AC 2012-4321: CREATING SCIENCE AND ENGINEERING PRACTICES IN THE K12 CLASSROOM: AN INITIAL SURVEY OF THE FIELD

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Creating science and engineering practices in the K12 classroom: An initial survey of the field

Abstract
The recently released Framework for K-12 Science Education Standards emphasizes the importance of science and engineering practices to the K-12 classroom. This continues the stress on process and authentic activities that has characterized science education reform over at least the last two decades . It also adds the more explicit inclusion of engineering that has characterized more recent efforts. However, creating these experiences in the classroom is far from trivial. Much of the work looking at the specific structure of such inquiry-based activities at the K-12 level has consisted of either articulating intended goals or rubrics for assessing the degree of inquiry learning. This paper is intended to illuminate the means for achieving those goals and levels by generating a taxonomy of different pedagogical structures used for inquiry activities. We aim to articulate structures that are more general than individual lessons but more specific than broad goals. By systematically reviewing over 300 activities across a variety of curriculum sources, content areas and grade bands, we have validated a set of eight *inquiry activity structures*: Protocol, Design Challenge, Product Testing, Black Box, Discrepant Event, Intrinsic Data Space, Taxonomy, And Modeling. We further explore how particular structures are better suited to emphasizing engineering in the K12 classroom, and assess the adequacy of engineering practice exercises across subject areas and grade bands. We found the prevalence of activities that included engineering practices to lag behind the prevalence of those including science practices. However, the dominant activity structure including engineering practices – the Design Challenge – was also far better at other activity structures at promoting inquiry-based learning.

Promoting inquiry-based teaching has become the central focus of reform in science education for more than two decade[1-4]. That is, there is a need to move instruction from traditional teaching, where the teacher and text acts as the source of clear, unchanging information to inquiry learning, where students are active constructors of knowledge, work with data and support conclusions with empirical warrants. This was a central feature of the original National Science Education Standards[1, 2]. The new Framework for K-12 Science Standards continues this call, making both the importance of process and the relevance of engineering more explicit[5]. Making this goal a reality, however, has not been easy[6-9].

The interest in promoting inquiry-based teaching has certainly generated actual instances of inquiry-based instruction - specific curricula and instructional plans. These have limits, though, as specific examples rather than broader concepts. In reviewing the state of inquiry as an organizing theme of science education, Anderson stresses "teachers have to be the focal point of a move towards more inquiry-oriented science education"[4]. Our concern, therefore, lies with what conceptual resources have been provided to support teachers in enacting inquiry. At the other end of the spectrum from specific instructional plans, well articulated, abstract goals have been established. Those embedded in the various standards documents are prime examples. But these are aspirational, rather than prescriptive. Our objective is to provide teachers tools that are more general than specific activities, but more concrete that aspirational goals.

As part of this goal, we aim to produce a taxonomy of the various pedagogical strategies behind creating experiences with science and engineering practices in the K-12 classroom. In this study, we have reviewed over 300 K-12 science activities from a variety of curricular resources. We have generated and validated a categorization of the structure of these lessons. In addition, by analyzing other aspects of each activity, we highlight several issues with the current state of inquiry learning in general, and engineering education specifically.

Nomenclature

Before proceeding further, there is an issue of nomenclature to deal with. The new Framework for Science Education does two things to improve terminology. By using the phrase “science and engineering practices” it makes clear the importance of inquiry as a reflection of what scientists and engineers do, not just inquiry as a pedagogical strategy. Second, it explicitly includes engineering, thereby stressing its importance and telegraphing that there are some differences between science and engineering.

What is lacking, however, in the Standards documents and the field at large, are umbrella terms for science and engineering, and scientific inquiry and engineering design. There is no doubt that there are important distinctions, and separate terms are often needed. However, there are also important similarities, particularly in noting the difference between inquiry in a science or engineering context and inquiry in other fields such as history, art or literature. The new Framework makes this clear in that two of the eight practices distinguish between science and engineering, but six do not. At a more practical level, in K-12 education, to the extent that students are exposed to engineering, it is in the context of a class that is otherwise called “Science class”.

Therefore, our use of the term “inquiry” here is intended in a broad manner. That is, it refers to the variety of investigative practices intended to expand our understanding of the natural and technological world. We mean to distinguish it from other forms of knowledge generation such as history, art or literature. Where we mean to distinguish within this category, we refer to scientific inquiry and engineering design. In our discussion of the work of others, we note their applicability to science and engineering. Likewise, when we refer to “science education”, “science class”, “science activities” etc. we are including engineering under the assumption that it is that part of the institution of K-12 education where experiences of engineering are likely to occur.

