IN PURSUIT OF MEANINGFUL LEARNING

Joel Michael

Department of Molecular Biophysics and Physiology, Rush Medical College, Chicago, Illinois 60612

The Bernard Distinguished Lecturers are individuals who have a history of experience and expertise in teaching that impacts multiple levels of health science education. Dr. Joel Michael more than meets these criteria. Joel earned a BS in biology from CalTech and a PhD in physiology from MIT following which he vigorously pursued his fascination with the mammalian central nervous system under continuous National Institutes of Health funding for a 15-yr period.

At the same time, he became increasingly involved in teaching physiology, with the computer being his bridge between laboratory science and classroom teaching. Soon after incorporating computers into his laboratory, he began developing computer-based learning resources for his students. Observing students using these resources to solve problems led to an interest in the learning process itself. This in turn led to a research and development program, funded by the Office of Naval Research (ONR), that applied artificial intelligence to develop smart computer tutors. The impact of problem solving on student learning became the defining theme of National Science Foundation (NSF)-supported research in health science education that gradually moved all of Dr. Michael's academic efforts from neurophysiology to physiology education by the early 1980's. More recently, Joel has been instrumental in developing and maintaining the Physiology Education Research Consortium, a group of physiology teachers from around the nation who collaborate on diverse projects designed to enhance learning of the life sciences.

In addition to research in education and learning science, Dr. Michael has devoted much of his time to helping physiology teachers adopt modern approaches to helping students learn. He has organized and presented faculty development workshops at many national and international venues. The topics for these workshops have included computer-based education, active learning, problem-based learning, and the use of general models in teaching physiology.

ADV PHYSIOL EDUC 25: 145–158, 2001.

How many of you have said to yourself or to your colleagues, "I want my students to understand physiology."? The answer is obvious. We all want our students to understand physiology, not just memorize it. Or at least we all say we do. This paper will focus on what we need to do to help our students learn with understanding.

A SHORT AUTOBIOGRAPHY OF A NAIVE TEACHER

I would like to start back at the very beginning of my pursuit of meaningful learning.

I graduated from MIT in 1965 with a PhD in neurophysiology and a burning desire to understand the visual system. Naively, I imagined that my professional life would be pursued in the laboratory, and it literally didn't occur to me that I would one day have to teach physiology.

When I began my first tenure-track appointment after 2 yr as a postdoctoral fellow, I still had not woken up to the realities of life in academia; for most of us, it is a mix of research ***and*** teaching.

So, my first exposure to medical students at the University of Illinois College of Medicine resulted in both surprise at being there at all and shock at being required to somehow help these people understand physiology. Like most new faculty in those days, I was first assigned to teach in a student lab. Here I was expected to, first, help future surgeons learn how to insert tracheal and femoral cannulas and only then help them understand the physiology that they were hopefully seeing before them.

What I discovered was that medical students could and did memorize everything. And when I asked them questions like "why did you see the response that just occurred?" I got back full paragraphs of memorized words. However, even though all of those words were correct, they somehow never quite constituted an explanation for the experimental results that they had just seen. My students were unable to draw any insights about physiology from what they were seeing in the lab. Regardless of the grades they were earning and the successes that followed them through their careers as medical students, I could not convince myself that they "understood" physiology.

In 1970, Rush Medical College reopened its doors after a more than 25-yr hiatus, and as the only "card carrying" physiologist on the faculty (I was already a member of American Physiological Society), I became even more heavily involved in physiology education, planning courses now, as well as again running student labs and lecturing.

It was soon after starting at Rush that I began to get really discouraged. Students would come to my office, either before an exam or afterward, with questions about physiology. From the conversations that ensued, it was once again quite clear that they could and did memorize everything that they thought was important; but they could do nothing with this memorized information! If I had the temerity to present them with a novel situation, one that we had not discussed in class or that they hadn't encountered in the textbook, they were at a complete loss about what to do, despite all that memorized information. It appeared that they ***knew*** a lot but didn't ***understand*** nearly as much.

Frankly, at this point, I seemed to be stuck. I really did not know what to do to solve the problem I seemed to have identified.

My colleagues at the time were of no help. They either had not seen the problem I was seeing or what they saw did not seem to constitute a problem to them. Or, perhaps, they simply were not concerned about my supposed problem. Even when they acknowledged that there was a problem, they had no more idea than I did about where to find a solution.

It was only years later that I realized how strange this was. When we encountered an interesting but puzzling observation in the ***laboratory***, we knew exactly what to do, go to the library (remember, this was the 1970's, and there was no World Wide Web). There, we would have browsed the journal shelves until we came upon an article that pointed us in the direction of current work in the area of interest. But, it frankly never occurred to me do something similar when faced with a question from the ***classroom***. I will come back to this difference between our usual behavior in the laboratory and our behavior in the classroom before I finish.

It was this growing dissatisfaction with the outcomes of my teaching that started me on a 25-yr pursuit of ways to help students to understand—not just memorize—physiology, ways that would enable them to use the information they acquired to do something more than regurgitate answers on tests.

So, I want to deal with four topics here: *1*) what is "meaningful learning," *2*) how can student use of the computer contribute to meaningful learning, *3*) how can problem solving help students achieve meaningful learning, and *4*) how do we foster "meaningful learning?"

WHAT IS MEANINGFUL LEARNING?

It may be useful to start by contrasting "meaningful" learning with "rote" learning. "Rote" learning is memorizing all the entries on a page from the Orlando phonebook. I am sure that I have some students who could do this if they thought it would help their grade in physiology. However, if you know nothing about the city of Orlando, a question like "How far from Mr. X does Miss Y live" is impossible to answer. So your having memorized the 100 names, addresses, and phone number has left you with completely inert knowledge with which you can do essentially nothing (except, of course, to recite the list from memory or call a bunch of strangers if you are so inclined).

