On Expanding the Scope of Design Science in IS Research

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Abstract. Design Science Research (DSR) has sparked a renaissance of contributions to IS, but its rigor and value of DSR could be increased by expanding its scope beyond its engineering roots to bring all modes of scientific inquiry to bear – exploratory, theoretical , experimental, and applied science / engineering (AS/E). All DSR Cycle activities can be realized as instances of one or more of the four modes. The rigor of DSR can therefore be defended in terms of the goals, research products, and standards of rigor already established for each mode. There is, moreover, a synergy among the modes that can only be realized when all four are brought to bear, because each informs the other three. To exclude any mode of inquiry from DSR, therefore, is to impoverish knowledge about its objects of inquiry. Based on these insights, we propose a modified Cycles Model for DSR realized under the disciplines of the four modes of scientific inquiry.

Keywords: Design Science, Scientific Methods.

1 On the Value of DSR

Design *Science* Research (DSR) makes important contributions to the information systems (IS) literature beyond those made by behavioral research [1]. Behavioral research focuses on the human element of IS, e.g., system usage [2], emotion in IS [3], and information overload [4]; its prevailing modes of inquiry are theoretical and experimental research. The primary mode of inquiry for DSR, by contrast, is engineering [5, 6], and DSR has as its objects of inquiry: a) <u>Design Processes</u> (methods and practices): e.g., agile development [7]; b) <u>Design Products</u> (ways of modeling IS): e.g., UML [8]; and c) <u>Designed Artifacts</u> (instances of technology): e.g., relational databases [9,10]. Hevner and Chatterjee [5] define three cycles for DSR: a) the Relevance Cycle for gathering requirements and field testing; b) the Design Cycle for building and evaluating design artifacts and processes; and c) the Rigor Cycle for grounding design efforts in the knowledge base and contributing

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knowledge to it. The formalization of DSR [1], and a DSR methodology [11] sparked a renaissance of contributions [12].

The value and rigor of DSR could be increased, however, by expanding its scope beyond its engineering roots to bring all modes of scientific inquiry to bear – exploratory, theoretical, experimental, and applied science/engineering (AS/E). All activities of the DSR Cycles [1, 5] can be realized as instances of the four modes of scientific inquiry. Indeed, a *single* DSR study could make exploratory, theoretical, experimental, and AS/E contributions. A DS researcher, for instance, having used a kernel theory to inform design choices for an IS artifact, might validate the solution by comparing it to a prior solution. If unexplained phenomena were to manifest during validation, these would contribute to *exploratory research*. If negative findings were to inspire improvements to the theory, that would contribute to *theoretical research*. If findings were positive, that would be an experimental test of the kernel theory, which would contribute to *experimental research*. If validation proved the new artifact to be superior, that would contribute to *AS/E*.

This paper argues that all DSR Cycle activities can be realized as one or more of the modes inquiry, so the rigor of DSR contributions can be defended in terms of the goals, research products, and standards of rigor for each mode. The paper demonstrates a synergy among the modes of scientific inquiry that can be tapped only by bringing all four to bear (Figure 1). It argues, therefore, that broadening the scope of DSR to incorporate all modes could increase the depth and value of DSR contributions. Based on these insights, the paper proposes a modified Cycles Model for DSR activities realized under the disciplines of the four modes inquiry (Figure 2).

2 On DSR Activities as Exploratory Research

The goals of exploratory research are to discover and describe unexplained phenomena, their correlates, and the contexts in which they manifest [13, 14]. A *phenomenon* is an outcome whose value varies across time, contexts, and conditions, for example, system reliability or user productivity. The phenomena of interest to DS researchers would be the outcomes that designed artifacts are meant to improve. In the Design Cycle, they would be embodied in design objectives for requirements and evaluation metrics for validation. C*orrelates* of a phenomenon are other phenomena whose variations appear to be related to it [15]. For example, end-user satisfaction sometimes varies with end-user user involvement in design processes (e.g., [16]).

