Judging the Quality of Operationalization of Empirical-Analytical, Interpretive and Critical Science Paradigms in Engineering Education Research

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Introduction

Paradigms are basic sets of beliefs that guide disciplinary inquiry. They can be constructed from a proponent’s responses to basic questions of ontology, epistemology, and methodology. The three basic questions are:

1. Ontological: What is the nature of the “knowable”? Or, what is the nature of “reality”? 
2. Epistemological: What is the nature of the relationship between the knower (the inquirer) and the known (or knowable)?
3. Methodological: How should the inquirer go about finding out knowledge? (p. 18)

Once constructed, the paradigms, which can neither be “proven” nor disproven in any foundational sense,” become entry points for conducting disciplinary inquiry.  

While methodologies (and indirectly paradigms) have recently been the point of discussion in engineering education literature, explicit discussion on judging the operationalization and quality of operationalization of paradigms in engineering education is limited. Operationalization is the process of defining a latent phenomenon (e.g. research paradigm) in terms of observable phenomenon (e.g. research outcomes). Researchers have discussed general qualities of major methodologies – quantitative, qualitative and critical theory- along with examples of engineering education research studies that operate from within the specific paradigms. More recently, they have described emerging qualitative methodologies along with an illustration of their operationalization in example studies from engineering education. Other researchers, who investigated the status of only qualitative research in engineering education, have found inconsistency in operationalization of (qualitative) paradigms in existing engineering education studies. Description of methodologies for judging the operationalization and the quality of operationalization of major paradigms in engineering education research is currently limited to the methods section in the cited study.

This (other category) paper complements previous research in explicitly describing Coomer and Hultgren’s paradigm classification criteria and how new researchers can use the paradigm classification criterion to identify and determine the quality of operationalization of paradigms in research studies. New researchers are often experts or graduate students in engineering or engineering education, who have primarily been trained in and are operating from the empirical-analytical paradigm, without formal education on different research paradigms. Hence, new researchers may benefit from a description of the different paradigm classification criteria and the process of using the paradigm classification criteria to determine the quality of existing research and design of future engineering education research.

Paradigm classification criteria for empirical-analytical, interpretive and critical science paradigms

Coomer and Hultgren provide paradigm classification criteria for the empirical-analytical interpretive and critical science paradigms in their studies. Very briefly, the empirical-
analytical paradigm rests on a “critical realist” ontology (i.e. reality exists outside the observer and cannot be fully captured), a “modified objectivist” epistemology (reality can be objectively approximated), and a “modified experimental” methodology (knowledge captured in controlled but more natural settings). The interpretive paradigm rests on a “relativist” ontology (reality exists as “multiple mental constructions” (p. 27) of the observer), a “subjectivist” epistemology (reality is based on the interaction between reality and the observer), and a “hermeneutic, dialectic” methodology (knowledge is “elicited and refined with interpretation of the text, and compared and contrasted via an argument” (p. 27) until a consensus on mental constructions is reached). The critical theory paradigm rests on a “critical realist” ontology, a “subjectivist” epistemology, and a “dialogic/transformative” methodology (“facilitates transformation” through removal of “false consciousness” (p. 27)). These differences are summarized in Table 1. A more detailed description of the three paradigms is available in cited studies. There is some overlap between Coomer and Hultgren’s criteria for paradigm classification.

Table 1. Ontology, Epistemology and Methodology of empirical-analytical, interpretive and critical science paradigms.

<table>
<thead>
<tr>
<th>Paradigms/Components</th>
<th>Empirical-analytical</th>
<th>Interpretive</th>
<th>Critical Science</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ontology</td>
<td>Critical realist</td>
<td>Relativist</td>
<td>Critical realist</td>
</tr>
<tr>
<td>Epistemology</td>
<td>Modified objectivist</td>
<td>Subjectivist</td>
<td>Subjectivist</td>
</tr>
<tr>
<td>Methodology</td>
<td>Modified experimental</td>
<td>Hermeneutic, dialectic</td>
<td>Dialogic/transformative</td>
</tr>
</tbody>
</table>

Coomer classifies paradigms based on eight features. The features include: areas of human life, cognitive interest, research purpose, research questions, assumptions about knowledge, assumptions about value, criteria of validity, and outcomes. Most of these criteria are explained on need-basis in the methods and results sections for papers that use the paradigms as modus operandi. Unexplained criteria (assumptions about knowledge and value) is available in the cited study.

Hultgren classified paradigms based on six features. The features include: primary interest and application, theoretical/philosophical orientation, research purpose, unit of analysis, validation procedure, and meaning of explanation. Most of these criteria are also explained on need-basis in the methods and results sections for papers that use the paradigms as modus operandi. Unexplained criteria (theoretical/philosophical orientation) is available for reference in the cited study.

Though not as popular in published research as the widely-used framework of Crotty, Coomer and Hultgren’s criteria are useful and accessible educational tools for new researchers in engineering education. Coomer and Hultgren describe their criteria in a simple way and compare and contrast format to assist new researchers’ easy understanding of basic paradigms. Moreover, the use of Coomer and Hultgren’s criteria is advantageous as their criteria directly correspond with several tangible components of research studies that new researchers may already be aware of or can easily grasp and apply in their review of engineering education research studies.
Therefore, Coomer and Hultgren’s criteria are used to illustrate the operationalization and quality of operationalization of empirical-analytical, interpretive and critical science paradigms for new engineering education researchers. The three paradigms are selected for analysis in this paper for their prominence (though unequal), as stated in study² and inferred from study³, in the engineering education literature.

