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Phenomenography: A Qualitative Research Method to Inform and Improve the Traditional Aerospace Engineering Discipline

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Phenomenography: A Qualitative Research Method to Inform and Improve the Traditional Aerospace Engineering Discipline

I. Abstract

This overview paper demonstrates the valuable attributes of phenomenography for investigating the varied experiences of engineers employed in aerospace businesses. One attribute is called *bracketing*, where the researcher makes no hypothesis of how participants perceive the phenomenon such that a fuller description of each participant's experience can be solicited. A second attribute is logical relationships among categories of experience, typically expressed as hierarchies, which imply a progression of learning and can easily be converted to a scale to create an assessment strategy in the classroom. A third attribute is the assumption of having a few categories of variation of experience, which is more readily accessible than highly nuanced taxonomies for education purposes. This theoretical framework is just one of several qualitative methods that can improve our understanding of the aerospace industry in order to improve classroom practices.

II. Introduction

Aerospace engineers continue to expand the boundaries of human knowledge in various aspects and with various purposes. For example, materials engineers, propulsion engineers, manufacturing engineers, and simulation engineers all have specific and differing goals and boundaries of knowledge that serve the larger goals and purposes of the entire industry. To that end, engineers need to develop the appropriate skill sets to challenge those boundaries. Several research endeavors have compiled lists from industry leaders that name necessary skills for future engineers.

Statement of some assumptions about aerospace engineering will help guide this overview. Firstly, aerospace engineers are often engaged in the design of large scale complex engineered systems, and design involves an individual's technical competency integrated into a team of specialists and generalists. For example, a team of propulsion engineers in an engine company may coordinate and communicate with a team of propulsion integration engineers in an airframe company, and those integration engineers are simultaneously coordinating with aircraft performance engineers and the flight test team. Secondly, because of complexity of the systems and specialty of the engineer, an engineer's experience is unique. For example, a propulsion engineer in a propulsion company may have a very different experience from a propulsion engineer in an airframe and powerplant integrator company, even though on the surface, these two engineers may bear the same job title. An engineer who also is a pilot or a mechanic may have a very different awareness of some aspects of the industry than those who do not have that knowledge. Thirdly, because the aerospace industry is conscious of the impact of risk in its various forms, acknowledgment of all factors, whether right, wrong, or neutral, natural or contrived, is necessary. For example, human fatigue is as significant as instrument calibration and unexplored aircraft maneuvers for quantifying risk to flight safety. In each of these examples, a multitude of skills are named or implied.

The new fundamental research work, then, is to discover and develop models for future engineers to learn those skills. There is a gap in qualitative research literature in learning aerospace engineering concepts and skills. A simple word search of AIAA's *Journal of Aircraft* shows some results for "qualitative engineering education", fewer results for "ethnography", and no results for "phenomenography". The *Journal of Engineering Education*, on the other hand, shows its last "aerospace"-specific paper in 2006. There are a few qualitative engineering education research results in aerospace-specific publications, but many more technical papers that focus on concepts and skills, but not how to learn them. There are many qualitative engineering education research results that are general to most or all engineering disciplines, but not very many recently that are specific to aerospace. How can engineering education researchers leverage research tools from other disciplines to conduct research in an aerospace context?

Engineering education researchers apply research to link professional practice to classroom practice in order to keep the classroom up-to-date or even anticipate the knowledge and skills that engineers will need to be successful in their careers. Engineering education researchers also investigate how students learn, from preschool years all the way through lifelong learning as adults. Because the uniqueness of the learner and context of learning influence each other, researchers must pay attention to the learner, the content, and the context. Therefore, a major agenda item for Engineering Education Research is to investigate engineering learning mechanisms [1].

In order to conduct research on how people learn, it is prudent to set a foundation of learning theory that is relevant to the research questions of any given study. More emphasis is being placed on learning theories within the constructivist paradigm, that the learner is not just a passive recipient of knowledge, but is constructing knowledge actively and in different ways [2-4]. At present, there is no one comprehensive learning theory by which all disciplines may operate, because each theory has its own applications and limitations. The corollary of limitations of learning theory is that there is no one research methodology that comprehensively investigates how people learn. However, certain research methodologies focus on how a learner understands or experiences the concept, whether or not the understanding is complete or correct, and this understanding by itself merits investigation in order to develop more effective learning interventions.

