Learning Biochemistry at the Mastery Level — Introductory Biochemistry at The University of Michigan

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Introduction

Two introductory Biochemistry courses are offered at The University of Michigan, one by the Department of Biology, College of Literature, Science and the Arts, and another by the Department of Biological Chemistry, School of Medicine. The course in the Department of Biology (Biology 411), with emphasis on metabolic pathways and their control, was first offered by the author in the fall of 1965 as an alternative to the other course which emphasized the structural aspects of biochemistry. As are most undergraduate courses, Biology 411 was originally taught by the lecture method in which information considered important is presented verbally in a 50 minute lecture thrice weekly. In 1971, a group of University of Michigan undergraduate students interested in alternative teaching methods introduced the author to the Keller Plan,[1] a self-paced, personalized system of instruction (PSI). Shortly after attending a meeting on the PSI at the Massachusetts Institute of Technology and learning of their experiences using PSI at that institution, I decided that this was exactly the kind of learning experience that I wished I could have had as an undergraduate and began to transform the Biology Department's Introductory Biochemistry course to the PSI format. What follows is a description of the many benefits, and some of the pitfalls, which we have experienced whlie employing the Keller Plan to teach Introductory Biochemistry at the mastery level.

Self-Pacing

In a traditionally taught course the professor sets the pace of the course by presenting information in scheduled lectures and examinations. Biology 411 starts with a lecture during the evening of the first day of each term which begins with the words "Welcome to Adult Education 411" and "Welcome to Behavior Modification 411" to indicate that success in this course requires that the student possess the maturity of self-pace and, if a procrastinator, to modify that behavior. They are also told that this will be a learning experience designed for students as themselves: very bright, highly motivated, and very interested in learning a good deal about the biochemistry of themselves, and that they will be expected to learn biochemistry at the level of mastery; that they will be engaged in a system designed to ensure that they will proceed through this learning experience at that level. It is also explained that the course adheres to the philosophy that the best time for a student to demonstrate knowledge is immediately upon their learning the required information. To facilitate this, the content of Biology 411 has been partitioned into fifteen discrete units, the contents of which are listed in Table 1. A set of Unit Guides, one for each unit, informs the student of what to study in the textbook and whether to learn sections at the level of recall or recognition. When the student feels that he or she has 'mastered' the content of a particular unit, he or she proceeds to a biochemistry teaching suite which is staffed by undergraduate teaching assistants, called Proctors, for approximately 70 hours per week including evenings and weekends. The student may ask the Proctor in residence either to clarify aspects of biochemistry with which they are having trouble comprehending or to administer a quiz on that particular unit.

The self-pacing aspect of the course requires that each student decide for themself when they are prepared to take a quiz. Because of the difficulty of preparing several equivalent multiple-choice midterm and final examinations, each of which contributes to the determination of the final grade for the course, one midterm and one final examination are administered at times chosen by the professor. In order to qualify to take the midterm

Table 1 Unit Contents for Introductory Biochemistry, Biology 411

Unit Number	*Topic*
1	Molecules and Life; Introduction to Protein Structure and Function; pH and Dissociation
2	A Detailed Analysis of Protein Structure; Allosterism; Discovery of the Basis of a Molecular Disease; Myoglobin and Hemoglobin
3	Enzymes: Properties, Kinetics and Mechanisms
4	Connective Tissue Proteins; Membrane Biochemistry
5	Biochemical Energetics and Glycolysis
6	The Citric Acid Cycle; Oxidative Phosphorylation
7	The Pentose Phosphate Pathway; Gluconeogenesis; Glycogen Metabolism
8	Fatty Acid Metabolism and its Regulation
9	Amino Acid Degradation; The Urea Cycle; Photosynthesis
10	Amino Acid and Nucleotide Biosynthesis
11	DNA; Messenger RNA; Transcription
12	The Genetic Code; Protein Synthesis
13	Control of Gene Expression; Eukaryotic Chromosomes
14	Free Radical and Antioxidant Biochemistry
15	Hormone Action; Integration of Metabolism

examination, the student must have completed (ie passed a quiz on) eight units prior to the evening of the midterm examination. In this one respect, (ie the dates of the two major examinations), Biology 411 is not self-paced.

