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# A Cybernetic Metric Approach to Course Preparation

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## ABSTRACT

This paper reviews and unifies 15 papers and book chapters written by the author over the past decade. The paper shows that an underlying commonality of all the author's approaches to a wide variety of pedagogical problems relies on three pillars: (a) a cybernetic approach that is independent of discipline and does not rely on specific content areas, (b) direct referral to established processes of the mind, and (c) a metric approach whereby a new pedagogic tool is formulated in terms of measurement enabling newcomers to instantly apply the new method. These three pillars are useful in improving all aspects of course pedagogy: delivery, retention, performance, and satisfaction. The use of a metric approach is often superior (easier to implement) than traditional approaches; the appeal to direct processes of the mind supplements reliance on experiments and surveys which focus on methods rather than on their underlying psychological basis. The three pillars apply to such diverse areas as pedagogic challenge, syllabus construction, computer assisted instruction (CAI), dealing with hard course components, formulating challenging practice exercises, enriching syllabus modules, and defining levels of problem difficulty. The mental processes on which the theory is based are executive function, atomic habit formation, Stroop interference, controllability (attribution) theory, and self-efficacy.

**Keywords:** pedagogical hierarchy, cybernetic, executive function, habit formation, self-efficacy, syllabus, pedagogic challenge, computer assisted instruction, CAI, attribution theory, Stroop interference.

## 1. OVERVIEW[1]

This paper reviews and unifies 15 papers and book chapters written by the author over the past decade. The paper shows that an underlying commonality of all the author's approaches to a wide variety of pedagogical problems relies on three pillars: (a) a cybernetic approach that is independent of discipline and does not rely on specific content areas, (b) direct referral to established processes of the mind, and (c) a metric approach whereby a new pedagogic tool is formulated in terms of measurement enabling newcomers to instantly apply the new method. These three pillars are useful in improving all aspects of course, pedagogy: delivery, retention, performance, and satisfaction. The use of a metric approach is often superior (easier to implement) than traditional approaches; the appeal to direct processes of the mind supplements reliance on experiments and surveys which focus on methods rather than on their underlying psychological basis. The three pillars apply to such diverse areas as pedagogic challenge, syllabus construction, computer assisted instruction (CAI), dealing with hard course components, formulating challenging practice exercises, enriching syllabus modules, and defining levels of problem difficulty. The mental processes on which the theory is based are executive function, atomic habit formation, strop interference, controllability (attribution) theory, and self-efficacy.

The paper first reviews the underlying mental processes (Section 2). It then outlines six areas of applicability: pedagogic challenge (Section 3), differentiated instruction (Section 4), application to computer assisted instruction (CAI) (Section 5), applications to constructing challenging homework exercises (Section 6), applications to syllabus construction (Section 7), and dealing with hard course modules (Section 8).

In the remainder of this first section, we review the principles of cybernetics which enable all results to be formulated independent of content. Cybernetics studies the interrelationship of the parts of a complex system independent of their system's purpose [2, 6]. It is thus ideal for studying the interrelationship of *the course* which consists of the *syllabus, the course modules, the course practice exercises (a.k.a. homework), computer assistance, differentiated instruction, and course support;* that is, cybernetics applies study of this interrelationship without referring to content and thus crystallizes key relationships.

We particularly mention the contributions of Ashby, the great cybernetician who emphasized and cautioned against using catchy phrases like pedagogic challenge, but rather replacing them with specific operational terms [6]. The influence of this perspective is seen in this paper's emphasis on measurability.

## 2. PROCESSES OF THE MIND

As will be seen in future sections, definitions of pedagogy, the utility of various strategies such as graphical and tabular representations, and the account of what works is typically justified by either well-designed studies or by references to authorities who put forth conjectures. Of course, studies are a

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golden standard for proving efficacy. Contrastively, this paper emphasizes underlying, well-known, and established mental processes as a source for ideas. In this section, we review five mental processes that are sufficient to account for the varied advice given throughout this paper: executive function, Stroop interference, habit acquisition, controllability (attribution theory), and self-efficacy.

