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Survey of Pedagogics Applicable to Design Education: An English-Language Viewpoint*

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Teaching and learning, as processes that are performed by teachers and students respectively, are outlined. Consideration is given to various types of knowledge, especially the knowledge required for designing in engineering. A relationship among theory, subject and method is postulated. Methods may be strategic (for education, these are called pedagogic) or tactical (didactic). Various factors that influence education are brought into relationship with a model of general transformation processes. On this basis, several educational theories are discussed, individually and in their relationships to one another and to engineering design education.

INTRODUCTION

> Who dares to teach must never cease to learn. (John Cotton Dana, 1912)

> Teacher: How do you distinguish between ignorance and indifference? Student: I don't know and I don't care.

DESIGN ENGINEERING is an economic necessity: modern human life would be unthinkable unless we could call on the products of engineering and technology. Therefore, educating our future engineers to use the best information, sciences and design methods to design and produce the most appropriate technical products is of paramount importance. This paper is coordinated with an earlier paper [1].

There is in engineering a general need to coordinate various subjects and their theories. All of the engineering sciences interact, and engineering must also consider the societal factors, economics, and many other subjects (e.g. human motivation [2]). This paper explores several of the theories of education and their relationships, so that educators may be able to improve their presentations.

In any form of education, two processes take place: teaching and learning. They are normally thought of as simultaneous; learning takes place as a direct consequence of teaching. This is partly true of compulsory education, where at one extreme the learning takes place immediately from the teaching. But it is not necessarily the case.

Learning usually requires more:

- several repetitions,
- added explanations by the teacher, text-book writer or others, even, and sometimes importantly, by fellow students,
- demonstrations,
- performing experiments and projects (experiential, 'learning by doing'), etc.

Learning can also take place by self-study, in which the 'teacher' has written the instructions (e.g. a book) some time before the self-study takes place. Learning can be:

- cooperative, collaborative or competitive,
- individual or in pairs or teams,
- in lock-step by timetabled periods devoted to subjects or activities,
- asynchronous by continuously available access to learning materials,
- teacher-centered or learner-centered, etc.,

but usually as a combination of these in some suitable mixture, depending on the teaching style of the instructor, the subject matter (including skills and abilities to be learned), the students, and so on.

A unique feature of education for engineering design is that the acquired knowledge must be applicable to the *processes of designing*, and to the systems, processes and products (artifacts) being designed. Design methods and information [3] must provide the means to search for and generate alternative solutions at various levels of abstraction, to select among these to find the most promising (optimal) solution for further elaboration, and to reflect on the results of design work [4]. It is in this sense that engineering design science [5–9] should prove useful [10].

A basic model within engineering design science is the transformation system, Fig. 1, in which a set of operators act (deliver effects) to change an operand in a transformation process.

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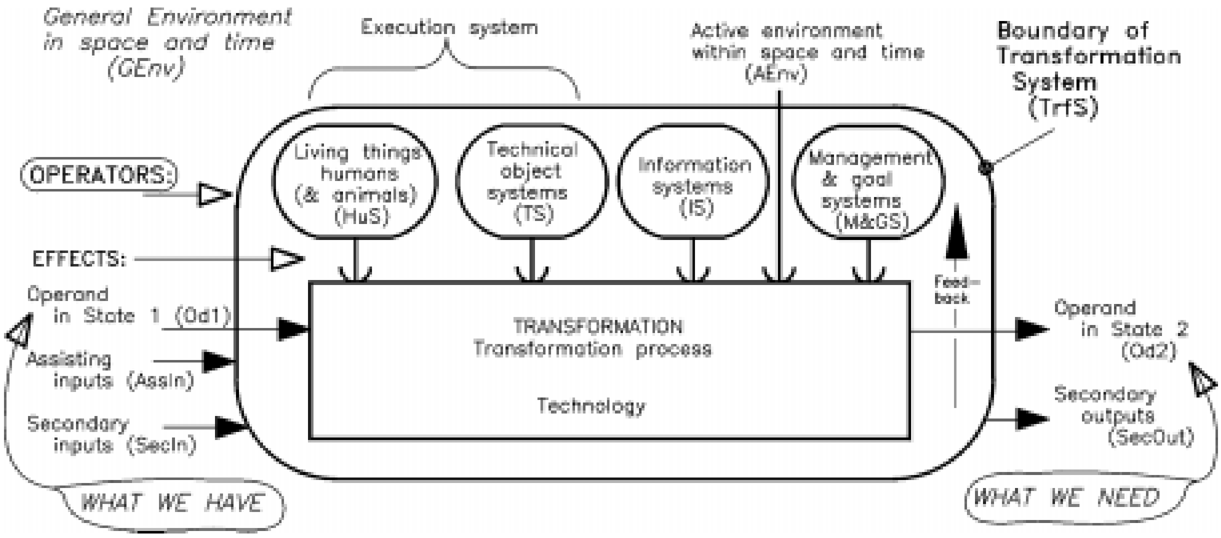

Fig. 1. General model of a transformation process [5, 6, 8].

The relationship to various forms of human interactions in educational situations should be obvious;

- teacher to student, student to teacher, student to student, sometimes even teacher to teacher;
- in settings that range between formal and informal;
- involving transmission of information, acquisition of abilities, skills and attitudes;
- common myth-making, acculturation into the approaches and jargon of a field;
- evaluation, of students, of teachers, of the subject matter being presented, and of the learned results (the outcomes of learning).

Teaching and learning can and does take place in all modes of human sensing:

- visual by graphic, diagrammatic and pictorial media, but also by the written or printed word (e.g. on a computer screen);
- auditory and verbal by spoken words;
- cognitive by fostering understanding and more complex usages of knowledge [11];
- affective by role modeling, encouragement and punishment [12];
- kinesthetic (psycho-motoric) by activities and actions;
- aesthetic by beauty of expression, usage of metaphors, etc.

In any case, teaching and learning can be looked at as a transformation system (and process), see Fig. 2. Learning will change the internalized (tacit) information and knowledge available to the student, both in its structure and its content, in the levels of incorporation from full understanding to mere awareness, and in its availability for use. According to John Dewey, *'Knowledge is constructed in the mind of the learner'* (referring to tacit knowledge—knowing—and experience), and *'No one learns anything until what is learned*

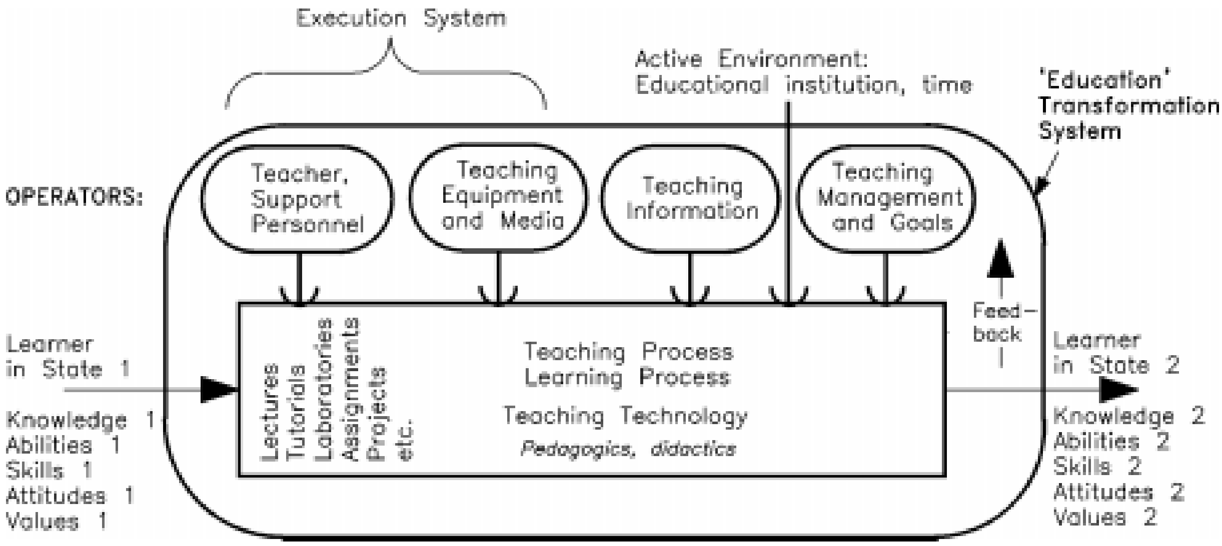

Fig. 2. Model of a teaching and learning system as a transformation [5, 6, 8].

Fig. 3. Model (map) of engineering design science [5].

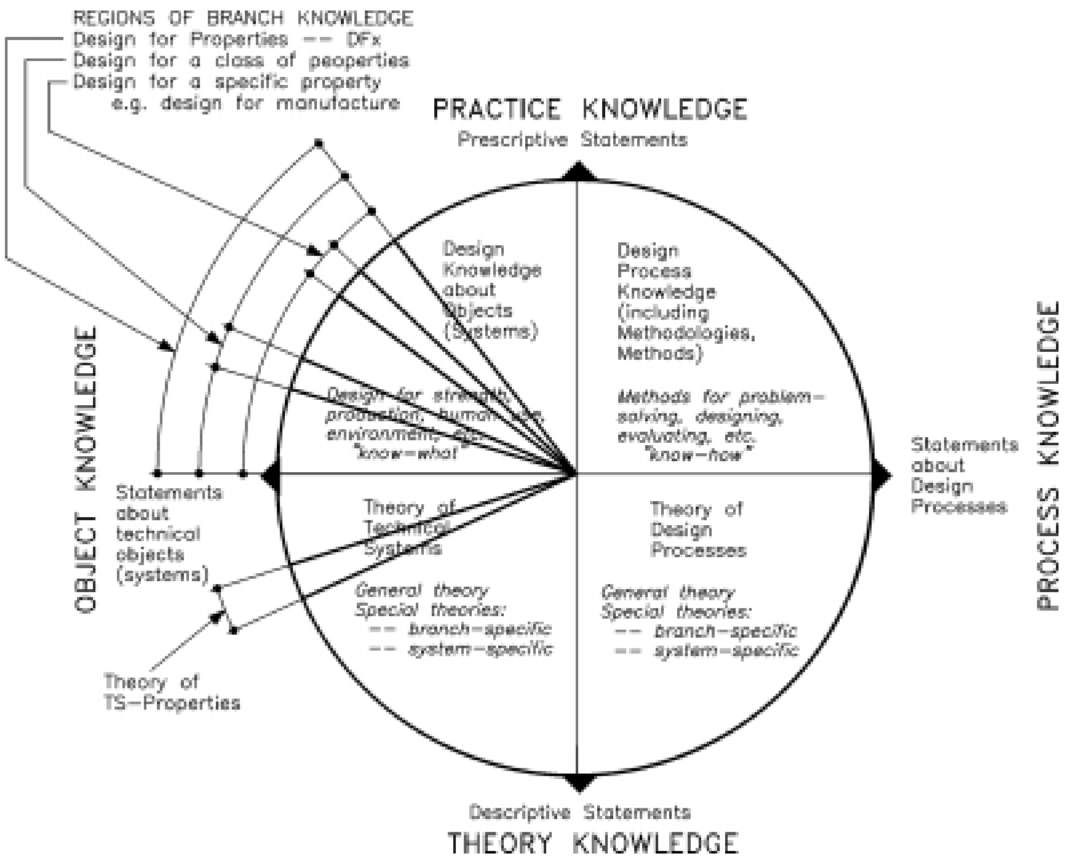

Fig. 4. Categories of engineering design knowledge, object region.

