AC 2011-535: A COGNITION-BASED CLASSIFICATION SCHEME FOR DESIGN TECHNIQUES

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A Cognition-Based Classification Scheme for Design Techniques

Abstract

A cognition-based classification scheme for design techniques is proposed and illustrated here as part of the new Cognition-Based Design (CBD) framework. The classification scheme is based on four components: (1) the stage of the design process in which the technique is applied; (2) the primary cognitive function supported by the technique; (3) the cognitive level required for mastery of the technique; and (4) the cognitive style simulated through the technique. The aim of this classification scheme is to help design students, their instructors, and other design practitioners make better choices about the techniques they use based on the given design opportunity and the desired outcomes, rather than choosing only those techniques with which they are comfortable or those they know best. Recommendations for making use of the new classification scheme in the design classroom are provided, as well as suggestions for future research.

1. Introduction

Although models of the design process may differ in some of their details, most of them share a fundamental functional architecture that mirrors the stages and flow found in general models of problem solving[3,4,5,11] – i.e., identification of the problem or need, generation of potential solutions, selection of the most appropriate solution, and the implementation and testing of that solution. Within each of these stages, different techniques such as the Pugh Matrix, Six Thinking Hats, and TILMAG (among many others) can be used to assist in meeting the appropriate design objectives. In fact, there are dozens (if not hundreds!) of related techniques available in the design and problem solving literature, but challenges remain in utilizing them successfully in practice.

In the classroom, one of these challenges is knowing *when* to apply *which* technique – and what to expect in terms of student outcomes in each case (i.e., what kinds of ideas/solutions are likely to result, student motivation to apply particular techniques, etc.). With limited time available, instructors cannot present nor can students practice all the techniques that exist. As a result, only a handful of techniques are typically introduced to engineering students, usually based on recommendations from the relevant textbook or the instructor's personal experience, rather than a deep understanding of which techniques are most likely to lead to successful solutions in different situations.

In this paper, our aim is to help students and their instructors make more effective use of the design techniques available through a new cognition-based classification scheme based on well-established cognitive constructs from the literature (e.g., Guilford[5], Kirton[11], and Sternberg[22]). The proposed classification scheme is based on four components that are linked to the design process and the cognitive diversity of the individual designer; we will describe these components further below. Specifically, in Section 2, we begin with a basic description of Cognition-Based Design (CBD), a new theoretical framework under development by the authors that integrates fundamental principles of design with well-established findings about cognition (including constructs from problem solving and creativity theory). One element of the CBD framework is the design process and the classification of design techniques across that process based on key cognitive variables, as we will discuss in this paper.

The structure of this technique classification scheme will be explained in Section 3, where we will also map a diverse selection of common design techniques using its four components. In Section 4, we will discuss how the new classification scheme can be used in the classroom, including a recommended process for its practical application. We close the paper in Section 5 with a discussion of questions that remain about the proposed classification scheme and suggestions for future work to support its continued development and validation.

2. Cognition-Based Design (CBD): A New Framework for Engineering Design

In order to fully appreciate the underlying structure and rationale of the technique classification scheme described in this paper, it will be useful to know something about the general design framework that lies behind it. This new framework, called Cognition-Based Design (CBD), is based on a systems view that integrates core principles from traditional engineering design with fundamental constructs from cognitive psychology and other fields related to cognition (e.g., problem solving, creativity, and learning theory). This paper marks its first formal introduction in the literature. At a basic level (see Figure 1), the Cognition-Based Design framework incorporates the "4P+N" model of Lopez-Mesa & Thompson[14], which includes the People, Process, Product, and Press (Environment) of design, along with the original design Need or Problem (also known as "Problem A"[6,8,11]).

