*Design Principles: The Foundation of Design*

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# DESIGN PRINCIPLES: THE FOUNDATION OF DESIGN

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## ABSTRACT

Design principles are created to codify and formalize design knowledge so that innovative, archival practices may be communicated and used to advance design science and solve future design problems, especially the pinnacle, wicked, and grand-challenge problems that face the world and cross-cutting markets. Principles are part of a family of knowledge explication, which also include guidelines, heuristics, rules of thumb, and strategic constructs. Definitions including a range of explications are explored from a number of seminal papers. Based on this analysis, the authors pose formalized definitions for the three most prevalent terms in the literature – principles, guidelines, and heuristics. Current research methods and practices with design principles are categorized and characterized. In analyzing the methodology for discovering, deriving, formulating and validating design principles, the goal is to understand and advance the theoretical basis of design, the foundations of new tools and techniques, and the complex systems of the future. Suggestions for the future of design principles research methodology for added rigor and repeatability are proposed.

## 1 INTRODUCTION

A number of technical research fields have grown and matured over decades through the investigation, study, experimentation, and validation of core principles. Accepted research methodologies and standards similarly emerge and mature, founded on the scientific method, but also tailored to the characteristics and scope of the field. The life sciences and physical sciences are classical examples of this growth and maturation process. Numerous cases are prevalent in these fields, such as the theories and laws from classical mechanics to explain the motion of particles, bodies, and systems of bodies.

Design research, or design science, is a relatively young field of research investigation. With the first treatises published around the mid-twentieth century, design science has grown steadily in the devoted attention and depth of investigation. From the very earliest discourse related to this field, such as Glegg's "The design of design," principles of design have been postulated [4]. Because of the broad and interdisciplinary or trans-disciplinary nature of design science, numerous forms of design principles have been suggested across disciplines, between disciplines, and at various levels of granularity or specificity. The time is now apparent to carefully study these efforts, seeking a formalization of design principles, definitions, and supporting research methodologies.

In this paper, we seek to make strides in formalizing design principles in terms of the various disparate theoretical, empirical, and experimental approaches. This research will assist in enabling a fundamental understanding and development of design principles, and associated processes, as well as guiding researchers and practitioners in advancements and use of such principles. Ultimately, the research provides foundations to design science.

## 2 BACKGROUND

The formalization of design research methodology is the indisputable path to the maturation of the field. Pahl and Beitz, some of the first to propose formalized design processes and research [1]. Blessing and Chakrabarti formulated a DRM (Design Research Methodology) process comprised of 4 main steps: (1) Research Clarification, or literature review to formulate a worthwhile research goal, (2) Descriptive Study I, or empirical data analysis in an exploratory study, (3) Prescriptive Study, or assumption experience synthesis into a vision of how to improve upon on the existing situation, and (4) Descriptive Study II, or empirical data analysis of the effect of the improvement support developed [2]. Finger and Dixon extensively reviewed design research methods, including descriptive models of design processes, prescriptive models for design, computer-based models of design processes, languages, representations, and environments for design, analysis to support design decisions, design for manufacturing and other life cycle issues such as reliability, serviceability, etc. [3, 4]. Many of the research efforts reviewed in this paper fall into one of these categories, whether through descriptive models like case studies, protocol studies, and observations, or prescriptive models of how the design process ought to be carried out [4]. Inductive vs. deductive research methodologies are a particular focus in this paper, where inductive research is based upon a process in which data is collected first, patterns are extracted, and a theory is developed to explain those patterns, while deductive research is based upon a process in which a theory is developed first, after which data is collected and analyzed to determine if the theory is supported. Though not perfectly aligned in meaning, descriptive research and inductive research methods are similar in that they both rely on discovery of patterns and findings in data, while prescriptive research and deductive research methods are similar in that they pose a theoretical solution or answer, and test if it is effective or supported. The methodologies reviewed in this paper tend to fit into one of these two categories, though some are both. In reviewing the current research efforts to extract design principles, effective techniques and areas for improvement and development of greater rigor can be identified toward a more formalized design principles research methodology.

## 3 RESEARCH METHODOLOGY

This paper is both a literature review and original critical analysis of the state-of-the-art with the goal of advancing and formalizing the field of design principles research. To gain an understanding of the types and prevalence of each type of methodologies for exploring, deriving and validating design principles, the authors reviewed 66 sources, including monographs, books, anthologies, journal publications, and conference publications. References were chosen based on either their seminal nature to the foundation of the field (noted by their longevity and/or high citation rate) or their publication in leading design engineering journals or conference proceedings. Figures 1, 2, and 3 show the proportional breakdown of types of references, the field that the references come from, and the distribution of references by year of publication.

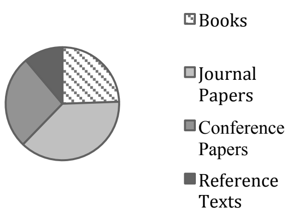


**FIGURE 1. PROPORTION OF REFERENCE TYPES**

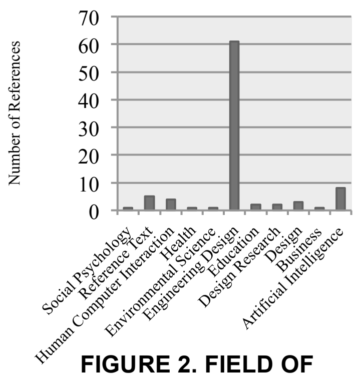


**FIGURE 2. FIELD OF REFERENCES**

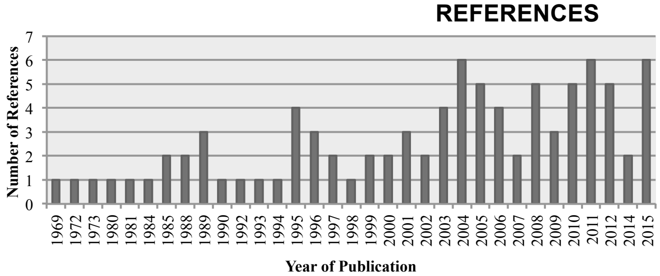


**FIGURE 3. REFERENCE YEAR OF PUBLICATION**

As each reference was reviewed, the authors tabulated the following information from each source where applicable: keywords/key topics, main contribution/brief synopsis, methods to find principles, methods to validate principles, principles discovered, and any articulated formal nomenclature definitions. This tabulation was analyzed in several different ways, as reviewed in the following sections.

