DISCUSSION PAPER

• *ABSTRACT*

This paper discusses the role of the physical world and technical logic in constraining the shaping of technology. For illustration, Edison's development of the electrical incandescent-lighting system is used as a didactic example of how such shaping can significantly limit engineers' room to manoeuvre in arriving at their design decisions. With these results as springboard, observations and reflections are offered about real-world and other technical and non-technical constraints in the total shaping process. Engineers are pointed to as among the mediators of choice, in varying degree, across the entire technosocial spectrum. This little-analyzed activity, including the concomitant technical shaping, needs increased study (possibly collaborative) by both social scientists and engineers.

The Technical Shaping of Technology: Real-World Constraints and Technical Logic in Edison's Electrical Lighting System

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Engineers, by the nature of their craft, must operate in a world of reality. Whatever one chooses to think about ultimate truth and scientific theory, a real world apart from human wishes does appear to exist out there – at least, engineers, whose job it is to make things that work in the world, had better proceed on that assumption – and this world imposes intractable, non-negotiable constraints on what engineers can and cannot do. Such technical constraints, combined with intractable though less inflexible cost constraints, frequently tie the hands of engineers in their design decisions. That is to say, once some basic elective decision has been made, possibly (even probably) on social grounds, a kind of technical logic can take over, leaving designers and inventors little

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or no choice in important aspects of their engineering solution. We should not, in our enthusiasm for social shaping (or construction) of technology, take such technical shaping as incidental if we want to understand technological change in all its fascinating complexity.

To illustrate my point, I will use the example of Thomas Edison's invention and development of the electrical lighting system in the United States in the years 1877 to 1882. The treatment here will be more didactic than historical. My goal is in no sense a rational reconstruction of what Edison thought and did, nor do I aim for an STS-type treatment of Edison's entire activity. I intend only a kind of technically informed dialogue with the past, to make evident the constraints and logic that inexorably hemmed him in. Elements of the argument appear variously in the historical works on Edison. Of those consulted, the volumes by Frank Dyer and Thomas Martin, John Howell and Henry Schroeder, and Thomas Hughes say the most about the reasoning Edison appears to have followed; Robert Friedel and Paul Israel provide the fullest and most suggestive account of the events themselves.[1] With different purposes in mind, I propose here to exhibit the underlying logic in a complete and connected way and abstracted from the complicating historical circumstances. Though specific to Edison, the situation exemplifies an experience common to engineering.

My approach to my task will be unashamedly that of a present-day engineer who knows the technical outcome and has the intellectual tools to see the necessity for it. Knowledge gained after the event is no doubt involved. The fact that Edison and his associates could not know the argument when they began, and had to learn it as best they could as they went along, in no way negates my point. Like it or not, the logic was implicitly there, helping to shape the course of events and its outcome.

I hope that I will not be seen as going out of my way to tilt at a straw person. Social scientists are not unaware, of course, that technical matters matter. I agree completely with sociologist John Law when he states that 'the stability and form of artifacts should be seen as a function of the interaction of heterogeneous elements', including, among others, the 'technical' and the 'natural'. I especially applaud his view that, among the totality of elements, 'the social should not be privileged'. This approach he contrasts to that of 'sociologists', who (in contrast to 'historians') 'In the end

. . . prefer to privilege the social in the search for explanatory simplicity'.[2] Nor do I claim privilege for the technical; I want simply to direct attention explicitly to the real-world element, on the grounds that, in implementing Law's dictum, it tends at times to be unmentioned or underplayed.

The Edison example, of course, has not been ignored by social scientists. Donald MacKenzie and Judy Wajcman, in the introductory essay of their collection *The Social Shaping of Technology*, cite the same events. Drawing on their collection's piece by Hughes, they focus on the cost element in Edison's calculations as evidence for 'the economic shaping of technology'.[3] Though I pay attention to cost, I will emphasize here the real-world technical element. My aim is to promote discussion of its role in the complex of social, cultural and technical constraints within which engineers operate.

Real-World and Other Technical Constraints

For an engineer designing an electrical power system, the real, physical world is represented in essence by two so-called 'laws', identified usually with the men credited with setting them down. Ohm's law, inferred by the nineteenth-century German physicist Georg Simon Ohm from systematic experiment, can be written:

$$I=\frac{V}{R}. \tag{1}$$

This equation says that the strength I of the electrical current flowing through a conductor increases in direct proportion to the voltage difference V between the ends of the conductor, and decreases in inverse proportion to the resistance R of the conductor; V, so to speak, 'pushes' the current through the conductor, while R resists the flow.

Joule's law, based on experiments by James Prescott Joule, Ohm's British contemporary, appears as:

$$P = R \times I^2. \tag{2a}$$

This equation is independent of Ohm's law – that is, it concerns a separate aspect of electrical reality. It says that the power P (that is, energy per unit time) produced by a current of strength I flowing through a resistance of magnitude R goes up in proportion to the product of R and the square of I. In the present application, R can be that of a lamp, in which case P represents the light (and heat) emitted, or of electrical transmission lines, where P represents the waste heat unavoidably generated. If we write Ohm's law (1) in its equivalent form $V=R\times I$ and use this to replace the combination $R\times I$ in Joule's law (2a), this law becomes:

$$P = V \times I. \tag{2b}$$

From a scientific point of view, these equations are, of course, theoretical representations of the real world. As such, they are human artefacts, subject to modification or correction over time. They are known from experience, however, to give realistically useful engineering results. In the absence of anything demonstrably better, power engineers have to take them – in fact, they think of them – as tantamount to the real world itself.[4] For design decisions on things that must work in that world, they represent absolute requirements not subject to alteration or negotiation on any grounds, social or otherwise. Engineers can vary the values of the quantities in the equations, but they *cannot* alter the laws; in that, they have no choice.