A few qualitative research vocabulary terms require definition for this paper. First, the definition of *theoretical framework* is akin to Kuhn's [5] *paradigm,* which are fundamental assumptions about knowledge and learning, that guides the construction of the research questions, the data collection methods, and the analysis of a study [6]. Second, the theoretical framework informs the *methodology* [7], which is composed of the data collection methods and analysis of the data. Third, a *conceptual framework* is defined in this paper as the definition, description, and attributes of a concept or phenomenon under investigation. In other words, it is possible to investigate the conceptual framework of an idea using several theoretical frameworks, depending on how the research question is written and which attributes are the most important to study.

What qualitative research methods are being employed in engineering education? The *Journal of Engineering Education* presents a list of emerging theoretical frameworks or methodologies, one of which is phenomenography. Phenomenography, a qualitative research methodology, can be employed to solicit the varied experiences of learners. Previously published literature on the topics of research interest can inform the semi-structured interview as the primary means of data collection. As can be typical in qualitative data collection, between 20 and 30 interviews with participants having purposeful variation in their demographics may be sufficient to make some defensible claims in the analysis. Previously published literature on a phenomenon also provides ways to describe and validate the results of the analysis.

Phenomenography's goal is to account primarily for variation in experience by uncovering the relation between the participant and the phenomenon [8]. The basic premise is that there are limited number of qualitatively different ways that a phenomenon can be understood or experienced [9]. The interpreter of the phenomenon is the participant, not the researcher. In order to solicit a variety of experiences and to allow all relevant voices to be heard [10], a highly varied sampling of participants is necessary. With a well-designed semi-structured interview, the participant can unveil the environment, the products, and the processes of their professional experiences. The creation of hierarchical categories as part of the analysis may uncover the development of mastery of the skill(s) under investigation.

While there has been work that shows a one-axis increase of awareness or mastery of a certain phenomenon, there is an increasing use of phenomenography where the results or outcomes are expressed in two axes, implying that some skills or awareness of a phenomenon are coupled. For example, human-centered design simultaneously improves awareness of the design process and the inclusion of stakeholders. In a second example, computing concepts include an awareness of conditional structures and simultaneous awareness of focus and generalizability. What does aerospace engineering stand to gain from this? Since other research has shown that discipline-specific skills may be coupled, perhaps aerospace-specific skills are also coupled, especially since aerospace engineering demands a large repertoire of skills and knowledge.

The following sections highlight the philosophical stance, goals, and accompanying methodologies and methods of two traditions of phenomenography, the original version by Swedish researcher Marton and the developmental version developed by Australian researchers Bowden and Green. The main purpose of this overview paper is to show how phenomenography can be used to investigate the development of technical and professional skills, using aerospace engineering as the backdrop or context because of the breadth of skills necessary for engineers to engage in design of large scale and complex engineered systems. An example of phenomenography applied to the skill of understanding uncertainty in aerospace design is also given.

III. Key Attributes of Phenomenography

The assumptions and the goals of phenomenography align with the assumptions and goals of the context of aerospace engineering and design, which assumptions include that while there are a variety of ways to experience and engage in design in aerospace, and these experiences can be distilled to a few distinct and hierarchical categories. Phenomenography is purely qualitative and non-experimental. Correct and mistaken concepts of the phenomenon are equally interesting to the researcher, because "A careful account of the different ways people think about phenomena may help uncover conditions that facilitate the transition from one way of thinking to a qualitatively 'better' perception of reality" [9]. The following subsections highlight the philosophical stance and goals of phenomenography.

A. Phenomenon

Phenomenon is defined from the Greek root word as "a thing as it appeared" [11] instead of "a thing in itself". "As it appeared" refers to the learner or the participant in the study, how that person views "a thing". The epistemological and philosophical stances are described as "The object of study in phenomenographic research is not the phenomenon being discussed *per se*, but rather the relation between the subjects and that phenomenon" [8]:

> Phenomenographers are among a range of qualitative researchers who take a non-dualist stance. We do not focus on hypothetical mental structures separate from the world. There is no dividing line between the inner and the outer worlds. There are not two world with one held to explain the other. The world is not constructed by the individual, nor is it imposed from the outside, 'it is constituted as an internal relation between them. There is only one world, but it is a world we experience, a world in which we live, a world that is ours'.

The seminal research that developed phenomenography as a research methodology, for example, investigated students' understanding of velocity in a physics class[9]. Velocity was the concept or "the thing", but the researchers were actually interested in how students understood velocity, which is "the thing as it appeared". It was the students' understanding that was the phenomenon of research interest.

