Engineering Education Requires a Better Model of Engineering Practice

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***Abstract**: Analysis of engineering education literature reveals that contemporary writers subscribe to a model of engineering practice based largely on technical problem-solving and design. Assessment of engineering communication skills is mostly based on technical reports and oral presentations. Communication is seen as a one-way information transfer process through which engineers deliver the designs and problem solutions to clients and others. Published research on engineering practice reveals that communication primarily consists of informal two-way communication with listening as the dominant mode, particularly for novice engineers. Engineers typically spend 60% of their time on communication with other people, mainly close associates. Less than 30% of their time can be ascribed to solitary technical work. Communication is as much a means for developing and maintaining a web of social relationships and shaping perceptions as information transfer. Informal technical coordination, which has been shown to dominate engineering practice, depends on cooperative social relationships.*

Introduction

Engineering is a technical and a social discipline at the same time: the social and technical are inextricably intertwined. Yet the social aspects can easily be taken for granted. It is not easy to find literature which examines the interaction between these two facets of engineering practice. Several studies of engineering practice have demonstrated the significance of social relationships in many different ways. For example, Bucciarelli (1994) focused on design and explored the significance of social relationships within small firms working on technological innovations. Vinck and his colleagues explored the intimate links between social relationships and technical issues, again mostly in the context of design (2003). Faulkner (2007) examined the tension between the social and 'technicist' aspects of engineering practice. Korte et al (2008) described how early career engineers approached problem solving, learning that so much depended on finding people with useful information in an organization. Lam (1996, 1997) compared Japanese and British electronics firms. Yet, with so relatively few systematically researched accounts, we still know very little about engineering practice (Barley, 2005; James P. Trevelyan & Tilli, 2007).

This paper reviews a selection of contemporary writing on engineering education and shows how a predominant focus on the technical has eclipsed the social aspects of engineering, leading to fundamental misalignment between education and practice. This misalignment is demonstrated by examining just one aspect of practice: communication. Assessment of communication in engineering education is misaligned with practice requirements. A review of published research results demonstrates that we need a more detailed understanding of communication in the light of studies of engineering practice.

Engineering Practice in the Engineering Education Literature

What does contemporary literature on engineering education tell us about engineering practice and communication?

The literature presents a fairly consistent view of engineering practice.

Sheppard, Colby, et al (2006) in their article "What Is Engineering Practice?" compared accounts of engineering practice in the literature with comments contributed in semi-structured interviews and focus groups involving 300 faculty and students at several US universities. They argued that "professional education must reflect practice" and that the university experience is an apprenticeship for the profession in which students acquire cognitive and practical skills.

They made their comparison with respect to three aspects:

- Problem solving, the systematic process that engineers use to define and resolve problems which are often ill-defined.
- Specialized knowledge used by engineers, both theoretical and contextual.
- Integration of process and knowledge used to resolve some particular problem, involving judgement, creativity and uncertainty.

The authors selected from (the limited) published literature on engineering practice as their starting point. In doing so, whether intentionally or not, they chose to focus on engineering design and advanced technology in computing and aerospace, widely considered to be the ‘leading edge’ of engineering. Their typology of engineering knowledge (p434) appears to have been drawn entirely from literature on aerospace, design and problem-solving.

The crux of their argument is that engineering “is focused on resolving an undesirable condition through the application of technologies” and therefore “the central activity of engineering work is solving problems” (p430). From this point, their discussion and comparison is centered on engineering as problem-solving. This reflects their respondents who said that engineering is about solving problems and therefore changing the world.

The model of engineering practice used by faculty that emerges from this study is primarily intellectual: engineers are engaged in problem-solving and design using specialized technical knowledge. The end point is a problem solution or design which then needs to be communicated. There seemed to be only slight differences between their analysis of engineering practice and the comments from faculty and students. Communication was mentioned by faculty in the sense that engineers need to communicate their findings to society at large. Teamwork was also mentioned, and the necessity for engineers to work with others who contribute different expertise in the context of design.

Tenopir and King presented a model of an engineer as an information processor in their book on engineering communication (2004, figure 3.1, p28). Inputs include time, information received, support staff time, computing equipment, instrumentation, facilities etc. Outputs include information created, information communicated (recorded information, interpersonal information), knowledge gained, etc.

