Thoughts on the Engineer of 2020
An Early 21st Century [Aerospace] Industry Perspective

John H. McMasters
Technical Fellow
The Boeing Company
Seattle, WA 98124
john.h.mcmasters@boeing.com

A Conference on the 50th Anniversary of Harvey Mudd College,
Claremont, California

January 14, 2006

Abstract

The purpose of this paper is to contribute to the commemoration of the 50th anniversary of the founding of Harvey Mudd College by discussing some of the challenges and opportunities we within the broader technical community - in industry, government and academe - face in assuring an adequate future supply of well prepared engineering and science graduates for the full range of employers who have need for such talent. While presented from an aerospace perspective and thus from that of a “mature industry” (at least in some major traditional product areas), it is believed that the issues to be addressed have far wider relevance. Our industry can provide a lens for discerning future trends in both professional practice and requirements for university and post-employment engineering education programs in a much broader context. Although much has been accomplished in the past decade to enhance engineering education, we, as both educators and practitioners, have much to do to cooperatively create a strong and vivid vision of our future, and assure the proper development of a future generation of engineers with the skills and motivation to meet society’s needs in our always evolving enterprise.

“It is suicidal to create a society dependent on science and technology in which hardly anyone [except a small, numerate elite] knows anything about science and technology.”

Carl Sagan

“The scientist discovers that which exists, the engineer creates that which never was.”

Theodore von Kármán

Introduction

For much of the 20th Century, advances in aeronautics and then aerospace have served as a sort of poster child for modern technological progress. More recently, however, a spate of national studies and articles in both the popular and professional presses1,2 has decried the seriously declining state of aerospace in general and aeronautics in
particular in this country. Whatever the reasons for the putative decline in aerospace, two fundamental factors have been cause for serious immediate concern. The first is that we as a technical community (industry, government and academe), within aerospace and aeronautics in particular, have continued to be unable to create a collective vision of our future as compelling and exciting as that which has driven our past – the technological dreams of Star Trek and quest for the discovery of life on Mars or elsewhere in our universe notwithstanding. A second factor, reciprocal to the first, is the need for an aggressive means to replenish and sustain our pool of technical talent in the face of a rapidly aging workforce. This is required to maintain and advance an industry that continues to find a multi-billion dollar a year market for its products and services, has almost singularly contributed a positive balance of trade to our economy, and is of fundamental importance to our national security. The present pool of skilled practitioners is rapidly approaching retirement, and despite concerns about “outsourcing” in our developing global economy, there is competition for both young and experienced talent in key technical areas (e.g. composite materials structural design, systems engineering, and computer/software engineering) from seemingly more dynamic sectors of our national and global economy. A central concern for our historically volatile and ever changing enterprise must be for the education and development of a future generation of practitioners as skilled and motivated as those who have created our history.

The author has spent the great majority of his over fifty-year careers as an aeronautical engineer and engineering educator; and as a matter of both personal and professional interest, has been wrestling with a suite of issues relating to the development of our technical workforce of the future for a long time. Faced with a number of challenges in our own industry and beyond, the author began a lengthening series of both independent and collaborative writings3-15 and lectures under the general rubric: “The Demise of Aerospace – We Doubt It”. As this series developed, so has the agenda which now includes making modest contributions to:

- A national need by our aerospace community to revitalize itself by creating a vividly positive vision of its future as compelling as that which has driven our past, as a means to…
- Attract a next-generation technical workforce that possesses a much broader multi-disciplinary and systems engineering perspective aided by…
- Reform and enhancement of our technical education system (beginning at the elementary school level) to…
- Attract and retain a diverse student population (especially women and minorities) that reflects the shifting demographics of our society.

These topic areas cover a lot of territory and briefly outlining how they relate one to another, as a system, with regard to the topic of the “Engineer of 2020” is a central purpose of this paper. While written from a predominantly aerospace industry-academic perspective, our base of experience also may serve as a lens for examining the future of other advanced technology industries as well. In this connection, it is important to note that while the apparent focus is on “aerospace” engineering, a company like Boeing (in common with most others in our industry) employs many more electrical, mechanical, materials, manufacturing and computer related engineering graduates than it does those with explicit aerospace engineering degrees. In this sense, the subsequent text relates to industry interests in engineering education enhancement in a broad sense.
Aerospace Today and Into the Future – Some Very Basic Challenges

The aerospace industry (aided significantly by government and academe) has traditionally been very effective in developing advanced technology of benefit to both our own business purposes and to a large portion of our society as well. Indeed, if one examines the first century of powered flight (Fig. 1) from the initial success of the Wright brothers in 1903 to beyond our success in placing humans on the Moon less than seventy years later, one sees truly dramatic progress, spurred by the simple mantra Farther, Faster, Higher. Driven more recently by competitive and economic pressures, and enabled to a massive degree by the advent of the computer and the broader scope of information technology (IT), many companies also have made great strides in improving their processes for doing work and increasing productivity – sometimes dramatically. In general, we know how to do these things, they are discussed exhaustively in our professional literature, and they are thus of peripheral (though significant) concern in discussions of some very basic issues that are of current and future importance to the long-term health of our enterprise.

Aerospace as a Poster Child for Technological Progress

Figure 1. The Tradition View of the History of Flight.

A principal motivation in the author’s earlier writings has been the simple observation that the most important assets of most companies and institutions in our society are their people (their “intellectual capital”) and the cash flow that results from their activities. In this people-centric view of our own industry, it may then be argued that: The best technology and processes in the world are useless without the right skilled and motivated people to develop and apply them. It is these social and “people” (technical workforce) aspects of our enterprise that underlie much of what we do and are of fundamental concern to our future. They are, however, too frequently ignored or treated as a separated, disconnected topics in the engineering literature. In reality, technology, processes and people form an inseparable triad in industry and it has continued to be
the author’s purpose to treat them as a unity with emphasis merely shifting depending on the specific topics to be discussed.

