TECHNOLOGICAL KNOWLEDGE

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The central aim of this paper is to overthrow the widely-held view that technology entails the mere application of knowledge derived from the sciences to the making of artifacts. The essential independence of technology from science has already been argued by distinguished scholars[1]. Herbert Simon, Edward Layton, E.S. Ferguson, George Basalla and Subrata Dasgupta stand out among those who firmly insist that the intellectual nature of technology can never be comprehended on the basis of the natural sciences alone. However, this very theme has not yet integrated into our intellectual tradition. In this paper I intend to bring to light the crucial, though largely unnoticed, fact that technological knowledge is far more than just scientific knowledge. This paper is divided into two sections. The first section tries to explain, in a nutshell, the essence of what technology is. The second section presents an example from the history of technology to demonstrate that technology has a distinct component of knowledge not derived from science.

I

Though ours is an age of high technology, the essence of what technology is and what the technologists do is not common knowledge. The anthropologists document that human beings have been conceiving, shaping and using tools from as far back as the early stone ages. This activity of conceptualizing, fashioning and using tools to meet human needs is basically what technology is[2]. Clearly then, technology is much older than science. It reaches back to the hominids and the stone tools of the lower Paleolithic Age when science, even in its earliest forms, didn't exist.

Dasgupta writes: "...Man had been making, treating, casting and forging metals and alloys, constructing roads, bridges, dwellings, and public buildings, crafting boats and ships; and shaping the instruments and engines of war many thousands of years before the rational comprehension of their respective underlying scientific principles could even be contemplated"[3].

Evidently, for a large part of the histoy of human kind technological development has been independent of the growth of scientific knowledge. If it is the case that technology itself generates no new knowledge but is founded on scientific knowledge- and given that most of science itself is essentially the product of only the past four centuries, then we are led to conclude, as Edwin Layton noted, that all artifactual creations prior to this period-that is, almost all of technological history from the emergence of hominids-entailed no new knowledge at all[4]. The absurdity of this conclusion demands the rejection of the widespread tendency to regard technology as involving essentially the application of knowledge derived from science.

More importantly, technology is basically 'teleological' in nature. It is concerned with the creation of artifacts. Artifacts, in simple words, are artificial products consciously produced or conceived in response to some need or desire. Technology is, thus, an activity that entails human needs, aspirations, wants and their satisfaction. The natural sciences, on the contrary, have nothing to say about 'wants' or 'desires'. The world that the technologists are principally concerned with is not the 'given' world of the natural sciences.

There exists a deep divide between the 'given' natural world and what Simon refers to as the 'artificial' world[5]. This artificial, engineered world- the world that the technologists themselves make is characterized by an endless variety of things. This astonishing diversity of the 'made' world reveals another significant aspect - the needs that drive human beings to fashion such a variety of artifacts are not the 'basic' human needs. The plethora of 'made' things are not mere instruments to meet our 'minimum' needs. The animals too have minimum needs which are not radically dirrerent from ours. Yet from the point of bare living the animals maintain themselves perfectly and require no technology at all. Ortege Y Gasset writes that human beings, unlike the animals, have no desire just to be in this world, just to 'live', they want to 'live well'. They conceive of life not merely as 'being' but as 'well being'[6]. Their struggle for well being certainly entails the idea of needs but those needs are what Basalla refers to as 'perceived' needs[7]. Such 'perceived' needs undergo constant change as human tastes, values, aspirations and resources vary widely from time to time, culture to culture, from one social organization to another. The artifacts, thus are not narrow solutions to problems generated in satisfying our basic requirements- rather they are material manifestations of the innumerable ways human beings have chosen to define their well-being and pursue existence.

We should also take notice of the fact that need or necessity is very much a relative term. A necessity for one people, generation or social class may have no utilitarian value for another people, generation or social class. Basalla documents that even the 'wheel' - popularly conceived as one of the oldest and most important inventions of the human race - was not necessary to all people at all times[8]. The first wheeled vehicles invented in Mesopotamia were used for ritualistic and ceremonial purposes. In the second millennium B.C. spoked wheels were introduced on war chariots. Much after its initial appearance, the wheel was used for transporting farm goods. The case of Mexico and Central America is even more interesting. Wheeled transport was not known to these people before the arrival of the Spanish, but they used to make miniature objects such as clay figures of various animals fitted with axles and wheels. It is quite surprising that the mechanical principle of the wheel was understood and applied by people who never put it into use for transportation. The wheel, comments Basalla, was not a universal need.

