

ABSTRACT

TWELVE LAWS OF DESIGN SCIENCE

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A science of generic design has recently been set forth. This science consists of three distinct parts: foundations, theory, and methodology. Foundations steer theory, theory steers methodology, and methodology is the basis for applications of the science. Experience with applications provides a basis for evaluation and improvement of the science.

The theory of the science incorporates twelve laws which are viewed as being applicable to all design activity, though not necessarily with equal intensity.

The twelve laws are:

- o Law of Gradation
- o Law of Universal Priors
- o Law of Inherent Conflict
- o Law of Limits
- o Law of Validation
- o Law of Success and Failure
- o Law of Requisite Saliency
- o Law of Requisite Variety
- o Law of Triadic Compatibility
- o Law of Structural Underconceptualization
- o Law of Requisite Parsimony
- o Law of Uncorrelated Extremes

In this paper each law is stated, evidence of its validity is examined, its significance for design and planning is presented, and the consequences of failing to recognize it are illustrated.

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1.0 INTRODUCTION

As discussed in [1], design science can be divided into three types of components: (a) specific design sciences, (b) generic design science, and (c) general design science.

The specific design sciences are those that traditionally are applied in specialized areas to describe particular objects of design (targets). Among these are those sciences relating to electricity, mechanics, physical chemistry, and economics.

Whether the specific design sciences are fully developed is arguable. It has been proposed that a "Domain of Science Model" be used to test the state of development of any field that is presented as a science. This test requires that the science be organized into three parts: foundations, theory, and methodology. Moreover, it requires that a clear relationship be demonstrable among these three parts, in that foundations must steer theory and theory must steer methodology. In addition, it requires that the methodology be tested in applications, with the results of the tests being applied to validate or to modify the science.

The generic design science is distinct from the specific design sciences in that it is applicable to the entire spectrum of design activity and, moreover, it does not overlap the specific design sciences. The twelve laws given in this paper are entirely laws from the generic design science.

General design science is the result of the integration of generic design science with the specific design sciences to form a cohesive, synergistic body of knowledge relevant to design. Since the generic design science has only recently been set forth, necessarily general design science does not presently exist in any recognizable form, though it can be seen as an objective to be attained in the future.

While there are numerous specific design sciences in various states of development, there need be only one generic design science and only one general design science. All of these sciences have in common that they are never complete, but are always in a state of development in the direction of higher quality and broader utility.

Capability to produce general design science will depend on reworking many of the specific design sciences to organize them properly to make possible their integration with generic design science. Most of them are not adequately organized into foundations, theory, and methodology; but rather they are amorphous bodies of knowledge in which foundations, theory, and methodology are mutually invasive. Such a hodgepodge frustrates improvement of the sciences and makes unnecessarily difficult their integration into a general design science.

None of the specific design sciences, by their very nature, is suitable to support the process of development of general design science. The generic design science, on the other hand, is very appropriate to provide support to the process of development of general design science. Thus the twelve laws to be presented can be seen not only as generally applicable to carrying out e.g., system design, but also as being generally applicable to improve the state of design science itself.

2.0 THE NATURE OF THEORY.

Theory is a part of a science that is supported by the foundations of the science. It is sensible that the body of knowledge forming the foundations would be small in comparison to the body of knowledge forming the theory.

Foundations of a science generally represent suppositions that cannot be supported rigorously by evidence. If, as knowledge grows, some foundations prove to be supportable by evidence, then those can advance into the theory of the science, and be replaced by foundations that continue to be speculative.

Any discussion of theory then presupposes the foundations. Theory has, as its primary attribute, the capacity to clarify the language of the science. Theory revolves around the clarification of key terms. But it must go beyond simply clarifying terms to clarify the relationships among those key terms because the relationships furnish the major portion of the clarification that is needed in any science.

It is only when the key terms and their relationships are understood that it becomes realistic to construct methodology, i.e., processes to be followed in applying the science.

The twelve laws to be presented are, therefore, not foundational. Nor are they methodology. This does not mean, however, that they cannot be prescriptive. While theory is intended to clarify, i.e., to describe thoroughly, it is possible to phrase descriptions so that they become prescriptive. Prescriptive theory clarifies general principles of action that must be further refined in methodology. The laws are part of the theory. Laws viewed in combination may engender additional theory in the form of more specific principles. In this way, laws phase into principles and principles phase into methodology, furnishing a kind of continuum of thought which makes the science organically coherent.