**2.1 Executive Function.** Executive function is that process of the mind that allows the mind to integrate several other processes. For example, the ability to recognize a sequence of numbers 1,2,3,4,… only requires one mental process, that dealing with numbers; the ability to recognize an interlaced sequence of numbers and letters 1,A, 2,B, 3,C … involves two mental processes. This may seem like an inconsequential distinction, but the difference in time it takes to recognize these two types of sequences is an important neuro-psychological measurement used in evaluation of stroke victims. Other executive function performance tests similarly measure the ability of the mind to simultaneously process inputs from multiple sources. For example, the Wisconsin Card Test flashes sets of cards which differ in card shape, their number, and color, and requests testees to evaluate resemblance to a new card. There is numerous literature available on the importance of executive function in neuro-psychological evaluation [5, 14, 18, 22, 25, 79, 91].

With an eye to the rest of the article, we point out that national standards of education such as the National Council of Teachers of Mathematics (NCTM), or the Common Core State Standards (CCSS), recognize executive function using the term *multiple modalities* indicating several parts of the mind being used in the educational process [17, 50, 72, 73, 74, 75, 76, 77].

**2.2. Stroop Interference.** Interference, first identified in the 30s of the last century has been rediscovered in multiple contexts. It refers to the fact that the tine it takes to recognize the words *red, blue, green, yellow* flashed on a screen when the font color of each flashed word corresponds to its meaning (thus *red* is flashed in red font, *blue* in blue font, etc.) is significantly less than recognizing *red, blue, green, yellow* when they are flashed in colors contradicted by their meaning (thus *red* is flashed in a blue color, *blue* in a green color etc.). Interference has its roots in executive function since recognizing the word *red* when it is colored in *blue* necessitates using two different parts of the brain and an executive function decision to favor the part of the brain recognizing the word form over the part of the brain understanding the word meaning [47,83].

**2.3. Atomic Habit Formation.** A complex task like writing a composition can be *decomposed* into several simpler tasks. Contrastively, a task like type-writing cannot be decomposed. The task consists of associating visual cues such as letters with certain finger motions which produce the typewritten image of these letters. We refer to a task like typing that cannot be decomposed as an *atomic* task.

An atomic task that is repeated becomes a *habit.* The speed of performance of the habit increases while the error rate decreases. Habits become fully or partially automated tasks; the acquisition of the habit allows one to devote attention to other tasks since the habit task no longer requires as much attention.

**2.4. Controllability (Attribution theory**). Attribution theory, the theory explaining how people performing tasks explain their successes and failures, has been rediscovered in numerous and varied contexts [32]. The theory reviews how people's beliefs that their successes or failures are due to innate ability (e.g., intelligence), luck, favoritism, effort, or task difficulty influences their ability to succeed. The theory shows that people are more likely to succeed if they attribute success to things they control and are not stable without continued intervention. In particular, if a person perceives his successes as due to how much effort they put in, they are more likely to succeed than people who attribute successes to other causes. Note that effort is controllable by the individual and requires continuous work (it is not stable and its benefits will decrease if expenditure of effort is not continued).

**2.5 Self-Efficacy**. Self-efficacy is late in the psychological arena, having been introduced by Bandura in the later part of the $20^{th}$ century [10, 11, 12]. Since its appearance numerous studies have shown that it is the single most reliable predictor of learning success. Moreover, the drivers of self-efficacy are well understood: The most important driver of self-efficacy is past performance successes (a.k.a. practice); the second most important driver of self-efficacy is the presence of role models (a.k.a. as tutors or mentors), particularly if these tutors have gone through a three-phase process of failure-struggle-recovery which the learner can benefit from; the third most important driver of self-efficacy is self-talk, the positive or negative way people gripe when they encounter failure, with positive responses (e.g. "I didn't practice enough…Let me review and try again") yielding superior outcomes to negative outcomes (e.g. "Darn it; I don't believe I did that.").

**2.6 Goal Setting**. Goal setting refers to the process of breaking up a complex task into subtasks. Optimal goal setting teaches that when the goals are unambiguously identifiable, that is, the subtasks are uniform and clear enough for a new person to immediately start performing, the subtasks are atomic, and can be mastered in a reasonably short amount of time, then the overall task gets completed quicker with less mistakes in the process. The process is further improved by immediate mentorship after each subtask, and with the provision of challenging tasks (beyond the current capability of the people) once mastery of subtasks is achieved [15, 62, 63, 64].