Other real-world constraints also enter. Electrical systems, like all technical systems, are limited by the requirement that the connected components within the system operate compatibly with one another. The output of one component often constitutes the input of another – and the reverse – and they must be designed with this in mind. The properties of available materials impose a similarly universal constraint. And in Edison's case, special facts about how the resistance of electrical conductors depends on their proportions are also pertinent.

Technical constraints, of course, can derive from other than the physical world. One of consequence here is 'the state of the art' – that is, the level of knowledge, experience and development – regarding a system or its components. A state-of-the-art constraint remains hidden in the logical argument. I will make it explicit later.

Economic Constraints

For anything that competes in a capitalist marketplace, economics also constrains design. To the extent that such constraints have less importance in non-capitalist societies, they can be seen as 'socially related'. Engineers in a competitive, capitalist society, however, must incorporate both capital and operating costs into their decisions on much the same footing as technical matters. Costs that show up directly in the course of design tend to be regarded, almost without thinking, as essentially 'technical' concerns. It is for this reason that I separate them from other 'socio-cultural' matters.

Socio-Cultural Concerns

Design, like all activities in society, is influenced by many factors besides the technical and economic. Political, social and cultural concerns – sometimes lumped together with economics under the label 'socio-cultural' – impose their own constraints. Such factors, along with the technical, also provide motives, goals and options. All must figure in any complete treatment of the shaping of technology. Without implying priority, I limit my focus here to constraints imposed by the 'real world' and, to a lesser extent, 'the state of the art' and 'economics' (or 'cost').

The Technical Shaping of Edison's System

We are now ready to examine the technical shaping of Edison's lighting system. Wherever electrical resistance is involved, Ohm's and Joule's laws come into play; in a lighting system, they apply generally and equally to the lamp filament, the electrical transmission lines and the dynamo windings. Combined with demands of cost and component compatibility, they often lead to specific constraints on component design. My aim is to exhibit this process fully (if in somewhat abstract detail) for the Edison example.[5] To do so, I will employ the kind of deductive logic that a modern engineer would use in trying to define the technical problems Edison was compelled to solve. This will require close attention to a (non-quantitative) mathematical argument based on Ohm's and Joule's laws and involving, at one point, a critical cost constraint.[6]

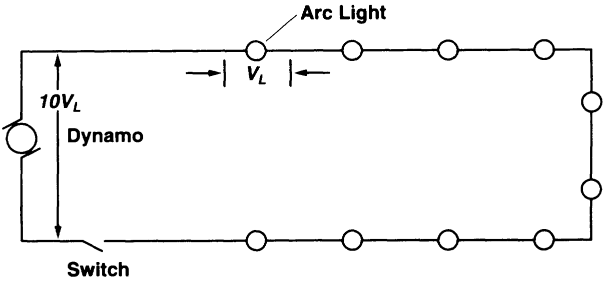
The logic flows from a basic decision by Edison – namely, that each lamp in his system should be capable of being turned on or off individually (or in small groups), rather than all together. Edison took his overall goal to be to replace the well-established and lucrative gas-lighting systems then in common home and office use – or, in his own words, 'to effect *exact imitation* of all done by gas, so as to replace lighting by gas by lighting by electricity' (emphasis added).[7] In gas lighting, separate control of each burner was the accepted practice, and Edison judged that this feature must be imitated if consumers were to be attracted away from gas and to electricity.[8] His overall goal was thus basically 'socio-cultural', inspired by a growing belief that society's demand for light might be satisfied by electricity, if such a technical innovation could be made competitive in the marketplace. But, in aiming for individual control, was Edison faced with a real 'option'? Given the commonplace facts of home and office living, it is hard to imagine any other choice; any engineer would be likely to make the same decision, even in the absence of prior gas lighting.

Whatever the circumstances, once individual control was adopted, real-world and cost constraints took over, dictating how certain things had to be done, like it or not. Let us begin with Joule's law in the form $P = V \times I$. Suppose the resistance in question is a source of light, and let us assume that the light output is some fixed fraction of P (the remaining power being dissipated as heat). Joule's law alone then allows a range of possibilities: any given light output can be obtained by combining a high voltage with a low current, a low voltage with a high current or something in between. The choice depends on the situation at hand.

Consider first the arc-lighting system coming into use for lighting streets and large interiors (see Figure 1) as Edison began his work. Here identical lights – ten, say – are connected in series with one another, a dynamo and a switch. The single switch turns all lights on or off together, an operation acceptable (even desirable) in streets or large auditoriums. When they are on, the same current obviously flows through each light, and the voltage supplied by the dynamo must equal the sum of the voltage drops across the individual lights. In the series circuit, that is, the current through all lights is the same and the voltages add.

