Towards a New Cybernetic Interdisciplinary Approach to Pedagogic Challenge

Russell Jay Hendel
Department of Mathematics
8000 York Road
Towson Maryland, 21252
RHendel@Towson.Edu

ABSTRACT

After reviewing the past half century of definitions of higher cognitive pedagogy, this paper presents a new approach rooted in brain function. We define higher cognitive pedagogy as indicating the presence of executive function. Executive function in turn is defined by the presence of multiple disciplinary areas and multi-parameter subject matter. We show this approach unifies the approaches of the great pedagogists such as Bloom, Anderson, Van-Hiele, Gagne, Webb, Piaget, Marzano, Bruner, Yazdani, Pegg and Hess etc. We illustrate the applicability of this executive function approach to several disciplines including mathematics, writing, law, music, and literary analysis. The proposed executive function definition is simpler to use than previous definitions and approaches and is equally discriminatory.

Keywords: educational hierarchy, pedagogic hierarchy, Bloom, Anderson, executive function, higher cognitive, Van-Hiele, Piaget, Marzano, cybernetic, Ashby

1. OVERVIEW AND OUTLINE

During the late 50s of the 20th century, Abraham Bloom, introduced the idea of educational hierarchy [5]. Bloom and later his student Anderson [2], introduced six levels of cognitive challenge, the lowest being raw *knowledge* and the highest being *analysis, synthesis* and *evaluation*. Bloom's actual six categories are *knowledge, comprehension, application, analysis, synthesis* and *evaluation*. Anderson modified this to *remember, understand, apply, analyze, evaluate*, and *create*.

Bloom's basic thesis was that the ideal instructor starts a course with the lower order thinking skills such as *knowledge, comprehension* and *application*, and progresses to the higher order thinking skills such as *analysis, synthesis* and *evaluation*. There is debate whether *all* six categories are sequential vs. the lower 3 together and then the top three. For purposes of this paper, this need not concern us.

A variety of criticisms were made on the Bloom taxonomy and several researchers modified Bloom's basic hierarchy[e.g. 20]. Over time several hierarchies were proposed. However, it was then shown that student improvement was the same under diverse approaches[e.g., 32].

A further requirement in implementing any theory, is training instructors on *how* to apply the hierarchy. This was typically done through synonym bundles applied to the domain. For example, Marzano suggested a hierarchy of 4 levels*: Retrieval, comprehension, analysis* and *knowledge utilization.* Suppose an instructor wanted to examine whether part of his/her course satisfied *analysis*. The instructor is trained to test this part of the course using a synonym bundle. The synonym bundle for *analysis is match, classify, error, analysis, generalize,* and *specify*. So if a particular part of a course illustrates a *matching* skill or a *classification* skill, the instructor had ascertained that the skill is classified under the Marzano *analysis* category.

It follows that the application of these theories is not necessarily straightforward. Instructors must learn the hierarchy, learn the synonym bundles and then apply them to each course section Furthermore, two instructors might disagree on classification. As a simple example of the possible ambiguity in classification, Bloom listed *evaluation* after *synthesis* while Anderson listed *evaluation* before *creation*.

The goal of this paper is to present a simplified approach to the hierarchies and higher cognitive challenge. The approach is rooted in brain function itself. Performance-executive function refers to the capacity of a brain to deal simultaneously with several areas. We propose identifying cognitive challenge with the presence of executive function: *A course topic is taught in a pedagogically challenging manner if it involves multiple areas of the brain and each area is characterized by multiple parameters.*

Such a definition is easy to apply. We illustrate this definition in diverse fields: mathematics, music, writing, law and literature.

An outline of the rest of this paper is the following: In Section 2 we review the existing hierarchies. We also introduce the idea of two stages in the hierarchy research. In the first stage different researchers presented their formulation of educational pedagogy, while in the second stage researchers showed these diverse hierarchies similar. In Section 3 we review several examples of performance executive function. Then in Section 4 we present our definition. We also show that the definition is cybernetic, content independent. In fact, the proposed definition follows the operational philosophy of the great cybernetician, Ashby. Finally, in Section 5 we illustrate the methodology in five disciplines where new methods of pedagogy are consistent with the proposed executive function approach.

