DESIGN SCIENCE RESEARCH IN INFORMATION SYSTEMS

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WELCOME

The intent of the Design Science Research in Information Systems (IS) page is to provide design science researchers in IS as well as others interested in design science research with useful information regarding understanding, conducting, evaluating, and publishing design science research. The goal of this page is to provide the IS community with useful information on design science research, both in and outside of the field of information systems. The page contains numerous citations permitting the interested reader to easily access original cited material on and examples of this unique and dynamic IS research paradigm.

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INTRODUCTION

Design science research is a "lens" or set of synthetic and analytical techniques and perspectives (complementing positivist, interpretive, and critical perspectives) for performing research in IS. Design science research typically involves the creation of an artifact and/or design theory as a means to improve the current state of practice as well as existing research knowledge (Baskerville, et al. 2018).

Design science research that focuses on the development of artifacts involves two primary activities to improve and understand the behavior of aspects of Information Systems: (1) the creation of new knowledge through design of novel or innovative artifacts (things or processes) and (2) the analysis of the artifact's use and/or performance with reflection and abstraction. The artifacts created in the design science research process include, but are not limited to, algorithms, human/computer interfaces, and system design methodologies or languages.

Design theories developed through design science research are a means to contribute knowledge by offering prescriptive statements and specification of outcomes for a system developed based on the theory.

Design science researchers can be found in many disciplines and fields, notably Engineering and Computer Science, and there are a variety of approaches, methods, and techniques used in design science research. Within the field of Information Systems, an increasing number of observers are calling for a return to an exploration of the "IT" that underlies all IS research (Orlikowski and Iacono, 2001) thus underlining the need for IS design science research.

This discussion of design science research is organized as follows. First, we provide a general overview of design science research. Next, we share the philosophical and epistemological underpinnings of design science research and contrast design science research in IS with traditional positivist and qualitative research in IS. This is followed by sections on design science research methodology, outputs of design science research, theory development in design science research, and general guidance on expected outcomes from design science research. Finally, we provide an extended discussion of a published example of design science research in IS. Through the example, we explain the phases of the design science research methodology: artifact design, construction, analysis and evaluation. This is followed by a design science research bibliography that provides more information about design science research in general as well as information about design science research in IS.

Overview of Design Science Research

Research

Research can be very generally defined as an *activity* that contributes to the *understanding* of a *phenomenon.* The *phenomenon* is typically a *set of behaviors of some entity*(ies) that is found *interesting* by the researcher or by a group—a research community. The set of activities a research community considers appropriate to produce understanding (or knowledge) are its research methods or techniques. Historically, some research communities have been observed to have nearly universal agreement on the phenomenon of interest and the research methods for investigating it, and these are considered *paradigmatic* communities. Other research communities are bound into a nominal community by overlap in sets of phenomena of interest and/or overlap in methods of investigation. We term these *pre-paradigmatic* or *multi-paradigmatic* research communities. Information & communication technology (ICT) based disciplines such as *information systems (IS)* are excellent examples of multi-paradigmatic communities.

In the multi-paradigmatic community of information systems, there are different means to conduct research and develop knowledge. *Understanding* in most positivist research communities is *valid (true) knowledge that may allow prediction* of the behavior of some aspect of the phenomenon. Thus, research must lead to contribution of knowledge—often in the form of a theory—that is *new* and *valid (true)*. Other paradigms, such as interpretivism and critical research, have different philosophies regarding what is truth, understanding, and knowledge (see the section on Philosophical Grounding of Design Science Research for more information).

In the case of design science research, all or part of the phenomenon may be *created* as opposed to naturally occurring (Kuhn 1996, 1962; Lakatos 1978). For a design science contribution to be valued and accepted by a research community, through its publication as research paper(s) or patent(s), it must also be something that is *interesting* to the research community (Gregor and Hevner, 2013; Wilson, 2002).

DESIGN

Design means "to invent and bring into being". Thus, design deals with creating a new artifact that does not exist. If the knowledge required for creating such an artifact already exists then the design is *routine*; otherwise, it is *innovative*. Innovative design may call for the conduct of research (design science research) to fill the knowledge gaps and may result in research publication(s) or patent(s).

DESIGN SCIENCE AND DESIGN SCIENCE RESEARCH

The design of artifacts is an activity that has been carried out for centuries. The activity of design also distinguishes the professions from the sciences. "Schools of architecture, business, education, law, and medicine, are all centrally concerned with the process of design" (Simon, 1996). However, in the 20th century, natural sciences almost drove out the design from professional school curricula in all professions, including business, with exceptions for management science, computer science, and chemical engineering (Simon, 1996).

Simon (1996) encourages professional schools, including schools of business (in which most IS departments are housed) to engage in design science and says: ". . . The professional schools will reassume their professional responsibilities just to the degree that they can discover a science of design [*design science*], a body of intellectually tough, analytic, partly formalizable, partly empirical teachable doctrine about the design process."

To bring the design activity into focus at an intellectual level, Simon (1996) makes a clear distinction between "natural science" and "science of the artificial" (also known as *design science*): A *natural science* is a body of knowledge about some class of things—objects or phenomenon—in the world (nature or society) that describes and explains how they behave and interact with each other. A *science of the artificial* (*design science*), on the other hand, is a body of knowledge about the design of artificial (man-made) objects and phenomena—artifacts—designed to meet certain desired goals.

Simon further frames the design of such artifacts in terms of an *inner environment*, an *outer environment*, and the *interface* between the two that meets certain desired *goals*. The outer environment is the total set of external forces and effects that act on the artifact. The inner environment is the set of components that make up the artifact and their relationships—the organization—of the artifact. Whether or not an artifact will survive or thrive is dependent on how well the artifact and outer environment interface or adapt with one another, particularly as social structures are disrupted by the embedding of the artifact within the environment (DeLeoz and Petter, 2018). The artifact is "structurally coupled" to its environment; many of the concepts of structural coupling that Varela (1988) and Maturana and Varela (1987) have developed for biological entities are applicable to designed artifacts.

The bringing-to-be of an artifact, components and their organization, which interfaces in a desired manner with its outer environment, is the design activity. Design can be thought of as a mapping from functional space—a functional requirement constituting a point in this multidimensional space—to attribute space, where an artifact satisfying the mapping constitutes a point in that space (Takeda, et al., 1990).

Design Science then is knowledge in the form of constructs, techniques and methods, models, and/or well-developed theory for performing this mapping—the know-how for creating artifacts that satisfy given sets of functional requirements. *Design Science Research* is research that creates this type of missing knowledge using design, analysis, reflection, and abstraction.

IS DESIGN RESEARCH?

In this section, we explore the question if the act of design can ever be considered an appropriate technique for conducting research in information systems and other ICT-based disciplines so as to create design science knowledge? In this section we discuss the question in the abstract—is design research?—using as exemplars from communities other than ICT where the question of whether or not design is a valid research technique has for many years been a resounding "Yes!"

Owen (1997) discusses the relation of design to research with reference to a conceptual map of disciplines (Figure 1) with two axes: Symbolic/Real and Analytic/Synthetic. The horizontal axis of the map positions disciplines according to their defining activities: disciplines on the left side of the map are more concerned with exploration and *discovery*. Disciplines on the right side of the map are characterized more by invention and *making*. The map's vertical division, the symbolic/real axis, characterizes the nature of the subjects of interest to the disciplines—the nature of the phenomena that concerns the research community. Both axes are continua and no discipline is exclusively concerned with synthesis to the exclusion of analytic activities. Likewise, no activity is exclusively concerned with the real to the exclusion of the symbolic although the strong contrast along this axis between the physical science of chemistry (real) and the abstract discipline of mathematics (symbolic) is strongly and accurately indicated in the diagram.