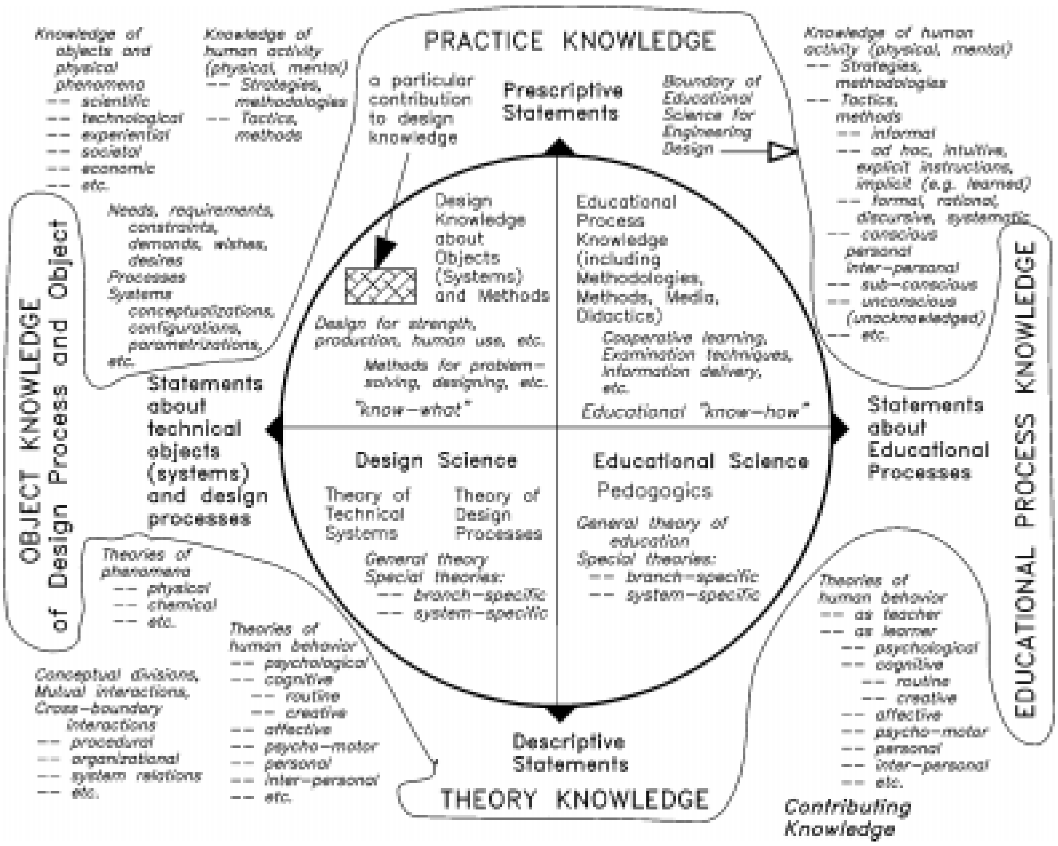

Fig. 5. Map of engineering education for design.

changes the learner' (George Leonard [13]). It is obvious that the student must be actively involved in learning.

This transformation can also be considered from the viewpoint of engineering design science. Figure 3 shows a map that summarizes the contents and context of engineering design science, on two axes, theory *vs.* practice knowledge, and object *vs.* design process knowledge (methods). Figure 4 indicates on the example of TS-properties that any practice-related knowledge should be supported by a suitable theory. Figure 5 shows a theory (or set of theories) of education, and its coordinated methods and subjects, as a map similar to that of engineering design science—the process knowledge now relates to education, and the object knowledge contains the subject of engineering design science, i.e. its object knowledge and its design process knowledge.

Any action (including teaching or learning) requires that it is planned, therefore a theory must exist (at least an informal 'theory' or hunch in the mind of the planner) to guide the planning and execution of the action (the proposed method). The theory may be fully formulated, or in speculative form (as a hunch, gut feeling, anticipation), the planning may be informal or formal. This relationship among theory, object and method needs further discussion, the purpose of the next section.

If the execution of the action does not deliver the expected result, a corrective action is usually taken, on one or more of the theory, the plan or the action—a feedback mechanism is active. This has been labeled 'reflection-in-action' [4, 14, 15], or iterative and recursive working (see below).

THEORY, METHOD, SUBJECT

As Klaus [16] formulated in cybernetics (see also [17]), close relationships exist between the subject under consideration (its nature as a product or process), the basic theory, and method (see also Fig. 6). The theory should describe and provide a foundation for the behavior of the (natural or artificial, real or process) subject, i.e. answer the questions of 'why', 'when', 'where', 'how'—its natural behavior—with adequate and sufficient precision. The theory should also support the utilized methods, i.e. 'how'—procedure, 'to what'—object, both for using and/or operating the subject, and for designing the subject. The method should also be sufficiently well adapted to the subject, its 'what'—existence, and 'for what'—anticipated and actual purpose. Note that these questions expand on the 'six W' work study questions as proposed by Taylor [18] and are adapted from the *topoi* of Aristotle. These three phenomena are of equivalent status to each other—a mutual interplay between subject (and phenomenon), theory and method, one refined and

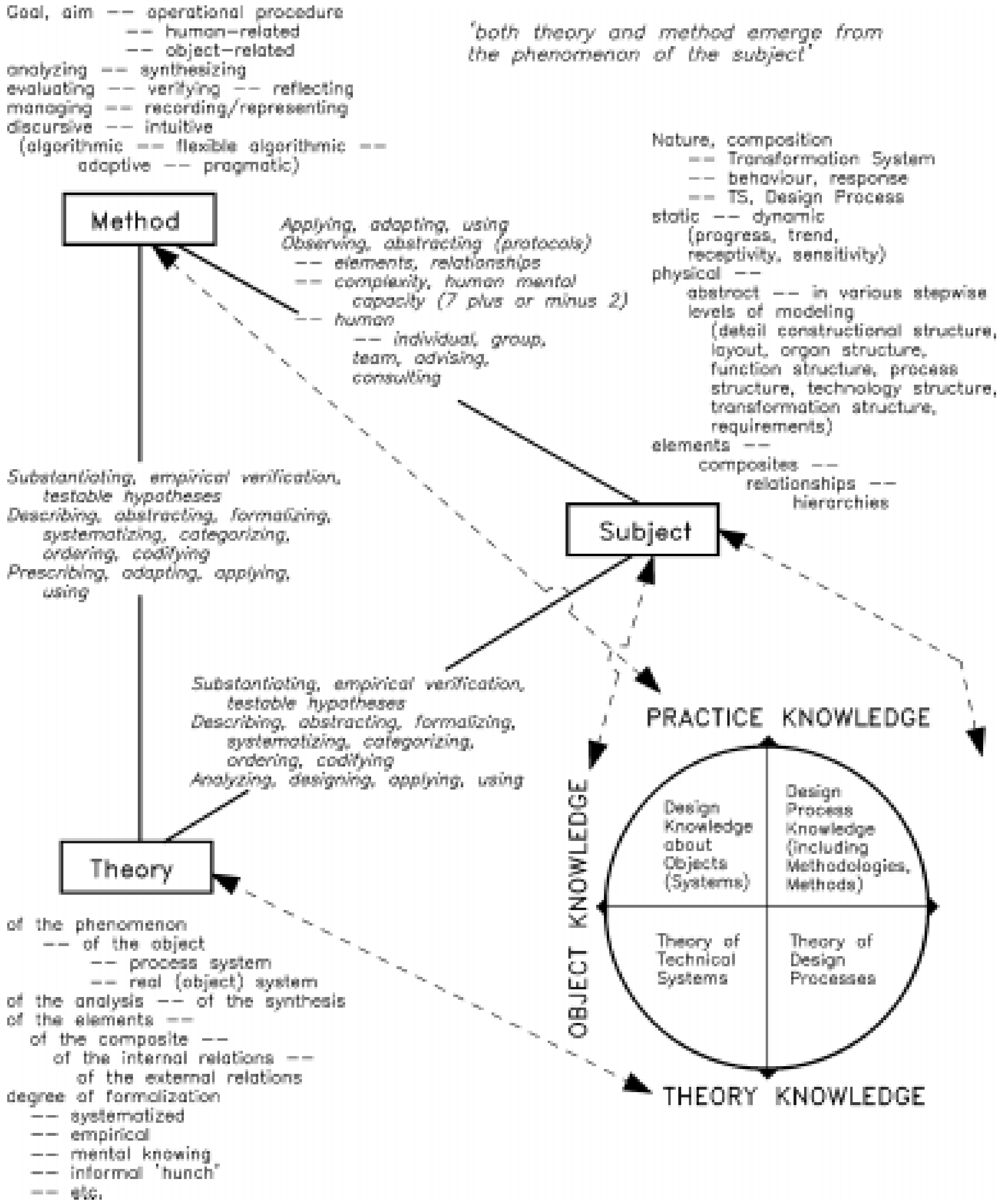

Fig. 6. Relationships among theory, subject and method [16].

examined on the other, characterizes the normal human social and scientific development and progress.

Quoting from Klaus:

> Both method and theory emerge from the phenomenon of the subject.

If the theory of a subject-region is mature, then the method is founded in the theory. The theory declares what is in reality the case, the method describes, on the basis of the declared facts, how the scientific and practical activities and behaviors of the humans should take place. This relationship is the basis for Fig. 6, refer also to Figs 3–5.

Where no comprehensive theory is available, methods to deal with subjects can be proposed, even where the structure of the subjects or their behavior is not completely known (this is the cybernetic and newer interpretation). The method can conceivably have the character of an input-output-relationship according to the 'black-box' principle first formulated by Ashby in 1956. We know that corresponding results will be generated when we act on a system in a certain fashion. The theory will then, once it is developed—and often after a lengthy delay—give an explanation of why this is so (to some extent an interpretation of the input-output relationship).

