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DISCUSSION PAPER

ABSTRACT This paper is conceptual and methodological. On the basis of both empirical and explanatory considerations, I craft a number of analytic categories – 'epistemic engines', 'meters', 'scopes', 'graphs' and 'chambers' – through which to investigate and understand the character of key forms of the material culture of scientific practice. I argue that much of modern science can be understood in its specificity as 'engine science', a tremendously powerful and generative culture of inquiry. The analytic categories have stability across temporal and spatial localities and have broad applicability across the sciences. The analysis circumvents dualisms, such as those between science and technology, micro and macro, and science and society, and indicates a way to conceptualize the character of 'engineering cultures' and 'engineering states'.

Keywords chambers, engineering cultures, epistemic, graphs, ingenuity, material culture, meters, power, scopes, specificity, stability, supra-local

Tools, Instruments and Engines:

Getting a Handle on the Specificity of Engine Science

Patrick Carroll-Burke

> After dinner we will have a Lecture concerning the Nature of Insects, and will survey my Microscopes, Telescopes, Thermometers, Barometers, Pneumatick Engines, Stentrophonical Tubes, and the like.[1]

> Night and day the conquering engines, advancing smoothly to their journey's end, and gliding like tame dragons into the allotted corners grooved out to the inch for their reception, stood bubbling and trembling there, as if they were dilating with secret knowledge of great powers yet unsuspected in them, and strong purposes not yet achieved.[2]

The sociology of scientific knowledge has demonstrated that science is a profoundly social activity.[3] A consequence of this finding, however, is that it seems increasingly difficult to specify what it is about science that distinguishes it in some special sense from other social activities.[4] One approach to the problem, advocated here, is to pose it within the framework of an analysis of material culture.[5]

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Research on material culture in science has been gaining ground recently, often as a result of a greater focus on practice and experiment.[6] A burgeoning literature is emerging on the 'instruments' of experimental practice.[7] Major advances in understanding have been achieved, yet talk of 'tools' and 'instruments' is often used with slight reflection upon the appropriateness of such terms.[8] Little attempt is made to develop non-localized analytic categories capable of sorting out the material culture of science in a way that aids understanding of the specificity of the practice. This paper develops an analytic conceptualization of the 'engines' of science that goes some way towards getting a handle on the stability of the material culture across spatial and temporal localities. Four categories of engine are distinguished, and conceived heuristically, as 'meters', 'scopes', 'graphs' and 'chambers'. Viewed through an analysis of these forms of material culture, much of modern science can be understood specifically as 'engine science', a form of inquiry characterized by engineering, ingenuity and the centrality of material engines in the practice. Though not the only way of generating knowledge, engine science is a tremendously powerful 'culture of inquiry'.[9]

The case is made in three parts. The first presents a broad methodological justification for the category 'engines', particularly in relation to 'tools' and 'instruments'. I discuss a method of sorting things out on the basis of both empirical (historiographic and orthographic) and conceptual (explanatory) grounds. The second part presents the case for conceiving of meters, scopes, graphs and chambers as key kinds of epistemic engine, akin to what Rheinberger calls 'epistemic things'.[10] Each category is justified by reference to the material character of the engines themselves, the names they bear, and the rôle they play in scientific *practice*. Epistemic engines are 'generative' in knowledge production, they are nodal points in the material infrastructure of experimental practice. Perhaps 'instruments' could also be conceived as epistemic things in this manner, but the purpose of the analysis is to orchestrate, in the analytic nomenclature itself, certain characteristics and associations that provide insight into the character of the practice.