## 4 DISCUSSION OF NOMENCLATURE

In the pursuit of standardization, formalization and added rigor to any scientific methodological undertaking, the articulation of clear and well-reasoned definitions for key concepts is imperative. Formal definitions ensure a common understanding and universal language, not only between the authors and reader, but hopefully spreading throughout the research community over time. In the following Sub-Sections (4.1-4.5), the authors present articulated formal definitions of design principles from the literature reviewed. A formal definition for each term is then posed based on an amalgamation and aggregate assessment of the literature findings and the expertise of the authors. These definitions are within the context of the design research field, and, therefore have an implied "design" before each term reviewed (i.e. *design* principle).

### 4.1 Principle

Design principles are the focus of this research, though the methodologies surrounding their conceptual kin (i.e. heuristics, etc.) can be and often are similar, relevant, and applicable to those for design principles. Several definitions and characteristics have been gathered and juxtaposed below in their original form. Researchers use a large variety of terms when defining "principle," including: technique, methodology, data, experience, example, recommendation, suggestion, assertion, and proposition. Factors considered when classifying and describing principles include: level of detail in which they impact the design, point of application in the design process, level of abstraction, specificity or granularity of the principle itself, the manner in which principle is applied, the level of refinement or success of the principle, among others. As expected, terms like "guideline" are used to define principles, and are often used interchangeably in informal settings. To summarize the literature review in Table 1, the common threads that can be observed throughout most of the definitions are:

- Principles are not universally applicable, effective, or true but instead are generally applicable, effective, and true in a given context.
- Principles are typically based on experiences, examples, or empirical evidence.
- The application of principles may be context and/or problem dependent, but should be more generalizable than a few isolated instances
- Principles are used as foundations for understanding and for the development of supporting methods, techniques, and tools.

Based on the literature review and analysis of the definitions, the following is a proposed formalized definition for *principle*.

**Proposed Formal Definition:**

***Principle***: *A fundamental rule or law, derived inductively from extensive experience and/or empirical evidence, which provides design process guidance to increase the chance of reaching a successful solution.*

**TABLE 1. LITERATURE REVIEW OF DEFINITIONS AND CHARACTERISTICS FOR "PRINCIPLE"**

| Source | Definition/Characteristics |
|---|---|
| [5] Merriam-Webster Dictionary | "A moral rule or belief that helps you know what is right and wrong and that influences your actions; a basic truth or theory: an idea that forms the basis of something; a law or fact of nature that explains how something works or why something happens" |
| [6] Moe et al., 2004<br>[7] Weaver et al., 2008<br>[8] Singh et al., 2009 | "A (transformation) principle is a **generalized directive** to bring about a certain type of mechanical transformation. A (transformation) principle is a ***guideline*** that, when embodied, singly creates a transformation." |
| [9] Glegg, 1969 | "Principles of engineering design can be divided into **three distinct types**:<br>1. **Specialized techniques**: **particular data** and **manufacturing techniques** that have been amassed over a long period of time with respect to a very specific technology that you cannot hope to design that product without - i.e. camshaft for a |

 