The relationships among subjects, methods and theories are significant for the situation of heuristic methods. For many currently interesting problem groups we lack an appropriate theory which can explain the method for its treatment and solution. In such problem situations, the method (frequently an heuristic method) must first serve to open up the problem field and disclose the structure of the problem. This kind of problem situation is increasingly found in recent research efforts, and therefore the interest in heuristic methods is rising. Koen [19] claims that 'all is heuristic', even the best verified theory.

Methods are generally prescriptions for action, and help to explore, reformulate, search the solution space, evaluate and choose among the available choices, guide towards a resolution of the problem, etc. Methods can be collected into sequences with logical connectivity, then called *methodologies*. Methods can be (somewhat arbitrarily) classified into strategy and tactics. A strategy provides a broad outline of the approach to a problem, and consists broadly of planning, doing, observing results, and revising, as a longer-term outlook and procedure. Tactics provide detail operational advice. They are seen as dynamic processes, like feedback control systems, but flexible and adaptive, with mainly immediate effects. Problem solving methods are usually regarded as tactical.

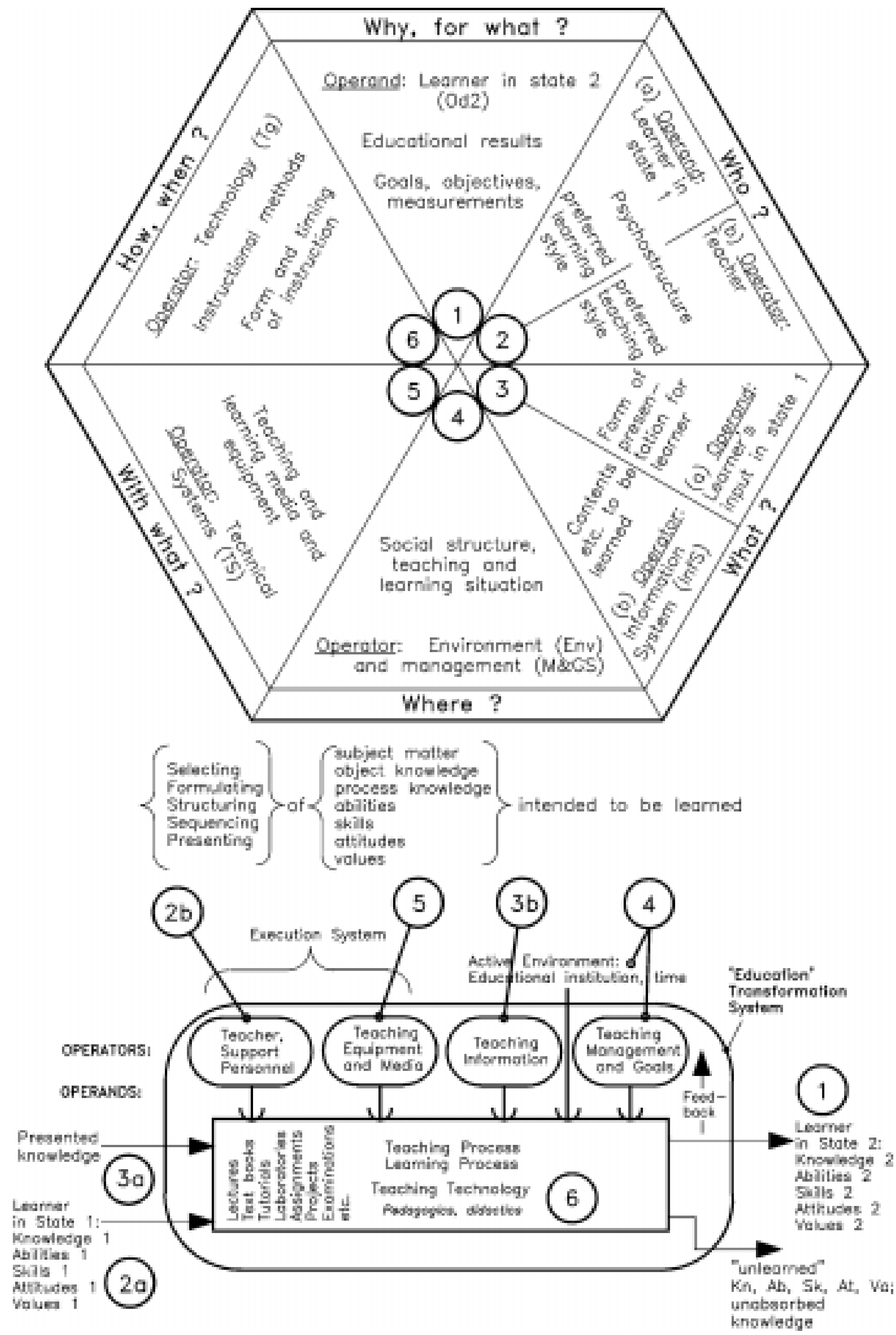

Fig. 7. Teaching and learning system and variables [18, 22].

According to Kuhn [20, 21], normal research adds to the available knowledge within an accepted *disciplinary matrix* (paradigm) of that discipline. When the accumulated knowledge can no longer be fitted adequately into the disciplinary matrix, a crisis situation emerges. Then several different alternative models are proposed and fight among each other and with the existing model for dominance—a *paradigm shift* may be in progress, but a fall-back is still possible. A new model is only established when sufficient evidence has convinced a sufficient number of powerful advocates of that model. A paradigm shift (from one certainty, through uncertainty, to a revised and usually more encompassing certainty) takes place over a longer period of time. Both the old and the new paradigms co-exist for some time and tend to interact iteratively and antagonistically.

The methods for education can be considered as strategic—pedagogics—and as tactical—didactics.

PEDAGOGICS AND DIDACTICS

The nature of pedagogics and didactics can in part be explored by looking at typical dictionary definitions. Distinct differences in scope, approach and attitude are detectable:

In English, the definitions are:

- *Didactic*—meant to instruct, having the manner of an authoritarian teacher
- *Pedagogy*—science or profession of teaching
- *Pedagogue*—schoolmaster, teacher, esp a narrow-minded pedant

The analogous German definitions (in translation) are:

- *Pedagog*y—theory and strategy of teaching
- *Didactics*—tactics of teaching

One of the first educational theories was propounded by Comenius (Jan Amos Komensky, Czech, 1592–1670), an educational reformer who revolutionized the methods of teaching, particularly for languages. Most of continental Europe recognizes Comenius as the founding father of pedagogics, the science of teaching.

The important influencing factors in education have been defined by Frank in [22], following work by P. Weimann. They are collected into the six pedagogic variables shown in Fig. 7 as the partial or contributing systems (with my added comments and interpretations), and relationships with the 'six W' questions to assist in work study as proposed by Taylor [18]:

1. Educational results: W*hy, for what*?
   a) purposes, aims, goals, objectives of teaching/learning—expected outcomes in knowledge, abilities, skills, attitudes and values, expected applicability—forms of measurement of outcomes;
   b) during learning, some prior knowledge, abilities, skills, attitudes and values must be 'unlearned' in order to accommodate the new learning, but also some parts of the presented information will not be included in the learner's mental structure.
2. Psycho-structure: W*ho*?
   a) student, customer, user, operator, individual, team, group, company, society—individual differences, academic abilities, prior knowledge and preparation, motives and incentives;
   b) teacher, instructor, tutor, role model, etc.
3. Subject matter: W*hat*?
   a) nature, contents, arrangement of the presented learning materials and tasks, planned structure and content of the curriculum and academic program;
   b) form of presentation of the learning materials and tasks, as perceived by the learner—e.g. as a formally constituted curriculum with constituent courses, alternatively as supervised practice in an apprenticeship model.
4. Social structure: W*here*?
   a) environment, space, educational management—situation or environmental variables for the learners, and for the teachers, which may be both subtle and complex in their effects on learning.
5. Media (learning and teaching means): W*ith what*?
   a) with what *means*, objects, tools, systems—equipment used by teachers and learners, including books, chalkboard, projectors, computers and their application programs, etc.
6. Teaching method (teaching technology, algorithm): *How, when*?
   a) with what *procedures*, processes, methods, strategies, tactics, didactics—timing, sequence, forms of repetition—nature and quality of instruction, conditions of practice, guidance, modes of presentation (verbal, graphical, hands-on activities, reflection, etc.), order of presentation ('from particular to general' or 'from general to particular').

These pedagogic variables are correlated with the constituents of the teaching and learning system, see Figs 2 and 7. The major additional consideration is that the operand in this case (the learner) is a living, thinking and feeling human with prior knowledge and experience, active in his/her own learning—compared to Fig. 1 in which the operand may be material (animate or inanimate), energy and information in a relatively passive role.

To variable (3b), it is worth pointing out that 'information' (and consequently 'knowledge', viewed as object-entities) mainly exists as records external to the human mind, is carried by various media, and consists of data, knowledge, structure, and abstractions (hypotheses, theories, etc.). Knowledge also exists within the human mind (as internalized, idiosyncratically structured, tacit knowledge). But 'knowing' (a process-entity) can only be performed by the mind.

The model of learning, Fig. 7, can also be interpreted for autonomous learning, e.g. from a text book or computer-delivered material. The 'teacher' (2b) prepares the subject matter in advance, based on the means and media (5) and teaching information (3b) available—management (4) enters in the production process for these teaching materials. The technology (6) is then that the learner (2a) searches out the available material (3a), studies it, reflects on it, and critically incorporates some relevant parts into his/her mental structures. In collaborative or cooperative learning, a learner at times plays the role of teacher.

The theories of education are closely related to psychology. In North America, these theories (if they are at all acknowledged) form a loose collection of relevant structures for organizing the topics (objects, subject matter, goals) and technologies (including methods) of instruction. Little serious attempt has been made to relate the educational theories to one another, but see [23]. Nevertheless, the individual theories and methods have their strong adherents and champions. Much of the information summarized in the following is abstracted from several papers included in [24]. The interpretations and attempts to provide relationships are mine.

During the recent centuries, teaching and learning theories have developed, starting from a paternalistic model of 'filling empty vessels with knowledge' through lectures, recitations, disputations and public debates. This is in contrast to the teaching methods of Socrates in ancient Greece, which used relevant questions to induce in the student a process of self-construction of philosophical knowledge. These were later augmented by demonstrations, laboratory methods, etc., when learning was seen as something more than rote memory.

Some differences were seen between different purposes for education:

- utilitarian vocational, related to jobs, occupations and careers;
- scientific intellectual, related to research and knowledge development;
- liberal general, related to social development.

This scheme seems to ignore the modern engineering fields which tend to bridge the other three and have the added purpose of generating technological solutions to societal problems.

