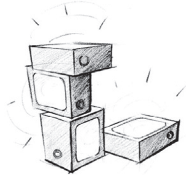
CLASSIC TRACK
Fuji
This fixed-gear bicycle has only one gear, with no additional freewheel mechanism.

SLIDE 61
Move one component smoothly along a surface or another component. This can expose or cover surfaces, open or close spaces, and offer options to the user.



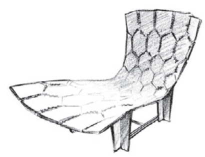
SLICE
Graypants
This chair has a separate ottoman that slides out from between the slats.

STACK 62
Stack individual components, or make the entire product stackable. This can save space, protect inner components, or change appearance by rearranging the stack.



CANDY 4 BLOCK SET
TwistTogether
This lamp is made of a set of four colored blocks, each with an LED light. The blocks can be rearranged by stacking them.

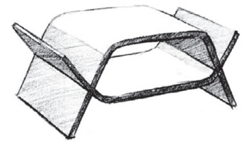
SUBSTITUTE WAY OF ACHIEVING FUNCTION 63
Replace one or more components with other designs that can achieve the same function. This can improve product performance, change product cost, and facilitate use of more readily available materials.



KNIT
Emiliano Godoy
This chair is made of small pieces of plywood sewn together instead of cushions and fabric.

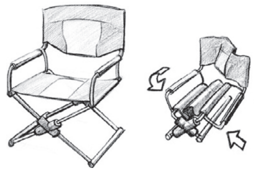
*Figure 6 (*continued*).*

SYNTHESIZE FUNCTIONS 64
Combine two or more functions by joining them to form a new, multifunctional product. Consider how the two functions can compliment each other. This can reduce material and increase efficiency.



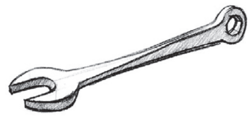
EMBRACE
John Green
This bench combines book storage and seating.

TELESCOPE 65
Identify long components and split them into sections that can slide into each other. This can help reduce product size when not in use.



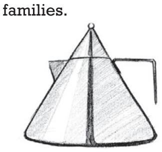
PICO TELESCOPING
GCI Outdoor
This chair's legs telescope in and fold down to fit in a laptop-sized carrying bag.

TWIST 66
Turn simple geometric forms in opposite directions single or multiple times. This can create new functional surfaces, allow for different user interactions, and change product aesthetics.



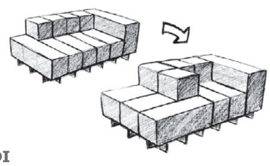
MACOR REVOLUTIONIZED WRENCH
Proprietary Technologies, Inc.
The ends of the wrench are twisted to be perpendicular to each other, allowing for a better grip and more leverage.

UNIFY 67
Arrange design elements within a product according to the relationships (e.g., similarity, dependence, proximity) among them to create visual consistency. This can make the product more elegant, and can be helpful in designing product families.



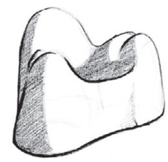
IL CONICO TEA KETTLE
Alessi
This product's components follow the same conical form to create visual consistency.

USE COMMON BASE TO HOLD COMPONENTS 68
Align multiple components on the same base or railing system. This can reduce the number of parts needed, allow users to rearrange components, and make the product more compact.



OI
Cocoon Branding
This modular sofa can be reconfigured to the users' preferences. It uses a common base to hold each cushion in multiple stable arrangements.

USE CONTINUOUS MATERIAL 69
Identify the different components of the product, and create them out of one continuous material. This can reduce the number of parts or joints, and simplify the product.



MOLAR CHAIR
Wendell Castle
This chair's legs, seat, arms, and back are made from a continuous sheet of molded plastic.

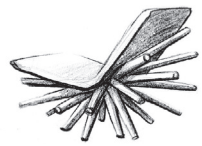
USE DIFFERENT ENERGY SOURCE 70
Replace the product's expected energy source and redesign it accordingly. Energy source possibilities include: agricultural biomass, chemical, fossil, geothermal, hydroelectric, nuclear, solar, tidal, and wind. This can preseve natural resources, reduce cost, or increase environmental awareness.

HOT BOTTLE HAND WARMERS
The Original Gift Company
Press a small button on this product to set off an exothermic chemical reaction. It can be recharged in hot water after use.