**Methods**

A qualitative research methods approach was taken to illustrate the operationalization of empirical-analytical, interpretive and critical science paradigms in research.

**Data Collection**

Data was collected in the form of observations (i.e. descriptive text) from three published studies on the topic of invention. The three example studies were judiciously selected after a systematic search of the literature. The author first searched for potential studies using keywords such as “creativity” and “invention” in EBSCO. New researchers can follow a similar analysis for their topic of interest. The titles and abstracts of studies were then surveyed for Coomer and Hultgren’s criteria of cognitive interest and application. Coomer⁶ defines cognitive interest in terms of technical (in case of empirical-analytical), practical (in case of interpretive), and emancipatory (in case of critical research) interest. Hultgren⁷ defines application of research in a similar manner. Examples of application interests such as “build[ing] abstract theory,” “enabling meaningful interactions” and creating “social change” (p. xx-xxi) are available in the cited study.⁷ The survey continued until a 100% inter-coder agreement (between a senior professor and the author) was reached for the example studies presented for each of the paradigms of interest. In other words, the example studies were selected for presentation only and only if both the senior professor and the author agreed that the studies belonged to the said paradigms. Achieving a high (intersubjective) agreement was important to establish reliability of findings from this study. While the example studies are not strictly engineering education studies, each of these studies can easily be extended to have implications for engineering design education. Similar paradigmatic analysis can therefore be applied to studies categorized explicitly as engineering education research studies. A small sample size (n = 3) may cause concern to reviewers; the sample size is appropriate for this research because the purpose of this research is to “facilitate individual/or collective meaning making” (p. 167) of the process of operationalization and judging the quality of operationalization of empirical-analytical, interpretive and critical science paradigms.⁴

**Data analysis**

Data analysis consisted of analyzing the content and the quality of content of the studies for Coomer and Hultgren’s criteria for paradigm classification. The author first read and summarized the three articles in entirety and then searched for descriptive texts against Coomer and Hultgren’s criteria for paradigm classification. Once found, the descriptive evidence along with its quality was noted down for each criterion. Judging the operationalization and quality of operationalization of paradigms from published research studies is a limitation of the data analysis process used in this research study as only the author’s perspective is typically highlighted during data analysis. To ensure validity of current findings, the same senior professor was debriefed about the classification process and the descriptive evidence. Since he was in
agreement with the author’s classification, the findings were considered adequate for the purposes of this research. Other limitations of conducting a content analysis of research studies are mentioned in Koro-Ljungberg and Douglas’s study. These limitations are inherent to the research process and therefore unavoidable. Nonetheless, the current findings are useful for the purpose of this research. Moreover, the author emphasizes that the critique of three articles is conducted to educate new researchers on the process of judging the operationalization and quality of operationalization of paradigms in research. It should not be taken as a criticism of the published work.

Results & Discussion

Results include summaries of selected articles from the empirical-analytical, interpretive, and critical science paradigms and textual evidence collected from the three published studies. The summaries and evidence are followed by a discussion of the operationalization and quality of operationalization of the empirical-analytical, interpretive and critical science paradigms in the respective articles using Coomer and Hultgren’s criteria.

Summaries of articles on invention

The author found three example studies that represent the respective paradigms. The studies are summarized first to contextualize the presentation of descriptive evidence of operationalization of the three paradigms for the reader.

Article I: Invention Heuristics and Mental Processes Underlying the Development of a Patent for the Application of Herbicides

The article “Invention Heuristics and Mental Processes Underlying the Development of a Patent for the Application of Herbicides,” by Weber, Moder and Solie, found in the New Ideas in Psychol. Vol. 8, No. 3, explores the cognitive process of invention using heuristics. The heuristic, “an internalized mental procedure that explains our problem solving behavior” (p. 323) and becomes a “helpful procedure for generating ideas or solving problems” (p. 323) on generalization and systemization, serves as an analytic framework for examining the cognitive dimension of the invention process. Using this model, the authors attempt to answer two questions: (1) how does an inventor think about forming a whole (complex device, tool or function) from parts (simple components)? (2) How can generalizations of thinking processes of inventors be derived to “guide the act of invention” (p. 321)?

Weber et al examined an actual patent (Patent # 4,683,826), granted to John B. Solie, H.D. Wittmuss and O.C. Burnside in 1987, and interviewed one of the inventors of the patent (John B. Solie) using a retrospective protocol method to understand the invention process and derive a set of heuristics to guide invention. Patent # 4,683,826 is an “agricultural invention for the application of herbicides” (p. 321) used to apply “herbicide uniformly in one pass over an area, using existing agricultural implements [(a sweep)], and avoiding destruction of surface residues” (p. 324). After examining the patent, the authors categorized available design choices in a frame description, which “provides a symbolic representation of an invention” for “compatibility and manipulability” of design variables and constraints (p. 325). The available design choices categories were (1) general purpose/need of invention, (2) external materials (which affect the invention), (3) component parts (of the invention), and (4) procedures (or functions the invention performs). Once the patent was described, the authors interviewed Solie, the inventor. Solie was
asked the following questions to understand how he invented the agricultural invention: where did his ideas for the sweep applicator originate from? What strategies and approaches did he use to develop his invention? How did he achieve his design goals? Did he rotate the sweep or mentally walk around it (to arrive at different design variables)? What function did his visual imagery play in the design process? The authors argued that the validity of the retrospective method is tested if plausible principles are determined and are useful to inventors elsewhere.