The goals of teaching and learning can generally be collected under the headings of knowledge, competency, and personal development. Competency as defined in [25], in turn, can be regarded as consisting of recognizable sub-groupings, i.e.:

- *heuristic or practice related competency*—ability to use experience (precedents [26] and heuristics [19], one's own, and that of others) as guidelines and prescriptions, including knowledge of values (e.g. of technical variables) as initial assumptions;
- *branch or subject related competency*—knowledge of a particular family of technical systems within which designing is expected (which can strictly only be developed once the graduate is employed in designing a particular family of TS), and for this purpose typical examples of families of technical systems should be included in the curriculum (i.e. in addition to conventional and newer machine elements; and the treatment should include not only their engineering sciences, but actual examples of realized systems);
- *methods related competency*—knowledge of and ability to use specific methods, under controlled conditions of following the methodical instructions (guidelines, prescriptions), and eventually (usually after thoroughly learning the appropriate method) using them intuitively—for diagnostics, analysis, experimentation, information searching, representing (e.g. in sketches and computer models), computer tools and aids, but especially for systematic and creative synthesizing in designing;
- *systems related competency*—ability to see analytically (reductionistically), and synthetically (holistically) beyond the immediate task, and to take into account the complex situation and its implications, e.g. as in the discipline of life-cycle engineering [27,28,29], and/or with respect to costs and economics;
- *personal and social competency*—including team work, trans-disciplinary cooperation, obtaining and using advice, managing subordinates, social and environmental awareness, micro- and macroeconomic and cultural aspects, etc.

Personal development concerns the degree of presence or absence of such factors as confidence, dogmatism and prejudice, impulsiveness, leadership, assertiveness, emotions, autonomy, identity (self-image), morality, aesthetic sensibility, integrity, purpose, inter-personal relationships, and others.

Teaching and learning are now regarded in a much more 'democratic' light, tending towards partnerships in learning between teachers and students. The *humanistic* view recognizes that students must learn for themselves, teachers must engage the students in the acts of acquiring meaning and understanding, which to some extent is a return to the Socratic ideals. The strict *behaviorist* view claimed that the environment must be manipulated to provide stimuli for the students, who will then respond appropriately, and learn the desired responses, in a rather mechanistic way. The strict *cognitive* view states that learners must process the information into their own mental structures, and each learner has a somewhat different set of mental structures. Obviously, all three viewpoints interact, and must be simultaneously considered.

In this cognitive view, subject matter (content, declarative knowledge) reposes in a *propositional structure* that includes the meanings of concepts and operations. A *procedural structure* includes the set of heuristics, rules, production systems and intellectual skills that establish the step-by-step procedures (including iteration and recursion) for solving problems or achieving goals. A *conditional structure* contains the knowledge of when and where to use the available procedural strategies and tactics, compare the discussion of theory, subject and method in the previous section of this paper.

The newer beliefs and methods (especially for education) are often seen as contrary to past experience of learner and teacher, and cause some anxiety by deviating from established ways. Faculty often claim that new methods are not academically rigorous, or are based on ideas that are not founded on research. But ideas must often be accepted, tried out and applied before they can be researched for their effectiveness, which leads to a tautological dilemma. And it is difficult to formulate learning in terms that is educationally relevant, as distinct from operational definitions that are more suitable to experiment designs and analyses in research. Alternatively, the too rapid adoption of the latest fad from educational research and methods can also be dangerous.

Teaching and learning, and the application of theories in these efforts, also depends on the bilateral nature of the human brain (see below), where each hemisphere shows some relatively specialized capabilities, and the newer information-processing models of intelligence. The effects of individual psychology as contrasted to the sociology (and psychology) of groups is also considerable.

Skills learning shows evidence of trial-and-error in the early stages. These include attentive selection of movements, functions and activities suitable for the task; encoding, storing, retaining, retrieving and applying suitable sub-skills; reinforcing successful actions; and 'unlearning' faulty actions. The result is a visible mastery of a skill, by competency, efficiency or ease with which the learners perform a task they could not do earlier.

EDUCATIONAL HYPOTHESES

Gagné [30] defines learning as 'a change in human disposition or capability, which persists over time, and which is not simply ascribable to the process of growth'. Learning is more than a change in performance, we should never equate learning simply with observable performance (e.g. as an 'outcomes assessment'). Learning is a process of progressive change from ignorance towards knowledge (i.e. not just an accumulation of information, but also a processing), from inability towards competency, and from indifference towards engaged understanding. It is led by external events in the form of stimuli (deliberately planned, designed, arranged and managed instruction, but also unplanned occurrences). It results from internal events in the form of memories that affect the learner to change performance, accounted for by information-processing models of learning and memory. The outcomes of learning can be classified under five capabilities:

- intellectual skills,
- cognitive strategies,
- verbal, graphical and symbolic information,
- motor skills,
- attitudes.

Compared with Fig. 2, the order of items is different, two sorts of skills are identified, but values are subsumed into attitudes.

The events of cognitive learning seems to occur in recognizable stages:

- sensory attending and selective perception—attending to or receiving information;
- storage in short-term memory, and rehearsal—assimilating (accretion), recalling and interpreting;
- encoding—attempting to order or rearrange the information for processing (tuning);
- storage in long-term memory, including possible changes in structuring—re-organizing and verifying, integrating with other information;
- retrieval and generation of responses;
- feedback or reinforcement.

It is only after the stage of storage in long-term memory that the information has been internalized as knowing (tacit knowledge) and understanding.

Gagné gives particular emphasis to the structure or organization of instruction, and the advantages of breaking down each learning task into less complex components.

Individualized instruction—behaviorist applications

Beginning in the 1930's, B. F. Skinner developed a technology of 'operant conditioning' as a teaching method, by proposing to manipulate the environment of the learner to provide stimuli, to which the learner responds. By shaping the behavior of the learner in small steps, and providing rewards for suitable responses, learning is induced. Yet organisms (learners) learn at different rates, and some custom designing of the environments needs to be individualized. This method for human learners follows from experimental work on learning in animals (Pavlov and subsequent investigators).

Cross (1976) [31] names the principles for allowing each individual learner to receive education independently as:

- self-pacing of learning,
- active participation of learners in acquiring knowledge,
- clear and explicit (measurable) goals,

- small units of instruction,
- feedback as immediate as possible.

These principles are the basis for programmed instruction: by suitable text books, linear or branching programs on teaching machines, computer-assisted instruction, and the Keller Plan [32] of the Personalized System of Instruction. These are better suited to transmitting object knowledge, but are of questionable benefit for teaching/learning of process knowledge (e.g. methods and skills). Students are generally examined at the end of each 'unit' of instruction, and are expected to achieve mastery learning (full knowledge) of that 'unit' before moving to the next. Interconnection of 'units' is difficult, i.e. the information of each unit is learned, but may not be transformed into knowledge context. Higher grades are usual, but many students find these methods unsuitable to their needs and inclinations. Administration is usually helped by computers, but is still person-intensive. Internet usage (e.g. World-Wide Web) probably results in the same advantages and disadvantages.

Structure of knowledge

Some psychologists tried to translate learning theories into workable theories of instruction. One leader in this field was Jerome Bruner [33, 34], who emphasized the structure of knowledge as the content of what is taught, and the scholar's methods of inquiry as the means by which learners should acquire knowledge. Bruner regarded a theory of instruction as *prescriptive* (compare Fig. 3), laying out rules for achieving knowledge and skills, but also as *normative*, establishing criteria for learning and stating under what conditions those criteria are met.

This leads to such techniques of representing the relationships among items of knowledge by mind mapping and concept maps, structured as networks (e.g. flow charts) or as hierarchies (with a loss of relationships among branches). Structuring of knowledge can also be assisted by keywords, hierarchies and relationships. It seems that giving learners a preview of the knowledge and its structure, providing *advanced organizers*, helps in the subsequent learning.

Glaser [35, 36] suggested that:

1. Knowledge may be specific to the fields of study where that knowledge was acquired (i.e. transfer of knowledge among fields tends to be difficult).
2. The acquired domain-specific knowledge may influence the way in which we acquire new knowledge, solve problems and process information.

A psychology of instruction should understand and facilitate the changes in cognition and performance that occur when a learner moves from novice status towards expert status. A theory of instruction must be related to an analysis of educational processes (methods) and results (objects)—see section Theory, Method, Subject, above.

Influence of psychological type

The Greek physician and philosopher Galen (about 130–200) divided persons into four types: choleric/hot-tempered, optimistic, phlegmatic/calm and melancholic/mournful. Immanuel Kant (1724–1804) set up a similar typology, in that he declared choleric and melancholic as high in emotionality, optimistic and phlegmatic as low in emotionality, choleric and optimistic as changeable (extrovert), and phlegmatic and melancholic as unchangeable (introvert). Wilhelm Wundt (1832–1920) [37] united these attempts, by plotting the main axes according to Kant, designating the sectors according to Galen, and expanding the sectors through some descriptors, see Fig. 8.

Jung [38] proposed that the nature of a person can be rational/judging or irrational/perceiving,

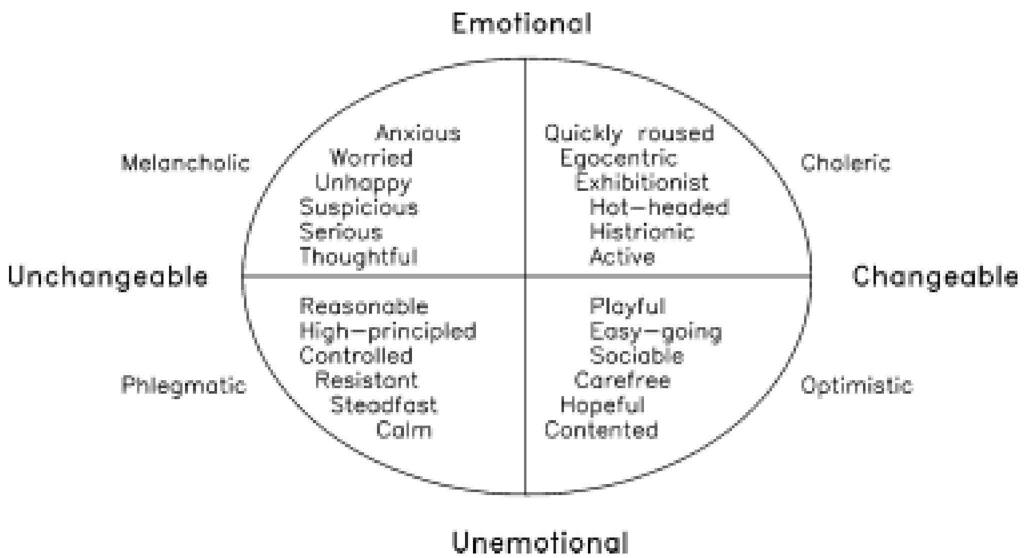

Fig. 8. Scheme of psychological types and human characteristics [37].

and the attitude within that nature can be extrovert (E) or introvert (I). This attitude is subdivided by applying four functions:

- *Thinking (T)*—yields a differentiation from ET to IT.
- *Feeling (F)*—yields a differentiation from EF to IF.
- *Sensing (S)*—yields a differentiation from ES to IS.
- *Intuiting (N)*—yields a differentiation from EN to IN.