In aerospace engineering, Subject Matter Experts are important assets to projects, and SMEs have deep conceptual understanding of a topic, such as thermodynamics or orbital mechanics. As engineering education researchers, we are interested in how SMEs developed this expertise on a subject that has a "right" understanding, and we are interested in how someone may misunderstand or incompletely understand it as well. Additionally, researchers may be interested in subjects that have multiple acceptable definitions, such as design, safety, or project planning. Phenomenography is adaptable for investigating the understanding of these concepts.

B. Observable Phenomena in Phenomenography

The primary observation is the relation between the subject (a person; in this paper, an aerospace engineer) and the phenomenon as the subject describes the phenomenon. The researcher brackets (see Section D) his or her own understanding the phenomenon and of the participant, but the researcher's deep, open interview technique causes the participant to reflect on the phenomenon richly [6]. It should be noted here that the participant's description and the participant's actions may be different from each other; therefore, phenomenographers do not claim that they have uncovered a positivistic or universal truth. Rather, researchers may claim that they have found something useful for education.

How can researchers create greater confidence that they have captured the full breadth of experience? Firstly, researchers should make a clear line of reasoning that the participants in a study have indeed experienced the phenomenon. Secondly, demographics of participants may or may not influence their varied experiences of the phenomenon under study. For example, significant criteria for participant selection may include the participants' education backgrounds, career trajectories, cultural experiences, and professional responsibilities within the larger scheme of their employers' relationships to one another. The employing companies may be considered as part of the context or as a demographic for varying. The goal of the researcher should be to include the maximum variation possible of the criteria significant to the study in order to achieve representative variation of the experience of the phenomenon.

C. Assumptions of Phenomenography

First, phenomenography assumes that there are a limited number of qualitatively different ways that people experience and understand a phenomenon [9]. While there is no limit to the number of potential categories, it implies that the outcome space should include just a few categories. While "few" means different numbers to different people, recent engineering education outcome spaces generally do not exceed seven unique categories [12-15].

Second, phenomenography makes no assumption of right or wrong interpretations, which would be some kind of interpretation from the researcher. This would include concepts about physical phenomena, such as velocity, for which there is a "correct" answer [9]. Applying an assumption of what is right or wrong would unnecessarily limit the researcher's understanding of the participants' understandings. This also guides the researcher to review the interview questions critically for leading participants.

Third, phenomenography does not assume a dualist view of the world as individual constructivism and social constructivism do. "Individual constructivism sees internal mental acts as being an explanation for external acts and behaviors. The reverse is true for social constructivism" [8]. Rather, phenomenography assumes a relational view, a point of controversy to some critics in Section F. Simply put, it does not matter in phenomenography whether a learner's mind first influences the environment and task or if the environment and task first influences the learner's mind; both influence each other and phenomenography does not seek to sort out which comes first.

D. Propositions and Expectations

Phenomenography takes a stance of having no qualitative expectations. (An expectation in qualitative research is like a hypothesis in quantitative research.) Rather, the researcher is bound to bracket him/herself from presuppositions and hypotheses, even from seemingly authoritative sources [16]. Ashworth and Lucas note that phenomenography suggests bracketing may go against the traditional tide of reviewing literature before conducting research in order for the researcher not to be biased. The researchers must bracket themselves (remove themselves from interpreting the phenomenon) [9]. Bracketing in phenomenography derives from phenomenology's *epoche*, meaning "to refrain from judgment" [17]. Since bracketing is almost humanly impossible, it is better to acknowledge biases in order to ensure reliability and validity.

This is particularly important as researchers approach aerospace engineering concepts, tasks, and skills. There are simply too many interwoven concepts, tasks, and skills involved in the aerospace business for any one researcher or even a small team of researchers to preemptively account for the breadth of experience and understanding of a phenomenon. According to the assumptions of phenomenography, there will be a few unique ways of understanding, but the researcher will not know at the beginning and may even be surprised at the end of analysis.

E. Outcome Space

After analysis is complete, phenomenography as a theoretical framework and methodology typically has as its outcome an arrangement of categories that is often hierarchical in nature, which are variations of human experience of a phenomenon. The outcome space often implies an increasingly comprehensive awareness or increasingly comprehensive experiences [12, 13]. The outcome space has three attributes: simple and clear, logically related typically by hierarchy, and parsimonious or few [18]. The outcomes must derive from the data and not from the researcher's preconceived notions or even from the published literature's results because the investigation focuses on the participants' understanding of the phenomenon. The goal is practical applicability, which is the goal in this paper for engineering education. If a researcher can first uncover how concepts are understood, then the researcher and educator can develop appropriate learning interventions to move a learner to a higher or deeper understanding.