Supporting Teachers in Conducting Inquiry

The most obvious resources lie at the other end of the spectrum of abstraction from specific lesson plans. There are well-established articulations of what inquiry learning needs to include. Table 1 shows the essential features of classroom inquiry as delineated by the inquiry addendum to the National Science Education Standards[1].

Essential Features of Classroom Inquiry
1) Learners are engaged by scientifically oriented questions.
2) Learners give priority to evidence, which allows them to develop and evaluate explanations that address scientifically oriented questions.
3) Learners formulate explanations from evidence to address scientifically oriented questions
4) Learners evaluate their explanations in light of alternative explanations, particularly those reflecting scientific understanding.
5) Learners communicate and justify their proposed explanations.

Table 1 From Inquiry and the National Science Education Standards[1]

Though one could easily argue that these are incomplete with regard to engineering, any of these are certainly applicable to engineering. The new Framework for Science Education achieves more balanced coverage by delineating eight "science and engineering practices"[5], shown in Table 2

Science and Engineering Practices
1) Asking questions (for science) and defining problems (for engineering)
2) Developing and using models
3) Planning and carrying out investigations
4) Analyzing and interpreting data
5) Using mathematics and computational thinking
6) Constructing explanations (for science) and designing solutions (for engineering)
7) Engaging in argument from evidence
8) Obtaining, evaluating, and communicating information

Table 2 From the Framework for Science Education[5]

But these are *aspirational* goals: they define a target without necessarily providing guidance as to how to get there.

Similarly, a number of rubrics have been developed for assessing the degree of inquiry in a given instance of instruction[1, 10]. Most are variants on the Herron Scale[11], where activities move up in levels as responsibility for conclusions, methods and questions move from teacher to student. These are applicable to both science and engineering contexts. While these can certainly play a role in guiding teacher practice through self-correction, they do not form conceptual resources for generating instruction.

Level	Problem	Ways & Means	Answers
0	Given	Given	Given
1	Given	Given	Open
2	Given	Open	Open
3	Open	Open	Open

Table 3 The Herron Scale, take from Shulman and Tamir[12], based on Schwab[13] and Herron[11]

Over the years there have been a number of approaches to defining inquiry for teachers, such as the Inquiry Cycle from White and colleagues[14] or Kuhn and Pease[15] set of ten skills. Bell and colleagues[16] comprised a meta-list of categories used in prior frameworks. What ultimately limits these approaches is that they are not constructed from the point of view of teachers. Rather, they are based on descriptions of either what scientists do or what we want students to do. This means they retain an aspirational rather than guiding character. Consider Harwood's description of his "activity model for scientific inquiry" as containing "10 activities in which scientists engage as often as necessary through the scientific process"[17]. Similar to the Essential Features of Classroom Inquiry from the NSES, these often have the problem of failing to cover engineering adequately. But they also have a more basic shortcoming. Such a format tells teachers what they should get *their students to do*, not *what teachers should do* to get students to do it. Even the Herron Scale is constructed around what teachers *should not* do. This often instills a subtractive approach to developing inquiry: teachers plan the same underlying activity, but give less instruction.

Difficulty in Inquiry

Defining what teachers should do, or alternatively, the options available to them, is important because devising inquiry-based activities is not trivial[18]. In previous research, we identified two intrinsic problems for instructional planners[19]. When researchers engage in inquiry, it is not in a vacuum. Rather, they are motivated to a particular course of action by the context of their field. There may be unanswered questions from previous research, or technological problems defined by a larger agenda. Hence the first practice in the new Framework for Science Education is “Asking questions (for science) or defining problems (for engineering)”. But doing this requires familiarity with the current context. So there is a Getting-on-Board Problem. In actual research, this is often accomplished through the apprenticeship structure of graduate studies: new researchers piggy-back on the work of practicing researchers. But this approach is generally not available at the K-12 level.

The solutions to the questions and problems that practicing scientists and engineers grapple with aren’t readily obvious. Data can be interpreted in multiple ways. Technical challenges have no perfect solutions, and researchers can choose to optimize different parameters. At the cutting edge of research, this state of ambiguity is natural. In fact, it’s why research is significant and interesting. But in the high school (or even college) classroom, it’s harder to create. The content of such classrooms is generally by definition well established. Furthermore, creating the conditions where a phenomena is both ambiguous and accessible (technically and conceptually) is not trivial. This leads to what we call the *variability problem*: How do we create a classroom context in which conclusions that vary in an authentic manner are possible?