How Many Engineers Do We Really Need?

Two inter-related technical workforce questions are of pressing current concern to our industry: “How many engineers will we need in our future (nationally, world-wide)?” and “What will these engineers need to know and be able to do as major changes continue to occur in professional practice?” Historically, the aerospace industry has had a reputation for being volatile, with a long series of well-publicized periods of either feast or famine in employment. It also has produced its share of notorious examples of supposedly “strategic” forecasts that have proved to be, on retrospective examination, extrapolations from either a bubble or a trough in longer-term business cycles. Recognizing that technical talent development requires a considerably different - and generally much longer - time scale than the product development cycles that are the basis for much of industries’ planning and general mindset, the challenge remains for us to make realistic forecasts as a means to assure that an adequate supply of talent in the right skill areas is available to us at any given time. The strategic forecasting problem has been exacerbated in recent years by the fact that the industry overall (which includes a large number of suppliers and customers which spread far beyond the relatively few remaining major flagship companies upon which the media tends to focus its attention) has been subjected to a rather massive consolidation and extended downsizing in the wake of the Cold War. To what degree this now may have ended remains unclear. Events such as 9/11 are almost impossible to predict and the degree to which their extended aftermath may cause reversals in trends is difficult to assess. While accurately predicting long-term workforce needs is probably impossible, reasonable estimates are still needed to assure that proper steps are taken to attract and educate the talent we will need to sustain the health of our industry.

Aerospace is a small segment of the engineering profession

Figure 2. Issues Determining Future Aerospace Engineering Needs.
As shown in Fig. 2, barring a complete collapse of the world economy or other massive
catastrophe, one may examine the basic factors that could lead to either a significant
increase or decrease in the number of engineers needed, relative to those we currently
have, over the next couple of decades. Some of these factors are readily recognizable,
and with regard to a need for more engineers and scientist, one must consider the
anticipated growth in the world population with their attendant needs. Added to this is
the growth in global commerce, made possible by a combination of the
IT/communications revolution and the existence of an effective global transportation
system; the continuing traditional need to maintain our national security, now
exacerbated by the increased threat of terrorism that now extends to our own shores;
and perhaps most importantly, the need to deal with a range of increasingly pressing
environmental issues.

Countering these growth factors are the parallel advances being made in the tools and
knowledge available to do our work, the mechanization of an increasing number of
routine, repetitious tasks and processes that have in the past provided employment for a
very significant percentage of our technical workforce; and the seemingly inexorable
economic pressure to improve productivity (i.e. squeeze as much useful work as
possible out of each individual still employed). Taken together with those factors which
indicate a need for more engineers, a case could be made that, on a long-term average
basis with fluctuations about the mean, the suites of factors might be roughly
compensatory, and thus the number of engineers we currently have is roughly the
number we will continue to need for the foreseeable future. This modestly optimistic
(and admittedly parochial) prognostication is based on the implicit assumption of
evolutionary rather than revolutionary changes in the nature of the basic technical work
or organizational context in which it is done on our path forward. The remaining question
is that of where the work will be done, and by whom. As we move toward further
globalization, however, this mildly optimistic estimate suggests a potentially grim
prospect for employment for U.S. engineering graduates unless they have skills and
expertise that are in high demand (e.g. system integrators and architects) or are
relatively invulnerable to off-shore outsourcing (e.g. involving services that require
significant direct interpersonal interaction with customers or suppliers).

Outsourcing and Globalization

From a domestic (U.S.) perspective, globalization has come to look more like a
revolution to some and carries with it the prospect of increasing outsourcing of work
(including engineering) to those countries where labor is cheaper and workers can now
compete with their U.S. counterparts thanks to the benefits of their own increasingly
high quality education systems. These educational infrastructures have been
constructed by increasing numbers of their own citizens who received their educations
in colleges and universities in Europe, the Soviet Union and, prominently, the United
States and then returned home, commencing from a trickle at roughly the beginning of
the post-Sputnik era in the early 1960’s. In the grand scheme of things, we in this
country can take some pride in what has been accomplished by those individuals who
shared in our educational wealth and then have worked on behalf of improving their own
countries’ standards of living and competitiveness in the world labor market.

To an increasing number of our own workers, however, there is cold comfort in our past
generosity and emerging opportunities for transferring work previously performed here to
other countries. To many, it can only raise the specter of continuing job loss among domestic engineers as well as factory workers who must now compete with increasing numbers of highly qualified non-U.S. citizens. While outsourcing may make good business sense (at least theoretically), it becomes something of a shell game for major manufacturers in dealing with related people issues. For a given work statement, the specified tasks have to be performed by someone, somewhere; whether inside our own fences or by an outside supplier. Continued process improvements can reduce the number of people required, but some bottom line number of highly qualified and knowledgeable individuals are required (to write specifications for work to be done, monitor supplier performance, etc.) at any given state of this evolutionary improvement process. A prudent balance in “sourcing” work is needed to manage risk and assure the integrity of the final products delivered.

Current concerns about outsourcing also have masked a more ominous prospect - that of simple job disappearance which, over the longer haul, may be much more significant and ultimately more disruptive at a societal level. Thanks to advances in IT and robotics, we are increasingly capable (in principle) of automating tasks that have become sufficiently routine and well understood unless there is some compelling reason a human must remain in the loop. The issue of job elimination, rather than mere job loss via outsourcing of work, is becoming of increasing concern to some of us. To our knowledge, the whole suite of longer-term implications surrounding it has not yet become a necessary subject of national discussion. If this seems to some a mere jeremiad, a reading (or re-reading) of Kurt Vonnegut’s possibly prescient 1952 ‘satire’, Player Piano, provides one darkly thought-provoking scenario for our possible future. As observed in our earlier writings, however, it is highly premature to write the history of our industry as an obituary, and attention may now turn to consideration of the question of what future practitioners in our industry must be capable of doing.