F. Boundaries, Limitations, and Controversies

The boundaries of phenomenography are related to several factors. First, the data collection method of semi-structured interviewing of an individual is not the same as interviewing a group, a team, or a project. Second, the participants reflect on their experiences, the account of which may vary from what a researching observer or another participant may observe. Experiences for which a person has deeply reflected may be communicated as a well-rehearsed speech, but first-time consideration to a topic may be communicated with pauses, *uhs* and *ums* [19]. Third, to the extent of established trust and comfort, the participant will share experiences with the researcher [20]. Within these boundaries and within the boundary of fatigue of the participant, responsibility rests with the interviewer to "dig deeply" into the participants' experiences.

There are several limitations of the data collection methods to acknowledge. First, this theoretical framework moves the interpretive work from the researcher to the participant. Also, different researchers may converge upon different outcome categories with the same data. Second, what the participant remembers and how the participant remembers could be a limitation. In learning, people tend to remember best the first thing, the last thing, and the most intense thing [21]. The participants, as they tell their stories, are attempting to make sense of their experiences [22], and will therefore put certain aspects in the foreground or background as part of their narrative [2, 19]. Third, participant selection could be a limitation, to assume that the participants have indeed experienced the phenomenon under investigation. In original phenomenography, the observation of a problem-solving task ensures that the participant has experienced the phenomenon, if only just in that moment. In developmental phenomenography, it is difficult to confirm beforehand without the researcher making some assumptions about the phenomenon and the participant. The researcher needs to be aware of these limitations.

There may be limitations in the results from several attributes of participants. First, self-selection of participants is unavoidable in the design of this study, generally based on their schedule, their interest, and whether contact information is available for recruiting. This is especially pertinent in recruiting older female engineers in the aerospace business with significant gender disparity, where the women might be fatigued with frequent requests to represent the female population. Second, it is unlikely (but not impossible) that several of the participants will have worked on the same project, so while literature shows that aerospace engineering relies on teams, it might not be demonstrated well in any given study. Third, focusing on working professionals' experiences may limit the results' applicability to the undergraduate curriculum. As with many qualitative studies, top candidates for inclusion can be identified but whoever is willing ultimately will be interviewed. The researcher needs to, within the boundaries of anonymity, provide demographics of included participants as part of the analysis.

There are some mitigating steps to address the limitations. First, include as much variation in participants' demographics as possible, which may involve several recruiting methods. Second, regarding the applicability of participants' experiences to curriculum experiences, the interview protocol should include primary questions on the participants' reflections on their learning trajectories, so there may be evidence linking the two experiences. Third, students can be included as the "starting point", though the participants' age is not necessarily directly correlated to level of awareness of the phenomenon under investigation. The researcher builds these steps into the study as part of recruiting and constructing the interview protocol.

The biggest limitation is the challenge of rigor [23] in developing the outcome space, especially to those who are purely quantitative researchers. The first mitigation is a member check and edit of the transcript from the participant, but not a check of the outcome space [24]. The second mitigation is multiple readings of the transcripts as a whole after all the data are collected. The third mitigation is team analysis that welcomes challenge, critique, and revisiting assumptions [8]. The fourth mitigation is to be transparent in the data collection and analysis process, providing documentation for further review by the research community at large. The fifth mitigation is to validate the results with other published literature, and to justify any discrepancies that may arise. After all of these steps, the outcome space is reliable and valid.

Richardson provides a thorough critique of phenomenography, including its incomplete development as a research methodology and its increasing application in education [11], as do Ashworth and Lucas [16]. Richardson claims that original phenomenography lacks a conceptual basis and epistemological foundation that other social-science research methods have, primarily compared to constructivism. He contrasts phenomenography's interviewing as shallower than ethnography's or anthropology's interviewing, especially because the analysis "depends on other people's discursive accounts of their experience". He shows phenomenography as being similar to grounded theory and phenomenology in analysis. The positive aspect of phenomenography is that the results are easily accessible by professors and students, so that pedagogy can increasingly be based upon evidence-based methods.

IV. Key Researchers and Their Perspectives

Original phenomenography, or the Swedish tradition, has been employed in order to understand students' conceptions of reality, including forces and optics, and it requires problem solving before interviewing as part of the data collection [9]. As researchers have employed simulation of a task to make knowledge in expert teams visible [25], so problem solving in Marton's phenomenography could be considered a simulation in order to understand the participants' knowing. Observation of the participants' interaction with the phenomenon is part of Original phenomenography, followed by semi-structured interview for participants to describe their understanding, thought process, or experience. The time scale of the participant's experience (a few hours) must be taken into account for practical research purposes in order to consider observation as part of the data collection method.