USE HUMAN-GENERATED POWER 71
Identify functions that require energy input, and have the user act as the power source for the product. This can preserve natural resources, reduce cost, encourage physical activity, and make the product usable in places without access to conventional power sources.

PROTONS LAMP
Eric Stangarone
This playful lamp operates by repeatedly pulling the attached cord.

USE MULTIPLE COMPONENTS FOR ONE FUNCTION 72
Identify primary functions of the product and use multiple distinct components to achieve the same functions. This can maximize functional output.

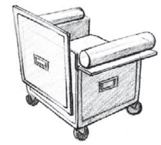


BURST
Oliver Tilbury
This chair has 31 legs with identical, repeated forms. Some are trimmed to provide a stable base.

Figure 6 (continued).

USE PACKAGING AS FUNCTIONAL COMPONENT 73

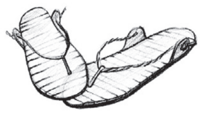
Instead of disposable packaging, incorporate packaging within the product to perform a supportive function. This can reduce waste and provide a storage or organizational option.



WHEELED CUBE
Heinz Julen
This chair can be folded into a wooden box with wheels when not in use, protecting interior cushions.

USE REPURPOSED OR RECYCLED MATERIALS 74

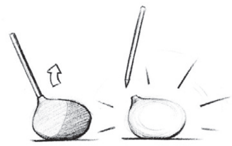
Explore the use of materials repurposed for different functions; for example, converting waste materials into usable components. This can decrease manufacturing costs, reduce use of natural resources, and increase consumer awareness about waste.



SOLEMATES
Satish and Falguni Gokhale
This disposable footware is made from recycled newsprint.

UTILIZE INNER SPACE 75

Identify inner volumes of the product or create them. Utilize this space to place other product components or a different product. This can increase compactness and provide storage space.



WRITE? LIGHT!
Jaeun Park
A pencil is housed in this lamp. The light is turned on when the pencil is removed.

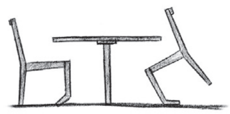
UTILIZE OPPOSITE SURFACE 76

Create a distinction between exterior and interior, front and back, or bottom and top. Make use of both surfaces for complimentary or different functions. This can increase efficiency in the use of surfaces and materials, or facilitate a new way to achieve a function.

980 TATOU
Annika Luber
The laces wrap around the bottom of this shoe and connect with the sole.

VISUALLY DISTINGUISH FUNCTIONS 77

Create visual relationships among product functions by changing dimensions, locations, colors, or materials of the individual design elements. This can make the product more intuitive.



WATERSHED OUTDOOR FURNITURE
Paul Galli
The front legs of these chairs are bent backward, indicating that they can be tipped forward when not in use.

Figure 6 (continued).

previously identified heuristics were observed in each study. This suggests the identification of heuristics had reached a point of saturation across the entire set of concepts in this compiled dataset.

The data observed led to seventy heuristics across the four studies. Splitting seven observed heuristics into two separate heuristics subsequently created seven new heuristics. For example, *Replace materials with recycled ones* included both the use of recycled material and recyclable products. This heuristic was then redefined into two: *Use repurposed or recycled materials,* and *Make product recyclable*. The intent in adding these seven heuristics was to provide clarification of their meaning given that two subcategories appeared evident in the concepts reviewed (see Table 3).

Across the four studies, the majority (51%) of the design heuristic observations occurred in Study 2. This study analyzed designs from a single industrial

Table 2 Observations of heuristics observed across Studies 1–4, presented in alphabetical order. Seven heuristics originated from subdividing other observed heuristics