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|---|---|
| | petrol engine.<br>2. **General rules**: **broader theoretical considerations** which are not confined to a single engineering mechanism - wide though their scope may be, they are not of universal application.<br>**3. Universal principles**: **underlying laws** which **cross** the **frontiers** of most **engineering design**. They are the rules behind the rules; they are not tied to any particular type of design, they concern the design of design." |
| [10] Bell et al., 2004 | Design principles are "…an **intermediate step** between **scientific findings**, which must be generalized and replicable, and **local experiences** or **examples** that come up in practice. Because of the need to interpret design principles, they are not as readily falsifiable as scientific laws. The principles are **generated inductively** from **prior examples** of **success** and are subject to **refinement** over time as others try to adapt them to their own experiences. In this sense, they are falsifiable; if they do not yield purchase in the design process, they will be debated, altered, and eventually dropped." |
| [11] Kali, 2008 | "**Specific Principles** describe the **rationale** behind the design of a **single feature or single research investigation**. Due to their direct relation to one feature, specific principles in the database are embedded within the features.<br>**Pragmatic Principles connect** several Specific Principles (or several features), …<br>**Meta-Principles** capture **abstract ideas** represented in a cluster of Pragmatic Principles." |
| [12] Anastas and Zimmerman, 2003 | "The principles are not simply a listing of goals, but rather a **set** of **methodologies** to **accomplish** the **goals**…The breadth of the principles' **applicability** is important. When dealing with design architecture, …the same…principles must **be applicable, effective, and appropriate**. Otherwise, these would not be principles but simply a list of useful techniques that have been successfully demonstrated under specific conditions. Just as every parameter in a system **cannot be optimized at any one time**, especially when they are interdependent, the same is true of these principles. There are cases of synergy in which the successful application of one principle advances one or more of the others." |
| [13] Mattson and Wood, 2014 | "A principle…[is] a **fundamental proposition** used to **guide** the **design process**. The principles in this paper are not suggestions or activities the designer should complete, they are assertions that can guide the designer to a **more effective outcome**. The principles do not explicitly say what should be done; they simply **guide** the engineer **as decisions are made**...Although principles are **not guaranteed**, and at times they **should not be followed**, they should **always be considered**" |
| [14] McAdams, 2003 | A design principle is "'a **recommendation** or **suggestion** for a **course of action** to **help solve a design issue'**. This definition is adapted from the definition for a design *guideline* according to Nowack (1997). **Off-line principles** are applied at the **design stage**. **On-line principles** are applied **anytime after this stage**, including manufacturing and during use. Another characteristic that distinguishes between the principles is the **level of detail** that they change the design." |
| [15] Perez et al., 2011 | "A set of principles can make this process **more efficient** as well as **improve on the design** of the original product. The principles provide a means of **processing the information** gathered in the reverse engineering step in order to **derive ideas based on specific details encompassed by the example products**." |
| [16] Sobek et al., 1999 | "…Principles…are **not steps, prescriptions, or recipes**. Rather, (Toyota chief) engineers **apply** the principles to **each design project differently**. Design engineers use the principles to **develop and evaluate a design process**. The key to success is the implementation of ideas as much as the principles themselves." |
| [17] Altshuller, 1994 | "Technical evolution has its own **characteristics** and **laws**. This is why different inventors in different countries, working on the same technical problems independently, come up with the same answer. This means that certain ***regularities*** exist. If we can find these regularities, then we can use them to solve technical problems – **by rules, with formulae**, without wasting time on sorting out variants." – in describing the 40 inventive principles of TRIZ |
| [1] Pahl and Beitz, 1988 | "Only the combination of the physical effect with the geometric and material characteristics (working surfaces, working motions and materials) allows the principle of the solution to emerge. This interrelationship is called the *working principle* …and it is the **first concrete step** in the **implementation** of the **solution**." |

## 4.2 Guideline

As discovered in the literature addressing the definitions and characteristics of principles, we find similar content for that of guidelines. Key terms found throughout the literature quoted in Table 2 include: prescriptive, imperative, advice, instruction, opinion, recommendation, assistance, prediction, and general. Descriptions address factors such as when to use guidelines during the design process, how they must be changed and revised, and how they must be presented and described to their user. There are two key differences that stand out between the definitions of principles and guidelines:

- Guidelines seem to be presented as more context dependent and changeable than principles – perhaps even less "universal" or "fundamental."
- The literature on guidelines places strong emphasis on their modality, organization, and level of detail of presentation for maximum effectiveness and usability, though this could be an artifact of the choice of references.
- Guidelines are described as more prescriptive than heuristics, presented in the next section, which tend to be descriptive or prescriptive.

Based on the literature review and analysis of the definitions, the following is a proposed formalized definition for *guideline*.

**Proposed Formal Definition:**

***Guideline***: *A context-dependent directive, based on extensive experience and/or empirical evidence, which provides design process direction to increase the chance of reaching a successful solution.*

**TABLE 2. LITERATURE REVIEW OF DEFINITIONS FOR "GUIDELINE"**

| Source | Definition/Characteristics |
|---|---|
| [18] Merriam-Webster Dictionary | "A rule or instruction that shows or tells how something should be done" |
| [19] Greer et al., 2002. | "Design guidelines provide a **means** to **store** and **reuse design knowledge** with the potential to be effective in the **early stages** |

 

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|---|---|
| | of design where…**broad knowledge** is **beneficial**. The format used to present the product evolution design guidelines is the **imperative form** from English grammar…According to Nowack, a design guideline has at least four parts: issue(s) addressed or impacted, links to design context, action recommendations, and rationale [20].” |
| [20] Nowack 1997 | A design guideline is “a **prescriptive recommendation** for a **context sensitive course of action** to **address a design issue**.” |
| [21] Kim, 2010 | “…Design guidelines can…be considered as an **intermediary interface** between the **designer** and …[expert] **knowledge**. The purpose of design guidelines is to **enable designers** to make **usable** and **consistent applications** that **conform** to **designated conventions**. To maximize the compliance of the resulting products, it is important to produce design guidelines that **designers can actually understand and apply** [22]. Design guidelines address a wide **range** of **design levels**; the contents are typically based on **laboratory experiments** and **experts' opinions**. These guidelines are being **continuously revised** and **updated** to meet technical and environmental **changes**.” |
| [23] Bevan and Spinhof, 2007 | “A good set of guidelines is composed of a **combination** of more **specific** guidelines for the **application** at hand and more **generic** guidelines that refer to more **general aspects**...”<br>“And the set of guidelines should be **well documented**, including **good or bad examples**, a thorough table of contents and glossaries [21].” |
| [24] Jänsch and Birkhofer, 2006 | “The **generality** inherent in all guidelines has been greatly increased… direction of the guidelines has changed from a personal support for individuals…towards a **general procedure** for a **company** addressing organization and content….advice within the guidelines [has] changed from addressing concrete thinking processes to **general problem solving advice**…instructions have changed from statements that can be immediately put into action or thought to **instruction on an abstract level**, which **need to be adapted to the current situation** of the designer… appearance of the descriptions of the guidelines have altered from a pure one-page text-based description to comprehensive descriptions with **figures**, in particular **flow charts and in-depth texts**….content of the descriptions has been enhanced with **figures**, **examples** and a **quantity** of **text**.” |
| [25] Matthews, 1998 | “Guidelines can provide **additional assistance** by **predicting likely outcomes** of **actions** and by **identifying additional issues** that should be **considered**. For guideline support to be effective, appropriate guidelines must be available to the designer at the **time of a design decision**.” |

