

# Effective Engineers\*

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*The aim of engineering education is to produce effective engineers. Achieving this aim depends on knowing what an effective engineer is. The present research looks at engineers in the workplace to determine what qualities make some engineers more effective than others. Effective engineer qualities were collected from engineer employers then tested using questionnaires designed to measure the predominance of the qualities in engineering individuals. Qualities associated with mental agility, enterprise and interpersonal capability correlated most significantly with effectiveness. Effectiveness did not correlate with achievement in tertiary education. The results showed that many of the qualities associated with effective engineer behavior are learnable and can be taught within an education program.*

## INTRODUCTION

ENGINEERING educators face an increasing need for clarity in what they are doing, why they are doing it, and how. There are two reasons for this: engineering practice and industry have fundamentally changing needs, and society is demanding greater accountability and attention to quality.

Early engineers believed in, and worked in a society that believed in, technology for its own sake. The paradigm was that the engineer was an agent of technological change, carrying little or no responsibility for outcomes. Today, engineers are faced with a significantly different paradigm. They are expected to bring a combination of technology, economics, social consciousness and environmental awareness to engineering works to ensure the 'most possible good' is derived for both present and future communities. Engineers have always had to deal with technological change, but now there is a different change, a change of role. The job they do has broadened significantly in scope, and engineering education must change in response.

The second reason why engineering education needs to rethink its direction is that in many countries there is an increasing demand for accountability by those who pay the bills. Quality assurance and quality management are demanded in education. Educators need to follow quality principles. One of the most important is to make sure the needs of the customer are met.

Unfortunately, the changing needs of practice are ill-understood. This is hardly surprising: it is not easy to see a pattern when one is in the middle of it. Yet the lack of clarity as to needs means that the needs of the customer, that is, of industry and practice, are themselves not clearly understood. To put it another way, the central task of engineering

educators is to produce engineering graduates who will be as effective as possible at their job. But in order to do so, the educators need to understand the characteristics of effective engineers. They need a clear specification of the product.

Evidence suggests, however, that at present many engineering educators are failing to take responsibility for the calibre of their graduates. Samuel [1] noted that engineering education has not developed a picture of its ideal end product, nor pursued any research that would provide measures of post-education engineering performance. In the medical profession the situation and attitude are different. Empirical studies of longitudinal performance (performance assessments conducted periodically throughout a subject's career) and the effect of educational disciplines on longitudinal performance are common. In essence, the medical profession has installed feedback loops and quality control measures to ensure that it keeps abreast of the changing needs of its profession and that its educational procedures are having the desired effect of producing effective doctors. In contrast, the lack of post-educational assessment in engineering suggests that engineering educators simply assume they are achieving the goal of producing effective engineers.

Many authors who are practicing engineers challenge this assumption. Wilkinson [2] produced figures showing a decline in the status and perceived credibility of engineers.

Wakelin [3] criticises engineers for their lack of management skills, illustrating how, although their personalities and education do not predispose them to leadership positions, engineers get things done through others and so by definition are managers. Wilkinson and Lewis [4] also write about the inability of engineers to fill leadership positions both because of the type of person that is attracted to engineering and also because the engineering education system does not encourage a

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leadership world-view. Thom [5], Wilkinson and Lewis [4] and Wakelin [3], who are all practising engineers, unanimously argue the need for differently educated engineers.

Thus the assumption of engineering educators that they are producing effective engineers is inappropriate in the face of the declining professional status and credibility of engineers, failure of engineers to secure leadership roles, and the often expressed need for differently educated graduates by industry.

Edward Deming [6] said 'Everyone doing his best is not the answer. It is first necessary that people know what to do.' This is very true of engineering education. In order to produce effective engineers, engineering educators must first understand what an effective engineer is. There are many opinions on the matter, but little systematic investigation.

The present paper attempts to remedy the situation. It describes a study [7] aimed at discovering the characteristics of effective engineers based on the assumption that engineering employers will be good judges of the effectiveness of their employees.

### THE NATURE OF EFFECTIVENESS

Because research in the area of engineering effectiveness is limited, it is difficult to define effectiveness succinctly.