Developmental phenomenography, or the Australian tradition, typically employs semi-structured interviews to elicit participants' reflections on their experience, where the intent is to seek depth in the experience [8]. While original phenomenography and developmental phenomenography can be centered on learning, developmental phenomenography does not include the observation of the participant encountering the phenomenon in a problem-solving task. The subject matter of engineering science, such as heat transfer or fluid mechanics, might be observed in a problem-solving task, but a design task may be a considerably different time scale. A task that could fit into the timeframe of an interview would be a simulation and not an actual design, thereby introducing the question if the subject would really apply the same techniques to the real design. As a result, only the semi-structured interview is employed in the Australian tradition. Table 1 below shows that the crucial difference between these two methods compared to the attributes of the research questions in phenomenography.

Table 1 Two types of phenomenography mapped to research question attributes.

Attribute	Marton Original phenomenography	Bowden Developmental phenomenography
Development of skill over time	Well-suited to describe a lived experience	Well-suited to describe a lived experience
Variation of experience of phenomenon	Well-suited to account for variation	Well-suited to account for variation
Context or environment of the experience	Prescribed design task or problem-solving is *in vivo* rather than *in situ*	Deep, open interview allows for reflection on environment
Products or results of experience	Prescribed design task or problem-solving aligned with short time scale or lower complexity scales	Deep, open interview allows for reflection on long time scale and/or higher complexity scales

V. Methodology

Now that the philosophical underpinnings of phenomenography have been discussed, we move to the "nuts and bolts" of using the theoretical framework. Certain decisions for the method are driven by phenomenography's purely qualitative nature. The design of this study is non-experimental, so any changes of behavior or skill noted in this work are not the result of a controlled intervention. The data collection method is semi-structured interview, possibly partnered with short observation. The accompanying analysis will be the creation of categories of qualitatively different ways that the whole transcripts reveal of experiencing the phenomenon, where within a category, participants have commonalities, and between categories, the participants have distinct differences. The researcher makes no assertion, claim, or hypothesis at the start of data collection what those distinct differences might be, but only that there are unnamed differences.

A. Purposeful Sampling for Maximum Variation

Attributes and demographics of the participants should be carefully considered and then documented as part of the data collection and analysis. Attributes that may be significant for maximum variation of the phenomenon under investigation may include: education type and level, job titles as reported by the participants, employing company or its portfolio of products, years of experience in the workforce, military experience, pilot experience, and international experience. Gender and race cannot be ignored, either. Women compose 52% of the workforce in the United States but only 9% of employed aerospace engineers are women [26]. Women and minorities may be purposefully over-sampled to insure their voices were included in the data. Also, if chain sampling is used (contacting your acquaintances and their acquaintances), some representation of degree of separation from the researchers may be valuable for ensuring validity and reliability. We recommend as well that anonymity of the participants be ensured, which may include the use of pseudonyms for the participant, their professional and academic affiliations, and allowing the participants the opportunity to review their anonymized transcripts.

B. Instrument Development

A typical semi-structured interview protocol in phenomenography consists of contextual questions, open primary questions, situated example primary questions, and follow-up questions [8]. Contextual questions provide an introduction and some understanding of a participant's current situation, encouraging the participant to reflect on their experiences. Open primary questions solicit the participant's understanding and meaning of the phenomenon. Situated example primary questions solicit concrete examples of the participant's own experience with the phenomenon. Follow-up questions encourage further elaboration of the experience, such as motivations and decisions related to the experience. Even though the researcher may have definitions of concepts and constructs from themselves or from a literature review, none of them should be included in the interview protocol because of bracketing in Section D.

Open primary questions should be written and asked in such a way that the participant is not led into the researcher's understanding of the phenomenon. That generally means avoiding the use of technical or academic terms in the questions until the participant uses such a word. For example, instead of a researcher asking "where was there uncertainty in your design process?" a researcher may instead ask "were there things that you did not know as you were working on the problem?" When the participant answers "safety of flight is most important", then the researcher should ask "can you tell me a little more about flight safety? What does that mean exactly?" The researcher should not assume that his or her own understanding of "flight safety" is the same as the participant's definition. Also, the semi-structured interview allows the researcher to ask certain questions; but to follow the flow of thinking of the participant, the researcher may ask the questions in a slightly different order as needed.