## 4.3 Heuristic

The term heuristic has an understandably broader and richer base of literature from which its definition can be derived, as it has both connotations with computational applications as well as analogue design process applications. Table 3 draws upon both sets of literature in an attempt to generalize the definition among the fields of application. Key terms used in describing and defining heuristics from the sampled literature include: rule-of-thumb, guideline, common sense, principle, experience, observation, knowledge, lesson, strategy, simple, concise. Again, as in the previous two section defining principle and guideline, we find the terms can be and often are used interchangeably in the literature. Distinctions that emerge based on the literature sampled that make heuristics unique include:

- Emphasis on reducing search time – not necessarily an optimal result, but satisfactory, practical or “quick and dirty.”
- Ability to be prescriptive or descriptive, unlike guidelines, which are mostly prescriptive.
- Value is typically defined by usefulness
- Heuristics are generally reliable, but potentially fallible depending on context and circumstances.
- There may not be as extensive evidence or validation of heuristics, compared to guidelines, and especially principles.

Based on the above literature review and analysis of these definitions, the following is a proposed formalized definition for *heuristic*.

**Proposed Formal Definition:**

***Heuristic***: *A context-dependent directive, based on intuition, tacit knowledge, or experiential understanding, which provides design process direction to increase the chance of reaching a satisfactory but not necessarily optimal solution.*

**TABLE 3. LITERATURE REVIEW OF DEFINITIONS FOR “HEURISTIC”**

| Source | Definition/Characteristics |
|---|---|
| [26] Merriam-Webster Dictionary | “Using experience to learn and improve; involving or serving as an aid to learning, discovery, or problem-solving by experimental and especially trial-and-error methods <*heuristic* techniques> <a *heuristic* assumption>; *also*: of or relating to exploratory problem-solving techniques that utilize self-educating techniques (as the evaluation of feedback) to improve performance <a *heuristic* computer program>” |
| [27] Stone and Wood, 2000 | “(Module) heuristics: A method of examination in which the designer uses **a set of steps, empirical in nature, yet proven scientifically valid**, to identify (modules) in a design problem. This definition requires another: the phrase ‘**proven scientifically valid**’ refers to a hypothesis, formulated after systematic, objective data collection, that has **successfully passed** its **empirical tests**. Thus, the **heuristics** are **proven** by following the **scientific method**.” |
| [28] Bolc and Cytowshi, 1992 | “Heuristics [are] **explicit rules** derived from **human experiences** and **tacit knowledge**.” |
| [29] Li et al., 1996 | “Heuristics are **rules-of-thumb** that have been successful in producing ‘**acceptable**’, **not necessarily** ‘**optimal’ solution** to a type of problem.” |
| [30] Chong et al., 2009 | Heuristics “…are **criteria, methods**, or **principles** for **deciding** which **among several alternative courses** of **action promises** to be the **most effective** in order to **achieve the desired goals**.” |
| [31] Nisbett and Ross, 1980 | “Heuristics are **reasoning processes** that **do not guarantee the best solution**, but **often lead to potential solutions** by providing a **“short-cut”** within cognitive processing.” |
| [32] Pearl, 1984 | “The term ‘heuristic’ has commonly referred to **strategies** that **make use of readily accessible information** to **guide problem-solving**.” |
| [33] Yilmaz and Seifert, 2011 | “The term ‘heuristic’ implies that it:<br>1) **Does not guarantee reaching the best solution**, or **even a solution**; and |

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| | 2) **Provides** a **'quick and dirty' (easier) method** that often leads to an **acceptable solution**." |
| [34] Koen, 1985 | "**All engineering is heuristic**.<br>"**Synonyms** of the heuristic: rule of thumb, intuition, technique, hint, aid, direction, rule of craft, engineering judgment, working bias, random suggestions, le pif (the nose)<br>A heuristic is an "**engineering strategy** for causing **desirable change** in an **unknown** situation within the **available resources**…anything that provides a **plausible aid** or **direction** in the solution of a problem but is in the final analysis **unjustified**, **incapable** of **justification**, and **fallible**. It is used to **guide**, to **discover**, and to **reveal**.<br>"Signatures of the heuristic:<br>• A heuristic **does not guarantee** a solution<br>• It **may contradict** other heuristics<br>• It **reduces** the **search** time in **solving** a problem for a **satisfactory solution**<br>• The **absolute value** of a heuristic…is based on the pragmatic standard …[it] depends exclusively on its **usefulness** in a specific context…a heuristic never dies. It just fades from use.<br>• One heuristic [replaces] another by…**doing a better job** in a given context." |
| [35] Magee and Frey, 2006 | "A heuristic is a **generally reliable**, but **potentially fallible**, **simplification** that enables a problem to be addressed within **resource constraints.**" |
| [36] Clancey, 1985 | "The heuristic classification model characterizes a form of **knowledge** and **reasoning-patterns** of **familiar problem situations** and **solutions**, heuristically related. In capturing problem situations that tend to occur and solutions that tend to work, this **knowledge** is **essentially experiential**, with an overall **form** that is **problem-area independent**." |
| [37] Maier and Rechtin, 2000 | "The heuristics methodology is based on "**common sense**," …comes from **collective experience** stated in as **simple** and **concise** a manner as possible… **Insight**, or the ability to structure a complex situation in a way that greatly increases understanding of it, is strongly guided by **lessons learned** from one's own or others' **experiences** and **observations**. But they **must be used with judgment**.<br>"People typically use heuristics in three ways…[1] as evocative guides... **evoke new thoughts**…[2] as **codifications** of **experience**…[3] as **integrated into development processes**.<br>"Two forms of heuristic[s]…[1] **descriptive**: it **describes** a **situation** but does not indicate directly what to do about it…[2] **prescriptive**: it prescribes **what might be done** about the situation.<br>"Heuristics…are trusted, nonanalytic guidelines for treating **complex**, inherently **unbounded**, ill-structured **problems**….are used as aids in **decision making**, **value judgments**, and **assessments**…provide the successive **transitions** from qualitative, provisional needs to **descriptive** and **prescriptive guidelines** and, hence, to **rational approaches** and **methods**.<br>**Heuristic evaluation criteria** "…to eliminate unsubstantiated assertions, personal opinions, corporate dogma, anecdotal speculation, mutually contradictory statements:<br>• … must **make sense** in its original domain or context…a strong **correlation**, if not a direct **cause and effect**, must be apparent between the heuristic and the successes or failures of specific systems, products, or processes.<br>• The general sense…of the heuristic should **apply beyond the original context**.<br>• The heuristic should be **easily rationalized** in a few minutes or on less than a page.<br>• The **opposite statement** of the heuristic should be **foolish**, clearly not "common sense."<br>• The heuristic's **lesson**, though not necessarily its most recent formulation, should have **stood** the **test** of **time** and earned a broad consensus.<br>• Humor (and **careful choice of words**) in a heuristic provide an emotional bite that enhances the mnemonic effect<br>• For maximum effect, try **embedding both descriptive** and **prescriptive** messages in a heuristic.<br>• **Don't make a heuristic so elegant** that it only has meaning to its creator, thus **losing general usefulness**.<br>• **Rather** than **adding** a **conditional statement** to a heuristic, consider creating a **separate** but **associated heuristic** that focuses on the insight of dealing with that conditional situation. |