Products of Exploratory Research: The products of exploratory research are descriptive reports of phenomena, their correlates, and the contexts where they manifest. In DSR these may be, for instance, reports of challenges in the user environment. Phenomena are generalized to explicitly defined constructs, which may be classified in taxonomies and synthesized synthesize grounded theories, which are correlative networks of interrelated constructs [13]. Grounded theories may predict outcomes in the contexts where they were developed, but may not generalize to other conditions. Different relationships may appear among the same constructs under different conditions. This would not necessarily be seen as contradictions or refutation, but would instead add richness to descriptions of the phenomena.

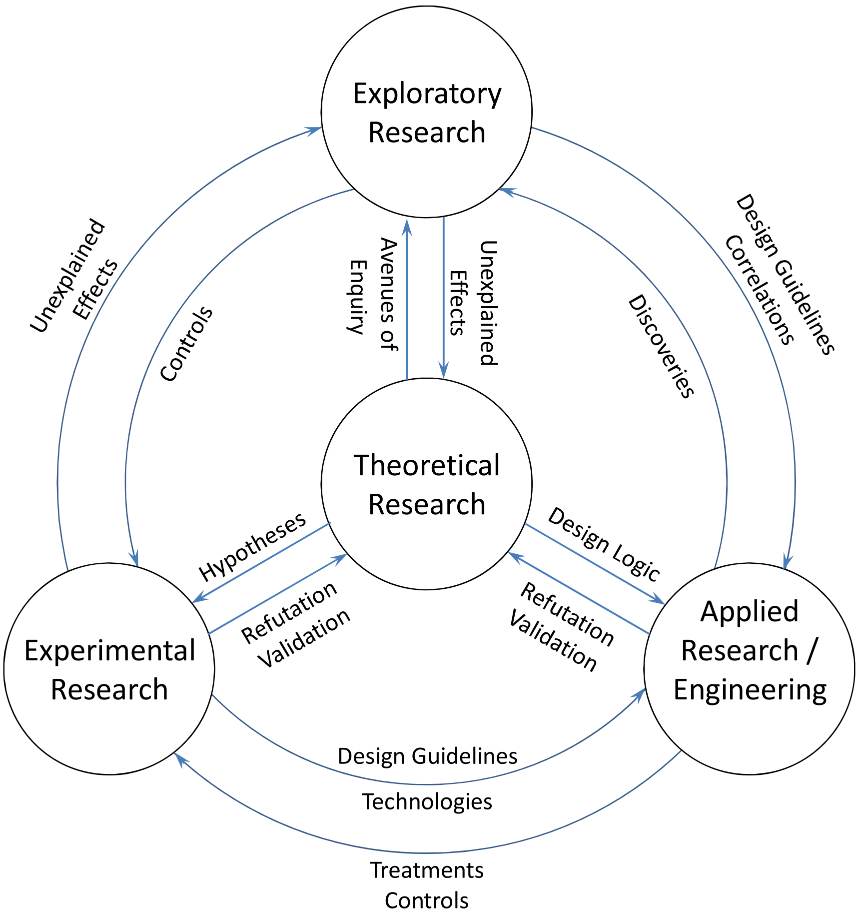

Fig. 1. Each Mode of Scientific Inquiry Informs the others. All for modes, therefore, can be brought to bear on the objects of inquiry for DSR to improve the richness and rigor of DSR findings. (Arrows are illustrative examples. Full articulation could occupy many pages.).

Standards of Rigor for Exploratory Research: The validity and generalizability of exploratory findings are established through *concatenation* - the accumulation of studies from which inductions may be made [13, 17], and by which inter-subjective concurrence on inductions may be established [18]. DSR may concatenate, for example, by testing related solutions to a class of problems across multiple domains. Definitions of constructs should be sufficiently explicit to demarcate them from other closely related constructs.

Exploratory research do not provide logic by which causality may be established. If two constructs correlate, it could be that the first causes the second, the second causes the first, or that some third unknown construct causes both [15]. The only logic for distinguishing among these possibilities is in theoretical and experimental research.

In exploratory papers, therefore, statements of relationships among constructs should be expressed in the language of association, e.g., *A is strongly associated with B; C correlates with D;* or, *E is inversely related to F.* Statements in exploratory models should exclude language that connotes causation, avoiding terms like *influences, impacts, affects*, *determines,* or *causes*. When discussing their models, however, exploratory researchers may, propose carefully qualified conjectures about *possible* causal relationships among the phenomena they describe, e.g. *G may influence H; I may be a function of J.*

Criteria for Exploratory Research Contributions: To be a contribution, an exploratory study should a) describe newly discovered phenomena and/or unreported contexts under which phenomena vary; or b) should concatenate previous findings , up to the point of conceptual saturation, where further exploratory studies yield no new insights [13].