A Longer-Term View of our Future

Looking farther ahead in general terms, the list of fundamentally significant things the aeronautical component of our industry alone has to do in the coming decades includes:

- Continue to maintain and develop an effective global transportation system that is increasingly safe and secure, and compliant with the needs of our society and our environment.
- Continue to contribute to our national security as threats and effective responses to them continue to change in significant ways.
- Contribute a necessary aeronautics component to the issue of providing affordable access to space, enabling the further exploration of our universe.

All of these topics represent a myriad of challenges and represent a solid base for continued employment of our aerospace workforce, nationally and globally, even if pursued in evolutionary ways. On a larger, global societal scale, however, we can already see (Fig. 3) some potentially revolutionary developments looming that will dwarf, but also strongly influence, the future concerns of our own industry. These include:
Some Global Challenges for the 21st Century

- Increasing World Population
- Cultures/Institutions Unable or Unwilling To Change
- Global Climate Change
- Finite Supply of Key Natural Resources (Oil, Water, Minerals)

Engineers must play a fundamental role in any solutions or ameliorations!

Figure 3. An Emerging Global “Perfect Storm”?

- The previously noted increase in the world’s population over the next fifty years to a level never before experienced in the whole of human history. One may quibble over the actual number of billions, but very substantial further growth and redistribution in world population appears to be inexorable.
- The prospect of major climate change, with the contribution of human activity to it the only real topic controversy. Examination of the climatologic record over the past several hundred thousand years alone suggests that major cyclic climate change has been the norm rather than the exception, and there is no reason to believe that mean temperatures on our planet we are accustomed to have somehow stabilized in perpetuity.
- The finite limit of our global supply of critical resources, specifically fossil fuels, but including potable water, fertile soil, etc. Fossil fuels are a non-renewable resource and the effect of an increasingly limited supply must have a very profound effect on the way we imagine future airplane development, as but one of many, far larger concerns.
- Confounding attempts to deal with the issues above is the inability or unwillingness of some of the foundational institutions in our global society to change – at least at a rate anywhere near consistent with the need to adapt to the massive challenges we seem likely to face in coming decades. This factor suggests the prospect of increased tensions and strife in our already heavily stressed global society. “Cultures” simply do not change rapidly, although some do become extinct under extreme circumstances.

All of these issues are global in character and know no national or state boundaries. All are real, and in a worst-case scenario, could conceivably coalesce into a global “perfect
storm” later in this century. Any one of them alone will likely have a serious effect on our global economy and on our own industry. To deal with them, it may be concluded that it is likely going to take all the global engineering talent we can muster, merely to ameliorate – let alone solve - the worst of these potential problems.

Up the Value Chain in Engineering Practice

Much thought has been devoted in both industry and academe to the increasingly uncertain future of our enterprise and the technical workforce needed to support it. In general, we have employed a “futurist’s” rather than Jules Verne approach in our earlier writings

3-14 to project further progress in airplane design, related technology and process developments, and education needs. In this approach, one examines a sufficiently long historical time period (centuries) to attempt to discern basic trends and durable characteristics (i.e. it is dangerous to focus on a too short-term time frame in any evolutionary process, and thus miss the real targets of importance or inadequately consider longer-term consequences). With this knowledge in hand, one then may examine what new developments such as possible “disruptive technologies”, changes in the geopolitical environment, etc. may occur and thus produce fundamental changes in the previous ways of doing business. Thus, the futurist’s role is not to predict the future with any certainty, but rather to attempt to estimate “what could happen, if wanted (and no unknowable events intervene)”.

“Desired Attributes” of an Engineer

= A good understanding of 
engineering science fundamentals  
  – Mathematics (including statistics)  
  – Physical and life sciences  
  – Information technology (far more than “computer literacy”)  
= A good understanding of design and manufacturing processes (i.e. understands engineering)  
= A multi-disciplinary, systems perspective  
= A basic understanding of the context in which engineering is practiced  
  – Economics (including business practice)  
  – History  
  – The environment  
  – Customer and societal needs  
= Good communication skills  
  – Written  
  – Oral  
  – Graphic  
  – Listening  
= High ethical standards  
= An ability to think both critically and creatively - independently and cooperatively  
= Flexibility - the ability and self-confidence to adapt to rapid or major change  
= Curiosity and a desire to learn for life  
= A profound understanding of the importance of teamwork  
= Global awareness (aided by knowledge of at least one language other than English)  


Diversity –wanted and needed

Figure 4. The Time-Worn, but Still Durable Boeing List

One successful example of this approach was its use in the construction circa 1993-94 of the Boeing list of “Desired Attributes of an Engineer” (Fig. 4). The original purpose in creating this list was to establish a basis for an on-going, constructive dialogue with
academe at a time when much legitimate criticism was leveled at various companies for a seeming propensity to “change their minds all the time” and sending conflicting messages to schools regarding “what industry needs”. What seemed needed instead was a simple listing of truly **durable** skills and knowledge that contained no “flavors of the month” (no matter how apparently worthy at the time) which could thus be used as a solid basis for making **systemic** changes in engineering education programs to better align them with **long-term** employer needs, i.e. teaching these **fundamentals** should stand any student in good stead, no matter how the world might change in the future. This list has stood us well for the past decade and has been used as one of three basic source documents in framing the “Student Learning Outcomes” section in ABET Engineering Criteria 2000 approved in 1996. The list as thus constructed (with one recent addition: “Global awareness”) has been considered a success in that it has not been found necessary to change anything on it over the decade since it was first created, and much constructive dialogue has been generated by it. It thus remains our basic message to academe regarding what industry needs of their graduates.

From this list, one may also construct the diagrams shown in Figs. 5 and 6 which attempt to clarify and describe in very general terms what may be both required and available in terms of future long-term employment opportunities and educational needs.