Weber et al found that Solie identified a need (a herbicide applicator, which could uniformly apply herbicides without eroding the soil) and sought solutions to the need (deliberate level of invention). He drew on memory to find alternatives using existing devices before consulting the patent records. In doing so, Solie was able to combine an existing implement (a sweep) and process of herbicide application (Joining approach to invention) to form the herbicide applicator. He was able to optimize his design (Fine Tuning approach to invention) via experimentation and form the final device via addition of upward pointing nozzles on the sweep (Major Adjustment approach). Solie also identified use of visual imagery and image transformation (such as zooming, panning and rotation) to find design variables to be minimized and maximized to meet the general purpose of the device and to systematically explore design constraints. These design constraints are “relationships between variables which must be accommodated in the invention process” (p. 329) as they lead to specific design choices.

Based on the above interview responses, Weber and colleagues conceptualize a general set of invention heuristics and procedures to “guide the act of invention” (p. 321). They suggest the following heuristics: (1) construction of a frame description for the problem to easily manipulate design variables, (2) development of a systematic min/max table to explore the relationships between different design variables and “hold down the demands on operating memory” (p. 335), (3) development of a systematic constraint table to categorize the relationships between constraint pairs as compatible (i.e. both variable can be optimized to desire), incompatible (only one variable can be optimized to desire), or irrelevant (no relationship between the two variables), (4) use of “visual imagery to explore alternatives and constraints” (p. 335), and (5) “metaphor or analogy” (p. 335). The following set of heuristic rules is also suggested for working with a systematic min/max table: (1) explore pair-wise variables for compatibility first; ignore higher order compatibility relations until needed and use the most important first, 2) focus on incompatible relationships to determine trade-offs; a different design approach may be needed if there are too many incompatible relationships between variables, and 3) assign weights to various incompatible variables as all of them are not equally important. In outlining these invention heuristics, Weber et al. emphasize that their purpose is not to be prescriptive but “to bring the inventive process out of the realm of intuition and into the domain of systematic thought” (p. 335).

**Article II: The Eureka Process: A Structure for the Creative Experience in Science and Engineering**

The article “The Eureka Process: A Structure for the Creative Experience in Science and Engineering,” by Shaw, found in the *Creativity Research Journal* Vol. 2, No. 4, explores the affective process of invention for scientists and engineers using a heuristic model with feedback. The model, which is comprised of six (temporally overlapping) states and five feedback loops, serves as an analytical framework for examining the affective dimension of the invention process. The six states are: immersion (experiential input from external/internal sources),
incubation (unconscious development), illumination (“aha” experience), explication (meaning of “aha” moment), creative synthesis (experience translated into product such as theory, artwork, etc.), and validation process (personal and societal acceptance of product). The five feedback loops, which allow for refinement of ideas, are: the Arieti loop (connects incubation to immersion), the Vinacke loop (connects illumination to incubation), the Lalas loop (connects explication to illumination), the Communication loop (connects creative synthesis to explication), and the Rossman loop (connects creative synthesis to explication, illumination, through the validation process to incubation, or immersion to lead to perfection of product).

Using this model, the author attempts to answer two questions: 1) “what is the experience of creating a mathematical model of a natural phenomenon?” 2) “What role do feelings play in the creative process?” (p. 286).

Shaw examined his and 11 other scientists and engineers’ experiences through an interview process to understand the experience of creating an invention. Prior to the interview, he gave the 11 (all male) scientists and engineers a week to reflect on a question: what is the experience of creating a mathematical model of a natural phenomenon? He then interviewed the scientists and engineers in his home in five or six sessions which lasted no more than 90 minutes each. Each of interviews was tape recorded and then transcribed. The author started noticing saturation in the descriptions in five or six sessions.

Ten major, five minor and two sporadic themes, which he later organizes into structural and textural categories, emerged from Shaw’s interviews. The ten major themes are: “the requirements for becoming immersed; the trusting of your intuition; the role of unconscious incubation; getting stuck; letting go and the use of recreation; illumination; emotional reaction to illumination and body sensations; explication and creative synthesis; rejection; and validation and acceptance” (p. 292). The five minor themes are: “recognizing the problem; pushing for a solution; external pressure; failure; and the general subject of creativity” (p. 292).

Competitiveness and aggression emerged sporadically during the interviews. These themes when organized into structural and textural categories describe the experience of creating a mathematical model and the role of feelings in the creative process of invention. The structural category is the basic heuristic model with feedback described in the introduction of this summary. The textural category is “the structure of the feelings evoked during the experience: the polarities, blockages, bipolar components, and unipolar components” (p. 292).