The final part discusses the empirical applicability of the analysis in general, and its capacity to circumvent conceptual dualisms (for example, micro and macro, science and technology, and science and society). I advocate a 'flexible' approach to 'sorting things out', and suggest an embrace rather than a denial of ambiguity in classificatory schemes. Ambiguity is incorporated into the analysis using the concepts of hybridity, liminality and 'centres of gravity'. The computer is presented as a special case of hybridity, constituted in and through other engine forms, yet qualitatively different from them. Most of the empirical exemplification in the paper is drawn from a study of the British context, and is applicable most clearly to the physical sciences.[11] But I argue that the conceptual method can be applied across national boundaries, and can be extended to a large number of natural sciences. The extent to which the analysis can be applied will vary, but this indicates something of the research agenda implied by the analysis rather than a shortcoming of the conceptual and methodological strategy itself. Finally, in offering an analysis anchored in an idiom of engines it is not my intention to replace talk of tools and instruments. The point is to create distinctions within those vocabularies for particularly crucial forms of material culture, forms which provide insight into the practice and culture of modern science. The idiom of engines foregrounds ingenuity, engineering and power, and evokes material and cognitive contrivance in the most complex and subtle sense of the term.

Tools, Instruments and Engines: An Historiography of Words and Things

Getting a handle on things requires sorting them out – conceptualizing distinctions between categories, types, classes, forms, kinds, species, variables – or whatever one wishes to call them. I advocate a method in which the words used to distinguish things are crafted from empirical sources but given form by theoretical considerations. The strategy aims at a constructivist explanation that can escape (within limits) the confines of specific historical localities. The material culture of science is sorted out by reference to 'centres of gravity'. Each category of material culture is conceived in terms of a centre of gravity that draws particular 'things' into its sphere by virtue of their significance in natural scientific practice. These are not ideal types. The image, rather, is one of many gravitational fields that interact by virtue of the integrated nature of a scoping, metering, graphing and manipulating practice. The practices of interest here are those organized around the material culture itself, rather than those associated with particular *fields* of science. They are 'supra-local' practices. Getting a handle on them, however, is facilitated by what can be described as an *idiomatic* analysis. The words used to describe things are taken as clues to the character of various forms of material culture. Single words are viewed as anchors for wider idioms that provide insight into the culture and practices associated with that material culture. The point is to develop a cartography of the material engines of science, but through an historiography and orthography. The approach uses cartographic, historiographic and orthographic methods in the service of an historical ethnography of science as culture and practice.[12]

In the spirit of Geoffrey Bowker and Susan Leigh Star's argument in their recent book, *Sorting Things Out*, I adopt a 'flexible' strategy for distinguishing the material culture of scientific practice, reflexively aware of its 'political and organizational dimensions', foregrounding its construction, and thus the construction of that which it seeks to comprehend.[13] The method seeks to unite an historicist approach, in which the meaning words hold for actors is respected and incorporated into the analysis, with a specifically conceptual and explanatory strategy aimed at yielding stable analytic categories. By way of introducing the approach, I will briefly indicate the difficulties involved in taking one or other of these two strategies. The first is represented by Jim Bennett, who argues from an historicist (or empiricist) perspective, that (early modern) scientific 'instruments' should be distinguished as 'mathematical, optical and natural philosophical types'.[14] Willem Hackmann presents a more theoretical strategy, distinguishing instruments abstractly and ahistorically according to whether they can be conceived as 'passive' or 'active'.[15]

A difficulty with the historicist approach is that the discourse of the actors is not stable across groups and does not, therefore, provide an unproblematic basis for an analytic understanding.[16] The communities that Bennett wants to show becoming more related in the 17th century have different idioms. The idiom of instruments, for instance, is strongly rooted in the practical mathematical and anatomical traditions. The idiom of engines, on the other hand, has a more common and vernacular usage, referring to pumps, battering rams, snares and torture racks. Robert Boyle and Robert Hooke regularly (though not exclusively) expressed themselves in the language of engines, while William Petty, with his training in medicine, mathematics and geometry, and his penchant for cartography and surveying, seemed more inclined to express himself in the language of instruments (though again not exclusively). Even in the context of the idiom of a single actor, consistency of expression is sometimes arbitrary. The names the actors use are numerous, fluctuating and contested. Thus the historicist method, though having major advantages within the value system of empiricism, makes it difficult to pursue the more general designs embodied in the engines of science, designs which I argue below remain relatively stable across local contexts.

