Experiental Design Courses in Engineering Education

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We outline the current debate on Design Science versus Experiential Design in American engineering design education. The rare Experiential Design portion must be not only preserved but improved by emulating the few existing successful programs. Jung's psychological theory of cognitive modes is developed as a framework to compare experiential design with engineering science approaches to educating engineers. Myers-Briggs personality measurement data is transformed to show quantitatively that the appropriate experiential attitudes can be learned by engineering professors in a couple of well-structured weeks. The experiential courses are seen to develop group creativity, a taste for action, and teamwork in ways not even considered in the usual engineering science offerings.

Historical Introduction

From an educational standpoint, the profession of engineering may be viewed as having three aspects. The first is the *practice* of engineering — its detailed facts and history. The second is the *science* of engineering, which concerns the analytic abstraction of its objective foundations. And the third is the *art* of engineering — the concepts and sometimes subjective intuitive procedures used for synthesising artefacts and systems. Much of engineering research and education concerns the reduction of the first, practice, into the other two — science and art — to make the profession more easily learnable, teachable and doable.

Four decades since the Grinter Report (1995) initiated pivotal reforms in the education of North American engineers, new changes are now being proposed in the USA affecting the "design" portion of the curriculum, that part largely untouched by the Grinter reforms. To understand the ensuing debate it is useful to review the differences between Engineering Science, which makes up most of the present undergraduate engineering program, and the remaining part which we informally call "Experiential Design". If Engineering Science is the result of Grinter's "scientification" of engineering education, then Experiential Design may be regarded as its "artification", to coin a parallel if awkward term connoting its motivation to supply artefacts to satisfy human needs. These words reflect the distinction between the science and the art of engineering raised in the opening paragraph.

A useful way to describe what we mean by experiential design (abbreviated "e. d.") is to contrast it with the more familiar engineering science (abbreviated "e. s."). Whereas e. s. involves inductive understanding from first principles, e. d. concerns the creation of artefacts to satisfy needs. Teaching e. s. is principally done by lecturing, certainly an efficient use of faculty and student time; e. d. is usually learned by hands-on sketching, building, measurement and testing, often an ill-defined and time consuming business.

Consider how differently these two approaches use student exercises. E. s. problems usually have a single correct solution; e. d. problems, many feasible solutions. E. s. problems are command-based in that they require students to follow orders; e. d. problems are need-based in that students often must find out for themselves what to do, applying e. s. knowledge either learned earlier or not yet taught. Consequently e. s. problems encourage student obedience and dependence while e. d. problems develop student autonomy, initiative and resourcefulness. E. s. problems illustrate principles already taught; e. d. problems require stretching the imagination to discover new ideas. Being prescriptive, safe and predictable, e. s. problem sets are easily and objectively graded. By contrast, e. d. projects must be evaluated subjectively, which is difficult because the student approach must be pragmatic, often fraught with risk and uncertainty. Finally, an e. s. problem is usually small enough to be worked alone by an individual, whereas an e. d. project is often so large in scope that a team is needed to carry out all the work.

Course and curriculum descriptions are precise for e. s. but vague for e. d. Memorisation, an effective study strategy for e. s. courses, does not work well on e. d. projects because they involve learning by doing. Tenure track academics with a scientific research speciality can in principle teach either type of course, but for e. d. courses there are also two other categories of valuable teacher. These are untenured or part-time non-academic practitioners, or project course supervisors who, if they have the proper attitudes, can successfully guide students in an over-the-shoulder manner. Although the management of such non-tenured faculty of experiential project and lecture courses can be an important factor in their success or failure, it often receives little recognition from the administration because no research is involved.

We see then that experiential design education is almost definable as whatever is not done by engineering science education. This makes the two approaches complementary, amounting to a partitioning of the various techniques available for educating engineers. From this global point of view it would seem that elements of both styles should be present in a good program. The only thing remaining to determine then is the relative proportions of each.

