Editor's Note: This is a special invited feature. The article and the commentaries address a topic that is of great importance to *Technometrics*—communicating with users of statistical methods. I thank the contributors for sharing their views on the extent and nature of the communications gap and their suggestions for bridging it. The editors of *Technometrics* are always interested in hearing from readers who have specific suggestions on how the journal can foster improved communications.

Communications Between Statisticians and Engineers/Physical Scientists

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Communications between statisticians and engineers or physical scientists range from outstanding to awful, but overall there are strong indications of serious problems that need resolution. Guided by input from many professionals with successes and scars from working at this interface, this article attempts to document the problems that affect communications and to outline remedies.

KEY WORDS: Collaboration; Education; Image; Language.

1. THE COMMUNICATIONS GAP

The opinions of 62 experts from a survey about the overall state of communications between statisticians and engineers and physical scientists are summarized in Figure 1. [Details about this judgment sample of experts may be found in Hoadley and Kettenring (1989); it consists mainly of statisticians who are involved in this interdisciplinary interface.] Opinions range from "awful" to "outstanding," but most are in the "poor" or "okay" categories. Several experts indicated mixed experiences—for example, "Communications is mostly 'poor,' but in exceptional cases has been 'outstanding' to the benefit of both groups of disciplines." A follow-up survey of reliability engineers at Bellcore revealed a similar pattern.

The purpose of this article is to explore in more depth the state of communications between statistics and its natural constituents in engineering and the physical sciences. The focus, however, is more on engineering than physical sciences because of greater information and experience in that direction.

On the positive side, one can point to the substantial role that statisticians have played in chemometrics and the field of quality assurance and improvement. These are two indisputable success stories. A third, less well-known example is the growing use of statistics—especially stochastic processes—in engineering design as in the work of Roberts (1989). And one could list others.

The negative side may be summarized as missed opportunities. This is dramatically illustrated by the space-shuttle-Challenger incident. Follow-up studies reported that *relevant statistical data had been looked at incorrectly* (*Report of the Presidential Commission on the Space Shuttle Challenger Accident* 1986, pp. 145, 146, and 148), that *quantitative, including probabilistic-risk, assessment methods were needed to support National Aeronautics and Space Administration (NASA) decision making*, and that *its staff lacked specialists and engineers trained in the statistical sciences* (*Post-Challenger Evaluation of Space Shuttle Risk Assessment and Management* 1988, p. 5). Again other examples could be cited, but this one was singled out for attention in this article because of Hoadley's involvement in the post-Challenger evaluation study.

Many of the difficulties in communications are mirrored, perhaps magnified, in the literature. Consider this journal. Its stated purpose is "to contribute to the development and use of statistical methods in the physical, chemical, and engineering sciences."

One measure of its overall success is the "impact factor" reported in the *Science Citation Index* (Garfield 1986). This reflects the frequency of citations of *Technometrics* articles. By this measure, the im-

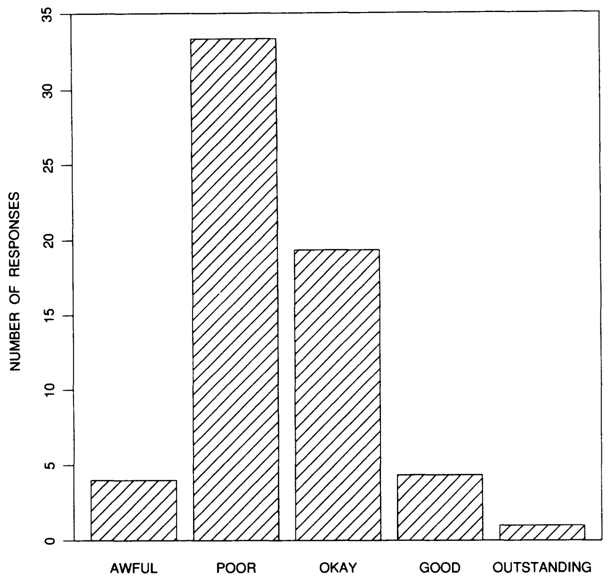

Figure 1. State of Communications Between Statisticians and Engineers/Physical Scientists.

pact of *Technometrics* is among the highest of all statistics journals.

A detailed picture of which journals are involved in the article-to-article citations is shown in Figure 2. The data, derived from Garfield (1985, 1986), are combined results of the number of citations of *Technometrics* by articles that appeared in 1985 and 1986. Journals that do not have at least six citations to *Technometrics* in both years are omitted.

