INTRODUCTION TO HEURISTICS
OF INVENTION AND DISCOVERY

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of Graduate Students to Make Planned Inventions

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A course designed to fill a recognized gap in engineering and applied science education (1) will be offered for the third time in January 1970 in the Materials Science Department of the School of Engineering at Stanford University. The course in intended for those graduate (2) students who are actively pursuing careers in applied science or engineering. Its aim is twofold: firstly, to transmit an understanding of discovertive and inventive human behavior; secondly, to assist in the development of these mental skills within the student's own field. Teaching to be inventive is quite analogous to Scheffler's carefully analyzed case of teaching to be honest (3). In Scheffler's own words, one is "confronted immediately with the delicate educational problem of attempting to develop at once patterns of action and impartial reflection on such patterns."

The idea to design and implement such a course was born from the desire to influence the trend of contemporary university education. It was felt that engineering education should be bent away from narrow patterns of introvertive technical training toward freer manipulations of these skills and exercising of services more responsive to societal needs. The inertia and opposition to the proposal for such an undertaking, which had been expected from the academic extablishment, did not materialize. The unexpected support for this undertaking can be traced to three factors: (i) the ground had already been cultivated by the late Professor John Arnold, who for several years had taught "Creative Engineering" at Stanford, a course which he originated at MIT fifteen years ago, (ii) the Department of Materials Science was already headed in the direction of despecialization (4) and (iii) students had a better appreciation of their educational needs than many faculty members were willing to give them credit for. The third factor's existence became quite apparent from the answers given in response to a questionnaire which was distributed during the first class meeting. Over 80% of the respondees expressed strong belief that such a course could enhance their creativity and needed no "selling" of the idea.

ENGINEERING AND SCIENCE

A great portion of contemporary engineering education at American universities has come under the tutelage of professors whose backgrounds are primarily in "pure science." This situation culminates a historical process which began seventy years ago. It was then that the American Physican Society was founded by individuals like Michael Pupin, the first professor of Electrical Engineering at Columbia University. He decried the lack of intellectual pursuits by the then older professional engineering societies, such as the American Institute of Electrical Engineering (5). In October 1899, Henry A. Rowland delivered the first APS presidential address in which he called physics "a science above all sciences" and physicists intellectual aristocrats "needing sustenance in the midst of a world which gives its highest praise, not to the investigator in the pure ethereal physics, which our society (APS) is formed to cultivate, but to the one who uses it for satisfying the physical rather than the intellectual needs of mankind" (6). Accelerated changes in the official United States' attitude toward science took place during the Civil, (7) First, (8) and Second (9) World Wars. The traumatic transformation from the obscurity of a University professor at Princeton Universisty in the mid-thirties to a public personality besieged by reporters and politicians in the mid-fifties was vividly autobiographed by Eugene Wigner during a public lecture (10). That practical fruits are derived from seeds of theoretical scientific contemplations has become part of the public belief system even though the intervening engineering growth and cultivation is often overlooked. A telling point is made by Kranzberg of the very complex interrelationships that exist between science and engineering (11). He states that no simple non-reciprocal coupling can be postulated in either direction and that snobbish attitudes of scientists asserting intellectual and moral superiority over engineering are responsible for a socially and psychologically perceived status gradient between these two professional segments of our society. According to Greenberg (12), Edward Teller is one of the apostles of the need to improve the quality and status of applied science. Teller complains that, in our educational institutions, it is located in a "no-man's land" (13). Teller, as well as two other prominent physicists, Wigner and Dirac, all come to science via an early engineering education. It is thus hardly surprising that they posses a dual insight; they understand the engineering as well as scientific points of view.

The accelerated importance of science caught engineering schooling off guard in the late forties. Only slowly did engineering educators adapt to the new climate and introduce contemporary science into their curricula. However, at the close of the sixties the pendulum has come full swing. It is now recognized by some government leaders that engineering education is overly based on science and removed from engineering and inventive acts needed to bring the benefits of science and technology to society (14).

In the words of the former Assistant Secretary of Commerce for Science and Technology, "Engineers in graduate education are concerned with learning more, rather than learning how to do more. Increasingly, engineering educators come from universities alone. Their backgrounds have been in the academic world, without experience either as engineers who design, inventors who invent, or enterpreneurs who establish invention-based businesses." These sentiments are shared by prominent educators (15) who find engineering and applied science education in general unsuccessful in the building of qualities of self-reliance, imagination and effective reduction to practice.

A much more critical position is taken by a psychiatrist specializing in the treatment of neurotic professionals who posses high creativity (16). He believes that contemporary educational practice is generally inhibitive as well as destructive of free expression and effective use of imaginative contributions. He calls education which interferes with uncouscious forces and damps thinking a fraud. Hence, it may indeed be the case that the disciplined butflexible exercise of choice, the essence of heuristic skills, survives in the student not because of, but in spite of the educational process.

The Stanford course is a conscious effort to wrestle with the above predicaments and impediments. It not only tackles the psychology of ideation and symboling, which underlies inventive behavior, but it also examines parts of the motivational power system that drives discoverers and inventors; thus sociological regulatory interactions of professional subcultures are made visible and related to personal motivational forces and their operation within specific reward networks.

Throughout the course science and scientists are systematically demythologized by topical injections of items from the works of writers such as Kuhn (17), Hagstrom (18), and Sykes (19). Confidence in the inherent value of engineering activities is promulgated by proposing a complementary role for the scientist, thus counteracting the stratification that socially subordinates engineering. Expressions of insight into the nature of professionalism in science and engineering are elicited from the students and their self-confidence level is steadily upgraded.