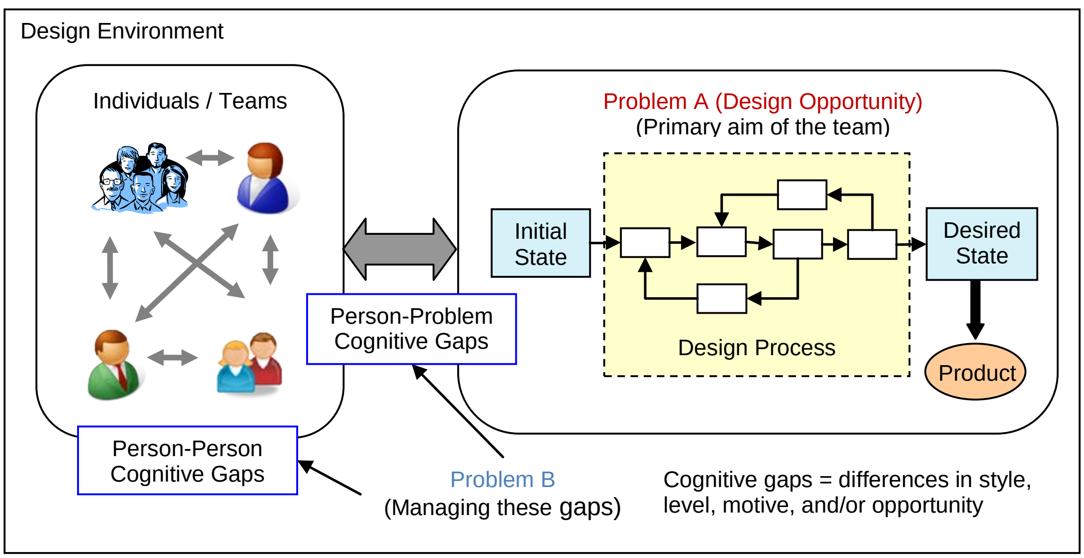

Figure 1. The Cognition-Based Design (CBD) framework

Next, key constructs related to cognitive diversity and its management (based on Kirton's Adaption-Innovation theory[11] and other related works[5,16,22]) are overlaid on this model. These constructs help establish rigorous definitions and descriptions of the cognitive variations that exist among individuals and groups, including differences in cognitive level (capacity), cognitive style (preferred cognitive approach), motive (driving energy), and availability and perceptions of opportunity. These differences between people and between people and the problems they solve are called *cognitive gaps* (Person-Person and Person-Problem, respectively)[6,8,11]. We refer to the management of cognitive gaps as Problem B[6,8,11], a challenge which must ultimately be addressed successfully if the design team is ever to resolve the original Problem A!

One way to manage Person-Problem cognitive gaps (in a design context) is to use techniques to narrow the distance between a designer's usual way of thinking and the type(s) of thinking required to resolve a given Problem A. For example, a designer whose capacity for sketching is low might learn some basic drawing techniques to help bridge this (level) gap. Or, a designer who tends to think tangentially may need to apply techniques that help him/her to "stay focused" (a different style) in order to solve a particular problem. Once again, we recognize the need for a systematic way to characterize design techniques, so the appropriate choices can be made; we turn now to our development of such a classification scheme.

3. A Cognition-Based Classification Scheme for Design Techniques

Based on the Cognition-Based Design (CBD) framework described briefly above, we have developed a classification scheme for design techniques based on four components:

1. Stages/sub-stages of the design process (define, discover, develop, demonstrate)
2. Primary cognitive operation supported (divergent vs. convergent thinking)
3. Cognitive level required for mastery of the technique (low to high)
4. Cognitive style simulated through the technique (more adaptive to more innovative)

In the following subsections, we will describe each of these components in some detail and provide a selection of design techniques for illustration.

3.1 Classification of Techniques by Process Stage and Primary Cognitive Operation

We begin by highlighting the "Process" component of design, in which we consider (first) "where we are" in the design process and (second) whether we are "fanning out" or "focusing in" our ideas. In other words, we would like to organize design techniques in terms of the design *process stage* in which they are most appropriately applied *and* in terms of the *primary cognitive operation* (divergent vs. convergent thinking) they support within that stage. The stages involved in the engineering design process are discussed extensively in the literature[3,4,9,19,20,23], so we will not review them here. Most design process models share a common understanding of these stages, which typically include some form of needs gathering, concept generation, detailed design, prototyping, and testing – although different terms may be used in each case. For our purposes here, we will use the simple four-stage model for design shown in Figure 2. Put simply: we first *define* the design opportunity, then *discover* ideas for addressing it, *develop* the details of the resulting design, and finally, *demonstrate* the solution.