---

**Which of these two archetypal technical employees is more valuable to the aerospace industry?** **They both are!**

![Diagram of Engineering Archetypes](image)

**A proper balance is needed as times continue to change.**

**Figure 5. Engineering Archetypes.**

Much of the emphasis in these figures is on “systems engineering” or more generally “systems thinking” which has proved to be surprisingly elusive to describe as a formal engineering discipline outside a defense industry context, as will be discussed later.
Knowledge of Many Skills with Career Choices Based on Talent, Ability, Interest and Ambitions

Foundational Technical Skills
- Math
- Science
- Analysis
- Computing

Engineering Skills
- Design
- System Integration

Professional Skills
- Communications
- Team Work
- Networking
- Interpersonal

Business Skills and Acumen
- Cost accounting
- Scheduling
- Planning

General knowledge and life experience

Technical Subject Matter Experts

Designers System Architects

Program Managers

Customer and Service Engineers

Marketing

Figure 6. An Educational Objective - The Well-Rounded Engineer of 2020

Industry Needs–University Responses

Industry Practice
- Heavy emphasis on experiment
- Limited to slide rule mathematics
- Heavy reliance on handbook methods
- Strong linkage of engineering to manufacturing
- Limited company funded research

Engineering Curricula
- "Vocational" orientation
- Limited mathematics
- Emphasizes on:
  - data gathering
  - problem solving
  - design (and drafting)
  - manufacturing

- Continued reliance on testing
- Early computational capabilities
- Gap between engineering and manufacturing "cultures"
- Increased company-funded R&D
- Increased need for technical and scientific knowledge

Figure 7. Long-Term Trends in Engineering Practice and Education

Rapid Industrial Expansion
Transform from agrarian to manufacturing economy

1900
WW 1

1950
Sputnik

Emerging post-Cold War global economy, enabled by transportation and communications technology

2000
9/11

Cold War Era
Big science, rapid technological advances, international perspective

9/11

Information Age

System Integrators/ Product & Process "Architects"
(Multidisciplinary Perspective)

Technical Specialists
(Core "Engineering Sciences")

- Emphasis on technical knowledge
- Emphasis on theory and mathematics
- Decreasing emphasis on design and manufacturing
- "Publish or perish"

- Retain strengths in math and physics
- Enhanced IT emphasis
- Emphasis on design and manufacturing
- Emphases on breadth, context, and process:
  - Economics, business, project management
  - Environmental and societal issues
  - Teamwork and communication skills
  - Career-long learning
Continuing in this vein, the issues of what will stay constant versus what will change in our enterprise over the coming decades in terms of both professional practice and education system responses may be examined in the historical context shown in Figure 7. It may also be noted that some of the factors that underlie the discontent about our future in aerospace are suggested in this figure. Many of our colleagues who grew up and matured professionally in the long-running Cold War era continue to lament the supposed end of farther, faster, higher as the driving force for progress, with maintaining national security under the threat of potential nuclear holocaust providing substantial license. Our older friends may be partially correct (from their perspective), as the far less dramatic quest for “quicker, better, cheaper” has become the more recent mantra for aerospace. The newer imperative of “cost \textit{uber alles}” has been forced on us by a new economic and geopolitical reality, however, as competition in all phases of the market have grown increasingly fierce. Such imperatives will not soon disappear, but more likely will simply increase in their complexity due to a formidable list of issues (environmental concerns, our finite global fossil fuel supply, etc.) and constraints (e.g. resources available, an aging infrastructure) in our current state of affairs. As suggested in the title of one of our recent papers\textsuperscript{5}, a new mantra for airplane development might properly be “Leaner, Meaner, Greener” as a somewhat more optimistic prospect for our future – at least technologically. It certainly presents a suite of opportunities no less creatively challenging than any our industry has faced in its first century of existence.

Meanwhile, the ways in which we design and develop our products to meet these new challenges will continue to change. This will be made possible, in part, by the continually increasing power of the computer and the tools (e.g. direct analysis and inverse design methods and simulations, CAD/CAM systems, multi-disciplinary optimization) available to exploit their capabilities. Further globalization of our economy and changes in societal priorities, combined with technological advances available or envisioned (new materials, robotics, nano-technology, etc.) will likely cause further transformations in the airplane design process and the products that result. At the same time, terms like “customer focus”, “lean manufacturing (and engineering)\textsuperscript{18}”, “up the value chain” and “integrated product teams” have become major elements of the new vocabulary of the aerospace industry, with all the baggage and implications they carry with them.

It is within the context above that one may now examine the skill needs one can anticipate in our future, particularly with regard to those buffered against outsourcing or mechanization out of existence. Referring again to Fig 7., it can be seen that as engineering practice and industry needs continue to co-evolve, the continuing need for the “subject matter experts” (engineering science specialists) that has been the central focus of most engineering education programs for the past forty years, will be increasingly complemented by the need for more “systems” talent – as system architects, integrators and analysts. Much of our earlier writing has been focused on this topic\textsuperscript{5-14} and creation and cultivation of this talent pool remains of fundamental importance to the future of our enterprise and a major challenge for our system of engineering education. Overarching this issue is the need for academe to educate the sort of well-rounded engineer (Fig. 6) that can assume the roles that will be the core of our technical workforce of the future.

Enhancing Engineering Education – From Conception to Legacy

While it may be argued that the U.S. retains the finest \textit{graduate}-level education in the world, over the past two decades our \textit{undergraduate} engineering education system has
been subjected to substantial criticism and calls for reform from industry, some government sources (NSF, NAE, NRC), and from within academe itself. Some of the more pointed concerns that have been widely expressed include:

• **Our future supply of engineering talent is threatened.**
  - Current engineering education programs are failing to attract and retain an adequate number of students, especially women and minorities
  - Undergraduate programs still look more like “preparation for a Ph.D. program” than “preparation for professional practice” in too many of our colleges and universities.
  - A too large majority of faculty have little or no significant industry experience, and have a very limited understanding of rapidly evolving employer needs.