Consistent with our educational philosophy that the goal of quizzes and examinations is to determine how much biochemistry the student has learned and to what depth, no time limitations are imposed on the students of this course with respect to completing the quizzes and examinations. By so doing, speed of recall and distraction of time limitations, which make testing difficult for many foreign students whose native language is not English, are eliminated as a component of the testing procedure. Instead, knowledge of biochemistry alone is the criterion of success.

Ensuring Mastery

In order to proceed to the next unit of the course, the student must have passed a quiz on the previous unit. Four written quizzes, containing fifteen to twenty questions requiring answers consisting of short discussions or calculations, have been prepared by the professor for each unit of the course. Upon requesting a quiz on a particular unit, one of the four quizzes prepared for that unit is chosen at random by the proctor, the student proceeds to the Quiz Room and completes the quiz at his or her own pace, ie no time limits are imposed. Upon completion of the written portion of the quiz, a proctor examines the answers with aid from an answer book provided by the professor. During this time, the student is occupied with writing some of the essential aspects of that particular unit as described in Table 2, which is included in the course Syllabus provided to each student at the beginning of the term. Thus, students are informed that they will have to demonstrate detailed knowledge of the contents of Table 2 before being given oral quizzes by the proctors.

Table 2 Essential Knowledge of Unit Information

Unit 1 Write the Henderson–Hasselbalch equation; know the structures of all 20 amino acids found in proteins; draw the peptide bond; define primary, secondary, tertiary and quaternary structure with respect to protein structure.

Unit 2 Understand the Bohr effect; know the differences between myoglobin and hemoglobin; understand cooperativity; know the basis of HbS and the effects of this mutation on the function of this protein.

Unit 3 Understand Michaelis–Menten concepts; know the difference between competitive and non-competitive inhibition; know how enzymes are regulated; know the events in zymogen activation.

Unit 4 Know the structure of collagen and the steps in its biosynthesis; know the components of biological membranes; know the Fluid Mosaic Model.

Unit 5 Be able to write glycolysis; know the enzymes involved, which ones are regulated and by what; know the names and structures of the intermediates.

Unit 6 Be able to write the TCA cycle, the reactions of the pyruvate dehydrogenase complex, and the electron transport chain; know the names of the enzymes and how they are regulated, by what and what that accomplishes. Know how oxidative phosphorylation proceeds and be able to describe respiratory control.

Unit 7 Know the pentose phosphate pathway in general and the function of transketolase and transaldolase in particular; know the gluconeogenic pathway, where it starts and finishes, and the enzymes and intermediates involved; know the pathways of glycogen synthesis and degradation, the cascades involved.

Unit 8 Know the pathways of fatty acid synthesis and degradation (the intermediates, enzymes and their regulation); know how much energy is conserved and how in β-oxidation; know the regulation and the energetic basis of fatty acid synthesis; know the committed step in fatty acid synthesis.

Unit 9 Know the several pathways for amino acid oxidation and which amino acids follow which pathway; draw the urea cycle (know what happens in the cytosol as well as the mitochondrion); be able to draw the reactions of both photosystems, its products, and the Hill reaction.

Unit 10 Know the nitrogenase reactions; know the glutamine synthetase reaction and its regulation; know which TCA cycle intermediates give rise to which amino acids; know the mechanism of transfer of one-carbon units; know the various means of regulating enzyme levels; know the sources of atoms in purines and pyrimidines.

Unit 11 Understand the structure of DNA; be able to write the reactions of DNA synthesis and the enzymes involved; know the difference between the structures of DNA and RNA.

Unit 12 Be able to write the reactions of protein synthesis; know the functions of the RNAs.

Unit 13 Be able to draw an operon; understand the role of repressor and cAMP too; understand the operation of the *lac* and *trp* operon and λ; know about nucleosomes.