Principles and Needs for New Resources

Given the current state of conceptual support for enacting inquiry available to teachers, we propose the development of categories – what we now term *inquiry activity structures* (IAS) - that meet the following principles:

1) *Have a level of abstraction in-between specific lessons and aspirational goals.* Teachers have been given resources that define what should happen in their classrooms. This is beneficial for judging *existing* practice, be it instructional materials or a teachers' actual practice. But these do not have heuristic power to aid in the generation of new instructional plans and practice. Teachers need assistance in how to bring about the experiences that define inquiry beyond specific lesson plans.
2) *Be pedagogical guides for how to structure instruction rather than characterizations of student action resulting from instruction.* Many of the attempts noted above to provide structure regarding inquiry for teachers retain an organizational structure based on analysis of the activities of scientists. They are based on lists of student actions such as observing, defining the problem, analyzing data, supporting conclusions, etc. Such a structure may be useful in assessment and research, but they fail to be pedagogically useful to teachers. Teachers need resources to guide them in creating the conditions under which carrying out those activities is meaningful. In providing resources to teachers, there needs to be more focus on means rather than ends by delineating pedagogical strategies rather than pedagogical outcomes.
3) *Require neither a single overarching framework that encompasses all possibilities nor mutual exclusivity among structures.* Such a principle may be aesthetically pleasing, but it conflicts with the varying nature of scientific work. The National Science Education Standards[2] explicitly describe inquiry as the "the diverse ways in which scientists study

the natural world" (p. 23). On a more practical level, we simply aim to provide teachers with as many conceptual resources as possible. If resources overlap, so be it.

These principles require us to consider not just the nature of scientific inquiry and engineering design, but the nature of designing scientific inquiry and engineering design experiences for the K-12 classroom. In other words, we want to consider what this task looks like from the point of view of the teacher or other instructional planner. The NSES list defines a good target, but we wish to address the problem of how to create the conditions in the classroom where these learner activities can happen. In general, these IAS's can be seen as solutions to the two problems in devising inquiry-based activities cited above.

Methodology

Initial development of *inquiry activity structures* (IAS) began informally in the context of guiding preservice and inservice teachers in teaching methods courses. Reflection on this work yielded first three[18] structures then followed by an expansion to six[20] activity structures. The present research is an effort to formally validate, and if necessary modify, this list. To further develop and verify the taxonomy of structures, we have systematically reviewed science activity plans from a variety of lesson plan archives and large curricula. In order to best ensure systematic review and avoid bias, we have selected several large repositories of activities as our sample pool. These include both coherent curricula and large collections of discrete activities, span middle and high school grade bands and cover biology, chemistry, physical science, environmental science and earth science. In total, our pool includes over 300 activities.

For each activity, descriptive information such as grade level and discipline were noted. As inquiry activity structures are not necessarily mutually exclusive, each activity could be categorized with both a primary and secondary IAS. Each activity was assessed regarding its inclusion of the five NSES essential features of inquiry[2] and the eight Science and Engineering Practices from the new Framework for Science Education[5]. In each case, an activity could be rated as “yes”, “possible” or “no”. The middle rating was used in cases where the written activity did not include that feature but it was easy to conceive of teachers including it at their own initiative. In the case of the two Framework practices that distinguish between science and engineering, these were assessed separately. Because the new Framework was only recently released, its use in assessment is on a smaller set of activities.

Activities were first reviewed jointly by the entire research team to develop both the definitions of each category and common standards among the group. Next, two rounds were conducted where a common group of activities were reviewed separately by individual team members and then compared for consistency. Subsequent activities were categorized by individual research members. Activities that were problematic were reviewed by the team as a whole, and where necessary, new categories were created.

Results

Our review of existing instructional materials succeeded in both validating existing categories and revealing two additional categories. Below we describe each IAS category. We then discuss our analysis showed about the state of inquiry activities in our field, particularly with regard to the inclusion of engineering.

Protocol

A protocol is a well-defined procedure for collecting data. In terms of definition and clarity of steps, it is quite similar to a traditional cookbook lab. However, it is portrayed as being clearly just a tool – as opposed to the entirety of the lab experience. More importantly, a protocol can be applied to a wide variety of situations – not just the situation in which it is introduced and learned. (Hence some cookbook labs can be adapted to form protocols, but others cannot.) Once students learn the protocol in an initial circumstance, they can then apply it to further research. This research can be more varied and more student-directed.

A prototypical case of a protocol is the lettuce seed bioassay[21]. Students are given fairly clear directions for producing a serial dilution of a salt solution, setting up a bioassay using lettuce seeds, and evaluating the results. Once they have had that experience, they can now engage in further, more varied research: other concentration ranges, other toxins, and even other biological indicators. At the most sophisticated end of the spectrum, the bioassay can become a moderate piece in a larger, extensive research endeavor.