2. THE PEDAGOGICAL HIERARCHIES

In this section we review several proposed educational hierarchies. We suffice with listing the categories involved and lightly discuss other aspects of the hierarchies. The references give further elaboration on each of the categories, as well as describe the synonym bundles by which instructors can apply the hierarchies. The references also describe the various criticisms that different researchers raised on previous models.

2.1. The First Generation of Hierarchies

The following list of pedagogical hierarchies is illustrative and not meant to be exhaustive.

- Bloom [5]: *Knowledge, comprehension, application, analysis, synthesis, evaluation*
- Anderson [2]: *Remember, understand, apply, analyze, evaluate, create*
- Van-Hiele [30]: *Recognize, analyze, order, deduction, rigor*
- Gagne: *Attention, objectives, short-term memory, information, presentation, performance, guidance, feedback, assessment , transfer*
- Marzano [20]: *Retrieval, comprehend, analysis, knowledge utilization,*

It is important to emphasize that the hierarchies do not exhaust themselves in a classification scheme. For example, Van-Hiele introduced the hierarchy attributes of *fixed sequence, adjacency, distinction, separation,* and *attainment.* These attributes describe important facts about the hierarchy: i) all students *must* go through each of the five stages, ii) the stages must be gone through sequentially, iii) the students at each stage have their own language and understandings which prevent them from receiving communication from other students or instructors at other stages.

2.2. The Second Generation of the Pedagogical Hierarchies

This paper introduces the concepts of the *first and second generation of hierarchies*. Analogous background from other fields may illuminate the terminology. We present two examples.

- Database: There were several attempts during the first half of the 20th century to define *database*. Different industries in different countries arrived at formulations and computer implementations that appeared totally distinct. But then mathematicians proved that all proposed definitions were equivalent in the sense that problems solvable in any particular formulation were also solvable in any other formulation. Thus we may speak about a *first stage* of databases when different definitions were proposed and a *second stage* when the definitions were found to be equivalent [11].
- Computable function: The definition of computable function went through two stages: An initial stage when different mathematicians in different countries proposed different definitions and a second stage when it was found that the definitions were equivalent in the sense that any function computable under one definition was also computable under any other definition [25].

We apply this concept of first and second generation to the hierarchies. As we saw in Section 2.1, different researchers developed distinct pedagogical hierarchies. The categories in each hierarchy look different. Yet their effect on students is equivalent. Here are three examples.

1. Yazdani [32] showed that the Gagne and Van-Hiele hierarchies which are quite different in categories have equivalent effect on students. That is, students equally improve in geometry whether exposed to the Gagne or Van-Hiele hierarchy.
2. Pegg [22] showed that Briggs [4], Bruner[7], Van-Hiele [30] and Piaget [23] illustrate a commonality: student progression from the *sensory to abstract*.
3. An interesting second generation study was performed by Hess [15] who collected several 1000 homework assignments from K-12 and analyzed them in a matrix whose rows were the Bloom-Anderson hierarchy and whose columns were the Webb [31] depth-of-knowledge categories. While Hess' goal was not to show the equivalence of Bloom-Anderson and Webb, the study did show that K-12 homework was mostly deficient (lower order thinking skills) according to both theories.

The proposed definition of hierarchy in this paper unifies the various hierarchies by showing that a driving force of higher order cognitive skill is performance-executive function and multi-parameter models. To fully understand this we first explore the meaning of performance executive function in the next section..

3. EXECUTIVE FUNCTION

The thesis of this paper is that higher cognitive function refers to the integration of several distinct disciplines.. The capacity to integrate diverse areas of brain function is itself a brain function called executive function. There are several types of executive function, the two main categories being performance and rating executive function [24, 27]. In this section, we examine three well-known performance tests.