Unit 14 Be able to list the sources, and be able to write the reactions leading to the formation, of free radical species; know the antioxidant protective factors and enzymes and how they work; know the structure of coenzyme Q and how it functions as an antioxidant; be informed about quinone toxicity and the function of DT diaphorase.

Unit 15 Know the various roles of cAMP; understand the second messenger concept; know the major metabolic pathways and their control sites; know the key junctions of metabolism.

In the event of unclear or incomplete answers on the written quiz, the student is given the opportunity to provide verbal answers. If the proctor concludes that the student has demonstrated mastery of the material in the written quiz, he or she proceeds to administer an oral quiz consisting of questions, which the proctor has prepared in advance concerning material not covered in the written portion of the quiz but that he or she considers to be essential aspects of that unit. If the proctor concludes, based on performance on both the written and oral portions of the quiz that the student has achieved the mastery level, the student is passed enabling the student to proceed to the next unit of the course. Mastery is defined as knowing all of the essential aspects and substantial associated details of the unit, which are identified by the professor. If, in the opinion of the proctor, the student has not gained mastery, the deficient areas are identified and additional study is suggested. As the final grade for the course is based upon a combination of the performance on the midterm and final examinations and the number of units completed during the term, the student is not penalized for not passing a unit quiz. The student may, hypothetically, take up to four quizzes for any particular unit but, in practice, it is rare that more than two are required. We have found that once the student has acquired a grasp of our concept of mastery, a single quiz is sufficient. We have also observed that the psychological challenge of having to demonstrate mastery to the proctor, who is also an undergraduate student, usually results in a high level of achievement on the part of the student.

The Role of the Proctor

The high level of individual responsibility required, a sense of accomplishment, and a desire to learn more biochemistry, inspire some students of Biology 411 to serve as proctors during a subsequent term. To do so, they must have completed most or all of the units of Biology 411 and, following an interview with the professor, enroll in another course, Biology 412, which is called Teaching Biochemistry by the Keller Plan. In addition to spending six hours each week in the Introductory Biochemistry Teaching Suite, available to help or quiz Biology 411 students, each proctor must identify three specific biochemical discoveries, all of which they found interesting as students of Introductory Biochemistry. The professor selects one of the discoveries and the proctor consults the original paper in the biochemical literature, prepares a short paper and a lecture on the discovery. The lecture consists of several aspects of the discovery, such as who made the discovery, why it was of interest to the investigators, and what techniques were employed. These lectures are delivered during weekly two-hour Biology 412 meetings which all proctors must attend, and to which the Introductory Biochemistry students are invited. Each proctor also generates a series of questions to be used in the oral quizzing and must produce a minimum of two multiple-choice questions for each unit. These multiple-choice questions form a pool from which the professor constructs the midterm and final examinations. Thus, in addition to gaining a deeper understanding of biochemistry (to which they were exposed previously as students of Biology 411) through repeated explanations and evaluations of unit quiz materials, proctors are exposed to additional biochemical concepts and information as a result of lectures by the professor and their classmates during the proctors' meetings. In an effort to ease the abrupt transformation from student to teacher, a Proctor's Manual containing instructions, procedures and advice with respect to their role as Proctors, has been prepared.

The Grading System

An objective system of assigning letter grades to Biology 411 students is employed, eliminating the use of a standard distribution of grades, and the ensuing competition between students for grades. Each student is provided with a grading grid (Table 3) which informs them of the means of acquiring a grade from the lowest E to the highest A+. As may be seen from Table 3, the final grade assigned is derived from a combination of the performance on the midterm and final examinations, and the number of Units completed. As the majority of Biology 411 students complete all fifteen units at a level of mastery and thus perform well on the examinations, their grades for the course usually reflect their high level of achievement. Students have the option, with certain courses, to have a Pass or Fail grade assigned to them, with the Pass grade category reflecting an achievement level between C− and A+, and the Fail category, a performance level between D+ and E. Students of Biology 411 electing the Pass/Fail option frequently complete 14 or 15 units, do not take the midterm and final examinations, and thus receive the Pass grade.