Hackmann distinguishes instruments that manipulate natural phenomena as active, and those that do not as passive. He suggests that measuring devices like the barometer are passive, while controlling technologies like the air-pump are active. Yet as Bennett has countered, the same instrument may, according to this scheme, be both passive and active. For instance, the early history of the mercury column is active: it was used for experiments related to pressure, and involved the manipulation of mercury in a controlled way. Later, as it developed into the barometer in the context of inquiry into the relations between atmosphere and health, it became a passive instrument: it simply measures phenomena without manipulating them. The same technology, Bennett argues, is active in one context and passive in another. Even though Hackmann's strategy of sorting things out differs radically from Bennett's, it suffers from similar difficulties.

Both Bennett and Hackmann implicitly agree, however, on the appropriateness of the idiom of 'instruments'. Thus whatever the difficulties with the distinctions they draw within that idiom, introducing talk of engines requires some additional justification. Once again, I take both a conceptual and empiricist strategy, considering the referential reach of the various terms (and thus their efficaciousness relative to the demands of specificity), and the historiography of their usage within science. I begin with the difficulties relative to referential reach, which are rather straightforward, and follow with the historiographic issues, which require a more detailed consideration.

Both the usefulness and the drawbacks of the word 'tool' derive from its universality. It links the practice of science to work of the hand, with the advantage of reconnecting scientific practice to craft and skill, and to an ancient history whereby humans engage with nature. On the other hand, this very universality means that the term tells us practically nothing about the specificity of the material culture of scientific practice. Anything can be viewed as a tool – concepts, mathematical formulae, and engineered natural materials like Onco Mouse,[17] not to mention a stick or stone mobilized without much alteration to perform a particular task. The idiom of tools, ironically, is not itself a very good tool. Its reach, by encompassing almost everything, tells us very little.

The idiom of instruments is not as universal as that of tools, but it retains many of the same disadvantages, designating anything from a scalpel to a free electron laser. It has a certain advantage over the idiom of tools since it evokes precision, a characteristic rightly considered specific to science, though not of course unique to it. It also has the capacity to evoke a cognitive culture of instrumentality, of means-ends reasoning. A difficulty is that the ends are often made to eclipse the significance of the means. Instruments are easily construed as 'merely' the means to an end, their rôle constructed as passive and transparent, of no significance for the action or belief in question. In this sense the idiom of instruments loses some of the advantages of that of tools, since the craft and engineering dimensions of scientific practice are more easily occluded.

In the second part of this paper, I will expand on the conceptual justification of engine-talk, but first I wish to provide an empirical and historiographic justification drawn upon the historical record. The aim is to show that talk of engines in science can be traced to the early modern period, and that competition between instrument-talk and engine-talk has been historically bound up in issues of class and status, in a politics of representing science.[18]

Instruments and Engines: A Brief History of the Politics of Words and Things

Widespread talk of instruments may be an idiomatic convention with roots in the class and status relations between genteel philosophers and 'vulgar mechanics' in the 17th century. As Steven Shapin and Simon Schaffer demonstrate, the increasing dependence of early experimental philosophy on the knowledge and skills of 'shopmen' and 'laborants' was not replicated in the realm of credibility and status. On the contrary, 'artificers' were translated into the mere instruments of the designs and claims of gentlemen philosophers, on whose behalf they laboured. They were, except when accounting for error, made 'invisible'.[19]

A similar politics of status occurs in non-laboratory science. As gentlemen increasingly became involved in military surveying and engineering, there is a proliferation of images of aristocratic engineers posed ballet-style, and highly decorative 'instruments'.[20,21] The fine arts and the refinery of nobility were linked together. These images of aristocratic bodies contrasted significantly with the more heavy-set bodies of the engineers and ordnance handlers. Heavy pieces of ordnance were regularly designated as engines, their designers amongst the earliest people to hold the title 'engineer'.[22] The word 'instrument' carried connotations of refinery not evoked by the word 'engine', and while Boyle and other members of the Royal Society tried to give it higher status through its slippage with 'ingenuity', it is not clear that they ever succeeded.[23]