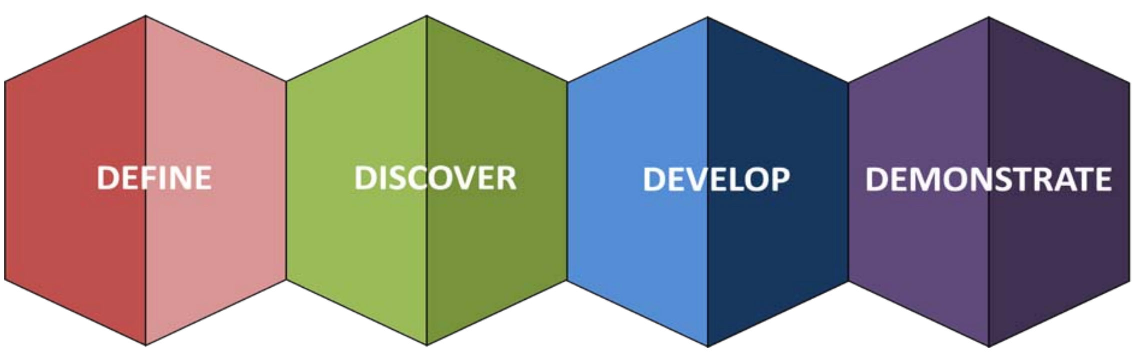

Figure 2. A simple four-stage model for engineering design

These four stages have been broken down into sub-process steps in Figure 3 to help describe what occurs in each stage in greater detail. Given this simple process flow, design techniques can be classified according to the stage or step of the design process in which they are most usefully applied. For example, in the Define stage, an individual (or team) may explore the definition of a design opportunity using ethnography[12] or the Nine Windows technique[15], while applying various Brainstorming techniques[17] or Forced Association[17] in the Discover stage. Knowing when to use a particular technique (and when not to use it!) is a skill all design students should learn.