To synthesize the three previous Sections (4.1-4.3), the authors pose a set of dimensions that form the definitions of heuristics, guidelines, and principles:

- Supporting Evidence or Validation Dimension: the degree of supporting evidence for the terms tends to be ordered as heuristics, guidelines, and principles in increasing evidence.
- Granularity or Specificity: the degree of granularity or specificity for the terms tends to be ordered as heuristics, guidelines, and principles in increasing formalization.
- Formalization Dimension: the degree of formalization of the terms tends to be ordered as heuristics, guidelines, and principles in increasing formalization.
- Prescriptive-Descriptive Dimension: the nature of the terms tends to be ordered as heuristics, guidelines, and principles, progressing from more prescriptive to more descriptive.

## 4.4 Additional Nomenclature

A number of terms fall into the same family as principles, guidelines, and heuristics, but are not used as prevalently in the literature. A few of these terms are reviewed here as acknowledgment of their importance, relationship, and distinction from the three terms defined thus far.

### 4.4.1 Rule/Commandment

Roozenburg and Eekels discuss design *rules* as dichotomous in nature, either being algorithmic or heuristic. Algorithmic design rules are "based on knowledge where the relationship between cause and effect is known well, as in physical laws, and they produce predictable and reliable results." Heuristic design rules are much less well defined, guaranteed, or proven. They state that "any design rule that cannot be converted into an algorithm is heuristic" [38]. In light of the discussion thus far, were there to be a continuum rather than a dichotomy between algorithmic and heuristic rules, it would be expected that principles might be placed closer to the algorithmic end, heuristics closer to the heuristic end (naturally), and guidelines somewhere in between.

Only one instance of the term *commandment* was encountered in the work of Hamstra [39], which presented a set of seven commandments for exhibit and experience design. The research describes commandments as "not written in stone…[as] creative work cannot be done from a straightjacket of design principles…[they] combine…beliefs about…goals and planning, …methods, and content development, and are designed to spark discussion and inspiration…and to clarify ambitions to clients" [39]. Interestingly, the author portrays design principles as restrictive, more so than commandments, despite the semantic connotation of the term. Commandments as defined come across as most similar to guidelines, in that they are prescriptive in nature, and based on beliefs rooted in successful design experiences.

**4.4.2 Facilitator** *Facilitator* is a term found in a series of related works that study the design of transformers [6-8]. As stated by the authors, "a Transformation Facilitator is a design archetype that helps or aids in creating mechanical transformation. Transformation Facilitators aid in the design for transformation but their implementation does not create transformation singly" [6-8]. This term harkens to the recommendation of Maier and Rechtin [37] to create associated heuristics one is tempted to add a conditional statement – in that there are corollaries and associations among them as well, in addition to being potentially descriptive rather than prescriptive.

**4.4.3 State of the Art (SOTA)** Koen inextricably links heuristics to the term *state of the art* [34], which he defines simply as a SOTA, or "a group of heuristics." He goes on to stipulate that "each should be labeled…and…time stamp[ed], [as]…SOTA is a function of time. It changes as new heuristics become useful and are added to it and as old ones become obsolete and are deleted" [34]. As stated earlier in the heuristic section, Koen sees all of engineering as heuristic, so naturally state of the art practice is defined by those heuristics.

**4.4.4 Ontology** Gruber provides a relevant and cogent definition of *ontology*, stating that "a conceptualization is an abstract, simplified view of the world that we wish to represent for some purpose. Every knowledge base, knowledge-based system, or knowledge-level agent is committed to some conceptualization, explicitly or implicitly. An ontology is an explicit specification of a conceptualization…When the knowledge of a domain is represented in a declarative formalism, the set of objects that can be represented is called the universe of discourse. This set of objects, and the describable relationships among them, are reflected in the representational vocabulary with which a knowledge-based program represents knowledge" [40]. Ontology, as Gruber defines it, could be conceived of as the umbrella under which all other terms discussed here may sit.