Shaw found that the textural structure can be delineated into four unipolar and four bipolar components. The unipolar components are either unipolar-positive, where feelings associated with the creative process range from neutral to positive, or unipolar-negative, where feelings associated with the creative process range from neutral to negative. The unipolar-positive components occur during the illumination and acceptance phases. The unipolar-negative components are blockages before the illumination and acceptance phases. The blockage before the acceptance phase “only appears when collective validation is sought” (p. 294). No such blockage occurs for the personal validation loop. The bipolar components, where feelings associated with the creative process range from positive to negative, occur during the immersion, incubation, explication and creative synthesis phases. The author observes a strong enmeshment between the immersion and incubation phases, where “the incubation phase seemed to be somehow imbedded inside the immersion phase” and there is a “constant interplay between conscious immersion and unconscious incubation” (p. 294) through the Arieti loop. Another
enmeshment occurs between the explication and creative synthesis phases. Based on these findings, Shaw proposes several implications for understanding human behavior, education, psychotherapy and motivation.

Shaw’s findings suggest the existence of a “dominant, preferred, or natural [unified] process,” (p. 295) which may explain the creative experience for all human beings. He also proposes that illumination and acceptance are as fundamental as our basic biological drives because of their unipolar-positive nature. Moreover, the author advocates that educators should teach students to accept the role of emotions, especially negative, in the creative process to enhance the “educational environment for our young people” (p. 296). Shaw’s findings also suggest helping patients overcome unipolar-negative blockages to insight (i.e. illumination) for the success of insight-oriented therapy in psychotherapy. Lastly, Shaw proposes that managers and leaders in business provide both verbal and monetary appreciation for creative personal to improve their motivation and optimize worker productivity. This proposal is based on his findings, which suggest that the collective mode of validation is more rewarding than the personal modes of validation in the creative process.

Article III: Once and Future Power: Women as Inventors

The article “Once and Future Power: Women as Inventors,” by Stanley10, found in the Women’s Studies Int. Forum, Vol. 15, No. 2, explores the paradigmatic shift from female to male control of technology “in terms of changing power relations between the sexes” and “role of play” (p. 193) to understand the current gendering of invention to empower women inventors. This exploration is based on four premises: 1) “Women were probably once the primary technologists of the species…”, 2) “Women still invent; that is, even after male take over” of female originated technologies, 3) “Women invent significant things, …as defined in male-oriented histories of technology or as redefined to include … taken for granted and [technologies] omitted from consideration,” and 4) “Knowledge of” the paradigmatic shift “can empower women” (p. 194). Stanley sketches a possible scenario for the paradigmatic shift and gendering of invention based on the four premises with the aid of three questions. The questions are: how did the paradigmatic shift from female to male control of technology (or a takeover) happen? What was the extent of this takeover? What implications does the takeover have for women’s empowerment?

Stanley stated several factors that are responsible for the present gendering of invention. These factors include commercialization or professionalization of women’s activities, introduction of outside technologies, birth explosion and population growth, climate change, warfare, and shift in religious order. She argued that inventions such as horticulture, pottery and herbal medicine, first invented by women for domestic use, were generally taken over by men when these activities became commercialized and required full-time commitment. Moreover, when technology was introduced from the outside, it was usually transmitted to sons through male figures in the family. The commercialization or professionalization of activities led to the male takeover of technology. In regards to population, both birth explosion and population growth caused “more reproductive and nurturant work for women” (p. 195) while increasing their “productive responsibilities” (p. 195). This also led to killing off of most prey and left men vying for another role. Men, who may have begun to see women fertility as a liability, took over cultivation. Moreover, a drying trend in climate led to the development of irrigation systems and later to “large-scale irrigation agriculture,” (p. 195) which became a “specialized, full-time occupation, knowledge of which [was] transmitted in writing from father to son” (p. 195). This
further shrank women’s role in cultivation. Conflicts, which escalated into warfare during population growth, provided men with another role that solidified and institutionalized their “powerbase within the society” (p. 195). Likewise, herbal medicine, which was originated and first practiced by women, became men’s domain when medicine became a subject to be learned at the university run by male-dominated Church and professionally practiced with a license and/or by male priests instead of female healers whose work was associated with an older religion. A combination of the professionalization of medicine and religious fervor of the Church further caused the technological takeover and led to the present gendering of invention.

Stanley believes that the technological takeover is incomplete and inventive trends show improving conditions for women inventors. She says that women produced about 90% of the goods into the 19th century. They “belonged to several of the guilds, invented insecticides, new fabric weaves, new kinds of lace, new foods, new art forms, new agricultural machines, rotary engines, and pneumatic tires” (p. 196). Women worked as healers, obstetricians, and midwives, “invented medical and surgical apparatus, new remedies and operations, and new contraceptives,” discovered penicillin “70 years before Fleming’s “discovery” of penicillin,” (p. 196) collaborated with men on several inventors, and invented modern day inventions such as Kevlar, Liquid Paper, blue-baby operation, etc. Stanley argues that even though women have been the primary inventors in the past, it seems otherwise now because 1) Western culture defines invention as “what men do” and name women’s inventions such that they “diminish” (ex. home remedy) or “conceal the fact that they are inventions” (p. 197), and 2) women “hold only a small fraction [~8%] of the world’s patents.” Incomplete records indicate women held less than 1% of all US patents in the 19th century. The latter is because women’s patents, inventions and the profits earned were considered their husbands’ property until the Married Women’s Property Acts were passed in the US. According to Stanley, these trends (for patents), however, are on the change. The percentage of women’s patents in the US doubled from the 19th to the 20th century, which is “a more than twenty-fold increase in the absolute numbers, from under 4000 to nearly 100,000” (p. 197) by the most conservative estimates. Moreover, the number of women’s patents in the US has increased since the end of Civil War; however, the difference in the number of male and female patents is still considerable because men have a greater initial base for patents. The increase in number of women’s patents in the US after the Civil War is “attributed to the war-time losses of supporting males” and “to the new property laws” (p. 197).