3.1. The Wisconsin Card Sorting Test (WCST) [14]

During the administration of the WCST, the examiner flashes several dozen two-row items such as those illustrated in Figure 1. The examinee is asked to *match* the card in the bottom row with the appropriate card in the top row. Typically, after a few attempts the examinee will discover the correct driver of resemblance. The examinee will then have a streak of correct answers. The examiner may then change the driving dimension. For example, if in the last 10 trials the correct answer was based on a match of *number*, the examinee may create new trials where the correct match is based on the dimension of *formatting*.

A wealth of information is gathered during the test. For our purposes, we see that the examinee is being tested on *his/her capacity to correctly identify the driving dimension from a set of competing multiple brain areas (formatting, number, and capitalization). Furthermore, the examinee must continuously reassess the correct driver of correctness.*

We conclude that the WCST is measuring the capacity of the examinee to *continuously process multiple-dimensional drivers of outcome in different brain areas.*

Abstractly, Figure 1 presents three dimensions: a) number (1,2 or 3 letters), b) formatting (italic or non-italic), and c) capitalization (caps on or off). The examinee must determine if the text in the bottom row of Figure 1: i) resembles the *a* card because of the dimension of formatting, ii) resembles the *bb* card because of the dimension of number, or (iii) resembles the *c* card because of the dimension of capitalization.

a	bb	CCC
	DD	

Figure 1. A sample card sorting test. The first row contains three cards. For further details see the text. Note: the actual WCST uses different dimensions; all examples in this paper are adapted for typographical reasons.

3.2. The Trailmaking test [6, 10, 12]
This deceptive but beautiful test has two parts: A and B. In both parts, the examinee is asked to make a trail: In part A, the trail is 1-2-3-…, while in part B, the trail is 1-A-2-B-3-C…. An illustrative example is presented in Figure 2. Although these tasks are easy, remarkably, the part B test always takes longer. The increased length is due to the presence of two dimensions or two brain areas: number and letter. The multi-dimensionality requires executive function and hence the increased time length. Despite the test's simplicity, it is useful in diagnosing brain damage and recovery possibility, for example, after a stroke.

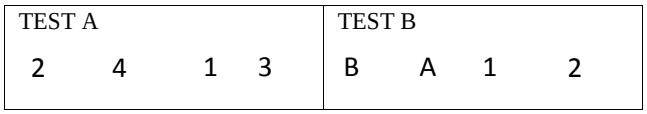

Figure 2: A sample trailmaking test. The correct trail in test A, is 1-2-3-4; in test B, it is 1-A-2-B.

The simplicity of this test highlights an important subtlety of our proposed definition of good pedagogy as multi-dimensional processing. The trailmaking test makes the point that *any* multi-dimensional processing transforms a mundane exercise into executive-function quality. Indeed, just adding the dimension of letter to the dimension of number in the simple task of making a trail raises the quality of the task to executive-function quality.

3.3. Stroop Inteference Test [26]
In the Stroop interference test the examinee is asked to identify the color of each word in a sequence. For typographical reasons we reformulate this test in terms of size. Consider the following two sequences of words.

Test 1: SMALL, big, huge, TINY, LITTLE
Test 2: APPLE, orange, pear, PEACH, PLUM

Figure 3. Sample Stroop test modified for purposes of this paper. The examinee must identify the size of each word.

Stroop observed that examinees took longer to perform Test #1 then Test #2. He hypothesized that the reason for it taking longer was *interference.* The words SMALL and APPLE clearly have a big size. However, the *meaning* of the word SMALL *interferes* or more precisely contradicts the size of the *form* of the word SMALL. This interference, explains Stroop, causes a bit of hesitation which leads to a longer performance time.

3.4 Summary and Commonality.
Each of the above tests is routinely used in neurological examinations. These tests despite their game-like nature and simplicity are powerful diagnostic tools for stroke victims and victims of car accidents. They are part of a larger battery of performance tests.

We suggest the following abstract commonality to the three tests we presented. In each test, the value of a dependent parameter Y, is inferred from a collection of independent parameters X_i. This abstract viewpoint is summarized in Table 1.

The interpretation of Table 1 should be clear. For example in the WCST, the examinee has to evaluate the bottom row in terms of number (in our example 2), capitalization (in our example upper case) and format (in our example italics). The examinee must then seek a similarity (based on current and past cards) to the top row.