Contributions of Exploratory Research to Other Modes of Inquiry: Exploratory research provides the foundation for all other modes of inquiry. It discovers the phenomena that theoretical research should explain. It's discoveries also inform experimental researchers about effects for which experimental designs should control. Its findings yield insights to AS/E researchers about the people, the problems and opportunities, and the environments that drive AS/E. Its correlative models let AS/E researchers predict possible consequences of design choices. Case studies of design projects yield design guidelines and best practices that inform design theories [19] (Figure 1).

DSR Cycle Activities as Exploratory Research: DSR Relevance, Design, and Rigor Cycles activities can be realized as exploratory research. For example, identifying problems, opportunities, stakeholders, goals, design drivers, constraints, and requirements during the design cycle corresponds to the discovery of phenomena and descriptions of the contexts in exploratory research. When solutions *have been derived by intuition,* field-testing in the Relevance Cycle constitutes primary exploratory research. In the Rigor Cycle, informing design choices with exploratory reports of correlation or association is, by definition AS/E research. Validation of such solutions constitutes exploratory concatenation.

3 On DSR Activities as Theoretical Research

The goal of theoretical research is to create models of cause and effect that predict and explain variations in phenomena. The phenomenon-of-interest in theoretical research is always an effect, never a cause. In DSR, the phenomena of most interest would be the outcomes the designer seeks to improve with designed artifacts. DS researchers need kernel theories that can predict and explain the effects of contemplated design choices.

The Products of Theoretical Research: The product of theoretical research is a *deductive nomological theory* that predicts and explains variations in a phenomenon. These are sometimes called causal, formal, or explanatory theories; Gregor [20] calls them "theories that predict and explain;" Stebbins [13] calls them received theories.

The term, “theory,” however, is overloaded, being also attached to other kinds of models besides deductive nomological theories – taxonomies, descriptive models, grounded theories, and design theories among them [20]. Each kind of theory models a different aspect of reality. Each has different kinds of statements, represents different relationships, has different standards of rigor, and serves a different purpose. These kinds of theory are useful to science, but are not the product of theoretical research. Descriptive and grounded theories are, as noted, the product of exploratory research. Design theories are a product of AS/E.

A deductive nomological theory has two kinds of statements (sometimes called covering laws or general laws): axioms[1] and propositions. A theoretical *axiom* states an assumption about mechanisms that could give rise to a phenomenon. For example, to explain user productivity, one might begin with an assumption like:

> ***Axiom 1***. *Human attention resources are limited.*

A *theoretical proposition* is a functional statement of cause-and-effect between two constructs. A construct is an abstract concept that represents a causal or consequent element in the environment. It should be possible to a derive theoretical propositions from its axioms by internally consistent deductive logic. For example:

> *If, as Axiom 1 posits, human attention resources are limited, and if productive effort requires attention, then it would have to be that:*

> ***Proposition 1:*** *User productivity is an inverse function of distraction.*

In DSR, the logic of a nomological theory can be used to predict and explain the effects of design choices. If Proposition 1 holds, for example, then a DS researcher should be able to improve user productivity by eliminating distractions from the system, and/or by using the system to mitigate distraction in the environment.

Standards of Rigor for Theoretical Research: Proposition should express causal relationships between constructs. Axioms should propose mechanisms that could account for the phenomena-of-interest. It should be possible to derive its propositions from its axioms by deductive logic. It should be possible to falsify the constructs and propositions of a theory by experience [18, 21]. Propositions should not be tautological (true by definition, or by circular reasoning). Definitions of causal constructs should be sufficiently explicit that one could devise treatments that instantiate differing values of the causal construct [21]. Definitions of consequent constructs should be sufficiently explicit that they can be measured in an operationally specific manner [21]. The term, satisfaction, for example, has been attached to both judgments and emotions in the IS literature. Definitions of satisfaction would therefore have to clarify that distinction. The construct, *outcomes*, which has appeared in many IS theories, is not sufficiently specific because it could refer to every phenomenon in the IS domain.