The system employed for assigning grades to Biology 412, the proctor's course, is more subjective. Each proctor must take the midterm and final examinations the results of which provide an objective baseline for his or her grade. Several criteria are employed to determine the degree to which the final grade is increased, such as the following: the degree of responsibility with respect to being in residence in the Introductory Biochemistry Teaching Suite during their assigned times, the quality of the Biochemistry Discovery presentation and written paper, the quality and punctuality of producing the multiple-choice questions, and the quality of the student evaluations.

Student Evaluation

The students of Biology 411 have the opportunity to evaluate aspects of the course at two distinct levels. Following each interaction with a proctor, whether to receive help or to be quizzed, the student is asked to complete a Proctor Evaluation form. The proctor completes the part of the form requesting his or her name, the date, the service provided and, if a quiz was involved, whether or not the student passed. The student is asked to

Table 3 The Grading System for Biology 411

	Combined Examination Score, %								
Units completed	*90–100*	*85–89*	*80–84*	*75–79*	*70–74*	*60–69*	*50–59*	*0–49*	*
15	A+	A	A−	B+	B	B−	C+	C	C
14	A	A−	B+	B	B−	C+	C	C−	C−
13	A−	B+	B	B−	C+	C	C−	D+	D+
12	B+	B	B−	C+	C	C−	D+	D	D
11	B	B−	C+	C	C−	D+	D	D−	D−
10	B−	C+	C	C−	D+	D	D−	E	E
9	C+	C	C−	D+	D	D−	E	E	E
8	C	C−	D+	D	D−	E	E	E	E
7	C−	D+	D	D−	E	E	E	E	E
6	D+	D	D−	E	E	E	E	E	E
5	D	D−	E	E	E	E	E	E	E
4	D−	E	E	E	E	E	E	E	E
3	E	E	E	E	E	E	E	E	E

*No midterm or final examination taken

rank the following statements from 1 to 5 with 1 equivalent to 'strongly disagree' and 5, 'strongly agree':
A The proctor's knowledge of biochemistry was adequate to proctor effectively;
B The proctor was able to transmit information effectively;
C If a quiz was involved, the proctor was too demanding;
D If a quiz was involved, the proctor was too easy (did not insist on mastery);
E If a quiz was involved, the written portion was fair;
F If a quiz was involved, the oral questions were prepared in advance;
G The proctor has the capacity to say, "I don't know, let's learn together";
H I have a good feeling about my interaction with this proctor.

A space is provided at the bottom of the evaluation form for written comments and suggestions.

The information on the evaluation forms is recorded and the proctors are given their evaluation forms at the weekly meetings. They are told to view the anonymous evaluations as valuable feedback from the students with respect to their performance as proctors. As their experience as proctors is, for most of them, pristine with respect to a position of authority and the power to not pass a student on unit quizzes, access to evaluation forms is, in a psychological sense, a valuable learning experience. Their previous experience as students of Biology 411 provides them with valuable insight into the student–proctor relationship.

Both Biology 411 students and proctors are provided with a detailed form at the time of the final examination in which they may evaluate the course in some detail with respect to many aspects of the course and their experience with it. They are also asked to write in detail on the aspects of the course which they liked best and least. Since its inception with respect to the PSI format, many changes have been incorporated into Biology 411, many of which have been stimulated by suggestions and complaints from past proctors and students. It is the author's opinion that such changes have made a significant improvement in this educational experience. The Introduction to the Unit Guides details some of these student-stimulated changes and informs proctors and students of the role that they may play in contributing to desirable changes in the educational system. Biology 411 students are also told that of the two major aspects of education, learning and teaching, learning is the more difficult. As they are much closer to the learning aspect than is the professor, they are also very sensitive to possible improvements in the teaching aspect.

Unit Guides as a Substitute for Lectures

As the self-pacing aspect of Biology 411 is incompatible with transmitting course information solely via lectures, an equivalent means of guiding the student with respect to what must be learned must be substituted. A set of Unit Guides (Table 1) has been prepared which informs the student of which chapters and sections of the textbook should be studied. The student is advised as to whether to learn the content of a section at the level of recognition or recall, learning concepts which are carefully defined. In addition, comments and interpretations which would ordinarily be an integral part of a lecture on a particular subject are also included in the Unit Guides.