A large panel of 40 academics and 25 industry representatives recently published a Body of Knowledge for Civil Engineering (BoK) (American Society of Civil Engineers, 2008). The authors adopted Bloom’s hierarchy of cognitive outcomes (Bloom, 1994; Bloom, Englehart, J., Hill, & Krathwohl, 1956) to define education achievement levels in each of the listed educational outcomes. The summary (p3) allows us to understand that engineering graduates need to be able to:

- Comprehend issues in public policy, business administration, professional attitude.
- Apply knowledge of science, materials science, mathematics, humanities and social sciences, sustainability, contemporary technical issues, risk and uncertainty, project management, globalization, leadership, and teamwork.
- Analyse situations to understand ethical issues and professional responsibility, identify problems, solve them, and perform mechanics analysis, and be able to perform analysis in range of different aspects of civil engineering.
- Synthesize experiments and solutions to design problems, and particularly in one specialized technical aspect of civil engineering, such as geomechanics, for example.
- The BoK states that “Civil engineers are fundamentally applied scientists.” (p50).

Civil engineering was described (p67) as “…the profession in which a knowledge of the mathematical and physical sciences gained by study, experience, and practice is applied with judgment to develop ways to utilize, economically, the materials and forces of nature for the progressive well-being of humanity in creating, improving and protecting the environment, in providing facilities for community living, industry and transportation, and in providing structures for the use of humanity."

Humanities were interpreted in terms of ethical, aesthetic and historic appreciation: "engineers must be able to recognize and incorporate such human elements into the development and evaluation of solutions to engineering and societal problems" (p117).

Engineering graduates are expected to be able to communicate "the essence of their findings and recommendations … to technical and nontechnical audiences" and to "to draw sketches by hand and via computer-aided drafting and design software" (p139).

Many who have contributed to design literature argue that engineering and design are almost synonymous. Even if engineering is more than design, there is a common perception that design is more important than other aspects, more complex, more difficult, and that everything in engineering starts from design (e.g. Dym, Agogino, Eris, Frey, & Leifer, 2005; Ferguson, 1992; Schön, 1983; Vincenti, 1990; Vinck, 2003). Vincenti (1990) in his well-known book "What Engineers Know and How They Know It" explains that engineering is based on design, construction and operation of artifacts and "of the three design is frequently taken as central." Dym, Agogino et al (2005) open their paper with the following: "This paper is based on the premises that the purpose of engineering education is to graduate engineers who can design, and that design thinking is complex."

Many advocates of problem-based learning explain their approach as an analogy of engineering problem-solving which starts with the client requirements (Heywood, 2005; Savin-Baden, 2007). The instructor allows students to explore possible solutions and identify needs for further information. The students, working collaboratively, each perform their own research to fill the information gaps and then analyze the alternative solutions until one solution has been confirmed to meet the client requirements. The students then write a document presenting their recommendation and the analysis supporting their conclusions (e.g. Hadgraft, 2008). Just as there are those who claim that engineering education is supposed to educate designers, there are others who claim that engineering education is all about educating people to solve problems (Jonassen, Strobel, & Lee, 2006).

Crawley, Malmqvist et al (2007) presented a reform agenda for engineering education based on a model of engineering practice that includes conceiving, designing, implementing and operating (CDIO). This has influenced curriculum development at several leading universities. They articulated a vision that extends beyond the design and problem-solving model and argued that engineers go on to guide the implementation and operation of products, systems and processes. They listed engineering tasks and included comments from leading corporate engineers (p7-15), though there was no explicit connection to the limited available systematic research literature on engineering practice or even engineering design. They presented examples of "design-implement experiences" (p110-112). The authors claimed many advantages for their approach, though it may be some time before systematic research can provide comparison with other approaches.

While the CDIO manifesto opens a wider perspective on engineering practice, and is still evolving, the case studies presented in their book reveal that it is difficult to move beyond the problem-solving model of engineering practice. Arguing for an integrated learning approach, the authors show how communication skills can be learned in a technical curriculum (p134-135). Yet the communication model that emerges is almost identical to the one presented by the ASCE BoK in which engineers communicate to present their recommendations in oral presentations, technical reports and scientific papers.