In having described above the contemporary problems of technical education, we might have overemphasized the shortcomings of the educational establishment. We would like to acknowledge that the present educational community nevertheless does offer various opportunities to resolve these problems. In fact, it was the "Cooperative Work Study Program" of the School of Engineering, University of California at Berkeley, which brought us together four years ago at the Hewlett-Packard Laboratories. The program is designed to supplement the student's academic experience by exposing him to an industrial atmosphere. The encounter between student-engineer and industrial researcher in a project situation (20) established ties which helped us to transplant our cooperation into a classroom environment. Consequently, last year's course benefited from a vastly improved communication path between student and teacher. This led to a better set of assignments and tests. We think that we arrived at a balance which realistically matches the students' potential to the teacher's expectations. In the writing of this article we have tried to preserve our dual view point of the educative process.

OVERVIEW OF LECTURE TOPICS

From the student's point of view, the lectures were indispensible. Unlike other courses, where the material covered can be more or less easily found in some published form, most of the subject matter and its background was available only through listening to the lively oral presentations. Parts of the course were quite foreign to physical science and engineering students. This is evident from the three major subdivisions of the course: i) a concerted treatment of the psychology of ideation with emphasis on the generation and evolution of scientific knowledge; ii) a multifaceted description of science from functional points of view; iii) a presentation of creative engineering that derives from a personal commitment to heuristically relate the available "know-how" to the desired aims of the inventive act.

The course was introduced through a description of a vague anthropological time-correlation between accelerated population growth and occurences of profound inventions and discoveries. This was followed by a classification and description of psychical events into perceptual, cognitive, and ideative categories in order to investigate the arousal capacity of symbols and signs without which apprehension and communication would not be possible (21). Sidestepping the usual philosophical and mathematical approach to formal logic (22, 23), a less rigorous psycholinguistic tack was taken to formulate generalized grammars dealing with attitudinal orientations in contrasting generalization against specialization, induction against deduction, and abstraction against concreteness. The Peircean retroduction (24) and the Hessean analogy (25) were introduced as more adequately descriptive of the psychology of invention and discovery. The Eatonian interpretations of objects, identities, diversities and universals were treated in detail (21). Symbols and other syntactical manipulants were then derived from them. The subject of scientific truths was examined from several vantage points and related to the credibility of conjectures, strength of evidence, deterministic against stochastic causal relations, and provisional against predictional beliefs or judgements (26).

The first view of science was presented as a method of retroductive modelling and theorizing of heuristically sampled observations, which, through unprecedented action, enables the thinking of new thoughts in a milieu not designed to receive them (27); the second view of science was described as a transpersonal system of retrievable, codified, and systematized information about the results of the above mentioned method (first view); the third view of science was given as a metastable portion of an interpersonal transaction known as common sense (28), which is subculturally shared by the scientific community operating under a set of values separate from those of other peoples (18). The fourth view of science was that of an historic process visibly separable into a predogmatic and postdogmatic period of paradigmatic belief (17). After this multifaceted description of science, several lectures centered on the patterns of discovertive behavior, their modifications and bias through cognitive, emotional and social inhibitors and their dependence on the topography of the existing boundaries of scientific knowledge. Models and theories of discovery were derived and checked through comparison with case histories of well documented events such as Kepler's planetary orbit discovery (27), Oersted's electromagnetic action discovery (29), Thomson's electron discovery (30), Roentgen's x-ray discovery (30), Dirac's hole discovery (30) and Bardeen's et. al. transistor discovery (31).

The concept of engineering was introduced through recasting and extending the Nagelean teleological description of biology (23). His definition of a goal oriented system of interdependent parts served to define the engineer as a systems designer exploiting the relevant characteristics of these parts and minimizing the effects of their nonessential and often detrimental aspects. Since the combinatorial possibilities of design are astronomical in number, a selective principle, heuristics, becomes indispensible. The medieval work of Lull (32) was introduced as an example of nearly automatic generation of combinatorial concepts which in turn could give rise to novel and unprecedented ideas. The Tuskaen classification of inventive methods (33) was contrasted with more systematic discoverative methods (34) and case histories were discussed (35, 36). The inseparability of engineering from common social values (37, 38) was compared with the mostly separatistic values of scientists (17, 18). The latter were presented through the medium of real-life episodes (39, 40, 41).

The concreteness of the student's role in inventive problem solving was established through an illustration of 24 possible steps. This was followed by a description of formal technological surveillance and forecasting procedures (42) useful in optimally selecting a high pay-off field or problem. The feasibility of automating discoveries and inventions was discussed in the light of contemporary views expressed by a number of experts on artificial and natural intelligence (43, 44, 45).

TESTS AND ASSIGNMENTS

In order to foster the development of inventive behavioral patterns, habits and skills, the student was asked to carry out home assignments and undergo in-class tests. These were formulated on the basis of selectively isolating elements of such patterns and habits and transforming them into assignable tasks.

The first test was given to demonstrate at the onset that strong lingual and psychological bias, generated by a relatively complex wording of the assignment, can slow or even block the solution of a simple mathematical problem. The test read: Try to devise at least one rule (not previously taught to you) which will enable you to select non-prime odd numbers. Construct a hisoriogram of your trials. If successful, can you identify the crucial hunch which led to the rule? Do you think that there is a rule for getting such hunches? Are you able to circumscribe such rule, even in the vaguest terms?