Simon Schaffer's work on automata in the 18th century indicates an intensification of the status hierarchy between 'vulgar mechanics' and 'enlightened philosophers'.[24] For Adam Ferguson, the 'mechanical arts require[d] no capacity', and 'succeed[ed] best under a total suppression of sentiment and reason'.[25] According to Jean D'Alembert, mechanics worked by 'instinct' rather than choice or reason.[26] Thus 'enlightened philosophers' and 'citizens' were set in opposition to mere 'mechanics' and 'subjects'.

The professionalization of engineers further subordinated the mechanic, since the engineer came to occupy the middle position between the 'genteel men of theory' and the worker who tended the machine. Schaffer notes how the 'enlightened engineer' served the élite's need to dominate the artisan by virtue of their special knowledge, a knowledge that linked philosophical concepts and designs with the organization of men and machines for profit. Engineers would henceforth become the middle-class of engine science. As Ken Alder observes, engineers destabilized the order of the *ancien régime* by bridging 'élite status and technical competence'.[27] In the 19th century, engineers and engineering remained subordinated in the status hierarchy through the language of 'pure science' and 'mere application'. Engines were (though never entirely peacefully) confined to the 'technology' side of a new idiomatic dualism, on the other side of which was 'science'. As Thomas Gieryn demonstrates, the growing centrality of 'technology' in 'science' led 'scientists' like Tyndall and Huxley to engage in boundary-work that sought to exclude 'mere mechanics' from the domain of science, while at the same time claiming technology as its bounty.[28] As Deborah Warner puts it, the professionalizing scientists 'tightened their allegiance to an aristocracy of the intellect', and reasserted the 'moral virtue of their disinterested search for the truth'.[29] This politics of class and status entered into historical and philosophical representations of science in the 20th century, and this partly explains how the idiom of instruments came to triumph over that of engines. Thus in order for the idiom of engines to speak once again, it is necessary to return to the time before it was subsumed into that of instruments.

Reclaiming the Idiom of Engines in Science

The word 'engine' was used, from at least the 17th century, to designate what today are universally called 'instruments'. Boyle's air pump was almost always described (in the vernacular) as a 'pneumatick engine'. Robert Hooke, Christopher Wren and William Petty designed 'experimental engines', Petty one he hoped would be 'moved by fire'. Hooke lauded Wren for his combination of 'mechanical hand and philosophical mind'. Microscopes and telescopes were regularly called 'modern engines', and the idiom was broad, even John Locke and Archbishop William King designing 'engines'.[30]

The idiom of engines in 17th-century English experimental science is explicable by reference to the various meanings the word held at the time, particularly its connotations of artifice and engineering, and the link it allowed to a cognitive culture of ingenuity. The word 'ingenuity' shares its Latin root with the word 'engine', and has the power to evoke a vast range of related meanings. Engine was often used as a cognitive category. Both the *OED* and middle-English dictionaries give the first definition in terms of native or innate intellect and skill (*OED*: 'native wit or mother wisdom'), the gin/gen share meanings of genesis (birth) and genius (talent), and thus allowed a connotation of nobility. Material engines were the products of ingenious minds, clever contrivances and artful designs. These meanings could express evil as well as good, 'malengine' indicating malicious design, crafty wile and underhanded stratagem. As a verb, engine meant to contrive, plan, or fit parts together, to take by craft or ensnare. It indicated the capacity to out-smart adversity, often with great subtlety. Members of the original Royal Society never tired of complimenting each other on their ingenuity, or of displaying to guests their collections of engines.[31]