Certain consequences follow. First, if we are to keep the dynamo (and supply-line) voltage below the 500-volt limit of the insulation materials available at the time, the voltage drop V across each light must be suitably low.[9] Given that $P = V \times I$, if V is low (and P corresponds to the light output from a feasible arc light), then the current I must be high. And, since Ohm's law

FIGURE 1
Series Circuit for Arc-Lighting System



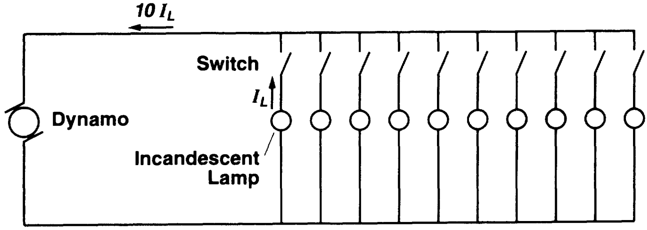
Source: After Harold C. Passer, *The Electrical Manufacturers 1875–1900* (Cambridge, MA: Harvard University Press, 1953), 81.

requires that $I = V/R$, the resistance R of each light must be correspondingly low. The logic of the situation is inescapable. We may doubt, though, that the developers of arc lighting reasoned this way; the resistance of an arc light, as it happens, is low by nature, so the question of any other possibility is unlikely to have arisen.

Edison, aiming for home and office use and individual control, was forced to a different path. He realized, as did others, that the blindingly intense arc light was unsuitable, but that the less developed incandescent lamp might serve. Though no one perceived the possibility at first, such a lamp can, in principle (and unlike an arc light), be made with any desired resistance. People like Joseph Swan in England, already struggling with incandescent lamps and perhaps influenced by arc lighting, were experimenting mostly with low resistances. But Edison quickly saw that for individual control he would need something other than the series circuit used in arc lighting, and he recognized that his lamp would have to be compatible with whatever the overall system turned out to be. He therefore came to see that, for reasons of physical reality and overall cost, a low-resistance lamp of any kind was out of the question and a high-resistance lamp was essential. Though Edison had to find his way haltingly to this conclusion, the logic behind it is unavoidable.

First, to turn lamps on or off individually, Edison realized that he needed a so-called parallel circuit (see Figure 2), with lamps connected between transmission lines, like rungs on a ladder, and

FIGURE 2
Parallel Circuit for Incandescent-Lighting System



Source: After Passer, op. cit. Figure 1.

a separate switch for each.[10] Though such circuits were little used or understood at the time, Edison could see that the current in the transmission lines between dynamo and first lamp must now be the sum of the currents through all the lamps with switches closed. Also, since the voltage variation along the lines from one lamp to another is relatively negligible, the voltage drop V across each lamp must be the same. For the parallel circuit, that is, the voltage is the same for all lamps and the currents add – the converse of the series situation.

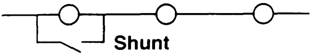
Suppose now that the current through each lamp is high, as it would be with a low-resistance unit like an arc light. If a number of switches are closed, the transmission-line current must be still higher by a sizeable factor. At this point, cost enters the argument. The current in the lines necessarily expends power in the form of heat loss, and this reduces the overall efficiency of the system. To minimize this costly loss when the current is high, Joule's law in the form $P = R \times I^2$ shows that the resistance of the lines must be made small. But, for a conductor of a given material, R is known to increase in proportion to the conductor's length and decrease in proportion to its cross-sectional area. Minimizing the loss by keeping the line length short was ruled out by Edison's sociocultural goal of 'imitation of all done by gas', including area-wide distribution from a central station. Edison and an associate are reported to have used the dependence on length and area to estimate the amount of copper for the resulting lines. They found that, for practically realistic lengths of line, the cross-sectional area needed to keep the energy loss acceptably low would require so much copper as to price the system out of the market. There was only one escape from this dilemma. Given that for a lamp

$P = V \times I$ by Joule's law, Edison had to keep the current I through each lamp low and obtain the required light P by a relatively high voltage drop – the converse of the arc-light situation. And since $I = V/R$ by Ohm's law, this need for low I and high V implies a lamp with high resistance. This ruled out the low-resistance lamps being developed by Swan and others. Given Edison's goal to imitate gas lighting, the real-world constraints of Joule's and Ohm's laws, plus cost, left no logical alternative.[11] Whatever Edison's thought processes, Hughes calls his realization that he must aim for an unprecedented high-resistance lamp his 'eureka moment'.[12] That we can now see that he had no alternative does not diminish his creative genius. His epic experimental search for a suitable high-resistance lamp filament was a consequence.[13]

But the logic does not stop with the lamp resistance; the parallel circuit also places requirements on the dynamo. Suppose, for example, that all switches in Figure 2 are closed, all lamps are lit and a switch is then opened to turn one lamp off. Whatever else the dynamo may do in response, it must maintain a constant voltage drop V across the lamps, whose resistance R has been fixed by the earlier considerations. To allow the voltage V to change with R fixed would (by Ohm's law) change the current I through the lamp and hence (by Joule's law) the brightness P of the lamp. To have the illumination in one room change when someone extinguished a lamp in another would hardly be acceptable (and, in Edison's time, contrary to people's experience with gas lighting). To avoid this, a constant-voltage dynamo was required. Since the total current for a parallel system is proportional to the number of lamps lit, the current produced by the dynamo must therefore vary. With the electrical knowledge of the time, achieving such a constant-voltage, variable-current dynamo was at least as difficult and technically demanding as developing the high-resistance lamp. Edison obtained his solution through innovative design of the electric coils that provide the dynamo's magnetic field, plus manual control of the current through those coils by a variable resistor (later replaced by automatic control).[14]