**4.4.5 Standard** *Standards*, as defined by Cheng [41], are "documented agreements containing technical specifications or other precise criteria to be used consistently as rules, guidelines or definitions of characteristics, to ensure that materials, products, process and services are fit for their purpose." This definition has a mix of softer, more subjective words like "agreements" and "guidelines" in combination with more definitive, strong terms like "precise criteria", "technical specifications", and "ensure". One interpretation of these mixed subtexts is that standards are often put into place through governmental regulations, relying upon agreement of law makers and technical experts, and the expertise of the state of the art practices, as translated (to the extent possible) into exact numerical specifications – no small feet to achieve, let alone define.

**4.4.6 Algorithm** Suh conceived of Axiomatic Design, from which the definition for *algorithm* and the following definition for *axiom* are taken [42, 43]. Suh states that "in purely algorithmic design, we try to identify or prescribe the design process, so in the end the process will lead to a design embodiment that satisfies design goals. Generally, the algorithmic approach is founded on the notion that the best way of advancing the design field is to understand the design process by following the best design practice" [42]. According to Suh, most terms discussed thus far would fit within the category of algorithmic design.

**4.4.7 Axiom** Suh goes on to define axioms as "generalizable principles that govern the underlying behavior of the system being investigated. The axiomatic approach is based on the abstraction of good design decisions and processes. As stated earlier, axioms are general principles or self-evident truths that cannot be derived or proven to be true, but for which there are no counterexamples or exceptions. Axioms generate new abstract concepts, such as force, energy and entropy that are results of Newton's laws and thermodynamic laws" [42, 43]. While Suh uses the term "principle" in the definition for axiom, the requirements for the level of unshakeable truth and correctness of them makes axioms the most stringent term discussed yet.

**4.4.6 Strategy** Merriam-Webster defines *strategy* as the following:

"1: a careful plan or method for achieving a particular goal usually over a long period of time

2: the skill of making or carrying out plans to achieve a goal" [44]

None of the sources reviewed here directly or explicitly defined *strategy*, but rather used rule of thumb as a synonym for other terms, such as principle or heuristic.

**4.4.8 Rule of Thumb** Merriam-Webster defines *rule of thumb* as the following:

"1: a method of procedure based on experience and common sense

2: a general principle regarded as roughly correct but not intended to be scientifically accurate" [45]

As with strategy, none of the sources reviewed here directly or explicitly defined rule of thumb, but rather used rule of thumb as a synonym for other terms, such as principle or heuristic.

## 5 DESIGN PRINCIPLES RESEARCH METHODS

To gauge the state of the art in research methodologies for design principles and their kin, 66 publications were analyzed. From this point forward in the paper, the term "principle" is used to refer to itself and any of the other familial terms reviewed in the nomenclature section, as the methods and sources for deriving and validating any of the knowledge codification types reviewed previously is valuable to this analysis. The research efforts analyzed in Section 5 include the following references: [2, 6-9, 11-17, 19, 21, 22, 24, 25, 27, 30, 33-36, 39, 40, 46-88]. The topics addressed in the research efforts reviewed include: transformational design, biomimetic/bio-inspired design, robotics, software design, user interface design, reconfigurable design, green/environmental design, TRIZ, biomechanical design, universal design, among other topics.

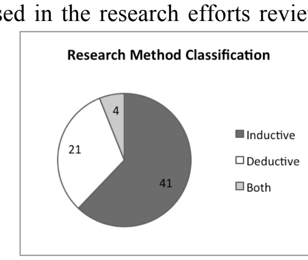


**FIGURE 4. RESEARCH METHOD CLASSIFICATION FOR ANALYZED LITERATURE**

In Figure 4, the proportion of research efforts in the literature that used deductive

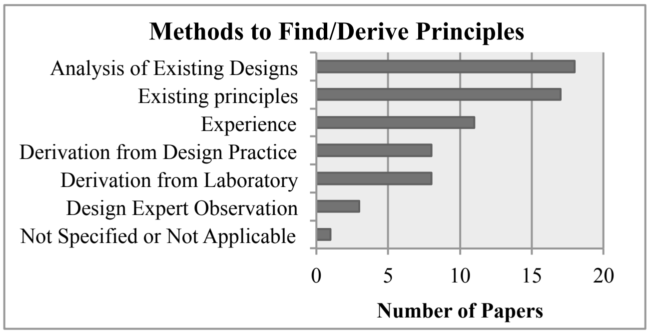


**FIGURE 5. METHODS USED IN LITERATURE TO DERIVE DESIGN PRINCIPLES**

vs. inductive approaches
is shown, including those that used both approaches. The majority of researchers used an inductive method, which will be discussed further in the next two sections.

### 5.1 Review of Methodologies for Extraction/ Derivation/ Discovery of Design Principles

Each of the 66 references was examined to ascertain the methodology used by the authors to derive, discover, extract, or codify design principles. These were first tabulated as their specific detailed methodologies, and then reduced to broader categories, including:

- **Not Specified or Not Applicable**: the authors did not state the method by which the principles were derived
- **Design Expert Observation**: *in situ* observation of expert designers at work expressly not a laboratory setting or study
- **Derivation from Laboratory Base Design Practice**: design study based data was collected, from which principles were extracted
- **Derivation from Design Practice**: based on design performed by the authors, from which principles are derived – can be less time and experience than expert level, otherwise would fall into the next category
- **Experience**: derived from the experience of an expert designer or collection of expert designers, usually the author(s)
- **Existing Principles**: existing literature was used as the source of principles, which were validated or tested using one of the means discussed in Section 5.2
- **Analysis of Existing Designs / Design Repositories/Empirical Data Sets**: consumer products, patents, nature, or even software are analyzed

As shown in Figure 5, the most publications derived principles by studying existing designs themselves, a methodology that has the benefit of publicly accessible data sources and large accessible sample sizes. The second most frequent methodology used principles derived by others, a clear deductive approach to design principles research, in which the theory is the starting point of the research confirmed by the validation step. Design experts often write about their career's worth of experiences in a memoir-esque format, sharing their life long lessons learned for designers to come. The least prevalent methodologies are those that are highly energy and resource intensive in terms of observation, data collection and data coding and analysis. Very few of the papers did not specify or address where the principles came from, or how they were derived.

