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Viewpoint: An Industry View of Engineering Design Education*

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The US industries are being beaten to the marketplace by foreign competition with a better quality product. What industry needs is clear: engineering graduates with a better design experience. American engineering schools respond to this need by producing great scientists but mediocre engineers. More priority must be given to developing engineers rather than research scientists if the schools are serious about meeting the needs of American industry. This will require a major restructuring in most engineering faculty and administrations in terms of attitudes and priorities. This will not be a major restructuring of current engineering curricula, but rather, more open-ended problems inserted into the engineering science courses with frequent and spirited discussions of the design process. The tools of design can be woven into existing curriculum courses. This design experience must occur all four years and be capped off in the senior year with a 'Capstone' design course(s).

THE VIEW

THERE is an interesting difference in opinion in America today between industry and the universities. American universities do not, in general, value engineering design as an intellectual activity either in research or in teaching. American industries, on the other hand, place the highest value on engineering design in their product development.

It is clear what American industry needs from its engineering schools: engineers who can solve open ended problems and produce quality design work. Our engineering schools are turning out great scientists but mediocre engineers. Mediocre won't make it in the world-wide competition marketplace.

Industry makes money by designing, manufacturing, and selling a product in the marketplace. That product has to beat the competition to the marketplace with better quality. Thus, timing and quality are essential and both are dependent on the design of the product.

America is losing the timing and quality race to foreign competition. They are beating us to the marketplace with better quality products (Figs 1, 2 and 3). So the bottom line is that foreign competition design is better than ours. A recent National Research Council report says 'the overall quality of engineering design is poor' [1]. Industry needs more engineers, not scientists. Theodore Von Karman argued that 'A scientist discovers that which exists. An engineer creates that which never was'. It is the 'never was' that makes money for industry.

A 1983 survey of the primary activities of employed engineers (Table 1) reveals that 28% of the engineers are involved in developing, including design. Typically over 40% of the engineers in the aerospace industry are involved, either directly or indirectly in design related tasks (conceptual design, preliminary design or detail/production design). Less than 5% of the design engineers are involved in conceptual design. Approximately 20% are involved in preliminary design and the remainder are doing detail/production design work on projects. The detail/production designers are producing engineering drawings that are given to manufacturing to start fabricating the parts and assembling the product. Engineering drawings include the analysis that supports the design, a description of the item, and the instructions for making, assembling and testing the item. The progress in a project is often measured by the number of engineering drawings released.

The American industry view is that for the past 30 years the engineering graduates have been weak in design. On the other hand, the engineering graduates' knowledge of engineering science, maths and analytical techniques is very good, but they are poorly equipped to sue the knowledge in the design of components, processes or systems. In other words, while our technology has flourished, our design has decayed.

In the '40s and '50s, the American engineering programs were very application oriented and design received a great deal of attention in the curriculum. After all it was America's design and manufacturing capability that won WWII.

In 1952 ASEE began a critical look at engineering curriculum issues and formed a prestigious 44 member committee chaired by L. E. Grinter. In 1955, the Grinter committee published their findings which recommended the following [2]:

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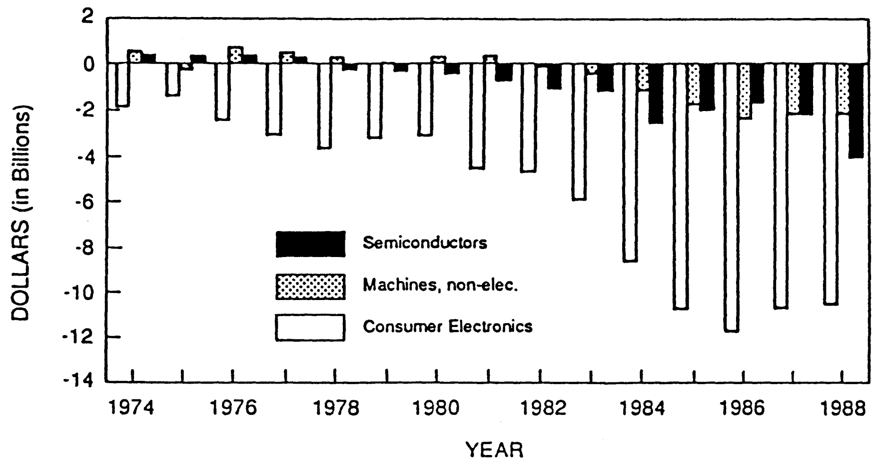

Fig. 1. US trade deficit in three key industries.