The present educational system, which functions primarily around lectures (usually of a technical nature) tacitly assumes that effectiveness is related to knowledge (and the more knowledge the better). The assumption is questionable. Knowledge is obviously necessary, but it is far from clear that it is sufficient. In a summary of research focusing on what makes individuals successful in their vocation, Klemp [8] reports that knowledge alone is unlikely to produce effectiveness, saying that: '... the most consistent finding we have discovered is that the amount of knowledge of a content area is generally unrelated to superior performance in an occupation and is often unrelated even to acceptable performance.'

Millar [9] suggests that it is actions rather than knowledge, that define effectiveness:

... it is not what a person knows, thinks, believes, or feels that gets wanted results but rather what s/he does and how it is done. The medical practitioner, who faints at the sight of a particularly gruesome accident, will be ineffective regardless of his/her technical competence. [9]

The present research, rather than grapple with the definition of effectiveness, focuses on practical ways of distinguishing effective engineers from average or below average performers in the hope that the identification of distinguishing qualities of effective engineers will work toward providing a greater understanding of effectiveness in engineering and provide engineering education with a clearer description of its ideal end product.

Literature that has attempted to identify qualities associated with effectiveness has taken one of two paths. It has focused either on engineer personality, or on engineer skills.

Several authors argue that engineer effectiveness is related to an 'engineer' personality. Millar [9], for instance, uses a Transactional Analysis model to formulate an 'engineer personality'. He compares the result to a list of attributes he determined as necessary for fulfilling the engineering role and concludes that effectiveness of engineers was cramped by an engineer personality that did not handle stress well, did not have the required mental flexibility, did not communicate well and frequently lacked self-confidence. Wilkinson and Lewis [4] use Herman's Whole Brain Model to illustrate the deficiencies in approach of engineers compared with leaders. They argue the need for engineers to develop intuition, flexibility, and holistic-synthesis approaches. Both Millar [10] and Wilkinson and Lewis [4] point to a predisposition of people attracted to engineering and an engineering educational system that encourages, and actively selects (through narrow maths and science based entrance requirements), quantitative, analytic, factual thinking which in turn creates or contributes to a deficient engineer personality.

Studies employing the second approach, that is, that effectiveness is related to skills, usually approach the clients of engineering education (normally defined as engineering employers but sometimes inclusive of students and the nation) to obtain an input as to what they consider effective for engineering education and practise. Henshaw [11], for instance, obtained importance rankings of engineer skills and attributes. His study compared employer, employee and faculty rankings of a stated set of skills and concluded that the people-skills associated with fluent communication, management, practical ability, organisation, teamwork and interpersonal relations were the most highly valued qualities. Evans and Shunk [12] also included the student body in a very similar study of customer opinion. Both Henshaw and Evans and Shunk identify a widening gap between the opinions of practising engineers and engineering educators which Henshaw summarises as 'the employers want more "human" engineering and less technology' [11].

While both types of study provide useful insight into the qualities considered important for effective engineering they have quite severe limitations. Both approaches rely heavily on author opinion. The personality-focused research uses engineering roles determined by the author as a comparative measure against the 'engineer personality'. In the skill-focused literature, the list of attributes being ranked by the customers is developed by the authors; therefore only skills considered important to the authors are ranked. Thus author bias is built into the studies, affecting the reliability of results. There is also a lack of validity testing (which would have reduced the author bias) of identified

qualities, hence the various qualities identified by the studies can be considered hypothetical effective engineer qualities only.

### THE EFFECTIVE ENGINEER STUDY

The limitations of previous research, the falling credibility of engineers and the increasing accountability of educators point to the need for more and better research into engineering effectiveness. As stated earlier, the research presented in this paper aims to identify the qualities of effective engineers. It is hoped that the identification of effective engineer qualities will provide greater understanding of effectiveness in engineering, and work towards providing engineering educators with a description of their ideal product. Because of the severe limitations of earlier work the present research aims both to eliminate author bias in the results and to test the validity of the identified effective engineer qualities. The research progressed in two stages. Firstly, open-ended interviews were used to identify a set of qualities or characteristics of effective engineers. Following that, a questionnaire technique was used to test the validity of the set of qualities and to establish correlations.

#### *Identification of hypothetical effective engineer qualities*

The aim of the first stage of the research was to identify a relevant set of potential effective engineer qualities. It was considered that a grounded theory approach [13] would be the ideal way to collect hypothetical effective engineer qualities. This type of approach builds theories from observations of reality and then tests the theory against real behaviour. Time constraints precluded the direct collection of observations by the researcher, therefore secondary observations (observations by other people who had close contact with and extensive knowledge of the study population) were collected and used to develop hypothetical effective engineer qualities.