Engine bears an important correlation with ingenuity, craftiness and inventiveness, a culture of inquiry quite distinct from contemplative (including 'Rational') modes of thinking. 'Ingyn' always evoked thinking connected to action rather than thinking set in opposition to action. It also, crucially, designated the material projects of engineering practice, signalling a Baconian form of science where power is realized through forceful engagements with nature. Nature is literally captured in the engine, subjected to extraordinary cultural force, and physically made to yield its secrets – just as subjects were made to confess 'unfailingly' when, upon the rack, they were 'ingyned' to the 'poynt of deth'. The idiom of engine, then, expresses a broad but surprisingly coherent array of cultural meaning and significance: intervention and manipulation; design, contrivance and art; ingenuity and engineering; body and mind united in praxis; the deployment of force and realization of power. It is in experimental philosophy that this cultural universe will find one of its primary spaces of sustenance and growth. Thus Boyle's pneumatic engine was made an emblem of experimentalism, and distinguished visitors to the Royal Society were regularly entertained by engine experiments.[32]

'Engine science' is distinct from, if intimately related to, the 'mechanical philosophy'. The term 'mechanics' had a number of meanings in 17th-century Europe, most commonly referring to the 'doctrine of the moving powers' derived from antiquity, and expressed in the six 'simple machines': the balance, lever, wheel, pulley, wedge and screw. It had a 'larger sense' in the context of early mechanical philosophy, comprising 'not only the vulgar staticks, but divers other disciplines, such as the centrobaricks, hydraulicks, pneumaticks, hydrostaticks, balisticks, &c'.[33] In this sense, mechanics was the branch of 'mixed mathematicks' that dealt with the formal expression of mechanical motions or tendencies. The mechanical philosophy involved the elaboration of a mechanical theory of nature, where the same kinds of causes and calculations posited for mechanical motions could be ascribed to the natural. Finally, the word 'mechanics' designated those whose art was the design and construction of machines, a practice pertaining to manual labour and skill, thus often qualified by adjectives like 'mean' (average) and 'vulgar' (common).

The mechanical philosophy, as a way of understanding the world, became quite divorced from mechanics, as a manner of acting in the world.[34] Hobbes disparaged Boyle's work by implying that it was a kind of 'engine philosophy'.[35] Experiments were conducted in a way that put nature out of its natural course, that vexed it, burned it, froze it and mobilized its force. Engine science was dependent on showy contrivances, artful designs beyond common experience, and vulgar mechanics. The laboratory was precisely, as its name suggests, a 'place of labour', a place where nature is worked upon, or more precisely where it is ingyned. The whole idea, for Hobbes, had a touch of the banausic (in the sense of 'merely mechanical') about it. It was tainted, inherently ignoble. One can observe, then, the distinction between the 'mechanical philosophy' and what Hobbes implicitly construed as engine philosophy. The former belongs to the domain of understanding, the latter to the domain of practice or method.[36]

The distinction can be mapped in the views of a number of natural philosophers in the 17th century. For instance, Boyle, Hobbes, Newton and Descartes agreed that the natural world could be understood in mechanical terms,[37] but they differed on the question of how one should *practise* mechanical philosophy. Descartes set out from individual reason, sequestering himself from the world, contemplating his own existence, and laying down his famous dictum as the foundation of ontology and epistemology: 'I think therefore I am'. Though he supported doing experiments with engines, his desire to secure absolute certainty as the foundation of natural philosophy made him more akin to Hobbes than to Boyle. The effects contrived in Boyle's engine could, according to Hobbes, contribute to natural history, but they could not provide the certainty necessary to found a secure and legitimate natural philosophy.[38] Only mathematical and geometrical demonstrations – that is to say, incontrovertible truths like the fact that drawing a line through the centre of a circle necessarily produces two equal parts – could serve to ground a true natural philosophical practice: this was 'method'.[39] Newton also, if in a more nuanced way, leaned towards giving abstract mathematical principles, what he called the 'doctrine', primacy over experimental accounting of matters of fact.[40]

While these natural philosophers agreed on the ontology of physical relations in the natural world, that they were mechanical, or at least could be understood in mechanical terms, they differed considerably on how to inquire into those mechanisms. As a general image of the world, the mechanical philosophy was crucially representational. Engine science, on the other hand, more centrally evokes a mode of practice: intervention rather than representation.[41] Thus Boyle and Hooke's unique contribution to the history of science, or at least to engine science, derived not so much from their adherence to the mechanical philosophy, but from their method of 'ingenious' inquiry, the central rôle they gave to engines in the generation of natural knowledge.