Stanley argues that invention can empower women if they overcome their denial as inventors and create breakthrough inventions. The author says that women tend to deny their role as inventors because of “cultural stereotype that women do not invent, the mixed reputation of the inventor role (complicated by women’s current distrust of high technology), and men’s resistance” (p. 198) to the idea/label of women inventors. The latter is attributed to the paradigmatic shift from female to male control of technology and men’s unwillingness to surrender their inventive role (“creative equivalent of women’s childbearing” (p. 198)) to women and adjust to changing gender roles in society. Moreover, Stanley says that “women tend to create the practical, immediately useful, problem-solving type of invention” compared to “men [who] create more of the visionary/foundational/breakthrough inventions” (p. 198). She attributes this phenomenon to discrimination against women’s contributions inherent in definitions of invention and freedom (in the form of time away from family for intellectual play, intellectually challenging jobs, and freedom from job distraction) unavailable to women in our society.
Stanley suggests four ways in which invention can empower women. First, “creating an invention” and “licensing it to others or starting a business” can give women an opportunity to earn more “income than available in most female-defined jobs” (p. 199). Second, “creating an invention can confer social mobility” to women; all they need is an original idea and technical help. Third, invention, pursued full-time, is an alternative to mind-numbing jobs and can provide women with freedom to manage their times between home and intellectual play time to invent future-oriented inventions. Fourth, “invention can give women a voice in social change” (p. 200). Successful women inventors have the chance to be role-models and model employees, who can employ disadvantaged women and provide employee benefits which include day-care, transportation, rest-time for elder employees, and comfortable work environments. Invention can therefore empower women in terms of social rewards, prestige, and admiration.

A short description of the summaries is presented as evidence for the tangible research components (e.g. research purpose, questions, methods, results and outcomes) in Table 2.

Judging the Operationalization of the empirical-analytical, interpretive and critical science paradigms
The operationalization of the empirical-analytical, interpretive and critical science paradigms is demonstrated using five of the twelve criteria from Coomer and Hultgren for the respective articles. The five tangible criteria are: purpose of research, questions addressed, criteria for validity, unit of analysis, and outcomes. The individual criteria are defined along with supporting examples to illustrate the operationalization of the criteria. Supporting examples for each of these criteria for the three articles is also illustrated in Table 2. Only five of the criteria are presented for the sake of brevity. New researchers can examine other criteria in a similar way. Textual evidence of each the criterion from the three articles is presented simultaneously to help the reader understand the differences between the types of evidence for the three paradigms.

Purpose of Research

Article I: Coomer⁶ and Hultgren⁷ explain the purpose of empirical-analytical research as explanation of human behavior and control and prediction of practice. In their work, Weber et al.⁸ explain how an inventor thinks about forming a complex device, tool or function, from simple components, with the purpose of deriving generalized heuristics, rules and procedures to guide the process of invention and design beyond the context of a particular invention. In doing so, they attempt to “bring the inventive process out of the realm of intuition and into the domain of systematic thought” (p.335). Their purpose of seeking an explanation for the inventive behavior of humans with the desire to help inventors control their inventive process demonstrates operationalization of the empirical-analytical paradigm.

Article II: The purpose of the interpretive paradigm is to understand human experience through conversation.⁶⁷ When Shaw seeks to understand the experience of creating a mathematical model through a conversation with 11 well-reputed scientists and engineers about their feelings during the creative process,⁹ his intent is to obtain a comprehensive heuristic model, which “mirror[s] the structures and processes of experience” (p. 291). His purpose of seeking an understanding of the human experience of creating a mathematical model demonstrates operationalization of the interpretive paradigm.
**Article III:** Conversely, the purpose of the critical science paradigm is to critique ideological beliefs or values to identify “potential for self-reflection and self-determination” for oppressed individuals. In her article, Stanley sketches a possible scenario for a paradigmatic shift from female to male control of technology to give women an opportunity to reflect on women’s role in invention in the past and on their personal biases regarding invention. In doing so, the author critiques the present gendering of invention to offer multiple possibilities for women empowerment (i.e. self-determination) through invention. Stanley’s purpose in critiquing the gendered nature of invention demonstrates operationalization of the critical science paradigm.