Observations of sixteen engineering supervisors (senior engineers) from a range of organisations and disciplines were collected using open-ended interviews. A breakdown of the sample group into organisation type and engineering discipline is shown in Table 1.

*Interview method.* The open-ended interview technique was chosen for its adaptability. The technique uses an informal mixture of conversation and structured questions to collect data. Because the interviews were collecting other people's observations the interviewer needed to be able to follow up ideas, probe responses and define answers to obtain a rich picture of the effective engineer. Therefore the open-ended interview technique was ideal.

Table 1. Sample group breakdown

Organisation	No.	Discipline	No.
University	3	Chemical	3
Public Co.	3	Civil & structural	5
Large private	6	Electrical	4
Small private	4	Environmental	2
		Mechanical	2

The interviews were structured around these four topics:

- the definition and measurement of effectiveness in engineers;
- the traits perceived as being essential to effective engineers;
- the descriptions of real effective engineers;
- the qualities sought when employing engineers.

Four pilot interviews were conducted and tape recorded so that 'interviewer leading' (the tendency of interviewers to 'seek out' answers which supports their theory) could be identified and minimised.

#### *Results*

*Topic 1: the definition and measurement of effectiveness.* Fourteen of the sixteen interview subjects used an operational definition; that is, they considered that the 'effective engineer' was defined primarily by what s/he did. In addition, the definitions contained strongly goal-oriented clauses such as 'gets the job done' and 'achieves objectives'. The remaining two subjects used a knowledge/skill definition. They focused on the understanding of the engineer: 'knows what needs to be done and how to do it', 'fully understands a problem and its context'.

When asked how they would assess an engineer's effectiveness all subjects referred to the person's 'productivity'. Clarification of 'productivity' suggested that it was goal orientated and focused primarily on the quantity of work achieved.

*Topics 2,3 and 4: effective engineer qualities.* The interviewees were asked to specify the personal qualities or characteristics expected of the most effective engineers. Their responses produced an initial list of over 200 qualities. The number was reduced to 84 by eliminating synonyms and overlapping items, then further reduced to 68 qualities by excluding items only mentioned in one instance. These 68 qualities resulting from open-ended interviews, form the 'Hypothetical Effective Engineer Qualities' list:

- technically competent
- takes responsibility
- efficient
- high level of integrity
- disciplined
- forthright

- organised
- talks freely
- objective
- negotiation skilled
- numerically proficient
- interpersonal skills
- deep understanding of engineering
- wide range of knowledge and interests
- principles
- sense of humour
- ambitious
- cheerful disposition
- motivated
- good listener
- enthusiastic
- politically aware
- individualistic
- environmentally aware
- active
- community aware
- cooperative
- business knowledge
- creative
- writing skills
- intuitive
- memory for detail
- lateral thinking
- conscientious
- not afraid to take risks
- methodical
- extraverted
- meticulous
- emotionally resilient
- industrious
- enjoys challenges
- team worker
- doesn't jump to conclusions
- critical
- flexible
- considerate
- pays attention to detail
- liberal
- resourceful
- optimistic
- takes initiative
- converses in ideas as well as facts
- perceptive
- understands wider ramifications of engineering proposals
- inquisitive
- intelligent
- computer literate
- easily able to separate feelings and ideas
- practically skilled
- calm in crisis
- shows good judgement
- leadership skills
- up to date with technology
- decisive
- interested in aesthetics
- alert
- physically active
- respects other people's opinions

#### *Testing hypothetical effective engineer qualities*

The second stage of the research involved testing the 'theory' (hypothetical effective engineer qualities) for validation or falsification. Because of the large number of qualities (68) and the need for a large sample population to provide meaningful information, questionnaires were considered the most practical form of data collection for validation testing. They are quick and easy to use, and enable the study of a large number of qualities over a large sample.

Two questionnaires were used in this part of the research. The first was for senior engineers to complete, with one for each engineer they supervised. The second questionnaire was given to the supervised engineers who had been the subjects of the first set of questionnaires.