	Design heuristic	*Study 1 Product analysis*	*Study 2 Longterm project*	*Study 3 Engineer protocols*	*Study 4 Ind. Design protocols*	*Total*
1	Add levels	0	3	0	6	9
2	Add motion	4	0	4	0	8
3	Add natural features – *split from 46*					
4	Add to existing product	12	49	32	19	112
5	Adjust function through movement	17	76	35	12	140
6	Adjust functions for specific users	23	50	1	1	75
7	Align components around center	5	22	0	0	27
8	Allow user to assemble	4	0	0	0	4
9	Allow user to customize – *split from 6*					
10	Allow user to rearrange – *split from 51*					
11	Allow user to reorient	5	0	0	0	5
12	Animate	16	0	0	0	16
13	Apply mechanism in new way	21	64	14	8	107
14	Attach independent functional components	0	145	95	34	274
15	Attach product to user	6	0	2	1	9
16	Bend	0	16	4	4	24
17	Build user community	4	0	1	1	6
18	Change direction of access	13	211	5	0	229
19	Change flexibility	8	12	17	10	47
20	Change geometry	0	12	25	0	37
21	Change product lifetime	8	4	0	2	14
22	Change surface properties	0	8	6	6	20
23	Compartmentalize	0	12	7	3	22
24	Contextualize	14	135	0	0	149
25	Convert 2-D material to 3-D object	9	8	4	1	22
26	Convert for second function	0	8	8	3	19
27	Cover or wrap	4	18	100	36	158
28	Create service – *split from 29*					
29	Create system	6	0	14	4	24
30	Divide continuous surface	0	31	32	11	74
31	Elevate or lower	0	31	66	27	124
32	Expand or collapse	11	49	10	4	74
33	Expose interior	0	0	0	1	1
34	Extend surface	0	28	7	5	40
35	Flatten	0	3	4	3	10
36	Fold	0	25	48	23	96
37	Hollow out	0	0	4	3	7
38	Impose hierarchy on functions	11	0	3	8	22
39	Incorporate environment	0	8	6	4	18
40	Incorporate user input	0	0	5	2	7
41	Layer – *split from 48*					
42	Make components attach/detachable	11	111	21	3	146
43	Make multifunctional	0	54	15	23	92
44	Make product recyclable – *split from 74*					
45	Merge surfaces	0	56	0	0	56
46	Mimic natural mechanisms	14	0	1	0	15
47	Mirror or array	0	7	7	7	21
48	Nest	13	32	11	6	62
49	Offer optional components	7	25	11	2	45
50	Provide sensory feedback	7	18	11	1	37
51	Reconfigure	0	28	10	2	40

Table 2 (*continued*)

	Design heuristic	*Study 1 Product analysis*	*Study 2 Longterm project*	*Study 3 Engineer protocols*	*Study 4 Ind. Design protocols*	*Total*
52	Redefine joints	24	16	0	0	40
53	Reduce material	16	9	2	0	27
54	Repeat	14	64	69	23	170
55	Repurpose packaging	6	0	0	0	6
56	Roll	0	1	6	1	8
57	Rotate	0	26	5	2	33
58	Scale up or down	0	21	16	2	39
59	Separate functions – *split from 77*					
60	Simplify	22	37	0	0	59
61	Slide	0	14	7	1	22
62	Stack	0	2	26	9	37
63	Substitute way of achieving function	0	10	28	1	39
64	Synthesize functions	13	6	4	5	28
65	Telescope	0	0	4	0	4
66	Twist	4	0	0	0	4
67	Unify	7	31	4	3	45
68	Use common base for components	0	73	1	0	74
69	Use continuous material	8	22	0	0	30
70	Use different energy source	0	0	3	1	4
71	Use human-generated power	13	0	0	0	13
72	Use multiple components in one function	0	0	27	1	28
73	Use packaging as functional component	5	0	1	0	6
74	Use repurposed or recycled materials	14	5	12	3	34
75	Utilize inner space	7	31	14	12	64
76	Utilize opposite surface	8	0	15	10	33
77	Visually distinguish functions	0	22	34	10	56
	Total heuristic instances observed	414	1749	924	370	3457
	Percentage	12%	51%	27%	11%	
	Number of new heuristics identified	39	25	5	1	
Number of existing heuristics observed		–	34	50	49	70

designer working on a long-term project. Though fewer concepts (218) were included in this study compared to the other studies, the concepts from this setting were rich in heuristic observations, with many concepts including multiple heuristics (an average of 8 heuristics per concept in Study 2, compared to

Table 3 Seven new Design Heuristics originating from subdividing seven observed heuristics

Initial heuristics coded	*Revised heuristic*	*New heuristic added*
Implement characteristics from nature within the product	Mimic natural mechanisms	Add natural features
Include user in the assembly or the customization of the product	Allow user to assemble	Allow user to customize
Flip the direction of orientation	Reconfigure	Allow user to rearrange
Create systems for returning to manufacturer after life cycle ends	Create system	Create service
Add gradations or transitions to use	Add levels	Layer
Replace materials with recycled ones	Use repurposed or recycled materials	Make product recyclable
Visually separate primary functions from secondary functions	Visually distinguish functions	Separate functions

1.5 heuristics per product in Study 1). While the product analysis uncovered 39 different heuristics, this case study of a single designer showed evidence of 57 different heuristics. This designer also used a subset of heuristics more frequently. For example, *Change direction of access* was used 211 times in these concepts, perhaps reflecting the challenge of designing universal access functions within a home bathroom. Other heuristics frequently observed in this study were *Attach independent functional components, Make components attachable/detachable,* and *Contextualize* (envision how and where the product will be used). This suggests the designer and the problem may play a role in determining which heuristics are frequently employed during idea generation.