Engine science, which forced the integration of philosophy, mathematics and engineering, did not fully triumph in the 17th century.[42] The 18th-century reverence for Newton, and the subsequent elevation of 'laws of nature',[43] indicate this, as does the surprising silence (until recently) regarding how and why experiment became so significant in modern science.[44] As Timothy Lenoir put it, 'history of science is almost always written as the history of theory', the 'body of practices and technologies forming the technical culture of science' receiving 'at most a cameo appearance'.[45] Hooke, in particular, has been neglected by theory-centred histories, and there is reason to suggest that it was precisely the partial success of Boyle and Hooke's vision of engine science, with its dependence upon the vulgar and the worldly, that generated the élite anxiety responsible for subsequent oppositions between 'science and technology', 'pure science and mere application', and so on. Thus William Thomson (Lord Kelvin), is snubbed in the early 20th century for being 'distracted' by 'practical engineering' unworthy of the 'natural philosopher'.[46] Engineering was subordinated in élite representations of science. It was made the handmaiden of science precisely by rendering 'technology' as the secondary form of 'mere application'.[47]

An analytic of engines reconnects theory to engineering and engineers, as well as to a cognitive culture of 'engenuity', and of course to power. Unlike the term 'technoscience', which assumes a process in the late 19th century that tied 'science and technology' together, the term 'engine science' suggests that it was precisely the marriage of the *practices* of natural philosophy, mathematics and engineering in the 17th century that created the conditions of possibility for the growth of one of the most successful and powerful forms of modern science.[48]

Epistemic Engines: Meters, Scopes, Graphs and Chambers

There are at least four kinds of engine whose integration in practice defines the centre of gravity, and thus the specificity, of engine science. Meters, scopes, graphs and chambers may be described as engines because, unlike a simple rule, they are complex and differentiated forms of material culture, sometimes incorporating hydraulic, pneumatic, chemical or electromagnetic components, 'engeniously' contrived and involving heterogeneous parts engineered in a relatively singular and autonomous form.[49]

Unlike an instrument, that might simply be a pencil, engines embody highly differentiated engineering knowledge and skill. They may be described as 'epistemic' because they are crucially *generative* in the practice of making scientific knowledge. Epistemic engines can be objects of knowledge in their own right, or they can be surrogates (or models) for other epistemic things, or they can be isomorphic with natural things, or they can consist of key components of an 'experimental system'. Indeed, they can be all these things at once. Their epistemic quality lies in the way they focus activities, channel research, pose and help solve questions, and generate both objects of knowledge and strategies for knowing them. Epistemic engines crucially embed the abstractions of 'knowing what' in the practices of 'knowing how'.[50]

Meters: Transducing the World into Number

It is instructive to begin with the example, used by both Bennett and Hackmann, of the barometer. A barometer is specifically a metering device. Like all meters, it renders phenomena in number. Its specific and general rôle of metering natural phenomena remains stable over its entire history, and across different contexts of use. The question of the difference between its significance when hanging on the wall of the average house, when used in meteorology, or when used to postulate causal relationships in nature – the context question – rather than altering its character as a meter, directs attention towards the way it is integrated or not into a specific practice, and engineered or not in conjunction with other engineered forms. The importance of meters in engine science lies in the fact that they transduce natural phenomena into number so that they can be abstracted, formalized and handled mathematically. 'Transduce' is more appropriate than 'translate', since meter engines draw phenomena over into the domain of mathematics. No doubt translation also occurs, but the point is that the engine is the active boundary object,[51] making the movement of the phenomena from one space to another possible. It transports phenomena into mathematical language, as well as translating them from another language.