On the other hand, if you were a native of Orlando (and if you know the geography of the city), you could probably at least estimate the distance between X and Y. And you might even be able to guess who they voted for in the infamous presidential election just from knowing where they live. In this case, your knowledge, the memorized list of names and addresses, exists in the context of other information, and the result is the ability to "do something" with all that memorized information.

"Meaningful" learning, then, involves the acquisition of knowledge in a way that allows you to do something with it (17). It results in knowledge that is stored in a way that allows it to be accessed from many different starting points. That is, it is knowledge that is well integrated with everything else that you know. Meaningful learning is accompanied by the building of multiple representations (mental models), models that are connected to models for many other phenomena.

What do we want our students to be able to do with the physiology knowledge that they acquire (15)? We certainly expect them to be able to ***predict*** the responses of a physiological system if it is disturbed. We expect students to be able to ***explain*** the responses that occur in systems that have been disturbed. Sometimes we want them to solve quantitative problems (***calculate*** something). And, we expect them to be able to do this with systems and disturbances that they have not encountered in lecture or the textbook. That is, we expect them to be able to apply what they know about physiology to novel situations. When they can do this, we say they "understand" physiology. Or, in the terminology I have been using, we can say that meaningful learning has occurred.

For more than 20 years, then, my goal has been to create and validate learning resources, or learning environments, which will help students to learn physiology meaningfully, to learn physiology with understanding.

In pursuit of this goal, I initially began working in the field of computer-based education.

USING THE COMPUTER TO HELP STUDENTS ACHIEVE MEANINGFUL LEARNING

In the early 1970's, shortly after we restarted the medical school at Rush, I got my first laboratory computer. As primitive as it was by today's standards (my wife's PDA is a bigger computer by every measure except physical size), it allowed me to do research in a whole new way. At some point, it occurred to me to ask whether the computer could be used to help my students learn some of the difficult things we were asking them to master. Could it be as useful (dare I say, as revolutionary) in the classroom as it was proving to be in the laboratory?

After several false starts, Al Rovick and I learned about a quite sophisticated mathematical model of the baroreceptor reflex system called MacMan (3). It contained hundreds of equations and data tables that together simulated the behavior of the cardiovascular system. One could change the values of a very large number of variables and could select many different outputs to be displayed on a line printer (the state of the arts for output devices in those days!). We wrote a lab manual that described several experiments for the students to do (variables to change, outputs to examine) and then asked the students to design their own experiments to explore the behavior of the system. This was a laboratory protocol in no essential way different from the one we had used at the University of Illinois in the dog labs. Then, we turned our students loose with MacMan in a computer laboratory.

The results were every bit as disappointing as the outcomes of the old dog labs. As long as Al or I were looking over the shoulders of a group of students, asking questions and prodding the students to think about what they were seeing, some learning seemed to be occurring. If we left and came back 10 minutes later, we found the groups floundering. They seemed to encounter three different problems. In most cases, the students were simply following the "recipe" we had provided in a more or less unthinking manner, and little learning was occurring. Another problem was that most groups seemed to have almost no idea about how to plan an experiment that would reveal something useful or important about the system. Finally, all groups were bogged down in attempts to understand the physiological "messages" buried in tables of numbers. By the end of the 2-hr computer lab, we had not seen much learning, meaningful or otherwise, taking place.

However, Al and I ***were*** learning. Two things quickly became obvious to us. The messages we wanted the students to carry away from this experience did not lie in the absolute values of the numbers they were seeing; the messages resided in the qualitative ***changes*** that occurred to those numbers (that is, whether the value of certain parameters increased or decreased as a result of the disturbance we were having them simulate). For example (see Fig. 1), if inotropic state decreased because of a myocardial infarct, then stroke volume would decrease, cardiac output would fall, and thus mean arterial pressure would decrease. It was also clear that the students needed continuous guidance of some sort to make sense of what they were seeing.

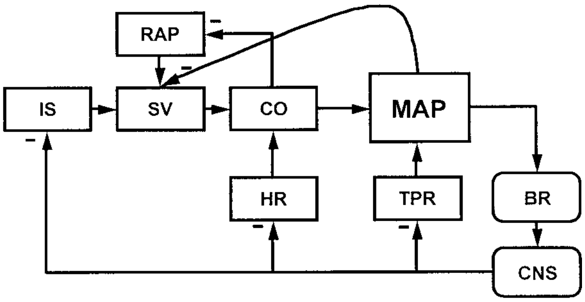

FIG. 1.

A causal diagram representing the baroreceptor reflex mechanism. If an individual suffers a myocardial infarct, the inotropic state (IS) of the heart will be reduced, causing a reduction in stroke volume (SV), which, in turn, causes a decrease in cardiac output (CO). The result will be a decrease in mean arterial pressure (MAP) and the eliciting of a baroreceptor reflex. CNS, central nervous system; RAP, right atrial pressure; TPR, total peripheral resistance; BR, baroreceptors; HR, heart rate.

So, a program called Heartsim (21) was written; it was MacMan embedded in a teaching routine that did several things. It defined a small set of experiments for the students to explore. It provided them with a list of only seven cardiovascular (CV) parameters to think about (see Fig. 2). This list also suggested the order or sequence in which they ought to be thinking about the variables. The program required them to think about the response to a disturbance or perturbation in three distinct temporal periods. And finally, it asked them to predict the changes that would occur to those seven parameters as a consequence of the disturbance acting on the system and subsequent baroreceptor reflex that was elicited.

Our students behaved in dramatically different ways when using Heartsim than did the students using MacMan. After only a few minutes with the first Heartsim problem, they recognized that all their memorized information about the CV system was not necessarily going to result in them getting many right answers. They were going to have to think about relationships between things! They were also going to have to learn a systematic way to think about what was going on here.

It is certainly true that many students were discomforted by this realization. After all, they had gotten into medical school by virtue of being quite skilled at a certain kind of learning, and here they were forced to master quite different rules for the learning game!