About half the students either failed to devise a rule or devised an incorrect one. Only a minority (35%) were able to exhibit an understanding of the structure of attack on the problem (46). The results of the test were used to illustrate the meaning of denumerative versus non-denumerative class formations, their definitions, and the apparent paradoxical character of negation which often generates "psychological sets" and "mental blocks."

The follow-up assignment required the idiocratic defining of concepts such as: common sense, evidence, harmony, and patterning. A subsequent comparison with their lexical counterparts sharpened the student's awareness of the uniqueness of his own idioms.

The next assignment dealt with signs and symbols selected to have a close proximity to each student's professional activity. It required a detailed signification mapping between the selected signs or symbols and the objects they signified. A search for both the historico-emotive charges engulfing the symbols and the potential problems which may arise through their excessive hold on the mind was carried out by the students. Several levels of abstractness and their historico-emotive charge in the interpretation of concrete symbols were illustrated through recounting an incident which occurred in September, 1960, during the First Bionics Symposium (47). At the conclusion of the meeting, Prof. Otto H. Schmitt pleaded for a futuristic symbol instead of the time-worn "tinner's soldering iron integrated with the resurrectionist's scalpel, all (three) essentially unchanged in the last century or two." He suggested " a neurone looped to a transistor via a circle of biochemist's process arrows." He was responded to by one of the contributors, E. E. Loebner, who criticized the literalness of such an interpretation and pointed out that the scalpel could funtionally symbolize analysis, the soldering iron synthesis, and the integral sign a unification of both (See fig. 1).

The fourth assignment followed a test of creativity based on the students' ability to mentally coexist at several levels of meaning, while remaining aware of the commonality as well as distinctiveness of relevant concepts, ideas and precepts at each level. This was done by testing their polysemantic skill to produce as many lexical definitions of homonyms selected from a long list that included words such as marble, mission, and matter, all of which have over ten dictionary definitions. The assignment required the student to sort out or discover a single algorithm which when applied to a majority of the polysemnants, produced a simple mapping between corresponding segments comprising the lexical definitions of the selected polysemnants. An example of such a task is shown in Table 1, which contains the segmented structure within analogy bands AB1 through AB5 for the various lexical definitions of the polysemnant word MATRIX.

The next assignment asked the student to invent a verbal or diagrammatic model of one of the following: 1) Science, 2) Common Sense, or 3) Discovery. Examples of students' work are discussed under the following subhead entitled "Models are Everywhere".

The last assignment consisted of a trip to the Sunnyvale Patent Library (48) where the students obtained the three most recents patents issued in the subclass of their interest. A detailed critical evaluation of these patents was called for. The subject of this assignment is discussed under the subhead "Getting Ready to Invent".

The final examination called for "structured inventing," and was specially written for each student. It demanded the solving of a problem in a manner inviting an inventive extension of selected aspects or concepts relating to the subject matter treated by the student in the above patent assignment. Most students produced valuable disclosures of original inventions in 2 to 3 hours. A description of the examination is given under the subhead "Inventing By the Clock".

MODELS ARE EVERYWHERE

The contemporary student of exact sciences is inevitably exposed to models. However not always does he realize that they are constructed through imperfect property mappings and are quite vulnerable to the passage of time. Thus he seldom acquires a flexible attitude toward their idiosyncrasies and constructional variants. Most often he is presented with established models on a silver platter and induced into thinking that original model generation is reserved for a higher level of professional maturity. In this course the student is encouraged to invent model after model at every opportunity.

Great insight and awareness of the benefits and pitfalls of modelling are found in a very famous and often referred to paper by James Clark Maxwell (49). The reader is cautioned that the words "physical hypothesis" are interpreted here as model. We quote:

"In order therefore to appreciate the requirements of the science, the student must make himself familiar with a considerable body of most intricate mathematics, the mere retention of which in the memory materially interferes with further progress. The first process therefore in the effectual study of the science, must be one of simplification and reduction of the results of previous investigation to a form in which the mind can grasp them. The results of this simplification may take the form of a purely mathematical formula or of a physical hypothesis. In the first case we entirely lose sight of the phenoma to be explained; and though we may trace out the consequences of given laws, we can never obtain more extended views of the connexions of the subject. If, on the other hand, we adopt a physical hypothesis, we see the phenomena only through a medium, and are liable to that blindness to facts and rashness in assumption which a partial explanation encourages. We must therefore discover some method of investigation which allows the mind at every step to lay hold of a clear physical conception, without being committed to any theory founded on the physical science from which that conception is borrowed, so that it is neither drawn aside from the subject in pursuit of analytical subtleties, nor carried beyond the truth by a favourite hypothesis.

In order to obtain physical ideas without adopting a physical theory we must make ourselves familiar with the existence of physical analogies. By a physical analogy I mean that partial similarity between the laws of one science and those of another which makes each of them illustrate the other."

We find it ironic that educators in physics and electrical engineering have drilled many generations of students in the recital and rederivation of the "four equations" without passing on to them Maxwell's philosophy and methodology of using models, which he considered indispensible and complementary to mathematical theorizing.

The function of models is debated in the delightful booklet by Mary B. Hesse (25) in the ancient manner of a Greek dialogue between two philosopher-physicists personified by Pierre Dubem and N. R. Campbell. The former claims that the whole of a physical theory is constituted by a cluster of abstract ideas and general propostitions, verbalized geometrically and algebraically and cemented by logic. Dubem objects to the incoherency and superficiality of models and their tendency to distort the mind from the search for logical order. Campbell dissents; he considers analogies to be utterly essential parts of theories. The suggestion that analogies are psychological aids, he finds "absolutely false and perniciously misleading".