A look at the dynamo problem for the series circuit (Figure 1) is also instructive. Since an arc light sometimes had to be shut down for repair while the system was operating, an essentially zero-resistance shunt was placed around each light (as represented in Figure 3). When such a shunt is closed, constant brightness of the still-lighted units (each of which has the same fixed resistance)

FIGURE 3
Shunt for Arc Light



requires, by Joule's law (2a), that the current *I* through each light (and hence the entire system) remain unchanged. It then follows from Ohm's law (1) that the voltage drop across each light will also remain unchanged. Since the number of active lights is now less, however, the voltage supplied by the dynamo must drop correspondingly. Thus, in contrast to the constant-voltage dynamo needed in a parallel system, the dynamo here must produce constant current (and variable voltage). Constant-current dynamos were, in fact, the practice in arc-lighting systems; Edison's constant-voltage machine was thus unprecedented.

One may wonder why Edison did not aim for individual control of his incandescent lamps by employing a series circuit with a shunt for each lamp, thus making feasible the use of a low-resistance lamp. It appears that he considered this possibility.[15] He probably noticed, however – as can we – that, as with arc lights, the current through the system would again have to be constant, irrespective of how many lamps were lit. The energy loss from transmission-line resistance would then be just as high with one lamp lit as with all, hardly an efficient and cost-acceptable arrangement. The parallel circuit with high-resistance lamps avoids this problem and remains the sensible choice.[16]

Observations and Reflections

My argument, I suggest, boils down to this: once Edison had made his decision, for whatever reason, to imitate and compete commercially with gas lighting, with its individual control of lights and central-station distribution (in effect, the engineering specifications for his task), his hands as a design engineer were, in important respects, tied. The consequences of Ohm's and Joule's laws, together with capital and operating costs (plus Edison's implicit, state-of-the-art restriction to direct current, which we shall come to presently), left him with no choice regarding fundamental features of major components of his system: the lamp must have high resistance and the dynamo must supply constant voltage irrespective of load. General constraints from the physical and economic world, taken together, thus led logically to specific constraints on design; and these constraints inescapably shaped Edison's developmental process, whether he realized it fully or not.[17] To reach this conclusion, we have proceeded deductively as might a present-day engineer on the basis of elementary textbook knowledge. Edison is known to have had a British text- and handbook of 1871 'for the use of telegraph inspectors and operators', which contained Ohm's and Joule's laws in the forms employed here.[18] Their use, however, was limited to problems in telegraphy (where parallel circuits appeared only in battery hook-ups) and to simple, two-path shunts. That Edison's team had to teach themselves inductively about lamps and power circuitry as they went along in no way invalidates the shaping role of the technical constraints that we have here followed deductively.

A state-of-the-art technical constraint has been implicit in our exposition. When Edison started, the 'art' in electric-power technology was almost non-existent. He had no choice but to depart drastically from what incipient 'art' there was for the lamp and dynamo; he can almost be said to have established that 'art'. He also departed from the prevailing practice in circuitry, introducing one of the early applications of parallel wiring (and, later, sophisticated innovations in related transmission-line design). He accepted without question, however, the existing exclusive use of direct current (dc). The practical application of alternating current (ac) was yet to come. Notwithstanding his later, bitter defence of dc against Westinghouse's espousal of ac,[19] Edison might well have used the voltage changes possible with ac transformers, had they been available, to solve the transmission-loss problem and to moderate the lamp's resistance constraint.

As the foregoing suggests – and the term itself implies – 'state-of-the-art' constraints are malleable and subject to change with time. Once established, they mostly remain fixed over a design cycle – an aspect of what I have referred to elsewhere (following Edward Constant) as 'normal technology'.[20] They do inevitably evolve, however, usually slowly and piecemeal, depending on the ingenuity of design engineers and inventors in solving specific problems. Edison realized that reaching his goal required advances in the states of the art concerning circuits, lamps and dynamos. His greatness as an inventor consists of having the insight to see this and the inspiration and ingenuity to bring it off. He thus established new state-of-the-art constraints for those who followed him. It probably never occurred to him to depart from dc – he had no unavoidable need to do so and apparently no inkling of the possibility; so far as he knew, he had no room to manoeuvre in that regard, and he left that portion of the state of the art unaltered. Since that time, not only have we acquired a versatile ac technology, but a more sophisticated dc capability as well (including ways of changing voltage). Our options in lights have also increased, and now include, among other things, practical low-resistance incandescent lamps. Without the discouragingly large investment of the power industry (and the preconceptions of engineers), someone tackling the electrical-system problem *de novo* today might well come up with a system different from – and superior to – the one we have inherited starting from Edison. As economic historians have been at pains to emphasize, the development of a technology is, in the long run, path dependent. This is in part a consequence of the time dependence of state-of-the-art technical constraints.[21]

Other constraints also evolve with time. Social, political and economic opportunities and situations obviously change; so do technical constraints not imposed by the physical world. The lone *un*changing elements in engineering practice – and they are basic – are the nature and phenomena of that world (including the 'compatibility' requirement). We can only presume that the constraints they impose remain fixed for all time. Engineers must take account of them as best they can. Scientific understanding and theoretical representation of the phenomena may change, requiring engineers to reconsider how to incorporate the constraints into their reasoning and calculation (though I am hard pressed to cite a clear example). Science may also discover phenomena not previously recognized (radioactivity, for example). But paradigmatic innovations and unanticipated additions from science in no way deny the operatively invariant quality of the real-world phenomena with which engineers must deal. Fortunately for the design profession, such changes are rare. It is not surprising that engineers, for practical purposes, see the scientific representations they must use as fixed and tantamount to the real world itself.