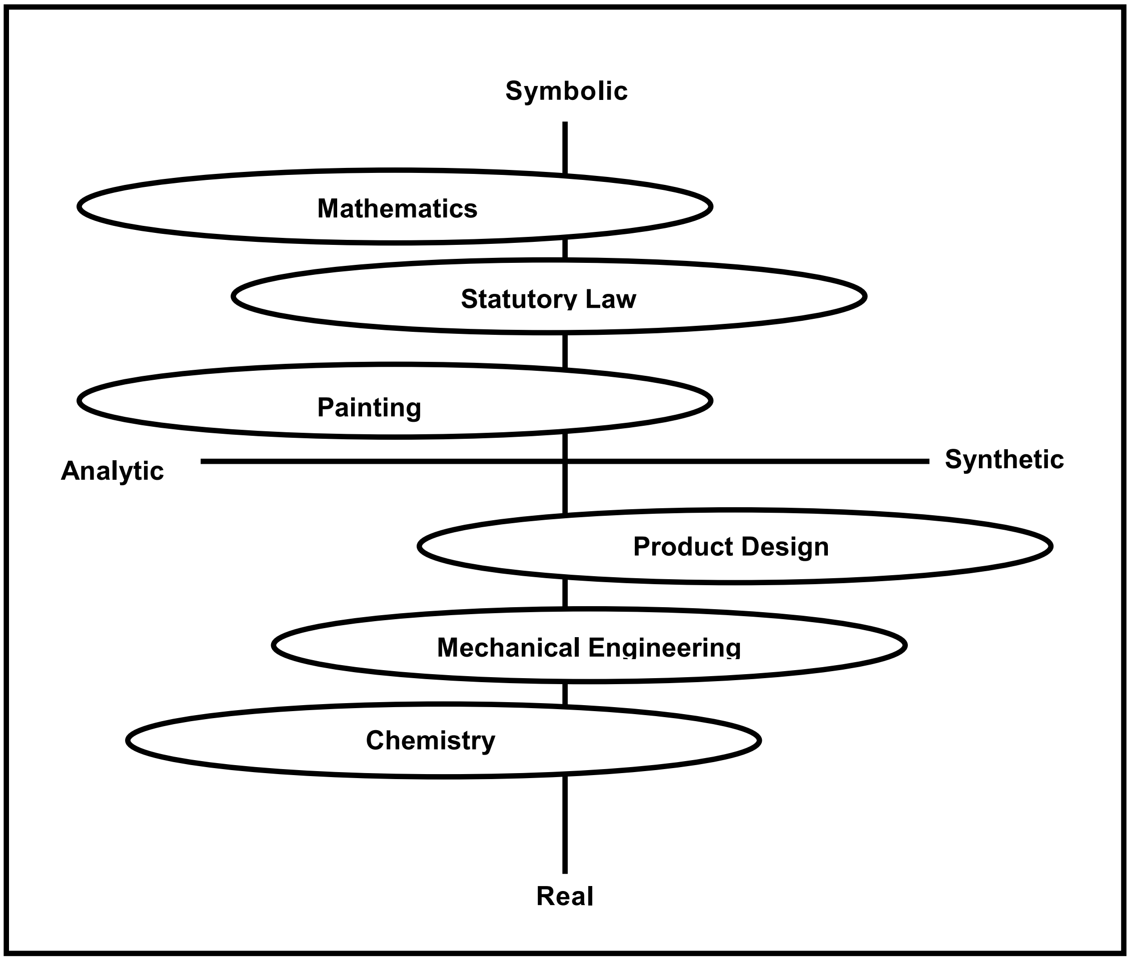


Figure 1. A Conceptual Map of Disciplines (Owen, 1997)

The disciplines that lie predominantly on the synthetic side of the map are either design disciplines or the design components of multi-paradigmatic disciplines. Design disciplines have a long history of building their knowledge base through making—the construction (creation) of artifacts and evaluation of the artifacts' performance followed by reflection and abstraction. Architecture is a strongly construction-oriented discipline with a history extending over thousands of years. The architectural knowledge base consists of a pool of structural designs that effectively encourage a wide variety of human activities and has been accumulated largely through the post-hoc observation of successful constructions (Alexander, 1964). Aeronautical engineering provides another example. From the Montgolfier balloon through WWI, the aeronautical engineering knowledge base was built almost exclusively by analyzing the results of intuitively guided designs—experimentation at essentially full scale.

Owen (1997) further presents a general model for generating and accumulating knowledge (Figure 2) that is helpful in understanding design disciplines and the design science research process: “Knowledge is generated and accumulated through action. Doing something and judging the results is the general model . . . the process is shown as a cycle in which knowledge is used [creatively] to construct (create) works, and works are evaluated to build knowledge." In addition, reflection and abstraction play a role in the knowledge building process. While knowledge building through construction is sometimes considered to lack rigor, the process is not unstructured. The channels in the diagram of the general model are the “systems of conventions and rules under which the discipline operates. They embody the measures and values that have been empirically developed as ‘ways of knowing’ as the discipline has matured. They may borrow from or emulate aspects of other disciplines’ channels, but, in the end, they are special to the discipline and are products of its evolution" (Owen, 1997).

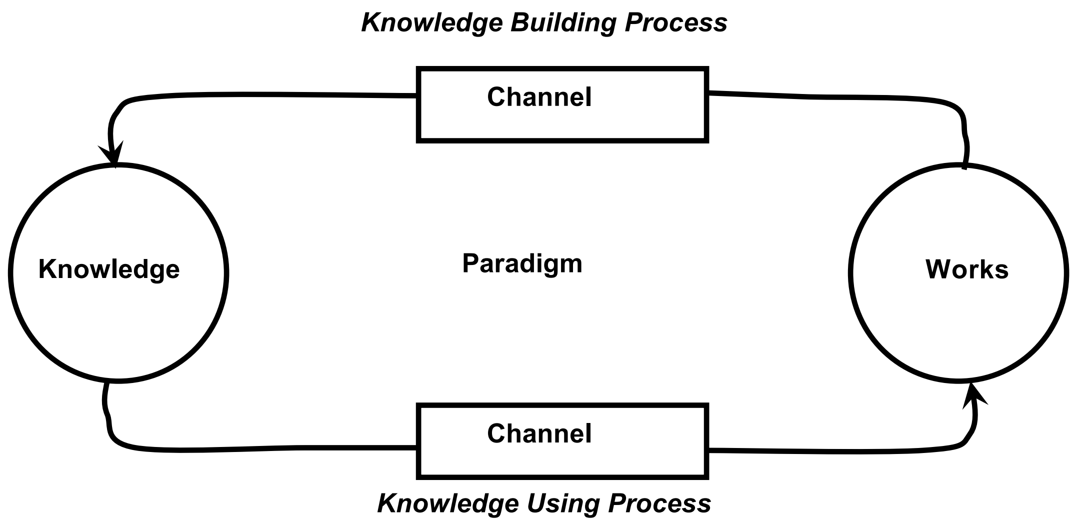


Figure 2. A General Model for Generating and Accumulating Knowledge (Owen, 1997)

Design Science Research vs. Design Research

Design science research is a rapidly evolving field. Within the last decade even the most commonly accepted name for the field has changed—from 'design research' (DR) to 'design science research' (DSR). As the DSR literature gained breadth and depth, researchers came to understand that the term 'design research' had a long prior history as the study of design itself and designers—their methods, cognition, and education. DR is a broad area spanning all design fields, but importantly, does not have the defining feature of DSR: learning through building artifacts. IS design science researchers began to add the distinguishing word 'science' to the field designation (see Hevner, et al., 2004). The distinction frequently expressed is that DR is research *about* design whereas DSR is primarily research *using design as a research method* or technique.

DSR when defined as learning through building is not unique to ICT. The fields of education, health care, computer science, and engineering also make extensive use of DSR. In education, curricula and learning programs are designed and empirically evaluated. In health care, programs of treatment are designed and empirically evaluated. These disciplines, among others, share the same concerns as DSR in information systems to develop solutions to problems and perform rigorous evaluation to codify design science knowledge as design theories (Kuechler and Vaishnavi, 2012). More information on the history of DSR in IS, especially in North America is available in Kuechler and Vaishnavi (2008b); Goes (2014) also provides an overview of publications using design science research in top IS journals.

DESIGN SCIENCE RESEARCH VS. ROUTINE DESIGN

A significant and valid question posed frequently to design science researchers is: How is your research different from a design effort; what makes your work research not simply state-of-practice design or consulting?

We propose that design science research is distinguished from routine design by the *production of interesting (to a community) new and true knowledge*. In *industry*, design efforts produce artifacts, but in most cases, the more successful the project is considered to be, the less is learned by the greater community. That is, it is generally desirable to produce a new product using state-of-practice application with state-of-practice techniques and readily available components. In fact, most product design efforts in industry are preceded by many meetings designed to "engineer the risk out of" the design effort. The risks that are identified in such meetings are the "we don't know how to do this yet" areas that are precisely the targets of design science research efforts. This is in no way meant to diminish the creativity that is essential to any design effort. We merely wish to point out that routine design is readily distinguished from design science research (within its community of interest) by the intellectual risk, which is the number of unknowns in the proposed design (missing knowledge).

Attempts at routine design can, however, also lead to design science research. To discover missing knowledge in a new area of design, it can be useful to create a design using existing knowledge to enable the researcher to identify the extent of missing knowledge and challenges associated with filling the knowledge gaps.

Design and Design Science Research—References

Philosophical Grounding of Design Science Research

Ontology is the study that describes the nature of reality: for example, what is real and what is not, what is fundamental and what is derivative?

Epistemology is the study that explores the nature of knowledge: for example, on what does knowledge depend and how can we be certain of what we know?

Axiology is the study of values: what values does an individual or group hold and why?

The definitions of these terms are worth reviewing because although assumptions about reality, knowledge and value underlie any intellectual endeavor, they are *implicit* most of the time for most people, including researchers. Indeed, as historians and philosophers of science have noted, in strong paradigmatic communities, people may conduct research for an entire career without considering the philosophical implications of their passively received areas of interest and research methods (Kuhn, 1996, 1962). It is typically only in multi-paradigmatic or pre-paradigmatic communities—such as IS—that researchers are forced to consider the most fundamental bases of the socially constructed realities (Berger and Luckman, 1966; Searle, 1995) in which they operate.