(Remark: 'N' is used for intuiting because 'I' is already used for introversion.)

Jung allocated the thinking and feeling functions to rational/judging natures, the sensing and intuiting functions to irrational/ perceiving natures. The different combinations of attitudes and functions has decisive effects on communication, both with other persons, and with ones self. Communication happens by oral language, in writing or by other signs (e.g. symbols, and drawings/pictures) and results in transmitting or exchanges of:

- thoughts, ideas, knowledge, concepts;
- information, news, opinions, facts;
- qualities (degree of adaptation of properties), valuations, feelings, concerns;
- ideas, hopes, visions, judgments.

The consequences concern the personal and interpersonal outlooks, attitudes, encounters and reactions to the communication, but not the quality (character, content, goodness) of the communication itself.

Based on Jungian typology and cognitive style, the Myers Briggs Type Inventory (MBTI), [39], tries to measure in what ways people process information and make decisions. The four dimensions recognized in this typology form continuous scales, namely:

- *Introvert–extrovert (I–E).*
- *Intuitive–sensing (N–S).*
- *Feeling–thinking (F–T).*
- *Perceiving–judging (P–J).*

A predominant tendency (however small) away from the center in each dimension sets the person 'clearly' into one of 16 groups, Fig. 9. The first two of these dimensions seem to state ways of behaving and of approaching problems, the other two relate more to the emotional and personal responses. A direct relationship of these styles and abilities to the conditions for learning is not immediately obvious. It is probable that the strength of preference for each dimension of the MBTI measures will affect the ability and performance in learning.

An investigation independent of the Jung theory has led to the Berkeley personality profile on five kinds of style [40]: expressive style, interpersonal action style, working style, emotional style, and intellectual style.

A newer consideration of the theory of Jung has led a research group to the PET-diagram (Personal Empowerment through Type) [41–48]. Thereby 8 groups emerge (ET, IT, EF, IF, ES, IS, EN, IN), with continuous data on scales between E and I on each of four dimensions (8 manifestations) of the functions, Fig. 10. The largest difference from E to I shows the prevailing (dominant) function. The smallest difference shows the subordinate function, normally paired with the dominant function—T with F, and S with N. The second largest difference is the supporting function—if T or F dominated, S or N must support, if S or N dominates, T or F must support. Supporting functions can appear to be almost equivalent, as first and second supporting function. The attitude, E or I, paired with the highest rated function works as determinant of the prevailing type designation, two letters, but the numerical values are also considered as significant. All of these function kinds can be more or less influenced by the individual person, normally improved. The largest influence can be achieved in the dominant function. The subordinate function can almost not be changed.

Influences of the types have been investigated (by PET) with reference (among others) to communication, conflict resolution, stress, kind the problem solving, decision-making, team work, preferred modes of operation, learning and teaching styles (also in crisis situations), leadership style, management (relationships between employer and employee).

Guilford's model

Guilford [40] hypothesized a structure of human intellect. Humans (with their aptitudes) handle information by performing *operations* on *contents* (types of information) to achieve *products* (results of thinking) in the context of temperament, motivation and forms of thinking,. These can be represented as three dimensions of cognition on a matrix, Fig. 11.

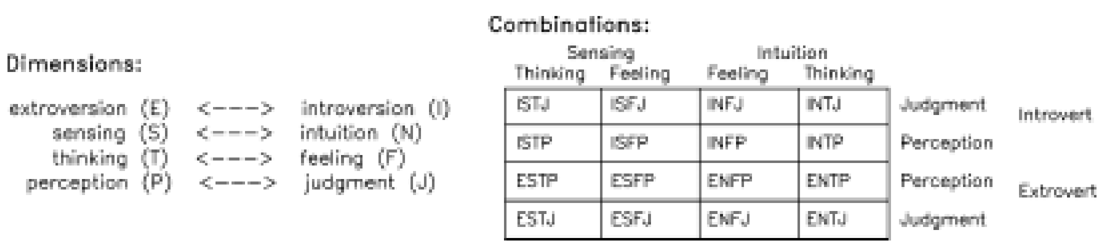

Fig. 9. Scheme of Myers-Briggs type inventory [39].

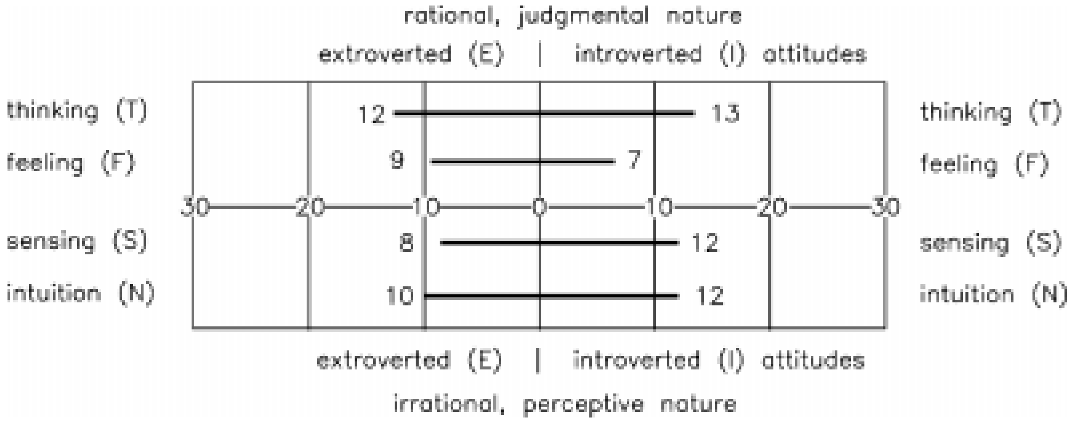

Fig. 10. PET Scheme (with calculated results for a test person) [41–48].

Right and left brain hemispheres

The right brain hemisphere is mainly responsible for the functions and actions of the left side of the body (and conversely). Some brain functions are somewhat further specialized in the hemispheres, although a productive connection (*corpus callosum*) coordinates the functions between them. The language centers are mostly located in the left hemisphere, which is regarded as working more *serialistically* (sequentially). Analytical processes occur more readily in the left hemisphere. Figural processing is more developed in the right hemisphere, which is also regarded as working more *holistically*. Creative and artistic processes are attributed more to the right hemisphere. The degree of development of this and other abilities coheres in part with the psychological type, but also with the other parts of thinking.

Combining emotions with the capabilities of the brain hemispheres, Herrmann [50] proposed a brain dominance model, Fig. 12, with steps and associated mindsets of problem solving processes.

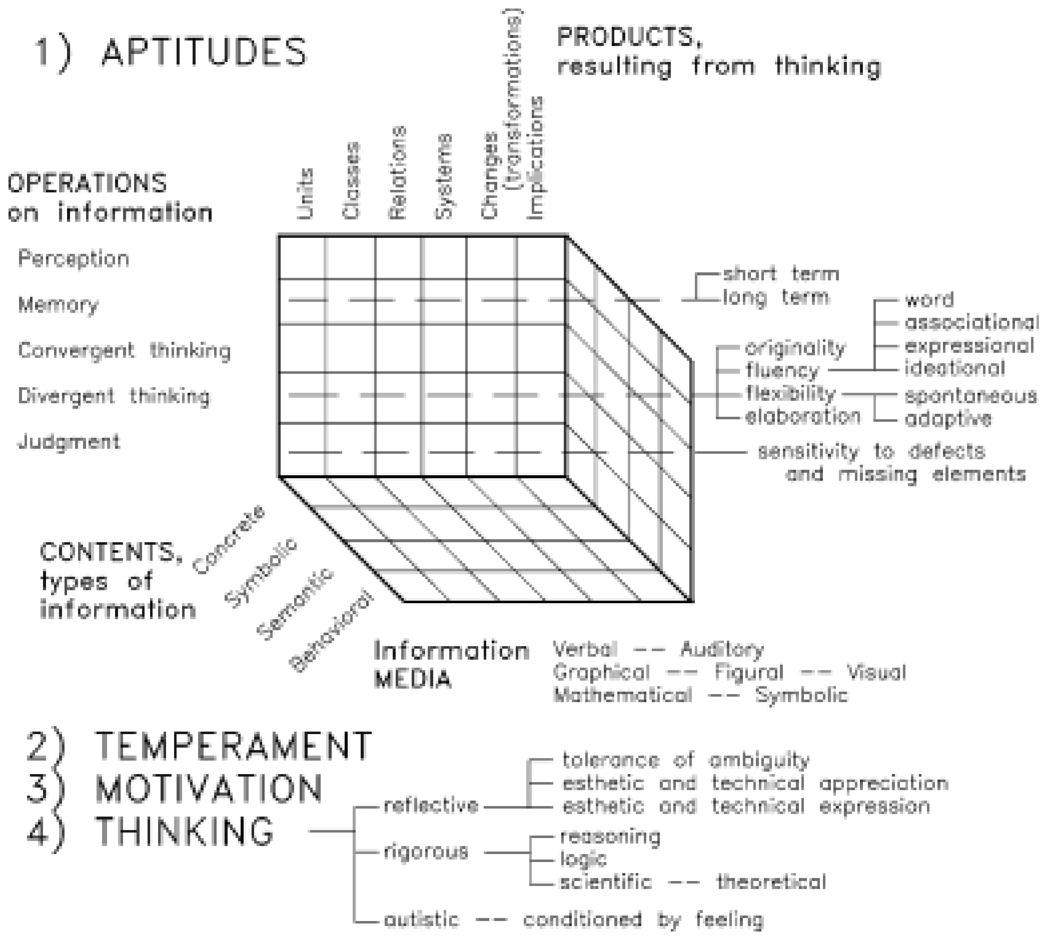

Fig. 11. Guilford's model of the structure of human intellect [49].