However, working with the program provided them with almost immediate proof that they were learning. As a result, they not only spent the 2 hr we had scheduled for our computer labs, but they returned after-hours—on their own time—to play with Heartsim for many additional hours. This behavior from a group of thoroughly overworked medical students confirmed for us that this approach to using the computer seemed to help promote meaningful learning.

PARAMETER	DR	RR	SS
Inotropic state	↓		
Central venous pressure	↑		
Stroke volume	↓		
Heart rate	0		
Cardiac output	↓		
Total peripheral resistance	0		
MEAN ARTERIAL PRESSURE	↓		

FIG. 2.
A prediction table from CIRCSIM [Rovick and Michael (24)]. The *left* column lists the cardiovascular parameters to be considered in an order that suggests how the student should think about the responses of the system. The next 3 columns represent the 3 temporal phases of the response to be considered: direct response (DR) is the period before the reflex occurs, reflex response (RR) describes the changes that occur as a consequence of the RR to the change in MAP that occurs in DR, and finally steady state (SS) is the state of the system after the reflex has occurred (it is the "sum" of DR and RR).

A number of years later (24), we actually did an experiment using a PC-based version of the program that we call CIRCSIM (22) that demonstrated the significant learning that occurs when students spend 2 hr working with our program. We pretested 50-some students and then assigned them to one of four treatment groups. Subjects in the control group did nothing special—that is, they studied CV physiology in any way they wanted as they continued with the course (but they did not use CIRCSIM before taking the posttest). One treatment group ("solos") were assigned to work with CIRCSIM by themselves with no interaction with other students or with an instructor. A second treatment group ("pairs") worked with CIRCSIM—two students working together at a computer—but again with no interaction between other pairs and no interaction with an instructor. The last group ("lab") simply worked in pairs at a computer in the scheduled CIRCSIM computer lab; each pair was free to interact with other pairs and with the instructor. All subjects then took a posttest.

We scored both the pre- and posttest and then looked first at the change in the total number of correct responses that the subjects had generated on each test (Fig. 3). All three treatment groups—students who had used CIRCSIM—learned more than the controls. And working in pairs produced more learning than working alone, a finding that many other educational researchers have also demonstrated. We also looked at the change in the number of misconceptions or "bugs" (errors about relationships between

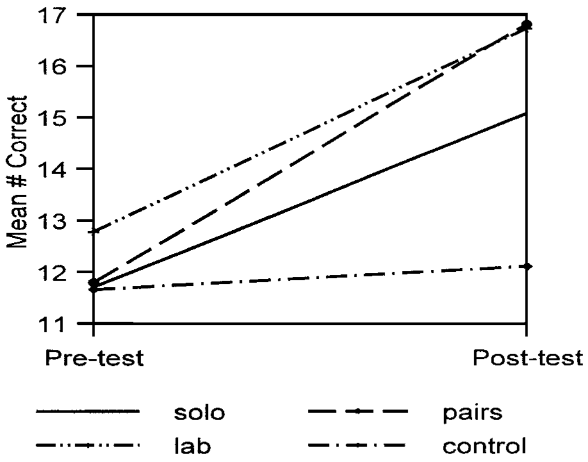

FIG. 3.
Results of the CIRCSIM experiment [Rovick and Michael (24)] in which the total number of correct answers on the pre- and posttest are plotted for the 4 experimental groups: *1*) controls, *2*) "solos", *3*) "pairs", and *4*) "lab." All three of the groups using CIRCSIM (*groups 2–4*) increased their number of correct responses to a greater extent than did the controls, and all 3 differences were statistically significant at the *P* = 0.01 level.

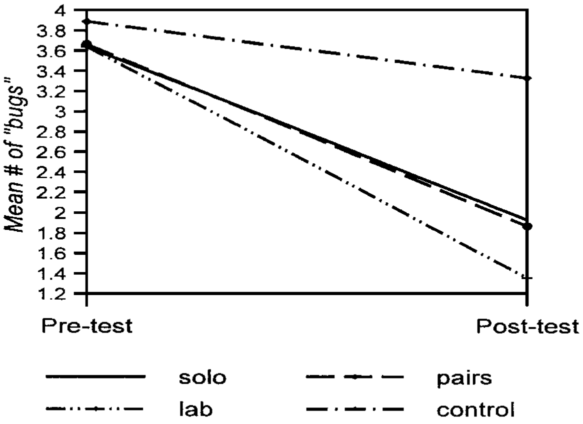

FIG. 4.

Results of the CIRCSIM experiment [Rovick and Michael (24)] in which the number of "bugs" or incorrect relationships on the pre- and posttest are plotted for the 4 experimental groups: *1*) controls, *2*) "solos," *3*) "pairs," and *4*) "lab." Using CIRCSIM (*groups 2–4*) reduced the number of "bugs" (*P* = 0.012). Having an instructor available (*group 4*) reduced the "bugs" to a greater extent than did using CIRCSIM without an instructor (*P* = 0.01).

variables) that were present in the students' responses (Fig. 4) and again found that using the program helped. The data also suggest that there is still a role for the instructor. Our third treatment group, the students that had worked with the instructor in the scheduled computer lab, showed the largest reduction in "bugs." Interacting with the instructor seemed to add some measure of learning to whatever they were getting from our computer program.

Al and I wrote two other similar programs: GASP (23) deals with chemical control of ventilation, and ABASE (8) is about whole body acid-base balance. Both of these programs are in use at Rush, and all three of our programs continue to be very highly rated features of our course. We have demonstrated these programs to colleagues in many different venues both here and abroad, and our programs are in use around the world.

We have also gone on to attempt to develop a "smart" computer tutor that can carry on a true dialogue with the student. The CIRCSIM-tutor project is a joint effort between Al and me at Rush and a computer science colleague, Dr. Martha Evens, at the Illinois Institute of Technology (1, 4, 6). This project has been funded for many years by ONR. We finally have a version of the "smart" tutor that is robust enough for routine use by our students; it too has received very high ratings from our students.