The Hessean approach to modelling and its meaning is illustrated in Figs. 2 and 3. Models are two-dimensional systems or structures (matrices) of ordered properties. The rows represent corresponding similarities (50). Column to column thus exhibits a similitude mapping. One row is presumed to be associated with a second row by some kind of causative link, expressable in terms of physical law statements. The mapping and similitude concepts of the MBH Model of Models (MoM) are closely related to the Shockley-Gong ACOR, one of their four "basic science-thinking tools" (51). The ordering by similitude offers a very powerful unique feature. It enables an inference based on analogy. It is one of Mary B. Hesse's important contributions to point up that startling new predictions about the real world are derived from the $B_1(W):B_1(M)::?:B_n(M)$ operation in the MBH MoM, whereas the classical inductive method of generalization is quite barren.

Under the preceding subhead we mentioned the three choiced assignment of inventing models. One student chose to model "science" and its relationship to engineering, technology and mankind in general through an animated flow chart diagram. In that model the scientist picks up individual facts and puts them through a sequence of processing machines which shape them into well formed "bricks" of scientific laws and theories. These bricks serve as building elements of a larger structure, which is part of overall "Science", which furthermore receives, as inputs, the byproducts of technology. Technology in turn receives its inputs from the engineer who draws on the supply of scientific laws and theories within science as his tools.

Another student's choice was a block diagram representing the function of common sense as part of our information acquisition, processing, storage and retrieval system containing several feedback loops linking observation, peer criticism and comparison against past experience. An example of the model of discovery was the use of an analogy to phase portraits as used in feedback control theory. It explained several categories of discoverative path patterns through mappings along the directions of experimentation and theorization. These in turn were adaptions of concepts from the egogram model discussed next.

A frequently employed model during the course was the tetrahedral egogram shown in Fig. 4. It was derived analogously to the square arrangement of the Greek model representing the four elements of matter: fire, air, water and earth flanked by their paired properties of dry, hot, wet and cold (see Fig. 5). In a lecture, it was pointed out that this ancient model of the building blocks of physical matter has lost most of its luster but not essential validity. In a world in which over a hundred further decomposable and transmutable chemical elements are recognized as nature's atomic building blocks, the four elements (also roots) of Empedocles are still participants in four states of matter. Here air represents the gaseous, water the liquid, earth the solid and fire the plasma state of modern physics, a classification quite pleasing when examining one's surroundings through biological senses alone.

The egogram is intended to be a psychological model of the four basic activities through which an individual acquires new knowledge. This tetrahedron is used to map the psychological dynamisms (52) that an ego experiences moving through this space. The four corners of the egogram symbolize idealizations, which cannot be realized in pure form. Physicists should find the concept of unattainable limits of pure dynamisms somewhat familiar. They will recall that quantum mechanics delimits the accuracy of simultaneously measuring conjugated quantities and of predicting the outcome of prearranged interventive actions. In other words pure observation without some interaction (for example the scattering of an electron by photons, which help to locate it) is not possible. The consequence to the model of this concept is the exclusion of the ends of the experimentation edge as allowable real world dynamisms. Loebner's conjecture is that a similar limitation and indeterminancy may be found operative for the other five pairs, symbolized by the remaining edges of the egogram. This conjecture is collaborated for the theorization edge by the above discussed Maxwell's suggestion that perfect and precise mathematical formalism without even the faintest intuitive grasp of the "physics" of the situation is as detrimental as the most wonderful insight when not accompanied by quantitative checks.

Just as people favor one hand over the other, the eye over the ear, or vice versa, so do individuals exhibit characteristic "ego-point" motions through the egogram space during discovertive and inventive behavior. The broader an individual, the more complete is his coverage of the egogram space and more diversified his abilities for innovative tasks. Inadequate coverage of a given corner can be used to diagnose more or less well known tendencies. Thus the want of formal deduction is characteristic of existential orientation, while the lack of intuitive insight leads to a pragmatism typified by Berthold Russel (53). Lack of employment of experienced observation leads to ideological activism while want of purposeful action produces ineffectual intellectualism. Quite often penetration toward the corners is limited to one or two corners. Three and four corner proximal individuals are quite rare.

In contradistinction to an astonishingly similar model (54) invented for the purpose of mapping research tactics, the "ego-point" motion through the tetrahedral egogram is not unidirectional but can take place in any direction.

The students in the course found the egogram model very useful in checking their problem solving behavior during assigned inventive or discovertive tasks as well as in developing the innovative aspects of their personalities.

GETTING READY TO INVENT

As part of the last assignment the students went to the Sunnyvale Patent Library (48) and found the patent office's class and subclass which best represented their academic and professional interests. Subsequently they located the last three issued patents in this subclass and carried out a critical study on them. This helped the students as well as the teacher to assess the current state of the art in a diverse number of fields.

The search for the appropriate class and subclass constituted a major portion of the assignment and contributed significantly to the student's understanding of the classification procedure used by the U. S. Patent Office. The students went first to the <u>Manual of Patent Classification and Index</u> and the Subclass definitions, and after choosing an apparently suitable class and subclass they used the <u>Annual Indexes to the Patents</u> to determine the patent numbers of the last three issued patents. The appropriate Gazettes (55) were then consulted and if the patent abstracts looked relevant to the student's area of interest, the patents were obtained and studied. For most of the students, this process had to be repeated several times before they were able to identify and locate the class and subclass most closely associated with their own interests.