The most frequent citers of *Technometrics* are statistics journals, especially *Technometrics* itself and *Communications in Statistics—Theory and Methods*. Roughly 25% of these citations are from standard statistics journals. Quality and reliability journals also have a strong presence, but they are essentially applied-statistics journals. *Analytical Chemistry* appears high on the list with 50 citations. The remainder are a mixture of less frequent citers, including some engineering and physical-science journals. In the other direction, about one half of the 1985–1986 article-to-article citations in *Technometrics* are to articles in these same standard statistics journals. The only other journal cited more than five times in both years is the *Journal of Quality Technology*. Overall, it is a mixed picture in terms of impact on the target areas of *Technometrics*. What the record shows is mostly statisticians citing statisticians.

Having argued that a communications gap exists, the second and third sections of the article discuss why and suggest some ways of closing the gap. All undocumented quotes are from the aforementioned survey of experts.

2. DIMENSIONS OF THE GAP

2.1 Image

The line from Auden's poem *Under Which Lyre* says it all: "Thou shall not sit with statisticians nor commit a social science." Is any modern scientific discipline so burdened by, and yet so dependent for its success on, its image as statistics? The gap between what statistics has to offer and what it is *perceived* to offer presents a major problem. There is "the perception that Pandora's box is being opened, because it will be impossible to understand anything that comes out" (E. R. Ziegel).

2.2 Orientation

Differing views of the world contribute to the tension between statisticians and engineers/physical scientists:

> engineers tend to see operational "problems" and are good at putting together "solutions." But they don't know much about scientific inquiry . . . in addition, there is a lack of any stochastic view of the world on the part of many types of engineers. (J. F. Lawless)

An overall summary of these differing orientations is shown in Table 1. These differences cause suspicion that the other person is "wasting my time" or "getting the wrong answer."

2.3 Commitment and Technical Focus

Issues of commitment and technical focus underlie much of what is wrong in communications between

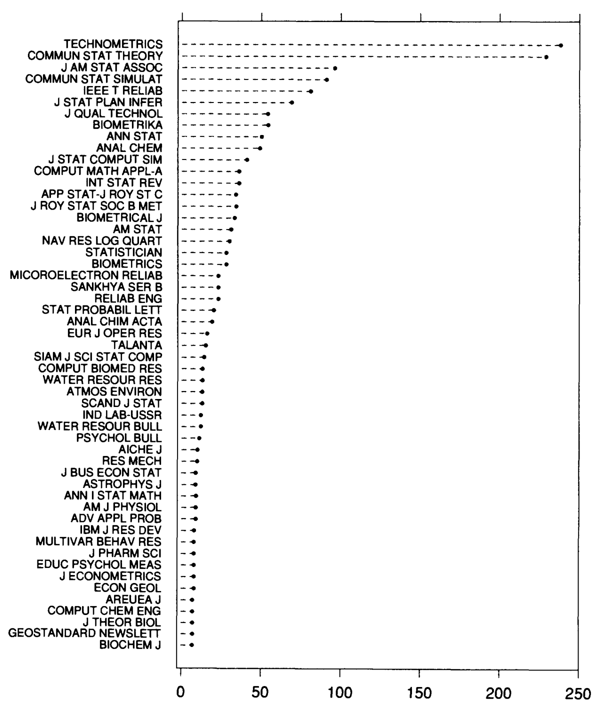

Figure 2. Number of Article-To-Article Citations of Technometrics in 1985 and 1986 Issues of Listed Journals.

Table 1. Components of Different Views of the World

Scale	*Engineers/physical scientists*	*Statisticians*
Use of scientific method	less	more
Use of quantification	less	more
Use of statistical methods	less	more
Knowledge of statistics	less	more
Use of random variables	less	more
Comfort level with uncertainty	less	more
Use of designed data collection	less	more
Belief in added value of statistics	less	more
Desire to be rigorous	less	more
Desire to keep things simple	more	less
Use of deterministic models	more	less
Action and bottom-line orientation	more	less
Knowledge of engineering	more	less

statisticians and engineers/physical scientists:

Whatever the reason(s) may be [whether it is training, values or instincts], most statisticians do not seem to become involved *deeply enough* in subject matter areas to understand the scientific problems in their contexts. This is particularly evident in the scarcity of statisticians working in the visible, "hot" topics of many sciences including engineering/physical sciences (e.g., neural networks, imaging, . . .). (R. Gnanadesikan)

A particular manifestation of the commitment issue is the "unwillingness of many statisticians to . . . rethink the conventional statistical formulations whenever they are inappropriate in a new situation" (J. W. Tukey). Another aspect of commitment is evident in the variety of ways statisticians are used—or not used—in technology-oriented organizations. For example, the conclusion stated in the *Post-Challenger Evaluation* (1988) is that "NASA is not adequately staffed with specialists and engineers trained in the statistical sciences to aid in the transformation of complex data into information useful to decision makers, and for use in setting standards and goals" (p. 55).