Sheppard and her colleagues have recently published an extensive survey of current "best practice' in engineering education and also advocate reform by broadening the curriculum and using better pedagogies (S. D. Sheppard, Macatangay, Colby, & Sullivan, 2009). They advocate that engineering education should be centred on professional practice and that only radical redesign will result in effective reform of what is currently a "dysfunctional system" (xxii-xxiv). They assert that "engineering practice is, in its essence, problem solving." (3)

This brief review reveals that there is a widely understood and consistent model of engineering practice among engineering faculty and advocates for improved engineering education. This model is centred on technical problem-solving and design. Engineering practice is, according to this model, principally based on solitary technical work, undertaken by teams of engineers sharing the work between them. The end point for engineering is communication of the design or problem solution (both verbal and written) to 'the client', and sometimes to society at large. Engineering communication, based on this model, is almost always assessed in the form of a technical report or a technical presentation. Effective written communication forms the single most significant component of assessment since almost all assessments in engineering education take the form of written documents.

While the importance of team work is emphasized throughout this literature, it is not so easy to find suggestions for assessing team behaviour. Sheppard and her colleagues wrote "We rarely saw an explicit focus on learning about and learning the skills of teamwork. As we discussed in the following chapters on pedagogy and assessment in the lab, the challenges of leading, coordinating, and grading group work create challenges and even disincentives to this important experience." (2009, 67)

In all the literature reviewed, there are few explicit descriptions of engineers as social actors. Engineers, by implication, process technical information, sometimes in teams, and the results of their work (reports, drawings, presentations) are transmitted to clients and largely undefined 'others', eventually having an impact on society and the world in which we live.

Engineering Communication from Observations

In contrast, studies of engineering practice and communication present a different view of practice, particularly engineering communication.

A longitudinal study of engineering graduates provided their perceptions on working time (Tilli & Trevelyan, 2008). They reported spending 60% of their time explicitly interacting with other people as shown in Table 1. These results agree reasonably well with several earlier research reports (e.g. Kilduff, Funk, & Mehra, 1997; Tenopir & King, 2004; Youngman, Oxtoby, Monk, & Heywood, 1978, p7-9). Tenopir and King (2004, p29-30) report results from several studies with estimates of the time that engineers spend on communication ranging from 40% to 75%, with the majority of estimates around 60%.

	%	Cum%
Face to face informal	11.6	11.6
With people on site	5.4	17.0
Meetings	6.6	23.6
Training sessions	5.2	28.8
Phone	3.3	32.1
Text messages	2.1	34.3
E-mail	8.1	42.4
Read, check documents	7.1	49.5
Write documents	11.0	60.5
Searching for information	8.2	68.7
Calculation, simulation	9.2	77.9
Design, coding	6.5	84.4
Debugging	2.3	86.7
Operating, testing	3.3	89.9
Survey, inspection, observation	4.0	93.9
IT, filing maintenance	2.6	96.5
Hands on work	2.5	99.0
Searching for lost items	1.1	100.0

Table 1: Perceptions of working time (expressed as a percentage) spent on different aspects of engineering practice by novice engineers after 9 months of experience (Tilli & Trevelyan, 2008). The top section groups explicit communication aspects: direct interactions with other people. The right-most column is the cumulative percentage.

Young engineers are likely to spend more time listening than speaking during conversations, especially in training sessions and meetings. From the data in table 1 which shows that 32% of the time was spent in conversations, we can estimate that between 20% and 25% of their time was listening.

An engineer's relative career level does not seem to affect communication patterns. Data in table 1was obtained from novice engineers in their first year of practice, when they were engaged in predominantly technical engineering roles. A smaller control group of novice engineers with three to five years experience reported almost exactly the same pattern of communication time (Tilli & Trevelyan, 2008). The literature on engineers' communication patterns reveals remarkably consistent estimates and there is no obvious difference in results for engineers at different career levels.

A large proportion of written communication takes the form of requests for information, or instructions to specify technical work to be performed, for example the production of work packages and technical specifications. Only part of the need for writing is represented by formal technical reports. Technical presentations are rarely reported in our fieldwork and interviews. Tenopir and King report one survey in which respondents indicated they spent less than 4% on technical presentations.

The explicitly technical aspects of the time spent by these engineers (design, calculation, coding, debugging, survey, inspection, operating and testing) varied between discipline groups (from 20% to 29%) yet remains a much smaller component of work time than communication and other information handling tasks. On average, these engineers reported spending 49 hours per week working. They also reported an additional 4 hours per week on work-related socializing which should be added to the communication time component reported above.