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[1] The term, *axiom*, has other connotations in other contexts. Some *authors* apply the term to theoretical positions that have accreted massive and unequivocal empirical support (e.g., F=MA). Others use the term to mean, “that which is widely assumed to be true.”

The generalizability of a theory is the range of contexts to which it can be applied. A more-specific theory may explain a phenomenon in a given context or under a bounded range of conditions, and may do so in terms more closely related to the context, making it easier to apply the theory in that context. At the same time, specificity limits the theory's generalizability. For example, early IS Satisfaction theories that included attributes of specific technologies were useful for predicting satisfaction with those objects, but did not generalize well to new technologies. More-general disconfirmation theories of satisfaction [22] explained satisfaction with any technology at the time outcomes were realized, but could not account for effects long before or after outcomes were obtained. Yield Shift Theory [23] is still more general, explaining satisfaction with any objects in any contexts (although it has not yet accrued sufficient empirical support to establish its scientific utility). At the same time, it may require more reasoning to apply a general theory to a specific case.

Note that it is neither required, nor logically possible to derive or defend the axioms of a theory. They are assumptions, and are deemed to be received [18]; their origins are not relevant to the logic of the theory.

Criteria for Theoretical Research Contributions: A nomological theory contributes to knowledge if its scientific utility or parsimony are greater than those that preceded it [21]. A theory has more utility if it accounts for more variations in a phenomenon in more contexts; having more explanatory power, it is a contribution to theoretical research. The parsimony of a theory is the number of constructs and statements it requires to achieve its explanatory power [18]. A new theory with same explanatory power, but fewer constructs or statements would be a contribution to theoretical research. If, however, adding more constructs, axioms, or propositions to a theory were to *increase* its explanatory power, then it would be deemed a contribution, even if it were less parsimonious.

Contributions of Theoretical Research to Other Modes of Inquiry: Theoretical research often anticipates effects not yet observed, suggesting fruitful lines of inquiry to exploratory research. Theoretical research is the *raison d'être* for experimental inquiry, which has as its purpose to falsify theoretical propositions [18]. To AS/E, theoretical research sends explanations with which designers can predict the consequences of new design choices (Figure 1). Theories may thus become design guidelines; e.g. if, as YST proposes, satisfaction is a function of shifts in yield for the active goal set, then UI/UX designers could invoke satisfaction responses with design choices that impact the perceived likelihood and/or utility of goal attainment [23].

DSR Cycle Activities as Theoretical Research: In the DSR Rigor Cycle, design choices may be informed by a nomological deductive kernel theory [5]. If existing theory does not explain the outcomes of interest, the DS researcher may improve existing theory or derive a new theory for that purpose, e.g., [23]. Doing so contributes to theoretical research. In the Design Cycle, validating an artifact derived from a theory would test that theory.

4 On DSR Activities as Experimental Research

The goal of Experimental research is to test the propositions of a deductive nomological theory. It may also be called *confirmatory research* [13], but confirmation should not be misinterpreted as proof; scientific method provides no logic by which a theory may be proven true. Results that are consistent with a theoretical proposition may support a proposition, but do not prove it. By the same token, no single experiment can claim to have broken a proposition. There are many threats to the validity of an experiment [24], and it is not possible to control for all of them in a single study. It therefore requires a body of experimental work by a community of researchers to credibly support or refute a theory.

Products of Experimental Research: The products of experimental inquiry are hypotheses, experimental designs and methods, and analyzed data sets. The term, hypothesis has several connotations in the scientific literature; it is sometimes used as a synonym for the terms, prediction, conjecture, and proposition [25]. In experimental research, a *hypothesis* is a comparative statement that contrasts the value of a dependent variable across treatments that instantiate differing values of an independent variable. A dependent variable always instantiates the consequent construct of a theoretical proposition. In DSR it is a measure of an outcome the designer seeks to improve with the artifact, and so measures the degree to which design objectives have been achieved. An independent variable always instantiates the causal construct of a proposition. In DSR, one of the treatments is likely to be a theoretically-informed designed artifact. Another treatment may be a previously designed artifact, or a control condition where no technological artifact is introduced. Hypotheses should be derived by internally consistent deductive logic from the theoretical propositions they are meant to test. For example, to test the Distraction proposition above, one could reason as follows: *If, as Proposition 1 states, end-user productivity is an inverse function of distraction, then it would have to be that:*

> ***Hypothesis 1.*** *People using a digital brainstorming tool that plays video clips of exuberant dancers at random intervals will produce fewer useful ideas than will people who use a tool that plays no clips of dancers.*

In H1, the clip treatment is a high value for distraction; the lack-of-clips a low value.