While pursuing meaningful learning with the help of the computer, we also pursued a different direction, one that involves no technology but is no less effective.

USING PROBLEM SOLVING TO FOSTER MEANINGFUL LEARNING

In the 1960's when I learned physiology, it is fair to say that much of what was understood about the functions of the body was derived from studies of human subjects with abnormal functions (from patients) or from animal models of these clinical problems. If we wanted to talk about diabetes, we talked about diabetic patients and the changes in their blood glucose following an ingested meal or we talked about the changes in their overall metabolism when they took their insulin shot. There wasn't much else that we could talk about at that time. So it was natural to teach human, medical physiology from a very case-based perspective.

By the 1970's, though, research was already taking our understanding of physiological phenomena down to the level of membranes, channels and pores, and intracellular organelles. Our focus in teaching was increasingly turning to these entities and away from patients and their clinical problems.

By the early 1980's, at the same time that Al Rovick and I were developing Heartsim and CIRCSIM, we came to the conclusion that there were two good reasons to reintroduce cases into our physiology course.

First, we were looking for approaches to helping our students learn to integrate the knowledge that they accumulated with relative ease into a deeper understanding of physiology, a task that was much more difficult for them. We thought that we could help them build bigger and more robust mental models of the cardiovascular and respiratory systems by asking them to think about, and explain, why a patient with mitral stenosis experienced shortness of breath when trying to sleep at night. Second, we felt that the

TABLE 1
A Typical Workshop Problem

Mr. AB, a 56-yr-old patient, was admitted to PSL Hospital complaining that he had recently begun to tire on exertion (a round of golf) and that he had had occasional heart palpitations. He did not appear to be in acute distress. Physical exam revealed a moderate systolic ejection murmur.

Do these signs and symptoms suggest any specific pathophysiology?

What aspect of cardiovascular physiology is each related to?

Try to construct a list of hypotheses.

"clinical" nature of such problems would be a strong motivator for learning; our students were, after all, intent on becoming physicians, not physiologists.

We began by writing a set of three cardiovascular problems based on actual patient data supplied to us by the cardiac catheterization lab at Rush (14). We carefully formatted these cases and made small changes in the patient data when that would make for a better teaching problem. We also incorporated a set of questions into the case aimed at guiding the students' thinking in directions that we thought would lead them to a more useful exploration of the patient problem. A short segment of such a problem, a brief piece of the patient history, and the questions that follow can be seen in Table 1.

We used these problems in small group sessions (perhaps 20–30 students) that we call tutorials. Each problem was assigned to a different small subset of students in advance of the scheduled tutorial session. The assigned group was asked to solve the problem and to prepare themselves to present and discuss it with the entire group. **All** students were asked to solve **all** of the problems, even if they were not going to be the primary presenters.

This protocol proved not to work to our satisfaction for a variety of reasons. Only the group assigned to a particular problem ever really looked at it. It seemed that only one or two members of the assigned group put in any obvious effort to understand the problem. And even when someone had "solved" the problem, they often were unable to explain their solution to the whole group in a satisfactory way. We had expected to actively engage all the students in the class in solving these problems, but it appeared that we were only producing opportunities for poorly organized student lectures or, hopefully, better prepared lectures from the faculty. We had tried to produce an active learning environment but only produced occasionally busy students!

We have tried several alternative formats since then and today employ problems like this in a setting that we call workshops (15). Each workshop session involves 25–30 students and one faculty member. The students do not see the problem until they come to the workshop, a simple change from our previous format but one that changes student behavior considerably. The instructor usually models the solution of an initial problem with the help of the students. This is followed by a problem or problems to be solved by the students working together in small groups of five or six. The problems have been carefully formatted so that they can be solved piecemeal (usually 1 page at a time). When the small groups have completed the solution to the current piece of the problem, the whole group comes together to post and discuss the answers that each group generated for that piece. When everyone is satisfied with the piece of the problem under discussion, the small groups tackle the next piece. Students are asked not only to solve the problem but to be prepared to explain their solution, i.e., describe how they arrived at their answer. Problems commonly call for predictions about alterations in function in the patient being considered (Table 2). These problems also typically ask the students to generate causal diagrams (Fig. 5) illustrating what is taking place in the patient under discussion.

TABLE 2
A Tutorial Problem [from Michael and Rovick (15)]

Consider an individual who develops a pathology that results only in a leaky glomerulus (permeable to plasma proteins).

1. Predict the changes that will be present in the following parameters in the steady state as a consequence of this pathology.

Parameters	Predicted Changes
Plasma protein concentration	
Plasma colloid osmotic (oncotic) pressure	
Total body sodium	
Plasma volume	
Insterstitial fluid volume	