• **Engineering education costs a lot for what we get.**
  - Engineering education programs are expensive to offer and costs are rising alarmingly, while too many undergraduate students are turned off by what is offered - especially women and minorities.
  - Employers continue to pay the full (often hidden) bill for teaching graduates what they need to know, but are not taught in school. There also is a potential major net savings for industry in investing early in the educational process, rather than paying the bill later. A better sharing of resources between industry and academe is necessary.

• **Major opportunities for reform exist but remain to be exploited.**
  - Significant advances have been made in our knowledge of how people learn and develop, while new teaching methods and curricular organization has been demonstrated¹⁹, but have not been widely accepted. Too little has changed in undergraduate engineering education delivery in the past 50 years.
  - ABET EC 2000 accreditation rules encourage rather than block educational experimentation¹⁹,²⁰, although too many schools have failed to respond fully to these new opportunities.

For many years, undergraduate engineering education has been based on the implicit (and foolish) assumption that we somehow need to teach students “everything they might need to know” before they enter professional practice – while trying hard not to lose too many of them in the process. If a new technological area became important in an engineering discipline, faculty would add a course on that subject to the curriculum. This “throw a course at the problem” mentality forces engineering programs to continually struggle with the question of what to take out of their curricula to make way for the next big item on the often conflicting agendas of faculty involved in graduate research programs and the needs of the employers of their graduates. With too much to know and too little time available to teach it in (as long as industry clings to an increasingly archaic engineering degree structure via its hiring practices⁰⁶), academe too often continues to use a balkanization approach in curriculum development, with the undergraduate student (especially women and under-represented minorities) too often the casualty of what is offered to them.

One possible solution to our overall dilemma is to expand the box and finally face the fact that the traditional B.S. degree is no longer adequate as the entry level requirement
for professional practice, and that some sort of 5– or 6-year program is needed. In whatever creative ways a new engineering degree structure might be contrived (e.g. Figs. 8 and 9); it remains the author's belief that this is at best only a partial (and potentially even more expensive) solution to the problem.

![Diagram showing the evolution of professional degree programs from 1900 to 1980 and beyond.](image)

**Figure 8. The Evolution of “Professional Degree” Programs**

*Note:* The traditional BS/MS/PhD degree structure is a legacy of the 19th Century origins of engineering education programs as “vocationally oriented” outgrowths of the science components of liberal arts curricula and is no longer consistent with the needs of a true “Professional Program”.

![Diagram illustrating a possible modern degree system for engineering.](image)

**Figure 9. A Possible Modern Degree System for Engineering**
At the undergraduate level, we need to adopt a modern “systems engineering” perspective and do a much better job of determining what really needs to be presented (and when and how to present it) in our efforts to educate students to operate in a modern engineering environment, rather than merely thinking about what specific skills they may need in order to gain their initial job assignments, or as preparation for a graduate program in research. Instead of creating courses to meet specific (and too often parochial) needs, we must develop in our students a basic understanding of the unity of the fundamental tools and concepts needed for engineering practice rather than providing them a vast bag of tricks for solving selected problems.

The author has long believed that the fundamental purpose and over-arching goal of our college and university system is to prepare our graduates to become informed, contributing members of our society, and that engineering is really about design (in the most general sense of “open-ended problem solving”). While science and mathematics provide the engineer much of the basic tool and knowledge suite needed for practice, it is design, and more recently its abstraction into systems engineering, that is the essence of our profession (with “business considerations” [i.e. costs, both monetary, and environmental and social] always in mind). In educating engineers for our future, we need to think in terms of a truly student-centered approach with quality rather than mere quantity being an objective at the undergraduate level, with much of the specialization in current programs deferred to the graduate level and continued career-long learning opportunities.

What this mean to the faculty in our universities is possibly even more work, with little prospect for near-term reward. Changing the goals and rewards for faculty may be more difficult than changing the curriculum they teach, but an effort must be made to attract diverse and well qualified faculties who have strong practice-oriented teaching ability, as well as a desire to perform meaningful research and publish in the right journals. Perhaps most difficult of all is to create a culture and climate where faculty are willing and able to function as a team. In doing so, they serve as powerful role models for their students—as a group of engineers who are true exemplars of life-long learning and team-based creative problem solving.

Connecting Some Dots

The preceding discussion suggests that engineering academe faces as many challenges today as does our industry as a whole. It also must be recognized that despite all criticism, any attempts to reform undergraduate programs must be done in a way that does not damage the quality of what we now have at the graduate level. In making this observation, it must be also recognized that research remains (perhaps regrettably) the life-blood of much of the current system, and without the revenue it generates, the quality of the undergraduate programs it directly and indirectly subsidizes would suffer dramatically. The basic problem thus posed to all of us is shown in Fig. 10. How all this is to be resolved is left as an exercise for the “student” and may be recognized by engineering faculty as just a major “system of systems design problem”.

Two specific opportunities may be identified here, however. After a long period of neglect in the 1970s and 80s, design-build-test/validation project experience has been increasingly reintroduced in many curricula as an effective means to bridge the gap between engineering theory and practice, and significantly enhance student learning, motivation and retention. For reasons elaborated in earlier papers\textsuperscript{5-7,9-11,15} even more is
needed, however, and this should become more pervasive from the beginning of the freshman year through graduation (at whatever level) as a fundamental complement to the math and science fundamentals that must remain a core element in any curriculum.

How to align many competing interests?