Figure 6 shows the sources that researchers used from which to derive principles. Many cited multiple sources, for example using both consumer products and literature review. If the authors generated principles from their own design activities, it was coded as "authors", rather than "design project/task." This choice was made to illustrate that many authors and researchers are writing about their own design experiences, lessons, and accumulated knowledge, rather than deriving it from an external source. The categories shown in Figure 4 are described as the following:

- **Design Project/task**: designers/study subjects perform a design task
- **Students**: students serve as the subjects for a design study
- **Not Specified/Not Applicable**: the authors did not state the source
- **Expert Designers from Industry**: expert industrial designers were observed, interviewed, or studied as the source
- **Nature**: natural phenomena, as in biologically inspired or biomimetic design

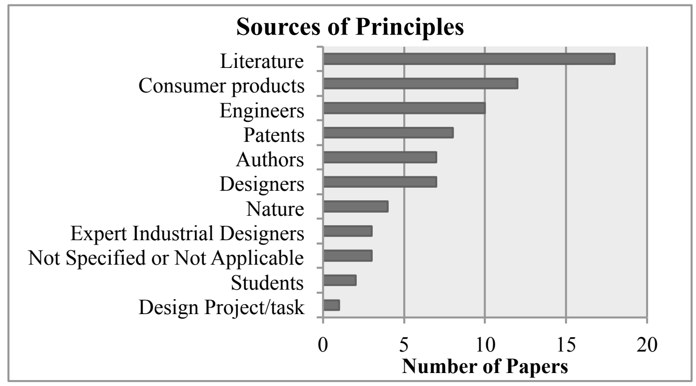


**FIGURE 6. SOURCES FROM WHICH DESIGN PRINCIPLES WERE EXTRACTED**

**TABLE 4. SAMPLE SIZES USED IN LITERATURE TO DERIVE PRINCIPLES**

| Methods to find Principles | Unit of Sample Size | Sample Size |
|---|---|---|
| Analysis of Existing Designs | Consumer products | 10, 46, 23, 15, 10, 3 |
| | Consumer products, Patents | 190, 90 |
| | Consumer products, Patents, Nature | 190, N/A |
| | Examples | 163 |
| | Nature | 1 |
| | Patents | 200,000, 41 |
| | Computer Programs | N/A |
| | Reconfigurable systems | 33 |
| Analysis of Existing Designs, Existing Principles | Patents | 90 |
| Derivation from Design Practice | Design project/task | 2, 1, 1 |
| | Engineers | N/A |
| | N/A (3) | N/A (3) |
| Derivation from Laboratory Based Design Practice | Design project/task | 5 |
| | Designers | N/A (2), 20 |
| | Engineers | 36 |
| | Students | 300, 29 |
| | Teams | 12 |
| Design Expert Observation | Designs (sketches, early stage) | 50 |
| | (Person) Years | 0.5 |
| | N/A | N/A |
| Existing Principles | Literature | N/A (5), 442, 10, 3, 2 |
| | N/A (6) | N/A (6) |
| Existing Principles, Experience | N/A (2) | N/A (2) |
| Experience | N/A (2) | N/A (2) |
| | (Person) Years | 30, 40, 40, 40, 40, 20, 1, N/A (2) |

- **Designers**: designers performed design tasks, neither novices nor experts, nor engineers or roboticists – a middle category for design study subjects
- **Authors**: the authors of the research publication served as the source either through design activity or experiential knowledge
- **Patents**: patents were analyzed as the source
- **Engineers**: engineers were studied, observed, or interviewed as the source
- **Consumer products**: consumer products were analyzed to extract principles
- **Literature**: principles were taken as already articulated in pre-existing literature

The sample sizes used for the derivation of the principles were also tabulated, as shown in Table 4. If any information was not included, N/A was marked. Numbers in parentheses denote the number of papers that did not specify that particular information. The largest sample sizes came from analysis based on student participant design studies, patent/consumer product analyses, and individuals reporting on their own person-years of experience.

### 5.2 Review of Methodologies for Validation of Design Principles

Similar to the analysis in Section 5.1, the source literature was also examined for the ways in which they validated the design principles that were derived. Figure 7 shows that the majority of publications did not address the validation of the principles, but rather focused on the derivation of the principles, or more often the pure presentation of the principles themselves without regard for methodology. The second most prevalent validation methodology was a design project or task – most often a case study of solving 1 to 3 design problems employing the design principles. Interestingly, a niche in the publication set [8, 74, 80] is represented by those who validated principles through:

***Convergence/Asymptotic Analysis***: *Examining a larger set of source material (test data) until the quantity of principles converged to a horizontal asymptote, i.e. asymptotic convergence. This numerical technique shows promise for its computational robustness, but does not address the validation of the utility of the principles.*

As expected based on the number of publications that did not address validation methodology, the source for validation was naturally not addressed either for the majority of publications, as shown in Figure 8. Most often, the authors or others performed small-scale implementations of the design principles in practice as proof of concept and initial validity at a case study level.