Learning a protocol is not just a question of now having a new technical skill. It overcomes the Getting-on-Board problem by introducing student to an entire way of looking at the natural world. The data set they produce in the initial learning round is also significant. It can be an indicator for what merits investigation next, just as with science at large. Hence the student has been brought on board the knowledge development cycle.

Design Challenge

Design Challenge activities are centered around an explicit task to produce a product. Just making something, however, does not make an effective design challenge. It can just be the Design Challenge equivalent of a cookbook lab. The details of the assignment are crucial in determining whether this is an effective design challenge. The assigned task and associated constraints must combine in such a fashion that tension – without a clear cut resolution – is created. Thus while many activities fail to be significant inquiry activities by being too constrained, a design challenge that is too open can be ineffective.

The design task motivates the practical need to acquire certain knowledge bases. Sometimes inquiry designers will use a jigsaw arrangement, where students are divided into specialty groups to learn one of those knowledge bases, then rearranged into design teams made up of representatives of each specialty group. Even when these knowledge bases are acquired in a fairly traditional manner, they are done so in the context of needing to apply them to the ultimate challenge.

A very common example of a Design Challenge is bridge building. The basic format is to challenge students to devise a structure to maximize the amount of mass it can hold without breaking. Various constraints can be imposed, such as limiting the amount and type of materials used, or challenging students to maximize the ratio of mass held to mass of the structure.

Product Testing

Product Testing activities present students with the task of evaluating and comparing performance. This requires students to devise and implement ways to consistently compare items, and often to quantify those comparisons. This means recreating a phenomena in a controlled, reproducible and measurable manner. This challenge often breaks down into three parts. First, students must determine what the desired attributes of the product are. Second, students must devise ways of consistently testing those attributes. Lastly, they must determine a way of combining the results.

A simple example of a Product Testing activity would be determining the best paper towel. Students would first have to design what attributes affect the desirability of a towel. This might include absorption, strength and price. Then they need to devise ways to test and quantify those attributes. And lastly, given the results of that testing, they must integrate the results to choose a best paper towel. The Product Testing structure therefore overcomes the Variability Problem with three separate opportunities for contention.

Overcoming the Getting-on-Board Problem is often helped through the use of a familiar phenomena (such as paper towel use). In addition, it is significant to note that students are not creating the products, but rather assessing them. In a sense, the Product Testing structure is the inverse of the Protocol and Design Challenge structures: rather than being giving a protocol and asked to find opportunities to use them, students are given the objects and need to create the protocols to apply; rather than creating a product to meet certain criteria, students are asked to create the criteria to assess given products.

Black Boxes

Black Box activities challenge students to determine the nature of things hidden from view. They require students form logical arguments since they must reach conclusions without direct observations. Hence, overcoming the Variability Problem is at the heart of their nature.

Depending on their nature and context, the Black Box structure can be used to highlight various concepts. The most common and broad is illustrating the difference between observation and inference. For example, the simplest Black Box activity is a literal box containing various objects, where students are challenged to determine the nature of the contents without opening the box. This also demonstrates how Black Box activities must not simply be puzzles, with one acceptable solution. Rather, the fact that one cannot directly examine the contents – their black box quality – means that the argument about the conclusion is even more essential than the conclusion itself.

The Black Box structure can also be used to make more specific connections to atomic theory. They illustrate the ability to reach conclusions despite a lack of direct observation. For example, students can be challenged to determine the size and shape of objects hidden form view with marbles or other small balls, thus being analogous to scattering experiments. Other Black Box activities can be devised where some observations also change the object, hence simulating the Heisenberg Uncertainly Principle.

Intrinsic Data Space

Intrinsic Data Space activities immerse students in a data space that inherently implies a question. They have a “sandbox” aspect that allow for easy exploration of the data. These overcome both the Getting-on-Board and Variability problems by presenting a natural puzzle.

An example of the Intrinsic Data Spaces structure is the Mystery Bones[24] activity. Student are presented with cut outs of bone fossils. Arranging the bones into possible animal formations is a natural task. Students can be further challenged to make conclusions the nature of the animal. Hence it should be pointed out that while the Intrinsic Data Spaces structure does depend on the natural draw of the data that does not need to be the full extent of the activity.

Simulated environments would be an important sub-category of Intrinsic Data Space activities. Such computer programs, such as Interactive Physics[25] or Stella[22] can be effective in allowing students the flexibility and freedom to explore (thus overcoming the Variability Problem) while lowering the technical and cognitive barriers (thus overcoming the Getting-on-Board Problem).

Discrepant Event

Discrepant Event activities center around an distinct, non-intuitive, and often impressive, event, and naturally poses to students the question “what is going on?”.