An illustrative example, mastering dart throwing, can clarify. Here the goal, hitting as many bulls-eyes as possible is clearly identifiable. The subtasks for dart throwing are hand grip, sighting stance, positioning, throwing, and after-throw recovery; each of these is relatively atomic and can be clearly described in such a way that any person desiring mastery can begin practice. People attempting to learn dart throwing do it quickest when these sub-tasks are used, particularly if feedback is given immediately after each throw and if challenging dart throwing is presented after mastery of the five sub-tasks [51, 52, 53, 54, 94].

Although goal-setting is not a mental process per se its principles are easily derived from the other mental processes enumerated previously in this chapter. For example, attribution theory states that people do best on processes they control while habit theory says that atomic habits with practice yield increased performance speed and decreased error rates over time. Attribution theory also says that people do poorer on processes with outside influences over which they have no control. These considerations immediately imply that overall task goals should be immediately recognizable, and that subtasks are best when they are atomic, uniform, and unambiguous allowing new learners to instantly start practicing until mastery is achieved. The principles and drivers of self-efficacy show that mentorship is important (after each practice) for achieving success.

## 3. THE FOUR PEDAGOGIC PILLARS

As indicated in the introductory section, the rest of the paper is devoted to applications of the basic mental processes to a wide variety of pedagogical issues, and moreover, identifies a metric for each such issue that allows anyone to quickly begin mastery of the underlying issue using the suggested technique. Each section, to the extent relevant, will explore current approaches to the issue studied and how the suggested metric approach improves the process.

The concept of defining pedagogic challenge was initiated by Abraham Bloom in the late 50s of the 21st century. Bloom achieved this through a pedagogic hierarchy starting at *remembering* and culminating with more challenging pedagogic activities such as *creativity, evaluation,* and *analysis.* Since Bloom, several other researchers have defined similar hierarchies. The most notable are those of Van-Hiele, Gagne, Anderson, and Marzano though many more exist [4, 13, 23, 61, 65, 67, 68, 69, 70, 93]. Additionally, experiments were introduced to validate that these hierarchies achieve better instruction, learning, retention, and learner satisfaction.

We clarify the meaning of hierarchy by considering Marzano's hierarchy which consists of four levels ordered based on the level of processing required: *retrieval, comprehension, analysis,* and *knowledge utilization.* Notice that these words while having well defined nuances are ambiguous. Hierarchies further defines the hierarchy levels by using sub-hierarchies. For example, Marzano's *analysis* level is further clarified by five items: *matching, classifying, analyzing errors, generalizing,* and *specifying*.

Thus, to use Marzano's' hierarchy (or any other hierarchy), one must be trained in recognizing the levels and sublevels. Contrastively, to identify pedagogic challenge, the author introduced the following simple metric based on executive function also known as multiple modalities: *how many mind processes are involved in learning; the more mind processes the more challenging the pedagogy* [27, 28, 29, 30, 32]. As indicated in the introduction, the use of multiple modalities in teaching is already advocated by the national standards such as those of NCTM and CCSS. The contribution of this author is that it *suffices* to simply count modalities. This act of counting can be done immediately by any new instructor with results.

Furthermore, this author defined four pedagogic pillars of which executive function is the first. The other pillars are goal-setting, attribution theory, and self-efficacy [27, 28, 29, 30, 31, 32, 40]. In the next five sections, the paper explores how these pedagogic pillars which are defined by clear metrics and easily implementable are sufficient to solve a wide variety of educational issues.

## 4. IMMEDIATE PEDAGOGICAL CONSEQUENCES

This section explores three immediate consequences of the four educational pillars for good instruction: The *rule of four,* the skillful use of *graphic organizers,* and applications to *differentiated instruction.*

4.1. **The Rule of Four**: Deborah Hughes-Hallet introduced the *rule of four* in the last decade of the 20th century. She participated in multi-school consortiums applying this rule to both pre-calculus and calculus teaching and was instrumental in changing the standards of textbooks.