The contrasting ontological and epistemological assumptions implicit in natural science and social science research approaches have been authoritatively explicated in a number of widely cited works (Bunge, 1984; Guba and Lincoln, 1994). Gregg, et al. (2001) add the meta-level assumptions of design science research (which they term the socio-technologist / developmentalist approach) to earlier work contrasting positivist and interpretive approaches to research. Drawing from Gregg et al. (2001), Table 1 summarizes the philosophical assumptions of three research perspectives which is also supplemented with our combined 70+ years of design science research experience. First, we stress *iterative circumscription* as an essential part of the design science research methodology that iteratively determines (or reveals) the reality and the knowledge that emerges from the research effort. Next, we included the row labeled "Axiology", which is the study of values. We believe it is the shared valuing of what researchers hope to find in the pursuit of their efforts that binds them into a community. Certainly, the self and community valuation of their efforts and findings is a highly significant motivator for any researcher, and we were surprised to find how little stress this topic has received in the literature, especially given the significant differences in what each community values.

Table 1. Philosophical Assumption of Three Research Perspectives

Basic Belief	Research Perspective		
	Positivist	**Interpretive**	**Design**
Ontology	A single reality; knowable, probabilistic	Multiple realities, socially constructed	Multiple, contextually situated alternative world-states. Socio-technologically enabled
Epistemology	Objective; dispassionate. Detached observer of truth	Subjective, i.e. values and knowledge emerge from the researcher-participant interaction.	*Knowing through making*: objectively constrained construction within a context. Iterative circumscription reveals meaning.
Methodology	Observation; quantitative, statistical	Participation; qualitative. Hermeneutical, dialectical.	Developmental. Measure artifactual impacts on the composite system.
Axiology	Truth: universal and beautiful; prediction	Understanding: situated and description	Control; creation; progress (i.e. improvement); understanding

The metaphysical assumptions of design science research are unique. First, none of the ontology, epistemology, or axiology of the paradigm is derivable from any other paradigm. Second, ontological and epistemological viewpoints shift in design science research as the research progresses through the design science research cycle (see Figure 3). This iteration is similar to but more radical than the hermeneutic processes used in some interpretive research.

Design science research, by definition, changes the state-of-the-world through the introduction of novel artifacts. Thus, design science researchers are comfortable with alternative world-states. An obvious contrast is with positivist ontology in which a single, given composite socio-technical system is the typical unit of analysis. However, the multiple world-states of the design science researcher are not the same as the multiple realities of the interpretive researcher in that many, if not most, design science researchers believe in a single, stable underlying physical reality that constrains the multiplicity of world-states. The abduction phase of design science research (Figure 4), in which physical laws are tentatively composed into a configuration that will produce an artifact with the intended problem-solving functionality, virtually demands a natural-science-like belief in a single, fixed grounding reality.

Epistemologically, the design science researcher knows that a piece of information is factual and knows further what that information means through the process of development/circumscription. An artifact is developed. Its behavior is the result of interactions between components. Descriptions of the interactions are information and to the degree the artifact behaves predictably the information is true. Its meaning is precisely the functionality it enables in the composite system (artifact and user). What it means is what it does. The design science researcher is thus a pragmatist (Pierce, 1931). Venable (2006) has proposed letting utility theory be an appropriate form of a design theory resulting from design science research, which makes utilitarian claims related, for example, to efficacy, effectiveness, efficiency, elegance, and ethicality (Checkland and Scholes, 1999) for the created artifacts(s).There is also a flavor of instrumentalism (Hendry, 2004) in design science research. The dependence on a predictably functioning artifact (instrument) gives design science research an epistemology that resembles that of natural-science research more closely than that of either positivist or interpretive research.

Axiologically, the design science researcher values creative manipulation and control of the environment in addition to (if not over) more traditional research values such as the pursuit of truth or understanding. The design science researcher must have a far higher tolerance for ambiguity than is generally acceptable in the positivist research stance. As many authors have pointed out, the end result of a design science research effort may be very poorly understood and still be considered a success by the community (Hevner et al, 2004). A practical or functional addition to an area body of knowledge, even as partial theory or incomplete theory (Gregor and Hevner, 2013), codified and transmitted to the community where it can provide the basis for further exploration, may be all that is required of a successful project. Indeed, it is precisely in the exploration of "wicked problems" for which conflicting or sparse theoretical bases exist that design science research excels (March and Smith, 1995; Carroll and Kellogg, 1989).

Finally, the philosophical perspective of the design science researcher changes as progress is iteratively made through the phases of design science research. In some sense it is as if the design science researcher creates a reality through constructive intervention, then reflectively becomes a positivist observer, recording the behavior of the system and comparing it to the predictions (theory) set out during the abductive phase. The observations are interpreted, become the basis for new theorizing and a new abductive, interventionist cycle begins. In this sense design science research is very similar to the action research methodology of the interpretive paradigm; however, the time frame of design science research construction is enormously foreshortened relative to the social group interactions typical of action research.

Bunge (1984) implies that design science research is most effective when its practitioners shift between pragmatic and critical realist perspectives, guided by a pragmatic assessment of progress in the design science research cycle. Purao (2002, 2013) presents a very rich elaboration on the perspective shifts that accompany any iterative design science research cycle. His analysis is grounded in semiotics and describes in detail how "the design science researcher arrives at an interpretation (understanding) of the phenomenon and the design of the artifact simultaneously."

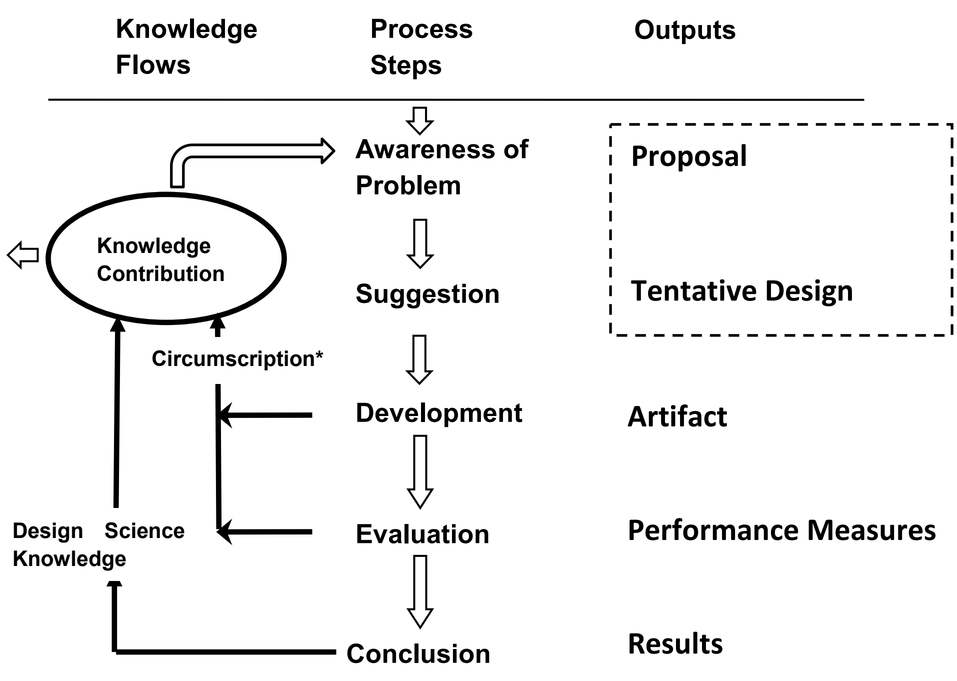
Philosophical Grounding of Design Science Research—References

DESIGN SCIENCE RESEARCH METHODOLOGY

This section predominantly focuses on the design science research methodology used in the creation of artifacts to solve problems. Later, in this essay, we discuss the process of creating design theory.

A DESIGN SCIENCE RESEARCH PROCESS MODEL

In this section, a model of the general process followed by design science research in its multiplicity of as-practiced variants is described. This model is an adaptation of a computable design process model developed by Takeda, et al. (1990). Even though the different phases in a design process and a design science research process are similar, the activities carried out within these phases are considerably different. Also, what makes the design science research process model different from the corresponding design process model is the fact that contribution of new (and true) knowledge needs to be a key focus of design science research. The research process model shown in Figure 3 can be interpreted as an elaboration of both the Knowledge Using Process and the Knowledge Building Process arrows in Figure 2. With reference to Figure 3, a typical design science research effort proceeds as follows:



* Circumscription is discovery of constraint knowledge about theories gained through detection and analysis of contradictions when things do not work according to theory (McCarthy, 1980)

Figure 3. Design Science Research Process Model (DSR Cycle)

Awareness of Problem: An awareness of an interesting research problem may come from multiple sources, including new developments in industry or identification of problems within a reference discipline. Reading in an allied discipline may also provide the opportunity for application of new findings to the researcher's field. The types of problems that are relevant for a design science research effort tend to be problem-solving focused in their approach as opposed to questions or problems that are answered through explanation. As part of the phase of becoming aware of the problem, the researcher(s) considers criteria for evaluating the final product of the research effort. The output of this phase is a Proposal, formal or informal, for a new research effort.