The Ammonia Fountain[26] is an example of the Discrepant Event structure. Here, students see water rise up a tube and turn into a pink fountain. The cause challenges students’ common conceptions of suction. This also illustrates how Discrepant Event activities have a strong content connection.

The non-intuitive aspect is crucial for overcoming both the Getting-on-Board and Variability Problems. It helps make the question to students both meaningful and non-trivial. And it provides opportunities for multiple positions. However, an effective activity requires that the students experience the phenomena as discrepant. Whether a particular phenomenon has that discrepant quality is dependant on the context and the students. What is obviously problematic for one set of students might not be for another.

Many Discrepant Event activities are done as a teacher led demonstration, for technical or safety reasons. However, they also illustrate how an otherwise teacher centered activity (the teacher is in control and doing the physical work of the activity) can be executed in an inquiry manner. And like the Protocol structure, the Discrepant Event structure provides a possible opportunity for turning traditional cookbook labs into inquiry activities.

Taxonomy

Taxonomy activities present students with a wide variety of samples. Students are then challenged to create a meaningful organization of the samples. A sufficient number and variety of samples is important, so that the exercise is not reduced to students simply finding predetermined categories. Likewise, students need sufficient context to both motivate the formation of organization, and to guide decisions as to what aspects of the samples matter over others.

Taxonomy activities are a clear part of biology courses, but do not need to be limited to this. For example, as part of an astronomy unit, students can be challenged to form a categorization of celestial objects. Students would be given a variety of data on a variety of objects, without names that would otherwise create preconceived notions.

Modeling

While models are often used as a broad concept in science education, we intend a more narrow definition here. In Modeling activities, students are challenged to construct a functioning model of a natural phenomena. By functional, we do not necessarily mean a physical model. For example Stella[22] is a computer modeling environment widely used in educational settings. There are two motivations for modeling. First, the phenomena being modeled is often too complex to allow for direct observation of key parameters. Instead, a model is constructed and adjusted until the behavior of the model matches the behavior of the real phenomena. Parameters can then be easily read off of the model. The modeling of ecosystems would be an example of this. Second, models are often used where logistics such as time or size bar use of the real phenomena. In either case, it is the making of the model that distinguishes this IAS from others.

The Mystery Tube[23] exercise presents students with a tube containing various ropes. Pulling on a rope may (or may not) affect the other ropes. Students are challenged to create a tube of their own that mimics the behavior of the target tube, hence modeling the phenomena. Since the inside of the new model is accessible, arguments can be made for the nature of the original tube.

Combinations and Overlaps

As noted in the principles outlined above, these activity structures are not intended to be perfectly distinct. It is certainly possible to envision activities that combine or overlap the different categories. For example, consider an activity intended to teach about erosion. Students are given a challenge to design a monument that will resist erosion, and develop an understanding of the factors involved through a series of mini-protocols. There are also instances were the same underlying phenomena can be approached using different activity structures. For example, simple paper helicopters (sometimes called "twirlies") can be made whose performance can vary depending on a number of parameters[27]. But students can be prompted to investigate this rich problem space in different ways. Asking students to begin by determining how flight time relates to release height would form a protocol activity. Challenging students to modify their helicopter to maximize flight time would form a design challenge activity.

Distributions and Other Ratings

Table 4 shows the distribution of analyzed activities across the inquiry activity structures. The Protocol structure was by far the most widely represented structure, followed by Modeling and Design Challenge.

IAS	
Protocol	96
Design Challenge	38
Product Testing	11
Black Box	6
Intrinsic Data Space	12
Discrepant Event	27
Taxonomy	22
Modeling	45
Can't categorize	112

Table 4 Distribution of activities across IAS's

Table 5 shows the distribution of activities across IAS's and grade level with the standard residuals. (Standard residuals with an absolute value of 1.65 and 1.96 indicate statistical significance at the 90% and 95% confidence level, respectively.) Chi squared test of showed statistical significance for the overall distribution. The overrepresentation of Discrepant Event activities at the elementary school level was the only specific result that was significant at the 95% confidence level. At the 90% confidence level, the Protocol structure was overrepresented in high school and underrepresented in middle school, the Design Challenge structure was underrepresented elementary school and Modeling was overrepresented in middle school. In addition, activities that could not be categorized were overrepresented in elementary school. This is likely connected to the overrepresentation of poor activities at the elementary level that we discuss below.