*Questionnaire 1.* The hypothetical effective engineer qualities were carefully moulded into a questionnaire designed to provide empirical data on an engineering individual's effectiveness and the extent to which the individual exhibited the hypothetical effective engineer qualities. The questionnaire used an adjective checklist format in the form of 'semantic differentials' set up on seven-point rating scales. For example:

active 1 2 3 4 5 6 7 passive

The semantic differential, or antonym, was included to ensure that subjects used the same meaning of the quality being assessed. For example the quality 'active' has the antonym 'passive' rather than 'inactive' because the first implies a general attitude whereas the second could be construed as just physical inactivity.

The technique used required senior engineers to complete a questionnaire for each (consenting) engineer they supervised. The supervisors were asked to mark scales to show the extent to which the engineering individual they were rating exhibited the qualities under test. To meet the aim of validating or falsifying the hypothetical effective engineer qualities, a measure of the engineering individual's effectiveness was also required. The supervisor, therefore, was also asked to rate the engineer's effectiveness on a seven-point scale (1 = very effective, 4 = moderately effective, 7 = not at all effective). It was considered appropriate to ask the supervisor for a measure of effectiveness as interview results indicated that effectiveness was about actions and results, both of which are observable, to a large extent, by a supervisor. Supervisors were also asked to indicate a preferred meaning and preferred measure of effectiveness from a prompt list created from interview results. The purpose of this was to observe if there was agreement between supervisors and interview subjects, and between supervisors as a group, as to what effectiveness meant and how it was measured.

In addition, supervisors were asked to list both qualities that assisted and qualities that diminished

the engineering individual's effectiveness. The main aim of these open-ended questions was to see if any additional hypothetical effective engineer traits came to light that might have been missed in the interviews.

The choice of supervisor assessment as the main source of empirical data with respect to the hypothetical effective engineer traits was made because it provided the most situationally-focused data. An alternative method would have been to use self-rating questionnaires. However, this was thought to be less desirable as the individual might have confused the social (non-work) self and the work self.

Despite the preferred choice of a supervisor rating approach, the method has a number of limitations. First, the immediate supervisor cannot observe all of an engineer's work performance so the ratings, at best, will be based on only a partial view of the individual's behaviour. Also, supervisors may in fact have relatively little contact with their engineers, or may place greater emphasis on certain aspects of work, such as time management, rather than others. To reduce the effect of these limitations, a second questionnaire was used in conjunction with Questionnaire 1. Questionnaire 2 was given directly to the engineers themselves, rather than their supervisors.

*Questionnaire 2.* Like the supervisors, the engineering subjects filling in the self-report Questionnaire 2 were asked to rate their effectiveness on a seven-point scale, to indicate a preferred meaning and measurement of effectiveness in engineering, and to list the things that prevented them from being more effective engineers. Questionnaire 2 also contained a question on academic achievement to assess the relationship between academic performance and effectiveness.

*Pilot study.* A pilot study of the questionnaires surveyed twenty-three supervisor-engineer sets and sought to answer three questions regarding the viability of the questionnaires:

1. Are there any problems with the questionnaire format or instructions?
2. What is the distribution of responses given to each item?
3. Are there any discernible relationships becoming apparent between effectiveness and the hypothetical effective engineer qualities?

Problems identified in the pilot study were remedied by adjusting the questionnaire. The questionnaires were administered to eighty-two engineer-supervisor sets. There were three criteria for an engineering individual's inclusion in the study sample:

- The engineer must have at least five years work experience.
- The engineer must work for a large (20+ employees) commercial engineering company.

- The engineer must both be willing to be involved in the survey and also have a supervisor willing to be involved in the survey.

The first two criteria were set to increase the reliability of results. It was felt that too little work experience would result in unreliable data as the engineer would still be learning the profession. The type of work environment was also restricted to large commercial companies to reduce the impact of situational factors. It had the additional practical benefit of allowing the survey of a large number of engineers at one site.

## RESULTS OF THE STUDY

Eighty-two engineer-supervisor sets attempted the questionnaires. Five questionnaire sets were eliminated from the sample because of incomplete or unreliable data.

Both engineers and supervisors generally considered effectiveness in engineering to be related to, and measured by, the quality of engineering work produced. Twenty five percent of supervisors qualified this by suggesting that effectiveness was related to both quality and quantity of engineering work. The focus on quality in the questionnaire responses is contrary to the results of the interviews. Interview subjects were very focused on quantity of work produced. Four of the interview subjects were asked for their opinion on the apparent anomaly. They suggested that the competitive nature of the engineering commercial environment creates a preoccupation with speed of outcome so that quality is ignored unless it is absent. Quality, they said, was implicit rather than explicit in the achievement of engineering objectives and productivity.