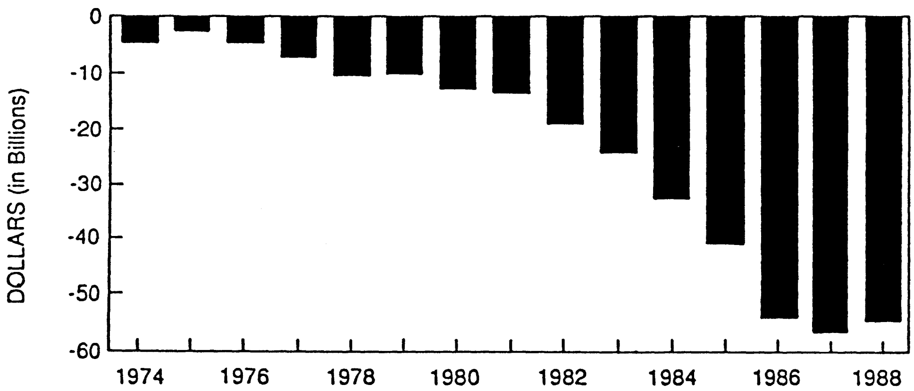

Fig. 2. US trade deficit in the auto industry.

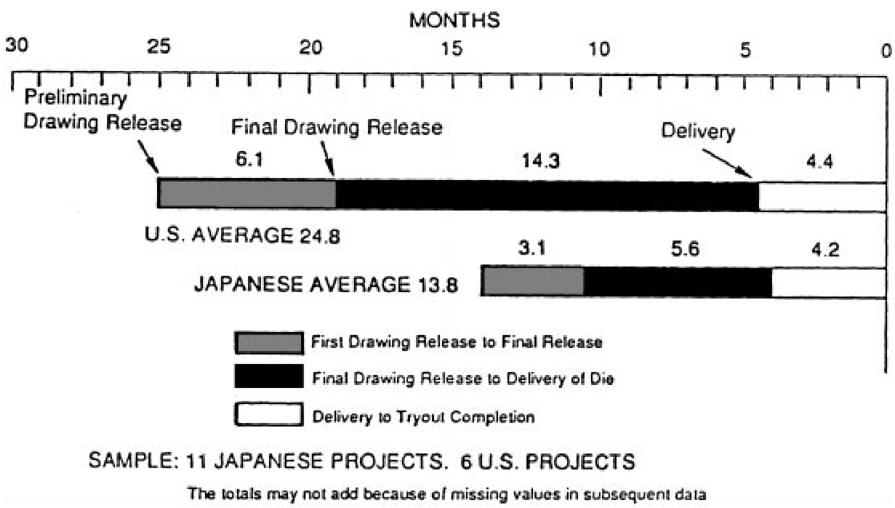

Fig. 3. Lead time for a major body die (months).

- Strengthening the courses in basic sciences with emphasis on mathematics, physics and chemistry.
- Incorporation of six engineering science courses as a common core of engineering curricula.
- An integrated study of engineering analysis, design and systems.

In 1958, the USSR launched Sputnik and the American people became concerned that our research and technology was not World Class. Almost overnight the engineering programs went from an application and design emphasis to reserach and analysis. ECPD (ABET in those days) went along with this change in thinking and implemented the first two recommendations of the Grinter report.