The Grinter Report led to the replacement of much of the descriptive courses on practice and technique by more rigorous engineering science, but it was recognised that laboratories, engineering graphics and design projects — what we would call the experiential portion of the curriculum — needed to be preserved even though they did not lend themselves to scientification. This preservation was accomplished by accreditation regulations specifying the minimum amount of time devoted to synthesis in an acceptable curriculum. Some engineering schools, especially the smaller ones, have found these rules burdensome because it is often difficult to find engineering scientists willing to teach an experiential subject like design.

Design Science

Complicating the accreditation situation is the continual transformation of some aspects of experiential design into engineering science, mainly through the application of mathematical analysis and, more recently, computer science. Lately the results of this healthy process, which might be regarded as the scientification of (experiential) design — the analysis of synthesis — have come to be labelled "Design Science". Understanding this newly proposed discipline of engineering science is important for comprehending the current debate on design curricula.

The growing content of Design Science is both considerable and respectable. Its antecedents appear in even the earliest handbooks as sizing formulas, usually obtained by closed form optimisation of simple objectives such as efficiency or weight. Abstract verbalisations of the design process known as "Design Morphology" first appeared three decades ago, about the time that the increasing use of computers lead to the forming of the Design Automation group in the American Society of Mechanical Engineers' (ASME) Design

Division. At its annual technical conferences, Design Automation has been the home of mathematical modelling, computer simulation, geometric modelling and the design applications of decision theory — optimisation, system decomposition, and probabilistic modelling. All of Design Automation, as well as the functional description, taxonomy and synthesis techniques of the German engineers Pahl and Beitz may also be regarded as Design Science.

The last decade or so has seen a further scientification of design leading to the annual Design Theory and Methodology (DTM) Conferences. The DTM people focus more on the organisation, sociology and psychology of design while sharing Design Automation's interest in design for manufacturing, quality and myriad other considerations. DTM, along with the axiomatic approach to design, can also be considered elements of Design Science. The point is that Design Science, which in fact will be the unifying theme of the International Conference on Engineering Design in Prague next year, is certainly engineering science rather than experiential design.

Dixon's design science proposal

This brings us to what we call the Design Science Proposal, a call for reforms in design education that has provoked the debate we wish to describe. In a widely read pair of articles in ASME's influential professional magazine *Mechanical Engineering*, the respected Professor John Dixon (1991) viewed with alarm the state of American design education and suggested many changes.

His basic premise is that design is not an art but a science. He asserts that most schools teach design poorly when they imitate industrial practices that are often obsolete. Many industries are further ahead in practice of anything being taught at most engineering schools. He concludes that such obsolescent material can and should be replaced in the undergraduate curriculum by Design Science. While never stating explicitly that the experiential design component should be eliminated to make room for Design Science, this would be the indirect effect of his proposal because the total amount of course time is strictly limited, especially in universities requiring substantial liberal arts of their engineering students. Dixon would not, however, eliminate the team project course; he would employ it in the service of teaching the methodology of Design Science.

Since Design Science has legitimate claims to being an engineering science, these reforms would be especially attractive where the engineering scientists control engineering education — most schools, given the dearth of good experiential design faculty. According to Dixon then, the teachers of Design Science would be engineering scientists with academically respectable research programs easy to evaluate for conventional academic promotion.

The experiential position

Recognising that the Design Science Proposal could implicitly mean the end of experiential design education, the authors of this article have formulated an antithesis which we call the Experiential Position. In expounding it here, we shall repeat point by point our understanding of the Design Science thesis and follow each with an antithetical statement, hoping that an intelligent synthesis of these opposing views will result. Before doing this it is well to compare basic motives. We see Dixon's interest as improving and modernising the content of engineering design education, whereas we experientialists seek to develop in students those personal attributes appropriate to being a creative engineering designer. These are complementary rather than opposing goals, for the achievement of both would certainly benefit the engineering profession. The conflict is over how to allocate the limited education time available.

Now to contrast the Design Science thesis with the experientialist antithesis. Dixon asserts that design is not an art but a science; the experientialists counter that design is both an art and a science. That is, the experientialists believe that the conjunction of art and science is inclusive in design rather than exclusive as the Design Scientists believe.