Seen as part of theory, any law must have some prior justification. Rather than provide an essay on the nature of justification of laws, each of the twelve laws will be discussed in terms of the prior justification that is relevant to each particular law. Some, but not necessarily all, of the justification will necessarily invoke the foundations of generic design science as set forth in [].

3.0 THE LAW OF GRADATION.

The Law of Gradation asserts that any conceptual body of knowledge can be graded in stages, such that there is one simplest stage, one most comprehensive stage (reflecting the total state of relevant knowledge), and intermediate stages whose content lies between the two extremes. The importance of this Law to the Science of Generic Design lies in the guidance that it provides to the designer concerning how to perceive any particular Design Situation with respect to the Science.

In this respect, one notes that design Targets may range from very small, limited-scope Targets to very large, broad-scope Targets.

It is not reasonable to take as a criterion for Generic Design Science that all of its Theory and all of its Methodology should be demonstrably required for all design activity. On the contrary, such a Science would be too brittle for use. The Law of Gradation overtly recognizes that Design Situations and Design Targets are themselves graded according to a variety of descriptions, not all of which can be foreseen. Accordingly, the Science of Generic Design should be applied judiciously, extracting from it one of its stages that is most appropriate for the particular Design Situation and Design Target.

The word "generic" does not mean "always required". What it does mean is "covering the set of gradations of Design Situations and Targets as a whole, without overlapping the applicable Specific Design Science; but subject to judicious restriction commensurate with the grade of the Design Situation or Design Target in any particular instance."

It is not the function of a Science of Generic Design to provide a recipe appropriate to every Design Situation. It is the function of such a Science to actuate the designer's professional responsibility to assess and correlate the gradation in the Situation and Target against the total sweep of the Generic Design Science; and to choose that restricted version of the Science which will be used openly, rather than to accept subliminally a restricted version that leads to underconceptualization of the Design Situation and the Design Target. It is the further function of the Generic Design Science to provide the means of documentation consistent with what the Design Situation requires.

The first Corollary to this Law asserts that the class of situations to which a conceptual body of knowledge may apply, in whole or in part, likewise may be graded according to the demands that individual situations can reasonably make upon the body of knowledge. This is called the Corollary of Congruence, because it relates to the congruence between the Design Situation and Target with a restricted grade of the Generic Design Science that is called into play in the specific case. Clearly the designer is not required to uncover every detail of relevance, no matter what the cost. When in doubt, a conservative posture will call for erring on the side of the higher grade.

The second Corollary to this Law is the existing economic Law of Diminishing Returns, which states that the application of a body of knowledge to a Design Situation should be made through that stage at which the point of

diminishing returns to the Situation (as opposed to only the user) is reached. This is called the Corollary of Diminishing Returns, and it highlights a major responsibility of the designer to make judgments about when this point is reached. Once again, a conservative posture will call for erring on the side of the higher grade.

The third Corollary to this Law states that the identification of the stage at which diminishing returns to the situation is reached normally requires the integration of the Virtual Worlds of the affected parties in the situation in relation to the dimensions of the situation. This is called the Corollary of Restricted Virtual Worlds, and it reflects the need for a global point of view in making the kinds of judgments that are required to achieve the appropriate congruence of gradation.

4.0 THE LAW OF UNIVERSAL PRIORS.

The Law of Universal Priors asserts the following:

The human being, language, reasoning through relationships, and archival representations are universal priors to science. (I.e., there can be no science without each of them.)

[Note: insert one more paragraph here from p. 13 of bk ms]

5.0 THE LAW OF INHERENT CONFLICT.

The Law of Inherent Conflict is stated as follows. If there is a group G of people concerned with an issue I, and if the issue I is complex, then there will be inherent conflict within the group G concerning the relative significance of the factors involved in the issue I.

Moreover, the following complementary statements apply:

- o The likelihood that any two people in G will agree on the significance of all factors is very small
- o The stability of the views of any one individual member of G, under the impact of a learning process that deals effectively with the relationships among the factors in the issue I is very low
- o With high probability, the views of every member of G concerning relative significance of the factors in the issue are wrong
- o Ordinary group processes that do not provide for appropriate learning within the group are unlikely to eliminate the inherent conflict

6.0 THE LAW OF LIMITS.

The Law of Limits asserts that to any activity in the universe there exists a corresponding set of Limits upon that activity, which determines the feasible extent of the activity.