Human beings create and use artifacts to meet their 'perceived needs' - the nature of which varies enormously. To put it in different words, artifacts are not elements of the given, natural world and they are intended to serve some purpose. Fulfillment of purpose, notices Simon, involves a relation among three terms : the purpose or goal, the character of the artifact and the environment in which the artifact performs[9]. In terms of purpose, to use Simon's example, a clock is to tell time. If we focus our attention on the clock itself, it may be described in terms of arrangement of gears, and on the application of the forces of springs or gravity operating on a weight. It may also be considered in relation to the environment in which it operates. To sum up, whether a clock is to tell time depends on its internal construction on the one hand and where it is placed, on the other. An artifact, in Simon's words, is a 'meeting point, or an 'interface' between its 'inner environment', i.e., the substance and the organization of the artifact itself and its 'outer environment', i.e., the surroundings in which it functions[10].

Natural science makes an effect on the artifact through two of the three terms of the relation that characterizes it : the inner structure of the artifact itself and the outer environment in which it performs. It is generally believed that the deeper the understanding of these environments , i.e., the more one understands the science underlying the artifacts- the more progress will one achieve in that technology. However, the fact is, even when the science behind the artifact is well understood-errors and failures occur. As Dasgupta explains that once created, the artifact "acquires a life of its own"[11] - it is governed by the principles and properties of its own inner and outer environments - which may well be far beyond the technologist's anticipation, understanding or cognitive capabilities.

The example of the Britannia Bridge, built by Robert Stephenson and his associates in the 1840's, is an interesting case in point. It was a huge tubular wrought-iron bridge through which trains could pass and it worked well for over hundred years. In structural terms, the bridge was undoubtedly a spectacular success. However, in Dasgupta's view, the bridge was literally an 'environmental failure[12]. The engineers were exclusively concerned with the 'load' imposed by the weights of the bridge itself, by the train, as well as the forces exerted by wind. But the actual inner and outer environment of this bridge were constituted of more than mechanical loads and wind forces. They also included the excessive heating of the wrought iron by the sun, the smoke expelled by the steam locomotive but entrapped within the tubular form of the bridge, the human passengers and the acute discomfort they had to suffer by heat, smoke etc. The engineers failed to anticipate that these factors were as much part of the bridge's outer environment as were the loads imposed by the weights of the moving trains, the bridge itself and the wind forces.

From whatever has been said so far one may assume that artifacts are necessarily material in nature. Such an impression is to be avoided.

There are artificial products capable of satisfying certain human goals despite being physically intangible. Methods, designs, strategies, plans, algorithms etc. cannot be touched the way we touch a machine, but once created, they can be used, communicated, analyzed and modified as well. Dasgupta considers them all examples of 'abstract' artifacts[13]. The most important characteristic of abstract artifacts is that they are rendered visible through symbols. For instance, the architecture of a building is explicated through architectural drawings. The creation of most material artifacts - a bridge, an engine, or a computer, for instance, necessitates a conceptualization or to use the technical term, a 'design' phase that precedes the manufacture, or 'making' phase. A design expressed in the form of an engineering drawing, for example, is itself an abstract artifact. Thus most acts of technology entail the production of abstract and material artifacts, the former being the artifactual form, the latter the artifact itself[14]. The artifactual form is 'conceptualized', the artifact is 'manufactured'. The technologist is as much concerned with the design or conceiving of the artifactual form as with the making of the artifact itself.

Broadly stated, design, is concerned with the conceiving of artifactual forms intended to satisfy certain desired objectives. It seems obvious that such an activity would only be initiated if no existing artifact exactly satisfies the given requirements. The very idea of design - to conceptualize something that never was, is what most distinguishes technology from science[15]. The major focus of the following section is on design.