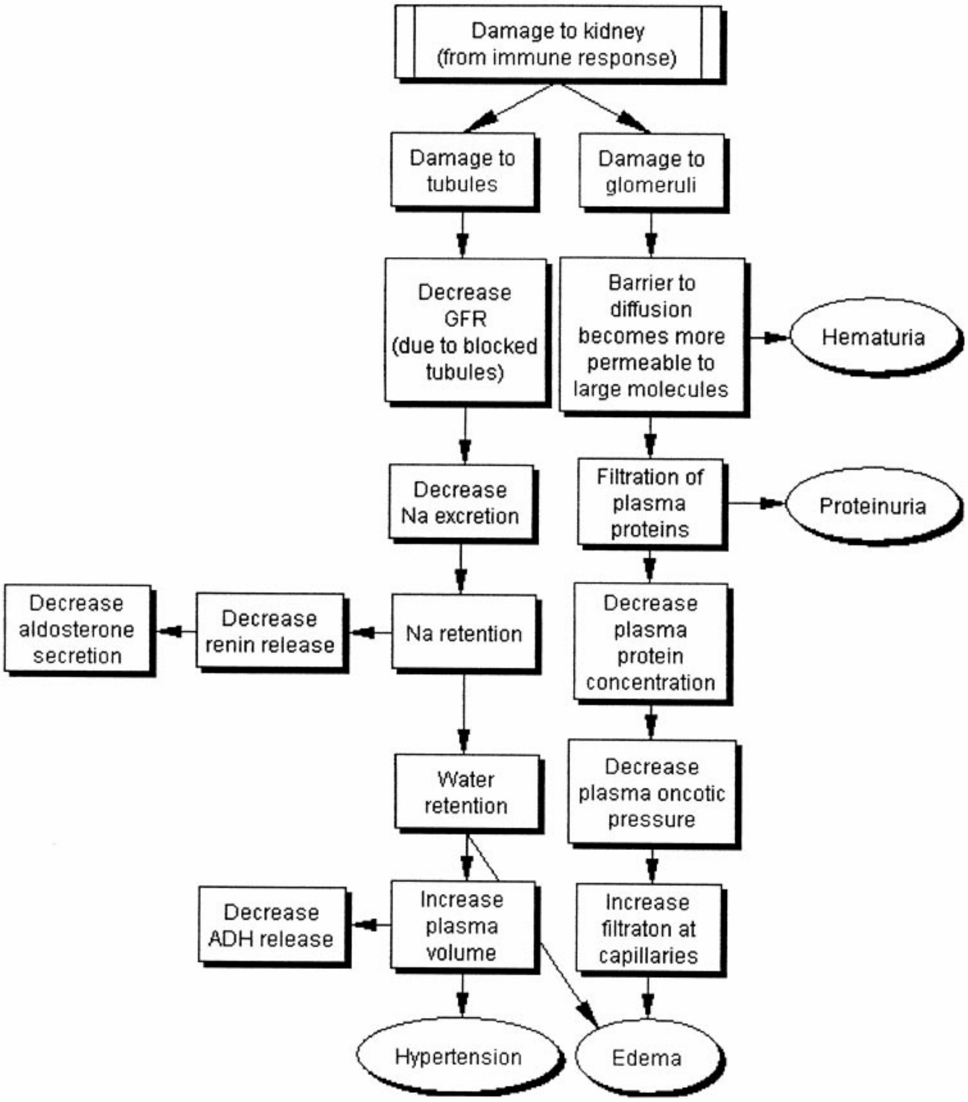

FIG. 5.

A causal diagram illustrating the consequences of having glomeruli that are leaky to plasma proteins [Michael and Rovick (15)]. The origins of 4 common signs and symptoms present in patients with such a problem are represented here: hematuria, proteinuria, edema, and hypertension.

The results of these workshops have been heartening for us. We see a great deal of cooperative learning and peer teaching taking place; students are learning from one another. They are “talking physiology”— using the language of physiology to share ideas about normal and abnormal function—with each other and with the instructor. Furthermore, because pathophysiology is rarely limited to a single piece of a system, the students are forced to integrate a great deal of knowledge to arrive at an answer. Their understanding of physiology seems deepened by the experience provided by these workshops.

We also find that the more clinical the problem appears to be, and I want to emphasize that we are charged with teaching PHYSIOLOGY, not pathophysiology and certainly not medicine, the greater the students' interest. They even come up with good questions that I cannot answer because I'm not a clinician!! But, I take that to mean that they are both truly interested in the topic and that they are thinking hard about it, and I can usually come up with an answer in time for the next class period.

Al Rovick and I have written some 60 such problems and answers and have recently had the collection published (15). We have heard from many colleagues that their students, at many different educational levels, learn from solving the problems in our book.

We are continuing to refine old problems and write new ones. We also continue to refine the protocol for conducting tutorial sessions, exploring alternatives that will result in still more meaningful learning by our students.

I have described some of the work I did in the 1970's and 1980's in pursuing meaningful learning. In the 1990's, my efforts have focused on research to validate the approaches to meaningful learning that I have described. This work has been supported by both ONR (4) and NSF (12, 13, 19, 25). One of the questions that Harold, Mary, Pat, and I have addressed in our current NSF grant is whether problem solving of the type described here does result in students developing more robust mental models and enhanced understanding of the physiology they have dealt with. I hope to have something to report about this question in the near future.

In addition, in recent years, Harold, Mary, Pat, and I have focused considerable effort on faculty development activities, seeking to educate physiology teachers and teachers in other science disciplines about these new approaches to fostering meaningful learning.

What has been learned during this pursuit of meaningful learning for our students? Some things have certainly been learned from our own experiences, from our various attempts to help students learn with understanding. I also discovered that there is an array of academic disciplines out there, beyond the boundaries of physiology, in which researchers are making impressive strides in understanding teaching and learning at all educational levels and in all sorts of subject matter disciplines. Over the years, I've learned from people in disciplines such as computer-based instruction, cognitive psychology, and science education.

HOW DO WE HELP STUDENTS ACHIEVE MEANINGFUL LEARNING?

What promotes meaningful learning? The most obvious thing I have learned is that meaningful learning is more likely to occur if you clearly and explicitly define it as a major objective for your course. The "trick" is to do it in a way that will be clearly understood by each student.

I cannot stress too strongly how important this is. My students, and all of your students, are very good at playing any "game" we ask them to play. When they believe that we only value the acquisition of information—memorization—then that is what they will attempt to do. On the other hand, if we can convince them that what we value is "understanding"—and if they know what's required to demonstrate that they "understand"—they will work to achieve this objective.

Meaningful learning is promoted by faculty modeling of the kinds of behaviors that we will ask our students to master as they pursue an understanding of physiology.

Modeling is one way that we can convey to the students the importance we attach to certain kinds of behavior. It also provides the students with examples of those behaviors that serve to clarify what we expect from them. And modeling does this in a way that may be much clearer than any written objective in your syllabus or study guide.