It is Dixon's implicit proposal that the experiential content be reduced to make room for Design Science that provokes the strongest reaction from the experientialists. Although acknowledging the potential intellectual and professional value of Design Science, experientialists would like to see some of this material — which we emphasise is engineering science, not experiential design — introduced only as a straightforward modernisation of the already large engineering science curriculum in which it would have to compete with such classical subjects as machine design and thermodynamics. Since Design Science is already too large to cram into an undergraduate program, we see it as a new speciality valuable mainly for expanding academic design programs at the Ph. D. level.

Recognising that students learn co-operation best by working in teams, Dixon would use project courses as an alternative way to teach principles of Design Science. However the experientialists would object that using projects only to reinforce subject matter misses an important goal of project work, namely the discovery of the unpredictable, including things different from or even contradicting the ideas intended to be taught by the professor. Experientialists would therefore count such an employment of projects as engineering science rather than experiential design and hence not really chargeable against the synthesis portion of the curriculum.

While agreeing that many schools teach experiential design poorly or, in most cases, not at all, experientialists reply that some schools, too few perhaps, teach design quite well. Our remedy for weak experiential programs would not be to replace them with more engineering science. It would be rather to strengthen them by introducing elements of the successful programs into them. In many cases this solution will require faculty re-education, always a delicate matter. The rest of this article will be devoted to arguing that more design teachers can and must be generated by re-educating engineering scientists, whose own graduate education and research activity are usually poor preparation for becoming experiential educators. It follows, not especially in reaction to any of the Design Science suggestions, that good design educators are a rare, perhaps endangered species who must be recognised, nurtured and valued if future engineers are not to lose altogether the chance to develop their inventiveness and integrative synthesis ability while they still are in college and have relatively open minds. It may be too late to do it when they are working in industry.

Students of this controversy may wish to consult a preliminary article written by Faste, Roth and Wilde (1993) to refute a Dixonian position paper written by Fisher (1993) and signed by ten others, including Dixon, for a meeting of Mechanical Engineering department heads organized last spring by the ASME. Both papers are cited among the references.

Jungian cognitive mode theory

Carl Gustav Jung's theory of cognitive modes (1971), as summarised by Brownsword (1987) and paraphrased here, forms the foundation for this article's approach to analysing the conflicts between the experiential and engineering science approaches, especially in regard to the engineering undergraduate curriculum. Jung partitioned mental processes used to collect information and make decisions into two opposing pairs of cognitive functions, four in all. The boldface and capital letters in what follows show the standard abbreviations used by personality type theorists.

The two perceiving functions by which people collect and generate information are: (1) Sensing perception (S), which collects information about specifics and (2) Intuitive perception or intuition (N), which generates information about meanings, possibilities and relationships. The two judging functions by which people make judgements and decisions are (3) Thinking judgement (T), which makes decisions that are logical, impersonal and analytical and (4) Feeling judgement (F), which makes decisions by arranging things in accordance with their value to the decision-maker and the emotional feelings of others.

Jung also postulated two ways to use each function. A function directed towards the world outside its user is said to be Extroverted, whereas one focused inside the user is said to be Introverted. Combining E and I with the four functions forms what Jung called the eight cognitive modes. Psychologists often abbreviate them, EN for example standing for "Extroverted intuition". The four introverted cognitive modes are thus IS, IN, IT and IF ; the extroverted modes are ES, EN, ET and EF. These combinations form eight Cognitive Modes in the four opposing pairs listed below along with keywords and a description for each.

Each keyword is a single word modifier of a mode, e. g., "Imagination mode", whereas each description tells in more detail how the mode is used, e. g., "Individualistic invention" By "opposing' is meant not only that one is introverted and the other extroverted, but also that the two functions (e.g., Sensing vs. intuitive or Thinking vs. Feeling) are opposed. Jung theorises that when one of an opposing pair is present, the other is absent. We shall see that the available measurements measure the differences between opposing pairs rather than the individual modes directly.