Although they may be hard both to discern and assess, real-world technical constraints inevitably appear in some form at some level of design, limiting the engineer's room to manoeuvre. All electrical engineers, if their devices are to work in the real world, have to adopt the concepts of resistance, voltage, current and power, plus the demands of Ohm's and Joule's laws, as absolute representations of that world. Until scientific understanding affords demonstrably better concepts and relations, they have no choice. Similar constraints, combined often with constraints of cost, have consequences for design in all branches of engineering. Much engineering labour is devoted to unravelling and implementing such techno-logical (or perhaps econotechno-logical) shaping, both to solve specific problems and to advance the related state of the art. To dismiss such activity as 'of course' (as has happened when I have presented these ideas) runs the risk of misreading this essential learning process.

Real-world constraints vary widely in the degree of their constraint and the directness of their application; complex reasoning may (or may not) be needed to trace their consequences. An extreme but telling example is provided by perpetual motion. Since ancient times, there have been many attempts to devise a machine that, once set in motion, would do useful work without external supply of energy. Though doubts had been voiced for some time, the possibility remained open theoretically until formulation of the first and second laws of thermodynamics in the mid-1800s. The modern-day engineer accepts these laws as reflecting reality and takes it for granted that, as a consequence, attempts at perpetual motion are doomed to failure. The real world appears to deliver an emphatic and categorical 'No!' (and the United States Patent and Trademark Office and associated boards and courts of appeal acquiesce).[22] The connection from constraint to result is direct, the logical trail is usually minimal and the answer is absolute. No matter how much we might desire perpetual motion, it realistically cannot be attained, a fact that has become integrated into everyday knowledge. Given this negative outcome, it would be an interesting exercise – and I mean this seriously – to write a history of the attempted social construction of perpetual motion.[23]

A less absolute example is that of gravity in mechanical flight. Even if aeronautical engineers did not subscribe to Newton's view and mathematical description of gravitational pull, they would have to accept that something like it exists in the real world. This constraint requires that, to achieve flight, a lifting force must be provided. The constraint here is less categorical and direct than with perpetual motion; it permits various possibilities (fixed wings, rotors, vertical jets, lighter-than-air). Whatever the choice, however, the engineer has no option but to provide *some* realistic means for obtaining lift. The constraint may seem so obvious as not to require mention, but the existence of gravity has shaped a vast amount of aeronautical-engineering (and other) effort.

Considerations like these suggest a kind of hierarchy of real-world constraints, depending on degree of directness and restriction. The first and second laws of thermodynamics constrain and deny the very possibility of perpetual motion. The existence of gravity leaves flight possible but constrains the engineer to devise some practical means to achieve it. More general constraints, as exemplified by Ohm's and Joule's laws in Edison's work, are further down the hierarchy; they and their consequences may therefore be harder to trace. Combined with compatibility requirements, they can lead, as we have seen, to constraints on the major components of a device or system. Still lower in the hierarchy lie all sorts of constraints on the detailed design of the components or their subcomponents; these may be almost invisible to anyone but the engineers dealing with them, but they are never absent. As we move down this loosely defined hierarchy, the constraints tend to become less restrictive and inflexible, leaving the designer increasing room to manoeuvre. But they are always present in some way at some level, helping to shape design activity and its product, which must in the end stand the test of operation in the real world.[24]

Whether or not these ideas are helpful for scholars, they reflect bread-and-butter realities for engineers. For me, the notion of technical constraints also fits nicely with the variation-selection model I see designers following to arrive at their solutions.[25] In the variation-selection view, the solution of design problems takes place by iterative cycles of (1) conception and elaboration of potentially suitable variants, followed by (2) selection, by analysis, test or use, of those that appear to 'work best' in some appropriate sense. Real-world requirements constrain this process throughout, limiting the designer's freedom of action. In Edison's work, variation-selection can be seen clearly in accounts of the development of both the lamp and dynamo – constrained, respectively, by the requirements of high resistance and constant voltage. Such procedures, in differing guises, typify the specification and solution of engineering problems.

Nothing I have said should suggest that I see any simple, literal technological determinism at work. The matter is one of real-world constraints and consequent logic, not impelling causes; 'room to manoeuvre' signifies just that. The technical matters we have focused on constrain, and thus help to shape, the course of technology. Except in the veto on perpetual motion, they in no way command it.

Digressions

Since this is not a research paper, I shall add a few digressions. Central concerns will reappear in the Conclusion.

1. We should note that the foregoing matters are not only practical; they are also motivational. For many creative engineers, logical puzzle-solving of the kind we have seen is basic to the fascination and excitement of engineering. No matter how great the social desire (or cunning), modern, sophisticated, dynamic engineering could not exist without it. It helps to fuel the entire enterprise. Such subjective matters are also important in the shaping of technology.