One aim of the contextual questions is to elicit the participant's description of the environment and his or her role within the environment. The open primary questions aim to uncover how participants experience and understand the phenomenon under investigation and how they learned or became aware of that phenomenon. Follow-up and probing questions, such as "why is that important or difficult (or other adjective that the participant used)?", "what were you trying to achieve by doing that?", and "can you think of another experience similar to this one?" should be asked if the participant needs prompting. Lastly, reflection questions ask the participant to explain the phenomenon to someone else less familiar with it.

Previously published work conducted provides some guidelines for constructing an interview protocol. One phenomenographic study of design was crafted to elicit participants' understanding of design, and the participants came from different disciplines [13]. Another phenomenographic study focused on experiences in designing for others, or human-centered design [12]. A grounded theory study specifically asked working professionals about the problems they encounter at work [27]. The grounded theory study provides questions to understand a participant's current workplace and responsibilities, and the phenomenographic studies provide questions worded particularly to elicit the participant's understanding of the phenomenon under study.

VI. Analysis

A. Method

The iterative analysis process includes reading the transcripts, describing the similarities and differences among one or several transcripts, and justifying the categories to at least one other researcher. The recommended analysis process is a team effort. Phenomenography can take at least two paths of analysis: 1) place the whole transcript into a category or 2) extract the quotes specific to the phenomenon into a category. It is becoming more common to place the entire transcript into a category, but justification is necessary for either path. For example, a protocol may be structured such that the beginning questions on context necessarily situate the experience of the phenomenon within one specific context. Therefore, most of the transcript would focus on one experience. Either way, "In the analysis stage, the controls involve:

- The use of no other evidence except the interview transcripts
- The bracketing of the researcher's own relation to the phenomenon
- The use of group analysis in order to ensure the first two controls are effective, and
- The analysis of the structural relation between the categories of description being postponed until after the categories have been finalized." [8].

B. Unit of Analysis

The unit of analysis in developmental phenomenography is the whole transcript, fit into a category. The researcher must be careful to say that the transcript and not the participant fits into a category, because it is unjust to categorize an entire person in only a two hour conversation [18]. Transcripts within a category have marked similarity to each other, and categories must have qualitative differences among each other. A category may be described by using the participants' words or phrases first, and the researcher may decide to summarize and rename at some later iteration of analysis.

There are factors to consider in analyzing the data in order for the researcher to actively bracket themselves. Firstly, the demographics of the participant may bias the researcher about how frequently or how deeply a participant may experience a phenomenon. Secondly, the participants may not use the same words as the researcher or the literature review might suggest for a phenomenon, necessitating several read-throughs of transcripts. Thirdly and most importantly, the level of awareness of the phenomenon for each participant is the driving factor of the arrangement of the outcome space.

C. Outcome Space

The outcome space of this study will primarily include some description of a category's awareness of the phenomenon. It is possible that the outcome space will have one, two, or three dimensions, but it would be difficult to visualize more than three axes of variation. More than three dimensions of variation may indicate another iteration of analysis is necessary. A category will have participants with common experiences, and different categories will highlight different experiences.

The resulting categories shall have substantiating evidence only from the transcripts [18]. Having three or more transcripts in a category is usually strong evidence, and there is not a requirement to categorize every transcript in the study. Each category will have a name or *handle*, hopefully condensed to one word. There will also be a one sentence description. Following will be a few paragraphs of researcher interpretation, including supporting quotes from the transcripts in that category. Also, as mentioned in Section B, the categories should be few, clear, and logically related.

When describing the outcome space, the researcher should present it in two parts:

- a description of each category
- a description of the relationship among categories, highlighting the differences between categories

Frequently, relationships among the categories are also provided in the final publication in some graphic, map, or plot, especially for an engineering audience that often communicates graphically and mathematically (see examples in Figure 1). The graphic often demonstrates the hierarchical attribute of the outcome space. A researcher should take in to consideration the potential engineering educator audience may bring their own habits of interpreting graphics, where up and to the right are frequently interpreted as "more". Among engineering audiences, the outcome graphics may be the most memorable part of the publication.