Fifteen percent of the engineers surveyed were considered 'very effective' (effectiveness rating of 1) by their supervisors. However no engineer rated him/herself as 'very effective'. The mean supervisor-rated effectiveness score was 2.90 (standard deviation  $\sigma = 1.30$ ) on the 7-point scale and the mean self-rated effectiveness score was 3.41 ( $\sigma = 1.06$ ). (Note that a lower score indicates greater effectiveness.)

Figure 1 shows the spread of effectiveness scores for both supervisor-rated and self-rated effectiveness. Most of the study samples lie on the first half of the effectiveness scale for both supervisor-rated and self-rated effectiveness but the supervisor-rated scores show greater spread on this part of the scale. For this reason, the supervisor-perceived effectiveness scores were used to calculate correlations between perceived effectiveness and the effective engineer qualities under test.

Of the sixty-eight hypothetical effective engineer qualities under empirical test, thirty-four correlated significantly with effectiveness. These are loosely categorised into three groups. In all cases a greater prevalence of the relevant quality correlates with greater effectiveness. The groups are:

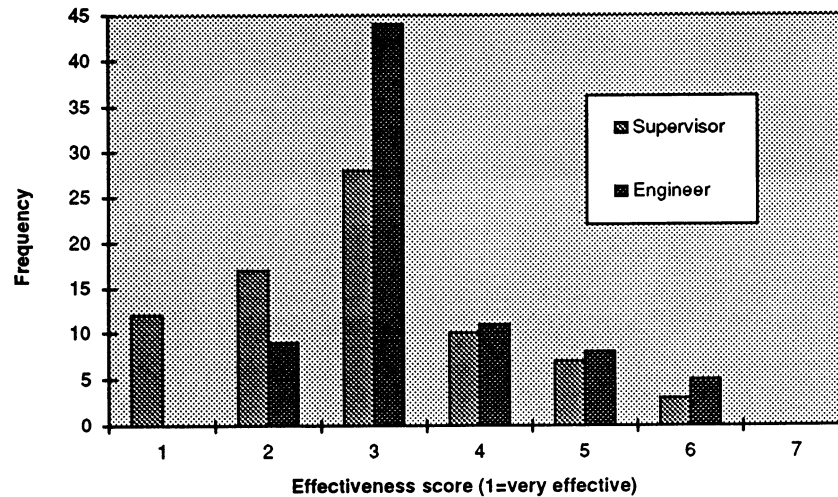


Fig. 1. Effectiveness distributions.

1. *Mental agility*: Lateral thinking ability, creativity, judgement, flexibility, intelligence, inquisitiveness, alertness, practicality, ability to work under pressure, ability to separate feelings from ideas, ability to recognise the wider issues of an engineering project, economic, environmental, political and community awareness.
2. *Enterprise*: Initiative, resourcefulness, motivation, ambition, confidence, energy, activeness, willingness to take risks, likes challenges.
3. *Interpersonal capabilities*: Perception, sociability, leadership skills, team-working skills, negotiation skills, interpersonal skills, people orientation, humour, respect for other opinions, decisiveness, extroversion.

The empirical identification of distinguishing effective engineer qualities was further supported by the results from the qualitative sections of Questionnaires 1 and 2. Supervisors most often identified reticence, lack of interpersonal skills, low self-esteem, lack of initiative, lack of communication skills, inability to operate under pressure and lack of good time management skills as preventing individual engineers from being more effective. All excluding the time management quality (which was not under test) are included among the empirically identified qualities. Individual engineers agreed that some of these qualities prevented them from being more effective but in addition they cited situational factors such as inadequate resources, lack of clear guidelines, and lack of time to do a good job.

Of particular interest were the qualities that did not correlate well with effectiveness. Significantly, academic achievement showed virtually no correlation with engineering effectiveness. The same was true of many of the qualities traditionally associated with engineers such as technical competence, numerical ability, logical thinking ability, methodicity, self-discipline, industry and integrity.