2. Scholars have rightly noted that much technological development is 'local' – that is, special to where it occurs; some claim that it is predominantly so.[26] In matters where real-world constraints and technical logic are paramount, however, some characteristics cannot help but be universal in space, as well as in time. Perpetual motion is out of the question everywhere, and aircraft must have a means of lift no matter where they are designed or flown. For less evident reasons, and in a less obvious and absolute way, modern high-speed airplanes, without exception that I am aware of, have retractable rather than fixed landing gear.[27] Examples of the last sort are not difficult to find. Engineers confronting the same problem in different places not uncommonly follow different paths, only to find themselves constrained to the same (or very similar) solutions.

3. The necessity to make things work in the real world helps distinguish engineering from science. Though scientific understanding must, in some sense, fit the real world, philosophers can argue about how laboratory measurements and theoretical formulations relate to that world, and scientists are free to toy with improbable theories and postpone judgements. Engineers, by contrast, must devise something that is meant to work and get it

out the door and into use, often on a tight schedule. Trial cannot be deferred indefinitely, and the consequences of failure can be dire – tanks explode, bridges collapse, airplanes crash, people get killed and companies get sued.[28] The real world shapes technology more immediately and consequentially than it does science. Making something that works economically, reliably and safely is a rather different thing in purpose and consequences from running a scientific laboratory experiment. Such differences help explain why engineering can never be simply applied science.[29]

4. Finally, our discussion illustrates a problem that is especially acute for historians and sociologists of engineering. Real-world constraints internal to a technology help shape the form of devices designed to work in that world. Identifying ahead of time how much room the designer had to manoeuvre can help understand the course of events, and this may entail knowledge the designer did not have at the start and had to learn along the way. Such knowledge and understanding, however, must not warp the investigation and presentation of the events themselves. The outcome may have been in part fore*shadowed*, but the process for getting there could not be fore*sighted* if the development was new to human experience. Such an 'unforesighted' process is typically contingent and social in its doing, filled with uncertainty, backtracking, negotiation and trade-offs. This, however, does not preclude its taking place within a boundary of non-negotiable, real-world constraints. The analytical trick is to be informed of both social process and technical reality, while at the same time imagining the learning process through the eyes and minds of the learners.

Conclusion

As Edison's experiences illustrate, engineers cannot but assume that a real world exists and that relevant aspects of it are susceptible to representation by physical theory. This world and its representation place general technical constraints on what is possible or requisite for engineers in their design activities. These constraints, combined with quasi-technical constraints such as cost, can have logical consequences that place specific limitations on design choice. An essential part of an engineer's task is to comprehend how far one can manoeuvre within such real-world limits. Might social scientists, in their efforts to understand the shaping of technology, find it useful to do likewise more specifically than they sometimes do?

In my study of the retractable airplane landing gear, I suggested that the overall place to discern the effective shaping of technology is in the considerations – the motives anconstraints – on which technological decisions depend. That is, do the technological choices in a given case flow mainly from social or technical concerns, or from some complex combination thereof? Such a range of considerations – social plus technical, or *technosocial* – can then be visualized as a kind of spectrum, with technical considerations becoming increasingly predominant in one direction and social (including economic and political) in the other.[30] At the 'hard' technical end, considerations stem entirely and directly from the real world, as with the veto against perpetual motion and the gravity-caused need for lift in aircraft. At the far social end, they are entirely and directly social – an example here might be the value our culture places on time leading to the goal of speed in commercial aircraft. In the spectrum between, where most of the action takes place, lies a varying, complex and less directly acting mixture. (As in the spectrum of visible light, though there is no difficulty distinguishing between red and violet, specifying where yellow becomes green is problematic.) In line with Law's recommendation, neither end is to be regarded as causatively privileged. The analytical task, in a specific instance, is to follow the technosocial shaping process as it moves back and forth along the spectrum.[31]

Engineers participate as mediators of choice, in some degree, across the entire spectrum. Toward the technical end, they predominate, but they are necessarily involved throughout, if only to testify as to what is technically possible and practicable in the face of other considerations. As our technologies become more complex and socially intertwined, engineers find themselves having to participate more – and more intimately – in the social direction, in what Law aptly calls 'heterogeneous engineering'.[32] Pressured and preoccupied by their technical problems, they usually give minimal attention to how best they can bring this off; except for cost, some seem completely to ignore the existence of social considerations. Scholars outside engineering, from lack of experience in the engineering game and in how obstinate and unforgiving the world can be in day-to-day technical work, may be tempted to neglect or underestimate the role of real-world and other technical constraints. It is essential to both groups, and in some ways to the welfare of our technological society, to transcend these limitations and develop a sophisticated and detailed understanding of how engineers and other mediators function across the technosocial spectrum.[33] This will require more – and more substantive – dialogue, cross-fertilization and even (I hope) collaboration between engineers and scholars than has existed in the past. Such work is more demanding than staying within a discipline, but I see signs it is beginning to happen.