Table 2: Supporting evidence for paradigm classification based on criteria from Coomer and Hultgren for Article I, Article II and Article III

<table>
<thead>
<tr>
<th>Title</th>
<th>Article I</th>
<th>Article II</th>
<th>Article III</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Authors</strong></td>
<td>Robert J. Weber, Carol Lynn Modern and John B. Solie</td>
<td>Melvin P. Shaw</td>
<td>Autumn Stanley</td>
</tr>
<tr>
<td><strong>Paradigm Classification</strong></td>
<td>Empirical-analytical</td>
<td>Interpretive</td>
<td>Critical Science</td>
</tr>
<tr>
<td><strong>Paradigm Classification Criteria (below)</strong></td>
<td>Supporting Examples from Article I (below)</td>
<td>Supporting Examples from Article II (below)</td>
<td>Supporting Examples from Article III (below)</td>
</tr>
<tr>
<td><strong>Purpose</strong></td>
<td>To derive heuristic sets, rules and procedures to guide the process of invention beyond the context of a particular invention</td>
<td>To obtain a comprehensive structure for the creative process</td>
<td>To sketch a possible scenario for the paradigmatic shift from female to male control of invention, which led to the present gendering of invention, and to offer possibilities for women</td>
</tr>
<tr>
<td>Questions Addressed</td>
<td>Article I</td>
<td>Article II</td>
<td>Article III</td>
</tr>
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<tr>
<td>How does an inventor think about forming a complex device, tool or function from simple components? Can generalizations of the thinking processes of inventors be derived to “guide the act of invention” (p. 321)?</td>
<td>What is the experience of creating a mathematical model of a natural phenomenon? What role do feelings play in the creative process?</td>
<td>How did the paradigmatic shift from female to male control of technology occur? What was the extent of this paradigmatic shift? What implications does the paradigmatic shift have for women empowerment in invention?</td>
<td></td>
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<tr>
<td>Criteria of Validity</td>
<td>Formulated hypotheses about origins of and approaches to invention; collected data using the retrospective protocol method; tested “plausibility of the principles uncovered, and the ultimate usefulness of those principles to other inventors” (p. 323) in publication</td>
<td>Self and the experiences of 11 scientists and engineers (Thick Description)</td>
<td>Discourse presented as publication on social origins of gendering of invention with alternative explanations for women to arrive at an intersubjective agreement with the author’s reasoning after self-reflection; change in practice of invention – from creation of practical inventions to breakthrough inventions, and pursuit of invention as a full-time business, and a tool for social mobility and social voice</td>
</tr>
<tr>
<td>Unit of Analysis</td>
<td>A patent for the application of herbicides and inventor’s (Solie) interview</td>
<td>Self; five or six, at least 90 minute long, tape-recorded and transcribed interviews of 11 male scientist and engineers</td>
<td>Changing power relations between the sexes; definition of invention and resistance to labeling of women as inventors;</td>
</tr>
<tr>
<td>Article I</td>
<td>Article II</td>
<td>Article III</td>
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<td>Article I</td>
<td>Article II</td>
<td>Article III</td>
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<td></td>
<td>Outcomes</td>
<td>patenting; role of play in invention</td>
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<tr>
<td>Tools: frame description; systematic min/max table; systematic constraint table; visual imagery; use of metaphor and analogy</td>
<td>Implications for learners and teachers in education, patients in psychotherapy, worker motivation in business, and improved human understanding</td>
<td>Reasoned alternatives – creating invention and licensing; starting own business; social mobility; invention as full time pursuit; voice for social change</td>
<td></td>
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**Questions Addressed**

**Article I**: According to Coomer⁶, scientists operating from the empirical-analytical paradigm ask technical means-to-ends and cause-effect questions. Weber et al.⁸, who ask questions in their research about how an inventor thinks about forming a complex device, tool or function from component parts and how generalizations of thinking processes of inventors can be derived to “guide the act of invention” (p. 321), are demonstrating operationalization of the empirical-analytical paradigm when they seek generalizations (i.e. means) to guide the process of invention (i.e. ends) for inventors as answers to their questions.

**Article II**: Scientists operating from the interpretive paradigm ask conceptual and context-bound questions about the meaning of experiences.⁶ In his study⁹, Shaw asks two questions: 1) “what is the experience of creating a mathematical model…?” 2) “…What role do feelings play in the creative process?” (p.286) In asking these questions, the author is seeking to conceptually understand the experience of scientists and engineers in the context of modeling a mathematical model. Thereby, he is operating from the interpretive paradigm as defined by Coomer.⁶

**Article III**: Conversely, scientists operating from the critical science paradigm ask critical normative questions.⁶ In other words, they ask questions which address “how certain individuals or groups can be freed through reason and evidence from a particular systematic misunderstanding (ideological beliefs) which interferes both with their freedom to think and act freely” (p. 31).¹¹ In her study, Stanley asks three questions: 1) how did the paradigmatic shift from female to male control of technology occur?, 2) what was the extent of this paradigmatic shift? and 3) what implications does the paradigmatic shift have for women empowerment in invention?.¹⁰ In asking these questions, the author addresses how women can empower themselves and others through invention if they are freed from the notion that invention is men’s domain. Stanley uses an analysis of the female to male takeover of technology and extent of
takeover as evidence to critique the gendering of invention, indicating her operationalization of the critical science paradigm.