COGNITIVE MODE DESCRIPTION	ABBREVIATION		KEYWORD
Extroverted Sensing	ES	Action	Hands on craftsmanship
Introverted iNtuition	IN	Imagination	Individualistic invention
Extroverted iNtuition	EN	Synthesis	Group brainstorming
Introverted Sensing	IS	Practicality	Attention to detail
Extroverted Thinking	ET	Organisation	Management
Introverted Feeling	IF	Evaluation	Critiquing
Extroverted Feeling	EF	Affiliation	Teamwork
Introverted Thinking	IT	Analysis	Investigation

Table 1.

Jung postulated that all human cognition takes place in one or more of these eight cognitive modes. This article shows how to compute numbers approximating the strength of a person's preference for each cognitive mode, or more accurately, the difference between opposing pairs.. But for now it is more important to examine the various ways of teaching and learning engineering in terms of these modes. The columns of T able 2. list these cognitive modes, both by abbreviation and by keyword, while the rows show the various education methods. The entries at the intersection of method and mode indicate, in our opinion, the modes used by each method, with "P" indicating the principal mode employed, "L" any lesser modes, and "O" any mode used only at the option of the instructor.

EDUCATION METHODS	COGNITIVE MODES							
Analysis	IT							
Practicality		IS						
Imagination			IN					
Action				ES				
Organisation					ET			
Synthesis						EN		
Affiliation							EF	
Evaluation								IF
ENGINEERING SCIENCE								
Lectures, problems	P	L	L					
Seminars, papers	L	L	L		O			
Demonstrations	L	P						
Descriptive technology	L	P	L					
EXPERIENTIAL DESIGN								
Laboratories	L	L	O	P	L			
Shops	L	L	O	P	L			O
Graphic communication	L	L	L	P	L			O
Individual design projects	O	O	P	L	L	L		L
Group design projects	L	L	L	L	L	L	P	L

Table 2.

One immediately notices that the e. s. courses concentrate heavily on three of the introverted modes: Analysis (IT), Practicality (IS) and Imagination (IN), with only the seminars with their open discussions focusing on the extroverted mode Organisation (ET). Among the experiential design courses, the labs, shops and graphic communication courses cover pretty much the same territory in that they all put their attention on Action (ES). These courses are not under attack by Dixon, since everyone realises the value of their action orientation. It is the design project courses on the bottom two lines that are at risk. Remarkably, both of them cover not only the ground of the e. s. courses, but also the remaining cognitive modes, especially the intuitive ones — Imagination (IN) for individual projects and Synthesis (EN) for group projects. Note moreover that only the group projects can stimulate the Affiliation (EF) mode so important in corporate relations. It is also important to observe that one of the introverted modes Evaluation (IF) is developed only in the project courses, although occasionally shop and graphic communication courses bring out this taste for quality and aesthetics at the option of the instructor.

Developing design educators

So far we have discussed how we think the various kinds of engineering course develop the cognitive modes. Now we would like to give evidence that certain important creativity and affiliation modes have been stimulated in design teachers by a workshop entitled "The

Integration of Creativity into the Engineering Curriculum" that we have held (Wilde, 1993). Taken by 65 North American engineering professors in all, this two week workshop has been given in four separate summers. To do this we must mention superficially the Myers-Briggs Type Indicator (MBTI) (Myers & McCaulley, 1985), a preference assessment upon which our measurements and analysis are based. In brief summary, our conclusions are based on MBTI measurements taken before and after the Creativity Workshop and then transformed mathematically in accord with theories for estimating the various cognitive modes. The changes observed suggest that the modes can and are developed by the workshop in ways consistent with the psychological theory (Wilde,1993).