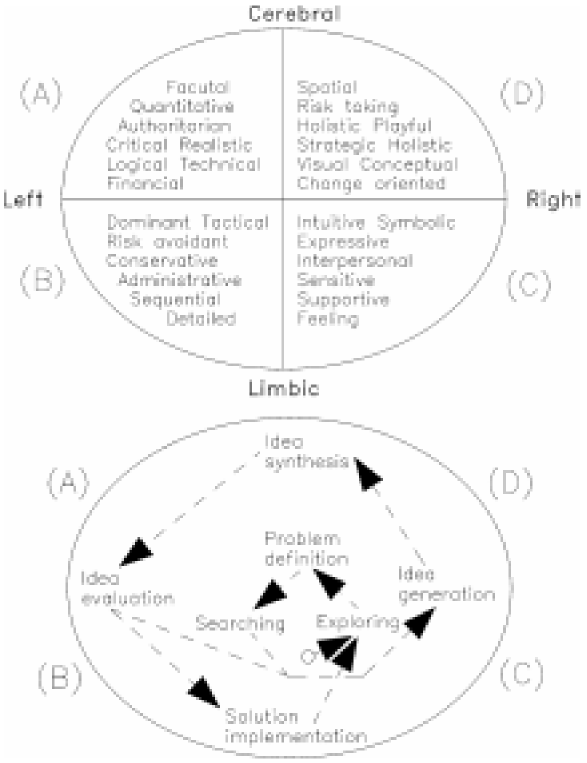

Fig. 12. Herrmann brain dominance model and problem solving process [50].

The resulting model fits fairly well with the Wundt scheme of psychological types, Fig. 8.

During designing, a more or less rapid cycle of basic activities takes place which is usually known as problem-solving [51, 52, 53]. Figure 13 shows a composite of various problem-solving models, including the role of reflection [4, 14, 15].

Human behavior models

For the purposes of investigating education, human behavior has been classified into four domains, the *cognitive* domain covering internalized knowledge (both object and process knowledge) together with its acquisition and use, the *affective* domain encompassing feelings, the *psycho-motor* domain dealing with mental control of actions, and the *interpersonal* domain. Various taxonomies exist to generate sub-classes within these domains, and to provide guidelines in deriving educational objectives for instruction.

Probably the best known of these taxonomies is by Bloom [11], regarding the cognitive domain, where the human capabilities (and educational objectives) are listed as a ranked hierarchy (lowest to highest capability—listed as nouns, but they would probably be better as verbs) of:

- knowledge (memorizing, i.e. internalizing)
- comprehension
- application
- analysis
- synthesis
- evaluation.

This sequence seems to be appropriate for analytical tasks (and educational subjects). For designing, synthesis should probably rank higher than evaluation.

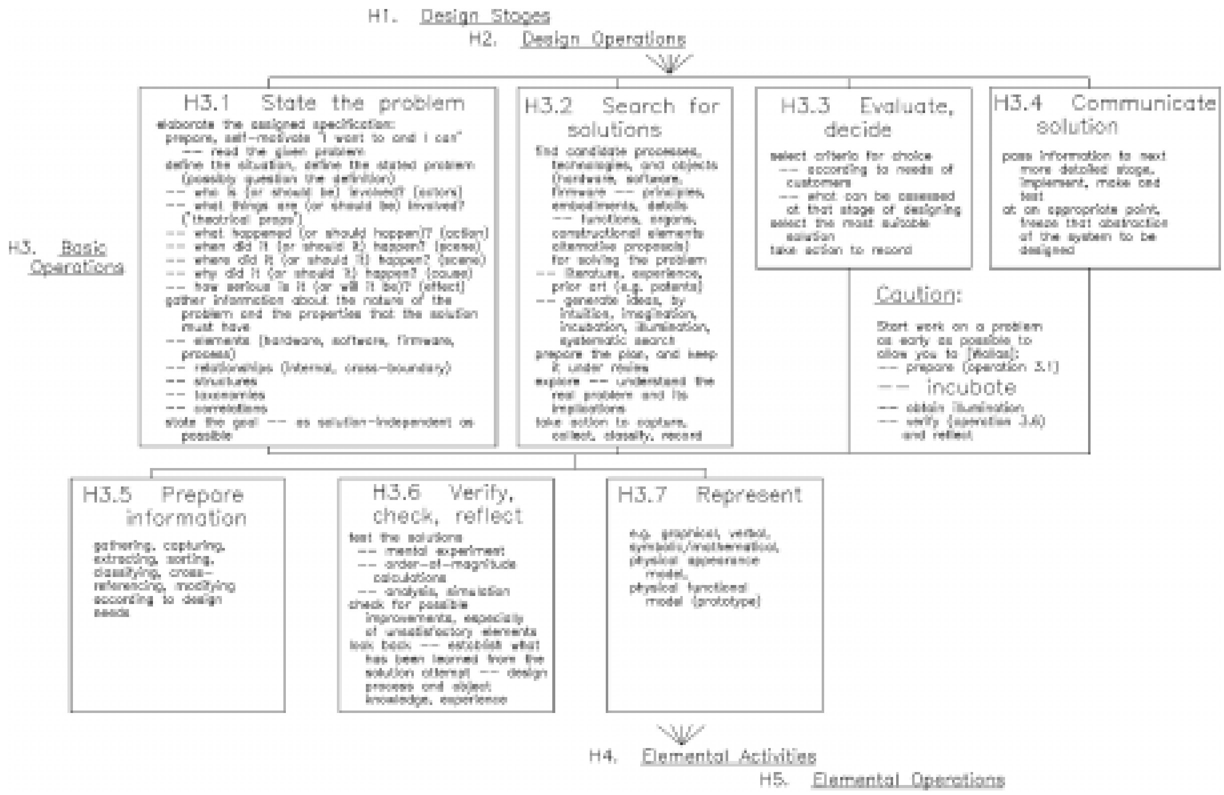

Fig. 13. Basic operations—problem solving in design engineering [4, 8, 14, 15, 19, 51–55].

Gagné in [30] proposed a similar list: signal response, stimulus response, chaining, verbal association, discrimination learning, concept learning, principle or rule learning, problem solving. This list seems to expand Bloom's 'knowledge' and 'comprehension' into seven items, but compresses 'application, analysis, synthesis and evaluation' into a single class of 'problem solving'.

Concerning the affective domain, Krathwohl [12] proposed the following classification:

- receiving—awareness, willingness to receive, controlled or selected attention;
- responding—acquiescence in responding, willingness to respond, satisfaction in response;
- valuing—acceptance of a value, preference for a value, commitment;
- organizing—conceptualization of a value, organization of a value system;
- generalizing—characterization by value, generalized set, characterization.

Simpson [56], has classified the psycho-motor skills as follows:

- perception—awareness of sensory inputs;
- set and ready to act—mental set (alert to act, organized and ready), emotionally set (willingness to respond, accepts signals);
- guided response (execution of acts of physical skills)
- imitation (execution according to directions), trial and error (execution by self-directed trial);
- mechanical response (execution by sub-conscious habit);
- complex-overt response-complex (highly skilled execution with confidence and accuracy), including resolution of uncertainty (smooth and efficient performance without hesitation);
- automatic performance (sophisticated skill executed with ease and perfection).

Interpersonal skills, according to Woods [57], include communication, listening and responding, negotiating, resolving conflict, coping with difficult behaviors, motivating others, networking, working effectively in groups, leadership and team building.

Piaget's model

Human development is a lifetime maturation processes in which education plays a role. Physical development (analogous to the *first idea*) starts at conception, but mental development can only start later. According to Piaget [58], certain stages generally characterize this mental development (especially in the first two years of age):

- sensory-motor—deals with objects in reachable space and thinking by means of actions,
- pre-operational 1—in a preparation phase, objects are classified by one feature, and language is used to develop concepts in a self-centered way,
- pre-operational 2—in the following acquisition phase, symbols start to be used and the idea of conservation is initiated,
- concrete—logical thinking is learned, reasoning about concrete objects is possible, but not about abstract or future events,
- formal—logical operations can be performed, including reasoning about abstract ideas and future events, the human can now fulfill a 'purpose'.

Human development usually continues.

Perry's model

One of the keys to human development, and the main purpose of education, is acquisition of new concepts. When a new concept is introduced to a person, one of two reactions occurs: either an immediate rejection takes place, or a tentative exploration is undertaken. Further explorations lead to a crisis in which that person questions his/her previous concepts and their mental maps. If the person does not accept the new concept, a fall back to the previous position occurs. Alternatively a behavior change takes place which leads to reestablishing the now revised pattern—teaching/learning is a process. This, to me, describes the transitions between and beyond Piaget's stages.

According to Perry [59, 60] this procedure of changing from one certainty through an uncertainty to a revised certainty can be described by nine *positions of intellectual development*:

1. *Dualism polarized*—everything is 'black and white', knowledge is right or wrong, the authority knows all—starting level of certainty'
2. *Dualism modified*—knowledge is generally right or wrong, alternatives are perceived as possible, good authority is right, complexity or uncertainty are errors or teaching tools.
3. *Complex dualism*—multiplicity is recognized as legitimate, but is temporary until it is resolved (the fall-back position), some knowledge is unknown at the time, authority seeks the right answers.
4. *Multiplicity pervasive*—everything seems to be relative, most knowledge is not yet known, everyone has a right to their own opinions, authority does not know the right answers.
5. *Relativism contextual*—everything must be considered in its context, and can be judged by qualitative means, but the existence of right decisions is questionable, commitment is foreseen—the point of maximum uncertainty.
6. *Relativism needing personal commitment*—knowledge is not absolute, students accept responsibility for judgments, good choices are possible, authority is placed in context.
7. *Initial commitment in relativism*—a personal commitment will resolve all issues.
8. *Implied commitment in relativism*—many commitments can be made, but contradictions are possible.
9. *Affirmed commitment in relativism*—commitments must be made and should be changed

as soon as this appears necessary—revised certainty.

It seems that such a sequence takes place for individual concepts, but also for complexes of concepts and even for general outlooks on life.

Kolb's model

Kolb [61] identified four preferred styles of thinking related to learning, Fig. 14:

- *Concrete experience* (CE)—tendency to experience something 'concretely' and to analyze that experience, analogous to H3.1 in Fig. 13;
- *Reflective observation* (RO)—tendency to reflect on an experience, observe and describe, similar to H3.2 in Fig. 13;
- *Abstract conceptualization* (AC)—tendency to conceptualize observations by means of abstract models, hypotheses and concepts, including some of H3.3 in Fig. 13;
- *Active experimentation* (AE)—tendency to actively experiment to test and extend models, the remainder of H3.3 and H3.4 in Fig. 13.

The model suggests (and shows by means of a psychological test instrument) that people are not equally good at these separate tasks. Kolb from these activities classified types of people into:

- the accommodator (preferred sector delimited by axes AE and CE);
  the diverger (sector CE–RO);
- the assimilator (sector RO–AC);
- the converger (sector AC–AE).