The student's difficulties in trying to find the appropriate subclassifications stemmed from either of two main deficiencies: Some lacked clarity in and experience with those aspects of their chosen fields, which are most likely associated with patentability. They either searched for non-existing labels or for descriptions which are non-specific, i.e., found in a large number of subclasses. Others found it troublesome to locate that general class (or classes) which contained the subject of their specific interest.

The study that each student made of the patents he selected was designed to serve several purposes. It provided factual, up to date and to him relevant, examples of those contemporary inventions which had been recognized as patentable by the U. S. Patent Office. The simplicity and straight-forwardness of typical patent specifications (once the cumbersome language is mastered) helped the student to demythologize invention and thus overcome any remnants of awe and feelings of his own inadequacy he may still have harbored in spite of the many case histories covered in the lectures and readings. The critical evaluation of the invention itself helped him to set his own criteria and establish his own ratings of the scientific and technological contributions made by the inventor.

Finally his deep involvement in the subject matter provided motivation and incentive to make his own inventive contributions. Some of the sixteen questions the student was asked to respond to were: What is the need and how great is it, that has led the inventor to create his invention? To what degree has he satisfied that need in a non-trivial fashion? What is your assessment of the future impact of the invention upon technology and life in general? What is the invention and what is it not? How great, how startling, how unusual is the technical contribution, i.e., the magnitude of the step taken over predecessors? What are the disciplines which had a bearing on the invention?

From the student's point of view this assignment was reasonably difficult since it depended almost exclusively on the student's own resourcefulness and allowed little guidance by precedent. From the teacher's point of view it provided a problem solving situation suitable for objective evaluation. For this purpose weights were assigned to specific answers which were required by the assignment. An area of difficulty experienced by many students was their inability to precisely circumscribe the invention. However, all students were sufficiently free to express criticisms of various kinds concerning the inventions they studied. It was from such definitive critical stands, which they individually took, that the subject matter for their final examination was gleaned. Great care was taken to shape the questions in their own words and in their own framework. This obviously required that each student's examination be written separately. While an individualized set of questions was provided, the examination followed a general and standardized pattern. In those cases where the work on the last home work assignment appeared insufficient to prepare the student for the final examination, further specific instructions for study of the patents themselves or related subjects were given.

The topics covered by the final examination were: vertical take off and landing aircraft, children's toys, accounting machines, new materials for bone implantation, bootstrap computer programs, sputtering of thin film semiconductors, new applications for beryllium alloys, synthesized inductances, improved radio frequency shields, solid state ignition systems and teaching machine systems. This multi-disciplinary coverage proved quite stimulating to both students and instructors.

INVENTING BY THE CLOCK

The course was structured to provide a gradual build-up to a finale. The student was guided to a point in his knowledge, attitude and motivation, from which he would dare to make the plunge - to invent. Inventing itself was structured for the student into an ordered sequence of events and processes. These, however, were not presented as a rigid scheme, but more as checking list to make sure that no major omissions were holding him back from achieving the end purpose - an original and useful solution of a real problem.

The approach to inventing was classified into two major categories: the PULL and the PUSH. The Pull approach was described as that process which illustrates best the proverbial expression: "Necessity is the mother of invention". This means a situation in which a well recognized difficulty or problem is understood to exist, but the solution to the problem is not known. On the other hand the Push approach describes a situation where an existing solution is going begging for a lack of a problem it can solve. In both cases the object of the inventive act is to bring together two parts, the problem and its solution, into a union for the first time.

An almost essential ingredient, which can hardly be overemphasized in the selection of the general technological area in which one desires to make the invention, is the possession of some combination of the following: a) reasonable familiarity with the chosen subject, b) genuine concern and/or feeling of urgency for finding a novel solution, c) unique or special skills not available elsewhere, d) unusual or rare insights gained from looking at the subject from an unconventional perspective.

A second prerequisite for a successful invention is a very detailed understanding of a large number of particulars and specific idiosyncracies of the problem one wishes to solve or the solution for which one is trying to find a matching problem.

In devising the individualized final examination the above two prerequisites were considered satisfied through the student's analysis of his chosen patents. The actual selection of the push or pull approach, as well as the specific problem to be solved or existing solution to be matched to a sought after problem, was made by the examiner. In this respect the final examination resembled an ordinary examination where problems are posed and the student is expected to have a fund of factual knowledge in the field to draw upon. The factual knowledge was contained in the patents that he studied and the subjects to which the studied invention related.

The first requisite of the examination was one of classification and systematization. The student was asked to set up a number of alternate systems of classifying potential solutions and relevant approaches. He was encouraged to set up analogies between them and generalize them into more abstract or fundamental concepts (inclusive causative linkages) following the Hessean Model of Models described previously. The student was also asked to search for new and non-obvious relations inherent in the predictive power demonstrated by the Hessean Model of Models. The heart of the assignment was the setting up of models of related past solutions which included beliefs, practices and logic of the practitioners of the state of the art. The student's ability to test the goodness of fit of various solutions was emphasized.

The establishment of a private language and terminology unhampered by existing conventions was recommended. The criterion for language creation was heuristics, ease of manipulation, and relevance to the problem on hand. An important aspect was the generation of a functional grammer within the language without which the new terms would have become just translated labels.