Table 1. Primary activities of employed engineers in 1983

Activity	Percent of engineers
Research	5
Development, including design	28
R & D management	9
Other management	19
Teaching	2
Manufacturing	17
Other	21

Source: National Research Council, Engineering Education and Practice in the United States: Foundations of Our Techno-Economic Future, 1983, p. 91.

Somehow the third recommendation got lost [3]. In the '60s design disappeared from most engineering curriculum as the faculties became predominantly analytical oriented and preoccupied with research.

In 1971 ABET saw the error in their thinking and required all engineering programs to have one-half year of design. This hit the engineering schools like at atomic bomb and the schools scrambled to find design faculty and/or loopholes in the criteria. ABET was very patient and the professional societies very lax in enforcing the new criteria. Some societies such as AIAA led the other societies in strict but pragmatic enforcement of the one-half year of design. As a result most graduates in Aerospace Engineering got an acceptable design experience. But this was not the case in some of the other engineering disciplines (such as EE) who have had real trouble in meeting the one-half year of design requirement.

Currently over 1/3 of the engineering programs do not receive a full 6 year accreditation because of a deficiency in meeting the design requirement. This problem is a reason for the recent ABET change to the criteria to delete the one-half year of design. In other words—if you can't meet the standards, lower the standards.

It is interesting to question if there is any correlation between a weak engineering design education over the last 30 years and our current poor engineering design capability in industry. Certainly the students of this weak engineering design education are now exercising great influence over our product design efforts. Figure 1 indicates that there may be a definite correlation between our loss of the consumer electronics market share and the fact that Electrical Engineering has had considerable difficulty in meeting the current ABET criteria for one-half year of design.

It should be noted that the aerospace industry is one of the few US industries that has produced a positive balance of payments over the last two decades. Perhaps this is a reflection of AIAA's strong emphasis on design in the Aerospace Engineering program criteria. However, the US dominance in the aerospace industry is under attack and our worldwide market share is eroding (currently 60% from a 1985 peak of 73%). The European and Japanese aerospace industries are stepping up the pressure, producing a trend that is chillingly similar to that experienced by the US auto industry two decades ago.

If you examine our competition in Europe or Japan you find that the foreign industries place the same high value on engineering design that we do. But a significant difference is that the foreign engineering schools respond with an engineering graduate who has received more design experience than do our graduates. For example, the last semester of the Aerospace Engineering curriculum at the University of Tokyo is devoted to a design project and thesis (no course work). The design content of the courses at the University of Tokyo totals more than one-half year.

It is therefore the view of industry that the American engineering schools are turning out great scientists, but mediocre engineers. Many articles have been written [1, 4, 5] about the American engineering schools turning out legions of research scientists who are repopulating the engineering department of the school from which they graduated. As a result, engineering schools are producing entire generations of engineering faculty who have never practiced engineering. They are more attuned to the needs of university research programs rather than to developing engineering that meets the needs of American business.

THE RECOMMENDATION

Is there a solution to this problem short of firing all the engineering faculty and starting over? I think there is but it involves a major change in the attitudes and priorities within the engineering departments and a minor restructuring of the curriculum.

To begin with, the engineering schools must get serious about meeting the needs of American industry by giving more priority to developing engineers rather than scientists. An attitude change is required that will make design faculty equal to analytical faculty. This should involve changing the reward/promotion system to be more compatible with the design faculty's situation. These changes are a major restructuring at most engineering schools.

In 1990 the College of Engineering at Arizona State University conducted a major evaluation of their undergraduate engineering curriculum [6]. They assembled a task force composed of students, faculty and industry representatives. The results of their two year study revealed that the unanimous number one attribute desired for a newly graduated engineer was the ability to identify and define a problem, develop and evaluate alternative solutions, and effect one or more designs to solve the problem. This attribute was rated significantly more important than the number two attribute which was a breadth and depth of technical background.