In a team, the person whose type is most suitable to the current step in problem solving (transition between axes of Fig. 14) is likely to take leadership of the team. Kolb's model also indicates that these steps should be followed, preferably sequentially, in order to effectively learn a new concept (or to solve a problem).

It seems to me that Kolb's sequence of steps forms a sub-process to each of Perry's positions. It also seems that the steps in the Kolb cycle are related to the structure of human intellect proposed by Guilford [49]. Among the operations, perception and memory seem to me to fit to Kolb's (CE), convergent thinking is similar to (RO), divergent thinking has analogies to (AC), and judgment relates to (AE). Whether any relationship exists to the psychological types is unclear, although extroverts tend towards divergence, and introverts towards convergence.

Pratt's model

Five perspectives of education have been identified by Pratt [62]. They represent purposes for providing learning opportunities:

- *transmission*—efficient, effective and accurate delivery of information (knowledge) to learners; normally teacher-centered, but can be achieved by textbooks and other resources;
- *apprenticeship*—watching, copying, applying, asking and receiving explanations; under supervision, in situations that are as authentic as possible (or are made progressively more authentic);
- *development*—inducing changes of thinking patterns; mainly learner-centered, but usually needs mentoring and guidance from a supervisor;
- *nurturing*—encouraging confidence, self-concepts and self-efficacy in the learner; usually needs mentoring from an experienced person;
- *social reform*—changing society in the process of changing the learners.

This shows a relationship to a useful guideline attributed to Confucius, which says:

Tell me and I will forget
Show me and I will remember
Involve me and I will understand
Take one step back and I will act.

The first two of this set of items are often used to advocate that only project-based education leads to learning. The last of these items is usually omitted—and, according to the same logic, would lead to rejection of project-based learning. These four statements are mutually supporting, synergistic and additive. Inducing learning requires a combination of explanation (telling),

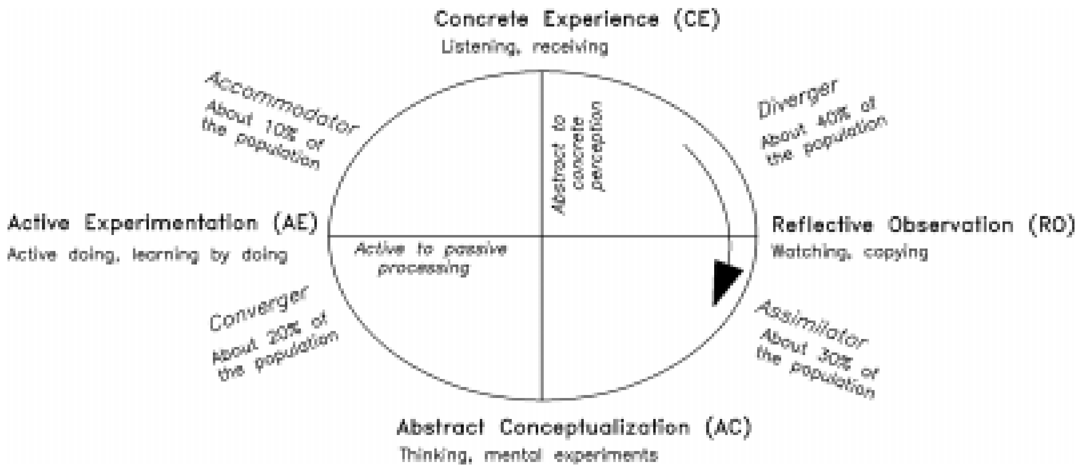

Fig. 14. Kolb's Model of Thinking Styles for Learning [61].

demonstration (showing), coaching (involving), and release from supervision (stepping back):

Do all four and I will become competent.

Cognitive styles and strategies

An individual's preferred way of organizing what is seen, remembered or thought about is, according to Messick [63], characteristic of that person's cognitive style. Cognitive styles seem to be high-level heuristics that organize and control behavior across a wide variety of situations, and are generalized and sub-consciously acquired. They include:

- concept formation, by using functional relationships (predominant in children), analyzing descriptive features (adolescents), or inferences from categorization (adults);
- breadth of categorization, preference for inclusive or exclusive categories;
- compartmentalization, ideas and objects may be isolated into discrete, possibly rigid categories;
- conceptual complexity or simplicity;
- equalizing (leveling) or sharpening of recalled memories;
- reflection (iterative review and correction [4, 14, 15]) or impulsivity (jumping to conclusions) in thinking;
- risk taking or cautiousness in judgment;
- field independence or field dependence (Witkin [64]), analytical or global thinking, serialistic or holistic thinking, tendency towards technical viewpoints or humanistic/social viewpoints.

Learning is seen as a function of individual differences in cognitive styles (including perception and personality) and cognitive strategies (including creative functioning).

Cognitive strategies for learning include:

- rehearsal, reciting, copying, naming, verbatim note-taking, underlining or highlighting text, reading aloud;
- elaboration, keywords, paraphrasing, summarizing, creating analogies, generative note-taking, answering questions;
- organization, mnemonics, outlining, abstracting, diagramming networks;
- planning, setting goals, skimming (and speed-reading), generating questions;
- monitoring, self-testing, attention-focussing;
- regulating, re-reading, reviewing;
- time management, scheduling;
- study environment management;
- effort management, stress and anxiety control, mood, self-talk, persistence, reinforcement;
- support with others, seeking help from teachers or peers, peer group learning, tutoring.

Cognitive strategies should not be regarded as recipes to be used routinely without thought. They need to be learned as consisting of components that are related to cognitive theories of learning, and should be used flexibly and reflectively. Direct instruction of strategies is useful and required, and they should contain both task specific and general cognitive strategies. This instruction must include modeling (worked examples) and providing guided practice in the use of the strategies. One such strategy is SQ3R—survey, question, read, recite, review.

Constructivism

Constructivism [65] contrasts a 'traditional' view of teaching with a 'new' paradigm of learning in a strictly dualistic and polarized way as in the table

Traditional	Constructivist
Teacher as expected model	Teacher as facilitator and guide
Textbook as primary source	Variety of sources and media
Facts as primary	Questions as primary
Information is packaged	Information is discovered
Emphasis on product of learning	Emphasis on process of learning
Assessment quantitative	Assessment quantitative and qualitative
Traditional media	Modern media

It seems typical that both viewpoints are described in extremes. The reality has always been somewhere in between. When holding tutorials or problem sessions, teachers have usually tried to be facilitators. Students have always been free to consult other works (e.g. in a library), and these have often been indicated by the teacher. Questions (as primary) need to be carefully planned to expose students to the whole range of subject matter, but revealing the accepted structure of the knowledge is still difficult in this mode. And so on.

Constructivist viewpoints have been implemented by using case studies, a method that was implemented in medicine and management studies, but has also found some use in engineering [66]. Its more recent application has been in problem-based learning [67] and project-based learning, with almost deliberate avoidance of lectures and explanations, leading to a probable lack of theoretical foundation, and possible deficiencies in relevant object knowledge.

Learning styles

Reichman and Grasha [68] define six learning styles which could characterize students' actions:

- *independent* learning, by learners who prefer to work on their own and think for themselves;
- *dependent* learners, who learn only what is required of them;
- *collaborative* learners, who tend to share duties and ideas, and cooperate in learning;
- *competitive* learners, who try to outperform each other to achieve a higher grade or ranking;
- *participant* learners, who learn most from class interactions and discussions;
- *avoidant* learners, who are either indifferent to or overwhelmed by the learning materials.

The learning style actually adopted by a learner may also be influenced by the teaching, evaluation and grading styles of the teacher, and the sophistication of students with respect to their educational goals, learning outcomes and instructional purposes.

A relationship to constructivism, and to Pratt's and Kolb's models seems to exist.

Smith model

Cooperative learning [69], or collaborative learning, involves formation of student teams (team work). The student teams are directed to divide the matter to be studied among their members. Each student studies (alone) the section of the subject, preferably by searching for the information (under guidance). Then each student explains that part of the subject matter to the other members of the team.

A similar purpose is fulfilled by Whimbey pairs, where one student observes a partner in an activity (e.g. problem solving [51–53, 57]), and tries to analyze and record the nature of each operation in that activity (according to a given model of the process). Students should then give each other feedback about their partner's actions, and their own actions and feelings.

Feedback—evaluation, outcomes assessment

In all cases, the educational theories call for provision of feedback to students about how well they are performing. During an educational experience, such feedback is a *formative* evaluation, intending to improve the student's understanding and capabilities. It is usually necessary for administrative reasons to make a *summative* evaluation of the student, e.g. at the end of a course, mainly to allocate grades or rankings to students in a course. It is also important to encourage a *self-evaluation* of students, to develop their critical and reflective [4, 14, 15] capacities.

Principles and styles of instructors

Changes depend to some extent on the teaching styles of the instructors, and on the (individual) learning styles of students. McKeachie [70] recognizes six roles for teachers:

- as experts who are knowledgeable about their own teaching fields;
- as formal authorities and disciplinarians;
- as socializing agents guiding students towards acceptable behavior;
- as facilitators to help students find and use their own resources and learning materials (object knowledge and process knowledge);
- as ego ideals or role models for students to emulate;
- as persons in their own right, with all their idiosyncrasies and behavioral patterns.

First-order principles for teachers to follow in preparation and teaching have been proposed by Boice [71]:

- moderate (a verb implying 'to actively control and delimit') classroom incivilities by using pro-social immediacies;
- wait;
- begin before feeling ready;
- work and teach in brief, regular sessions;
- stop;
- moderate over-attachment to content and over-reaction to criticism;
- moderate negative thinking and strong emotions;
- let others do some of the work;
- welcome learning and change;
- build resilience by limiting wasted effort.

These may seem to be internally contradictory, but they are not intended to be followed serialistically.

Teaching is also a 'reflective' activity [4, 14, 15, 72], teachers need to continually review their subject matter (contents and structure), their teaching methods, etc., as well as the developments in educational theories and methods.

Closure

Education, both teaching and learning, are affected by the knowledge, abilities, skills, attitudes and values of students (as active *operands* of the teaching/learning process, see Fig. 2), of teaching staff, and of support personnel (as *operators* of teaching/learning). The attitudes (including motivation, attentiveness, etc.) can change over fairly wide ranges from day to day, and over shorter and longer periods. The other variables are much less changeable. The management (especially in goal-setting and establishing a general atmosphere) and environments of education also have their influences.

This picture is thus extremely complex. Both teaching and learning depend on many different factors.

