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From Mathematics to Technology: A Bridge through Physics and Engineering

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Abstract — The deaf and the dumb equations of *mathematics* are made to speak through *physics*, which is the formulation of general laws applying, mainly, inductive logic. *Engineering* is modeling from the general laws to create practical systems. *Technology* is the implementation and the adaptation of a laboratory model to create a working system, which could be mass-produced. The journey from *mathematics* to *technolog*y could be considered as a journey from the abstract to the concrete, *mathematics* being in books, in the minds of philosophers, *physics* making contact with the outside world, *technology* becoming the stage, where one enjoys the blessings. The training of mathematicians and physicists should inculcate creative thinking and make them capable to critically analyze problems, taking them from various stages of concept building to equip them with problem-solving skills. Problem solving in the classroom should prepare them to problem solving in the laboratories, and, eventually, problem solving in the industry. This paper illustrates how simple activities, like measurement of height and determination of safe-viewing distance for watching television could reinforce concepts and techniques from various disciplines, including biology, chemistry, engineering, health and safety, mathematics as well as physics. Mathematics curricula should give students the practical skills needed by a prospective employer. The paper describes the behavior-based interview format for teachers in mathematics, elaborating technical and performance skills needed for these jobs and examines if the recently-prepared mathematics curricula for BS, MS and PhD by Higher Education Commission, Government of Pakistan are preparing students in this regard and whether they are, properly, interfaced with the pre-university curricula.

Keywords: Curriculum development, concept building, problem solving

Introduction

In order to capitalize on the strengths of mathematics, having the power of generalization and the power of application, to formulate and to propose “smart” solutions, which enhance man's quality of life by converting them into technological products, services and processes, which are comfortable, economical, environmentally friendly and safe, one needs to build a bridge from mathematics to technology, passing through physics and engineering. It will only be then that the number and the equations of mathematics shall have impact on technologies and job-market shall be opened to mathematicians. However, it must be realized that the mind-set of a mathematician is to be able to obtain the solution, whereas the mathematician might not be able to set up the problem, efficiently. A physicist, one the other hand, may formulate the problem in the best-possible framework, but may not be well equipped to solve it. In other words, the former *can do, but not see*, whereas the later *can see, but not do*. The solution, therefore, lies in dialog between the two.

The study of Physics occupies a most important part of today's education. However, physics without mathematics would become philosophy. An important question may be what is, really, physics and what is not physics. Is physics the answer to all of the questions faced by the humankind? One must realize that physics has its limitations. In fact, it can only deal with what can be observed or felt. It is unable to make value judgments. Further, there are limitations of time to find the answer as well as lack of absolute certainty in the answers. One must be surprised to realize that even the well-accepted theories have a dead end, somewhere. Consider big-bang theory of creation of the universe. What was there before the big bang? How was there such a huge energy concentrated in a small volume? These questions and others do continue to haunt minds of the inquiring and the seekers of truth. To quote Freeman Dyson [1] of the Institute of Advanced Study, Princeton, USA: "no matter how far we go into the future, there will always be new things happening, new information coming in, new worlds to explore, a constantly expanding domain of life, consciousness and memory".

Physics teaching in Pakistan is facing a dilemma these days [2]. Students are not motivated [3]. Most of the time they lack basic concepts of the scientific

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method [4, 5]. There is a need to develop undergraduate and graduate physics curricula [6, 7], which inculcate creative thinking and critical analysis in students [8]. Mathematical foundations, needed to develop the concepts and the ideas of physics, must be a part of this curriculum [9]. A physicist's training [10] should result in creating concepts about energy, conservation laws, equilibrium, steady state and non-equilibrium. It should introduce the incumbent to paradigm shifts in physics [11]. A physicist equipped with crystal-clear concepts should be able to solve problems, in the classroom, in the laboratory and, finally, practical problems related to industry.