Test	**Independent parameter, y**	**Dependent parameters, x_1,x_2,x_3**	**Summary $y=f(x_1,x_2,x_3)$**
Wisconsin WSCT	Similarity	Number, caps, format	Similarity=f(number, caps, format)
Stroop	Size	Meaning, form	Size=f(meaning, form)
Trail making	Next member	Number, letter, value	Next member = f(number, letter, value)

Figure 4. Summary of the 3 performance executive function tests in terms of an abstract Boolean function relating dependent and independent parameters. For more details see the text.

We close this section with a light discussion of problems, or more precisely, further directions of research. This paper has identified higher cognitive pedagogy with *one* aspect of executive function, performance executive function. There are other aspects of executive function and it is very conceivable that future research will relate these other aspects of executive function to higher cognitive pedagogy. A further criticism is that our proposed generalization may have overstated the case and ignored important features. For example, we explain Stroop interference in terms of *general* Boolean inference. But Stroop explained it in terms of the *specific* Boolean function of interference: `(Form Size) AND (NOT Meaning)`. We would counter-argue that while particular performance tests identify with *specific* Boolean functions the aggregate performance on multiple tests is simply testing for the *general* capacity of the examinee to relate dependent and independent variables with a Boolean function.

4. THE EXECUTIVE FUNCTION HIERARCHY

Our fundamental thesis is that pedagogy is advanced if it teaches skills that can be formulated in terms of multiple parameters and multiple brain areas. The fundamental equations indicating higher cognitive thinking aredfsssssssssssssssssssssssssssssssssss0 of the form

$$
\begin{aligned}
Y &= f(X_1, X_2, \ldots, X_M)\\
X_1 &= f_1(v_{11}, v_{12}, v_{13}, \ldots, v_{1n(1)})\\
X_2 &= f_2(v_{21}, v_{22}, v_{23}, \ldots, v_{2n(2)})\\
&\ldots\\
X_m &= f_n(v_{n1}, v_{n2}, v_{n3}, \ldots, v_{nn(m)}),
\end{aligned}
$$

where X_i and v_{ij} are Boolean parameters and Y is a predicted outcome that is learnt. Heuristically, the X_i correspond to multiple brain areas while the v_{ij} correspond to multiple parameters. A pedagogy is low order if the skill taught involves one area of the brain with no or little variation in independent parameters.

In the next section we illustrate, in the brief space we have, how adding geometric visualization to such areas as math, writing, law, literature and music enhances pedagogy and is consistent with modern approaches to education.

We point out three important attributes of our proposed definition:

- Cybernetic: The definition does not depend on content. What is important for pedagogy is the *relationship* between independent and dependent parameters. Consequently, our definition is cybernetic in flavor [1].
- Operational: Our definition is highly operational. To ascertain whether a pedagogy is higher order one simply counts the areas of the brain involved and the number of independent parameters.
- Ashby: Our definition follows the school of the cybernetician Ashby who sought to replace jargon about the brain, terms like *higher order*, with operational and clear definitions [3].

5 EXAMPLES

In this section we illustrate our proposed definition of higher cognitive pedagogy. We study the introduction of executive function in five disciplines using visual geometric aids.

5.1. Mathematics

We present two examples, one from algebra and one from calculus.

Algebra: The Core standards [8] represent the efforts of many states to make mathematical pedagogy more meaningful. The Core standards strongly advocate use of verbal problems. This is consistent with executive function since a verbal problem involves the verbal and formal areas of the brain. The driver of difficulty in verbal problems is the difficulty in simultaneous handling of verbal and formal. A model verbal problem is presented below. The two columns illustrate the verbal-formal duality.

English	**Formal**
Amy purchases for her friends	
4 bags of peanuts	4P
And	+
one quart of orange juice	1Q
for	=
a price of 6 dollars.	6
Had Amy purchased 1 bag of peanuts	1P
And	+
4 quarts of orange juice	4Q
it would have priced	=
at 9 dollars.	9
How much do a bag of peanuts and quart of orange juice cost.	P,Q

Figure 5. A sample verbal algebra problem. The two columns correspond to the two brain areas of the verbal and formal.