Standards of Rigor for Experimental Research: Many issues of validity surround Experimental research. This section only lists a small but important subset: construct validity, internal validity, external validity, and experimenter bias [24]. Construct validity is the question of whether the variables used in the hypotheses actually instantiate the constructs in the proposition. Science has no definitive proof for construct validity, but statistical tests for convergent and discriminant validity are at least useful for excluding some flawed measures [24]. Internal validity is the question of whether the observed results were actually caused by the experimental treatment instead of by something else. Numerous disciplines pertaining to experimental designs and controls should be brought to bear to improve internal validity (see [24]). External validity is the degree to which results of the experiment would generalize to contexts other than those of the experimental conditions. If for example, a DS experiment user interface color were run with two-color monitors, the study would have low external validity since results might differ on commonly-used monitors that display 16 million colors [24].

Experimenter bias is the question of whether the experimenter's expectations, preferences, actions, omissions, or limitations skewed experimental results. There is a widespread misconception that the philosophy of science considers the scientist to be objective. On the contrary, causal epistemology assumes the observer is subjective [18]. The validity of any finding is therefore in question until an experiment has been replicated by other subjective observers under other conditions. Inter-subjective concurrence – all subjective observers obtaining similar results – provides some assurance that outcomes may be sound [18].

Studies that *measure* the independent variable, rather than manipulating it with treatments, do not conform to the logic of experimental research, so no causation may be inferred from the results. Such studies are exploratory; to minimize confusion they should be labeled as *investigations* or *explorations* rather than as experiments.

Criteria for Experimental Research Contributions: Experiments contribute to scientific knowledge if a) hypotheses were derived from theoretical propositions by sound deductive logic; b) construct validity is reasonably argued; c) experimental design rules out most alternative explanations for the results, and threats to validity that could not be controlled are noted; d) Statistical analyses are a sound test of the hypotheses, e) the analyses support the hypotheses, and f) the literature is not already saturated with replicated studies supporting the proposition being tested. Negative experimental results may also contribute to science if a) the first four conditions above hold; b) statistical analysis reveal very high statistical power (had there been an effect, the study would have been likely to reveal it); and c) the literature contains robust empirical support for the proposition. This would be a credible challenge to a generally accepted position, and so worthy of further attention from the scientific community.

Contributions of Experimental Research to Other Modes of Inquiry: Experiments sometimes reveal previously unknown phenomena and patterns of correlation, and contribute to exploratory research. Negative experimental findings sometimes inform ways to improve a theory, and so contribute to theoretical research. Positive findings build support for a theory, increasing its value to society, and so contribute to theoretical research. When experimental findings inform design processes and choices, or validate artifacts, they contribute insights to AS/E.

Although the only purpose of Experimental *research* is to test formal theoretical propositions, experimental *techniques* are also useful in Exploratory and AS/E. An exploratory study based on experimental techniques can reveal new phenomena and new details about known phenomena, even though its results cannot be interpreted as having tested a theoretical proposition. Likewise, the findings of an experimental validation of a DSR artifact inspired by intuition would be both a contribution to AS/E, in that they validate the new solution, and a contribution to exploratory research, in that they explore phenomena in previously unexamined contexts and conditions. Such findings, though they would be regarded as AS/E and exploratory respectively, they would not be contributions to experimental research because they do not test a theoretical proposition. When experimental techniques are used in exploratory or AS/E studies, hypotheses should not be advanced, because there will be no theoretical propositions from which to derive them. One can use instead research questions or conjectures. A research question would convert hypothetical language to a question (e.g., RQ1. Will people who use an electronic…score higher on…than people who use…?). A conjecture would differ linguistically from a hypothesis in label only, (e.g., *Conjecture 1. People who use an electronic…will score higher on… than people who use…*). The conjecture label will show readers that the author knows the study does not test a theoretical proposition, and so may preclude them from demanding experimental rigor for a study where it would not be logically or philosophically warranted (Figure 1).