A second opportunity, connected to the first, is to adopt a much more multidisciplinary perspective than is customary and greatly increase the intellectual playing field of engineering enquiry. With respect to aerospace interests, the author has found the biomechanics of flight and, by large-scale extension, ecology (or more completely, paleo-ecology to add a needed time dimension to the “mother of all systems of systems”) to be a very fruitful areas in which to expand student (and his own) thinking and to introduce the concept of “systems thinking” and a myriad of potential new student and faculty research and project ideas. In the context of the current paper, it has been the author’s intent to demonstrate that flight (and “aerospace”) has far broader implications and applications than merely the design of airplanes and space vehicles, and that even interests in botany and horticulture may be included. All this also serves to address the broader issue of the proper “pipeline” needed to aid in attracting and motivating the long-term supply of engineering and scientific talent we require as shown in the suite of Figs. 11-14.

And Then What?

Although aerospace indeed may now be considered a mature industry even as it continues to change dramatically, that is far from identifying it as a dying industry as the author has attempted to demonstrate. It also serves as a useful example of the range
The Technical Workforce Pathway - System Framework

Overall education system → Jobs

Many of our best students become “hooked” on the topic that will form their future career decisions at ~10-12 years of age. Most will not begin to make important contributions to their professions until ~15-20 years later. Preparing for our (and their) long-term future starts now.

Technical (engineering, math, science, computing) education and employment pipeline

Note: This pathway model is just as relevant to the creation of the future faculty who will educate a future generation of industrial and other practitioners.

Figure 11. Where to Really Begin Science and Engineering Education

“Technical” Hooks
- Airplanes
- Rockets
- Astronomy
- Cars
- Dinosaurs
- Birds
- Bugs
- Plants & Gardening
- Computers
- Etc.

Physical Sciences

Engineering

Information Technology

And business, law, etc.

Biomechanics

Bridge

Biological Sciences & Medicine

Kid’s can do math

K- 8 → High School – College → Careers

Figure 12. Hooking Students on Math and Science at an Early Age.
Figure 12. A More Complete History of Flight (cf. Fig. 1)

**Analyses**

<table>
<thead>
<tr>
<th>Pterosaur</th>
<th>Airplane</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Brain</em></td>
<td>Computer</td>
</tr>
<tr>
<td><em>Nerves</em></td>
<td>Fiber optic strain gages, pressure sensors</td>
</tr>
<tr>
<td><em>Bone and tissue</em></td>
<td>Composite materials</td>
</tr>
<tr>
<td><em>Variable geometry control via large and small muscles</em></td>
<td>Electro-mechanical control of large and small aerodynamic devices distributed over wing trailing edge</td>
</tr>
</tbody>
</table>

**Potential Benefits**

- Reduced wing weight for a given wing span
- Increased span (reduced drag) for wing of given weight
- Active load alleviation for enhanced ride quality and comfort

Figure 13. “Smart Wings” Inspired by 150 Million Years of Pterosaur Success.
issues and concerns we have in common with many of the other sectors of our economy involved in developing advanced technology in a “large-scale system” sense both domestically and globally. While aerospace can be expected to remain volatile and dynamic through the rest of its foreseeable history, design and systems thinking likely will remain a core capability in any imaginable version of our industry in the future. At this point in our history, aerospace engineering remains the single institutionalized multidisciplinary, large-scale systems-oriented program in our current engineering education system. As our need increases for “systems of systems thinkers” across a broad range of professions, we can expect to need more, not less “aerospace engineering” graduates in our national future. Colleges and universities that offer such programs should learn to effectively market their graduates as such, as an aid to assuring a continued supply for both our own industry needs and in many others as well.

At the same time, a purpose of this paper has been to outline some of the formidable challenges academe more generally faces in creating the graduates who will become the engineers and scientists of 2020 and beyond. It is here that one must celebrate the existence of a too small suite of select schools like Harvey Mudd that serve as exemplars of what high quality undergraduate engineering education can be in practical reality.

What has not yet been discussed is what we – you and I, regardless of title or position – can do to advance our collective interests in the future of our global society. Actively participating in education is perhaps the single most important contribution any of us can make – whether in a classroom, through service on a school board, or as a member of an advisory committee on issues in which we have needed expertise. The immediate rewards may not be apparent, but the long-term effect can be profound, and very many of the benefits can be reciprocal. As in politics, it is at the local and individual level that many of us can make perhaps the most important contributions. First, and perhaps foremost is to recognize that each of us – whether we like it or not – is a role model for others in our various professions. The image we present to students and the public may be positive, negative or neutral, but we all have an influence we may not fully appreciate. By our professional and ethical conduct, as well as our positive accomplishments, we can make a difference. Serving as mentors to others can leverage this in constructive ways.

If we again examine the whole workforce pipeline (or “pathway” in currently favored jargon) as shown in Fig. 11, it may be observe that focusing our attention on the college or university level of education is really too late to have the greatest leverage. Having worked for engineering education reform at the post K-12 level for a number of years\textsuperscript{14, 22} it finally became clear to the author that a necessary beginning point in the subsequent development of future engineering talent (especially women) was to find those things that would create the necessary early fascination with anything technical among children at a fairly early age. There are a very large number of factors which influence a student’s choices of fields of study and subsequent career decisions as shown in Fig.14. Over many of these we can have only limited influence. The one thing we all can do, however, is demonstrate examples of the work we have done, and the pleasures we have derived from it, to children who may know nothing about what an engineer or scientist actually does. The central objective in this is to inspire and motivate those who might wish to become future engineers and scientists – to find the hook, any hook, which will create in them a desire to explore a technical topic in further depth and breadth.
Factors Influencing Student Learning

**Student(s)**
- Interests and motivation
- Talents and ability
- Needs and wants
- Attitude and values

**School**
- Faculty
- Advisors
- Role models
- Curricula and pedagogy
- Academic environment
- Facilities (labs, etc.)

**Employers and Jobs**
- Scholarships/financial aid
- Intern/coop opportunities
- Tutoring/mentoring (Volunteerism)
- Advisory boards/review panels
- Adjunct faculty
- Real world experience and inspiration