One important and rapidly developing area of biochemistry which, except for minor details, has not found its way into modern textbooks of biochemistry, is free-radical and antioxidant biochemistry. In order to prepare Biology 411 students with a foundation enabling them to appreciate and interpret future developments in this area of biochemistry with its many medical implications, the author has prepared appropriate text material which has been included in the Unit Guides as Unit 14.

As many textbooks of biochemistry do not treat the quantitative aspects of biochemistry with depth, three

learning programs have been included as appendices to the Unit Guides in the areas of pH and dissociation, enzyme kinetics, and bioenergetics. In addition, a fourth appendix has been included containing a short biography of Linus Pauling, who has made many basic contributions to chemistry and biochemistry.

Despite lectures not being a required means of transmitting information in the PSI format, weekly lectures on topics of biochemical interest to many students *are* presented. Attendance at these lectures is not mandatory, and the students are informed that the material covered will not be the subject of questions on the examinations. The lecture series is designed to give the students an opportunity to become acquainted with the professor and, in addition, to be exposed to biochemical information of interest to their lives not ordinarily available in introductory biochemistry courses. The first two lectures are designed to satisfy their curiosity with respect to the research interests of their professor. The current lecture topics are listed in Table 4.

*Table 4 Introductory Biochemistry Lecture Series, 1989**

(1) Your professor's biochemical interests: The biochemical functions of coenzyme Q (ubiquinone).
(2) More on your professor's research interests: DT diaphorase is an anticancer enzyme.
(3) We made an evolutionary mistake; the *truth* about vitamin C.
(4) More about vitamin C, allergies, cancer, etc. The biochemical evidence and literature will be reviewed.
(5) The biochemical basis of adaptation to endurance exercise.
(6) Loss of biochemical function accompanying ageing; how to delay them (ie, what to chide your parents about).
(7) The biochemical interaction between exercise, ageing, and cancer; or how to avoid the increase in cancer and other disease states which accompany ageing.
(8) The biochemical/pharmacological basis of drug abuse; the dangers and the myths.

*Ample time is made available to answer questions as well as for elaboration and discussion of the implications of the subject matter of these lectures.

Pitfalls

For many students, exposure to a PSI course is their first experience in the educational setting in which they, instead of the instructor, are required to set the pace of the course, and to acquire information from texts instead of from a series of frequent lectures. Some of these students are unable to adjust to this substantial difference in their life-long educational experience in which they must substitute for an authority figure, namely the teacher/lecturer. With the teacher no longer providing the motivation to study course material, they procrastinate, fall behind, and do not complete as many units as they had wished. Others have difficulty with the concept and the reality of having to demonstrate their knowledge and to be evaluated by Undergraduate Teaching Assistants (Proctors) who are their peers in all respects but one, having previously completed the Introductory Biochemistry course. Some of these students study and master many units before forcing themselves to 'confront' a proctor. When their fear of such a 'confrontation' is intense, too long a period transpires before they begin the quizzing process. This has resulted in a small number of individuals who have studied a good deal of the content of the course, but have completed too few units to obtain a grade representing their view of their accomplishment. As students of Biology 411 are encouraged to discuss such problems with the professor, the number of such occurrences have been few. A number of students with one or both of these problems have expressed, in the course evaluation, great pride in having overcome these impediments, and feel that this accomplishment has contributed to their maturing process.

As proctors, for the most part, have never been in a position previously to have to decide as to whether or not to pass another student on a quiz, some have great difficulty actually not passing a student. Consequently, from time to time a student is passed who has not achieved mastery. In order to obviate this, techniques for informing students of their weakness and that they cannot be passed are discussed in some detail during proctors meetings early in the term.