The degree of success that each student was able to realize was directly related to his ability to generate a meaningful "Shopping List". The shopping list fell into one of the following three general categories: a shopping list of missing links in the solution of the problem, a shopping list of procedural functions belonging to the selected field, or a shopping list of needed items in terms of requirements which had to be satisfied. This, and the subsequent procurement (on paper) of some of the missing links, procedural functions or needed items, helped the students to separate the known from the unknown. In many cases such a visible division was sufficient to provide the necessary impetus to arrive at a solution to the posed problem. In any case, the last required step of the examination was an attempt at synthesizing ones own solution.

The students completed this last step with varying degrees of success. Some generated truly startling and original solutions. Others contributed only relatively mundane extensions of the state of the art. This was not unexpected. Whether an invention does or does not come to fruition in a limited period of time can in part be attributed to chance. Consumation of the invention was not considered essential in the grading of the examination.

COURSE RESULTS AND SUMMARY

A course teaching not only the methodological skills of inventing, but also the recognition of conditions conducive to the acts of invention and discovery, has met with reasonable success at Stanford University. Graduate engineering and non-engineering students, most of them without prior history of inventive technical contributions, were stepwise disinhibited and freed of cognitive, emotional and interpersonal (cultural) blocks and induced into a state of preparedness for the conception of significant inventions. Through psychological and sociological insights into the motivational gradients of scientists and engineers a partial reestablishment of an attitudinal balance between the two "multiprofessions" was attempted.

The concrete results of the teaching, attained to various degrees by the students, were as follows (56):

1) The students became familiar with the heuristics of invention and discovery.

2) Their personal confidence into inferential, empirical and predictional methods was enhanced and they became encouraged to further develop their skills in these areas.

3) They individually established self-critical and self-correcting procedures over behavioral and interpersonal inhibitions to heuristics.

4) They improved their skills of transdisciplinary communications of technological concepts and, to a lesser degree, of recognition of the potential social consequences to innovation.

5) They enhanced their understanding of the business and promotional aspects of technological innovations.

We feel that the above results not only give credence to the past criticisms voiced concerning the shortcomings of contemporary higher education for engineering and applied science, but also point toward one approach capable of overcoming some of these shortcomings by teaching students to discover and invent.

The successful establishment of this innovative credit course at Stanford University is in no small measure due to generous help received from several engineering faculty members. Among these are prominently represented Professors R. H. Bube, H. O. Fuchs, R. Hemmes, R. H. McKim, J. M. Pettit, and W. A. Tiller.

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50. Similarity is defined as a generalization of the geometrical and algebraic concept of similitude. Two items are considered similar if they are factorable and contain at least one common factor.

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56. A 75% success of these objectives was indicated by an opinion survey of the students at the end of the course.

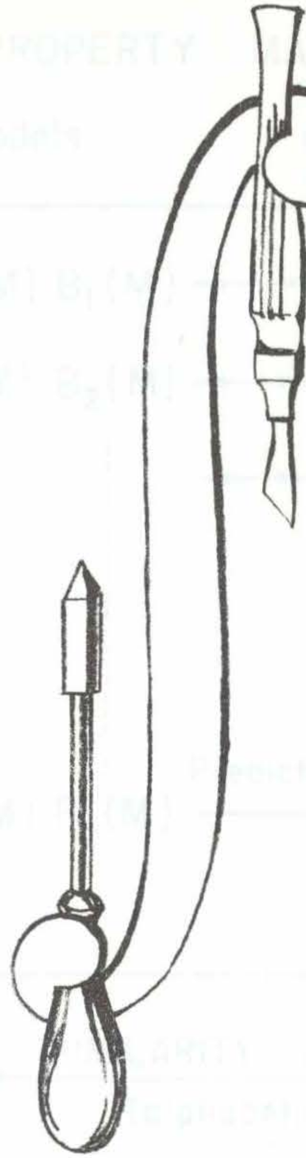

Figure 1. The symbol of the First Bionics Symposium was used in class to illustrate the historico-emotive charges engulfing symbols and the potential problems which may arise through their excessive hold on the mind.