So, what is the most critical skill that our students need to develop if they are to learn physiology with understanding? I think it is the ability to reason causally and qualitatively about physiological systems. We saw the importance of this when we wrote Heartsim and CIRCSIM and then watched our students attempting to solve the problems presented to them. What we saw then, and continue to see today, is the gradual development of the ability to figure out where to start (what's being perturbed?) and to then reason in a stepwise fashion from that starting point to all of the other variables they have been asked to think about.

We also saw this when we began doing our workshops and tutorials. If our students were to successfully solve the problems we gave them, they needed exactly the same skills; they need to know where to start and then how to reason from the identified perturbed variable to either predict or explain the presence of the patient's signs and symptoms. And from listening to the students in our workshops, it is clear that there is a transfer from one setting to the other; the practice they get in the computer lab helps in the tutorials and vice versa.

I was, therefore, fascinated to learn that physics and chemistry educators, as well as cognitive scientists, have for many years been pursuing studies of the role of qualitative, causal reasoning in both disciplines. Deep knowledge, or learning with understanding, of physics (29), chemistry (31), and biology (20) has been clearly shown to be promoted by an emphasis on qualitative, causal reasoning.

I have also learned that two other things are likely to foster meaningful learning: providing opportunities for peer teaching and encouraging students to "talk physiology."

Meaningful learning is more likely to occur when we require our students to "talk" physiology with one another and with the faculty.

One of the most "active" ways to help students to challenge with their own mental models is to get them to "talk physiology." Discussing, justifying, or explaining their answers to questions with one another, or with the instructor, is a powerful way to encourage meaningful learning. Even "talking to themselves"—generating self-explanations—has been shown to significantly increase learning (2). However, it is more common for the instructor to talk to a room full of students than it is for students to be talking to students.

How do you get students to "talk physiology" (as opposed to having them listen to you talk physiology)? Providing opportunities for cooperative work and peer teaching seems to be the most direct way. Whether our students are in front of the computer, working together to solve a CIRCSIM problem, or working as a group to solve a problem in a tutorial session, our students are "talking physiology" with one another. In both settings, when they encounter a problem, or do not know how to proceed, they "talk physiology" with the instructor. We even have whole class problem-solving sessions in the lecture hall, with nearly all of our 120 students, in which peer teaching and "talking physiology" are expected behaviors.

And again, we discovered that there is a rich literature out there describing the benefits for student learning, at all levels and in all disciplines, of encouraging peer teaching and the "talking" of the discipline. More specifically, we discovered that others had developed and described approaches in physics (9), chemistry (7, 26), and biology (16, 28) teaching that bear great similarities to our techniques for engendering the kinds of student-to-student interactions that lead to greater understanding.

Another thing we have learned is that meaningful learning is enhanced by requiring students to integrate larger and larger chunks of physiology.

One of the things that makes learning physiology difficult is the fact that everything ultimately is connected to everything else. Disturbances to one part of one system will give rise to consequences that involve many organs or organ systems. Our computer programs require students to integrate many of the "facts" they have memorized. Our clinical problems require the same sorts of behavior. So, students must be encouraged to break down the walls between the "pigeon holes" in which they tend to store the knowledge they acquire. . .CV knowledge here, respiratory here, etc. They need to recognize the necessity of doing this, and they need to practice it. The result will be mental models that are linked to other models in ways that make ***all*** the models more robust, more durable, and more useful.

Meaningful learning is enhanced by scaffolding students' learning, giving them the most support when they are starting out and giving them less support as they gain the level of mastery you expect.

The notion of scaffolding, of providing support when and where it is needed, is a very powerful one (5, 30). Teachers of elementary and middle school children know this and behave accordingly. Teachers of older students frequently ignore this. But all learners benefit from help initially and equally will benefit from that help being eliminated as the need for it wanes. It's sort of like training wheels for bicycles!

The "bottom line" is this. Meaningful learning of physiology, "understanding" physiology, is possible, but students need our help to get there.

Now, if this list of factors that promote meaningful learning does not look much like the description of the average physiology course in which students hear a great deal but do not do much of anything else in class, you are correct. Helping your students to achieve meaningful learning is going to require you to learn new ways of interacting with your students (see Refs. 10 and 18 for examples).

I want to end with a reprise of my autobiography as a teacher because I think there is another message there that needs some additional attention.

WHAT'S WRONG WITH PHYSIOLOGY TEACHING TODAY?

Thirty years ago, as a new faculty member, I was put into the classroom as unprepared as I could possibly be. All that I knew about teaching physiology (or, for that matter, anything) came from having been taught: 4 yr of high school, 4 yr of college, and 4 more yr of graduate school. All that I knew about learning came from that same set of experiences. If I became unhappy with my students' learning outcomes, all I could do was to look to my senior colleagues in the department. And all I could see was that they were teaching in exactly the same way that they had been taught. If we had talked about teaching. . .but then we never did talk much about teaching. We talked about science, about physiology research, about the National Institutes of Health and grantsmanship, and I learned a great deal from these conversations. But we almost never talked about teaching.

Has anything changed in the intervening 30 yr? On good days, I am inclined to think so.

Several years ago, much to my surprise, the graduate students in the Biology Department at Marquette University invited me to give a seminar on teaching to their department. When I asked why they had picked teaching as a topic for the department's seminar series, their reply was encouraging. Many of them recognized that some knowledge about teaching might be an asset when they tackled the increasingly difficult task of finding a tenure track position. That attitude represents progress.

More and more universities, or individual departments, are beginning to offer formal courses on teaching as part of their graduate training programs. Several years ago, Dan Richardson invited me to visit the University of Kentucky where he had organized a course on teaching for graduate students in the Physiology Department. There I spent the day interacting with graduate students about ways to help students gain an understanding of physiology. That course has recently been superceded by a similar, university-wide course. Such courses are another example of progress.

Nevertheless, I want to leave you with a quite eloquent and pointed description of the continuing, fundamental problem with teaching in higher education. Just days after being notified that I had been selected as the Claude Bernard Lecturer, I came across an article in the Rush library that contained a very powerfully worded indictment of much of the teaching that occurs in medical education (27).

