A Taxonomy of Technical Knowledge

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I. Introduction.

Knowledge, most people will agree, is a very valuable and important commodity. Consider the ways. It was eating of the fruit of the tree of knowledge of good and evil that, according to some religious traditions, led to mankind's fall from grace. People spend great quantities of money and great amounts of effort in the pursuit of and acquisition of knowledge. The developed world, we are told, now operates in what has come to be called the knowledge economy. Knowledge, it seems, makes the world go 'round.

It has often been said that universities are in the knowledge business. Universities *generate* knowledge in their research and scholarship activities. Whether this knowledge is generated by creation or discovery can be argued, but a successful university will be the repository of more knowledge at the end of the year than it was at the beginning. Universities also *preserve* knowledge. They do so by maintaining an expert faculty and also by serving as a repository of recorded material, be that material clay tablets, paper books, audio recordings, magnetic or optical discs, or terabytes of storage in a remote server. Of course, the most obvious of a university's functions is to *transmit* knowledge from one generation of scholars to the next through its education programs. Finally, most universities – particularly those with a land grant mission – also *apply* knowledge through various service activities.

It seems that everyone – except for the unavoidable curmudgeon – agrees that knowledge is very important. This is curious, because there seems to be great disagreement on just what knowledge is. Consider these definitions from the Merriam-Webster Online Dictionary:

- the fact or condition of knowing something with familiarity gained through experience or association
- acquaintance with or understanding of a science, art, or technique.
- the fact or condition of being aware of something
- the range of one's information or understanding
- the circumstance or condition of apprehending truth or fact through reasoning
- the fact or condition of having information or of being
- the sum of what is known
- the body of truth, information, and principles acquired by humankind

While all these definitions are valid in some context, do they provide much guidance to a student who is told that his or her task is to acquire knowledge or to the teacher whose task is to generate or transmit it? The author recognizes the futility of pursuing a universally accepted definition, but he will dare, in a section of this essay, to offer a definition that will be useful to both teachers and students.

Knowledge is important and knowledge is hard to define. It is also a challenge to organize. It has, however, been recognized that not all knowledge is created equal. Some knowledge is more intellectually challenging than other knowledge. Probably the best known exponent of this view was Benjamin Bloom who created his taxonomy of learning objectives. While his contribution was immense, there are some features of his taxonomy that do not lend themselves well to the technical/scientific disciplines or, perhaps better said, could benefit from some interpretation. In the following sections, Bloom's taxonomy will be explored and a taxonomy that is perhaps better suited to the technical disciplines will be defined.

II. A Working Definition of Knowledge

If one is to develop a useful taxonomy of a commodity, it seems essential that a clear definition of that commodity be established. It would be folly to attempt a classification of, say, birds, if there is no agreement on just what a bird is. A simple definition is best since that will allow for fewer arguments about those members of the set that push the boundaries of the definition. As noted in the introduction, there is no single definition of knowledge, and those that exist are not particularly simple.

Indeed, the word is sometimes used in ways that are quite opposite. In one usage, knowledge is differentiated from skills. The distinction is not always clear, but it does seem apparent that skills are inferior to - or at least less deserving of respect than – knowledge. This is conveyed by such statements as, “My course deals with knowledge. He teaches skills”. Conversely, Bloom, as will be discussed later, uses the term knowledge to designate the least challenging of the educational objectives in his taxonomy; memorization and rote learning. So in one case, knowledge denotes the most abstract cognition; in the other, the least abstract. Clearly, some clarification would be helpful.

For the present purpose, it might be wise to paraphrase Einstein and specify that a definition of knowledge should be as broad as possible, but no broader. Thus it should encompass the high-end knowledge – as sometimes differentiated from skills – and also the low-end knowledge as designated by Bloom. For that matter, why not include skills as well? With all this in mind, for the purpose of this essay, we offer the following definition:

> Knowledge is the ability to do.

According to this definition, what I know (i. e., the knowledge that I possess) determines what I can do and, conversely, what I can do defines what I know. Every thing that I know allows me to do some thing. Every thing I can do defines some thing that I know. Knowledge and the ability to do are identical.

Knowledge is acquired through the process of learning: a process managed - with varying degrees of success - by educators or, for more mature learners, the learners themselves.

Educators are likely to agree with the definition of knowledge as the ability to do because it supports the contention that educators can determine whether or not their students have acquired (learned) the knowledge they were supposed to. Examinations (written or oral), essays, speeches, laboratory reports, designs, projects, problem sets, etc., all require students to do something to demonstrate that they have acquired the desired knowledge. The degree to which they can do it is then the basis upon which the educator assigns a grade, whether it be a letter, a number or pass/fail.