Suggestion: Immediately following the development for a proposal based on an awareness of a problem is the phase of suggestion. Suggestion is a creative step wherein new functionality is envisioned based on a novel configuration of either existing or new and existing elements. Indeed, in any formal proposal for design science research, such as a proposal for a government grant agency or an industry sponsor, a Tentative Design and the performance of a prototype based on that design would be an integral part of the Proposal. Moreover, if after investing considerable effort on an interesting problem a Tentative Design or at least the germ of an idea for problem solution does not present itself to the researcher, the idea (Proposal) will be set aside. It is this intimate connection between the Proposal and Tentative Design that serves as the reason for the dotted line surrounding the outputs of the Awareness of a Problem and Suggestion phase in Figure 3.

The suggestion phase has been criticized as introducing non-repeatability into the design science research method since human creativity is still a poorly understood cognitive process. However, this creative step has necessary analogues in all research methods; in positivist research, for example, creativity is inherent in the leap from curiosity about a phenomenon to the development of appropriate constructs that operationalize the phenomena that yield an appropriate research model.

Development: The Tentative Design is further developed and implemented in this phase. There are many forms of artifacts that can be developed that range from design theories (Gregor and Jones, 2007) to concepts, models, processes, or instantiations (March and Smith, 1995; Hevner, et al., 2004). The techniques for implementation will, of course, vary depending on the artifact to be created. An algorithm may require construction of a formal proof to show its correctness. An expert system embodying novel assumptions about human cognition in an area of interest will require software development, probably using a high-level package or tool. The implementation itself can be very pedestrian and need not involve novelty beyond the state-of-practice for the given artifact; the novelty is primarily in the design, not the construction of the artifact.

Evaluation: Once constructed, the artifact is evaluated according to criteria that are always implicit and frequently made explicit in the Proposal (Awareness of Problem phase). Deviations from expectations, both quantitative and qualitative are carefully noted and *must be tentatively explained*. That is, the evaluation phase contains an analytic sub-phase in which hypotheses are made about the expected behavior and impacts of the artifact using an evaluation strategy consistent with the needs for evaluation (Venable, et al. 2016).

This phase exposes an epistemic fluidity that is in stark contrast to a strict interpretation of the positivist stance (more discussion about this appears earlier in the section on Philosophical Grounding of Design Science Research. At an equivalent point in positivist research, analysis either confirms or contradicts a hypothesis. Essentially, save for some consideration of future work as may be indicated by experimental results, the research effort is over in most positivist research efforts.

For the design science researcher, by contrast, things are just getting interesting! Rarely, in design science research, are initial hypothesis concerning behavior completely borne out. Instead, the evaluation phase results and additional information gained in the construction and running of the artifact are brought together and fed back to another round of Suggestion (cf. the circumscription arrow of Figure 3). While design science research often focuses on examining the utility of an artifact (e.g., Hevner et al, 2004), others have suggested that the evaluation of the artifact is evaluated for its fitness to adapt and survive within an environment (Gill and Hevner, 2013) or by considering the social impacts of the artifact (DeLeoz and Petter, 2018). The explanatory hypotheses, which are quite broad, are rarely discarded, but rather are modified to be in accord with the new observations. The results of evaluation often suggest a new design, frequently preceded by additional research to understand the reasons why the behavior and impacts of the artifact deviated from the expected, theoretical performance.

Conclusion: This phase could be just the end of a research cycle or is the finale of a specific research effort. The finale of a research effort is typically the result of satisficing, that is, though there are still deviations in the behavior of the artifact from the (multiple) revised hypothetical predictions; the results are adjudged "good enough." Not only are the results of the effort consolidated and "written up" at this phase, but the knowledge gained in the effort is frequently categorized as either "firm"—facts that have been learned and can be repeatedly applied or behavior that can be repeatedly invoked—or as "loose ends"—anomalous behavior that defies explanation and may well serve as the subject of further research. Communication is very important in research (Hevner, et al., 2004). Therefore, this phase, as a conclusion of a research effort indicated by the small leftward arrow coming out of Knowledge Contribution in Figure 3, needs to appropriately position the research being reported and make a strong case for its knowledge contribution (Gregor and Hevner, 2013). Depending on the type of knowledge contribution and the state of knowledge in the area of research, the expectations on the nature and depth of knowledge contribution outputs can vary; see the next section (Outputs of Design Science Research).

COGNITIVE PROCESSES USED IN DESIGN SCIENCE RESEARCH

Figure 4 models the cognition that takes place during a design science research cycle. Both design science research and design (Takeda, et al., 1990) use abduction, deduction, and circumscription but there is difference in how these cognitive processes are used in each approach. Figure 4 demonstrates the flow of creative effort through the types of new knowledge that arise from design science research activities. The reason that this knowledge is most readily found during such effort will become apparent in the subsequent discussion.

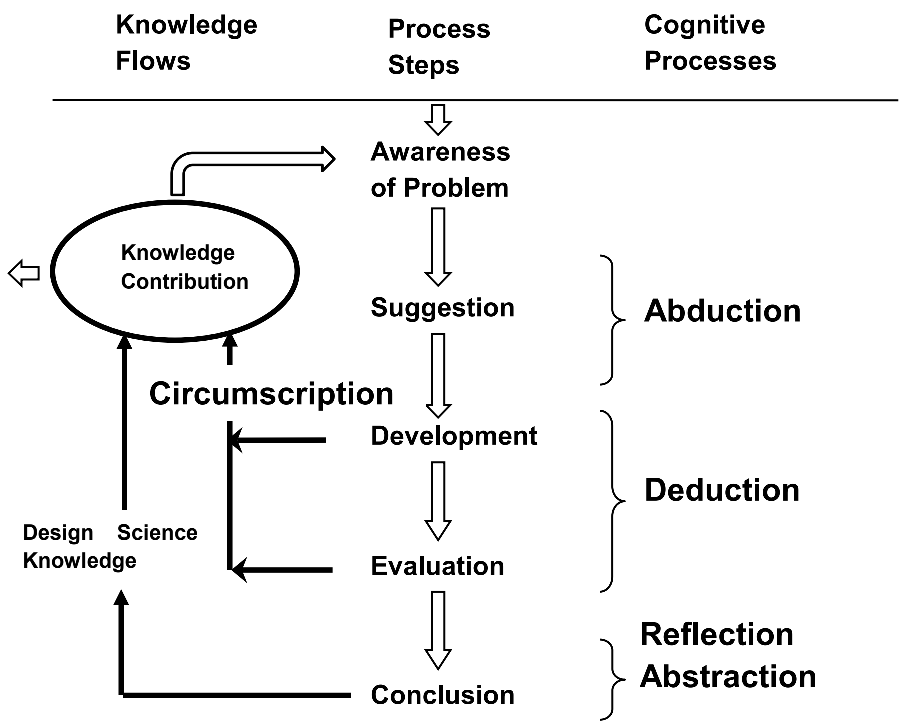


Figure 4. Cognition in the Design Science Research Cycle

Consistent with the design science research model previously described, research begins with *Awareness of a Problem*. Design science research is sometimes called "Improvement Research" and this designation emphasizes the problem-solving/performance-improving nature of the activity. *Suggestions* for a problem solution are abductively drawn from the existing knowledge/theory base for the problem area (Pierce, 1931). These suggestions may, however, be inadequate for the problem or suffer from significant knowledge gaps (which make the problem a research problem). Using existing knowledge, an attempt is made at creatively solving the problem. The solution—a tentative design—is used to implement an artifact in the next phase shown as *Development* in the diagram. Partially or fully successful implementations are then *evaluated* according to a functional specification (sometimes implicit) during the *Evaluation* stage. *Development*, *Evaluation,* and further *Suggestion* are frequently iteratively performed in the course of the research effort. The basis of the iteration, the flow from partial completion of the cycle back to *Awareness of the Problem,* is indicated by the *Circumscription* arrow. This allows for a deductive cognitive process as additional premises about the artifact and its environment become studied and/or known. *Conclusion* indicates the end of a research cycle or the termination of a specific design science research project. In the conclusion stage, the researcher reflects on what was learned, what worked, and what did not work to solve the problem. Furthermore, in the process of communicating the results and contributing to the larger knowledge base, abstraction enables the researcher to draw broad and generally applicable conclusions based on the knowledge gained from the research effort.

Knowledge contribution resulting from new knowledge production is indicated in Figure 4 by the arrows labeled: *Circumscription* and *Design Science Knowledge*. The *Circumscription* process is especially important to understanding design science research process because it generates *understanding that could only be gained from the specific act of construction*. Circumscription is a formal logical method (McCarthy, 1980) that assumes that every fragment of knowledge is valid only in certain situations. Further, the applicability of knowledge can only be determined through the detection and analysis of contradictions—in common language, the design science researcher *learns or discovers* when things *don't* work "according to theory." This happens many times not due to a misunderstanding of the theory, but due to the necessarily incomplete nature of *any* knowledge base. The design science research process, when interrupted and forced back to *Awareness of Problem* in this way, contributes valuable *constraint knowledge* to the understanding of the always-incomplete-theories that abductively motivated the original research.

The creative cognitive processes of reflection and abstraction are used in the *Conclusion* phase to make contributions of design science knowledge. At the conclusion of the research project, the overall contribution made by the research project to advance knowledge in the research area—preferably as a design theory—needs to be argued (see the later section on <u>Outputs of Design Science Research</u>).