**Government** (Federal, State, Local)
- Policy and requirements
- Funding
- Initiatives

**Society & Culture**
- Family
- Friends/peers
- Role models
- Ethnicity/heritage
- Media
- Needs and wants

**Other**
- Professional societies
- ABET
- Affiliations (e.g. NAE, NAS)
- Extracurricular activities (sports, music, etc.)
- Unions

**Money**
- Recognition/Rewards

**Figure 14. Influencing Student Learning**

And finally we might return to the institutional or systemic level of our education endeavor to examine a set of simple goals in creating the engineers and scientists of 2020. Perhaps foremost of these would be to create a far more positive image of the engineering profession than currently seems to exist in the public mind. Identification of engineers as “society’s technical problem solvers” in the context shown in Fig. 15 would, in the opinion of some us, go a long way toward resolving a significant portion of the roadblocks to attracting a future generation of needed talent – both male and female and of any ethnic origin. From this base one could then hope to create a systemic educational system from birth to post retirement along the lines shown in Fig. 16 – perhaps as the proper vision of a fully modern “liberal arts education for the 21st Century”, per the opening quotation by the late Carl Sagan.

“I don’t know why people are so frightened by new ideas. It’s the old ones that frighten me.”

John Cage
American composer

“O you who love clear edges more than anything…watch the edges that blur.”

Adrienne Rich
American poet
Engineering Isn’t Just “Applied Science”

Engineering is about applying knowledge (in a systems sense) from a broad range of disciplines (including mathematics, science, economics and information technology) to create products, services and processes that meet societal needs and enhance the quality of life.

Figure 15. The Desired Image of Engineering in the 21st Century.

A “conception to legacy” [cradle to grave] hierarchy for engineering education

Figure 16. A “Holistic” View of a Modern Engineering Education
Acknowledgements and a Disclaimer

The author owe a substantial debt to many individuals who have contributed thoughts or inspirations used in this article. While too many to list exhaustively, several must be acknowledged for their singular importance including: Robert E. Spitzer, Boeing (ret.); Dr. John Prados, University of Tennessee; Dr. Wm. Wulf, NAE; Dr. Bruce Kramer, NSF; Clive Dym, Harvey Mudd; Dave Wisler, GE Aircraft Engines; Earll Murman, MIT; and our old friend, “Dr. Sliderule” (wherever, and whoever, he may be). The author, however, remain solely responsible for all opinions expressed which in no way reflect the views or positions of his employers, The Boeing Company, and the University of Washington.

References

Non-Systems Thinking in a Global Environment

“I'm sure glad the hole isn't in our end...”

Industry  

Academe  

Government

Thanks to Peter Syng.
Addendum I

Since this paper was written, it has been observed that the picture of our domestic future in engineering, technology development and employment in the face of globalization and “outsourcing” is more pessimistic than the author intended to present. Of special concern to those who find themselves to be hard-core “specialists” and specific “subject-matter experts” is the fact that nothing was shown for them in Fig.6 of the paper. The following, far from exhaustive, list is meant to partially address this issue. Major categories for future “subject matter experts” include:

• Human-Machine Interactions

  This topic is an extension of what usually been called “human factors”, but which now extends to the whole suite of issues involved in how humans interact appropriately and effectively with machines of all kinds, especially in an IT and “robotics” context. This requires knowledge of not only the traditional technologies involved, but also of parallel advances in neurophysiology, cognitive psychology, and perhaps even cultural anthropology.

• Advanced Materials

  The current need for many more engineers with knowledge of how to design and manufacture composite structures is only a significant subset of what we need to know to invent future “designer materials” with unique properties which require re-thinking how one appropriately designs with them and then manufactures the products which use them. Nanotechnology may be considered a major subset of this topic.

• Energy and the Environment

  The looming prospect of “peak oil” and global climate change raise a huge suite of interacting issues regarding the fuels (energy sources) to be used in the future for transportation, and how alternatives to traditional fossil fuels may interact with the environment.

• Program and Project Management

  Good one’s are always in short supply, much as are true systems engineers.

Despite these needs (many of which are far from unique to the aerospace industry), it may be observed that much of this work may also be “outsourced” to non-U.S. countries and thus does not offer a satisfactory suite of secure employment opportunities. The primary observation the author can offer on this issue is that historically, a root-strength of American culture has been it entrepreneurial spirit, creativity, and ability to innovate. These can remain central strengths and “protections” in our future, even in a fiercely competitive global environment, unless we choose to lose them.
Addendum II

Concerning the Use of Undergraduate Grade Point Averages (g.p.a.) as an Indicator of Subsequent “Success” in Professional Practice.

The use of a student’s undergraduate g.p.a as a prime metric for making admission and hiring decisions, etc. has been common practice for a long time. For many of us who have observed the subsequent performance of these people in the workplace, there has always been skepticism about the validity of this metric. This has been exacerbated in recent decades by ‘grade inflation’ and some of us have found that the current extreme competition among the “best students” to gain admission to the schools of their choice leads to an over-emphasis on grades at the expense of actual learning.

Correlation Between Undergraduate Grade Point Average (g.p.a.) and Boeing “Work Performance Metric” [1987 Study of ~460 Aerodynamics Engineers]

Concerned about the g.p.a. *uber alles* issue as it might relate to a graduate’s actual work performance in professional practice, two of the author’s management colleagues performed an experiment in the late 1980s-early 1990’s. The first involved comparing the undergraduate grade point averages for 460 aerodynamicist employed by Boeing at that time with the metric used to rank these employees for retention (in the event layoff might be required) and merit pay, as rough measures of the employees’ “value to the company”. The result was a vast “scattergram”, with the observation made that a fair “least-squares circle could be drawn around the data”. The g.p.a.s in this sample ranged from a low of 1.8 to highs of 4.0 on a 4-point grading scale. [Amazingly, the holder of the “record” 1.8 g.p.a. was ranked as one of the “most valued” employees after twenty years]
with the company.] While hardly a scientific survey, and colored to some degree by issues of “seniority” within the population sample, there was no apparent direct correlation between school performance as measured by g.p.a. and subsequent work performance. It also turned out that within this sample, by the time a graduate had been out of school for five years or so, there was little observable correlation between the individuals’ work performance and the schools from which they had obtained their degrees. Doubting the results of this first analysis, a second manager repeated it with a sample of 140 structural dynamicists, and obtained very similar results.