DSR Cycle Activities as Experimental Research: In the Rigor Cycle, when one draws on a theory to inform design choices, that frames a treatment for an experimental hypothesis. In the Relevance Cycle, validating a theoretically-informed artifact by comparing it to a prior solution could be an instance of an experiment on a hypothesis derived from the theory. Positive findings would both validate the artifact, and support the theory.

5 On DSR Cycles as Applied Research/Engineering

The goal of AS/E research is to use scientific knowledge to solve important practical problems. AS/E is distinguished from engineering practice in that engineering practice seeks to create a specific instance of a useful artifact to solve a specific problem, (e.g., [26, p. 86]), while AS/E seeks to create novel, generalizable solutions for an important class of problems, and to synthesize bodies of knowledge, construction principles, and generalizable work practices that can increase the likelihood that designed artifacts will meet design objectives. In DSR, the synthesized knowledge would include the kernel theories and other findings that could inform the design choices. Construction principles encompass structure and function of existing and possible technology [26, p. 90]. The generalizable work practices would be engineering methodologies. These contributions can, over time, be codified into a *design theory* (DT) that a) defines the purpose and scope of a design methodology; b) identifies principles of form and function for design solutions in that scope; c) defines criteria for generalizability of solutions by identifying requisite variety that a solution in the scope should accommodate (called "artifact mutability"); d) identifies justificatory knowledge in the form of kernel theories and other knowledge that can inform designs in the scope; e) provides guidelines for implementation; and f) provides an expository instance of a solution in the scope [19].

Where theoretical inquiry seeks relationships in the form, *A causes B*, the logic of AS/E is, *If you want to achieve B, then you should do A*. German technology philosopher Kornwachs [27, p. 72] condenses Bunge's [28] pragmatic syllogism more concisely as: *If A --> B*. This expression means: *Under certain circumstances, realizing State A will cause State B to exist. If State B is desired, then try to bring about State A*. While *A causes B* should be true in all contexts, *If you want to achieve B, then do A* is dependent on its specific socio-technical context for two reasons. Firstly, there are many interacting conditions other than the designed artifact that may affect its utility for achieving *A*. An artifact requiring electrical power, for example, may be deployed in an environment without electricity, and so be incapable of creating *A*. Likewise, a good artifact may be used badly, and so not produce *A*, despite its potential. In Engineering research, therefore, is often useful and necessary to inform design choices by a mixture of scientific knowledge (from the natural and social sciences), intuition, empirical knowledge (e.g., from tests) and prior technical knowledge [29].

Products of AS/E Research: The research products of AS/E research are: a) detailed descriptions of important classes of problems, and the contexts in which they emerge; b) generalizable design objectives, constraints, and requirements for addressing a class of problems; c) generalizable solutions for a class of problems, e.g., design patterns [30, 31]; d) expository instances of generalizable solutions; e.g., reference models [32], and proof-of-concept prototypes [1]; f) evidence that solutions are useful and generalizable; and g) the elements that comprise design theories for implementing solutions for a class of problems, e.g., methods such as object-oriented analysis and design [33].

Standards of Rigor for AS/E Research: Where an exploratory researcher says, “Gee, that’s *funny*,” (Isaac Asimov quoted by [34]) and a theoretical researcher shouts, "Eureka!" the successful AS/E researcher exclaims. "It works!" [26. p. 97]. The principle criterion for a contribution to AS/E knowledge is its usefulness. As with theoretical contributions, AS/E contributions should be original, generalizable, and validated. Originality may be established by comparing contributions to the state of the art. Generalizability may be established by demonstrating the applicability of the solution to a range of contexts. Validity may be justified by the evaluation of the results [35]. Justification efforts could include pilot tests in the natural environment [36], experiments, expert evaluations, or, in some cases, the consensus of the scientific community.