OTHER DSR PROCESS MODELS

There are a number of other excellent DSR process models—descriptions (and diagrams) of design science research process (cf. Peffers, et al., 2008; Hevner, et al., 2004; Purao, 2013; Gregg, et al., 2001; March and Smith, 1995; Nunamaker, et al., 1991). The model we described above is similar to these models; the emphasis of the design science research model provided above is on a detailed process for generating design science knowledge.

The design science research methodology process model developed by Peffers, et al. (2008) attempts to synthesize selected prior literature on the topic. This model, in comparison to the model shown in Figure 3, breaks the *Awareness of Problem* phase into two phases, *Identify Problem & Motivate* and *Define Objectives of a Solution*; merges the *Suggestion and Development* phases into a single phase, *Design & Development*; breaks the *Evaluation* phase into two phases, *Demonstration* and *Evaluation*; and finally renames the *Conclusion* phase as *Communication*. A distinguishing feature of this model is identification of the fact that the design science research process can be initiated from a variety of contexts—Problem-Centered Initiation, Objective-Centered Solution, Design & Development Centered Initiation, Client/Context Initiation—and start in a corresponding phase of the nominal process sequence shown.

Design Science Research Methodology—References

OUTPUTS OF DESIGN SCIENCE RESEARCH

The output of a design science research project should be design science knowledge. To understand what form this knowledge contribution can take it is good to start with understanding the possible types of knowledge contribution of design science research.

Design science knowledge is manifested in the form of artifacts—constructs, models, frameworks, architectures, design principles, methods, and/or instantiations—and design theories (see Table 2). Instantiation is generally referred to as a *material* artifact while the other types of artifacts are referred to as *abstract* artifacts. A design theory usually includes abstract artifacts and can also include instantiations. To provide a better understanding of the different forms of knowledge contribution of design science research, we discuss the different forms of design science knowledge culminating in a detailed discussion of design theory in the next section.

Table 2: Outputs of Design Science Research

	Output	**Description**
1	Constructs	The conceptual vocabulary of a domain
2	Models	Sets of propositions or statements expressing relationships between constructs
3	Frameworks	Real or conceptual guides to serve as support or guide
4	Architectures	High level structures of systems
5	Design Principles	Core principles and concepts to guide design
6	Methods	Sets of steps used to perform tasks—how-to knowledge
7	Instantiations	Situated Implementations in certain environments that do or do not operationalize constructs, models, methods, and other abstract artifacts; in the latter case such knowledge remains tacit.
8	Design Theories	A prescriptive set of statements on how to do something to achieve a certain objective. A theory usually includes other abstract artifacts such as constructs, models, frameworks, architectures, design principles, and methods.

March and Smith (1995), in a widely cited paper, contrast design science research with natural science research and propose four general outputs for design science research: *constructs*, *models*, *methods,* and *instantiations*.

Constructs are the conceptual vocabulary of a problem/solution domain. Constructs arise during the conceptualization of the problem and are refined throughout the design science research cycle. Since a working design (artifact) consists of a large number of entities and their relationships, the construct set for a design science research experiment may be larger than the equivalent set for a descriptive (empirical) experiment.

A *model* is "a set of propositions or statements expressing relationships among constructs." March and Smith identify models with *problem and solution statements*. They are proposals for how things are or should be. Models differ from natural science theories primarily in intent: natural science has a traditional focus on truth whereas design science research focuses more on (situated) utility. Thus, a model is presented in terms of what it does, and a theory described in terms of construct relationships. However, a theory can always be extrapolated to what can be done with the implicit knowledge and a set of entities and proposed relationships can always be expressed as a theoretical statement of how or why the output occurs.

A *method* is a set of steps (an algorithm or guideline) used to perform a task. "Methods are goal directed plans for manipulating constructs so that the solution statement model is realized" (March and Smith, 1995). Implicit in a design science research method then is the problem and solution statement expressed in the construct vocabulary. In contrast to natural science research, a method may well be the object of the research program in design science research. Since the axiology of design science research (see the earlier section on Philosophical Grounding of Design Science Research) stresses problem solving, a more effective way of accomplishing an end result—even or sometimes especially a familiar or previously achieved end result—is valued.

The final output from a design science research effort in March and Smith's explication is an *instantiation* which "operationalizes constructs, models and methods." It is the realization of the artifact in an environment. Emphasizing the proactive nature of design science research, they point out that an instantiation sometimes precedes a complete articulation of the conceptual vocabulary and the models (or theories) that it embodies.[1] It is unlikely that the understanding would ever have occurred in the absence of the working artifacts. Thus, *situated implementation* may be a better phrase to capture the nature of this output.

Rossi and Sein (2003) and Purao (2002, 2013) identified their own list of design science research outputs. All but one of these can be mapped directly to March and Smith's list. Their fifth output, *design theories*, is highly significant and merits inclusion in our general list of design science research outputs. We also add to the list of outputs, additional abstract artifacts such as *frameworks,*

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[1] This is demonstrated in the aeronautical engineering example provided in the previous subsection entitled, "Can Design be Research". Aircraft flew for decades before a full understanding of how such flight was accomplished.

architectures, and *design principles* as identified by various researchers (Purao, 2002; March and Smith, 1995; Gregor and Jones, 2007; Gregor and Hevner, 2013).

Figure 5 shows a knowledge contribution framework for design science research (Gregor and Hevner, 2013). In this framework, *Invention* (inventing *new knowledge/solutions* for *new problems*), *Improvement* (developing *new knowledge/solutions* for *known problems*), and *Adaptation* (non-trivial or innovative adaptation of *known knowledge/solutions* for *new problems*) can all be types of knowledge contribution in DSR, and a single research project can make more than one type of knowledge contribution. *Routine Design* (applying *known knowledge/solutions* to *known problems*) by itself would seldom be considered as a research contribution. For knowledge contribution to be considered as a significant research contribution, it must be judged as significant with respect to the current state of the knowledge in the research area and be considered interesting.

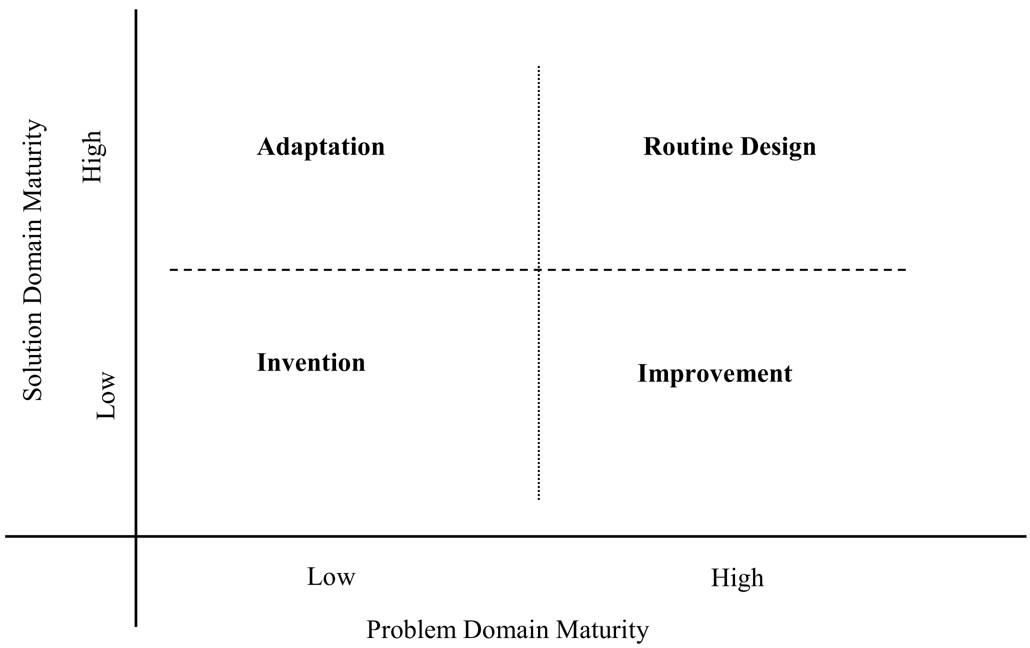


Figure 5. DSR Knowledge Contribution Framework
(adapted from Gregor and Hevner, 2013)

Figure 6 presents a slightly different perspective on the outputs of design science research (Purao, 2002, 2013; Gregg, et al., 2001; Gregor and Hevner, 2013). In this figure, the multiple outputs of design science research are classified by level of abstraction and generalization; outputs at higher levels are preferred since it reflects a more general advancement of knowledge in the area.

Explicitly the upper level of Figure 6 and the middle level are theories about the emergent properties of the embedded phenomenon. However, in any complex artifact, at either level of abstraction, multiple principles may be invoked simultaneously to explain aspects of the artifact's behavior. In this sense, the behavior of the artifact in any single design science research project is over determined (Carroll and Kellogg, 1989). This inevitable aspect of design science research has consequences discussed in the earlier section on Philosophical Grounding of Design Science Research.