Stages of Concept Building

No matter how good the curriculum is, it would not serve its purpose unless the teachers are motivated and their own concepts are clear and firm [12]. A concept is built in four stages — acquisition, formation, development and application. Before teaching a new concept students' perception of the topic must be assessed [13]. Any wrong or distorted concept, already, present must be identified. With the right concepts mapped properly, the students shall be able to relate and to borrow concepts and techniques learnt in various disciplines and sub-disciplines for the solution of problem(s) at hand [14, 15]. Given below are examples, which show similarities in different disciplines**:**

a) Electrical and gravitational potentials**:** similarity in mathematical expressions
b) Fast freeze in structural biology and fertilizer production**:** similarity of processes

Concept Building through Activities

Here is an example of how the author introduced a few concepts in physics and mathematics through activities. A seven-year old child, student of class two, was watching television, while sitting close to it. She had not learnt measurement techniques and multiplication. The goal was to measure a distance five times the diagonal length of the television screen, to be marked as proper watching distance. The child did not know how to measure a length. First, she had to be taught how to take the length of an object, say, a pencil. To find the length she aligned the pencil with a ruler, placed, somewhere, in the middle of ruler. She took one reading at the tip of pencil and another at the end. She, then, subtracted the later from the former. This was a practical application of subtraction. She was suggested that a length should not change if readings are taken using some other part of ruler. She verified the idea and, hence, learnt the concept of reproducibility. Next, she applied the measurement technique, just learnt, to measured the diagonal length of the television screen. Since, she had no concept of multiplication, she added the figure five times to obtain safe distance. Finally, she measured this distance from the television screen to find a proper seating place. Such activities reinforced the concept of safe-viewing distance, at the same time teaching many other concepts and skills. The concepts learnt were**:**

a) Meter as unit of length
b) Measurement techniques
c) Reproducibility of measurements
d) Mathematical concept of multiplication as repeated addition
e) Practical application of subtraction (to compute length)
f) Health and safety concept of safe distance to watch television

Concept Mapping through Different Disciplinary Perspectives

Height measurement may be looked from different perspectives and used as an activity to generate, illustrate and link concepts in various disciplines:

Biology:	Food metabolism
Chemistry:	Conversion of food into "tissue synthesis" (gaining of height)
Engineering:	Level surface needed, mounting of engineering tape
Health and Safety:	Ascertaining nutritional status, failure to gain height may be a signal to some physical or psychological problem
Mathematics:	Serial measurement, graph, slope, time series, prediction of adult height
Physics:	Measurement technique, reproducibility, applying equal weight on both feet

Application of Concepts: Problem Solving

There has been a saying: I have learnt all the theory, but I cannot solve any problems. In other words, I have crammed all the equations and the formulae, without understanding their significance, their applicability and their limitations. A hands-on approach is required to *Experience Physics*. If one learns physics concepts properly, one should be able to solve *unseen problems* (unseen problem is the one not covered in tutorial or in homework). This is the major difference in teaching strategies of Pakistani institutions versus US institutions. The former focus on definitions and derivations, whereas the later emphasize on concept building and problem-solving skills.

Problem Solving in the Classroom

Students face difficulty in setting-up a word problem. Solution becomes easier if the word problem is dissected as follows**:**

*Data***:**	Whatever is “given” in the problem
*Objective***:**	Whatever is "to find" (to draw, to prove) in the problem
*Solvability***:**	Whether the problem is over determined, critically determined or under determined
*Strategy to solve the problem***:**	The physical law or the mathematical equation applied to solve + the assumptions/the limitations of the model used [mention of alternate methods available, the most efficient and the most effective method to reach a solution]
*Setting-up of the problem***:**	Coördinate axes, diagrams, conversions in SI [include a table of conversion factors used, symbols/terms used] [16]
*Solution of the problem***:**	Solution using mathematics, physics or logic [solution to be in two columns, the left-hand column containing steps of the solution and the right-hand column their justifications]
*Result(s)***:**	Should be quoted to proper significant figures, solely in the language of data and objective, without referring anything introduced in setting-up of problem

Problem Solving in the Laboratory

Laboratory problem solving is a very systematic activity. Following are the steps needed to solve a problem using the scientific method [17]**:**

a) Observing a natural phenomenon.

b) Developing a question about cause and effect.

c) Formulating a tentative answer to the question (the hypothesis) through inductive generalization from the observations.

d) Testing the hypothesis by taking further observations/conducting an experiment.