Calculus: Deborah Hughes-Hallet has made significant contributions to the current revamping of calculus pedagogy. She has led educational projects with multiple institutions and authored several books. She has aggressively sought to identify critical components needed for eliminating the high failure rate in Calculus. Her major tool for improving pedagogy is the *rule of four* [9, 16, 17], which states that *each* course concept, *each* course illustration, and *each* course exercise, be approached using four areas: *geometric, verbal, computational,* and *formal.* In terms of our approach, we would identify the success of this approach in its use of multiple brain areas, that is, executive function.

5.2. Writing

A recent approach to improve narrative writing uses tree diagram aids. The student first jots ideas down; then the ideas are connected. The graph (actually a tree) of ideas is used as a basis for writing the essay [21]. Figure 6 illustrates the technique using Genesis Chapter 1 as an example, the description of the creation. The student writes the chapter theme, *creation*, on top. The student then jots the ideas of Day1, Day 2,…,Day7. Each day is connected with what is created. More ideas can be inserted. The tree is used to write the detailed narrative essay.

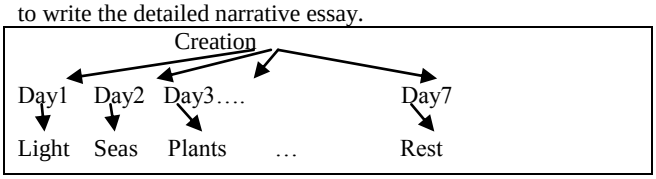

Figure 6. Illustration of the tree technique for facilitation of writing using Genesis Chapter 1 as an example.

Several points should be made about this illustration:

- Executive Function: This pedagogic approach uses the visual and verbal areas of the brain. Since the technique uses two areas it requires executive function.
- Emotional effect: Besides the improved pedagogy, improved feelings are reported experienced by users. In fact, a merging of several studies suggests a distinct transitional path to these positive feelings: i) Teaching the visualization technique, ii) mastery of the technique, iii) feelings of self-efficacy, iv) removal of writing anxiety, v) more practice writing, vi) and improved writing.
- Remediation: This writing technique was initially developed as a remediation technique, not as a technique to challenge students to higher cognitive levels. This point highlights a duality about executive function: It simultaneously remediates and challenges to higher cognitive levels.
- Alternative formulation: Obviously, this graphical technique generalizes the traditional outlining method. Thus it is not totally new. The outline approach to essay writing (outline first, essay second) has several formulations including the Graham-Graham approach using the technology of Microsoft Powerpoint [13].

5.3. Music

Music is strongly executive function in many aspects. The following list of musical topics are illustrative:

- Performance: Performance typically involves both visual, kinetic, and auditory skills.
- Piano Performance: Piano performance involves coordination of distinct playing patterns in the two hands as well as keeping track of rhythm with one's feet.
- Ensemble: Conductors and performers in an ensemble such as a trio, quartet or orchestra must coordinate with multiple players.
- Rhythm: Recent approaches to rhythm coordinate auditory and visual representations [28].
- Harmony/Melody: Recent advances in melodic-harmonic progression interrelate melodic-harmonic distance with visual distance in an appropriate coordinate framework [29].

Comparing music with mathematics and writing we note that:

- The coordination of music and geometry is used for both advanced analysis of music as well as for remediation.
- Executive function in music, as in writing, gives rise to positive feelings of self-efficacy as well as the satisfaction that comes from teamwork.

5.4 Law

Israeli public education is unique in its requirement of exposure of grades K-12 to the advanced study of law. The driver of this requirement comes from exploration of the national heritage which includes the enormous *Talmud*, the written record of the advanced legal examinations of Jewish law. It is traditional for religious schools both in Israel and outside Israel to study *Talmud* at an early age. Israel secular education has made *Talmud* study a requirement in its public education.

Law is an advanced subject. Teaching it to K-12 students poses unique educational challenges. Teaching it frequently has the opposite effect from that intended by the requirement; by exposing young students to advanced legal methods, negative feelings are created.