An example is the need for statistical information for probabilistic risk assessment. It is generally accepted that part of the definition of space-shuttle risk is the probability of critical failure modes that can lead to loss of life or vehicle, but prior to the space-shuttle-Challenger accident in January 1986, NASA made no attempt to develop these probabilities—even for critical failure modes that were of concern, like the solid-rocket-motor field-joint O rings that failed on the Challenger. The reason for this was that NASA did not believe that probability of failure could be estimated well enough to be useful. Apparently previous attempts to do so had failed. This left a bad taste in everyone's mouth at NASA.

Statistical science does not seem to deal well with the probabilistic risk assessment of complex engineered systems. There are too little data in the traditional sense. Nuclear engineers [app. D of the *Post-Challenger Evaluation* (1988) was coauthored by a nuclear engineer] seem to have taken the lead in integrating information from various sources. Statisticians have been critical of their attempts, often with good reason, but the subject is vitally important.

2.4 Interpersonal Relationships and Language

Even when there is potential for productive communication based on the technical aspects of a problem, it may never be realized because of poor chemistry between the parties involved.

Much in communications depends on subtleties or accidents of interpersonal relationships. In the National Bureau of Standards environment, we have opportunities to develop relationships gradually, and options to try different pairings between scientist and statistician. (J. R. Rosenblatt)

An unfortunate aspect of such relationships is that the well-intentioned statistician may be blind to some of these subtleties that affect communication. See Zahn (1988) for further discussion.

Language, a basic tool in interpersonal relations, also stands out as a major stumbling block. Several respondents to the survey mentioned that this is *the* biggest problem:

The imposition of statistical jargon on top of scientific problems . . . [they] become afraid that we are deceiving them by the use of all the fancy rhetoric. (H. F. Martz)

[Our] inability to discuss the engineering/science problems in the language of the engineer/scientist. (R. Lundegard)

A moment's reflection shows the magnitude of the problem from the client's perspective. Some of the vocabulary of statisticians is, at least, suggestive of its meaning—outlier, trimmed mean, minimal spanning tree, and so forth. Much less so are terms such as parameter (often confused by engineers with "variable"), m estimate (what is "m"?), semiparametric estimation (how does "semi" enter?), twicing (the dictionary will not help), and so forth.

Bayesian statistics can offer some real tongue twisters. How about "posterior variance of the process variance"? Here the term variance is used to represent two distinct concepts (at least in the minds of engineers/physical scientists), uncertainty and physical variation.

2.5 Leadership

Leadership, or the lack thereof, has a profound effect on the communications gap. Deming (1986, pp. 466–468), following ideas of M. H. Hansen, recommended that companies should organize for quality and productivity by appointing a leader of statistical methodology who reports to top management. In the professional and scientific arenas, people with enough talent and stature to be recognized by both sides can do much to increase understanding and transfer ideas.

As a crude measure of the current state of interdisciplinary leadership between statistics and other fields, a check was done on the number of Fellows of the American Statistical Association (ASA) as of 1987 who are also Fellows of the American Physical Society (APS), the Institute of Electrical and Electronics Engineers (IEEE), the American Psychological Association (APA), or the American Society for Quality Control (ASQC). The results are shown in Table 2. The high number for "ASA and ASQC" is probably because ASQC has a statistics section. These numbers suggest that interdisciplinary leadership ties with physics and engineering (excluding quality) are weak.

Bode, Mosteller, Tukey, and Winsor (1949, p. 553) called for the education of scientific generalists who can "practice science—not a particular science." In their plan, statistics has a prominent role because "as the doctrine of planning experiments and observations and of interpreting data, [it] has a common relation to all sciences." The sparsity of such generalists is even more evident 40 years later in this time of hyperspecialization.

2.6 Education

Statistical education, a topic to which so many experts have contributed (e.g., see Moore 1988), is still a point of serious debate and contention. It is clearly a major dimension of the communications gap.