There is a theory of education – rarely seen in engineering – that might be called "sitting at the master's knee". The idea is that just being in the presence of a master practitioner of an art and watching how she or he thinks and works will have a desirable effect on the student. It is often then asserted that there is no way to determine if that desirable effect has indeed been achieved because it is intangible. Educators who adhere to this theory (faith-based education?) will probably not accept the definition of knowledge as the ability to do.

We have occasionally heard the statement, "He knows a lot, but he can't do anything with it". If true, this would be the antithesis of the notion that to know is to be able to do. Or would it? If one expands the statement to be, "He knows (and hence can do) a lot of things, but he can't do (and hence doesn't know) the things that I want done", the statement makes a lot more sense. Or at least it makes sense if knowledge can be classified and these "things" carefully defined. Such a classification and definition is the subject of the next sections.

III. The Domains of … What?

Our brains store information by establishing connections among the innumerable nerve paths that make up those brains. When we are born, our brains are essentially devoid of connections that are created by experience since, obviously, we have had no experience. As time progresses, however, billions (trillions?) of connections are created that determine our future capabilities and behavior. In other words, they store our knowledge – as defined in this essay – but they also store something more. The author cannot decide what to call this general sum total so will avoid calling it anything but will rather describe the three domains into which this sum total is divided.

The Psychomotor Domain. As we develop and gain experience, our brain and our body work together to learn certain physical tasks: to crawl, to walk, to run, to throw a ball, to use tools – a thousand different things we can do. These capabilities, the ones involving physical activity, make up our psychomotor arsenal. This domain fits quite easily into our definition of knowledge – the ability to do – because it is easy to observe the doing. Furthermore, it fits our understanding of education because it is possible to learn to do physical tasks and also to improve one's ability in the performance. There are limits, of course; not everyone can hit a home run every time. But anyone who can swing a bat can improve their batting average with proper instruction.

The Cognitive Domain. This is the domain of thought, of reasoning, of the drawing of conclusions, of decision making. By far the greatest portion of effort in our education systems is directed toward developing capability in this domain; certainly that is true in university and most secondary education.

Again, capabilities in this domain fit into our definition of knowledge – the ability to do. While it may be more difficult to determine the ability to do something in the cognitive domain than it is in the psychomotor, it is perhaps more essential that we do so. That determination is the basis on which academic grades are given, professional work performance is assessed, promotions are given and responsibility is assigned.

The Affective Domain. While people are capable of thought and capable of action, there are other elements of the mind that help to direct that thought and to determine what that action will be. These are the values and attitudes that have been acquired through experience and instruction throughout our lifetime. They are learned primarily by experience in the home and the community but can also be taught. Much religious instruction has its goals in the affective domain, with the intent of modifying the moral position of the instructees.

It is in this domain that it becomes more difficult to classify those brain connections as knowledge as defined in this essay – the ability to do. Values and attitudes do not seem to define any ability to do but rather will affect what course we choose to follow. It may be said that the cognitive and psychomotor domains determine what we are able to do and the affective domain determines what we are likely to do. Consequently, it also becomes difficult to assess one's status in the affective domain. How can we determine another person's values, however important they may be?

In summary, a taxonomy of knowledge would seem to be possible for the cognitive domain, definitely; the psychomotor domain, probably; and the affective domain, not likely. In this essay, attention will be focused on the cognitive domain since that is the main area addressed by educators in engineering, science and technology - the target audience. This is by no means intended to deny the importance of the other domains. It is clear that without capabilities in the psychomotor domain, nothing would ever get done. And without the (we hope) positive values of the affective domain, we would be likely to do the wrong thing, however the "wrong" thing may be defined.

IV. Bloom's Taxonomy

Benjamin Bloom (1913-1999) was an educational psychologist who made significant contributions to the role and understanding of educational objectives and the theory of mastery learning. In a seminal work of 1956, he formalized the notion that educational objectives can be classified with respect to the level of abstraction involved in their attainment. Clearly – at least it is clear now – rote learning or memorization is not as abstract a task as, say, solving a physics problem.

While Bloom focused on learning objectives, the fact that learning is the process of gaining knowledge establishes a clear link between a taxonomy of such learning objectives and the taxonomy of knowledge that is the subject of this essay. Indeed, it was a study of Bloom's taxonomy that led to the classification presented herein. Thus it will be useful to explore Bloom's thinking on objectives before proposing our own classification of knowledge.

