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From "Science versus Art" to "Science and Art"

Reflexive Modernization in Engineering

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Introduction

It is a common belief that modern engineering owes its leaps of progress to the application of science. The history of technology is often told as developing from the crafts and arts of earlier centuries towards engineering, which from the late 19th century onwards has become science-based in both methodology and data. Over the last century empirical and personal skills have increasingly and successfully been transformed into objective and testable knowledge giving rise to the “modern folklore”[1] of engineering as applied science. Extrapolating the past and projecting it into the future, many engineers still believe that all design problems will eventually be translated into algorithms. In this linear model of history, engineering *art* one day will be made fully redundant by engineering *science* completely run on computers.

Historians, however, know that history has never been linear. Philosophers know that man (and therefore man-made machines) at best can think correctly but never comprehensively. And one of the greatest economists of our time has observed that all we know for certain about the long run is that we’ll all be dead. Instead of the metaphysical hope of eventually translating every problem into algorithms, this paper proposes a strategy of reflexive modernization in engineering which is derived from insights from social sciences and humanities.[2]

The theory of reflexive modernization [3] accepts the well-known limitations of formal reasoning and pragmatically builds them into its theorems and strategic recommendations. In contrast to earlier, “simple” modernization theories, “reflexive” modernization takes account of the many unintended side effects of modernization which create new insecurities and new risks but also new unforeseen chances. In continuously changing the fabric of society and the environment, modern science and technology keep destabilizing the very system they set out to control. Science and technology are creating and detecting new problems at a similar rate as they are solving old ones. Society cannot rely on progress in science and technology alone to manage its problems. Proven pre-modern or non-scientific methods, like art and crafts in the case of engineering, will continue to successfully contribute to problem solving and inventiveness. In the theory of reflexive modernization these pre-modern and non-scientific methods are not seen to contradict or replace but to complement science in fields where the codified knowledge of scientific theories fails to meet the complexity of the situation or proves unworkable within the given constraints of time and/or human and material resources.

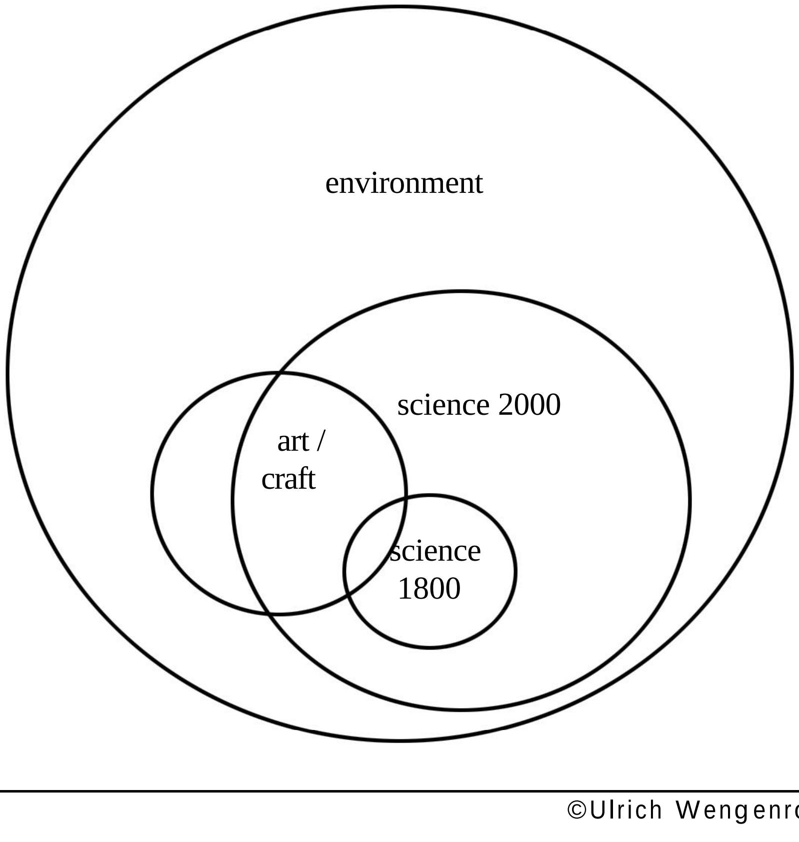
Three observations help to clarify the restraints of formal, codified knowledge in engineering:

1) In fostering new and ever more complex technology, engineers have substantially if unintentionally created a dynamic environment in which the number of problems is constantly expanding. Most engineers today work on problems unimaginable to earlier generations.
2) Most real-world problems typically are 'ill-structured' in the sense that system-boundaries are unpredictable and environments are heterogeneous. They are "messy" and resist codification and modeling.
3) Problem-solving takes place under time constraints favoring fast, workable solutions over fully investigated, "comprehensive" solutions. This is crucial for two important dimensions of modern engineering, risk management and product innovation under global competition. What can and must be done in the real world is quite different what can be imagined "in principle".

Observation number 1: the changing technological environment

The orthodox view of technological progress portrays science as expanding into ever more fields of human environment and eventually displacing pre-modern arts and crafts as means to create and control technologies. Knowledge about an ever larger subset of the world has been codified in theories and algorithms. After all, objectivity is one of the great achievements of modern science in the sense that it does not depend on individual "esoteric" forms of insight; it is abstract in the sense that it can be transferred and employed independent of localities and individuals. Because of science, mankind could control ever more of the environment which itself is seen to be of static dimensions and remains to be fully conquered by scientific knowledge.

Figure 1: science in a static environment (orthodox view)

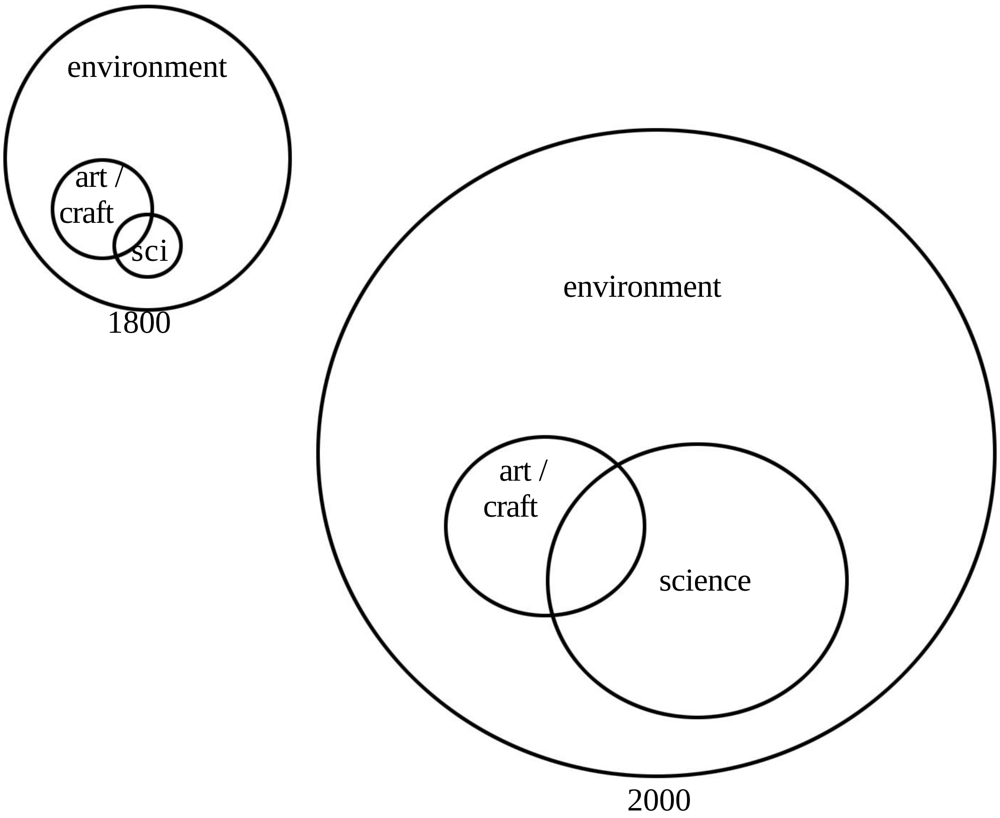


In this orthodox view science has been displacing arts and crafts as strategies to control parts of the human environment. From a junior partner to traditional approaches two centuries ago, science has become the dominating factor of managing the environment in our days. This interpretation of human environment is static, with development and change only happening inside the system.