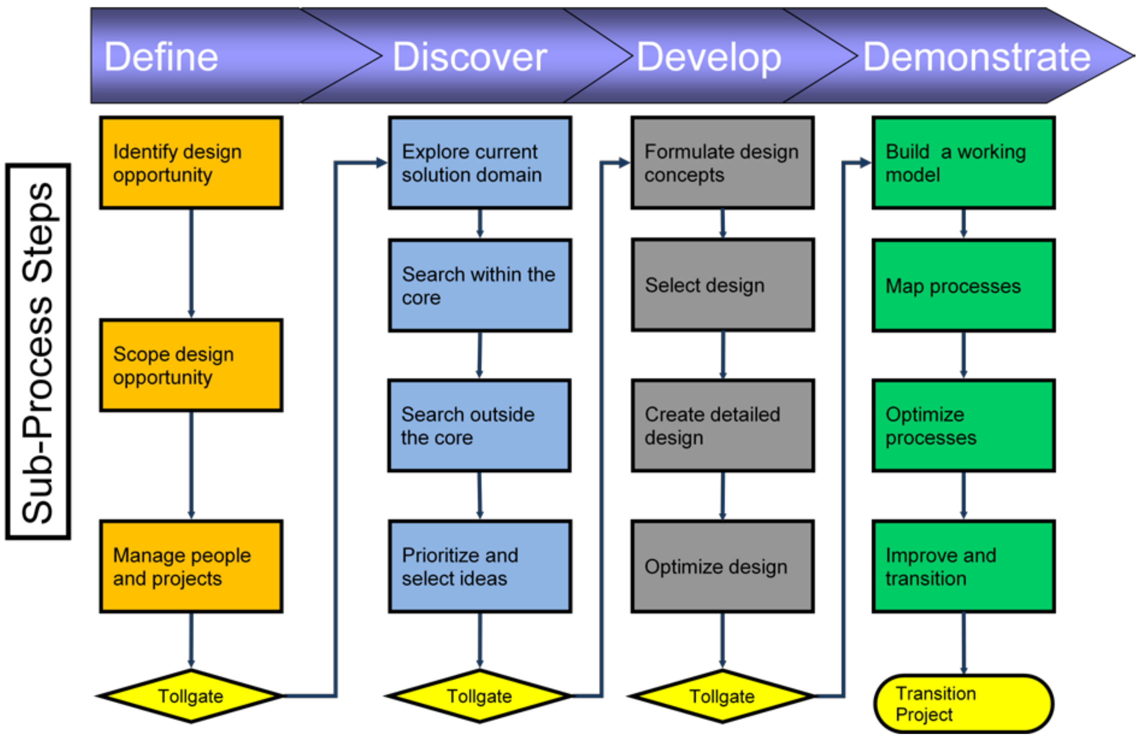

Figure 3. Four-stage model of the design process with sub-process steps

A selection of design techniques is mapped onto the four stages of the design process for illustration below (see Table 2), but first, it will be convenient to describe the second component of our classification scheme – i.e., classification of techniques by primary cognitive operation. Each stage of the design process is associated with two fundamental cognitive operations, namely: *divergent thinking* and *convergent thinking*, which have their roots in problem solving research[5,11,22]. The *divergent thinking* operation involves searching for ideas and increasing one's options through elaboration of the design problem, redefinition of the problem, and by exploring, connecting, and/or combining potential ideas/solutions. In contrast, the *convergent thinking* operation involves evaluating ideas and narrowing or reducing one's options through the imposition of value judgments, exploiting the information available about the ideas, prioritizing, and selecting.

In both cases (divergent and convergent thinking), the resulting ideas/solutions may fall inside, at the edges of, or outside the relevant technical domain/paradigm[5,8,11]. We make this statement to ensure that divergent thinking is not considered synonymous with "out of the box" thinking nor convergent thinking synonymous with "in the box" thinking. All designers both diverge and converge, at different cognitive levels and with different preferred styles; these operations lead to solutions throughout the design space. Divergence and convergence do take on slightly different interpretations when put into the context of different design stages, however, as described in Table 1. These variations of contextual interpretation are important when it comes to identifying the techniques that support each cognitive operation in different process stages.

Table 1: Contextual Definitions of Divergence and Convergence for Each Stage of the Design Process

Design Process Stage	Contextual Definition of "Divergent"	Contextual Definition of "Convergent"
Define	Generate multiple options for the problem statement or design opportunity; reframe the problem in many different ways.	Determine the main direction to take; reduce the number of design opportunities to pursue; select and focus the problem statement.
Discover	Generate multiple ideas to address the problem statement formulated in the Define phase; increase options based on the problem definition. Note: Ideas can come from anywhere relative to the current technical domain or paradigm.	Narrow down the number of potential solutions to pursue; reduce the design space to "a few" potential solutions. Note: Ideas may fall anywhere relative to the current technical domain or paradigm.
Develop	Generate multiple design options within the solutions carried over from the Discover phase – i.e., generate options for realizing the potential solutions from that phase.	From among several design concepts, choose which is "best" based on relevant criteria; reduce the number of options for testing and implementing.
Demonstrate	Generate multiple options for testing, experimenting, optimizing, and collecting data about a particular design option; generate multiple options to explain weaknesses and strengths in a given design.	Narrow the solutions to those that best meet the original design intent (problem definition) and to those that optimize the design.

Combining the "process stage" perspective with the primary cognitive operation supported by a particular technique, we can provide design students and instructors with a roadmap for choosing the most appropriate technique(s) based on these two components. Here, we have analyzed a selection of 24 design techniques commonly used in practice (see Table 2) to illustrate how this portion of the new classification scheme works. These 24 techniques are described briefly in Appendix A and in more detail in the associated references listed there.