## DISCUSSION

The distinguishing qualities of effective engineers identified by the study are not qualities that traditional academic appraisal techniques assess and therefore the low correlation ( $r = 0.0002$ ) between effectiveness and academic achievement is perhaps not at all surprising. Traditional engineering academic appraisal most frequently assesses technical knowledge and numerical ability. Neither of these qualities correlated significantly with effectiveness.

Significantly, however, the bunching of individual scores in the traditional engineer qualities such as technical competence, numerical ability, logical thinking ability, methodicity, self-discipline, industry and integrity suggests that the qualities are equally prevalent in all engineers. Wilkinson and Lewis [4], Millar [11] and Vesilind [14] believe that these traditional qualities are sought and encouraged by engineering education. It could therefore be said that while it is nearly impossible to obtain an engineering degree without being technically competent, numerically skilled, etc., the possession of these qualities does not guarantee success or effectiveness. They are necessary, but not sufficient. However, it is also true that a minimum level of attainment is all that is required. Outstanding academic achievement does not necessarily lead to greater effectiveness.

Categorising the distinguishing effective engineer qualities by type of learning experience (See Table 2) reveals a large number of 'skill' qualities. This has a positive implication for engineering education as it suggests that the qualities are learnable, and that therefore they are teachable within an education program. The 'knowledge' areas identified in the study can also be incorporated into an education program. The categories used in Table 2 are based on Carter's [15] 'Taxonomy of objectives for professional education'.

Table 2. Effective engineer qualities identified by empirical test

<b>KNOWING</b>			
	<b>Factual knowledge</b> <i>awareness needed of:</i> business knowledge environmental issues political issues community issues	<b>Experiential knowledge</b> practical experience	
<b>DOING</b>			
<b>Information skills</b> inquisitive perceptive resourceful	<b>Analytical skills</b> easily able to separate feelings from ideas recognition of wider issues application of lateral thought critiquing skills	<b>Action skills</b> initiative decisiveness good judgement	<b>Social skills</b> leadership skills interpersonal skills negotiation skills respect for others' opinions teamwork skills
<b>BEING</b>			
<b>Mental characteristics</b> flexibility creativity lateral thinking ability intelligence	<b>Attitudes and values</b> self esteem ambitiousness optimism	<b>Personality characteristics</b> active energetic extravert enthusiastic motivated	enjoys challenge prepared to take risks calm in crisis sense of humour handles pressure well

It is significant that many of the distinguishing effective engineer qualities fall into the knowledge and skill categories. This has a positive implication for engineering education as it suggests that the qualities are learnable (and therefore trainable) and could be incorporated into an educational program.

A limitation is that the research has not attempted to give weightings to the qualities shown in Table 2. Some may be more important than others. Nevertheless the matter was not investigated not only because of time and resource constraints but also because it was thought inappropriate to work at such a level of detail before a more overarching analysis had been carried out.

### CONCLUSIONS

The present research has attempted to identify the distinguishing traits of the effective engineer in commercial industry and practice. The main findings are:

- Effective engineers have a broad knowledge base which encompasses political, environmental, business and community areas in addition to technical knowledge.
- Effective engineers are more entrepreneurial than those less effective.
- The distinguishing entrepreneurial traits possessed by effective engineers include better leadership skills and judgement, the ability to handle pressure, being calm in crises, enjoyment

of challenges and willingness to take risks. Effective engineers are also characterised by high self-esteem. They are ambitious, highly motivated, active and energetic. They are more decisive, have greater foresight and take the initiative more often than less effective engineers.

- Effective engineers are perceived as having better interpersonal abilities. The distinguishing interpersonal traits of effective engineers are respect for others' opinions, teamworking skills and enthusiasm. They are also characterised by a more extravert, forthright, talkative and optimistic nature, a well developed sense of humour and an open mind.
- Effective engineers are more mentally agile than less effective engineers. This is suggested by the high correlation of mental agility traits, such as flexibility, creativity, lateral thinking ability, intelligence, inquisitiveness and resourcefulness, with effectiveness.
- As no significant correlation was found between effectiveness and academic performance, effective engineers are not necessarily good academic performers, and vice versa.
- An effective engineer is not necessarily more technically competent than a less effective engineer.

The research results imply that engineering educators have more areas to address than technical competence alone if they are to produce highly effective engineers. Furthermore, many of the distinguishing traits of the effective engineer are learnable, and therefore can be taught within an educational program.

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