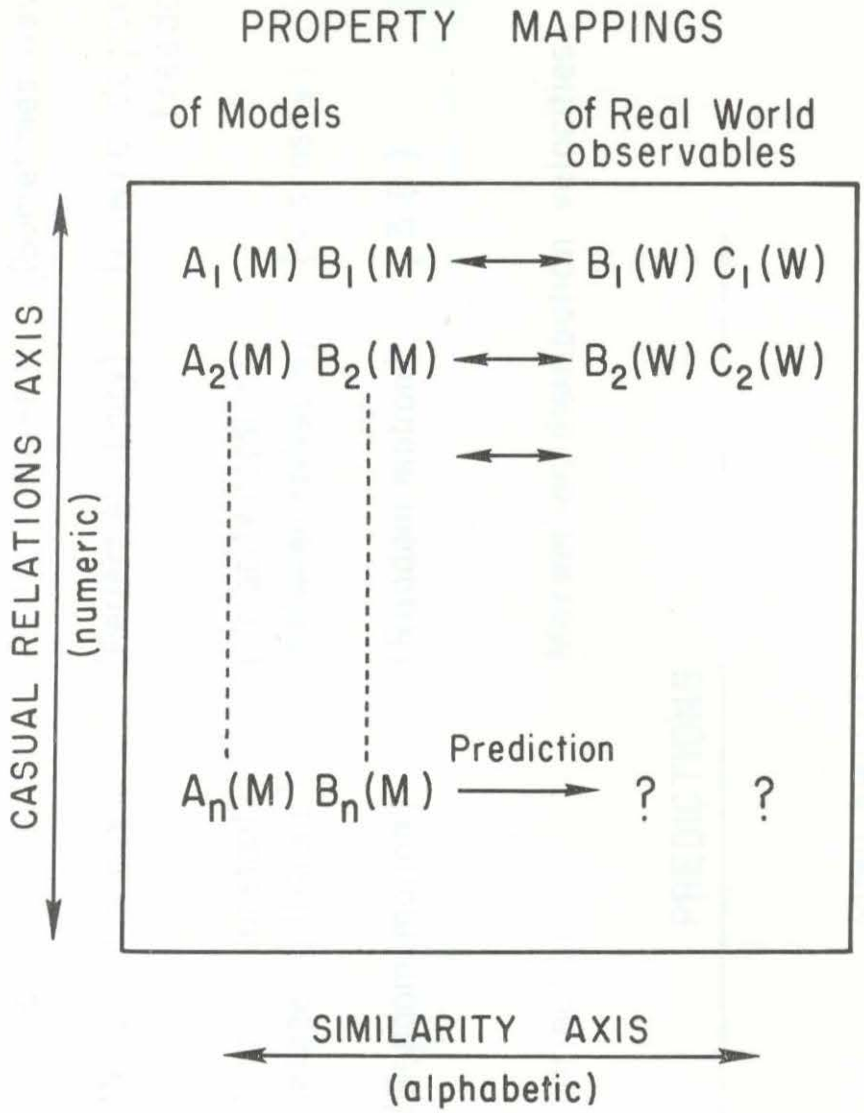

Figure 2. The Mary B. Hesse Model of Models enables one to make startling new predictions about the real world.

BILLIARD BALL MODEL		GAS MOLECULES	
A's	B's	B's	C's
(Small deviations)	(Perfect spheres)	(Perfect spheres)	(Sometimes deviate)
(Heat losses)	(Perfect elasticity)	(Perfect elasticity)	(Internal degrees of freedom)
(Friction)	(Velocity constant between collisions)	(Velocity constant between collisions)	(Viscosity)
(2 D)	(Random motion)	(Random motion)	(3 D)
Calculated velocity distribution		Maxwellian distribution velocities	

LAWS OF PHYSICS and PROBABILITY

PREDICTIONS

SIMILARITIES

Figure 3. This is an example of how the Mary B. Hesse Model of Models is used to enable inference based on analogy.