A different kind of investigation can help us understand why engineers are communicating and what they achieve through communication that helps them perform their work. Trevelyan (2007; James P. Trevelyan, 2008) has reported results from a series of ongoing qualitative studies of engineering practice based on interviews and field observations. Analysis of the data from interviews and field studies revealed that informal coordination of technical work by other people dominated the data, presented in numerical form in table 2. Informal coordination, engineering processes (such as project management), business development, procurement, financial work and human resource development together account for almost two thirds of the interview references and all of these are based almost entirely on communication activities. Even though these seem at first to be non-technical activities, discourse analysis revealed that technical issues pervade most engineering communication.

Aspect of engineering practice (grouped)	% interview references
Coordinating people (informal)	27.4
Engineering process, management systems	19.1
Technical review, check & test	15.5
Technical, creative	13.5
Self & Career Development	7.5
Business Development	6.0
Procurement	4.5
Financial	3.9
Human resource development	2.5
Hands on work	0.1

Table 2: Percentage of interview and field data references to different aspects of engineering practice reported by Trevelyan (2007).

These results not only provide close agreement with quantitative studies of engineering communication discussed above, but also provide richly detailed explanations. While there are large variations in data between individuals and only averages have been reported, references to informal coordination showed the least relative variation between individuals.

The qualitative analysis also revealed that informal coordination seldom involves organizational authority. Effective coordination relies on a complex sequence of social interactions with people at different levels in organizations as well as outsiders such as clients and suppliers. These social interactions rely on personal relationships to secure 'willing cooperation' and 'conscientious' performance of technical work. What we learn from this is that understanding the role of communication in engineering requires that we depart from the conventional view that communication is simply the transfer of information. It is also a means for establishing and maintaining relationships and shaping perceptions.

Conclusions

This brief analysis provides two useful conclusions. The first is that contemporary literature on engineering education contains only sparse references to published accounts of systematic research on engineering practice. The likely explanation is that these accounts are not easy to find and there are not many (Barley, 2005; James P. Trevelyan & Tilli, 2007).

The second conclusion is that the assessment of engineering communication is largely based on a narrow view that engineering communication is an information output transfer process, from the engineer to the client. Not only does this view take input for granted. It also overlooks the reality of engineering practice in which social relationships form a critical component. There is an obvious difference between the narrow view of communication in engineering education (a one way information transfer) and the realities of practice (the means by which complex social interactions are sustained). It is possible that this difference could explain why employers complain about graduates' communication skills while graduates think they can communicate well.

An accurate model of engineering practice which is soundly based on empirical studies could help correct this fundamental misunderstanding.

Lee (1994) demonstrated that social relationships with experienced engineers and outsiders tend to predict the work performance of novice engineers. He reported that young engineers fear that they will seem incompetent if they ask for too much help from others. However, they cannot perform without learning about expectations and obtaining the technical information they need, so engineers need to form cooperative relationships in order to perform their work. Social relationship skills, like any other aspect of engineering, can be learned and there is sufficient evidence to be confident in predicting performance improvements as a direct result.

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References

American Society of Civil Engineers. (2008). *Civil Engineering Body of Knowledge for the 21st Century: Preparing the Civil Engineer for the Future* (No. 978-0-7844-0965-7). Reston, Virginia, USA: ASCE Committee on Academic Prerequisites for Professional Practice.

Barley, S. R. (2005). What we know (and mostly don't know) about technical work. In S. Ackroyd, R. Batt, P. Thompson & P. S. Tolbert (Eds.), *The Oxford Handbook of Work and Organization* (pp. 376-403). Oxford: Oxford University Press.

Bloom, B. S. (1994). Reflections on the development and use of the taxonomy. In L. W. Anderson & L. A. Sosniak (Eds.), *Blooms Taxonomy. A 40 Year Retrospective: 73rd Yearbook of the National Society for the Study of Education*. Chicago: University of Chicago Press.

Bloom, B. S., Englehart, M. D., J., F. E., Hill, W. H., & Krathwohl, D. (1956). *Taxonomy of Educational Objectives: 1 The Cognitive Domain*. New York: David McKay.

Bucciarelli, L. L. (1994). *Designing Engineers*. Cambridge, Massachusetts: MIT Press.