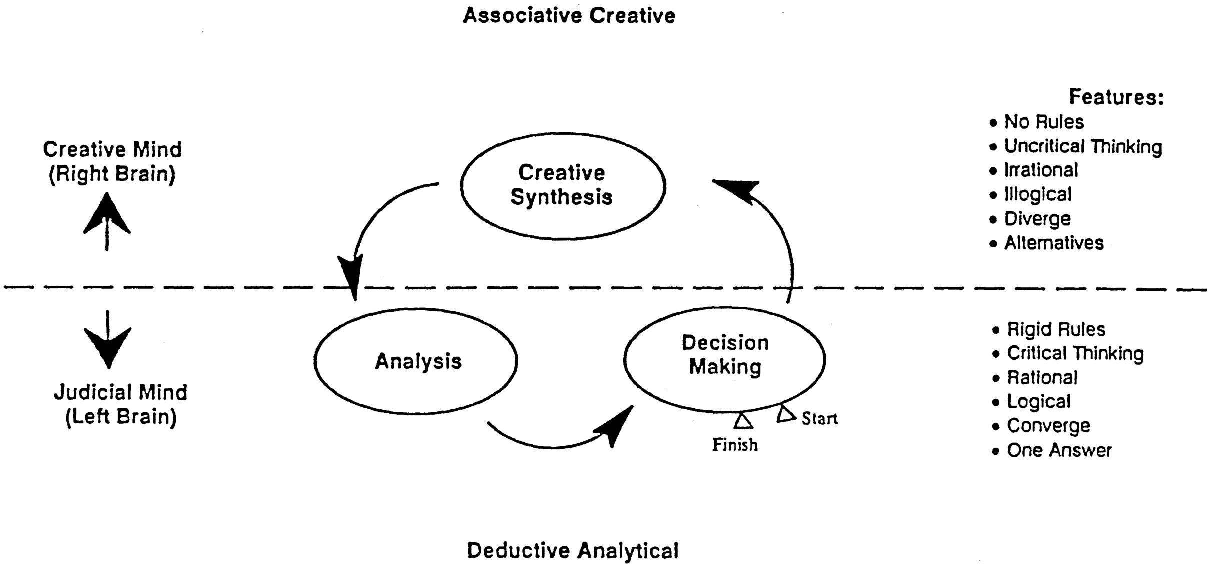

Fig. 4. The design process is an open-ended problem where the engineer has to flip from left brain, to right brain and back again.

The engineering curriculum must let the student experience being an engineer by introducing problem situations which force the student to link engineering theory to real-world problems by doing some original thinking, evaluating alternate solutions, making a decision and defending it. The best way to do this is by giving the student open-ended problems since these are the only type of problems that occur in industry. The students must become comfortable with working open-ended problems. An open-ended problem or design problem process is shown in Fig. 4 [7].

The beauty of the open-ended problem is that the student becomes very emotionally involved as the available information is insufficient to solve the problem and the student must generate the missing information which makes the answer unique to him/her.

Table 2 shows an example of two parallel problems, one a closed-form and the other open-ended, which reinforce an engineering theory. In this example the closed-form problem would measure the student's understanding of high lift theory. The closed-form problem is a subset within the open-ended problem and is represented by the analysis bubble on Fig. 4. The open-ended problem would ask the student to apply this theory in the design of a product (in this case a wing). The answer that the student gets to the open-ended problem is not nearly as important as the student's logic and rationale for his/her wing design.

In this example the student would have to decide who is the customer and what is important to that customer during the decision-making phase of the Fig. 4 design process. For example, the student would have to decide among:

- Safety—low stall speed requiring large wing area (low w/s), sophisticated/complicated flap arrangement, thick airfoil, full span flaps, etc.