I want to read to you an extended quote from it. In their introduction the authors say. . . "There is a remarkable difference in attitude between university staff as teachers and as researchers. As researchers we critically read the newest literature, we think of new approaches and theories, look for empirical verification and submit our work to the critique of others through rigorous peer review. The scientific attitude lies at the heart of scholarship and is accepted by everyone in the field. We also have clear rules about becoming a researcher. Good researchers are carefully selected and trained before they are allowed to contribute independently to the research. We require degrees, expertise in methodology, a demonstration of scientific ability through output assessment, and so on."

The authors go on to describe a similar situation in the practice of medicine and then continue. . . . "The situation seems quite different in education. As teachers we seem to have a different attitude. We do the things we do, because that is the way we have been raised ourselves and that is the way it has been done for many years, even centuries. We hardly read the literature on education, or, more appropriately, are not even aware that such literature exists. It is difficult to change things in education, because as teachers we are highly convinced that what we do is appropriate and any challenge to one's convictions is an actual challenge to one's professional integrity. Becoming a teacher requires us to be licensed in a professional area, e.g. in medicine [or for most of us, physiology], and that is it. We are assumed to be good teachers, because we are qualified in a professional area. The better we are in that area, the better we are as teachers. Specific didactic training or other educational programmes are not required or, in many cases, even offered. Once we are teachers we have quite some autonomy in deciding what and how to teach. Peer review, quality control, follow-up training—quite common in research activities—hardly exist in education."

In their discussion, van der Vleuten and colleagues (27) conclude with an even more pointed statement that I want to paraphrase both for clarity and to add my own emphasis.

Too many of us, the community of scientists/teachers in every discipline, all too often can only teach the way we were taught. Put most bluntly, the reason is simply ignorance. Too many of us know little or nothing about the advances that have occurred in the understanding of teaching and learning in the sciences. We go into the classroom assuming that all we need to bring there is our content expertise, our long years of having taught the discipline, and our dedication to doing the best job we can do.

BUT THAT IS NOT ENOUGH! We would never dream of going into the research lab without knowing the latest methodologies and without knowing what those other "experts" out there are thinking about. But we routinely do just that when we go into the classroom.

So, we need to teach the way we do research. We need to start by educating ourselves through faculty development programs, through our own reading (*Advances in Physiology Education* is a good place to start; see Ref. 11 for an annotated bibliography of other relevant journals), and by attending teaching sessions at professional meetings (there are several such sessions at the Experimental Biology meeting every year). The list of possibilities is a long one.

And we need to approach the phenomena that occur in our classrooms, what works and what doesn't work, what helps our students to learn and what doesn't seem to help them, with the same attitude of inquiry with which we approach interesting phenomena in the laboratory. We must be prepared to "experiment," to make changes in what we do and how we do it when we observe that things aren't working or when we learn about better ways to accomplish whatever we seek to accomplish. If nothing else, such an approach to teaching makes teaching a more intellectually stimulating activity and, as a bonus, a lot more fun!

This is NOT to say that we all have to become educational researchers. That will not happen, and I am not sure that it should. However, I do believe that, as a community, we need to participate more in educational research. If we are responsible for helping students to learn physiology, then we also have some responsibility to contribute to furthering the knowledge of how to do this effectively.

In *Man and Superman*, George Bernard Shaw quipped, "He who can, does. He who cannot, teaches." As much as I have always enjoyed Shaw's wit, I find this canard to be one that personally has always offended me (and I understand that was probably the point of it!).

But in an important sense, we have turned Shaw on his head, and it would, I think, be accurate to restate it this way "He (or she) who can, does (research), but is expected to teach anyway!" An equally accurate restatement might go something like this, "He (or she) who can, does (research), and because of this is presumed to be capable of teaching!"

This, I would argue, is more damaging than Shaw's original bon mot, and it is time for us to make a change in this attitude.

This afternoon, we look back and honor Claude Bernard. His notion of the constancy of the internal environment provided physiology researchers with a powerful tool for exploring the functions of the body and at the same time provided teachers of physiology with a powerful organizing concept to help our students understand those functions.

Now we can also look forward to the dawning 21st century. Physiology is just beginning to explore the human genome, but it is clear that this exploration will lead to growing knowledge of the workings of the organism at a deeper level than others we have obtained yet. At the same time, we should also look forward to applying our growing understanding of how people learn to helping all students gain a deeper understanding of physiology. The time has come to revolutionize both our research and our teaching.

I must acknowledge the contributions to the ideas I have presented in this paper made by two friends, colleagues, and collaborators, Al Rovick and Harold Modell. I have known Al and Harold for about 25 years, and we have spent much of that time discussing, debating, arguing about, and collaborating on research and development efforts on teaching and learning physiology. I have learned a lot from the two of them over the years and, equally important, it has always been fun!

I also want to acknowledge my colleagues in the Physiology Educational Research Consortium for enthusiastic participation in the educational research with which I have been involved for the past 7 or 8 years.

Some of the work discussed here was supported by the ONR, and some of it was supported by the NSF. The opinions expressed here are those of the author and not necessarily those of ONR or NSF.

Address for reprint requests and other correspondence: J. Michael, Department of Physiology, Rush Medical College, 1750 W. Harrison St., Chicago, IL 60612 (E-mail: jmichael@rush.edu).