Problem Solving in the Industry

Industrial problem solving is a focused activity. One has to develop a marketable product/service or improve properties of an existing product. For this purpose one needs to have a well-defined statement of the problem, formulated after comprehensive literature survey. Before embarking on a full-scale project, one must conduct feasibility studies, and run pilot projects. For this purpose, one may need to design *efficient experiments*. Efficient experiments identify scope of the project, the variables of interest and their interaction at a very early stage. *Poor experiments* can result in wrong decisions. *Inefficient experiments* result in excessive cost or time delay in reaching a decision. The main reasons are lack of training in the strategy of experimenting, incorrect decisions based on insufficient data, bad engineering decisions by setting vague objectives for projects, inappropriate statistics courses taught in the colleges and in the universities [17]. One may, then, embark on developing prototype, phenomenological, or fundamental models as per requirements of the end user. Simulations, test runs and field trials may be needed to improve the model, so as to make the product/the service commercially viable [18].

The first stage of industrial problem solving is developing a project proposal, outlining the funding, the resources and the time constraints involved in accomplishing the task. The outcome could be a product or a service.

Curriculum of Mathematics at the University Level

The philosophy behind developing university and pre-university curricula is to cultivate habits of creative thinking and critical analysis by providing highly-motivated students sufficient depth as well as adequate breadth of the core and the related subjects so that they can make informed, independent decisions under stressful situations and to integrate the various aspects of curriculum development (Fig. 1) – why to teach**:** philosophy; what to teach**:**

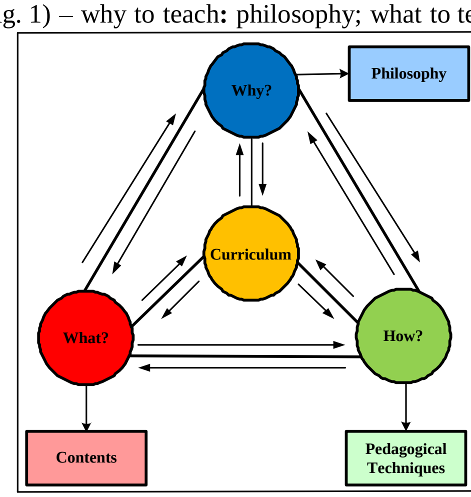

Fig. 1. Philosophy, contents and pedagogical techniques — their relationship with curriculum development (Mathematics Curriculum of HEC 2008)

contents; how to teach**:** pedagogical techniques – in such way that the student is educated to become a *manager* of resources of the universe (not a *thief*) and shall know relationship with Allah, self and environment [19].

Mathematics curricula need to be developed taking into account the breadth (reinforcing and building on the concepts and the techniques taught in other allied branches, say, physics, without duplicating) and the depth (preparing content-outline chart, containing the level, the concept, the activity/the experiment to reinforce this concept, the reference and the philosophy behind teaching this concept). There should be customized mathematics courses for students majoring in different disciplines. Guidelines for mathematics courses for non-mathematics majors are presented below. Each guideline should be read with the statement — the course(s) should make the student**:**

Mathematics for Biologists

a) Identify the essential mathematical tools to appreciate biological processes, *e. g.*, exponential functions to model cell growth, logarithmic functions to model ear response

b) Learn mathematical techniques in physiological modeling, *e. g.*, equation of straight line to predict height and weight of child and compute growth velocity

c) Be exposed to basic statistical tools, *e. g.*, concept of percentile to interpret growth curves

d) Mathematics of equilibrium, steady state and non-equilibrium (as rates of energy transfer as well as probability of occupation) to study physiological processes

Mathematics for Chemists

a) Visualize of periodic table as a matrix, with rows representing number of shells and columns representing valiancy

b) Appreciate that balancing a chemical equation is a problem of solving system of linear equations

c) Interpret the law of mass action (to determine reaction rates) as a special case of law of conservation of energy

d) Recognize structures (tetrahedron, hexagon, cube, cuboid) for the study of molecules and lattices

e) Use polynomial equations of order 3 or more to compute reaction rates

f) Develop understanding of curvilinear coördinates (cylindrical, spherical polar) to model various chemical processes, *e. g.*, flow in a pipe, computation of surface tension of a water drop

Mathematics for Linguists

a) Appreciate symmetry in nature and recognize in rhyming

b) Understand circular functions and Fourier series to get the concept of harmonics in generating difference in sound produced by various instruments as well as recognition of speech of different persons

c) Get the basic knowledge of functional analysis to establish one-to-one correspondence between the written word and the spoken word.