**Criteria of Validity**

**Article I:** Coomer describes meeting the test of the scientific method as criteria of validity for the empirical-analytical paradigm. In keeping with the scientific method, Weber et al. examined the patent # 4,683,826 and formulated hypotheses about (1) the origins of the invention for the application of herbicides and (2) the inventor’s (Solie) approaches and strategies for developing the invention. They then interviewed the inventor, Solie, using the retrospective protocol analysis to collect data to make inferences regarding the invention process. Lastly, the authors document their hypotheses, data collection methodology, analysis and results in Weber et al. to give other researchers an opportunity to test the “plausibility of the principles uncovered, and the ultimate usefulness of those principles to other inventors” (p. 323). This indicates that Weber et al are operating from the empirical-analytical paradigm in their usage of the scientific method as criteria of validity.

**Article II:** Intersubjective agreement (an agreement between two or more subjects) and reasoning is the criteria of validity for the interpretive paradigm. As described in the summary of Article II, Shaw interviewed 11 well-reputed scientists for five or six sessions lasting at least 90 minutes each. The author ended the interviewing process at five or six sessions because he believed he hit a saturation point (i.e. thick description). He then examined and organized the observed responses into two broad categories based on thematic (ten major, five minor and two sporadic themes) agreement that emerged during his interviews. The author’s description indicates he is operating from the interpretive paradigm when he uses thick description and intersubjective thematic agreement as validation criteria for constructing the textural structure of the creative process.

**Article III:** Conversely, reasoned reflection and change in practice is the criteria of validity for the critical science paradigm. In her critique, Stanley traces the social origins of gendering of invention to professionalization of women’s activities, introduction of outside technologies, birth explosion and population growth, climate change, warfare, and shift in religious order and offers alternative explanations – creation of patriarchy, patent laws, and role of play – to reveal the unjust notion of invention as a male domain. Moreover, the author offers possibilities such as pursuit of invention as a full-time business and tool for social mobility and social voice for women empowerment in invention. Clearly, the author is operating from the critical science paradigm when she documents her discourse in her study to give women an opportunity to arrive at an intersubjective agreement with the author’s reasoning through reasoned reflection and offers possibilities for change in practice of invention as valid criteria for preparing the discourse for women empowerment.

**Unit of Analysis**

**Article I:** According to Hultgren, observable and inferable behavior is the units of analysis for the empirical-analytical paradigm. As described in the summary of Article I, Weber et al. examine an actual patent for the application of herbicides and categorize the origins of invention and Solie’s approaches to invention based on inferences drawn from the his responses to the interview. Analyzing a patent and inventor’s approaches are illustrative of the kind of
observable and inferable units of analysis used in the operationalization of the empirical-analytical paradigm.

Article II: Conversely, experiential meaning of a purpose is the unit of analysis for the interpretive paradigm. In examining his own and tape-recorded and transcribed experiences of 11 scientists and engineers for five or six sessions lasting at least 90 minute each for the purpose of understanding the creative process of creating a mathematical model, Shaw is using units of analysis which are illustrative of the operationalization of the interpretive paradigm.

Article III: Values (power), communication (language), and instrumental actions (work) are the units of analysis for the critical science paradigm. Stanley, as described in the summary of Article III, examined changing power relations between the sexes i.e. creation of patriarchy (power), invention terminology such as breakthrough or foundational technology or labeling of women as inventors (communication), and the role of freedom for intellectual play in invention (work) to sketch a possible scenario for the paradigmatic shift from female to male control of technology and the extent of female to male takeover of technology. In doing so, the author is using units of analysis which are illustrative of the critical science paradigm.

Outcomes

Article I: Coomer and Hultgren describe natural laws and scientific generalizations as outcomes for the empirical-analytical paradigm. The natural laws and scientific generalizations are “newly developed means to achieve established ends,” which influence practice. In their study, Weber et al. developed a generalized set of heuristic tools such as a frame description, a systematic min/max table, a systematic constraint table and procedures such as the use of visual imagery or metaphor and analogy to guide inventors through the process of invention in any context. These outcomes are generalizations that are indicative of the empirical-analytical in action.

Article II: Conversely, Coomer and Hultgren describe meaning as the outcome for the interpretive paradigm. This meaning is established through interpretations of authentic experiences to inform policy and practice. In his study, Shaw examined his own experience and that of 11 scientists and engineers to arrive at a textural structure for the creative process. An interpretation of this textural structure led him to derive implications for learners and teachers in education, patients in psychotherapy, worker motivation in business and an improved understanding of human beings. These outcomes, which inform practice in the listed fields, are indicative of the interpretive paradigm in action.

Article III: Coomer describes reasoned choice as outcomes for the critical science paradigm. In her study, Stanley offers four well-reasoned choices for women to empower themselves as inventors. These choices include pursuing invention full-time as a business, creating breakthrough technology instead of practical technology, and using invention as a tool for social mobility and social voice. These outcomes, which offer possibilities for women empowerment in invention, are indicative of the critical science paradigm in action.

Paradigmatic analysis of the articles illustrates that the authors’ research maps fairly well onto all five paradigm classification criteria from Coomer and Hultgren. According to the evidence, Weber et al. appear to operate from the empirical-analytical paradigm. Shaw appears to operate
from the interpretive paradigm and Stanley\textsuperscript{10} appears to operate from the critical science paradigm.