The significance of this Law to the Science of Generic Design is that it conveys the importance of discovering (a) what the Limits may be upon design in general and how these Limits may relate to any particular Design Situation and (b) those additional Limits that are at work in a particular Design Situation.

This Law has strong implications for the development of Theory because it imposes upon Theory the requirement that the Theory contain explicit identification of generic Limits and explicit provision for the incorporation of special Limits.

In addition to the illumination provided by the Law itself, several Corollaries add further insight.

The first Corollary to this Law asserts that for any particular situation, the set of Limits can be partitioned into two blocks: an active block and an inactive block. This Corollary is called the Corollary of Active Limits.

The active block is the subset of the set of Limits that is determining at a given time, while the inactive block is not determining at that time.

The active block may often consist of a single, dominating member of the set of Limits. Such a member may be so strong in its power to limit that, in effect, all other Limits are forced into hiding by the dominant one. When this occurs, it has both advantages and disadvantages. An advantage is that the designer who recognizes this situation can focus attention upon the dominant Limit and look for ways to modify its impact. A disadvantage is that the non-active Limits may go unrecognized, only to make their impact felt later upon the design activity that has focused overly on overcoming the dominant Limit.

The second Corollary to this Law asserts that the set of Limits also can be partitioned into these two blocks: movable and fixed. A movable limit is one that can be altered, while a fixed limit is one that is unchanging. Clearly if there is a dominant Limit and it is fixed, the potential exists for wasting substantial amounts of time, effort, and resources if one does not understand that it is fixed. On the other hand, if one mistakenly assumes that a Limit is fixed, when it really is movable, the potential exists for missing opportunities for major improvements. This Corollary is called the Corollary of Movable Limits.

The third Corollary to this Law asserts that the movable subset of Limits can be partitioned into these two blocks: movable through discretionary action by people, and autonomously movable. Limits that are autonomously movable change on their own, and thereby drive the system. Clearly the strategic posture for dealing with such Limits is to maintain cognizance of their status and to have some predetermined alternatives in mind

for coping with them when they move into prominence. This Corollary is called the Corollary of Discretionary Action.

Limits that are movable through discretionary action by people are, of course, those that should be clearly recognized by designers, and to which attention should be given in the event that they are not overshadowed by more prominent Limits that effectively nullify the latent impact of those lying in the background.

The fourth Corollary to this Law asserts that the membership of the active blocks and of the inactive blocks of the partitions changes with time. If, for example, discretionary action brings about a change in some moveable Limit that previously was dominant, one or more new Limits will take the place of the previously dominant Limit. This Corollary is called the Corollary of Shifting Limits.

The Law of Limits does not provide any means of identifying the Limits or of partitioning them after they have been identified. This capability must arise from other sources.

7.0 THE LAW OF VALIDATION.

The Law of Validation asserts that the validity of a science depends upon substantial agreement within the scientific community of meaning at its highest grade, i.e., meaning attained through Definition by Relationship.

This Law is a necessary, but not in general, a sufficient condition for scientific validity.

A Corollary to the Law of Validation is as follows:

The validity of a science depends upon the capacity of the scientific community to construct definitions through Definition by Relationship for the full complex of relevant concepts involved in the science.

8.0 THE LAW OF SUCCESS AND FAILURE.

The Law of Success and Failure for Generic Design asserts that there are seven critical factors in the SUCCESS BUNDLE for the Design Process. It further asserts that inadequacy in any one of these factors may cause failure. The seven factors are: leadership, financial support, component availability, design environment, designer participation, documentation support, and design processes that converge to informed agreement.

This Law indicates that a Science of Generic Design must define these critical factors in sufficient depth to enable (a) the assessment of their adequacy and (b) their application in the Design Situation. Success and failure must also be elaborated and, in this context, success in all stages of work, including the implementation and operation, is required in order to proclaim that the design is successful; while failure in any stage is sufficient to constitute failure of the design.

This Law furnishes the impetus for what is called the Sigma-N Concept to be elaborated in Sec. 6.9. This Concept will also be relevant to the use of the Law of Gradation, as will be seen.