• NOTES

This paper is a revision and extension of a talk given at the Conference on Technological Change, Oxford, 8–11 September 1993. I am especially indebted to Robert Rosenberg and Paul Israel of the Thomas A. Edison Papers for useful information and criticism and to Edward Constant for his always insightful comments. Valued help of one kind or another also came from Ronald Bracewell, Bernard Carlson, Paul David, David Edge, Rosa Haritos, Barry Katz, Steven Kline, Edwin Layton, Kenneth Lipartito, Robert McGinn, Donald MacKenzie, John Peschon, Russell Robinson, Nathan Rosenberg, John Schlicher and Ralph Smith.

1. Frank L. Dyer and Thomas C. Martin, *Edison: His Life and Inventions* (New York: Harper, 1910), Vol. I, Chapters XI and XIV; John W. Howell and Henry Schroeder, *History of the Incandescent Lamp* (New York: Maqua, 1927), Chapter 2; Thomas R. Hughes, *Networks of Power* (Baltimore, MD: Johns Hopkins University Press, 1983), Chapter II; Robert Friedel and Paul Israel, *Edison's Electric Light: Biography of an Invention* (New Brunswick, NJ: Rutgers University Press, 1986). I have also drawn upon Arthur A. Bright, Jr, *The Electric-Lamp Industry: Technological Change and Economic Development from 1800 to 1947* (New York: Macmillan, 1947); Matthew Josephson, *Edison* (New York: McGraw-Hill, 1959); and Harold C. Passer, *The Electrical Manufacturers* (Cambridge, MA: Harvard University Press, 1953).

2. John Law, 'Technology and Heterogeneous Engineering: The Case of Portuguese Expansion', in Wiebe E. Bijker et al. (eds), *The Social Construction of Technological Systems* (Cambridge, MA: MIT Press, 1989), 111–34, at 113. For similar remarks regarding the study of science, see Ronald N. Giere (ed.), *Cognitive Models of Science* (Minneapolis, MN: University of Minnesota Press, 1992), xix–xx.

3. Donald MacKenzie and Judy Wajcman (eds), *The Social Shaping of Technology* (Philadelphia, PA & Milton Keynes, Bucks.: Open University Press, 1985), 2–25, at 13.

4. The provisional nature of this use of science to represent the real world is

consistent with Michael Mulkay's conclusion that, in reverse, 'the successful use of scientific theories [in technology] establishes neither their validity nor their privileged epistemological status'; see M. Mulkay, 'Knowledge and Utility: Implications for the Sociology of Knowledge', *Social Studies of Science*, Vol. 9 (1979), 63–80, at 77.

5. The result, in effect, elaborates a paragraph from my book: W.G. Vincenti, *What Engineers Know and How They Know It* (Baltimore, MD: Johns Hopkins University Press, 1990), 204.

6. Though I present the argument in the context of published information about Edison, I make no attempt to trace his thinking and action. Such a task, though desirable, calls for focused search in Edison's notebooks and other primary sources. (Important work along such lines for other of Edison's inventions is being done by Bernard Carlson and Michael Gorman in their ongoing study of Edison and contemporary inventors; see, for example, W.B. Carlson and M.E. Gorman, 'Understanding Invention as a Cognitive Process: The Case of Thomas Edison and Early Motion Pictures', *Social Studies of Science*, Vol. 20 [1990], 387–430.) Statements here about Edison are based on information taken variously from the references in note 1. Except for quotations, I do not in most instances attempt specific citation. A few notes offer limited observations about Edison's experience and some additional references.

7. Quoted by Dyer & Martin, op. cit. note 1, 264. Contrary to these authors' characterization of the note as among the 'very first', Robert Rosenberg (personal correspondence) informs me that it actually appears in a notebook begun in January 1881 – that is, after the fact. On the basis of their thorough study, however, Friedel & Israel, op. cit. note 1, 14, confirm that 'gas represented . . . a guiding analogy every step of the way'. See also ibid., 236.

8. The overall problem of providing numerous small lighting units (including, by implication, individual control) was referred to by Edison and contemporaries as 'sub-dividing the light', in recognition of the fact that arc lights were too bright for home and office use. Some eminent scientists had gone on record claiming that such 'sub-division' was theoretically impossible; see Dyer & Martin, op. cit. note 1, 241, 247; Friedel & Israel, op. cit. note 1, 75, 89.

9. A probable secondary consideration here was that of safety – line workers, in fact, did later suffer injury and death. (See Paul A. David, 'Heros, Herds, and Hysteresis in Technological History: Thomas Edison and "The Battle of the Systems" Reconsidered', *Industrial and Corporate Change*, Vol. 1 [1992], 129–80, esp. 154.) Safety constraints, which we have not discussed, are 'real-world' to the extent that they derive from the fixed limitations of the human body, and 'socio-cultural' to the extent that the value put on human well-being is culture-bound and can change with time. In a given culture at a given time, however, engineers see them, for all practical purposes, as effectively 'technical'.

10. Tracing the emergence of parallel circuits in Edison's work awaits the careful study of his notebooks and other evidence now going on at the Thomas A. Edison Papers. Robert Rosenberg (personal correspondence) informs me that 'we see parallel and series circuits popping up out of nowhere in the desultory experiments during the fall of 1877'.

11. Though the voltage drop across the lamp here is high relative to that across an individual arc light in the series system (Figure 1), it turns out to be smaller than

the overall drop in that system. The overall drop in the parallel system, which is essentially the same as that for a single lamp, thus causes no safety hazard.