II

In order to attack the long-held view that whatever knowledge may be incorporated in the artifacts of technology must be derived from the sciences, an examination of the very nature of technological knowledge is required. For this purpose I would like to consider the example of the design of the Britannia Bridge. The design of the Britannia Bridge, despite being criticised in economic and aesthetic terms holds significanse as it generated 'knowledge' whose benefits extended far beyond the realm of the bridges[16].

The Britannia Bridge came into existence at a point in history when basic science and technological theory were beginning to make their presences felt. However, when Robert Stephenson (1803-1854) and his associates embarked on the design of the bridge in 1844, much of the requisite theoretical knowledge did not preexist. The body of knowledge these engineers relied upon as a basis of their design and reasoning did not entail basic science. Thus it is of crucial importance to see what kind of knowledge helped the engineers tide over the problems faced while conceiving the novel form of the bridge.

The basic task of Stephenson, the chief engineer of the project, was to design and construct a tubular railway bridge across the Menai strait in North Wales. At that time there were two main types of long-span bridges in use - a) cost iron arch bridge, and b) suspension bridge. Initially Stephenson rejected both - the former because it used to obstruct navigation and the latter because "... the failure of more than one attempt had proved the impossibility of running railway trains over bridges of that class with safety."[17] In other words, Stephenson initially rejected the suspension bridge form because of the following proposition p_1 : Suspension bridges are not sufficiently rigid for the support of rapidly moving railway trains[18]. What is to be noted in this proposition is that it relates the structure or form of suspension bridge to a functional property, namely, the ability to withstand a particular kind of dynamic load. If we look closely into the nature of such knowledge we will see that it is not basic science, rather it is of how certain kinds of structural forms behave and appear under certain conditions. Such knowledge according to Dasgupta, is likely to have originated from experience of the behaviour and structural capabilities of suspension bridges[19].

Later, Stephenson's attention was drawn towards J. M. Rendel's mode of 'trussing' to prevent oscillation in the platform of suspension bridges. Stephenson envisioned that Rendel's trussing system while adequate for ordinary roads, would not be strong enough for the purpose of a railway bridge. In other words, he felt that a stronger trussing system would be needed because of the proposition - P_2 : Road bridges are generally not as strong as railway bridges[20]. Here again we see that P_2 is a comparative statement about two specific artifactual classes, namely, road bridges and railway bridges with respect to a performance property (strength). Dasgupta thinks it is quite conceivable that P_2 is a generalization based on empirical evidence[21]. Such knowledge of how certain kinds of structural forms perform under certain conditions is clearly distinct from scientific knowledge.

Dasgupta maintains that for a given class of artifacts any such proposition, rule, procedure, or conceptual frame of reference about artifactual properties or characteristics that facilitates action for the creation, manipulation, and modification or artifactual forms and their implementations is an 'operational principle'[22]. Thus, P_1 which relates the suspension bridge form to a functional property as well as P_2 which compares two specific artifactual classes with respect to a performance property, are operational principles. The knowledge, Stephenson used as a basis of his reasoning was not scientific knowledge, rather it was the knowledge of these opertional principles.

Let's proceed further with the design of the bridge to see the influence of operational principles as the principal source of knowledge. Stephenson decided to combine the use of the suspension chains with trussed vertical sides and cross braces on the top as well as the bottom. He planned to use riveted wrought iron plates for the trussing and cross braces. The resulted form of the bridge was that of a rectangular tube supported by suspension chains and surrounded by a trussed framework. At that time there existed neither theoretical nor experiential knowledge that could be fruitfully applied to the design of such a structure.

Stephenson eventually came to realize that the hollow tube could be viewed as a 'beam'. By 1845, the basic theory of how beams resist the bending caused by vertical loads had been established. From this theory formulas were available for calculating the internal stresses in beams of different cross-sectional shape under certain special assumptions. However, this theory was inadequate for computing the ultimate strength or breaking load, of a beam of some specified material. Working in such an atmosphere is far from an easy task.

Stephenson had felt the need for 'model' tests, and these preliminary tests were carried out by William Fairbairn (1789-1874), a versatile engineer, experienced in both mechanical and structural testing and design. These tests were on tubes of circular, elliptical and of rectangular section.