9.0 THE LAW OF REQUISITE SALIENCY.

The Law of Requisite Saliency, supported by empirical evidence showing that wide variability invariably exists among members of task forces in their assessment of relative saliency of factors pertaining to a complex situation or to a complex issue (Appendix 5), insists that the Design Process must incorporate specific provisions for human learning that offer the strong possibility of diminishing significantly the variability in perception of relative saliency of design options. The statement of the Law is as follows.

The situational factors that require consideration in developing a design Target and introducing it in a Design Situation are seldom of equal saliency. Instead there is an underlying logic awaiting discovery in each Design Situation that will reveal the relative saliency of these factors.

Characteristically individuals who become involved in the design process exhibit great diversity in their assessment of relative saliency (App. 5). This diversity, if uninfluenced by thorough exploration of the Design Situation, will support unfocused dialog, unjustified decisions, and arbitrary design outcomes not likely to be understood or even actionable.

The design process must incorporate specific provision for uncovering the relative saliency of the factors in the Design Situation and the factors that characterize the Target, in order to achieve the kind of understanding that is needed to put the design factors in proper perspective.

10.0 THE LAW OF REQUISITE VARIETY.

The Law of Requisite Variety indicates the need for a match between the dimensionality of the Design Situation and the Target of the Design Process. This Law was discovered by Ashby [3], the version being presented here having been inspired by his work and informed by the Theory of Dimensionality given in Sec. 6.2.

This Law asserts that a Design Situation embodies a requirement for Requisite Variety in the design specifications. Every Design Situation S implicitly represents an (initially unknown) integer dimensionality K_S such that if the designer defines an integer K_m number of distinct specifications (whether qualitative or quantitative or a mix of these), then:

- i) If $K_m < K_S$, the Target is underspecified and the behavior^S of the Target is outside the control of the designer
- ii) If $K_m > K_S$, the Target is overspecified, and the behavior^S of the Target cannot be compatible with the designer's wishes

- iii) If $K^m = K^s$, the design specification exhibits Requisite Variety,⁵ provided the designer has correctly identified and specified the dimensions; and the behavior of the design should be that which the Situation can absorb and which the designer can control, subject to the requirement that the dimensionality of the Situation is not modified by the introduction of the Target into the Situation. If the dimensionality is changed thereby, the design process can apply the Law of Requisite Variety iteratively, taking into account the dynamics of the Situation.

The Theory of Dimensionality has been introduced, in part, to make possible this formulation of the Law of Requisite Variety, especially to enhance applicability of it to those situations where some dimensions are naturally quantitative and some are naturally qualitative, requiring that both kinds of dimensions be in a common space and subject to comprehensive interpretation in order to achieve a sound design result.

The question might be raised as to how designers have succeeded in the past in the absence of overt response to this Law. Many, if not most, Targets of design are redesigns that benefit from decades of experience which have permitted the development of intuitive knowledge that substitutes for overt application of this Law. Regrettably, it is this same cumulative experience that mistakenly leads designers and their managers to believe that somehow they can intuitively design systems much larger in scale that have never been designed before.

11.0 THE LAW OF TRIADIC COMPATIBILITY.

The Law of Triadic Compatibility quantifies the limitations of short-term memory as they relate to human reasoning and decision making:

The human mind is compatible with the demand to explore interactions among a set of three elements because it can recall and operate with seven concepts, these being the three elements and their four combinations; but capacity cannot be presumed for a set that both has four members and for which those members interact.

A Corollary to this Law is the Principle of Division by Threes. This Principle is:

Iterative division of a concept as a means of analysis is mind-compatible if each division produces at most three components, thereby creating a tree with 1 element at the top, at most 3 elements at the second level, at most nine at the third level, and so on.

12.0 THE LAW OF STRUCTURAL UNDERCONCEPTUALIZATION.

The Law of Structural Underconceptualization is stated as follows:

Given any group G and an issue I with which G has some familiarity, if the issue I is complex it is virtually certain that any structuring of the issue done by G, whether individually by its members, or collectively through a group process, will be highly underconceptualized, unless the process provides the opportunity for structuring the issue using the concept of computer-assisted structuring that allows for the possibility of hybrid structures.