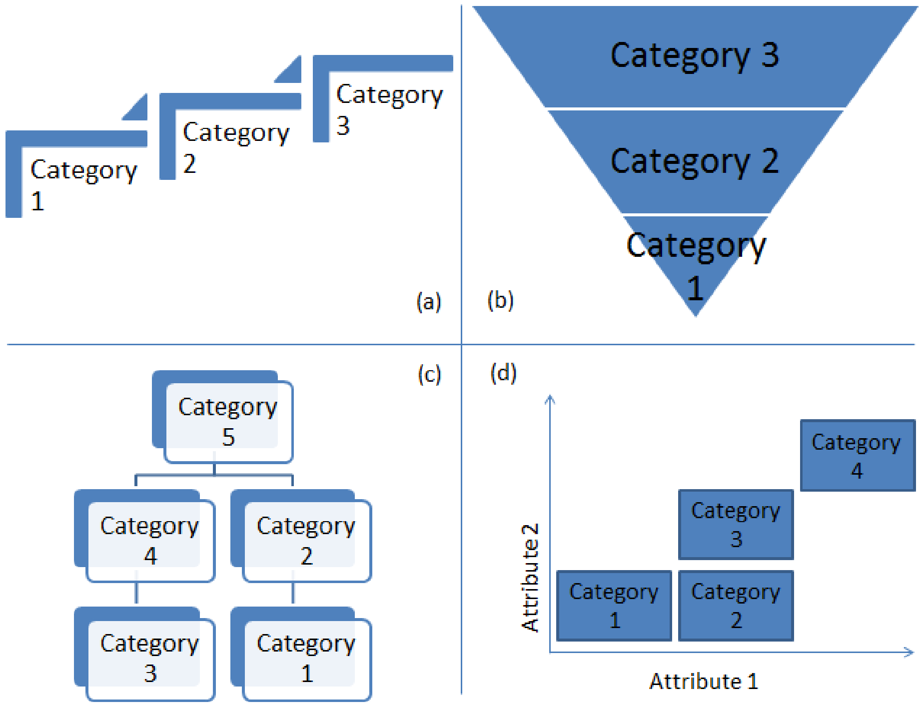

Figure 1 Example graphics to represent the relationships among categories

D. Process of Analysis

The execution of data collection and analysis merits a brief description here for reliability and validity purposes. For the interview, the researcher should have the interview protocol visible and should have a way to take notes in a manner that does not distract the participant. The researcher should have a recording device so that the researcher can engage in a conversation with the participant without the responsibility of taking field notes. Different researchers have different opinions about how conspicuous the recording devices should be, but the participants should be made fully aware of recording and should provide consent for recording.

The first cycle of familiarization with the data after obtaining transcripts from a third party service may be accomplished by listening to the audio and correcting the transcripts or by transcribing the audio/video recording personally. The corrected and de-identified transcripts could then be sent to the participants for any and all edits they wish to make. These member-checked transcripts and the other transcripts should appear in the final analysis. Different researchers have different preferences for electronic software management of iterations of analysis compared to paper and handwriting management. Researchers have been rumored to stack piles of transcripts around themselves on the floor as a first visualization of categories. Either way, researchers should take care to document iterations of category descriptions of similarities and differences based on quotes from the transcripts. There could be around 10 iterations of analysis that a researcher may share with another researcher for justifying, explaining, and refining.

Part of the evidence of having reached a valid outcome space is that subsequent cycles of analysis result in the same groups of transcripts [8] for all the perspectives considered. The second piece of evidence is that the explanations of categories were reviewed by other researchers on the team and found to be logical and consistent. A third piece of evidence, though less emphasized in phenomenography, is that there is no obvious and unjustifiable contradiction in this outcome space with other published literature, which a researcher may use after a few iterations only with transcripts. A fourth piece of evidence is comparing the categories to the demographics of the participants for any superficial clustering. The reliable and valid results are presented as 1) categories and 2) differences between categories.

VII. Example of Phenomenography in Aerospace Engineering

As the aerospace industry engages in designing Large Scale Complex Engineered Systems, uncertainty must be confronted by the designers. In particular, Deshmukh and Collopy [28] posed fundamental research questions that this work explores: "*Investigation Area 2) Uncertainty and Decision-Making c)* Where is the optimal balance between gathering information to refine uncertainties and making a design decision with already available information? *... Investigation Area 6) Research in Engineering Education a)* What are the key attributes of a successful engineer in the design of large complex systems? How can an aspiring engineer acquire these attributes? and *b)* For developing engineers, how effective is learning from failure? What is gained in learning from success?"