REFERENCES

1. **Chang RC, Evens M, Rovick AA, and Michael JA.** Surface generation in tutorial dialogue based on analyses of human tutoring sessions. *5th IEEE Symposium on Computer-Based Medical Systems*, Durham, NC. Los Alamitos, CA: JEEE Computer Society Press, 1992, p. 554–561.
2. **Chi MTH, DeLeeuw N, Chiu MH, and LaVancher C.** Eliciting self-explanations improves understanding. *Cognitive Science* 18: 439–477, 1994.
3. **Dickinson CJ, Goldsmith CH, and Sackett DL.** MACMAN: a digital computer model for teaching some basic principles of hemodynamics. *J Clin Comp* 2: 42–50, 1973.
4. **Hume G, Michael J, and Evens M.** Hinting as a tactic in one-on-one tutoring. *J Learning Sciences* 5: 23–47, 1996.
5. **Jonassen D.** Designing constructivist learning environments. In: *Instructional Design Theories and Models, A New Paradigm of Instructional Theory*, edited by Reigeluth CM. Mahwah, NJ: Lawrence Erlbaum, 1999, vol. 2, p. 215–239.
6. **Kim N, Evens M, Michael JA, and Rovick AA.** An intelligent tutoring system for circulatory physiology. In: *Computer-Assisted Learning*, edited by Maurer H. Berlin: Springer-Verlag, 1989, p. 254–266.
7. **Krajcik JS.** Developing students' understanding of chemical concepts. In: *The Psychology Learning Science*, edited by Glynn SM, Yeany RH, and Britton BK. Hillsdale, NJ: Lawrence Erlbaum, 1991, p. 117–147.
8. **Li J, Rovick AA, and Michael JA.** ABASE: a hypermedia-based tutoring and authoring system. In: *Computer Assisted Learning (Proceedings of the 4th International Conference, ICCAL '92)*, edited by Tomek I. Berlin: Springer-Verlag, 1992, p. 441–452.
9. **Mazur A.** *Peer Instruction: a User's Manual*. Upper Saddle River, NJ: Prentice Hall, 1997.
10. **McNeal AP and D'Avanzo C.** *Student-Active Science: Models of Innovation in College Science Teaching*. Fort Worth, TX: Saunders College Publishing, 1997.
11. **Michael JA.** Where to find the literature: an annotated bibliography of sources for life science education. *Ann NY Acad Sci* 701: 91–94, 1993.
12. **Michael JA.** Students' misconceptions about perceived physiological responses. *Am J Physiol Adv Physiol Educ* 274: S90–S98, 1998.
13. **Michael JA, Richardson D, Rovick AA, Modell H, Bruce D, Horwitz B, Hudson M, Silverthorn D, Whitescarver S, and Williams S.** Undergraduate students' misconceptions about respiratory physiology. *Am J Physiol Adv Physiol Educ* 277: S127–S135, 1999.
14. **Michael JA and Rovick AA.** CV pathophysiology problems in small group tutorials. *Physiologist* 26: 225–228, 1983.
15. **Michael JA and Rovick AA.** *Problem Solving in Physiology*. Upper Saddle River, NJ: Prentice Hall, 2000.
16. **Mierson S.** A problem-based learning course in physiology for undergraduate and graduate basic science students. *Am J Physiol Adv Physiol Educ* 275: S16–S27, 1998.
17. **Mintzes JJ and Wandersee JH.** Reform and innovation in science teaching: a human constructivist view. In: *Teaching Science for Understanding*, edited by Mintzes JJ, Wandersee JH, and Novak JD. San Diego, CA: Academic, 1997, p. 29–58.
18. **Modell HI and Michael JA.** Promoting active learning in the life science classroom. *Ann NY Acad Sci* 701: 1–151, 1993.
19. **Modell HI, Michael JA, Adamson T, Goldberg J, Horwitz B, Bruce D, Hudson M, Whitescarver S, and Williams S.** Helping undergraduate students repair faulty mental models in the student laboratory. *Adv Physiol Educ* 23: 82–90, 2000.
20. **Paton R.** Students' deductive reasoning about state changes in model biosystems. *J Biol Educ* 25: 129–134, 1991.
21. **Rovick AA and Brenner L.** Heartsim: a cardiovascular simulation with didactic feedback. *Physiologist* 25: 343, 1982.
22. **Rovick AA and Michael JA.** *CIRCSIM: an ICM PC Computer Teaching Exercise on Blood Pressure Regulation. XXX Inter-*

national Union of Physiological Sciences Congress. Vancouver, Canada, 1986.

23. **Rovick AA and Michael JA.** GASP: a Computer Program for Teaching the Chemical Control of Ventilation. XXXI International Union of Physiological Sciences Congress. Helsinki, Finland, 1989.
24. **Rovick AA and Michael JA.** The prediction table: a tool for assessing students' knowledge. *Am J Physiol Adv Physiol Educ* 263: S33–S36, 1992.
25. **Rovick AA, Michael JA, Modell HI, Bruce D, Horwitz B, Adamson T, Richardson D, Silverthorn D, and Whitescarver S.** How accurate are our assumptions about our students' background knowledge? *Am J Physiol Adv Physiol Educ* 276: S93–S101, 1999.
26. **Towns MH and Grant ER.** "I believe I will go out of this class actually knowing something": cooperative learning activities in physical chemistry. *J Res Sci Teaching* 34: 819–835, 1997.
27. **Van der Vleuten CPM, Dolmas DHJM, and Sherpbier AJJA.** The need for evidence in education. *Medical Teacher* 22: 246–250, 2000.
28. **Walters MR.** Case-stimulated learning within endocrine physiology lectures: an approach applicable to other disciplines. *Am J Physiol Adv Physiol Educ* 276: S74–S78, 1999.
29. **White BY and Frederiksen JR.** Qualitative models and intelligent learning environments. In: *Artificial Intelligence and Education, Learning Environments and Tutoring Systems*, edited by Lawler RW and Yazdani M. Norwood, NJ: Ablex, 1987, vol. 1, p. 281–305.
30. **Wood D, Bruner JS, and Ross G.** The role of tutoring in problem solving. *J Child Psychol Psych* 17: 89–100, 1976.
31. **Zoller U, Lubezky A, Nakhleh MB, Tessier B, and Dori YJ.** Success on algorithmic and LOCS vs. conceptual chemistry questions. *J Chem Educ* 72: 987–989, 1995.