Bloom defined six competences in the cognitive domain, listed here in order of increasing level of abstraction or intellectual complexity:

Knowledge. This is simply memorization and recall. Demonstrating "Knowledge" merely requires the individual to provide facts without any need to know why the facts are true, how the facts affect other situations or, indeed, if any of the facts are contradictory. (At this point, the reader can probably sense why the author, who defines the human body of knowledge as the sum total of what people are able to do, finds Bloom's use of "knowledge" to be less than useful)'

Comprehension. The word generally associated with this competency is "understanding" although that word itself is not generally well defined. Broadly, it means knowing something about the subject: how it works, how it relates to other subjects, what it means in a broader context, how it differs from other subjects, what are its limitations.

Application. This competency encompasses the ability to *use* information that has been acquired. One might know that a tool is called a saw (knowledge, in Bloom's terminology) and be able to describe how it has sharp teeth that act like miniature chisels or knives and even know that it is used by drawing it back and forth (comprehension) but can one use it to make two boards out of one?

Analysis. Now things start to become a bit more complex. Analysis involves such processes as identifying connections, comparing characteristics, classifying subjects and breaking complex systems into their component parts. While comprehension means that you know how something works and can describe it, analysis requires that you figure out how it works without being told. In engineering, we devote a great deal of attention to teaching analysis.

Synthesis. This competency involves the creation of new - or at least new to the learner – connections and relationships. It will use various bits of information and may well integrate knowledge from different areas. Synthesis may employ various formal techniques or may result from the development of an idea or an artifact through the process we call creativity.

Evaluation. The processes of analysis and synthesis often result in several products that have different characteristics but perform essentially the same function. How to choose among them? Or even how to compare them? Evaluation is the process of making such comparisons in a systematic and objective manner. In most interpretations, this competency also involves making decisions based on these comparisons.

V. Toward a Different Taxonomy

In 1978, the author and a colleague, Ronald J. Schmitz, undertook the development of a system of instruction wherein a student could assess his or her own learning and, using the materials developed, effect remediation of any deficiencies. It was obvious that such a system would benefit from - or would indeed require – a base of clear learning objectives. A study of the theory of learning objectives led quite naturally to Bloom’s work and an attempt was made to organize the desired material into the competencies that Bloom had defined. Several difficulties ensued.

One problem was the terminology. As noted earlier, the use of Knowledge was quite unsatisfying. There was also difficulty with the category of Application since it seemed that application of some kinds of information required little comprehension while another required a great deal. Should Comprehension be considered of greater intellectual complexity than Application or vice versa?

Another difficulty arose as there were arguments about whether synthesis was involved in solving basic engineering problems or if it was just a matter of applying analysis. Does Evaluation go far enough in describing one of the steps in the process of engineering design?

Overall, there was dissatisfaction in our ability to effectively apply the concept of competencies as opposed to categorizing objectives in terms of verbs. Finally, it was decided to develop our own taxonomy, using Bloom’s work as a basis but adapting it to our perception of learning objectives in engineering. After many hours of discussion and innumerable refinements, it was determined that without too much stretching, our learning objectives could be described in terms of five verbs. These verbs describe a taxonomy of learning objectives and also, as noted earlier, a taxonomy of technical knowledge.

While the taxonomy was originally formulated around 1980, the concept has continued to develop in the ensuing years, both through further reflection and in discussions with colleagues. There have been minor changes in terminology and a deepening understanding of the various categories.

VI. The Taxonomy

If knowledge is defined as the ability to do, it can be classified by verbs which, of course, describe action or the doing of something. The following verbs define the several classes of competencies that are embodied in technical knowledge. Following the example set by Bloom, they are arranged in order of increasing intellectual complexity or abstraction:

Define. State the definition and meaning of various terms and processes. For the most part, this is primarily memorization and recall but may also require more detailed descriptions of terms and processes including units, dimensions and inter-dependencies. It also includes the ability to identify, classify and sort.

Compute. Given specified conditions or values, follow established procedures to determine resultant conditions or values. The origin and derivation of the procedures may not be known but there should be reasonable confidence they are valid.

Explain. Verbally and mathematically reproduce the underlying theory of various principles and processes including the variables and parameters that describe them and their inter-relationships. This may include how they are derived, how they operate, their limitations and, as appropriate, their relevance to the field.

Solve. Given a situation that is unresolved or that is not completely specified (e. g., has variables whose values are unknown) formulate the problem by determining conditions, constraints, parameters, and variables and apply techniques of analysis and synthesis to determine one or more resolutions.