4 Discussion

Across four empirical studies, 77 Design Heuristics were identified. These heuristics were observed in multiple concepts and studies, and across designers and design settings. These results show that examining designers' concept sets during idea generation provides a rich source of information about how they introduce variation into concepts for a given problem. In comparison, analyses of existing or award winning products (Cormier et al., 2011; Haldaman & Parkinson, 2010; Perez & Linsey, 2011; Saunders et al., 2011; Singh et al., 2009; Skiles et al., 2006; Weaver et al., 2010; Yilmaz, Seifert et al., 2016) and patents (Altshuller, 2005) provide a single design concept for each design problem as observations. These observations may limit the opportunity to observe how designers create a concept set containing multiple, varied concepts to consider. In the combined studies presented here, the methodology added the collection of observations *during* the idea generation process. Observing the generation of multiple candidate concepts appears to give rise to heuristic patterns not evident when examining only final designs. Through systematic observation of multiple concepts created by many designers in varied design problems, we can attain a deeper understanding of the role of design heuristics in idea generation.

Of course, not all designers intentionally create a large set of candidate concepts for a given design problem. With expertise, and perhaps experience regarding when specific heuristics may prove useful, a more directed process may occur, where a designer can focus more quickly on promising concepts (Cross, 2016). Certainly, there is ample evidence that designers often consider only a small set of related concepts when generating ideas (Ball et al., 1994; Chrysikou & Weisberg, 2005; Dong & Sarkar, 2011; Linsey et al., 2010; Purcell & Gero, 1996; Sio et al., 2015; Smith, 1995; Viswanathan & Linsey, 2013; Youmans & Arciszewski, 2014). This small set of concepts in idea generation may also occur when designers fixate on specific design features (Jansson & Smith, 1991; Purcell & Gero, 1996; Sio et al., 2015). Logically, the idea generation process benefits from considering as many different concepts as possible (Akin & Lin, 1995; Atman et al., 1999; Brophy, 2001; Liu et al., 2003) in order to cover the space of possible designs (Gero, 1990; Goel & Pirolli, 1992; MacLean et al., 1991; Simon, 1981). To do so, the evidence from the combined studies here suggests the use of design heuristics.

One open issue regarding design heuristic use is how to decide which heuristic to apply in any given design context. The data from existing design solutions collected in these studies suggests the heuristics are readily applicable across design problems. Other approaches, such as Design to Connect (Bleuze, Cioccib, Detandb, & De Baetsc, 2014), have tested whether organized cues for heuristic use are helpful. Their study found that including a set of 'design drivers' (e.g., usability, aesthetics, economy) did not improve performance of designers; instead, the student designers in their studies preferred an unstructured use of their connection guidelines. In studies with Design Heuristics, providing a subset of heuristics to designers to be selected at random has produced improved design outcomes (Daly, Christian et al., 2012; Daly, Yilmaz et al., 2012). In the open-ended idea generation process, less determinate methods like Design Heuristics may be preferable for creating alternative design concepts in the early phases of conceptual design.

Another question is whether the set of 77 Design Heuristics represent a definitive description, or whether more such heuristics may be uncovered in future research. In the present study, we analyzed concepts from 400 consumer products, 218 designs by a professional industrial designer, and 247 concepts from 48 different designers. This represents a large sample of design solutions across many different types of products and designers. Across these studies, the identification of new heuristics slowed, so that it appeared the readily evident heuristics had been uncovered, with only one new heuristic observed in the last study. However, further research on identifying new heuristics may identify new heuristics when different design problems are included, or when different designers' work is sampled. Because heuristics are based upon experiences, new design goals and contexts may give rise to innovation in heuristics as the field of product design (and designers' experiences) changes dynamically over time. In addition, the organization of these 77 Design Heuristics may be refined under further research (Design Heuristics, 2012). Finally, the empirical data described here was specific to the domain of product design. Future research should examine other domains, such as service design, software programs, and chemical engineering, to determine how heuristics may differ by domain.