Consider the situation at Purdue University, which has one of the best known and largest engineering schools. Moore (1988, personal communication) pointed out that, of roughly 4,000 eligible students, only 25% will take a statistics course and 40% a probability course. The difficulty in turning the situation around is reflected in the view: "Engineering is going through . . . competing changes, such as use of computer-aided design . . . [statistics is] fighting for the small amount of time available" (N. R. Ullman). Apparently, engineers tend to think of statistics more as an elective than as a fundamental aspect of their training. The challenge in other areas may be equally daunting: "The current level of probability and statistics training in the atmospheric sciences is very low and declining" (J. A. Flueck).

Table 2. Number of Dual Fellowships

Organizations	*Persons holding dual fellowships*
ASA and APS	1
ASA and IEEE	2
ASA and APA	10
ASA and ASQC	31

3. CLOSING THE GAP

Perhaps the most important area of need is effective "marketing" of statistics to surmount its negative image. Above all, success stories need to be publicized. Dalal, Fowlkes and Hoadley (1989) provided an after-the-fact statistical analysis of what could have been learned prior to the Challenger launch. But stories of where statistics *did* make a difference, not just where it *might* have made a difference, need to be widely disseminated also. Perhaps this is an opportunity for *Technometrics*. One approach would be to arrange with selected engineering and physical-sciences journals to publish each other's best articles of interest to the other group.

One author of this article is a confessed Bayesian. The other thinks he is a data analyst. When we sit together to discuss our differences, we find much common ground. Labels are not so important after all. Statisticians need to present a united view to engineers and physical scientists as broadly useful statistical scientists rather than as picky experts who cannot help because "your experiment was poorly designed," and so forth.

Deep immersion in and collaboration on hot topics in engineering and the physical sciences should help to keep statisticians in the spotlight. Current examples of topics with such potential include image analysis, neural networks, and risk assessment of complex systems.

Along with immersion, there needs to be focus on substantive issues and decision points to achieve maximum impact. In the case of the Challenger, an intermediate question of some interest was the effect of temperature on the performance of O rings, but the larger issues were about overall levels of risk and the decision of whether or not to launch (Dalal et al. 1989).

A second area of need is the nurturing of both interpersonal and intersociety relationships between the statistics community and the engineering and physical-science communities. A commitment to "long time association is almost mandatory for fruitful results" (G. J. Levenbach). A particularly sound piece of advice at the interpersonal level is "to be clear to yourself and your clients that you are using statistics to *catalyze* their problem solving and subject matter knowhow, not to replace it" (G. E. P. Box). On the intersociety scale, statistics organizations should be aggressive at establishing beachheads with engineering and physical-sciences groups to promote collaborations—for example, in statistical ecology.

A third and closely related category of suggestions concerns the cultivation of statisticians who can serve as bridge scientists. The potential impact of such broadly skilled statisticians was observed by Lowrance (1985, p. 87), using F. Mosteller and J. W. Tukey as examples.

Specific ideas for encouraging such bridging behavior would include implementing the University of Wisconsin model [as described by Box to DeGroot (1987)] of joint academic appointments and tuning financial and promotional reward systems to encourage work at the interface of statistics with these other disciplines.

A fourth compelling need is for educational reform starting perhaps with introductory statistics courses. Hahn (1986) elaborated on the challenge, and a range of related educational issues was explored by Hogg et al. (1985) and Moore (1988).

Finally, a serious response is called for to the thorny issue of language development. Jargon must be replaced by words that communicate.

Perhaps something can be learned from the engineers about language. When nuclear engineers do probability risk assessment, they compute posterior distributions but call them "state-of-knowledge curves." This expression evokes a strong sense of what is going on. During the development and field use of an engineered system, the state of knowledge of the system changes as data are collected. In the *Post-Challenger Evaluation* (1988), state-of-knowledge curves were used for probability distributions that represent uncertainty.

Some of the survey respondents noted encouraging signs that the communications gap is already shrinking. On the education front, the Accreditation Board for Engineering and Technology is studying ways of integrating statistics into the undergraduate training of engineers.

Still, the overall condition seems to be accurately reflected in Figure 1. The challenge for statisticians is to lead the way in closing the gap by replacing rushed and superficial interactions and dated instruction with genuine collaborations that are long on mutual respect and understanding and revitalized courses that reflect the excitement and utility of modern data analysis/statistical science.

A part for statistics must be added to the elegant plea of Feynman for bringing the pieces together:

> If our small minds, for some convenience, divide this glass of wine, this universe, into parts—physics, biology, geology, astronomy, psychology, and so on—remember that nature does not know it! So let us put it all back together, not forgetting ultimately what it is for. Let it give us one more final pleasure: drink it and forget it all! (Feynman, Leighton, and Sands 1963, pp. 3–10)

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