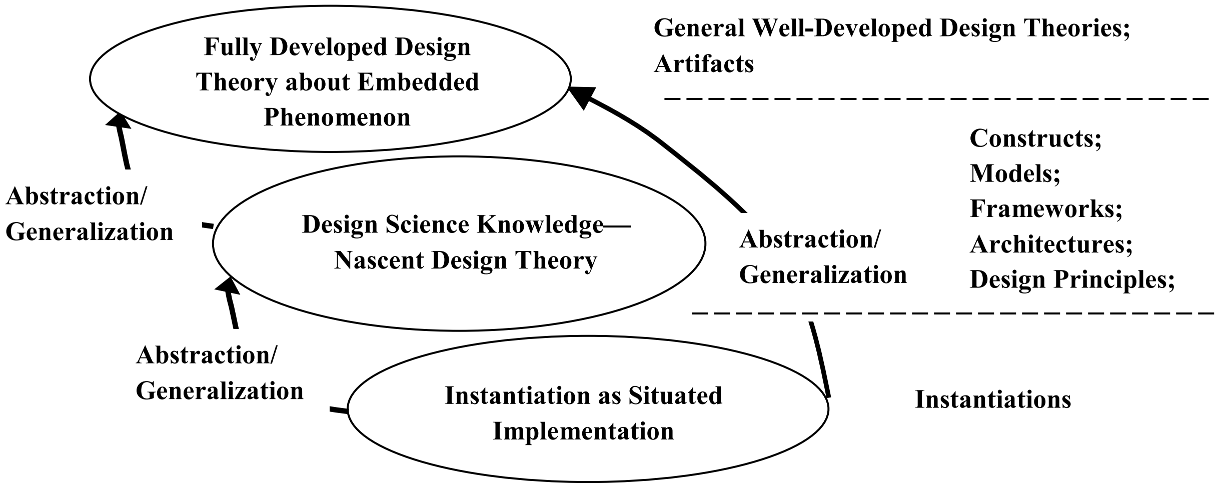


Figure 6. Design Science Knowledge Hierarchy
(adapted from Purao, 2002)

Design Science Research—General References

THEORY DEVELOPMENT IN DESIGN SCIENCE RESEARCH

To understand the different concepts of theory in DSR, we first explain the traditional *natural sciences* conception of theory with an example. In high-school physics we learn that force is equal to mass times acceleration (F = m*a). The second of Newton's laws of motion began as a theory relating three well defined constructs, force, mass and acceleration, in a formal, mathematical way. Hypotheses could be derived from the theory of the form: if Newton's theory is true, then if I apply force F to mass m, then acceleration of that mass, a, should result. The theory is a formal statement from which formal implications of the type (if action A is performed on a system, then action B should result) can be derived.

In design science research, the phenomena of interest are *created* and so design theories have a form different from but analogous to natural science theories. A design theory is a set of prescriptive statements and outcome specification from which the implications can be drawn: if a system is constructed according to the (design) theoretical prescription, then that system will behave (or have outputs) as specified in the theory. We discuss three conceptions of design science theory: fully developed design theory, nascent design theory, and design relevant explanatory/predictive theory (DREPT), which is a type of theory that attempts to provide a bridge between design and underlying natural phenomena.

A design theory (fully developed or nascent) is a prescriptive type of theory, the fifth type of theory in Gregor's taxonomy of theories (Gregor, 2006). Walls, et al. (1992, 2004) provide one way of defining design theory for information systems and call it Information Systems Design Theory (ISDT). Gregor and Jones (2007) extend this work to provide a revised definition of Information Systems Design theory (discussed in more detail in the next section).

Design theory is the desired form of knowledge contribution from a design science research project. However, a well-developed and general design theory in a research area may take years of effort by the research community in the area. It is thus more likely for a DSR project to contribute a nascent design theory that is not so well developed; a nascent design theory can be a preliminary contribution to a new design theory or an incremental contribution to an existing broader design theory in an area. Also, nascent design theories can vary in terms of their maturity and could be qualified with phrases such as 'preliminary', 'rudimentary', 'reasonably developed', etc.

Artifacts such as constructs, models, methods, etc. (see Table 2) are constituents of a design theory but do not by themselves constitute a design theory unless the other requirements of a design theory (see Table 3), particularly those related to evaluation/validation and justificatory knowledge, are fulfilled. The knowledge contribution of DSR may be merely an instantiation with no or minimal contribution of abstract artifacts. This is possible in a situation where the knowledge contribution is of the Invention type (see Figure 5). It is also possible that the knowledge contribution is an interesting partial or even an incomplete design theory with potential for further work.

Design theory is about how to do something to meet a certain objective without fully answering why the prescribed actions should work. Design relevant explanatory/predictive theory, also known as DREPT (Kuechler and Vaishnavi, 2012), is a type of design-realm theory that augments the 'how' part of a design theory with explanatory information on 'why' one should trust the design action to work. The explanatory information is provided using 'kernel theory', established theory in natural, social, design, or mathematical sciences; the term 'kernel theory' is used here with a broadened scope compared to its traditional use.

Design science research can contribute to better theories (or theory building) in at least two distinct ways, both of which may be interpreted as analogous to experimental scientific investigation in the natural science sense. First, since the methodological construction of an artifact is an object of theorizing for many communities (e.g., how to build more maintainable software), the development phase of a design science research effort can be an experimental proof of a method, an experimental exploration of a method, or both.

Second, the artifact can expose relationships between its elements. It is tautological to say that an artifact functions as it does because the relationships between its elements enable certain behaviors and constrain others. However, if the relationships between artifact (or system) elements are less than fully understood and if the relationship is made more visible than previously during either the construction or evaluation phase of the artifact, then the understanding of the elements has been increased, potentially falsifying or elaborating on previously theorized relationships. For some types of research, artifact construction is highly valued precisely for its contribution to theory. Human-computer interface (HCI) researchers, Carroll and Kellogg (1989), state that ". . . HCI artifacts themselves are perhaps the most effective medium for theory development in HCI." Walls, et al. (1992) elaborate the theory building potential of design and construction in the specific context of IS.

PROFILE OF A DESIGN THEORY (DT)

The profile of a design theory, particularly one for the information and communication technology (ICT) field, is described below and summarized in Table 3. The structure of a design theory is adapted from Gregor and Jones (2007), which is an extension of the structure provided by Walls, et al. (1992; 2004).

Table 3: Profile of a Design Theory (adapted from Gregor and Jones, 2007)

Component	**Description**
Core Components	
1) Purpose and Scope	Provides a clear description of the purpose and scope of the new theory,
2) Constructs	Describes all the existing or new entities or concepts relevant to the description of the theory.
3) Knowledge of Form and Function	Includes the full description of models, frameworks, methods, and/or other abstract artifacts that form the body of the design science knowledge contribution.
4) Abstraction and Generalization	Is at such an abstract and general level that the artifacts resulting from the theory can change or be changed without affecting the theory.
5) Evaluation and Validation Propositions	Has been evaluated for its truthfulness, i.e. assertions made based on the theory have been tested in an appropriate manner.
6) Justificatory Knowledge	Includes references to justificatory knowledge—tacit theory (informal experience-based insights and intuitions), kernel theory—that can provide a reasonable degree of justification of the theory.
Additional Components	
7) Principles of Implementation	Describes the process for instantiating the theory.
8) Expository Instantiation	Includes an instantiation (possibly situated implementation) that can be used for exposition of the theory and/or for testing the theory.

To further explain, the design theory profile has multiple components:

- **Purpose and Scope:** A design theory, like any theory, should be new, interesting, and true. There should be enough information in this component of the theory to argue that the theory is new and interesting (to the relevant research and possibly practice community).

- **Constructs:** All the existing and new concepts and entities that are needed to fully understand the theory should be fully described.

- **Knowledge of Form and Function:** These form the body of the theory—the design science knowledge contribution—and thus should be described and explained in detail.

- **Abstraction and Generalization:** Generality and abstractness are the hallmarks of theory. A theory should cover a variety of ways the theory will get instantiated or changed, or even allow evolution, adaptation or learning of the resulting artifacts without affecting the theory. In other words, a design theory should have a degree of permanence and range of coverage so that one does not have to create a new version of the theory for each new situation.