Fairbairn's friend Eaton Hodgkinson (1789-1861) helped the former by analyzing the data of these experiments. These engineers found that tubes of all three sectional shapes failed by 'buckling' of the upper sides of the tubes. In addition, the circular and elliptical tubes were distorted. Finally, the rectangular section became the preferred shape, and the 'buckling' problem the major focus of attention. The experiments with the various tubular forms produced the following hypothesis : H_1 - the rectangular tube section is superior to elliptical and circular sections in its resistance to destortion[23]. This hypothesis was undoubtedly an operational principle derived from experiment.

The buckling problem was eventually solved in a second lot of experiments conducted by Fairbairn between August and October 1845. These experiments established that a rectangular section with a multicellular top did not buckle under load. This cellular top was a novel feature at that time. Let's examine the knowledge that these engineers brought to bear in arriving at the multicellular top flange for the tubular beam.

It has already been mentioned that the early preliminary experiments had revealed failure of the top of the experimental tube by buckling. One of the elementary behavioural characteristics of beams is that if a beam is supported at two ends and subjected to a vertical load, it bends such that the top sufrace is in a state of compression and the bottom is in a state of tension. Under this circumstance, the engineer can conceive the top flange of the tube as an isolated bar in a state of compression. To isolate a structural component and treat it as a 'free body' with forces acting on it from its environment is in Dasgupta's view, another operational principle[24]. Operational principles isolate the situation to which theoretical knowledge can then be applied. This is exactly what happened here.

Engineers had known for some time that the buckling load of a long strut of fixed length and fixed amount of material can be increased by making the strut in the form of a tube instead of a solid bar. This effect results from the fact that in a tube the material is placed further from the centerline, thereby increasing the rigidity of the strut against sidewise flexure. Rosenberg and Vincenti maintain that ideas such as these were undoubtedly behind Fairbairn's tests on tubes with cellular tops[25]. Thus, the knowledge that led these engineers to the idea of the multicellular top flange for the tubular beam was in part, structural theory and the theory of strength of materials (i.e. technological theory) and, in part, a model of the top flange as a thin strut in compression, which is an operational principle.

The basic form for the tube thus settled, the task became one of deciding on the detailed shape and proportions of the various parts - in particular, the determination of the proportion of the cross-sectional areas of the top and bottom flanges so that they would be equally strong. The knowledge from the preliminary experiments was insufficient for such purposes. Therefore, additional experiments began.

These experiments were of two kinds : tests by Fairbairn of a relatively large-scale model of the entire cellular-flanged tube as then conceived and experiments by Hodgkinson of plates and simple tubes in compression and bending. These experiments gave a wealth of results. Besides indicating the most advantageous distribution of material Fairbairn's tests let the engineers know that the sides or webs of the beam had an essential structural function and would have to be considered carefully. On the other hand, Hodgkinson's compression experiments were the first experimental study of buckling of compressed plates and thin walled tubes. The theoretical study of these problems began much later in 1891 with the work of G. H. Bryan on the stability of compressed plates.

During this period (early 1846 to early 1847) ideas were examined, changed and refined - until the final design was complete. Stephenson and Fairbairn eventually agreed on a modification to the design, wherein, in addition to the multicellular top flange, the bottom flange was also constructed in multiple cells.

The train of reasoning underlying this design process was quite complex and entailed the development of several hypotheses which have not been mentioned here. What I have tried to point out is that a great deal of knowledge that the design of the Britannia Bridge yielded was of the operational kind, and much of this, in turn, was generated directly from experiments. In other words, the work of the engineers involved not the application of existing scientific knowledge but the design and development of techniques that provided by means of experimental investigations, knowledge of operational principles.

The design process is the most explicit means for the production of an operational principle. The output of any design process is an artifactual form which, when built, is intended to satisfy certain desirable artifactual properties. It has already been noted that such knowledge of how certain kinds of structural forms function, behave, perform, or appear under certain conditions, is the knowledge of operational principles. As designs embody operational principles, and since operational principles constitute technological knowledge, the processes of design necessarily generate technological knowledge.

Operational- principles - as - knowledge are also produced by experiments. Recall the hypothesis H_1 which was not deduced from any theoretical premise, but served as the basis for the engineers' decision to adopt a rectangular section for the tubular bridge. It was an operational principle derived from experiment. Likewise, the later experiments produced the knowledge of how the buckling of the top flange of the tube could be eliminated by adopting cellular form for the top.