Judge. Establish criteria by which alternative scenarios are to be evaluated, perform the evaluation and select the most appropriate scenario. The process will often involve subjective elements and may be informed by external considerations such as the values of the individual and the interests of society.

VII. Using the Taxonomy

Given the definition of knowledge as the ability to do and an understanding of the taxonomy of knowledge just presented, there are a number of ways in which the taxonomy may be used beneficially in education. A number of these applications are listed.

Orienting students Depending upon the maturity of a student, he or she goes to college to a) get away from home, b) get a degree, or c) get an education. The movement of students along this scale can be hastened by helping them to understand the nature of knowledge and its relation to learning and then the relation of learning to their activity in their courses and their curriculum. Using clear learning objectives helps to establish these relationships but it is also helpful if they understand that knowledge is the ability to do and that achieving their learning objectives adds to their knowledge.

But there is yet another principle that students can benefit from understanding; this is the fact that different chunks of knowledge – i. e., the ability to perform different tasks - involve different levels of intellectual complexity or abstraction. If they don’t appreciate this, they can be frustrated because they don’t understand why they have no problem listing the electrical units and their dimensions but can’t determine the current in one leg of an unbalanced Wheatstone bridge. It seems likely – and those more versed in the theory of how the brain works can probably confirm or refute this – that the brain is working in a different fashion when it is doing recall than when it is doing analysis or synthesis. Understanding this could help students "switch gears" or at least help them understand that a different level of effort is required. The simple taxonomy presented in this paper is an excellent vehicle for helping students to understand the nature of knowledge and to understand what is expected of them as they progress through a course and a curriculum.

Organizing learning objectives If an instructor explains to students the definition of knowledge and the relation of knowledge to learning objectives using the taxonomy, it is both natural and beneficial to organize the course learning objectives using that same taxonomy. Indeed, if students have developed an understanding of the five verbs, the instructor will find there is no need to use any other verbs in writing the objectives for a course. This is a tremendous saving of time for the instructor and, with a little experience, the students as well.

The author – and many other teachers who have learned about the taxonomy – have written objectives by simply listing "things" under each of the five verbs. Because the students have been introduced to the taxonomy and to the kind of mental activity needed in each category, the intent of the objective is understood without a great deal of additional discussion. The initial list of objectives is, of course, distributed at the beginning of the course or unit. It is then easy to add to that list as the learning activity progresses.

Analyzing courses, examinations and curricula A surprising and somewhat disconcerting result of using the taxonomy to list objectives is seeing how many items are found at the top of the list, where the intellectual complexity is minimal and how the number decreases as one progresses down the list. On reflection, however, this is quite reasonable. In any new subject there is the language to be learned, computational techniques to be developed, and principles to be mastered before we ever get to solving problems within that area. And in most courses, we never get to the step of making judgments about the merits of various solutions. But is that what we should be doing? The taxonomy provides a vehicle for analyzing the content of a course from the standpoint of intellectual complexity.

In a broader usage, a faculty can integrate the objective lists of all their courses and then analyze the intellectual level of their curriculum as well as the subject content that is the traditional grist of the curriculum analysis mill. There should be little disagreement that an engineering curriculum must, in its terminal phases, provide considerable experience at the Judge level. A thorough curriculum analysis using the taxonomy can help to determine whether - and in which courses - that is being done.

Finally, it is – or should be – accepted practice that an examination is closely linked to course learning objectives. After all, why would we tell students they should learn something and then not check to see if they have learned it? Or worse – and, unfortunately, more common – why would we check to see if students have learned something that we never told them they needed to know? But even if examinations are based on objectives, it is helpful to ascertain that some of the objectives being tested are at the higher levels of intellectual complexity. The author has seen examinations that never tested beyond the Compute level.

Developing self-directed learners One of the most important functions of a teacher – particularly at the university level – is determining what is to be learned. Self-directed learners face the same task and our education system, in general, does a poor job of preparing them for it. The use of the taxonomy and the concomitant simple system of preparing and presenting objectives can help correct this deficiency.