The Stanford Design Workshops involved two uninterrupted summer-term weeks of concentration on the issues of teaching experiential design: sketching, intention, goal-setting, introspection, need-finding, co-operation, brainstorming, building, performing and critiquing. The MBTI gives four scores, three of which have already been mentioned in the discussion of cognitive modes. These are expressed as differences between the following opposed tendencies: (1) Introversion and Extroversion, (2) intuition and Sensing perception, (3) Feeling and Thinking judgement, and (4) – the new pair – Perception and Judging itself. The four scores can be arranged into a four-component vector of signed numbers which is transformed into a new vector of cognitive mode differences, in order: (1) the difference ES-IN, (abbreviated eS.p),(2) EN - IS, (eN.p), (3) ET- IF, (e.Tj) and (4) EF- IT, (e.Fj). In the abbreviation, used in Figures 1. and 2., the single psychological function involved (e.g., S in eS.p) is capitalized, the first and fourth letters indicating which attitudes dominate: introversion or extroversion, judgement or perception. The dot (.) holds the place of the omitted function pair. The only normal orthogonal transformation which can do this is described in Wilde (1994); it is the following: ES-IN: (-1, -÷2, 0, 1)/2, EN-IS: (-1, ÷2, 0, 1)/2, ET-IF: (-1, 0, -÷2, -1)/2, and EF-IT: (-1, 0, ÷2, -1)/2.

This showed the following cognitive mode pair changes in the Workshop. The most important, and the only statistically significant one, was the change in the difference between EN (Synthesis) and IS (Practicality). The difference increased from 1 to 18, certainly a noticeable change, given the scale of the numbers. This is easily rationalised as the effect of the creativity training, which certainly greatly enhanced the EN Synthesis mode. in addition there was probably also a slight increase in the students' attention to detail (IS), but the difference still changed appreciably.

The next difference change was only barely significant statistically but still worth noting. It involved the difference between ES (Action) and IN (Invention). The difference increased from -20 to -13, noticeable although only barely significant statistically. We rationalise this by noting that the hands-on work built the ES while the creativity training probably increased the lone invention IN slightly. Another effect was what might be called the "Extroversion of intuition", by which we mean the conversion of the introverted mode IN into the extroverted form EN by overall increase in both extroversion and the preference for perception over judgement, both of which work for increased extroversion of the perceptive function intuition. Notice that the scores, although increasing, remained negative, which indicates that on the average the participants were and remained lone inventors, merely increasing their taste for action during the workshop.

Figure 1. shows these changes, as well as those for the three facilitators, which took the same form. It appears that the participants changed in the same way as the facilitators, who continued evolving in the same way. The dot at the tail of each arrow is the group average at the beginning of the workshop; the head indicates the average at the end.