Moreover, the following principles apply as part of this Law:

- o the likelihood that cycles are required in any accurate structuring of a complex issue is very high
- o the likelihood that cycles will be identified in ordinary conversation groups, whether facilitated or not, is low
- o if any cycles are identified in structuring complex issues, the likelihood that they will be under-conceptualized is very high
- o capacity to deal with cycles through ordinary prose is extremely limited
- o the ease with which cycles can be discovered through ordinary conversation groups, whether facilitated or not, is higher when the relationship applied to structure the issue is temporal than for other types of relationships, but the main effect of this is to mislead people about the difficulty of discovering cycles using processes not specifically designed to facilitate such discoveries

13.0 THE LAW OF REQUISITE PARSIMONY.

The Law of Requisite Parsimony indicates a need for controlling the rate of presenting information for processing to the human mind, in order to avoid its overload during the Design Process.

This Law has been formulated in the light of the findings of Miller, Simon, and others concerning bounded rationality of the human mind. Its statement has been tailored to be responsive to their findings.

Every individual's short-term brain activity lends itself to dealing simultaneously with approximately seven items (a number that is reached with three basic items and four of their joint interactions). Attempts to go beyond this scope of reasoning are met with physiological and psychological Limits that preclude sound reasoning. For a given designer, there is some number K_d that is characteristic of that designer which typically is chosen from the set {5,6,7,8,9} that represents the Limit of that designer's short-term idea-processing capability. If a design methodology requires a designer

to cope intellectually at any one time with some number of concepts K_c , then

- i) If $K_c < K_d$, the designer is underburdened, being uninfluenced by the Law of Requisite Parsimony, since the designer is operating in a Situation that exhibits the Requisite Parsimony, through regulation of the rate of flow of information to the designer as the designer engages in the design process
- ii) If $K_c = K_d$, the designer is operating at the Limit of Reasoning capability
- iii) If $K_c > K_d$, the designer is overburdened and no reliance can be placed on the designer's decisions.

It can be confidently predicted that the Target will embody bad outcomes that are beyond the control of the designer, because the design process did not exhibit the Requisite Parsimony, but instead allowed the rate of flow of information to the designer to exceed processing capacity.

It may be questioned why designs have succeeded in the past without overt adherence to this requirement. Again one must consider the Law of Gradation, and note that design Targets vary tremendously in their scope. If this Law is being unknowingly violated, one would expect that the impact would be revealed in the failure of large system designs. This is precisely what is being observed all around the world. Those who doubt this Law must accept the burden of providing other explanations for the failures. The explanation of "operator error" may often, itself, reflect the same fundamental cause to which this Law responds in terms of the design process.

14.0 THE LAW OF UNCORRELATED EXTREMES.

The Law of Uncorrelated Extremes is stated as follows:

Given a group G working on a complex issue I, the correlation of the structure S_1 of the issue I before G has applied the science of generic design to understand it, and the structure S_2 of the issue I developed by G using the science of generic design will be very low.

The term "extreme" here relates to the conditions of "before" and "after", one extreme being a view before the work has involved any significant exploration or relationships among factors, the other extreme being a view after all exploration of relationships has been completed.

The following principles augment the statement of this Law:

- a The cause of the lack of correlation will, in general, be attributable to two sources, which will vary in significance from one combination (G,I) to another

- o One of the sources will be the learning that takes place in applying the science of generic design
- o The other source will be the absence of any credible basis for the initial structuring of I by G

15.0 CONCLUDING REMARKS

Virtually all of the twelve laws stated here take their greatest significance in planning and design in which the target of the activity is complex.

Persons accustomed to working with issues that are not complex acquire points of view and habits that do not take into account these twelve laws. When they come into contact with complex issues, they generally bring those views and habits to the work with those issues.

Issues that are marginally complex may yield when one or more of the Laws is overlooked. But issues that are complex almost certainly will not yield to conditions in which all of the Laws go unrecognized.

Experience in working with many groups on many complex issues shows that when these Laws are observed significant progress can be made in working with complex issues. Before these experiences can be transformed into a wide recognition of the importance of the Laws, enough time must elapse to get still more experience. Moreover people must become aware that the processes in which their success is experienced are processes in which these Laws are honored, both in principle, and in practice.

When enough people recognize the importance of observance of these Laws in working with complexity, it can be expected that the society will experience a significant improvement in its effectiveness in dealing with complex issues. Until that happens, it is necessary to continue to work in a disciplined way to adhere to the Laws and, if appropriate, to modify them to reflect still more experience to the end that they become progressively more refined in their statement and in their application to human activity systems.

REFERENCES