Table 2. Example of an aero/performance problem cast in close-form and open-ended format

Problem statement: Determine the stall speed at LAX airport for a 2-place General Aviation aircraft at 30° flap deflection with the following characteristics:

Item	Closed-form problem	Open-ended problem
Pilot/pax baggage	392 lb	392 lb
Fuel weight	147 lb	147 lb
Empty weight	1136 lb	920 lb (less wing)
Airfoil	NACA 2412	TBD
Wing area	159.5 ft^2	TBD
Flaps	Single Slot $C_f/c = 0.2$ 33% span	TBD
Wing span	33.3 ft	TBD
Aspect ratio	6.95	TBD
WIng taper ratio	0.7	TBD
Wing sweeps	0	TBD
ANSWER	42 kts	Depends on wing design

- Small/light aircraft—small wing area, thick airfoil, etc.
- Low cost—small wing area, simple flap arrangement, no sweep or taper, constant flap chord, etc.
- Appearance—moderate sweep and taper, tapered flap chord, thin airfoil.
- Reliability/maintainability—KISS (Keep it Simple, Stupid).
- All of the above—best balance (compromise) of the conflicting MoMs (Measures of Merit).

Clearly the open-ended problem is not an easy task for the student—but very valuable experience as it represents a typical assignment the graduate engineer will be given (or participate in) in industry. The graduate engineer that is uncomfortable with open-ended problems will have a difficult time in industry.

Several engineering schools have had great success in teaching engineering science by introducing the course material from a design approach rather than the traditional analytical approach. Table 3 shows two ways of teaching heat transfer that have been tried at the University of Toledo, College of Engineering. After several years of using the design approach for teaching heat transfer, they report that the students learn the material better, retain it longer, and enjoy it more (based on student course evaluations and grades).

The engineering curriculum needs to be modified to give the engineering graduates the following preparation:

Solid grasp of the fundamentals in maths, basic sciences, and engineering sciences

- These fundamentals are necessary to do competent analysis work. Currently, most schools do very well in giving the student a good understanding of the analytical fundamentals.

Understand and experience the design process (Fig. 4)

- Since industry's problems are open-ended, the new engineers must be comfortable with open-ended problems. They must be able to flip-flop between left brain (deductive/analytical) and right brain (associative/creative) mental activities. They must be able to perform trade studies and make the compromises necessary to achieve a balanced design. They must be able to develop selection criteria considering all relevant issues, develop and evaluate alternate solutions, and make a decision from the possible design solutions.

Understand and apply the tools of design

- Drawing/sketching/descriptive geometry—this skill is needed to communicate design ideas to others for technical reviews and discussions. The new engineer needs to sketch his ideas by hand first, before burning up valuable time on the CAD/CAM system. This does not have to be a whole course, but rather part of a course called Engineering Drawing and includes descriptive geometry. The student must understand that engineers draw. The new engineer needs to be able to visualize in 3D and in different orientations. He must be able to project from a 3-view to examine fit, clearances, interferences, etc.
- Communication skills—(writing, speaking, and drawing) are very important since the new engineer will be part of a team and must be able to communicate ideas and concerns. The communication must be clear, concise, logical and reflect the proper use of the English language (this includes spelling).
- Kinematics—since most products will move, fold, rotate, expand/retract, etc. the young engineers need to understand kinematics. They need to understand what will work and what won't, and how to find information on mechanism design. Even though kinematics is normally taught in the engineering science series, it deserves special mention here and needs to be given a design flavor.
- Statistics—this is statistics from the point of view of how it is used to design experiments and statistical quality control, rather than the theory of statistics. Also, since many technology

Table 3. Two ways of teaching heat transfer

Traditional (analytical) approach	Alternative (design) approach
○ Students must know the fundamentals	○ Students must know the fundamentals
○ Minimal computer use	○ Extensive computer use
○ Only one 'correct' solution expected	○ Multiple solutions/alternatives expected
○ Right-or-wrong answers	○ Contextual problem solving
○ No solution; this is unacceptable	○ No solution; this may be the best solution
○ Narrow focus on course or discipline	○ Multidisciplinary focus
○ Pure analysis—no design content	○ Application to design is central
○ Students work alone	○ Students work alone and in teams
○ Problems are fully defined	○ Problems are open-ended (less defined)
○ Students spend much time substituting in equations (plug-and-chug)	○ Students spend much time in critical thinking and in asking 'what if' questions
○ Learning is teacher-centered	○ Learning is student-centered
○ Students fear risk; failure is punished. Learning from failure does not occur.	○ Students are encouraged to examine causes of failure for continuous improvement
○ Quick idea judgement	○ Deferred idea judgement.

data bases are statistically based, the engineer needs to understand statistics to work with the data.