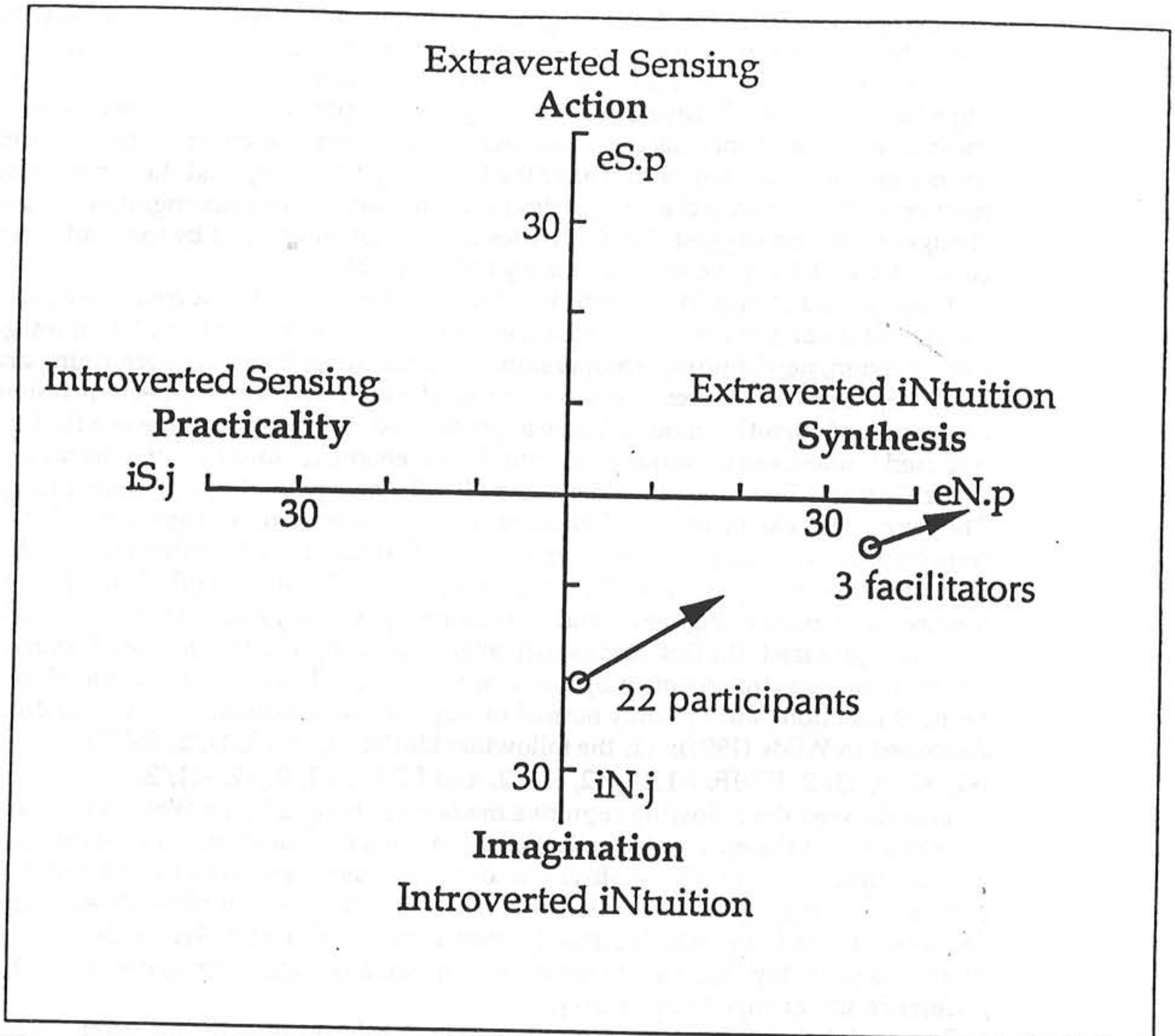

Figure 1.

The third difference change was measurable, but not statistically significant in the sample of 22 studied. It showed the difference between EF (Affiliation) and IT (Analysis) to increase slightly from -17 to -12, easily rationalised as the affiliation effect of the teamwork required by the short group project. The analytic ability IT was of course unaffected. In fact, the average stayed on the analytic side, these being after all engineering professors.

The final difference was similarly measurable but not statistically significant. It involved the slight decrease from 11 to 1 of the difference between ET (Organisation) and IF (Evaluation). We explain this by the need-finding and critique training, which certainly enhanced the IF, although we would contend that the management training also increased the ET slightly. Indeed, both were emphasised, and Figure 2. shows the students ended about where the facilitators started, and the facilitators evolved further in the same direction — towards more EF and IF. That is, evaluation was emphasised so much that it seems reasonable that both the student beginners and the more experienced facilitators would see the workshop as a place to develop their evaluative powers. Figure 2. plots these changes.