Summary

A self-paced, personalized system of education has been applied to the teaching of Introductory Biochemistry to undergraduate students at The University of Michigan, departing from the traditional mode of teaching by imparting knowledge via optical rather than auditory means. Unit Guides and textbook material are substituted for formal lectures, and help from Undergraduate Teaching Assistants is available on an almost unlimited basis. In addition, the student proceeds through the course material at his or her own pace with gentle support from the professor to maintain linearity of knowledge learned *vs* time. One may reasonably inquire into whether or not this self-paced, personalized method of teaching has any pedagogic advantage over the conventional lecture mode. Despite several attempts to evaluate the efficacy of this method of teaching with respect to the amount of information learned, and retention over a period of time as compared with another Introductory Biochemistry course conventionally taught at the same institution, this has not been possible. Nevertheless, on the basis of informal comparison by students of examinations, expectations from faculty, and discussions with their friends, it is the students' impression that this personalized system stimulates them to learn more and to retain the information studied for a longer period of time. Consistent with this impression are the results of a number of published investigations[2,3,4] on the efficacy of the PSI method that conclude 'that PSI generally produces superior student achievement, less variation in achieve-

ment, and higher student ratings in college courses.' These results stem from several aspects of this teaching/learning method which are also employed in Biology 411, viz, 'frequent quizzing, immediate feedback, a mastery requirement.' Keller, in his original paper describing the PSI method,[1] identified five features that distinguish PSI courses from conventional ones. PSI courses are: (1) mastery-oriented, and (2) individually-paced courses which use (3) a few lectures for stimulation and motivation, (4) printed study guides for communication of information, and (5) student proctors for quiz evaluation. A review[4] of PSI suggests that students learn and retain more in PSI classes '(*a*) when this progress is evaluated frequently using brief quizzes, (*b*) when they receive feedback immediately after each assessment, and (*c*) when they are required to re-do work until mastery is achieved.'

Information on obtaining the teaching materials employed in this Introductory Biochemistry course may be obtained by writing to the author.

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References

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Announcement

15th International Congress of Biochemistry Jerusalem, Israel, August 4–9, 1991

Every three years the advances in biochemistry are presented during the International Congresses of Biochemistry organized under the auspices of the International Union of Biochemistry. The *15th International Congress of Biochemistry* will be held in Jerusalem, Israel, August 4–9, 1991. The Organizing Committee invites you most cordially to participate in this Congress. The early registration fee will be $340, and for young scientists (under the age of 30) $170.

The first Circular with the pre-registration form is available from your local Biochemical Society or directly from the Secretariat of the 15th International Congress of Biochemistry, KENES Ltd, P.O. Box 50006, Tel-Aviv 61500, Israel

RGD — Tutorials Teaching on Fibronectin

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Introduction

One aim of education is to prepare individuals to be able to function professionally over the next 30–40 years of their lives. In Biochemistry, professionals obviously need an extensive and flexible vocabulary and a good understanding of the major principles, models and investigative processes of the subject. They also need skills in problem-solving, the ability to find and use appropriate information, and the resilience that is essential if they are to cope with the changes in concepts, models and instrumentation that will occur during their working lives. The majority of teaching institutions have tended to 'give' more and more information to students and to reinforce the notion that this should be memorised more or less by rote, by asking for its recall, often in detail, in examinations. Writers of articles in this Journal have commented on this custom time and time again.

I was reflecting along these lines when I found myself required to deal with the protein fibronectin as part of a course of 30 BSc Biochemistry students in their second year on the components of the extracellular matrix. Fibronectin is a very interesting protein from a number of viewpoints and my initial view was that students could hardly fail to be interested in it. However, on further reflection, it seemed to me that the topic was so information-rich, that, with the best will in the world, all that students could do, during a series of lectures on the topic, was to write down facts presented by the lecturer as fast as they could, without time for understanding and making connections. The letters RGD (arg-gly-asp) are associated with fibronectin, and it occurred to me that instead of giving a series of information-rich lectures, it would be possible to devise a *Review*, *Get*, *Do* approach with a view to turning the lecture time into an active, interactive, useful experience for learning and understanding. Here is a brief account of how it turned out.

Review what I already know: make connections

Get information for a specific purpose (*not* for writing down undigested in the examination)

Do something: sitting in lectures listening is *passive* and is not conducive to learning