Operational principles, as has been suggested, form the dominant type of knowledge that the technologist resorts to when designing artifacts. And we have also seen that operational principles can originate in the absence of scientific understanding of a technological phenomena. In fact this is how technology has developed primarily in the course of history till relatively recent times when basic science began to play more substantive roles. However, Dasgupta draws our attention to the fact that the technologists in the course of their practice do not always resort to basic science as the source of their immediate knowledge, even when such knowledge exists. Very often such scientific knowledge is abstracted into the form of operational principles. Thus even in domains that do have a scientific base, operational principles continue to serve as the dominant type of knowledge.[26]

Once we recognize this epistemic character of technology, we can also begin to appreciate the thesis articulated most convincingly by E.S. Ferguson in his influential article "The Mind's Eye : Nonverbal Thought in Technology"[27]. Thinking with pictures', writes Ferguson, is an essential strand in the intellectual history of technological development[28]. For, as already noted, the output of every act of design is an operational principle describing the form and behaviour of some desired artifact. An artifactual form, i.e. an arrangement of components and its behaviour lend themselves most naturally to the construction of pictorial mental models, in other words, a mental representation of what the artifact will look like and how it will behave and operate in the world. Much of the thought of the technologists of this artificial world, is therefore, non-verbal, its language is a picture or a visual image in the mind. This intellectual component of technology, which is non-scientific and non-literary, has generally been unnoticed.

NOTES

1. See H. A. Simon, *The Sciences of the Artificial,* Cambridge, MIT Press, 1969, E. Layton, "Technology as Knowledge", *Technology and Culture,* 15, No. 1 (Jan. 1974); E. S. Ferguson, "The Mind's Eye : Nonverbal Thought in Technology", *Science*, 197, no. 4306 (Aug. 1977); G. Basalla, *The Evolution of Technology,* Cambridge, Cambridge University Press, 1988; S. Dasgupta, *Technology and Creativity,* New York, Oxford University Press, 1996.
2. S. Dasgupta, *Technology and Creativity,* New York, Oxford University Press, 1996, p.3
3. *Ibid.* p. - viii
4. E. Layton, "Technology as Knowledge", *Technology and Culture,* 15, No. 1 (Jan. 1974), pp.31-41.
5. H. A. Simon, *The Sciences of the Artificial,* Cambridge, MIT Press, 1969, p.3
6. J. Y. O. Gasset, "Thoughts on Technology" in C. Mitcham and R. Mackey (eds.) *Philosophy and Technology,* New York, The Free Press, 1983, p.293
7. G. Basalla, *The Evolution of Technology, Cambridge,* Cambridge University Press, 1988; p. 14.
8. *Ibid.* p. 7-11.
9. Simon, *op. cit.*, p.6.
10. *Ibid.* p. 7.
11. Dasgupta, *op. cit.,* p. 17.

12. *Ibid.* p. 18.
13. *Ibid.* p. 11.
14. *Ibid.* p. 12.
15. H. Petroski, *Invention by Design, Hyderabad,* Universities Press (India) Limited, 2000, p.2.
16. N. Rosenberg and W. Vincenti, *The Britannia Bridge The Generation and Diffusion of Technological Knowledge,* Cambridge (Mass), MIT Press 1978, pp. 45-63.
17. S. Dasgupta, *op. cit.,* p. 156.
18. *Ibid.* p. 156.
19. *Ibid.* p. 158.
20. R. Stephenson, "Introductory Observation on the History of Design", in E. Clark, *The Britannia and Conway Tubular Bridges,* vol. 1, London, Day and Son, 1850, p.21.
21. S. Dasgupta, *op. cit.,* p.159.
22. *Ibid.* p. 156.
23. *Ibid.* p. 171.
24. *Ibid.* p. 160.
25. N. Rosenberg and W. Vincenti, *op. cit.,* p.23.
26. S. Dasgupta, *op. cit.,* p.156.
27. Published in Science, 197, no. 4306 (August 1977).
28. E. S. Ferguson, *op cit.*, p. 827.