The centrality of meters in science is indicated by the scores of variously complex devices (such as 'spectrometer', 'galvanometer' and 'micrometer') the names of which contain the word 'meter'.[52] The large number of meters need not, however, imply that quantification is necessarily more important in scientific practice than, for instance, visualization. It may only indicate that little gets to be known by number except through some device for rendering phenomena as such. In any case, the point is that despite the variation that occurs in the meanings that orbit and intersect with particular meters, and despite the fact that the integrity of measures is always open to question, it is still possible to craft an analytic conceptualization of the engine that can, within specified parameters, remain stable across different temporal and spatial contexts.

Viewed alone, a barometer may appear ‘passive’. Situated in the wider context of engine science, however, its generative agency in the culture of standardized measures is evident.[53] In the 17th century, William Petty consistently argued that all ‘matters’ – natural, governmental and commercial – be rendered in ‘number, weight, and measure’.[54] By the 19th century, a ‘metrological system’ had been engineered which was constitutive of both modern science and the social order of modernity.[55] Meter engines became crucial boundary objects in the standardization of commodities (alcohol and tobacco), currency (the hydrometer), taxation (Excise Laboratory), manufacture (machining standards) and science (Fahrenheit scale, micrometer, chronometer etc.). As one might expect, in every case the metrological drive was contested. Customary gauges of measure were literally ruled out of court, metrology being a ‘political and moral problem’ as much as a scientific one.[56]

As metrologies become established they increasingly regulate research activities, but such regulation can only be achieved if the meters are embedded in systems of social order. Standardized meters are secured through the controlling activities of guilds, professions and governments.[57] The activity of metering thus becomes a *condition* that governs the research. Because they are enforced, metrologies serve to align and integrate otherwise local practices. The nationalization and internationalization of standards are driven by the forces of state formation and globalizing capital, but metrologization is also crucially driven by engine science itself. Thus the integration of local orders of research into supra-local political economies of practice emerges out a complex traffic of ideas and things across relatively distinct boundaries. Engine scientists have often been at the forefront of this process. James Clerk Maxwell, for instance, argued in the second half of the 19th century that ‘the state’ was obliged to enforce, with ‘punishment’ if necessary, metrological consistency across electrical and telegraphic manufacture and commerce, and electromagnetic science.[58]

Scopes: Rendering the World Sensible

Scopes are also engineered forms that embody a stable purpose in scientific practice. Scopes frame, target and augment phenomena to the senses. They are almost always engineered with a particular sense in mind, whether it be hearing in the case of the stethoscope, seeing in the case of microscopes and telescopes or, in the case of the gyroscope, sense of dynamic orientation (initially the axial plane of a rotating body – by empirical surrogate, the earth). Sound waves can be used to render something sensible to sight, as in the case of ultrasound devices, while dye can be used in a water medium to render visible the patterns and turbulence of fluid behaviour. In the 20th century, a range of probes, detectors, scanners and sensors are engineered (mostly made possible by developments in electrical and electronic engine science). The dozens of engines that bear the suffix ‘scope’ in their names obviously do not exhaust the range of the material culture of scopes in scientific practice. Included also are radar, sonar and various probes and scanners.[59]

The practice of scoping has been central to the history of experimental science, particularly in relation to seeing. Vision reigns as the supreme sense in science, linking the practice of scoping with diagrammatic and other visualization technologies.[60] The oscilloscope is a good example, in that electrical signals are scoped and made sensible to sight, but in a way that overlays the image with a fixed range of axial coordinates and numeric values. Scopes may vary considerably depending upon context, but they materially express a basic design and purpose that remain relatively stable across different spatial and temporal localities. As a form of material culture they embody the designs of a sensitive practice, a contemplative gaze, attentive ear and worldly orientation.[61]