Table 2: Classification of Techniques by Process Stage and Primary Cognitive Operation

Process Stage	Primary Cognitive Operation	Technique
Define	*Divergent Thinking*	Jobs To Be Done
		Ethnography
		Nine Windows
	Convergent Thinking	Heuristic Redefinition
		Value Analysis
		Project Charter
Discover	*Divergent Thinking*	SCAMPER
		Forced Associations
		Biomimicry
	Convergent Thinking	Kawakita Jiro Method
		Six Thinking Hats
		Multi-Voting
Develop	*Divergent Thinking*	Function Structure
		TILMAG
		Design Catalogues
	Convergent Thinking	Finite Element Analysis
		Design FMEA
		Pugh Matrix
Demonstrate	*Divergent Thinking*	Design of Experiments
		Rapid Prototyping
		Conjoint Analysis
	Convergent Thinking	Control Charts
		Process Map/VSM
		Standard Operating Procedures

3.2 Classification of Techniques by Cognitive Level and Cognitive Style

With the first two components of the classification scheme in hand (those related most closely to "Process"), we move now to the third and fourth components of our classification scheme, which highlight the cognitive diversity of the individual designer (i.e., the "Person"). These are: the *cognitive level* required for mastery of a technique and the *cognitive style* simulated through use of that technique.

The distinction between cognitive level and cognitive style has been discussed by many scholars, both in a general context[8,11,22] and in the specific contexts of engineering education[6,7] and design[13,14,24]. In general, *cognitive level* is a unipolar construct that relates to an individual's mental capacity, both *potential* (e.g., intelligence, aptitude, talent) and *manifest* (e.g., extant knowledge, skill, experience). Manifest level can be measured in terms of both *type* (i.e., domain – discipline, area of study) and *degree* (i.e., amount – novice, expert). *Cognitive style* is defined as a "strategic, stable characteristic – the preferred way in which people respond to and seek to bring about change" (including the solution of problems)[11]. As such, cognitive style is a bipolar construct that is independent from level; it also has multiple dimensions, including Adaption-Innovation (A-I)[11] and Introversion-Extraversion[18], among others[22].

Here, we begin our discussion with cognitive level, as it is often readily understood by engineering students and instructors alike, even if that formal term is not used. After all, in the classroom, both students and instructors are in the habit of assessing themselves and others in "level" terms – i.e., "how good" someone is at doing something, "how much" they have achieved, the particular "areas of study" in which they excel, etc. In earlier work [references to be provided after review], we demonstrated that techniques used in the early stages of design (e.g., for concept generation) can be characterized in terms of the degree of difficulty associated with learning and using them effectively. Here, we extend this proposition to design techniques across <u>all</u> stages of the design process, using the following scale to reflect the level required for their mastery:

- Level 1 = very easy to master
- Level 2 = easy to master
- Level 3 = mid-level difficulty to master
- Level 4 = hard to master
- Level 5 = very hard to master.

The same selection of 24 techniques that appeared in Table 2 will be mapped according to this level metric below (see Table 3), after we have discussed the classification of techniques according to simulated cognitive style.

Just as there are many dimensions of cognitive level, there are many dimensions of cognitive style as well. Here, we will focus on the dimension of cognitive style known as Adaption-Innovation (A-I)[11], as it was specifically developed and validated in the context of problem solving, making it highly suitable for design studies. A-I cognitive style is defined on a bipolar continuum that ranges from high Adaption to high Innovation (see Figure 4). The key distinguishing factor between individuals who are more adaptive and those who are more innovative (using relative terms, as befits a continuous model) is the type and amount of structure they prefer when solving problems, whatever the difficulty (i.e., level) of those problems may be[7,8,11].

In particular, the more adaptive prefer <u>more</u> structure when problem solving, with more of that structure consensually agreed, while the more innovative prefer <u>less</u> structure and are less concerned about achieving consensus around the structure they use. Said another way, the more adaptive prefer to work with and within existing guidelines or rules in order to achieve solutions that improve a system, whereas the more innovative are more likely to feel constrained by rules, preferring instead to operate at the edges of or even across structures in order to solve problems differently. Here, it is important to emphasize once again that the distinction between Adaption and Innovation is not one of dichotomy, but a spectrum of preference, which is far more useful for comparative purposes. Every individual (here, engineer or designer) is more adaptive when compared to some individuals and more innovative when compared to others[8,11].