12. Hughes, op. cit. note 1, 36.

13. For real-world and cost constraints on contriving such a filament and lamp, see Dyer & Martin, op. cit. note 1, 252, 322. The fact that arc lights could not supply the required high resistance made the decision for an incandescent lamp also not a matter at choice.

14. Hughes, op. cit. note 1, 42–43. For a diagram and description from the time, see also Silvanus P. Thompson, *Dynamo-Electric Machinery: A Manual for Students of Electrotechnics* (London: E. & F.N. Spon, 1888), 128. To make his system competitive, Edison also had to attain considerably higher efficiency than that of earlier machines, but this necessity is not pertinent to the present argument.

15. Hughes, op. cit. note 1, 32, n. 46.

16. The series arrangement also would not have conformed to Edison's decision to imitate gas lighting, where the burners were connected effectively in parallel. Besides, when an accidental failure of one lamp caused all lamps in the series to go out, the user would be faced with the troublesome and irritating task of locating the failed lamp. Anyone experienced with the old-fashioned series lights for Christmas trees knows how socially unacceptable this can be.

17. That he did *not* realize it and had to learn his way through on the basis of his 'expectations, resources, and confidence' is nicely delineated by Friedel & Israel, op. cit. note 1, 227.

18. Latimer Clark and Robert Sabine, *Electrical Tables and Formulae for the Use of Telegraph Inspectors and Operators* (London: E. & F.N. Spon, 1871), 9–11, 30–31.

19. For an interesting account and assessment of this legendary 'battle of the systems', see David, op. cit. note 9.

20. Vincenti, op. cit. note 5, 7–8; Edward W. Constant, *The Origins of the Turbojet Revolution* (Baltimore, MD: Johns Hopkins University Press, 1980), 10–11.

21. Economist and economic historian Nathan Rosenberg writes of one set of factors that determine the timing and rate of technical growth under the heading 'the loosening of supply side constraints'. State-of-the-art constraints (though Rosenberg doesn't use the term) are one such factor. Rosenberg's views are well worth reading in the present context: see N. Rosenberg, *Technology and American Economic Growth* (New York: Harper & Row, 1972), 165–71; see also 'Science, Invention, and Economic Growth', in his *Perspectives on Technology* (Cambridge, MA: Cambridge University Press, 1976), 260–79.

22. See *Manual of Patent Examining Procedures* (Washington, DC: US Department of Commerce, 5th edn, 1983, rev. March 1994), Section 706.03(p) and *Newman* v. *Quigg* 877 F.2d 1575 (Federal Circuit, 1989).

23. For a recent view of the history of perpetual motion, see Arthur W.J.G. Ord-Hume, *Perpetual Motion: The History of an Obsession* (New York, NY: St Martin's Press, 1977).

24. Ways also exist in which the real world constrains engineering design beyond those discussed here. Examples are easily found in particular with regard to reliability, durability and, in part, safety (see note 9). A taxonomy of real-world constraints might be useful to compile.

25. Vincenti, op. cit. note 5, Chapter 8. As discussed there, the process depends heavily on available or concurrently generated knowledge. For a more recent conceptualization of the kinds of knowledge required for innovative design, see Wendy Faulkner, 'Conceptualizing Knowledge Used in Innovation: A Second Look at the Science–Technology Distinction and Industrial Innovation', *Science, Technology, & Human Values*, Vol. 19 (1994), 425–58.

26. For a recent, useful example of this view, see Mikael Hård, 'Technology as Practice: Local and Global Closure Processes in Diesel-Engine Design', *Social Studies of Science*, Vol. 24 (1994), 549–85.

27. W.G. Vincenti, 'The Retractable Airplane Landing Gear and the Northrop "Anomaly": Variation-Selection and the Shaping of Technology', *Technology and Culture*, Vol. 35 (1994), 1–33.

28. For instructive examples of such real-world occurrences, see Henry Petroski, *Design Paradigms: Case Histories of Error and Judgement in Engineering* (Cambridge: Cambridge University Press, 1994).

29. For related differences between social constructivist studies of science and of technology, see Sergio Sismondo, 'Some Social Constructions', *Social Studies of Science*, Vol. 23 (1993), 515–53, esp. 540–44.

30. Vincenti, op. cit. note 27, 27–28, 31.

31. People who know the literature better than I tell me that recent STS scholarship has been aimed precisely at denying the usefulness of the social/ technical distinction and showing that it is itself a 'social construct'. I invite such scholars to join me in estimating the performance of a device involving an unusual turbulent flow, programming the solution of a complex system of non-linear partial differential equations on a supercomputer, or assuring that a retractable airplane landing gear can be relied on to go up and down on order. Such problems, which can be highly demanding, arise out of the need to attain some larger engineering goal. That goal may have been socially derived, and solving the problem may involve limitations of time and money or other socially related concerns. The problem itself, however, is purely a 'technical construct'. For me and my fellow engineers, who may devote whole careers to the solution of such purely technical problems, the distinction is very real (though we seldom think about it).

32. Law, op. cit. note 2, 113.

33. For an exemplary effort in this direction, see Donald MacKenzie's examination of Charles Stark Draper as a heterogeneous engineer in the development of inertial navigation: D. MacKenzie, *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance* (Cambridge, MA: MIT Press, 1990), 85–92 and passim.

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