What is the 'right' level of heuristic definition? Is it best to have few heuristics that capture more abstract similarities across designs, such as only three principles (*expand/collapse*, *expose/cover*, and *fuse/divide*) identified in transforming products (Singh et al., 2009)? Having a few, more general heuristics makes learning and remembering them easier, but requires more effort in deciding how to apply them within a new design problem. Alternatively, having more heuristics and conditions on their application, such as the 40 TRIZ principles and contradiction matrix (Altshuller, 1997, 2005), may be easier to apply to specific problems. However, a system with more heuristics may be harder to learn and remember, and likely requires more training (Ilevbare et al., 2013).

Goel and Bhatta (2004) describe this issue of 'granularity' (Fu et al., 2015) as the problem of specifying generic relations (independent of any specific design situation) among abstract design elements. The specificity of an identified heuristic can be characterized at varied levels, from 'very general' (abstracted away from observed examples) to 'very specific' (closely tied to the observed example). At the extreme, a complete example, as in case-based design (Kolodner, 1993, 1997) and analogical approaches (Ball, Ormerod, & Morley, 2004; Bonnardel, 2000; Casakin, 2004; Christensen & Schunn, 2007; Helms et al., 2009; Linsey, 2007; Linsey et al., 2012; Perkins, 1997; Qian & Gero, 1996; Visser, 1996) provides specific information about implementation. However, application to new design problems requires the abstraction of heuristics with each use, costly in cognitive effort. Case approaches also raise the problem of access, or finding relevant analogies given the present design problem. This suggests a trade-off between heuristic specificity (that aids application) and generality (that increases relevance) that has consequences for the access and ease of heuristic application (Gray et al., 2016).

In the extraction of Design Heuristics, we propose a criterion of efficacy for heuristics: The success of heuristic definitions can be assessed based on their effectiveness in helping *other* designers create novel designs through their application during idea generation. Further research would then determine whether a candidate set of design heuristics captures design variations at a level useful in concept generation. The 77 Design Heuristics presented here offer an intermediate level of description that facilitates implementing the heuristic in a new problem context. The needed information about how to create a new concept is readily available within the heuristic. Yet, many decisions must still be made about how to apply the heuristic in a given problem. This includes the possibility of reapplying the same heuristic to the same problem again to create a different concept, as observed in Yilmaz and Seifert (2011). The challenges of organizing many heuristics during idea generation can be managed through an external representation of each heuristic and random selection among heuristics; then, if more concepts are desired, more heuristics can be considered. It is possible that further research might identify cues that indicate when specific heuristics are most relevant for application in a problem. Whether it is better to have 10 principles, or 77, or 1000, depends on what designers find helpful to their idea generation process.

In future research, it is important to compare the 77 Design Heuristics to other proposed methods of idea generation in order to assess its efficacy. Increasingly, studies are showing the advantages of specific idea generation methods, and suggesting which methods are more effective in given design circumstances

(Hernandez et al., 2013; Jensen, 2012; Jensen, Weaver, Wood, Linsey, & Wood, 2009; Ogot & Okudan, 2007; White, Wood, & Jensen, 2012). Empirical studies can identify which approaches work well for specific types of design problems, design domains, and types of designers. In addition, it is important to establish the value of generating multiple candidate concepts for later selection and implementation. The present findings provide evidence for a new tool to aid designers in the process of idea generation. In the past, the use of heuristics in idea generation likely depended solely upon the generalizations each designer was able to build from their own design experiences. The use of a shared, external tool like the 77 Design Heuristics may facilitate the creation of innovative concepts by even novice designers in the early stages of conceptual design.

5 Conclusion

Design heuristics offer a conceptual bridge between more general design theories and individual design precedents often provided to learners. The empirical observations presented here combine data from four studies of many designers working on a wide variety of products and problems in order to identify common patterns evident in their designs. The resulting identification of 77 Design Heuristics provides a collection of strategies grounded in observed use in concepts, and demonstrated across design problems, multiple concepts, and designers. This empirical approach to defining heuristic strategies is unique among the approaches in the field because it includes protocols from designers where more than one concept is sampled. By examining the candidate designs generated in addition to complete designs in the form of products and patents, rich information about how designers successfully create alternative concepts becomes evident. The results provide a collection of Design Heuristics suitable for use as a tool to explore possible alternative concepts. Design Heuristics may enhance the idea generation process by providing multiple strategies to consider, increasing the likelihood of innovative solutions.

Acknowledgments

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