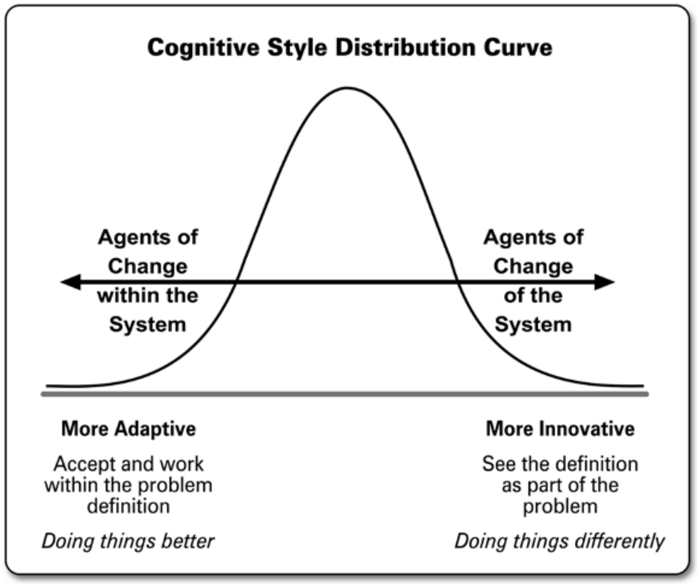

Figure 4. The Adaption-Innovation continuum of cognitive style

Based on these characterizations, techniques that simulate more adaptive thinking can be used to help design students generate and work with ideas that support and refine the structure of a system (making it more efficient), while those that simulate more innovative thinking can be used to help students generate and work with ideas that loosen or reframe the system's structure in tangential ways[7,13,14]. Clearly, many styles of thinking are required within any complex design effort, so it is important for students (and their instructors) to be able to choose techniques wisely and to build a "toolbox" of diverse techniques that can be used to meet different aims in a variety of circumstances. In addition, based on a student's own cognitive level and cognitive style, different amounts of individual coping behavior (i.e., behavior away from one's cognitive preference) will be required depending on which technique is used, all of which will impact the student's motivation and performance[6,8,11].

Supporting the integration of all four components into a single classification scheme, Jones[9] maintains that general problem solving techniques can be classified into those that aid convergent and divergent thinking operations, respectively, while Lopez-Mesa, *et al.*[13,14] suggest that they can be further classified into those that simulate more adaptive and more innovative styles. In other words, problem solving techniques can be classified as adaptive divergent techniques or innovative divergent techniques, or as adaptive convergent techniques or innovative convergent techniques. Strictly speaking, as with the continuum of cognitive style for individuals, this classification also spans a spectrum of style, with some techniques being more adaptive or more innovative than others, rather than "bunched" into two piles or categories.

So, in general, adaptive divergent techniques will help a designer generate a sufficient number of ideas through a process of successive refinement (e.g., Brainwriting 6-3-5) and systematic frameworks (e.g., Design Catalogues). Innovative divergent techniques enable the proliferation of ideas through concept re-structuring and increased boundary spanning (e.g., Brainstorming), as well as through abstraction and analogies (e.g., Forced Associations). Adaptive convergent techniques reduce or narrow the spectrum of ideas through detailed analysis (often quantitative in nature) of the ideas (e.g., Monte Carlo simulations) and through more structured processes (e.g., Control Charts). Innovative convergent techniques enable the evaluation and selection of ideas through the analysis of approximate or soft information (e.g., Pugh Matrix) and using more qualitative assessments (e.g., the Kawakita Jiro Method)[21].