IAS	HS	MS	ES
Protocol	68	33	12
	1.90	-1.77	-0.57
Design Challenge	25	29	2
	-0.34	1.44	-1.89
Product Testing	6	8	0
	-0.27	1.04	-1.32
Black Box	2	4	0
	-0.51	1.05	-0.87
Intrinsic Data Space	10	8	0
	0.47	0.32	-1.50
Discrepant Event	15	12	10
	-0.64	-0.70	2.50
Taxonomy	13	11	5
	-0.23	-0.15	0.72
Modeling	27	38	6
	-1.19	1.85	-0.97
Can't categorize	75	57	28
	-0.17	-0.81	1.79

Table 5 Distribution of activities across IAS's and Grade Bands with standard residuals

Table 6 shows the distribution of activities across IAS's and subject areas, which was also shown to be statistically significant with the chi square test. Several relationships were significant at the 95% confidence level. The Protocol structure was overrepresented in chemistry, but underrepresented in physics. The Design challenge structure was the inverse – underrepresented in chemistry and overrepresented in physics. The Product Testing structure was over represented in biology, while the Discrepant Event structure were underrepresented. Modeling was overrepresented in biology and underrepresented in chemistry.

IAS	Biology	Chemistry	Physics	Earth&Space	Environmental Science	Physical Science
Protocol	14	57	5	17	11	8
	0.55	5.52	-3.28	-1.56	0.82	-2.56
Design Challenge	3	5	23	24	2	20
	-1.84	-3.23	2.63	1.69	-1.61	1.86
Product Testing	5	5	3	3	1	2
	2.06	0.13	-0.17	-0.59	-0.38	-0.70
Black Box	0	1	1	3	0	0
	-0.73	-0.22	0.14	1.80	-0.62	-0.93
Intrinsic Data Space	1	4	4	6	1	7
	-0.94	-0.72	0.00	0.40	-0.58	1.53
Discrepant Event	0	11	13	9	2	14
	-2.30	-0.34	1.54	-0.56	-0.91	1.92
Taxonomy	4	6	4	6	3	4
	0.64	-0.28	-0.32	0.01	0.64	-0.30
Modeling	18	4	13	20	7	13
	3.48	-3.39	-0.01	0.84	0.52	0.03
Can't categorize	14	43	29	33	15	26
	-0.78	0.51	0.23	-0.40	0.77	-0.29

Table 6 Distribution of activities across IAS's and subject areas with standardized residuals

Table 7 shows the Herron Scale scoring for the analyzed activities, both in general, and across the IAS's. The chi-squared test of the distribution was statistically significant. The general results are not surprising – the higher up the scale, the fewer the activities.[1] But some details are important. First, a disproportionate number of activities that could not be categorized were also rated as Level 0 on the Herron Scale. This further supports our categories: those activities could not be labeled with an inquiry category because they were bad inquiry activities. While all of the activities were underrepresented at Level 0, the underrepresentation of the Protocol, Design Challenge, Taxonomy and Modeling structures were statistically significant at the 95% confidence level. Of those four, Protocol, Taxonomy and Modeling were all overrepresented at Level 1. The Design

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[1] The very small number of 3's should not be seen negatively. Three's require even the question to come from the student, while our analysis is of planned instructional activities. These can be seen as contradictory.

Challenge structure was distinct in being underrepresented at both Level 0 and Level 1, and over represented at Level 2.

IAS	Herron Scale Score			
	0	1	2	3
Protocol	10	59	14	1
	-3.32	2.79	-0.39	-0.02
Design Challenge	0	6	27	1
	-3.33	-2.52	7.80	0.91
Product Testing	1	4	3	0
	-1.34	0.82	0.40	-0.36
Black Box	0	3	0	0
	-1.34	0.82	0.40	-0.36
Intrinsic Data Space	1	4	3	0
	-1.34	0.82	0.40	-0.36
Discrepant Event	2	15	5	0
	-1.74	0.69	0.70	1.30
Taxonomy	1	16	1	0
	-2.07	2.02	-0.58	-0.48
Modeling	2	30	6	0
	-3.07	2.65	-0.32	-0.70
Can't categorize	87	7	1	0
	9.86	-4.80	-4.30	-0.20
All	103	139	56	2

Table 7 Distribution of activities across IAS's and Herron Scale score with standard residuals

Table 8 and Table 9 show how the activities were scored on the essential features of inquiry from the 1996 National Science Education Standards, and the science and engineering practices from the 2011 Framework for K-12 Science Education, respectively. Recall that the latter was applied to a smaller set of activities. What can be seen is that while the analyzed activities do a good job supporting students' work with data, they are weaker in what comes before and after that work.