Crawley, E. F., Malmqvist, J., Östlund, S., & Brodeur, D. R. (2007). *Rethinking Engineering Education: The CDIO Approach*. New York: Springer.

Dym, C. L., Agogino, A. M., Eris, O., Frey, D., & Leifer, L. J. (2005). Engineering Design Thinking, Teaching, Learning. *Journal of Engineering Education, 94*(1), 103-120.

Faulkner, W. (2007). Nuts and Bolts and People. *Social Studies of Science, 37*(3), 331-356.

Ferguson, E. S. (1992). *Engineering and the Mind's Eye*. Cambridge, MA, USA: MIT Press.

Hadgraft, R. G. (2008, July). *Keynote Presentation: PBL for Sustainability - Emergence in Action.* Paper presented at the UNESCO Research Symposium on PBL in Engineering Education PBL-2008, Aalborg, Denmark.

Heywood, J. (2005). *Engineering Education: Research and Development in Curriculum and Instruction*. Hoboken, New Jersey: John Wiley & Sons, Inc.

Jonassen, D., Strobel, J., & Lee, C. B. (2006). Everyday Problem Solving in Engineering: Lessons for Engineering Educators. *Journal of Engineering Education, 95*(2), 139-151.

Kilduff, M., Funk, J. L., & Mehra, A. (1997). Engineering Identity in a Japanese Factory. *Organization Science, 8*(6), 579-592.

Korte, R., Sheppard, S., & Jordan, W. (2008, June 22-26). *A Qualitative Study of the Early Work Experiences of Recent Graduates in Engineering.* Paper presented at the American Society for Engineering Education, Pittsburgh.

Lam, A. (1996). Engineers, Management and Work Organization: A Comparative Analysis of Engineers' Work Roles in British and Japanese Electronics Firms. *Journal of Management Studies, 33*(2), 183-212.

Lam, A. (1997). Embedded Firms, Embedded Knowledge: Problems of Collaboration and Knowledge Transfer in Global Cooperative Ventures. *Organization Studies, 18*(6), 973-996.

Lee, D. M. S. (1994). Social ties, task-related communication and first job performance of young engineers. *Journal of Engineering and Technology Management, 11*, 203-228.

Savin-Baden, M. (2007). Challenging Models and Perspectives of Problem-Based Learning. In E. De Graaff & A. Kolmos (Eds.), *Management of Change: Implementation of Problem-Based and Project-Based Learning in Engineering* (pp. 9-30). Rotterdam / Taipei: Sense Publishers.

Schön, D. A. (1983). *The Reflective Practitioner: How Professionals Think in Action*: Basic Books Inc., Harper Collins.

Sheppard, S., Colby, A., Macatangay, K., & Sullivan, W. (2006). What is Engineering Practice? *International Journal of Engineering Education, 22*(3), 429-438.

Sheppard, S. D., Macatangay, K., Colby, A., & Sullivan, W. (2009). *Educating Engineers*. Stanford, California: Jossey-Bass (Wiley).

Tenopir, C., & King, D. W. (2004). *Communication Patterns of Engineers*. Hoboken: IEEE Press - Wiley & Sons Inc.

Tilli, S., & Trevelyan, J. P. (2008, June 20-22). *Longitudinal Study of Australian Engineering Graduates: Preliminary Results.* Paper presented at the American Society for Engineering Education Annual Conference, Pittsburgh.

Trevelyan, J. P. (2007). Technical Coordination in Engineering Practice. *Journal of Engineering Education, 96*(3), 191-204.

Trevelyan, J. P. (2008, June 20-22). *A Framework for Understanding Engineering Practice.* Paper presented at the American Society for Engineering Education Annual Conference, Pittsburgh.

Trevelyan, J. P., & Tilli, S. (2007). Published Research on Engineering Work. *Journal of Professional Issues in Engineering Education and Practice, 133*(4), 300-307.

Vincenti, W. G. (1990). *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History*. Baltimore: The Johns Hopkins University Press.

Vinck, D. (Ed.). (2003). *Everyday Engineering: An Ethnography of Design and Innovation*. Boston: MIT Press.

Youngman, M., Oxtoby, R., Monk, J. D., & Heywood, J. (1978). *Analysing Jobs*. Farnborough, Hampshire, UK: Gower Press.