Returning to the argument that there are a variety of ways to experience a phenomenon in aerospace engineering, let's look at the experience of uncertainty in design, where uncertainty is the phenomenon, decision-making in design is the task, and the aerospace engineering industry is the context. The aerospace industry is risk-averse and seeks to reduce risk and cost by reducing uncertainty [29]. Lately, the aerospace business has taken a systems-of-systems approach to design [30-33] in order to decompose the design space and to integrate the solutions with awareness of and planning for uncertainty resolution. Uncertainty plays a significant role in design and every participant in the design process may have a slightly different understanding, where their understanding may not fall into a "right", "wrong", "better" or "worse" understanding, but rather "more comprehensive" or "less comprehensive".

Successfully managing uncertainty is a desirable professional skill, and it may have several names. There is a distinct call in industry and academia alike for engineers to be *tolerant of ambiguity* [34-38], to be *flexible* [39-42], and to be *adaptable* [39, 40, 43-46]. This skill appears to be in contrast to the Piagetian human tendency to attempt to reduce uncertainty and non-equilibrium [47]. How do people, especially designers, move from wanting to reduce uncertainty to being tolerant of uncertainty?

Using developmental phenomenography as the theoretical framework to guide a study of an engineer's experience of uncertainty in design, we can develop research questions and a data collection instrument. Notice the phrases "qualitatively different ways… experience" in the research questions, which are phrases from the assumptions of phenomenography. These research questions, though, will not be asked of the participants directly. The purposes, assumptions, and strengths of the theoretical framework influence the construction of the governing research questions:

- What are the qualitatively different ways that engineers in aerospace businesses experience uncertainty in design decisions?
- How do aerospace design engineers develop successful uncertainty management skills?

The contextual questions include the participant's workplace description, the participant's education, and the participant's current role in the workplace, including design projects. The open primary questions and situated example questions are the center of the data collection:

- The participant's experiences in making design decisions with uncertainty
- The participant's description of sources of uncertainty and the participant's management of identified sources of uncertainty
- The participant's reflection on the learning trajectory he or she experienced related to his or her awareness of uncertainty in design

The purposes, assumptions, and strengths of the theoretical framework influence the construction of the interview protocol questions. A portion of the interview protocol focusing on uncertainty includes questions that are open-ended and use not the vocabulary of the research questions but simple vocabulary:

- Were there things in this design experience that you did not know?
- Where was there uncertainty?
- How was the uncertainty treated?
- How did the uncertainty affect the decisions you made about the design?
- Did you learn anything about uncertainty in design from your experience?

The main purpose of this example is to demonstrate how the data collection instrument can be constructed so as not to influence or lead the participant with any interpretations from the researcher (bracketing). This also shows that many professional skills that engineers need to develop in their undergraduate years can be investigated with this theoretical framework and data collection instrument. The results of the phenomenographic study on experiencing uncertainty when making design decisions will be published elsewhere.

VIII. Implications

Aerospace engineering and design often involves projects that involve years and decades of engineering effort. The time commitment of observation of actual aerospace design efforts would not be practical for researchers, and researchers might have trouble gaining access to the sites where aerospace design occurs. If research questions focus on events that may take years to unfold, phenomenographic research provides an alternative to observation as the means of data collection.

Because phenomenographic outcome spaces are often hierarchical, it implies a progression of learning or experience. A progression can be operationalized in order to be measured quantitatively. The results of a phenomenographic study may reveal indicators for which a scale can be developed specifically for a particular phenomenon. Likely, the scale will be also only as large at the number of categories in the outcome space, perhaps between three and seven. This leads to future research questions:

- How can an aerospace engineering student's experience of a phenomenon be measured?
- What are effective interventions and classroom modules that increase an aerospace engineering student's experience with a phenomenon?

Professional development is a subset of learning and phenomenography focuses on learning. Therefore, phenomenography can investigate research questions on the professional formation of undergraduates, a topic of national interest [48]. The undergraduate curriculum benefits by staying up to date with industry practices. Undergraduates have the opportunity to be more prepared for the competitive high-stakes workforce. They have the opportunity to practice difficult aspects of engineering and design. They have an opportunity to understand the workforce they are about to enter. Industry gains new employees who are potentially better equipped and trained for the technical and professional skills needed for the job.

The major contribution of this paper is the use of phenomenography to investigate development of technical and professional skills of engineering students. While the context of this study was specifically the aerospace engineering because of the industries' commitments to safety and to expanding the boundaries of knowledge, the elements of the skills here are applicable to other engineering disciplines engaged in design of complex systems. The discoveries in this study of key behaviors and cognition will ultimately assist educators in better preparing the next generation of engineering leaders in aerospace and students who will help solve the world's Grand Challenges [49].

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