Criteria for AS/E Research Contributions: AS/E Research applies scientific knowledge to solve important practical problems. It is by definition, therefore, informed by the other three modes. AS/E, however, also informs the other three. An AS/E researcher who investigates a previously unexamined domain *to* identify its problems, opportunities, constraints could make a contribution to exploratory research. Likewise, an AS/E researcher who tests a new design inspired by intuition rather than theory may be conducting exploratory research. When an AS/E researcher develops or improves a theory to better inform design choices, the resulting model could be a contribution to theoretical research. An AS/E researcher who validates a theory-informed artifact with an experiment, contributes to experimental research.

Contributions of AS/E Research to Other Modes of Inquiry: When an applied researcher *discovers* a previously unreported effect, that may be a contribution to exploratory research. If the applied researcher develops a theory to explain an effect in order to inform design choices, that would be a contribution to experimental research. When an applied research validates a technology whose design choices were informed by a theoretical proposition by comparing it to an earlier solution, the results may be a contribution to experimental research. If the experiment fails to support the theory, that may also be a contribution to exploratory research.

DSR Cycle Activities A AS/E: Because the roots of DSR are in engineering, the activities of the DSR closely parallel those of AS/E; indeed, the current framing of DSR may be seen as a domain-specific reinvention of AS/E. The parallels can be demonstrated by considering three key activities of AS/E:

1. Identify an important class of unsolved problems. This corresponds to the *Requirements* activity of the DSR Relevance cycle, where the current state and desired state are identified by identifying the actors, their goals, the design objectives and key design drivers and constraints. AS/E outputs, like DSR requirements, should be generalizable to a class of problems and a range of contexts .
2. Design generalizable solutions. This AS/E activity corresponds closely with the *Design and Build Artifacts* activity in the DSR Design Cycle, where theories, intuition, and prior engineering knowledge are used to produce classical *engineering* outputs: models, methods, and expository instances of a generalizable solution.
3. Validate the solution. This AS/E activity maps directly to the *Validate* and *Field Test Artifacts* activity of the DSR Relevance cycle. As in AS/E, DSR validation consist of an empirical test of the designed artifact or process with, for example, experimental techniques. Where exploratory or theoretical knowledge is realized in the artifact, the validation produces research spillovers in those domains (Figure 1).

6 On Expanding the Scope of Design Science Inquiry

6.1 Increasing the Rigor of DSR by Expanding Its Scope

The preceding sections define the goals, research products, and standards of rigor for each mode of exploratory, theoretical, experimental, and AS/E inquiry, and demonstrate that DSR Cycle Activities can be realized as instances of one or more of the four modes of scientific inquiry. Depending on the needs of the DS researcher and the phase of the research, Relevance Cycle activities like *Identify Requirements* and *Do Field Tests,* can be realized variously as exploratory, theoretical, experimental, and AS/E modes of inquiry. Various aspects of the *Build Design Artifacts and Processes* activity in the Design Cycle can be realized across as instances of all four modes. The Rigor Cycle activity, *Ground design in applicable knowledge,* corresponds exactly to the AS/E activity, *Identify relevant scientific knowledge.* Elements of the Rigor Cycle's *Add Knowledge to Knowledge Base* activity can be realized in each of the four modes of scientific inquiry, because all activities of the four modes of scientific inquiry contribute to the knowledge base, and all are instantiated by one or more DSR Cycle activities.

Given that all activities of the DSR Cycles Model can be realized as one or more instances of the four modes of scientific inquiry, and given that all four modes have accepted standards of rigor, and assuming that the DS researcher implements an activity under the disciplines of a mode, the standards of rigor for the four modes of inquiry can be used to defend the rigor of DSR. Expanding the scope of DSR to bring all four modes of scientific inquiry to bear on the DSR objects of inquiry would therefore increase the rigor of DSR. It is important to note, however, that all DSR activities can also be realized in ways that do not conform to the logic and disciplines of any of the four modes of scientific inquiry. In such cases, the rigor of the DSR could not be defended by the standards of rigor for the modes. Given that lack of rigor, however, one might argue that such activities are not, in fact, design *science*.