NSES (1996) Essential Features	Yes	Possible	No
Learners are engaged in scientifically oriented questions	205	105	26
Learners give priority to evidence	216	90	33
Learners formulate explanations from evidence	192	101	45
Learners evaluate their explanations	90	133	115
Learners communicate and justify their explanations	104	143	91

Table 8 Inclusion of Essential Features of Inquiry

Framework (2011) Practices	Yes	Possible	No
Asking questions (for science) and defining problems (for engineering)	73	110	21
Developing and using models	48	33	124
Planning and carrying out investigations	62	116	27
Analyzing and interpreting data	118	62	24
Using mathematics and computational thinking	60	54	91
Constructing explanations (for science) and designing solutions (for engineering)	103	79	24
Engaging in argument from evidence	35	112	59
Obtaining, evaluating, and communicating information	62	112	32

Table 9 Inclusion of Science ad Engineering Practices

With regard to distinguishing science from engineering, of the activities rated as "yes" for the first practice, approximately 70% were rated as the science version and 30% as the engineering version. Of those rated "yes" for the sixth practice, approximately 80% were rated science and 20% engineering. The ratio became even more extreme – 90% to 10% on both practices – when considering the activities rated as possible.

Table 10 and Table 11 show how the activities were distributed across IAS's and the two engineering specific practices from the new Framework ("Defining problems" and "constructing solutions"). Both distributions were statistically significant according to the chi square test. Protocol was underrepresented and Design Challenge was overrepresented among those activities that provided opportunities to define problems. Likewise, Protocol was underrepresented and Design Challenge was overrepresented among those activities that provided opportunities to construct solutions. A less intuitive result was that Discrepant Event was overrepresented among activities that had the possibility of providing opportunities for defining problems.

	Defining Problems		
IAS	Yes	Possible	No
Protocol	2	4	59
	-2.11	-1.27	1.34
Design Challenge	15	2	3
	8.03	-0.20	-3.14
Product Testing	0	1	6
	-0.93	0.22	0.29
Black Box	0	0	3
	-0.61	-0.59	0.47
Intrinsic Data Space	0	0	9
	-1.05	-1.02	0.82
Discrepant Event	0	5	6
	-1.16	3.32	-0.82
Taxonomy	0	0	6
	-0.86	-0.83	0.67
Modeling	0	4	14
	-1.48	1.34	0.07

Table 10 Distribution of activities across IAS's and "Defining Problems" practice with standard residuals

	Constructing Solutions		
IAS	Yes	Possible	No
Protocol	2	4	59
	-2.11	-0.50	0.98
Design Challenge	15	2	3
	8.03	0.33	-3.25
Product Testing	0	1	6
	-0.93	0.60	0.17
Black Box	0	0	3
	-0.61	-0.49	0.39
Intrinsic Data Space	0	0	9
	-1.05	-0.84	0.68
Discrepant Event	0	2	9
	-1.16	1.21	0.07
Taxonomy	0	0	6
	-0.86	-0.69	0.55
Modeling	0	2	16
	-1.48	0.48	0.43

Table 11 Distribution of activities across IAS's and "Constructing Solutions" practice with standard residuals

Table 12 and Table 13 show how the activities were distributed across subject and the two engineering specific practices from the new Framework. Both distributions were statistically significant according to the chi square test. Chemistry was underrepresented and Earth & Space Sciences was overrepresented among activities that provided opportunities for both engineering practices. In addition, Environment Science was overrepresented among activities that had the possibility for providing opportunities for constructing solutions.

	Defining Problems		
Subject	**Yes**	**Possible**	**No**
Biology	3	0	12
	0.40	-1.53	0.53
Chemistry	3	6	94
	-3.30	-2.50	2.77
Physics	11	10	26
	1.30	1.00	-1.10
Earth&Space	17	12	33
	2.29	0.77	-1.47
Environmental Science	1	4	9
	-0.82	1.24	-0.20
Physical Science	13	15	34
	1.01	1.74	-1.31

Table 12 Distribution of activities across Subject and "Defining Problems" practice with standard residuals

	Constructing Solutions		
Subject	**Yes**	**Possible**	**No**
Biology	3	0	12
	0.40	-1.30	0.32
Chemistry	3	4	96
	-3.30	-2.22	2.41
Physics	11	6	30
	1.30	0.32	-0.73
Earth&Space	17	9	36
	2.29	0.77	-1.37
Environmental Science	1	4	9
	-0.82	1.94	-0.38
Physical Science	13	11	38
	1.01	1.53	-1.07

Table 13 Distribution of activities across Subject and "Constructing Solutions" practice with standard residuals

Lastly, we should point one area where there was not a pattern. The distribution of activities across grade bands and the engineering practices was not statistically significant. While the total numbers of elementary school level activities were low, there was no statistically difference in how often those activities provided opportunities for engineering practices when compared to the middle and high school levels.