**Judging the quality of operationalization of empirical-analytical, interpretive and critical science paradigms**

Paradigmatic evaluation of the example studies indicated the quality of operationalization of the empirical-analytical, interpretive and critical science paradigms in the respective research studies. The author’s analysis suggested that the first two studies\textsuperscript{8,9} can be strengthened to more consistently represent their respective paradigms. The third study\textsuperscript{10} is of fairly high quality as it perfectly meets all of Coomer & Hultgren’s criteria for good critical theory research.

Weber et al.\textsuperscript{8} operationalize the empirical-analytical paradigm fairly well; however, they self-acknowledged the lack of generalizability and prescriptive nature of the outcomes of their empirical-analytical research. The authors analyzed only one patent and interviewed one inventor to generate heuristics to aid in the process of invention (due to difficulties with recruitment). Examining more than one patent and interviewing multiple inventors can be one way to improve control, internally corroborate and collect statistical data on the usefulness and generalization of outcomes and strengthen the compromised operationalization of the empirical-analytical paradigm in this study. Moreover, laying out the hypotheses clearly in their text can avoid reader misinterpretation of the operationalization of their research paradigm.

Shaw\textsuperscript{9} also operationalizes the interpretive paradigm fairly well; however, the operationalization of interpretive research can be strengthened with a more clear description of the methods and results sections. Missing description about how the intersubjective meaning from interviews was constructed from the interviews and findings validated hampers active meaning-making of the results of this research study, and therefore can be added to improve operationalization of the interpretive paradigm. Providing quotes and text from interviews can also enhance meaning-making of their results.

Stanley\textsuperscript{10} demonstrates high quality operationalization of the critical science paradigm throughout her paper. She clearly analyzes the paradigmatic shift from female to male control of technology and the extent of the paradigmatic shift to address how women can empower themselves and others through self-reflection and action based on the author’s critique of the present gendering of invention. The author identifies and documents the social origins of gendering of invention in the context of changing power-relations between the sexes, invention terminology, both male and female resistance to women being labeled as inventors, and role of (intellectual) play in invention to critique and reveal the faulty notion of male control of technology. Stanley also constructs an alternative explanation for the present gendering of invention in terms of patent laws, Married Women’s Property Acts, women’s self-denial about being inventors and creation of practical over breakthrough inventions. Moreover, she argues that women were and remain productive contributors to invention of technology and offers multiple suggestions for women empowerment based on the corrected notion of female control or perhaps a female and male control of technology. In using everyday language and providing tangible examples (for ex. work-life balance) to ground the intangible concepts (role of intellectual play), Stanley clearly communicates her discourse to her audience.
**Improving the quality of engineering education research**

New engineering education researchers can use this study to help them improve the quality of future engineering education studies in multiple ways. One, they can use this study as a tool to first understand the empirical analytical, interpretive and critical science paradigms and then as a template to evaluate the quality of existing research in engineering education during the literature review phase. For example, new researchers can use Coomer and Hultgren’s criteria to learn to classify a research study into empirical-analytical, interpretive, or critical science paradigm. Once classified, they can evaluate the consistency of operationalization of a paradigm in a research study using the method described in this research study. This evaluation may help them decipher high quality studies they can use to support their work and/or weigh in the pros and cons of including or excluding research studies for their current and future research. The right decisions may improve the quality of studies conducted on basis of previous research.

Two, new engineering education researchers, who have insufficient qualitative research methods background, can use the template as a guide to review qualitative engineering education journal and conference papers. For example, engineering education researchers may use their new knowledge of qualitative paradigms to provide more meaningful and/or corrective feedback to their peers/authors of qualitative research papers. Quality feedback may then assist the authors in improving the quality of published research.

Three, new engineering education researchers can use the template to think critically about the tangible components of their current and future research studies in terms of Coomer and Hultgren’s criteria. In using Coomer and Hultgren’s criteria, the researchers may start to feel comfortable with the design of their research studies or notice areas of inconsistency, which they will need to improve upon to enhance the overall quality of their future research.

**Conclusion & Implications**

While paradigms have recently been the point of discussion in engineering education, explicit discussion on judging the operationalization and quality of operationalization of paradigms has been limited. This paper described Coomer and Hultgren’s criteria for paradigm classification and illustrated how new researchers can use these criteria to identify the operationalization of empirical-analytical, interpretive and critical science paradigms in research studies. Critique of the operationalization of three published studies against Coomer and Hultgren’s criteria highlighted how new researchers can judge the quality of operationalization of the empirical-analytical, interpretive and critical science paradigms in research studies.

The author expects this paper to serve three major purposes in explicitly stating Coomer and Hultgren’s criterion for paradigm operationalization and analyzing the quality of operationalization of three paradigms in context of studies of invention. One, the paper can support new engineering education researchers’ understanding of three major paradigms in engineering education research via contextualized examples. Two, it can assist new engineering education researchers in identifying individual components of a study that form the basis of and determine the operationalization and consistency of a paradigm in research studies. Three, it can scaffold critical thinking of new engineering education researchers in judging the design and quality of existing, current and future studies. This in turn may improve the overall quality of engineering education research studies generated by new engineering education researchers.
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