Mathematics for Physicists

a) Realize that visualizing form of mathematical equation describing a physical system would give insight into the nature of the associated physical system or process, in particular, properties of space-time, which are expressed in the form of scalar or tensor (relationship of eccentricity of orbit to energy and latus rectum to angular momentum in two-body problem, diagonilization of inertia tensor equivalent to rotating axes to align with axes of symmetry – principal axes of inertia, form of electric-susceptibility tensor for nonlinear, linear-isotropic, linear-isotropic-homogeneous dielectrics)

b) Appreciate the situations, where mathematics brings in new physics (negative eigenvalues of energy and suggestion of existence of positron [9], discovery of omega meson from group-theory prediction, experimental verification of bending of light near massive objects from a prediction of general theory of relativity, mathematical predication of expansion of universe, although not realized at that time), and where physics generates new mathematics (bosy numbers to model bosons, determinant of general tensor to model relativistic kinematics [20], astrodynamical coördinates to model planetary orbits [21])

c) Understand that setting up a physical problem closer to natural symmetries of a system (using appropriate curvilinear coördinates) shall render the equation simple to visualize and to handle (*e. g.*, using plane-polar and spherical-polar coördinates for problems having circular and spherical symmetries, respectively) — main consideration in choice of gaussian surface [22] and enunciation of strong Noether's theorem [23]

d) Apply exponentials to study of radioactive decay, charging of a capacitor

e) Obtain solutions of the second-order-linear-differential equation to study damped and driven oscillations and appreciate the phenomenon of resonance

Mathematics for Social Scientists

a) Learn the basic concepts of calculus to model changes in attributes and opinions

b) Know basics of statistics to design and to analyze surveys, *e. g.*, concept of percentile to interpret standardized tests

Salient features of mathematics curricula at the university level are given here [24, 25]. For the BS program, courses are prioritized according to must know (foundation), should know (major) and nice to know (electives). The depth and the breadth are given in terms of *precedence graphs* (flow charts) [depth**:** pre-requisites] and *influence graphs* [breadth**:** co-requisites], respectively (Fig. 2). Course Supervisor is required to distribute syllabus-breakdown into 14 units, each unit completed within a week. Lecture sessions of each unit (normally, 2-3 lectures) are followed by a tutorial session (reinforcing the concepts taught through examples, alternate derivations and proofs) as well as a problem-solving session (teaching skills of problem formulation, quailtative analysis and finding solutions), each of these sessions conducted, separately, by the Associate Instructor at the end of lecture session of every unit. In addition, a review session should be arranged prior to each monthly test (hourly) and a comprehensive review before the final examination, both sessions conducted by the Course Supervisor. Course Supervisor (Instructor) is required to prepare a progress report after each hourly, mentioning tentative grade (cumulative grade based on all hourlies, quizzes, problem sets and assignments taken to date) and attendance record (pilot tested at IBA and SZABIST by the author). It may, also, include qualitative description of student's weaknesses and areas needing special attention. Laboratory and theory portions are separate passing heads. This report is discussed with the student as well as student's parents, if unsatisfactory. For the MS (PhD) program, GRE (General) and GRE (Subject) are entrance requirements, whereas masters (qualifying inations), consisting of both written and oral portions are required for confirmation of admission. Graduate problem-discussion session focuses on reinforcing the concepts taught through examples, alternate derivations and proofs as well as innovative solutions to the problems. It is considered essential to impart some teaching experience to graduate students at the university level by asking them to act as Associate Instructor (Teaching Assistant) in a BS course. Each course taught by the student earns a practical-experience credit and is graded according to at least two of the following evaluation criteria:

a) Feedback from students

b) Lecture/Tutorial/Problem-solving session observation by senior teachers

c) Videotaped lecture/tutorial/problem-solving session evaluation by experts

Pre-University Curricula of Mathematics

It is imperative to interface university curricula with pre-university curricula. A survey of pre-university curricula was done earlier [2]. As Member of Expert Panel (Mathematics), National Curriculum Council, Ministry of Education, Government of Pakistan, the author reviewed outline for Classes I-XII Mathematics Curricula [26-28] as well as developed and applied criteria for review of textbooks. This exercise has helped National Curriculum Review Committee (NCRC) for Mathematics, Higher Education Commission to interface BS curricula with pre-university curricula (NCRC has 2 members, who, also, worked for developing the pre-university curricula).