Historically, this orthodox view fails, however, to take account of the consequences of industrialization proper. As every historical comparison shows, the world we live in is dramatically different from the world of about 1800 or earlier. Our environment is man-made to an extent that philosophers speak of our habitat as technospheres rather than biospheres.[4] More than ever it is the man-made rather than natural environments that constitute the "problems" for scientists and engineers. Engineers have forcefully expanded our environment and its complexity by building artificial superstructures to the world which we increasingly take to be our "second nature". Our environment is made of cars, motorways, buildings of steel and concrete, railroads, telecommunication, airplanes, electronic media for entertainment, synthetic materials and 'engineered' organisms, to name but a few examples which did not exist in 1800.

The instruments created to understand and control the environment were also responsible for complicating it. In using these instruments for both understanding and expanding the environment our relative position could not make as much progress as the orthodox view did suggest. This historically dynamic perspective of scientific and technological progress suggests a quite different interpretation.

Figure 2: science in a dynamic environment



This dynamic view is a much better representation of technological progress. It takes account of the enormous quantitative growth of man-made environments which eventually came to dominate the lifeworld of mankind. The world we live in, the world we perceive every day is incomparably richer in artifacts than the pre-industrial world. The cultural value of this material wealth might be controversial, but there is no doubt about complexity and the proliferation of 'things'. Whether the subset we control is growing, stagnant or even declining we do not know since we do not know how to measure the totality of the environment. In this respect figure number 2, as was figure number 1, is a mere illustration without any quantitative authority.

Observation number 2: "messy" problems, complexity and knowledge

One of the most successful strategies of modern science was to reduce the complexity of an object by creating a simplified, abstract representation which could eventually be transformed into theories and algorithms. Complex real world phenomena were thus slimmed down not only to fit the intellectual capacity of the human mind but to be transferable in the form of text, graph and equation. This intellectual rationalization (Max Weber) made much of the material world calculable and predictable allowing for more efficiency, security, and confidence in technological design. The success of rationalization, however, depends on the appropriateness of the reductionist path chosen. Since employing rational procedures depends on prior reduction of complexity, the choice of a reductionist path can only be pre-rational, i.e. intuitive, even if based on a large body of empirical experience. Errors and failures will eventually expose poor choices but there is no preemptive method to avoid them other than intuition. Knowledge that engineers employ to reduce complexity is largely tacit. It is the very personal launchpad at the beginning of each project and very often the only means to come to solutions when confronted with ill-defined, complex, real-world problems that withstand algorithmic representation.

Fortunately, most engineers possess the mental agility and capacity to deal with this kind of complexity. Michael Polanyi, the author of the notion "tacit knowledge" summed it up as: "We can more than we can tell."[5] Or, reverse: We cannot tell everything we can do or know. Modern science's great achievement to codify a large body of knowledge is not available without loss of tacit knowledge. Every codification, being an exercise of reducing complexity, necessarily involves data sacrifice and leaves some knowledge behind with the experienced individuals: "sticky information"[6] that cannot be abstracted. Cognitive science suggests that codified knowledge may be only the tip of the iceberg of all available knowledge. The relative size of art/craft and science for the year 2000 in figure 2 would then appear to privilege science. But since we cannot measure these subsets, we will not argue over their correct representation. There is no reason to assume, however, that the importance of tacit knowledge has significantly shrunk.

Innovation theory has argued recently that the growing complexity of technological systems stresses the importance of tacit knowledge as a strategic tool to promote and control technological progress.[7] Tacit knowledge, which might also be called 'implicit' or 'procedural' knowledge, is typically the ability to perform some activity in varying and new contexts while explicit ('codified', 'declarative') knowledge is of a more retrospective nature in knowing established facts, causal relations etc.. At the same time, the ability to do something tends to be retained longer than the ability to correctly remember codifications. Noteboom gives the example of speaking a foreign language. “Having learned a foreign language, later one can often recognise whether a sentence is well-formed, without recalling the grammatical rules for sentence formation. ... Then one can say that one knows the grammar in the procedural [=tacit, U.W.] but not in the declarative [=codified, U.W.] sense.”[8] Routinisation of complex and theoretically widely underdetermined procedures is at the root of the great efficiency that innovation theorists appreciate in tacit knowledge.