Sample sizes used for principle validation were also tabulated, as they were for derivation. Table 5 shows the samples sizes and units of those samples for each paper analyzed. Notice that nearly half (28) of the papers did not report the method to validate principles nor the source nor sample size. The largest sample sizes came from analyses of consumer products, patent analyses, and customer review analyses. Most papers went about validation with 1-3 design tasks implementing the derived principles.

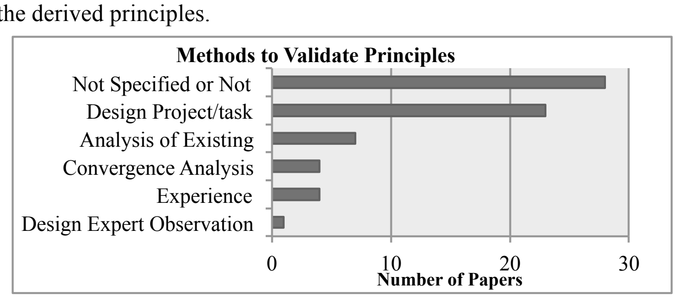


**FIGURE 7. METHODS USED IN LITERATURE TO VALIDATE DESIGN PRINCIPLES**

## 6 PROPOSED FUTURE DIRECTIONS FOR DESIGN PRINCIPLES RESEARCH METHODOLOGY

**TABLE 5. SAMPLE SIZES USED IN LITERATURE FOR PRINCIPLE VALIDATION**

| Methods to Validate Principles | Unit of Sample Size | Sample Size |
|---|---|---|
| Analysis of Existing Designs | Consumer Products | 4, 17, 70, 645 |
| | Industrial Products | 2 |
| | N/A (2) | N/A (2) |
| Convergence Analysis | Customer reviews | 200 |
| | Patents | 41, 50 |
| Convergence Analysis, design project/task | Design project/task | 1 |
| Design Expert Observation | Designs | 218 |
| Design Project/task | Design project/task | 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 2, 2, 3, 3, 3, 4, 4, 28 |
| | Students | 6, 64, N/A |
| | Team | 1 |
| Experience | N/A (4) | N/A (4) |
| N/A (28) | N/A (28) | N/A (28) |

The review of the design principles literature indicates some key opportunities for future directions of design research methodology. First, most research efforts focus on the presentation of principles themselves, with very few offering any prescriptive application of these principles into design practice for their validation. Author experience should be combined with empirical derivation/discovery of design principles so as to combine the benefits of longitudinal expertise and reduction of bias in reporting on just one personal perspective or experience. As is true of much of design science research, more investment must be made into the study of expert designers, regardless of energy/time/resource intensive requirements – or alternatively, a solution to this problem should be developed. This issue of sample size and access to expert or advanced level design participants is being addressed innovatively through efforts like the use of crowd-sourced design and other online platforms [89].

There is also an opportunity for more computational and numerical validation of the principles, through techniques like convergence analysis referenced earlier [8, 74, 80]. Alternative computational validation might include other data mining techniques, agent based modeling of design processes, modeling of human cognition through Bayesian statistics or other philosophical approaches, artificial intelligence models implementing methods like neural networks, decision trees, and complex systems modeling. An increased level of formalism in the articulation of principles, using tools like logic operators, language structures, etc. is an additional way to add rigor and repeatability to the research methodology.

As discussed earlier, there are dimensions of principles that emerge from the various definitions that should be considered or even explicitly stated, including level of supporting evidence or validation, level of granularity or specificity, level of formalization, and position

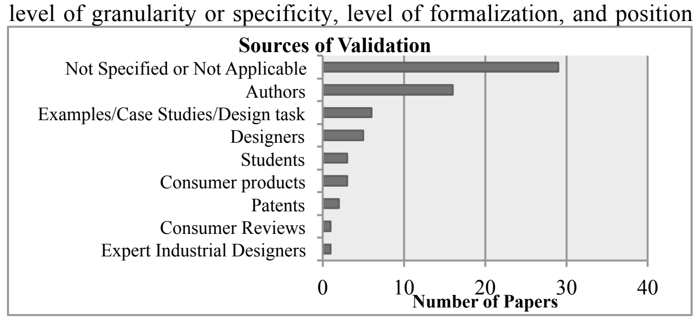


**FIGURE 8. SOURCES USED IN LITERATURE TO VALIDATE DESIGN PRINCIPLES**

on the spectrum of prescriptive-descriptive. Other important aspects to consider and include when articulating design principles are the time stamp (to indicate a sense of where state-of-the-art, technological, social and economic trends stand in relation to the principle), the context in which the principle is usable/useful/relevant, the intended users of the principle and any expected background or knowledge for proper application, and any conditions or qualifiers for applicability.

## 7 CLOSURE

Design Science, or in general design research, has received increasing attention of the last few decades. The future of products, services, systems, software and architecture rely on advancing design, both in terms of our foundation or formalized understanding and our inspirations for practitioners. Design principles represent a key component of description and characterization of design and associated design processes.

In this paper, we study past contributions to the area of design principles, developing a discourse and definitions for related formalizations, and analyzing different research methodologies. Key contributions of this work include working definitions for researchers and practitioners to investigate, share, and utilize design principles. These definitions may be used to share and describe design principles across design communities, but also as part of disciplinary fields. Building on these definitions, alternative research methodologies are presented including the concepts of sources, sample size, and approaches for validation. Researchers from disparate fields may engage these methodologies to improve the rigor of their studies, as well as consider the recommendations for even greater rigor and to raise the research field. Future directions include further formalization of methodologies for design principles research, and implementation and validation of those methodologies with applications in the areas of digital design for manufacturing and bio-inspired design.

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