Training for Practical Life

Through the professional-skills-seminar series,

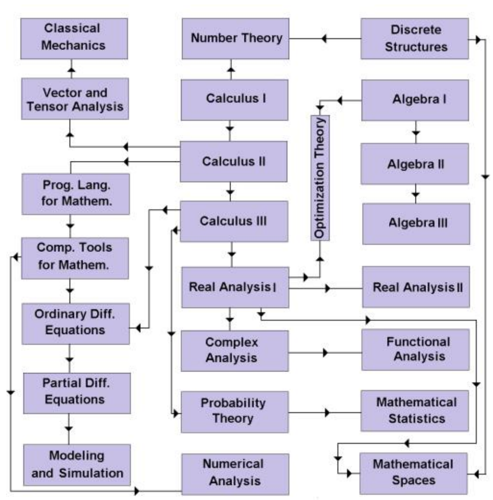

Fig. 2. Precedence and influence graphs representing pre-requisites and co-requisites for BS courses (Mathematics Curriculum of HEC 2008)

the students are trained in the skills required at the job. Department of Mathematics holds regular seminars and engages in dialogs with prospective employers to bridge gaps between the skills taught in academia and those required in the job market (one such skill is *Mathematics of Experiment Design* [29]). Students are trained through vita preparation and mock interviews to present their technical and performance skills, backed up by concrete evidence. Here is the format of behavior-based interview, regularly conducted to hire contract teachers in Department of Mathematics (Fig. 3).

Conclusion

In the words of *Daniel Tanner* and *Laurel N. Tanner* (Curriculum Development**:** Theory into Practice), curriculum of a subject is "the planned and the organized learning experiences, formulated through the systematic reconstruction of knowledge and experience, under the auspices of the institution, for the learner's continuous and willful growth in personal-social competence." By looking at the curriculum, one can judge the state of intellectual development as well as the state of progress of a nation. World has turned into a global village. It is, therefore, imperative that curriculum development must be a *process* not an *event*. It must be constantly evolving on the basis of inputs from students, peers, parents and experts, and must conform to needs of the society it is designed for, dealing with indigenous problems.

Job Announced	**CO-OPERATIVE TEACHER (MATHEMATICS)**						
Date & Time of Interview[1]	Tuesday, August 8, 2006; 0830h						
Venue	Office of the Chairman, Department of Mathematics, University of Karachi						
Name of Candidate[2]							
Interview Structure		*Technical Skills*	*Résumé*	*Actual*	*Performance Skills*	*Résumé*	*Actual*
Introduce Panel		Right Concepts			Concept Building		
Rapport-Building Question		Numeracy			Concept Mapping		
Open-Ended Question[3]		Problem Formulation			Generating Questions		
Specific Examples[4]		Problem Solving			Handling Questions		
Allow Silence/Maintain Control		Creative Thinking			Handling Large Class		
Contrary Evidence		Critical Analysis			Handling Smart Students		
Proper Conclusion		Equation Formulation					
		Interpretation of Graphs			Handling Trouble-Making Students		
Knowledge		Time Management					
MA/MSc in Mathematics		Chalkboard Organization			Motivating Students		
		Lecture Planning			Creating Leaders		
Attitude		Lecture Organization			Guiding (Academic)		
Grooming/Tidiness		Covering Entire Syllabus			Guiding (Career)		
Punctuality		Continuous Assessment			Character Building		
Confidence/Posture/Gait		Classroom Layout			Cultivating Emotional Intelligence		
Positive/Negative Thinker		Oral Communication					
Determination		Research Methodology			Cultivating Relationship Strategies		
Perseverance		Project Management					

1 *Basic Principle*: Past behavior is the best indicator of future performance.
2 All names must be written in BLOCK LETTERS.
3 Generalities
4 Past Examples
Learn to interpret the answers
Plenty of questions

Marks out of 100 ____ Marks out of 100 ____ Marks out of 100 ____

Member *Member* *Member*

Recommended/Not Recommended

Chairman of the Interview Board

Fig. 3. Behavior-based interview for mathematics teachers

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