Kanarek has done extensive research in to making study of *Talmud* both understandable and enjoyable. Kanarek himself calls his method SVT, *self-study*, *visual*, and *technology*. We see here the rule of 2: i) *visual-technology*, the geometric aids, and ii) the *verbal* text of the Talmud [18].

Kanarek advocates use of 4 types visual cognitive maps to help students master legal content. Besides assessing mastery of material he also meticulously administered student questionnaires to assess emotional impact. These studies show that students using his methods experience positive emotions.

One of Kanarek's cognitive maps, the chart, is presented below in an application to the opening paragraph of the Talmudic tractate dealing with responsibilities of finders of lost articles.

Law	**Cases**	**Cases**	**Reason**
Lost articles that may be kept	Scattered fruit	Scattered coins	No sign by which owner can reclaim.
Lost articles that must be returned	Fruit in a vessel	Wallets	There are signs by which an owner can reclaim

Figure 7. Use of a contrastive chart to organize several legal passages in the *Talmudic* tractate dealing with responsibilities of finders of lost articles. This chart is slightly modified – with contrastive rows - from the chart on page 12 of [18].

Students learn to read the Talmudic passage by themselves and organize it using the cognitive maps. Such a representation leads to both mastery of content and feelings of self-efficacy.

Comparing this domain, law, with the previous domains that we have studied in Section 5, we note the following:

- Pedagogy, emotions: There is emphasis both on improved pedagogy as well as increased positive emotional effect on students.
- Executive function: Executive function is present since both visual and verbal areas of the brain are used. Note for example the similarity of Figures 5 and 7.
- Advanced, Remediation. The cognitive map pedagogy both enhances advanced mastery as well as remediates. Indeed, the subject matter content, legal analysis, is an advanced topic. However, since the methods are being applied to helping K-12 students who have difficulties mastering the advanced techniques, the executive function pedagogy is also remedial in nature.

5.5. Biblical Literature

Biblical literature is vast. Its methods are also quite diverse. However, one powerful geometric method, *parallelism*, is very widespread [19]. Two examples of applications of parallelism to biblical exegesis are provided below in Figures 8 and 9.

He washes	In wine	his *suth*
---	In the blood of graphs	his garments

Figure 8. Biblical text of Gen. 49:11. The italicized word, *suth* is a Hebrew word that occurs once in the bible. The parallelism, aligns *wine* with *blood of grapes*, clearly a metaphor for wine. The parallelism suggests that the Hebrew word *suth* means *garment.*

Ex 20:07	Do not	Bear	The name of God thy Lord	For naught
Lev 19:12	Do not	Swear	By my name	falsely

Figure 9. Parallelism of Ex. 20:07 and Lev. 19:12. We suffice with pointing out the implications of the parallelism in the last column: Both swearing falsely – e.g. *I swear this apple is an orange* – as well as swearing for naught – e.g. *I swear this apple is an apple* – are biblically prohibited. The inference is powerfully highlighted by the parallelism which contrasts *falsely* and *for naught.*

Comparing biblical literature with the other disciplines studied in Section 5, we see that:

- Executive function. Executive function is present since the method of study combines the visual method of parallelism with the verbal reading of the text.
- Advanced. The parallelism leads to an advanced reading of the text (this is contrastive to the use of visual aids to assist in remediation seen in several previous examples)
- Emotions. There are strong similarities between parallelism and the use of cognitive maps in writing and the study of law. Although I have found no studies, we expect that parallelism would provide the same feelings of self-efficacy seen in the writing-tree studies and the list-law studies.

6. CONCLUSION

In this paper we have proposed a new definition of higher cognitive pedagogy. The new definition i) is rooted in brain function, ii) is cybernetic, content independent, iii) is operational, iv) unifies advanced pedagogy in several diverse disciplines, v) is simultaneously advanced and remediating, and vi) produces positive emotional feelings.

We have identified several areas of future research such as applications of other definitions of executive function to pedagogy as well as the assertion that a battery of performance executive function tests in the aggregate are measuring the abstract capacity for general Boolean inference.

We believe the ideas in this paper will prove useful to both pedagogists and researchers.

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