My own conclusion from these data after forty years as an engineer and educator is that g.p.a. is a fairly weak metric for making hiring decisions, largely because it doesn’t reflect the full suite of skills, abilities and talents a graduate may have that are of real value and importance in professional practice (at least in a company like Boeing). What g.p.a. does tend to measure is:

- How competitive a student may be
- How hard a student is willing to work (in the courses taken in school)
- The quality of the graduate’s short-term memory and test-taking ability

These attributes certainly are of interest, but are inadequate as a basis for making hiring (or any other) decisions in this author’s opinion. Far more interesting and instructive would be a “portfolio” of the students’ actual project work and accomplishments – even as a mere neophyte engineer.
Addendum III

Desired Elements of a Model Engineering Education Program

- Curricula with a proper balance between fundamentals (math, engineering sciences, IT, etc.) and provision of in-depth experience in skills and issues important to professional practice
  - Fully compliant with the spirit and intent of ABET EC 2000 [cf. Boeing’s list of “Desired Attributes”]
  - Provides a solid foundation for subsequent graduate study, professional practice and continued career-long learning
  - Built on strengths in graduate education and research programs where these exist
  - Strong emphasis on design-build-test project experience from the freshman year through graduation (at whatever degree level)
- A diverse, well qualified faculty
  - Strong teaching as well as research ability
  - Industry and professional practice “literate” and experienced
  - Willing and able to function as a team
  - Exemplars of life-long learning
- Effective mechanisms in place to integrate knowledge transfer (teaching, etc.) with research and community service
  - Vertically between graduate and undergraduate programs
  - Horizontally across department, college and discipline boundaries
- Adequate facilities and institutional support
  - Classroom space suitable for cooperative/collaborative learning pedagogical models
  - Dedicated student design-build-test project labs
  - Laboratory and computational facilities with modern equipment and technician support
- Strong external (industry, government, etc.) relations and support
  - Use of adjunct faculty from industry, etc. to degree practical
  - Strong, effective “external advisory boards” (with industry, government, peer institution representation) at both departmental and college levels
  - Effective networks and exchange opportunities with industry, peer university programs (both domestic and international) and alumni

The model program outlined here pertains to a standard “engineering core” (to which requisite general education/liberal arts content may be added) in universities with both graduate and undergraduate degree programs. Most elements are applicable to those programs devoted primarily to providing quality undergraduate education as well.

After a long period of neglect in the 1970s and 1980s, design-build-test (or validation) project experience has been increasingly reintroduced in many curricula as an effective means to bridge the gap between engineering theory and practice. Even more is needed, however, and this should become more pervasive from the beginning of the freshman year through graduation (at whatever level) as a fundamental complement to the math and science fundamentals that must remain a core element in any curriculum. Design-build-test projects are of substantial benefit because they can:

- Teach students how to deal with realistic engineering problems, the single right answers to which are rarely even numbered in the back of the text book.
- Teach students how to formulate an engineering problem and differentiate between “requirements” and “objectives (wishes)”
- Require development of both creative and critical thinking skills and abilities.
- Demonstrate the design-build-test/validation cycle, and reinforce the concept that “if you can’t build it, you can’t use or sell it”
- Introduce and develop project management skills and an awareness of business practices
  - Budgets and costs (everything one does or makes has both a dollar and an environmental cost)
  - Project planning and scheduling
  - Work and task allocation
Documentation requirements

- Demonstrate the importance of communication skills (written, oral, graphical and listening) – i.e. “if you can’t explain your solution to someone else, you haven’t solved the problem”.
- Demonstrate the value of teamwork (synergy and diversity – that two or more diverse heads are often better than one)
- Expose students to ethical and intellectual property issues.
- Be highly motivational – and thus help retain students in engineering programs.

Thus even high school-level students can be exposed to and encouraged to deal with real societal issues and needs, and developing awareness of these should be part of the project. Finally, and importantly, such projects can be even more educational for the faculty than for the students. They need not even be expensive as shown in the following example.

John’s Favorite Basic Student Design-Build-Test Project

**Problem:** Design and build a simple (or complex if you prefer) bridge to span a space between two rectangular block supports placed 18 inches apart. A “roadbed” at least 1 inch wide shall be provided at end support level. Your choice of construction materials is limited to the following with associated costs of each:
- Plain (non-corrugated) cardboard @ $1.00 per sq. in.
- White bond paper @ $0.10 per sq. in.
- Soda straws @ $1.00 each (uncut length)
- Toothpicks @ $1.00 per dozen
- Sewing thread @ $0.25 per foot
- “White” glue (not to exceed ~3 oz.) – free

**Performance Criteria:** This is a competitive project with grades to be assigned on the basis of the relative maximum values of the performance index ($\Phi$), with:

$$\Phi = 10U/WxC$$

$U$ = maximum load carried at structural failure (lbs.)
$W$ = weight of bridge (ozs.)
$C$ = cost of bridge ($)

**Notes:** Bridges shall be constructed to allow installation of a simple harness at the center of the span on the road bed. The bridges will then be loaded to destruction to establish the maximum value of $U$. Cost calculations, with supporting documentation shall be provided by the student(s) at time of testing.

[To make the problem more challenging and interesting for advanced students, they may be asked to predict the maximum load their bridge can support at failure.]