Briefly, the rule of four asserts that every illustrative problem and every homework exercise should reflect four mind modalities: the verbal, the graphic, the formal, and the computational. The theory of extrema amply illustrates this. First, students must be able to recognize that a verbal problem can be modeled as a problem in finding the extrema of a function. They should be able to identify these extrema on graphs of the function as well as in tabulated computational values of the function. Finally, they should be aware of the formal process of finding extrema using first and second derivatives [16, 42, 43, 44, 45].

Textbooks and classroom instruction using the rule of four are superior in terms of instruction, learning, retention, and student satisfaction.

But the rule of four is nothing more than an application of executive function, the first of the four pedagogic pillars introduced by the author [27, 28, 29, 30, 32].

**4.2 Graphical Organizers:** There is a rich literature showing the educational benefits, including its benefits to diverse populations such as the mentally challenged, of teaching using graphical organizers [1, 8, 9, 21, 60]. Tables are a good example of a graphic organizer. The advantage of the table over narrative is that the table graphically emphasizes two dimensions of the subject as represented by the rows and columns of the table. Here again, we see application of executive function: First, the table itself is visual and accompanies the verbal narrative; more importantly, the table itself facilitates seeing a subject governed by *two* dimensions, this *two*ness also reflecting executive functions [35, 36, 80].

**4.3 Differentiated Education.** The core idea of differentiated instruction is for the instructor to tailor classroom pedagogy to each individual's student's learning style. In theory this certainly sounds appealing and in fact there is a rich literature on differentiated instruction [56, 59, 81, 82, 87, 88, 89, 90]. However, the following description of differentiated instruction requirements highlights the challenges with implementing it [46]:

> The teacher: a) *continuously* monitors student learning, b) *collaborates* with learners, c) implements *relevant* learning experiences, d) accesses *family and community resources*, e) *varies* his/her role, f) provides *multiple models and representations*, g) guides students' engagement and learning by using a *range of learning skills and technology,* h) uses a *variety of instructional strategies*

Each of the italicized words in this citation are open-ended requirements that operationally are not possible for each instructor to implement in each classroom. As a simple example, instructors have fixed amounts of time which are already devoted to creating the curriculum; they don't have time to *continuously* monitor student's learning (versus checking it periodically), nor do they have time to consult with each student's *family and community resources.* Additionally, the requirements of a *range* of learning skills and a *variety* of instructional strategies are open-ended without specificity.

The author alternatively proposed that differentiated instruction can be accomplished using the four pedagogic pillars [39]. Already, the requirement of executive function, equivalently multiple mind modalities, meets the requirement of a *range of teaching strategies.* More importantly, the requirements of the four pillars of optimal goal settings and that students perceive success as due to their effort and not to outside influences, in effect, means that each student learns the *same* material albeit at their pace.

This is particularly apparent when computer assisted instruction (CAI) is used and is in fact common today in textbooks accompanied by CAI targeted to basic algebra. Basic algebra is understood well. The textbooks and software have modules corresponding to each skill competency. Thus, students with different backgrounds approach the same syllabus each at their own pace practicing till a minimal mastery level is achieved as defined by the course instructor. Moreover, to the extent that the software uses multiple modalities of instruction, for example algebraic exercises, numerical computations, graphical representations, tips to get started, etc., the software itself provides differentiated instruction.

## 5. COMPUTER ASSISTED INSTRUCTION (CAI)

There is a rich literature on CAI in education with however differing results on its efficacy [3, 19, 45]. The author has conjectured that the differing results on efficacy arise because the focus is on computer use including familiarity and comfort with computers without always adding to the evaluation the method of instruction; computers do not teach; pedagogical delivery methods do teach [34, 38].

Thus, if an instructional delivery method uses the four pillars, CAI will improve instruction if it is consistent with the instructional delivery. This means that (i) consistent with the drivers of self-efficacy, a large data bank of questions exists allowing sufficient performance for mastery, (ii) also consistent with the drivers of self-efficacy, mentorship, either human or embedded in the program, is beneficial, (iii) consistent with the requirements of goal-setting, problems of differing levels of difficulty, say, easy, moderate, and hard must be present to allow initial mastery of skills and afford challenge upon achieving that mastery, (iv) consistent with the requirements of attribution theory the computer assessment of mastery should be transparent to the student and be dependent on the level of effort, practice, and performance put in by the student. Moreover, in addition to the CAI, instructors should provide written homework exercises which are evaluated by hand to ensure that the requirements of executive function are met with students approaching the exercises with multiple modalities.