Discussion

Our taxonomical study of existing material was fruitful in enumerating the pedagogical strategies available to enact inquiry in the K-12 classroom. The consistent alignment between activities that could not be categorized and poor rating on the Herron Scale contributes to the validity of our categories.

Beyond the taxonomy itself, our analysis of the activities raises several important points. The distribution of IAS's was not uniform across the contexts of subject area and grade levels. What is unclear is if this is an indication of each IAS's utility, or if these are signs of missed opportunities. For example, the Design Challenge structure was not common at the elementary level. This may mean that Design Challenge activities are comparatively hard to conduct at the elementary level, and that instructional planners would be better off considering, for example, Discrepant Event activities in that context. However, Design Challenge activities would seem to have some intrinsic appeal to the elementary level. They have the advantage of a very concrete objective. So it may be that the gaps in the distributions should be considered as opportunities to expand the range of typical inquiry activities that are available in each context.

Very early in our ratings of the inclusion of elements from the Standards documents, we decided on the need for the "possible" rating. We felt there were instances where the activity created the context in which it was feasible to meet the particular requirement, but the written instructional materials gave no indication to do so. As can be seen in Table 8 and Table 9, there were a considerable number of activities that met this description. On the positive side, this means that it is quite feasible to create the contexts in the classroom where those various elements can be met. In essence, this is the hard part of promoting inquiry in the classroom. On the negative side, however, it is a failing on the part of the activity designers not to include such elements, when it was clearly possible. The Discrepant Event structure stands out as a particular IAS that may not be utilized to its full potential.

While there is reason to be positive on the availability of inquiry activities in general, the state of things for engineering practices is more mixed. There is a clear lag between resources for science and resources for engineering. Chemistry also stands out as a subject that is particularly weak with regard to engineering. It is very possible that with the increased attention to engineering at the K12 level, particularly within the new Framework for K-12 Science Education, engineering will catch up. Our study makes clear the need, but we do not see any systemic reason why this cannot be remedied. In fact, our analysis pointed to the utility of engineering contexts. Design challenge activities were far more likely than the other IAS's to be at Level 2 on the Herron Scale. So engineering is in a strong position as a *means*, even if not as an *ends*.

Future Work

This study has served as an introduction for the concept of *inquiry activity structures*. We see five areas for future research.

Additional Data for Taxonomical Study

Additional analysis would benefit from a larger pool of activities. While we were able to address some issues of distributions – basically those across two analytical categories - more fine tuned questions – across more categories - would need more data. For example, does the performance of different IAS's on the Herron Scale vary across grade levels or subject areas?

Identification of Key Curricular Features

Apart from identifying the key features that distinguish each IAS from the others, utilization of IAS's by science teachers will require identifying what the key curricular features are that make each IAS work as strategy for inquiry learning. From the point of view of instructional planning, what are the aspects that teachers need to attend to? What are the options they have available? For example, in creating design challenges, teachers need to carefully consider the nuances of the challenge and parameters they provide to students. The challenge must establish a meaningful objective, and together with the parameters will define the problem space in which students will work[28].

Research into Interactions with Educational Contexts

Finally, there is significant research to be conducted in exploring the interaction between each IAS and aspects of the learning context. How do different age groups respond to different IAS's? How does student motivation operate in the different IAS's? What inquiry skills are developed by the IAS's? How does each IAS impact student content learning? How are different IAS's represented across the science disciplines?

Additional Sources for Engineering Activities

This study was conceptualized as a taxonomical study, and so it was based on an assumption that if an approach to inquiry was viable, someone would have used it already and eventually we would find it. However, as can be seen by our data, the field is lagging in its attention to engineering. It therefore can be questioned whether all the approaches that reflect engineering are out there waiting to be found. A full set of *inquiry activity structures* would benefit from also considering other sources of inspiration for categories. In addition, the Discrepant Event structure was shown to be an activity type with unrealized potential.

The Nature of Engineering in K-12 Settings

Lastly, this study raises some issues regarding the nature of engineering in K-12 settings. Consider the weakness of chemistry in providing opportunities for engineering practices. Is this a problem? The answer really depends on how engineering is made part of the K-12 curriculum. If it is to be considered a separate discipline/course, than the question is less relevant. If it is to be integrated in some manner with the existing science disciplines, our research raises issues of how and where that may be possible. In either case, the scope of engineering at the K-12 level is at issue. Earth & Space Science topics (and to a lesser extent physical science topics) were shown to be more fruitful in providing opportunities for engineering practices. But chemical engineering, for example, is certainly also real engineering discipline. The pertinent issue is is it a viable discipline in K-12 education?

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