- CAD/CAM—automated 3D graphics systems have replaced the drafting table as surely as the hand calculator has replaced the slide rule. We are becoming a paperless society because electronic drawings are faster to generate, easier to control, transmit, change and store. The young engineer must know how to operate a CAD/CAM system (specific software is not important since there is not a standard software in industry).
- Materials and processes/manufacturing—since the purpose of design is to have something built, the new engineer must understand materials and processes, and manufacturing methods. They must be given a healthy respect for the people on the shop floor who will 'bend the metal' according to their drawings. The young engineer must know how to communicate with the shop people and recognize that they are an essential part of the team. Manufacturing must receive spatial emphasis as reported in the 23 March 1992 US News and World Report [8]. As American industry restructures to keep up in an increasingly more competitive world, the once lowly field of manufacturing has become the priority program in graduate schools of engineering.
- Economics—the new engineer must understand that cost is the bottom line and will usually determine whether a product sells or not. This is not a course in micro or macro economics (although these courses are useful as part of the HSS series). This is a course in cost awareness, the parts of cost (RDT&E, production, operation and support), what determines cost, general cost estimating relationships, learning curve, time-to-market, etc. The young engineer must appreciate that cost is usually part of the selection criteria and a major trade-off item.

Experience realistic engineering design problems

- This experience encompasses all of the previous recommendations and needs to occur in all four years. The student needs to experience working in small teams (3–5 students) as this will be the way they operate in industry. Team efforts are a marvellous place to develop the communication and interpersonal skills. The team approach reduces the individual work on the part of the student and the instructor as well. Most open-ended problems lend themselves to a team effort. It is important to get industry participation to inject realism and timeliness into the problems.

SUMMARY

The consensus of industry, engineering societies, the Federal Government, and even the schools themselves is that American engineering schools are producing great scientists but mediocre engineers. The US industries are being beaten to the marketplace by foreign competition with a better quality product. What industry needs is clear: engineering graduates with a better design experience. I don't see this as a major restructuring of current engineering curricula, but rather, more open-ended problems inserted into the engineering science courses with frequent and spirited discussions of the design process. The tools of design can be woven into existing curriculum courses. This design experience must occur in all four years and be capped off in the senior year with a 'Capstone' design course(s). I do see this as a major restructuring in engineering faculty and administrations in terms of attitudes and priorities. More priority must be given to developing engineers rather than research scientists if the schools are serious about meeting the needs of American industry.

REFERENCES

1. *Improving Engineering Design, Designing for Competitive Advantage*, National Research Council, Washington, DC, 1991.
2. L. E. Grinter, *Report on Evaluation of Engineering Education*, ASEE, Washington, DC, 1955.
3. M. Tribus, Afterthoughts from a found(er)ing father. *Engineering Education*, ASEE, July/Aug 1990, p. 523.
4. D. T. Curry, Engineering schools under fire, *Machine Design*, 10 Oct 1991, p. 50.
5. J. H. McMasters and S. D. Ford, An industry view of enhancing design education, *Engineering Education*, ASEE, July/Aug 1990, p. 526.
6. Engineering Education: Preparing for the Next Millennium. Arizona State University, College of Engineering and Applied Science, Tempe, Arizona 85287, Dec 1991.
7. L. M. Nicolai, Designing a better engineer, *Aerospace America*, AIAA, Washington, DC, April 1992, p. 30.
8. America's best graduate schools, *U.S. News and World Report*, 23 March 1992.

Dr Nicolai's education consists of BS (Univ. of Washington), MS (Univ. of Oklahoma) and PhD (Univ of Michigan) degrees in aerospace engineering and an MBA from Auburn University. In addition, his military education consists of Squadron Officer School, Command and Staff College and Air War College. His military/industrial experience

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