Obviously, the goal is to involve students in writing the course objectives. In one effort to do so, the author broke a course into three units and developed – or guided the development of - an objective list for each unit. In the first unit, the author prepared and distributed the list in the same manner as in other courses, organized according to the verbs of the taxonomy. In the second unit, the class began with a blank slate (except for the five verbs) and each class session began with a few minutes wherein the students suggested objectives to be added to the list. These were discussed and evaluated as to their appropriateness and the class jointly decided where they should be listed in the taxonomy. The end result was an objective list shared by all. In the third and final unit, each student developed his or her own list. It was handed in at about the midpoint of the unit and evaluated and commented on by the instructor. The final lists were submitted at the end of the course and were evaluated and returned. Students were encouraged to work together and discuss the development of their lists. After all, self-directed learning is rarely a solitary activity. The lists were not given a score that counted in the course grade but submission was required and the lists were evaluated and returned.

Informally, students reported that this was a useful exercise and that they learned a considerable amount about how to go about learning a subject on their own. Regrettably, there has been no follow-up to determine whether it had a long term effect on the students.

The knowledge/skills question Earlier in this essay the knowledge/skills dichotomy was mentioned. If there is now general acceptance of the definition of knowledge as the ability to do, this question becomes moot because of course a skill denotes the ability to do something. We would probably say that the levels of Define and Compute constitute what we previously called skills. If anyone cares.

Or perhaps the statement may now be re-phrased with the academic snob now saying, “I teach students to Explain, Solve and Judge. He only covers how to Define and Compute”. But doesn’t this provide a better framework upon which to hang a discussion or even to deliver or parry an insulting thrust? At least terms are well defined and it should be much easier to get beyond the, “Is not!”, “Is so!” stage.

The process of engineering design In early discussions about the taxonomy, the vexing question of where to place design continued to plague us. Our first thought was to equate it to synthesis and place it between Solve (analysis) and Judge. This was rendered unsatisfactory by our growing belief that Solve - as we understood the process of scientific and engineering problem solving – included elements of both analysis and synthesis, often interlaced. Further, as we worked to unravel the knot, we were also developing a better understanding of the process of engineering design. In what seemed like a revelation at the time but what now seems quite obvious, we found that engineering design spans the entire range of the taxonomy. Consider a design problem from inception to completion.

As a design problem is formulated, it is essential that all participants in the process speak the same language. To Define the various terms and processes is not a great intellectual challenge, but it is essential and must be done with care and precision. And everyone must agree with those definitions.

Every engineering design problem depends upon principles of natural science and engineering science. To do the job well, the designer needs to understand – and hence be able to Explain those principles. The same may be said about the components and subsystems that will be employed in the design.

There will undoubtedly be a number of problems to Solve as the process of design continues. The problem will have to be carefully formulated and techniques of analysis and synthesis applied to arrive at various candidate solutions.

Much of the work of developing a design is not especially challenging, but employs techniques of calculation, use of handbook data, etc. The designer will have to Compute numerical values but will also be following predetermined and accepted procedures that fall under this category of the taxonomy.

Finally, virtually all engineering designs require tradeoffs and decision making. Throughout the process, and particularly in the last phases, the designer or the design team will have to Judge among several paths that can be taken and, in the end, which design is to be implemented.

Thus, the process of engineering design requires the application of knowledge from every level of the taxonomy. It will be helpful to designers and to teachers of design if they understand the taxonomy and recognize the various kinds of mental activity that are taking place.

VIII. Conclusion.

A useful technique for understanding a complex situation is reduction and classification; break the situation into subsets and seek to understand each of those smaller components, then conceptually recombine them to get a better grasp on the overall system. That has been the goal of this essay; to gain a further understanding of knowledge in the technical fields by dividing knowledge according to its intellectual complexity and then considering how these components interact in our various endeavors such as engineering design. It is not unlikely that other people will have other names for these components or will disagree with the use of verbs to delineate them. However, the principle that knowledge can be divided according to intellectual complexity seems fundamental.

Others may object to the definition of knowledge as the ability to do as being too simple. Some maintain there is a kind of knowledge that is intangible and that therefore does not result in any ability to do something. Perhaps, but if that is so, the author maintains there is no way to determine if an individual has that knowledge because to make that determination we would require that individual to *do* something.

Finally, as mentioned earlier, there has been no formal research on the benefits of using this taxonomy in understanding knowledge, helping students to understand how the education and learning process works, and writing learning objectives. The author regrets this but hopes that others will submit the system to a more rigorous examination. A number of people have used the system over the years and their anecdotal evaluations have been very encouraging and, in many cases enthusiastic. However, a more general understanding of the efficacy of the system would be helpful.

IX. Acknowledgements

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A Taxonomy of Knowledge

- Define
  - Identify, classify, sort
- Compute
- Explain
- Solve
  - Characterize
  - Analyze
  - Synthesize
- Judge
  - Evaluate
  - Compare & Select

} DESIGN