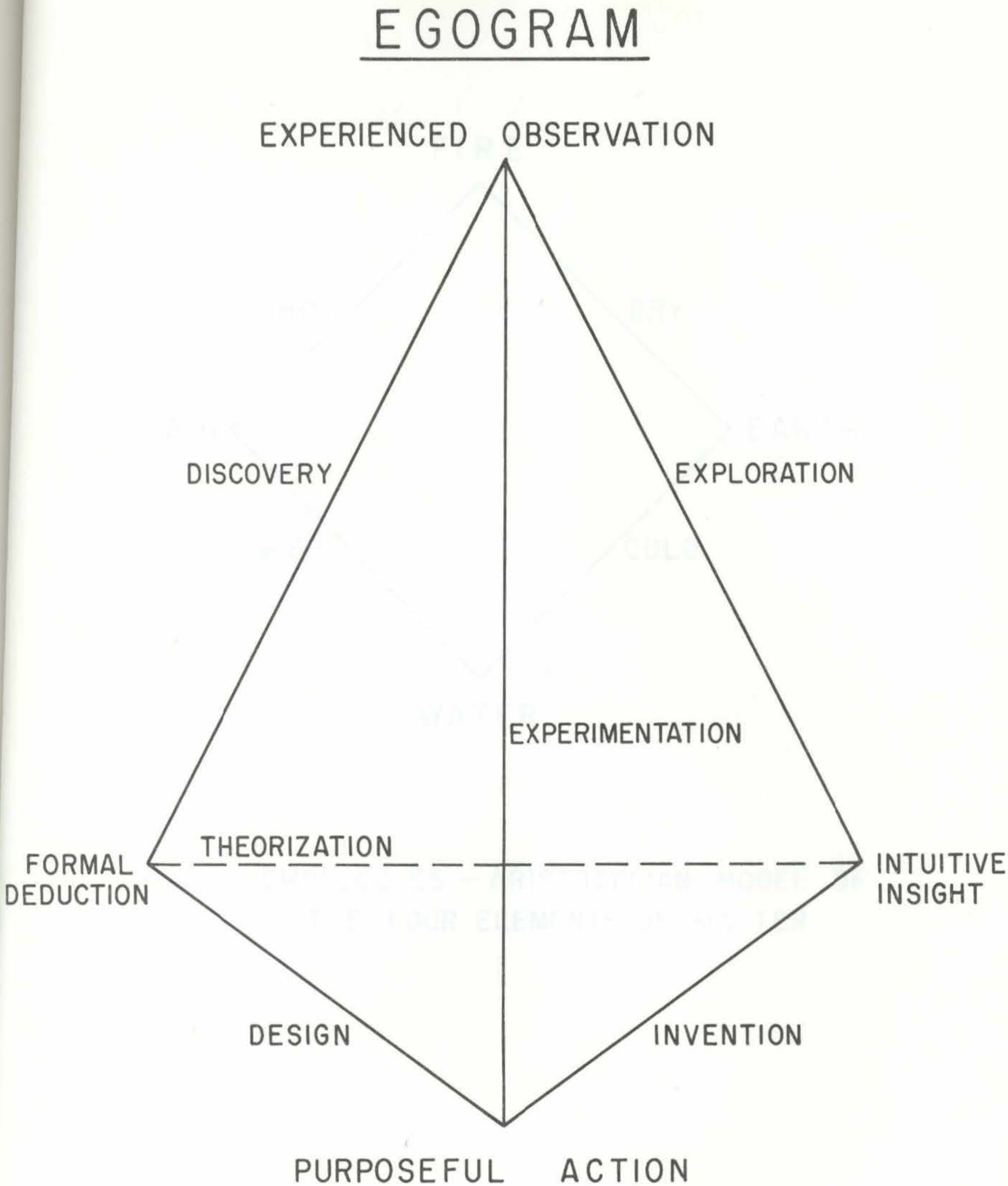

Figure 4. This tetrahedron is intended to be a psychological model of the four basic activities through which an individual acquires new knowledge.

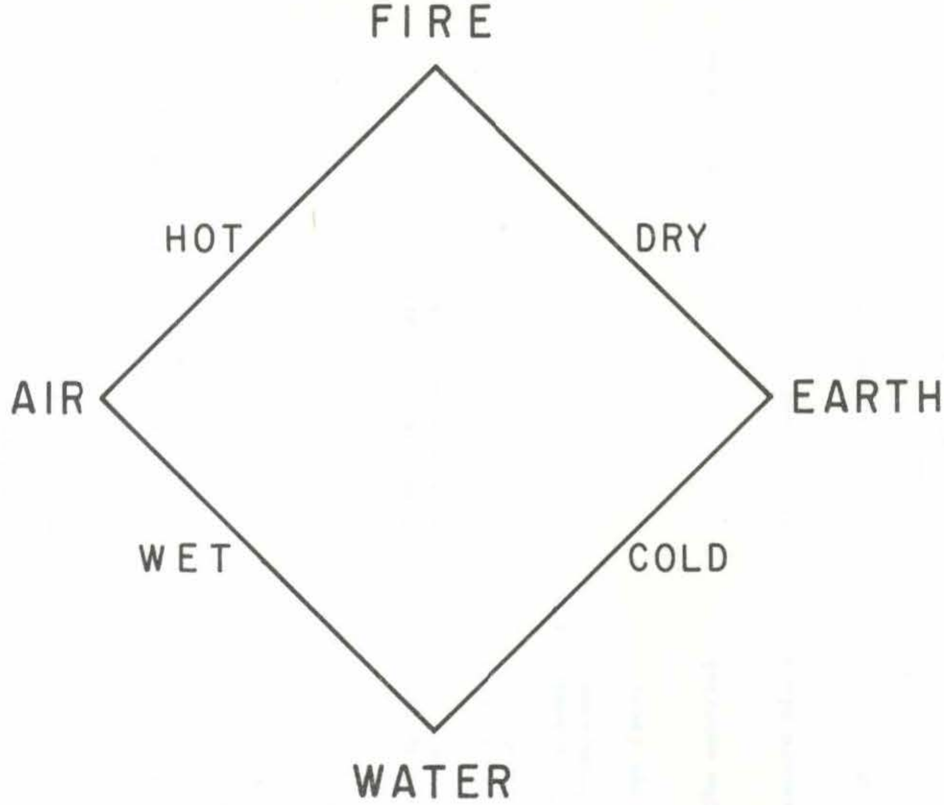

Figure 5. EMPEDOCLES — ARISTOTELIAN MODEL OF THE FOUR ELEMENTS OF MATTER

SENSE†	AB1††	AB2	AB3	AB4	AB5	REFERENCE §
Arch Word: Womb	An organ in female mammals	For containing and nourishing	The young	During development	Prior to birth	W2: 1. W3: 1a. RH: 14.
Geology	Fine grained rock	In which is embodied	Metal, fossil, or crystal	(During sedimentation formation)	(Prior to separation)	W2: 3a. W3: 3a1.
Materials	A fine material (cement)	Which binds together	The coarser materials (stones and sand)	Which takes form during setting		W2: 5e. W3: 6. RH: 5.
Math	A rectangular array	Which orderly contains	Its elements	Subject to transformations	Into new forms	M.
Botany	The substrate	On which or within which grows	A fungus or lichen			W2: 8. W3: 8.
Jewelry*	A gem stone (opal or turquoise)	Which was cut	From another and its surrounding matrix			W2: 10. W3: 7.
Anatomy	The thickened epithelium	At the base of	A fingernail or toenail	From which new nail substance develops		W3: 1c.
Biology	The intercellular substance	Encompassing	The cells of a tissue			W2: 7a. RH: 3.
Biochemistry	A DNA layer	Surrounding	Chromonemate of a chromosome			W3: 3b.
Typesetting	A mold	For casting	Type faces			W2: 5c. W3: 4a.
Stamping (Machining)	A multiple die or perforated block	On which is placed	The material		Prior to forming	RH: 10.
Record Fabricating	An electroformed mold	From which	Record discs	Are pressed		W2: 6. W3: 4f.
Electronics	An array of electronic devices	Within which	Codes	Are transformed or translated		RH: 13.
General	A place or enveloping element	Within which	Something	Originates, takes form or develops	Prior to its final form taking	W2: 2.

* Analogy inverted

† This is a representative, but not exhaustive sample of the semantic domains.

†† Analogy Band Number 1, etc.

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