Once the above is done, the assessment of the CAI of the student is accomplished by a suite of metrics implementing the various required mental processes.

## 6. HOMEWORK EXERCISES

An important principle of any theory of pedagogy is that its principles be applied to both instruction and homework exercises. The effect of instruction which uses multiple modalities can be defeated by poorly designed homework exercises.

**6.1. Periodicity.** The following interesting experiment illustrates what can happen in practice. The author reviewed a variety of pre-calculus books on the topic of trigonometric representation of periodic phenomena [7, 24, 49, 57, 84, 85]. Periodic phenomena occur frequently in the real world and include such diverse items as the periods of the seasons, human heart rate, human temperature, spending patterns of consumers, etc. The functions modeling these phenomena use four parameters: the period length (how often the phenomenon cycle repeats), the amplitude (how wide a difference is there between the high and low of each cycle, phase shift (to what extent does a cycle begin at some baseline point, beneath it or above it), and displacement (how much does the displacement of the baseline differ from 0).

The author assessed the textbooks by the percentage of homework exercises with 1, 2, 3, or 4 parameters as well as the count of real world (vs. computational) problems. The results of the analysis showed that: (i) many textbooks sufficed with 1-parameter exercises thereby violating the pedagogic principle of executive function, (ii) only one textbook had a variety of 4-parameter problems including a variety of real-world problems thereby fulfilling the requirement of executive function, (iii) some textbooks gave many 2-parameter problems with few real-world problems and with few 3 or 4-parameter problems [30].

This study shows the importance of simultaneously using executive function both in instruction and in exercises.

**6.2. Quadratic Functions**. In another study the author reviewed a collection of pre-calculus books for their treatment of the quadratic functions [7, 20, 24, 49, 57, 71, 84, 85, 92]. The review focused on real world problems as well as graphing techniques and uncovered some simple metrics to improve homework exercise quality [33, 78].

The collection of textbooks identified seven types of quadratic real-world problems: projectile, suspension bridge, profit, parabolic reflector, work, geometry, and number theory problems. As in the other study on periodicity, only 1-2 of the books presented most of these seven types, the remainder of the books sufficing themselves with 2-3 types.

The situation was similar with graphic techniques and representations of quadratic functions. Several representations of quadratic functions exist each reflecting different possible interests: the root form, the vertex intercept form, and the standard form. Only a few of the books presented all three types. Some presented all three but did so to some of them in passing in the homework exercises.

**6.3. Metrics and Summary**: The requirements of executive function and multiple modalities naturally gives rise to the metric of the number of parameters in exercises as well as the number of forms tested in exercises. This simple metric allows an instructor to select a good book, or to supplement the current textbook with a wider selection of problems.

**6.4 Further Research.** The author has attempted to formulate problem difficulty using the pedagogic pillars [37]. This research is still embryonic but shows promise. The simplest type of problem is a plug-in problem where the solution is obtained by plugging in numerical or function values into an equation. The simplest type of challenging problem is one using minimal executive function where the solution requires two or more applications of the same formula. Here, the executive function arises from the number of applications (two or more) rather than the number of multiple mind modalities. The next level of challenge is when a problem uses at least two mind modalities. In these cases, the solution is algorithmic but requires integration of disparate modules and mind modalities. The highest level of challenge is where the solution cannot be arrived at by formulas but requires identifying patterns which are then applied to the particular problem. The author has found this classification useful in his own instruction and continues to explore and refine it.

## 7. SYLLABUS CONSTRUCTION

The machinery we have put forward, the four pedagogic pillars based on processes of the mind accompanied by metrics enables us to give useful principles of syllabus construction without reference to content. To achieve this, we adopt the perspective that the purpose of the syllabus is to enable the student to solve real world problems. That is, we regard the syllabus as a vehicle that serves course illustrative problems and exercises.