GENERAL PRINCIPLES

Some general principles may be developed from the above, including:

1. Learning depends on the capacities of the learner.
2. Learning is a function of the conditions of practice and/or instruction within which the learner functions.
3. Subject matter and tasks to be learned that are meaningful are more easily mastered; this implies suitable organization, logically related parts, and specifications of the conditions and circumstances in which they will be used.
4. Learning is assisted by knowing the immediate and specific results.
5. Learning can be transferred if the learning tasks and/or principles and work methods can be applied in similar ways in the transfer situation.
6. Learning depends on the amount and quality of motivation; learners with intrinsic (self-generated) motivation learn better that learners

with extrinsic (externally imposed) motivation, and respond better to rewards than to punishment.

7. Learning also depends on the goals of the learner, and the experience of success or failure in attempts to reach these goals.

Corollaries may be stated as:

a) Learning should be active, not just a passive receiving of information and stimuli, even though some explanation by an instructor usually assists active learning.
b) Motivation is necessary for learning, but too much motivation may reduce the effectiveness of learning.
c) Intrinsic motivation is better than extrinsic motivation, but the main control available is to provide incentives.
d) Some experience of success is needed, and helps to encourage a tolerance for failures.
e) Guidance should be given early and in relatively small amounts, preferably concerning one thing at a time.
f) Transfer of learning is helped by understanding the principles and relationships, but repetitive practice is needed for acquiring and developing a skill.
g) Educational methods must consider both the result and the process of learning, 'what to do or learn' (object knowledge) and also 'how to do it' (process knowledge).

Nevertheless, the capabilities, aptitudes, interests, anxieties, independence, etc. of learners interact in complex ways with the methods and conditions of instruction. Learning outcomes will always differ because of human differences. Effectiveness of instruction may be impeded or facilitated in subtle and unanticipated ways by the characteristics of learners, and by the situation in which the instruction takes place. These are statements of learning guidelines rather than principles, and must be conditional. Learning is not just dependent on instruction or on 'doing', but can also take place by observing other people, viewing demonstrations, watching models, listening to lectures, reading books or papers, constructing images, formulating ideas into sentences, etc. Traditional modes of teaching and learning are still valid and useful.

Tyler [73] contends that we know a great deal about stimulating and guiding learning, and need not wait for final or conclusive answers from experimental research.

APPLICATION IN DESIGNING AND DESIGN EDUCATION

It is noteworthy, drawing not only on his research [74] and his industrial experience, but also on his involvement in progressively defining engineering design science [5–9], that only Hubka (among the design methodology community) has considered the pedagogic and didactic theory and drawn some conclusions for education towards design engineering, i.e. the processes of designing for technical products and systems, which needs to be contrasted with the more artistic designing needed for consumer products [75].

The main part of this consideration by Hubka happened before many of the outlined psychological and educational developments occurred. The range of authors who have generalized beyond the immediate classroom experience towards pedagogic and didactic considerations is small. Educational theory is almost never discussed with respect to design education.

Most papers in conferences and journals on engineering education deal with specialized subtopics, usually without acknowledging the broader issues. Many of these papers describe the contents and ways of operating a particular course. Others describe how a particular characteristic of the human being could be achieved, sometimes without being able to provide a measurement of the student's achievement. Yet others present a disjointed philosophy, but present it with such enthusiasm that they hope it will achieve something useful. Some papers describe particular projects and competition entries, which are probably too complicated, especially if they are the only design-related effort that students see in a three-, four- or five-year course. Several papers describe the use (and advantages) of discussion-type case studies derived from industry, to generate active student involvement. Some papers consider the use of computers, including the internet and world-wide-web.

In the large majority of cases, something useful is achieved in teaching students something about designing, preferably including at least one systematic method. But these approaches cannot deliver a comprehensive transmission of the nature (including its theory) of design engineering, and experience of applying the appropriately wide range of methods (including the formalisation of problem solving as in Fig. 13) to a suitable selection of progressively more difficult design problems.

Designing is reputed to involve some human flair, ability, intuition, creativity [76], spontaneity, etc. (and consequently some mystery), but also judgment, reflection-in-action [4, 14, 15], conjecture and case-based reasoning, feel, and experience of individual designers. It is necessarily heuristic [19], iterative, recursive, opportunistic, flexible, and idiosyncratic. Teamwork among designers and other participants within and outside a company plays a large role in the design process. All these are essential to designing, but as individual statements none of them captures the essence of designing, they are necessary, but not sufficient conditions.

These factors seem to indicate that designing is purely a very personal and human matter. If this were so, the only way to teach anything about designing would be by studio work in an apprenticeship style, such as is usual in 'industrial design' education and practice. This requires that the teacher act as a role model, and as a critic. In the second role, the teacher can only show personal opinions about the effects of a product proposal on the critic. Little can be said about the procedures that students actually use, compared to the procedures that students could (and even should) use to obtain better, more optimal results. Much has been written and published about this mode of operation, but none of it has shown any theory base, or any repeatable measure of learning.

Nevertheless, designing (especially design engineering) is not isolated, it concerns an activity, performed within an organization and under specific circumstances, Fig. 15, and about an object—a product. Some coherent and comprehensive systematic and methodical procedures are available from and within engineering design science, and are useful, if applied appropriately and flexibly. Such methods should be formally presented and practiced in design education [77]. Other methods exist that mainly consist of prescribing parts of the process, for instance Suh [78] deals with a limited theory and mathematical method of decision-making. These methods include heuristic and 'industry best practice' methods, usually without an adequate theory of either the design process or the generalized object being designed. Some exposure to these methods is also useful in design education, especially if these less formal methods are improved by bringing the insight of engineering design science into their scope.

Such methods can be taught as step-wise procedures. If a theory exists, it and the method can also be explained. Figure 5 presents an overview of the categories of knowledge needed for education in engineering design. The right hemisphere indicates both the theories of education and their practical application in instruction. The left hemisphere indicates the subject matter and experience of engineering design, and is a compilation of the general map of engineering design science [5], Fig. 3.

In using exercises and projects, students can and should be advised to use the methods flexibly, to re-formulate their thoughts and records, to explore alternatives, to review and reflect upon their previous work on the project, to question the given information (e.g. about requirements) and their own results, to search for more general and alternative principles, to obtain and use the experiences of others (personal, and recorded in the literature).

Design engineering must attempt to anticipate all other uses (and abuses) that the product may reasonably be expected to experience, including manufacturing, assembling, transporting, operating, failure, etc. Various levels of abstract modeling are available from engineering design science [5–9]:

- *Requirements specification, design specification*—a statement of goals for designing as given to engineering designers, and/or developed for their own understanding.
- *Transformation process and technical process*—defining what materials, energy and information the customer wishes to transform from an input state to the desired output state with the help of an artificial system.
- *Function structure*—define what system-internal transformations are needed to make the system work.
- *Organ structure*—define what principles and conceptual hardware/software items can be used to generate the system-internal transformations.
- *Constructional structure*—define what material embodiments can achieve the organs, usually in four distinct forms of modeling.
  a) *Preliminary layout*—mostly in sketch form and with only rough sizing.
  b) *Dimensional layout*—mainly as formal assembled representations (e.g. drawings or

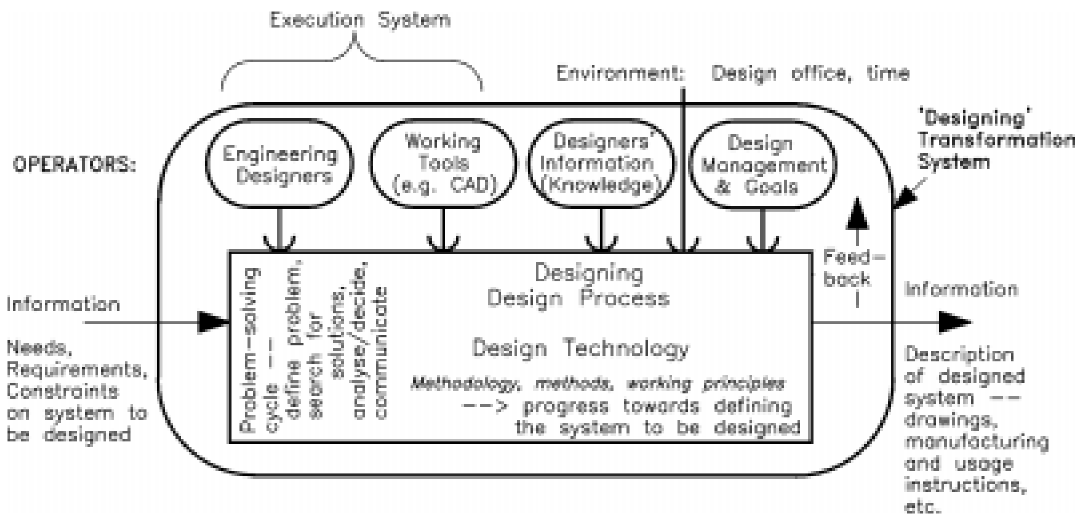

Fig. 15. Model of a design process [5, 7, 8].

computer-resident models) with correct scale and sizes.

c) *Details*—individual components with all dimensions, tolerances, surface finish, etc. as instructions for manufacture.

d) *General assembly*—assembled components, as check on the details and giving instructions for assembly and adjustment.

The modeling levels of transformation process, function structure and organ structure are usually referred to as the *conceptualization* stage of designing. *Embodiment* takes place in the transition to the component structure, particularly in the preliminary and dimensional layouts. *Detailing* completes the definition of the constructional structure.

During designing, the needs, requirements and constraints for a potential solution to a problem are progressively transformed into a full description of a system that can be manufactured and implemented. Various major decision points occur in this process, which are related to modeling and abstraction levels which encourage *generating* the available alternative solutions by search and imagination, necessary parts of designing, and selecting the most promising solution proposals. As understanding of the *problem* increases by proposing solutions, *iteration* (repeating a series of design steps with improved assumptions) and *recursion* (breaking a problem down into smaller parts, solving them individually, then recombining the parts to a whole) are essential. This development has parallels to Perry's model of acquisition of knowledge and incorporation into a person's mental maps, a transition from one level of knowledge to a more comprehensive level.

CONCLUSIONS

Education for engineering design is even more complex than education in the more factual subjects, e.g. the engineering sciences and the humanities. A good survey of the existing educational theories and methods should provide a basis for developing educational experiences to teach (and learn) designing. The theories and objects of design must also be considered in this process.

Similarly, various theories of education and human development can be brought into a hierarchical relationship. Even though these theories have been modified by recent additions of knowledge, they still seem to be basically valid. Newer theories are not necessarily alternatives or replacements to the older ones, in most cases they address a different viewpoint or hierarchical level. This is demonstrated by tracing analogies between learning theories and engineering design, and is supported by the similarities among models in Figs 1, 2 and 12 (adapted from [5–7]).

A further conclusion can be drawn—with the help of rational design processes and the knowledge of these learning theories it should be possible to design courses and curricula for engineering instruction which will result in competent and creative engineering graduates.

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