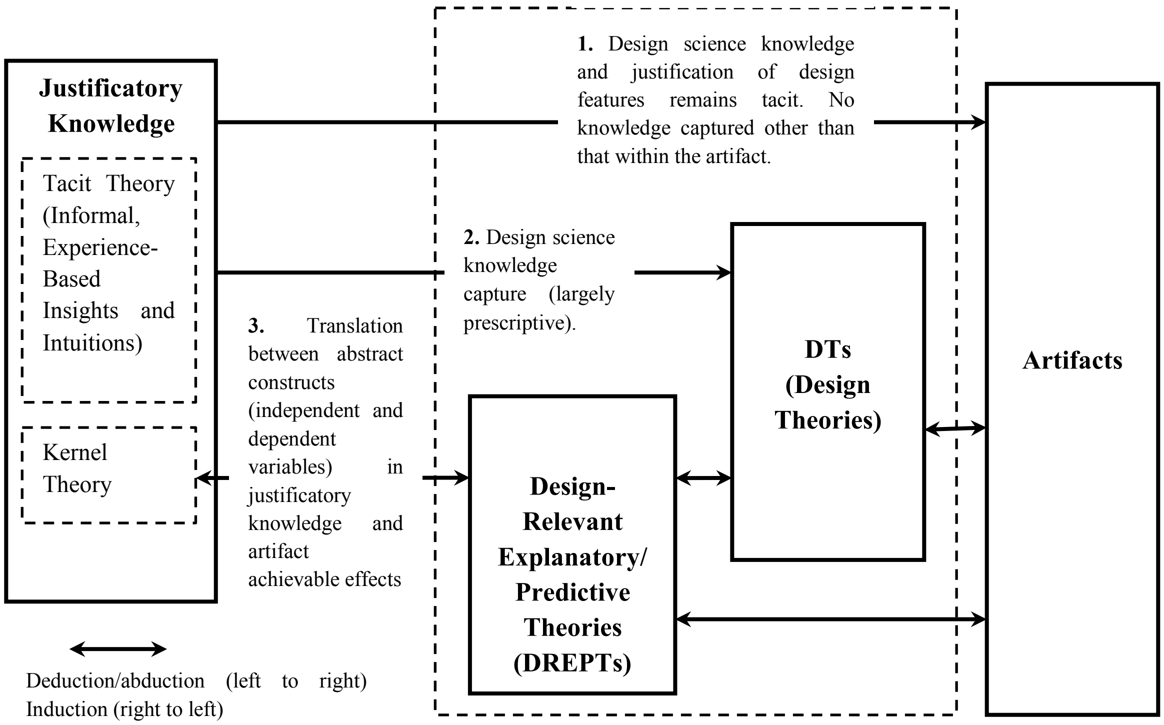
- **Evaluation and Validation Propositions:** A theory, in addition to being novel and interesting, should be true. Thus, sufficient effort should be invested in evaluating and validating the theory propositions. The method of evaluation and validation can vary and can range from logical arguments to experimentation or mathematical proof.

- **Justificatory Knowledge:** In addition to trusting a theory based on its evaluation and validation, the researcher needs to provide some insights into why one should believe that the theory is likely to be true.

The other two components, Principles of Implementation and Expository Instantiation, may or may not be needed for a design theory depending upon the nature of the theory and the state of the art in the area of research.

A Framework for Theory Development in DSR

Figure 7 shows a framework for theory development that extends the framework proposed by Kuechler and Vaishnavi (2012) for information systems theory development, to one for design science research, particularly for DSR in ICT. The figure shows three paths for the development of artifacts with theory development ramifications. Path 1 represents the development of artifacts without any explicit development of theory. Path 2 indicates the use of existing justificatory knowledge (Gregor and Jones, 2007) in the development of a design theory and its instantiation into an artifact or the creation of an artifact with further refinement and development of design theory from the artifacts using reflection and abstraction. Path 3 illustrates a strategy in which any relevant kernel theory (in terms of independent and dependent variables) from natural science, social science, design science or mathematics is translated to artifact achievable effects in a design-relevant explanatory/predictive theory (DREPT), which after its evaluation through a created artifact can in turn lead to refinement and enrichment of the kernel theory. This path also provides a vehicle for not only showing how to design an artifact but also for understanding why the artifact should work.



Kernel Theory: Social, mathematical, and design science theories as well as natural science (e.g. physics, psychology) theories

Artifacts: Constructs, models, frameworks, architectures, design principles, methods, instantiations

Figure 7. Framework for Theory Development in Design Science Research
(Adapted from Kuechler and Vaishnavi, 2012)

THEORY DEVELOPMENT IN DSR—A BRIEF LITERATURE REVIEW

An example of the rapid evolution of DSR is the recent attention directed to theory. One of the seminal DSR papers in information systems (IS), Nunamaker, et al. (1991), allude to theory and refinement of theory as an output from what they term the "engineering model" of IS research. Shortly thereafter, Walls, et al. (1992) presented a conception of IS Design Theory (ISDT), a prescriptive encoding of design science knowledge abstracted from a DSR-IS project. A number of widely cited IS papers have subsequently made use of ISDT, such as Kasper (1996) and Markus, et al. (2002).

Two influential papers subsequent to Walls, et al. (1992), that is, March and Smith (1995) and Hevner, et al. (2004) do not explicitly mention theory. The absence of a discussion of theory in these seminal works on design science research has been interpreted by some in the field as suggesting that theory is *not* an output to be sought from the design science research approach in information systems. Yet, more recent papers including Gregor (2006), Gregor and Jones (2007), Kuechler and Vaishnavi (2008a), Arazy, et al. (2010), Kuechler and Vaishnavi (2012), and Gregor and Hevner (2013) explicitly mention theory as a DSR project output and present methods for developing such theory during the course of design science research. Gregor (2006) provides a taxonomy of IS theory and proposes 'Theory for Design and Action' as a type of IS theory (Type V Theory). Gregor and Jones (2007) builds upon the work of Walls, et al. (1992; 2004) and revises the structure for ISDT. Kuechler and Vaishnavi (2012) puts forward a framework for theory development in design science research in the context of information systems. Niehaves, et al. (2012) devises a framework for adding rigor to the translation between a design theory and the corresponding design artifact. Gregor and Hevner (2013) stresses contributions to knowledge as the expected output, which could be "partial theory, incomplete theory, or even some particularly interesting and perhaps surprising empirical generalization in the form of a new design artifact."

Wagner et al. (2017) examines factors that affect the impact of design science research articles published in the field of information systems. The authors found that there was strong support that articles that have stronger theoretical contributions have higher levels of citations (i.e., impact) than articles with less theorizing. Their study identified other reasons for design science research articles to be cited; however, their work demonstrates the value of including theorizing in the design science research process.

Theory and Theory Development in DSR—References

GENERAL GUIDANCE ON EXPECTED OUTPUTS FROM DESIGN SCIENCE RESEARCH

The general goal of design science research is to create or contribute to new and interesting design science knowledge in an area of interest that is "a body of intellectually tough, analytic, partly formalizable, partly empirical teachable doctrine about the design process" (Simon, 1996). The desired form of such knowledge is a design theory and/or artifacts such as constructs, models, methods, and instantiations (Table 2), among other contributions (Baskerville, et al., 2018). The creation of a fully developed theory, however, cannot be expected from a single design science research project. It usually gets created as a community effort through multiple iterations of research, development, and practice, and many times includes active participation of the industry.

The creation of design science knowledge in an area usually begins as an Invention type of knowledge contribution (see Figure 5) and is at the lowest level of abstraction/generalization according to Figure 6. This type of output is a situated implementation with possibly some work at the middle level of the abstraction/generalization framework shown in Figure 6, which may lead to the development of a nascent design theory. It is very likely to have followed Path 1 or possibly Path 2 in the theory development framework shown in Figure 7. It is accepted as a design science knowledge contribution for the novelty and significance of the contribution from both problem definition and solution/ knowledge development standpoints and gets published or gets patented. Chen's work on the ER model (Chen, 1976) or the work of Agrawal et al. (1993) on data mining are examples of such research contributions that have spawned entire fields of research.

After the initial breakthrough type of research, design science research contributions in the area need to be Improvement and/or adaptation types of knowledge contributions according to the knowledge contribution framework shown in Figure 5 and need to make progress on the level of abstraction/generalization of the research outputs (according to Figure 6). For such research, creation of a general well-developed design theory would be a goal but depending upon the state of knowledge in the area, a nascent design theory can be an acceptable form of output as long as it is deemed to make significant contribution to the state of art in the research area. The research could follow Path 2 or Path 3 of the theory development framework (Figure 7). For Improvement type of knowledge contribution, the research needs to produce a better solution according to some acceptable metric and for the Adaptation type of knowledge contribution, the research needs to show the challenges and the non-trivial nature of adaptation of existing knowledge for a new problem or for a new version of an existing problem that usually manifests itself because of technology changes. In either case the research needs to be deemed as making a significant and novel contribution and the outputs need to be at as high a level of abstraction and generalization as is possible.

In summary, to understand the expected outputs of a design science research project one needs to first assess the type of knowledge contribution being made with respect to the existing knowledge (see Figure 5). If the knowledge contribution can be argued to be significant but of the Invention type, then it can even be at the lowest level of abstraction and generalization. If, on the other hand, the research does not make an original Invention type of contribution but instead makes an improvement type of contribution and/or makes a novel use of existing knowledge in a new area (Adaptation) then the research outputs need to be at higher levels of abstraction/generalization according to Figure 6. They should include at least a nascent design theory, and one needs to argue how they are advancing the state of knowledge in the area.

AN EXAMPLE OF COMMUNITY DETERMINED OUTPUTS

Precisely what is obtained from a design science research effort is determined by (1) the phase of research on which reflection and analysis focuses (from Figure 5) and (2) the level of abstraction to which reflection and analysis generalize the knowledge contribution (see Figure 6). These factors in turn are strongly influenced by the community performing the research.

To illustrate the different outputs that are commonly seen as the desired result for design science research, consider the *same* artifact development as carried out by different ICT research sub-communities: database, software engineering, Human-Computer interface (HCI), decision sciences, and IS Cognitive Researchers (IS Cognitive Research Exchange—IS CORE): the construction of a data visualization interface for complex queries against large relational databases. For all of the communities, the research is motivated by common *problem awareness*: that a better interface needs to be developed that will allow users to more quickly and effectively obtain answers to questions about the performance of their business operations.