This perspective that the syllabus should be written to enable problem solving can be further clarified with an English composition course. The syllabus' goal is to enable students to write essays on a wide variety of topics. Therefore, the course illustrative problems and course homework exercises are the writing of essays. The syllabus accomplishes its goals if it gives the student the tools needed for writing essays; these tools include methods of paragraph development, classification of sentences useful for paragraph writing etc. Not all English textbooks view composition writing as a collection of skill competencies similar say to the skill competencies in a mathematics course. A good textbook illustrating this approach is [48]. Moreover, instruction in English just like in mathematics benefits from multiple modalities. For example, [66] provides instruction to composition using a graphical tree method in which the student writes a theme for an essay, connects this theme to half a dozen sub-themes, and then connects each subtheme to development of the subtheme. The student then uses the graphical interface consisting of a tree structure of themes and subthemes to perform the actual syllabus construction.

But if the syllabus is to serve problems, the construction of the syllabus is derived from problem solutions. Each problem solution reflects some sequential step by step process with some problems having longer sequences than others. In fact, as the course develops, certain solution sequences presented earlier in the course naturally embed themselves in longer sequences for the latter parts of the course. This reflects the principles of the pedagogic pillar of goal setting which requires breaking up a complex topic into a series of subtopics, each of which may have its own goal setting sequence.

It follows that the larger sequences of solution steps provide an outline of a suggested syllabus. Assign each step in a long solution to a course day or week and aggregate these course days or weeks into course modules representing intermediate steps in the course. In this way, a syllabus can be constructed, and independent of content, which presents exactly the sequences whose mastery is needed by the student to solve course exercises where, as mentioned above, the word *solve* is used in a broader sense so as to include essay writing [40]. The use of sequences with multi-step solutions is analogous to the use of critical paths in the PERT techniques of operation research [86].

## 8. TEACHING CHALLENGING COURSE MODULES

The four pedagogic pillars can be used to create metrics identifying difficult course modules. Quite simply, one can count the number of potential Stroop interferences in the solutions to the problems characteristic of a course module.

For example, the binomial probability module in a standard probability course might present a problem of the form, "Calculate the probability, $P$, of obtaining 3 correct answers in a 5-item multiple choice test where each item has a 20 percent chance of being correct." The solution to this problem depends on the parameters $n$=5, $r$=3, $p$=0.20, and $P$, with $P$ indicating the desired probability. Notice how the counts $r$=3 and $n$=5 Stroop interfere with each other one being a count of items per individual question and the other being the count of correct answers on the entire test. Similarly, $p$ and $P$ interfere with each other one being the probability of correctness on an individual question and the other being the probability of a score on the entire test. Therefore, the interference count for this problem type is two. The modules whose problem solutions have higher interference tend to be harder, especially for weaker students.

Identifying these harder modules is important so as to prevent weaker students from giving up on the course when they encounter a hard module. Moreover, the Stroop interference theory provides a solution: Testees *can* recognize words flashed on a screen whose meaning and form interfere; it just takes longer. Thus, when an instructor has prior awareness that certain modules are harder, the instructor can prepare by allotting more time to the harder modules. This straightforward strategy has enabled the author to successfully turn around many failures in classes [41].

## 9. CONCLUSION

This paper has shown unifying themes of (a) cybernetic discipline-independence, (b) underlying psycho-neural processes, and (c) clear identifying metrics for a wide variety of pedagogical issues including pedagogic challenge, course instruction, skillful use of CAI, creation of meaningful homework exercises, syllabus construction, and dealing with difficult course topics. The metrics provided are in many cases easy to apply immediately with consequent improvement in course delivery, learning, retention, and student satisfaction. We encourage instructors, whatever their discipline, to employ these metrics in the courses they teach.

We emphasize that underlying these pedagogical tips is the belief that anything can be taught to anyone given the proper exposure to multiple mind processes, skillful goal setting, and clear metrics. To illustrate this point, that learning is universally accessible, we briefly review the history of chess [26, 58, 95]. Chess went through a romantic era in which masters who won games were considered geniuses, people with an innate talent who could arrive at the proper move in a position. This romantic era ended when metrics identified key position attributes which lend themselves to winning. Chess pedagogy then changed. Chess could be taught. Today it is routine to instruct students who are willing to devote the time on the basic skill competencies needed to arrive at winning games.

A similar atmosphere pervades education today. Anyone can be taught anything albeit after the instructor has identified the sequence of courses and skills to master and the students are willing to put in the time to practice until mastery. We do hope that this inspires readers of this essay to apply this very beautiful theory in their own domains.

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