Tacit knowledge is a complementary path to successfully reduce complexity. It has been around in the form of art long before the modern scientific revolution and continues to be a powerful tool to cope with an environment that cannot and probably never will be fully codified. Harnessing tacit knowledge has become a prime target of management with Japanese firms being seen in the forefront by some scholars.[9] The inadequacy of the orthodox view, that relying on codified knowledge alone was the superior strategy to generate novelty and innovations is well illustrated by the wide-spread experience that rotating staff is a more efficient means to diffuse knowledge in a firm than rotating written documents and formal procedures.[10]

Observation Number 3: time constraints and moral responsibility

Acknowledging ‘tacit knowledge’ as a crucial condition for successful engineering is acknowledging the complex nature of real-world problems and the necessity to come to solutions without being able to fully assess, let alone control, the environment. One of the most limiting factors is time-constraints. The solution of engineering problems is always time-critical. This is not only true for new products which have to come to the market fast enough to be competitive. Since human capacity for rational evaluation is limited, it is both rational and efficient to routinise many mental operations and practises by transforming them into or generating them in the first place as tacit knowledge. This at the same time releases mental capacities to focus on further codification and application of codified knowledge.[11]

What is evident for the design of new products is also crucial when it comes to risk-management and protection from hazards. In both these instances windows of opportunity and available resources largely decide over the appropriateness of methods employed. A solution based on codified knowledge is no solution when it comes too late. Lengthy and thorough research can kill many projects – and firms. When disaster (=contingency in a complex system) strikes, there is often only tacit knowledge left to meet the rapidly contracting scope of action. The history of technological disasters is full of illustrations for complexity driven accidents which could, if at all, only be averted by “common sense” or “tacit knowledge”.[12] It is often an issue of moral responsibility, therefore, to resort to the method that works and not to the one that can be put in writing.

Of course this does not mean, like some post-modernist thinkers want to make us believe, that “anything goes” (Paul Feyerabend). This is most certainly not the case and would be a fundamental misunderstanding of the cognitive theories about ‘tacit knowledge’. Tacit knowledge can be and is being tested for success like any other form of knowledge. Societies do it when making the candidate drive around in the inner city before issuing a driver’s license. Insurance companies do it when choosing experts to check a technological project or to investigate the causes of damages. Employers do it when they ask for evidence of what applicants have done and can do rather than relying on diplomas only. The further engineers (like all other professionals) proceed in their career the more important proven ‘tacit knowledge’ becomes. ‘Good teams’ are examples of socially well embedded tacit knowledge that cannot be abstracted nor can it easily be transferred by taking the team apart. While team knowledge cannot be codified, team performance can be measured, as is reflected in the reward structure of firms.

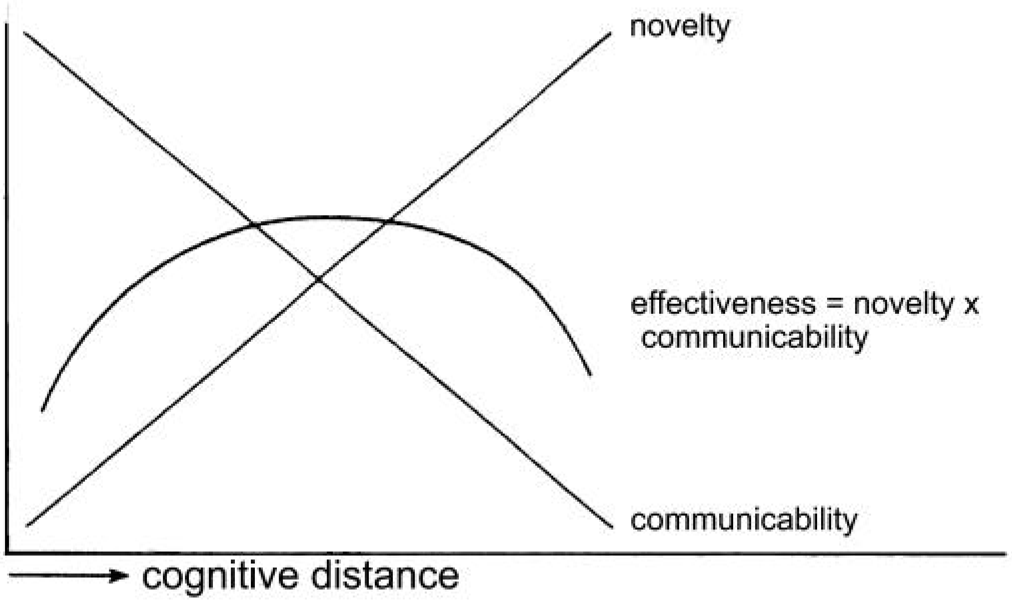
If it is possible to make a conceptual distinction between tacit and codified knowledge, it is very difficult to separate them in practice. Mostly, these two forms of knowledge are mutually constituted. In learning and employing codified knowledge students acquire tacit knowledge. Much of tacit knowledge effectively builds upon a solid foundation of theories and algorithms which makes it inaccessible to those who have not mastered their academic training. It requires a thorough scientific education to develop a ‘feeling’ for technologies. It is the one-sided engineer who fails the real-world test.