To illustrate the third and fourth components of our new classification scheme, the 24 techniques selected and classified according to process stage and cognitive operation in Table 2 are now presented in Table 3 (divergent techniques) and Table 4 (convergent techniques), respectively, where they are organized in terms of the range of cognitive styles they simulate and the level required for their mastery. Note how, in general, techniques of different levels and styles span across the stages of the design process. Also note the introduction of a few familiar techniques (e.g., Brainstorming and Brainwriting 6-3-5[17]) into Table 3; these were added for reference due to their relative popularity and as benchmarks with respect to many students'/instructors' experience.

Table 3: Classification of Divergent Design Techniques (Across Process Stages) by Level and Style

Mastery Level	**More Adaptive Cognitive Style**	←	→		**More Innovative Cognitive Style**
5			Biomimicry		
4	Conjoint Analysis; Design of Experiments	Rapid Prototyping	TILMAG; Function Structure		
3				Nine Windows	Ethnography
2	Design Catalogues	SCAMPER		Forced Associations	
1		Brainwriting 6-3-5	Jobs to Be Done		Brainstorming

Table 4: Classification of Convergent Design Techniques (Across Process Stages) by Level and Style

Mastery Level	**More Adaptive Cognitive Style**	←	→		**More Innovative Cognitive Style**
5	Finite Element Analysis				
4			Heuristic Redefinition		
3	Control Charts	Value Analysis	Pugh Matrix		
2	Standard Operating Procedure (SOP)	Design FMEA	Process Map/VSM; Project Charter	Six Thinking Hats®	
1				Kawakita Jiro Method	Multi-voting

4. Practical Use of the Classification Scheme in the Classroom

To make best use of the new classification scheme in the classroom, and using the sample tables we have included here for purposes of illustration, we recommend that design students and their instructors take the following approach:

1. First, determine which stage of the design process you need to address (i.e., define, discover, develop, demonstrate) for your particular design opportunity.
2. Next, determine whether you need to expand (diverge) or focus (converge) your options within that stage.
    a. Use Table 2 to identify a set of techniques that meet these criteria.
3. Now move to a consideration of cognitive style and determine whether a more adaptive approach (tightening structure) or a more innovative approach (loosening structure) is required at present. (Note: the "best" approach in terms of style is likely to shift over time and across iterations of each design stage.)
    a. Use Table 3 or Table 4 (depending on your need for divergent or convergent thinking in Step 2) to down-select your set of techniques to those that meet the style criterion.
4. Finally, again using Table 3 or Table 4 as appropriate, select the technique(s) that best reflect the cognitive level available within your group (e.g., can you/your team manage high level techniques, or would a moderately simple technique be a better choice).
5. Repeat these steps as you move through the stages of the design process for your current design opportunity, revisiting the same techniques or choosing different ones based on the needs of the problem, even within a single stage.

In order for this approach to work well, of course, more design techniques than we have presented here will need to be mapped onto the classification scheme; we discuss this as future work below. For now, we want to emphasize that effective use of this classification scheme will require students and instructors to become familiar with a significant number of techniques – most likely, a number far beyond what is typically offered in standard design texts and typical design courses. This will require added time within the course curriculum, but the return on investment will be realized when the "right" design solutions are reached more quickly in the end, and with heightened awareness and insight – rather than purely as a result of trial and error.

5. Remaining Questions and Future Work

The new classification scheme presented here makes good conceptual sense, but at this point, the mapping of techniques is based mostly on evaluation (and some debate) by the authors and a few others. We will need a consensus of multiple design practitioners (including students and instructors) to confirm our findings and to evaluate an expanded list of techniques. We are currently designing and validating a survey that will serve this purpose; at last count, over 500 design techniques have been collected for review.

This brings us to the small sample of techniques listed here. Due to space and other practical limitations, we selected only 24 techniques for analysis in this paper, and as a result, our tables clearly have gaps in them. In analyzing and classifying an expanded number of techniques (as described above), we will need to remain cognizant of how well the cognitive design space represented by Tables 2, 3, and 4 is being "covered" by the techniques that already exist. In other words, we want to be sure that sound techniques are available for every combination of process stage, cognitive operation, cognitive level, and cognitive style. If a technique cannot be found to fill a particular position within the tables, then new techniques will have to be created or existing techniques adapted to fill that void.