6.2 Increasing the Richness of DSR by Expanding Its Scope

The preceding sections also demonstrate that there is a synergy among the four modes of scientific method because each mode informs the others; none stands on its own (Figure 2). Increasing the scope of DSR beyond its engineering roots so as to bring all four modes to bear on the DSR objects of inquiry would therefore increase the depth and variety of DSR's normal AS/E contributions, increasing the strength of DSR's foundation. It would also initiate a fresh stream of DSR contributions to exploratory, theoretical, and experimental research.

7 On Cycles Model for DSR Informed Four Modes of Scientific Inquiry

If DSR activities are realized as instances of the four modes of scientific inquiry, then the *activities* and their findings will be scientifically rigorous. Under those conditions there is no need for a separate Rigor Cycle in a DSR cycle model. If realized rigorously, all DSR activities have the potential to contribute to the knowledge base. Given that stakeholders could be involved in all DSR activities, all activities could require interactions with the environment. We therefore propose a modified DSR Cycles Model for activities based on the four modes inquiry (Figure 2). It characterizes DSR as three activities: 1) Discover Problems and Opportunities; 2) Design and Build Artifacts and Processes; and 3) Validate Artifacts and Processes.

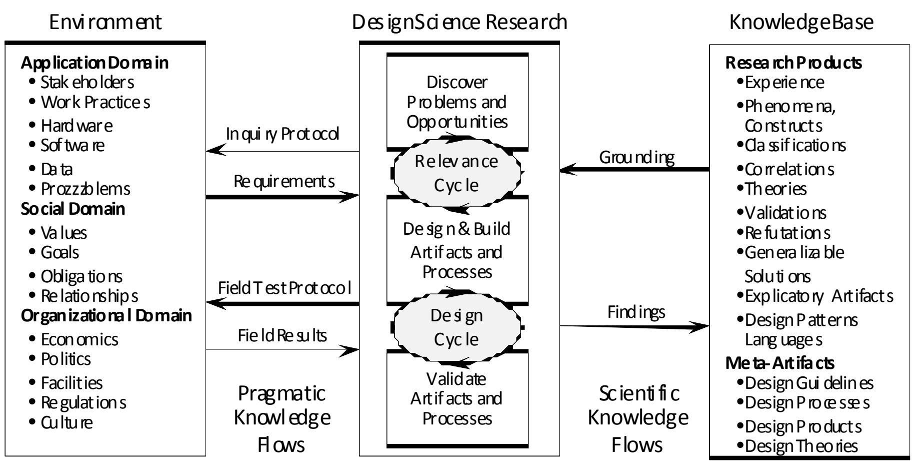

Fig. 2. A MODIFIED DSR CYCLES MODEL for Activities Informed by the Four Modes of Scientific Method: Exploratory, Theoretical, Experimental, and Applied Science/Engineering. If all DSR activities are conducted with scientific rigor, there is no need for a separate Rigor Cycle. Arrows signify information flows among DSR activities, the environment, and the knowledge base. (Lists of concepts are exemplary rather than exhaustive.).

The model depicts a Relevance Cycle between the Discovery and Design activities, and a Design Cycle between the Design and Validate Activities. It signifies that any DSR activity may draw from or add to the Knowledge Base. It further signifies that any DSR activity may engage with stakeholders in the environment to learn more about their problems and opportunities and to involve them in the DSR process. This model reflects the rigor and richness that can be gained by broadening the scope of DSR modes of inquiry. The arrows signify flows of knowledge between DSR activities, the knowledge base, and the environment.

8 Conclusions

This paper argued that DSR activities can be realized as instances of four modes of scientific inquiry: exploratory, theoretical, experimental, and AS/E. It shows a synergy among the four modes of inquiry, because each mode of inquiry informs the other three. To exclude any of them from DSR, therefore, is to impoverish that body of research. It is consequently important to the advancement of DSR to expand the scope of DSR beyond its engineering roots to embrace all four modes of scientific inquiry.

We argue that, because DSR *activities* can be realized as instances of the four modes of inquiry, it is possible to defend the rigor of DSR activities in terms of the goals, research products, standards of rigor, and criteria for contributions to knowledge that have already been established and accepted for these modes of inquiry. The paper demonstrates this position by enumerating aspects of each mode of inquiry and linking them to DSR activities. It would be useful to the advancement of DSR, therefore, to execute DSR activities according to the precepts and disciplines of the established modes of inquiry until such time as other means of defending its rigor may be established.

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