The theoretical impetus for the prospective improvement would vary between research communities. For the software engineering or database communities, the motivation could be new knowledge of faster access techniques or visual rendering techniques. For the decision sciences, HCI, and cognitive research communities, the impetus could be new research in reference disciplines on visual impacts on cognition and/or on decision-making. The resulting artifact would be quite similar for all communities, as would the construction mechanics—the computer languages used in development, the deployment platforms, among others. However, the stages of development on which observation and reflection is centered and the measures used to evaluate the resultant artifact (cf. Figure 3) would be considerably different for each community. Table 4 lists the communities that might construct a data visualization artifact, the primary perspective with which they would view the artifact and the different knowledge that would emerge from the research effort as a result of the differing perspectives.

Table 4. Design Science Research Perspectives and Outputs by Community

Community	Perspective	Knowledge Derived
HCI; IS CORE; Decision science	Artifact as experimental apparatus	What database visualization interfaces reveal about the cognition of complex data relationships
Database; Decision science Software engineering	Artifact as focused design principle exploration	Principles for the construction of data visualization interfaces
Database; Software engineering	Artifact as improved instance of tool.	A better data visualization interface for relational, business oriented databases.

Some explications of design science research in IS have stated that the primary focus is always on the finished artifact and how well it works rather than its component interactions i.e. *why* it works (Hevner, et al., 2004) but more recent work (e.g., Gregor and Hevner, 2013) and our exemplar in a later section present a broader view. The apparent contradiction may simply be in how wide the net of ICT research is cast and the selection of sub-communities it is considered to contain.

An Exemplar of IS Design Science Research

The example (case study) we have chosen to add detail and concreteness to the discussion of design science research philosophy and method in ICT is one from our joint experience. We make only two claims for this research: (1) it is a reasonable example as it comfortably encompasses all the points of the preceding discussion and (2) since it is our research we are privy to and able to present a multitude of details that are rarely written up and available in journal publications. We describe the research, from conception to the first publication drawn from it, in phases corresponding to those in Figure 3.

Smart Objects: A Design Science Research Project

Awareness of Problem

In the mid-1980's one of the senior project participants, Vijay, began actively seeking to extend his research from designing efficient data and file structures (a primarily computer science topic) to software engineering (an area with a significant IS component). In the course of a discussion with one of his colleagues at Georgia State University (GSU) he became aware of a situation that showed research promise: development of a computerized decision support system for nuclear reactors. Three Mile Island had brought national awareness to the problems associated with safe operation of a nuclear power plant, rule-based decision support systems were a current area of general IS interest, and the director of the research reactor at Georgia Tech was interested in developing a system to support its operations.

A doctoral student (Gary) was brought into the project to begin a preliminary support system development in the rule-based language, Prolog. Within a few weeks it became apparent that a system to support the several thousand procedures found in a typical commercial power plant would be nearly impossible to develop in Prolog; and if developed, would be literally impossible to maintain. The higher-level expert system development packages available at the time (and currently) were more capable but still obviously inadequate. The difficulty of constructing and maintaining large expert systems was widely known at the time; however, the Prolog pilot project gave the research group significant insights they would not otherwise have had into the root causes of the problem: continuously changing requirements and the complexity inherent in several thousand rule-based interlocking procedures. Out of detailed analysis of the failed pilot system emerged the first *awareness of the problem* on which the research would focus: how to construct and continuously maintain a support system for the operation of a complex, hierarchical, procedure driven environment.

SUGGESTION

There are many approaches to the problems of software system complexity and the research group discussed them over a period of months. Some of the alternatives that were discarded were: development of a new software development methodology specifically focused on operations support systems, automation of the maintenance function, and development of a high-level programming environment. New insights into the problem continued to emerge even as (and precisely because) potential solutions to the problem were considered. One key insight was that the system complexity resided primarily in control of the system, that is, although the individual procedures could be modeled straightforwardly, the procedure which should take precedence (control) over the others and where the results of that procedure should be routed depended in a highly complex fashion on past and present states of multiple procedures. Essential to the development of the system was the effective modeling of this complex control structure.

By this point Gary had decided to adopt the problem as his dissertation topic and under Vijay's direction began extensive research into various mechanisms for modeling (describing in a precise, formal way) control. As the realization grew that they were in effect seeking to describe the *semantics* of the system, his reading began to focus especially on some of the techniques to emerge from the area of semantic modeling.

During the alternating cycles of discussion, reading and individual cogitation that characterize many design science research efforts, several software engineering concepts were brought together with a final key insight to yield the ultimately successful direction for the development. During one discussion Vijay realized that the control information for the system was knowledge, identical in form to the domain knowledge in the procedures and could be modeled with rules, in the same way. However, since the execution of the individual procedures was independent of the control knowledge, the two types of rules could execute in different cycles, partitioning and greatly reducing the complexity of the overall system. Finally, the then relatively new concept of object orientation seemed to be the ideal approach to partitioning the total system knowledge into individual procedures. And if each "smart" object were further partitioned into a domain knowledge component and a control knowledge component, and the rules were stated in a high-level English like syntax that was both executable and readable by domain experts . . .

AWARENESS OF PROBLEM REVISITED

As noted in the general discussion of the design science research method, any of its phases may be spontaneously revisited from any of the other phases. Especially in the early stages of a project, this results in a conceptual fluidity that can be disconcerting to practitioners of less dynamic paradigms. Though it is difficult in retrospect to pinpoint exactly where in the process the change occurred, by the inception of the development phase the problem statement had changed to a sub-goal implicit in the original problem statement: *how to effectively model operations support* *systems for complex, hierarchical, procedure driven environments* with *control modeling* as the specific research problem. [This sort of "drilling down" into the problem or re-scoping the research at a more basic level occurs frequently in all research but is effectively part of the method in design science research.]

Development

Although development of a design science research artifact can be straightforward, that was not the case for 'smart objects'. The construction was completely conceptual and involved the "discovery" through multiple thought and paper trials of the details of the novel entity that had been conceptualized at a high level in the Suggestion phase, the "smart object."

For example: what (exactly) would the syntax be for the two types of rules, domain and control? How (exactly) should the two rule evaluation cycles for each type of knowledge interleave? Should the two types of knowledge be permitted to interact? If so, how? Should control rules have the ability to "write" or "rescind" domain rules, a la Lisp? Or, vice versa?

In a conceptual development such as this, the suggestion and construction phases blur because a successful design decision *is* an output product. The final deliverable (from this initial development) was a conceptual model consisting of: (1) a set of meta-level rules for implementing domain knowledge and control knowledge separately, but within a single structure, the "smart object" and (2) another set of meta-rules that described how the domain and control knowledge, once "modeled" as smart objects, would be interpreted (a virtual machine for executing the smart objects).

Evaluation

In a sense evaluation takes place continuously in a design process (research or otherwise) since a large number of "micro-evaluations" take place at every design detail decision. Each decision is followed by a "thought experiment" in which that part of the design is mentally exercised by the designer. However, for the remainder of this section we will describe the "formal" evaluation that occurred after the design had stabilized.

In order to test the conceptual design, various operating environments were modeled and "hand-stepped" through the execution rules to determine that logically correct system behavior occurred at appropriate times in the simulation. The simulation that appeared in Gary's dissertation, the first publication to result from the research, was a grocery bagging "robot." This example had been popularized in a best-selling artificial intelligence textbook of the time and had the advantage of being a familiar logic test bed to many external evaluators of the artifact. Exponents of other IS research paradigms may find the evaluation criteria simplistic, and wonder why, for example, modeling of the nuclear power plant operating environment was not the obvious choice. The answer is: resources; the modeling and hand testing of even the grocery-bagging example occupied several man-months. During the evaluation, minor redesign of the artifact (the smart object conceptual model) occurred on several occasions, which is a common occurrence in design science research. By the end of the evaluation phase, the smart object model had successfully completed simulation of numerous bagging exercises that included complex control situations and was adjudged a success by the design team.

CONCLUSION

The finale for the first research effort involving Smart Objects was the codification of the problem development, design basis in prior work, the design itself, and the results of the evaluation effort in Gary's dissertation (Buchanan, 1991) The successful defense of the dissertation at GSU required careful consideration and judgment of the artifact and its performance by a committee made up primarily of other design science researchers. The core concepts were considered to have substantial merit, and Gary and Vijay produced several conference papers based on smart objects.

EPILOGUE

After Gary's graduation Vijay and Gary collaborated on a paper based on the research project and submitted it to *IEEE Transactions on Knowledge and Data Engineering (TKDE)*. The paper was returned for substantial revisions. At this point Gary's interest in the project waned, however a recently admitted GSU CIS doctoral student (Bill Kuechler) found the concepts interesting enough to enter into the research group and continue the development effort. After four years, three conference papers on smart objects and related topics and three major revisions, the TKDE paper was finally published as "A Data/Knowledge Paradigm for the Modeling and Design of Operations Support Systems." (Vaishnavi, et al., 1997). By the time of acceptance, smart objects had been through several additional design science research cycles, each focusing on the refinement of a different aspect of the original design, or a critical support function for its use-in-practice such as the methodology developed for partitioning workflow information systems into smart objects.

Understanding Design Science Research in the Context of Information Systems Research—References

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