Finally, it will be necessary to test the clarity and effectiveness of this classification scheme and its application in practical settings. We have supplied a recommended process for using the new classification scheme in Section 4, but further vetting inside and outside the design classroom will be required. Plans for testing the efficacy of the scheme and its application in both academic and corporate settings are under development.

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Appendix A: Selected Techniques and Brief Descriptions

The brief descriptions provided below are intended only as introductions to the selected techniques. Additional details about each technique can be found in works by Christensen, *et al*.[2], LeCompte & Schensul[12], Mann[15], King & Schlicksupp[10], Terninko, *et al*.[25], Michalko[17], Benyus[1], Pugh[20], and Pahl & Beitz[19], among many others available in both the scholarly and popular literature.

Table 5: Design Techniques and Their Brief Descriptions

Technique	Brief Description
Biomimicry	A technique for learning from and then emulating nature's solutions to complex problems.
Conjoint Analysis	A simplified experimental technique for determining the best combination of attributes to include in a product or service design based on the trade-offs customers are willing to make.
Control Charts	Used to monitor the performance of a process, product, service, or solution at the output (Y) and input (X) levels, answering the question: is the process running as expected?
Design Catalogues	A collection of known and proven solutions for design problems. They contain detailed data regarding solutions, such as phyiscal effects, limitations, and operating environments.
Design FMEA	Design Failure Mode and Effects Analysis (Design FMEA) is used to anticipate possible failures or problems with new solutions before they occur and to have a plan for what to do in response.
Design of Experiments	A set of systematic experiments carried out under controlled but varying conditions of input variables in order to discover an unknown effect, to test a hypothesis, or to illustrate a known effect .
Ethnography	Based on the practice of observing how customers try to "get their jobs done" using products, services, and solutions.

Finite Element Analysis	A numerical technique for finding approximate solutions of partial differential equations or integral equations that can be used to model a product under design and development.
Forced Associations	Uses association in connection with an arbitrary word or image to generate ideas.
Function Structure	Breaks down the intended overall design function into cohesive and naturally workable sub-functions that lend themselves to error-free development.
Heuristic Redefinition	A visual approach for focusing and scoping a design project at the right level in a system.
Jobs To Be Done	Leads designers to the higher purpose for which customers buy and use products, services, and solutions.
Kawakita Jiro (KJ) Method	A way to organize and refine design ideas (also known as an "affinity diagram").
Multi-Voting	Assists in reaching team consensus quickly when the team is ranking several ideas or selecting the best choice among them. Each member is given a finite number of votes to rank the ideas, and the votes are collated into a team consensus.
Nine Windows	Helps designers examine a design opportunity across the dimensions of time (past, current, future) and space (super-system, system, sub-system).
Process Map/VSM	Basic flowcharts that depict the progression of steps, decisions, and handoffs involved in transitioning a new product or service from design to production/delivery.
Project Charter	A project summary document that includes the design project objectives, business case, key assumptions, milestones, resources applied, the projected return on investment, and many other data points for communicating among various stakeholders.
Pugh Matrix	Assists in evaluating multiple ideas or design concepts against each other in relation to a baseline or datum.
Rapid Prototyping	A design and communication technique that quickly creates a 3D model of a new product design.
SCAMPER	A set of directed questions that help evolve an existing product, service, or solution into one that is more ideal. (S=Substitute; C=Combine; A=Adapt; M=Modify; P=Put to other uses; E=Eliminate; R=Rearrange)
Six Thinking Hats	Leverages different points of view (one view per "hat") to help evaluate ideas.
Standard Operating Procedures	Describes a procedure or set of procedures to perform an operation, detailing all steps and activities of the process.
TILMAG	Uses pair-based analogical thinking to transform a design's main features into unique design concepts.
Value Analysis	The ratio of a solution's desired outcomes to its undesired outcomes – relative to some Job To Be Done (also called "value quotient").