Good knowledge management

The issue is not to choose between either ‘tacit’ or ‘codified’ knowledge but rather to strike the optimal balance between the two. Innovation theory can help us to understand the pattern of good knowledge management. Codified knowledge offers the great advantage of being relatively easy to communicate, which after all was the great achievement of the modern scientific revolution. The inevitable sacrifice of data in the process of codification, however, reduces the level of novelty that can be read in texts, drawings and algorithms. Complexity and the insights that go with it get lost. Tacit knowledge on the other hand is a perfect vehicle for novelty. Its drawback is the absence of formalized and objective mechanisms of communicating its content. In the case of tacit knowledge, communicating and understanding another’s ideas can be difficult. Innovation theory refers to this as cognitive distance. It is unpredictable to say the least and tends to impede the progress of a design team unless arrangements for tacit communication can be made.

The effectiveness of knowledge management, therefore, can be understood as a balanced combining of novelty and communicability.

Figure 3: effectiveness of knowledge management[13]



The history of science and technology knows about a great number of geniuses whose world of thoughts, and often the very persons themselves, were impenetrable to most of their environment. Great novelty was available at the cost of low communicability. What is true for the communicative problems of outstanding scientists is also true for creative members of research and development teams. It is shared experience and cultural proximity in these teams which help to translate individual members’ ideas into a common understanding. Closeness in the many non-explicit dimensions of social interaction, cultural values, and ‘styles’ of communicating and problem solving becomes of paramount importance to the transfer of non-codified knowledge. This is one reason why ‘expensive’ teams in the right cultural setting often perform so much better than groups that appear to have equal or even better qualifications.

Conclusion

Reflexive modernization offers engineering a third position in the ideological debate between the total scientification of the world and the postmodern relativism of ‘anything goes’. The linear model of modernization rested on the assumption that engineering, with its historic roots in the largely tacit knowledge of art and craft, and science converge towards ever higher degrees of formal, scientific knowledge leading to unified, highly formalized technoscience. Reflexive modernization assumes a continuing parallel development of science and art in engineering for the foreseeable future with cross-fertilization but no substitution. In view of the many unintended side effects of technology in a dynamically expanding environment, well proven forms of tacit knowledge remain an integral part of engineering methodology. Since the ultimate test of engineering is not a solved equation on the blackboard but successful operation in the world, all forms of knowledge available to the practitioner must be judiciously put to use. In the real world of ill-defined problems and mushrooming complexity technology will continue to be solved by science **and** art. And so, we should teach young engineers the art as well as the science, for art like science can be learned and taught.

References

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[2] This paper is based on research in the Collaborative Research Center (Sonderforschungsbereich) 1714 “Reflexive Modernization”, funded by the Deutsche Forschungsgemeinschaft. See also: Wengenroth, Ulrich: Der aufhaltsame Weg von der klassischen zur reflexiven Moderne in der Technik, in: Thomas Hänseroth (Ed.), Technik und Wissenschaft als produktive Kräfte in der Geschichte, Dresden: TU Dresden, 1998, pp. 129-140.

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[13] Reproduced from Noteboom, p. 140.