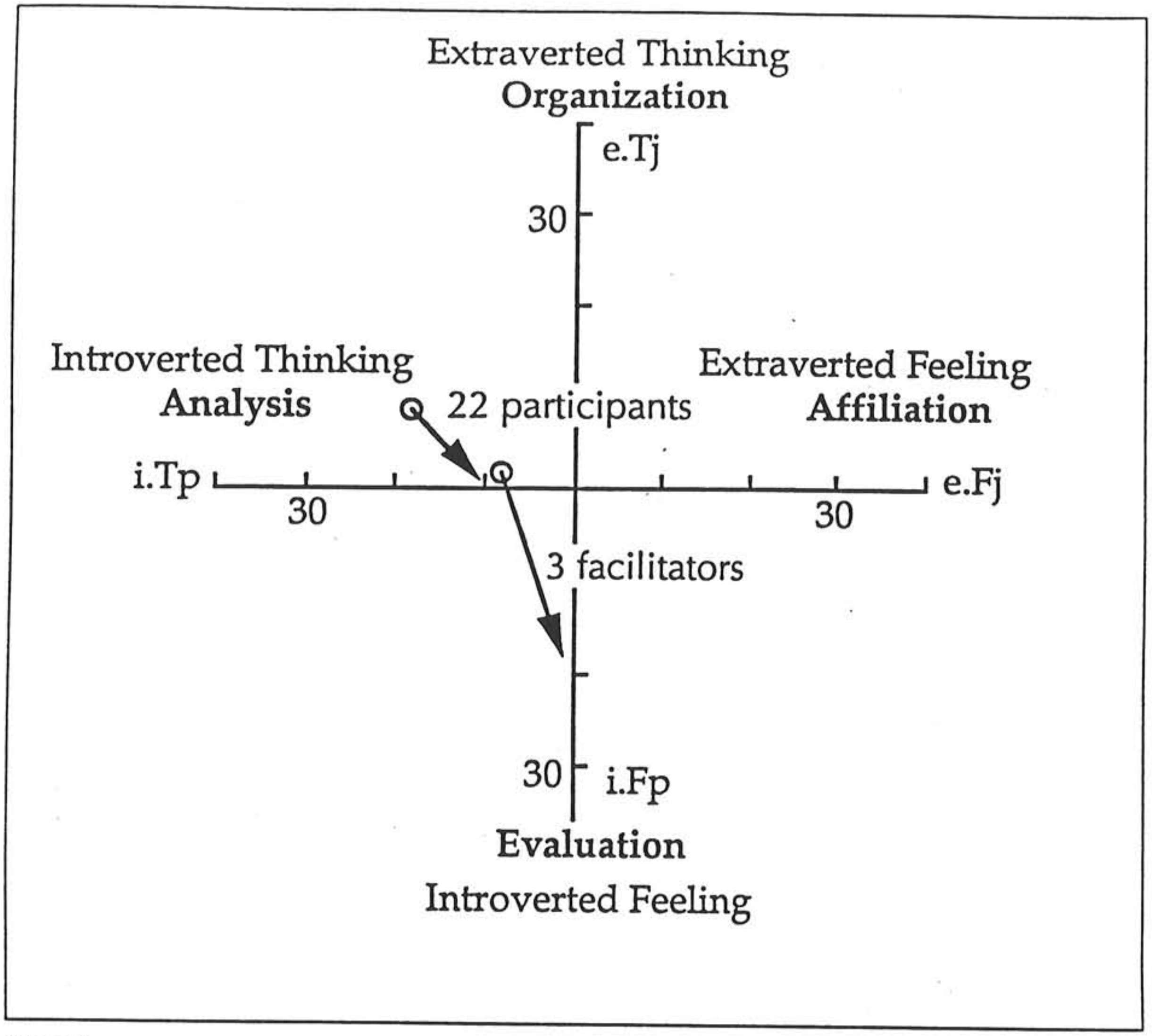

Figure 2.

In summary, the workshops did seem to develop the creativity of the participants as advertised. In addition there were less pronounced enhancements of the extroverted Action (ES), Affiliation (EF) and Evaluation (IF) cognitive modes in the participants. The facilitators changed in the same way, qualitatively speaking at least. The bottom line is the proof that these valuable attributes can be developed in engineering professors, even decades after leaving graduate school. A secondary conclusion of importance is the original character of the participants developed by graduate school — mild individual (IN) rather than group (EN) creativity, and a mild preference for analytic (IT) over affiliate (EF) skills. On the average the group seemed balanced originally between organisers (ET) and evaluators (IF).

Concluding summary

This article has surveyed a current discussion about design programs in the American undergraduate curriculum growing out of the Grinter Report Engineering Science reforms started four decades ago. It has outlined and compared the two main positions. The first is the Design Science Position calling for replacement of weak experiential design programs by