Highlighting the stability of scopes does not detract from the findings of science studies concerning the 'theory-ladenness' of observation, the importance of perspective, and the disciplined (by schooling as well as by conceptual framework) character of scientific perception. Scopes have been viewed as evidence for a raw empiricist epistemology, but the question of what is being sensed, what is seen or heard, always remains. Michael Dennis has demonstrated how the first microscopes, though generating immediate interest amongst experimental natural philosophers, generated problems concerning what was actually being perceived. It was not sufficient simply to see, one had to represent what was seen, to write and draw it so it could be 're-viewed' by members of the experimental community;[62] only then could 'virtual witnessing' occur.[63] Until written, that which is sensed can have little epistemic sway within the community of practitioners. Hence Hooke's *writing*, his *Micrographia*, is as important to the history of microscopy as the material scope itself.

Graphs: The World Writ Small

The word 'graph', at root, is a verb that designates the act of writing and drawing. While the term has become more narrowly associated with axial data plots, there are good analytic reasons for reclaiming the more general meaning.[64] Given the importance of the linguistic turn in social theory, and the need for broad (for example, discourse/semiotics)[65] as well as narrow (for instance, idiom/pidgin)[66] categories of representational analysis, it is useful to view various formulae for writing phenomena through a single lens. Hydrographs, cartographs, spectrographs, ethnographs, orthographs, cardiographs, geographs, and so on, can all be viewed together as so many strategies and technologies for generating formalized 'inscriptions'.[67] In this sense, the scientific illustrations of naturalists are no less graphs than the scatter diagrams of physicists.[68] One is centrally a 'drawing' and the other unmistakeably a 'plot', but both write phenomena through a highly formalized technique. Similarly, to ethnograph is to write a people, as to orthograph is to write their words and names. Thus there is analytic value in conceiving of graphing in a manner that embraces all scientific writing and drawing, the strategies of elevation and projection, of translating the complexity that is everything into the formal expressions of discrete selections.[69] Literary graphing need not be viewed as necessarily less scientific than other kinds of graphing. On the contrary, literary forms are powerful precisely because of their capacity to graph complex and subtle relationships and advance novel reconceptualizations. The literary graphs of ethnography and historiography, for instance, are informed by genuine empirical sensibilities, and thus are not simply parcel carriers for a science that takes place elsewhere and by other means.

A recent paper in *Social Studies of Science* sought to develop a 'Latourian' analysis of 'graphism in science'. Drawing on the work of William Cleveland, however, the authors employ a more limited conceptualization of graphs than one finds in Latour.[70] Cleveland, by requiring that graphs convey quantities, conflates graphs and meters. A host of graphing practices, from cartography through geography to the graphic representation of chemical formulae, is excluded from his understanding of graphs in science.[71] What Cleveland calls 'graphs' are more precisely hybrid forms of graph and meter contrived together. As graphs that represent measures, their dual character is perhaps better captured by the word 'diagrams'. They can then be conceived as *one* product rather than the *only* product of the activity of graphing.

James Griesemer makes a similar distinction with respect to drawings and diagrams.[72] A diagram, as its prefix suggests, is a hybrid between two forms of 'gram': picture and symbolic character. Adding alphanumeric notation to a drawing instantly transforms it into a diagram.[73] The suffix makes sense because it designates that which is written. Graphing is thus the *practice* of producing grams. This indeed is how the language is often used in engine science. Thus 'telegraph' is the communication (action), 'telegram' the printed message – as 'cardiograph' is the engine and 'cardiogram' the paper record. These nuances indicate the need to view graphing as an activity, and to distinguish that activity from the formalized inscriptions themselves. In respect to the latter, explanatory distinctions anchored in empirical observations can be drawn between literary, pictorial and diagrammatic forms, and within these between vocabularies, plots, figures, tables, schemes, drawings, photographs, and so on.

In terms of graphing, however, the focus can be productively targeted on the engines themselves, such as seismographs, kymographs and spectrographs.[74] Further distinctions might be drawn with respect to graphic instruments, particularly those used in geometry, as well as the wealth of forms of material culture which proliferate graphic capacities, such as inks, moving type and paper. As indicated at the outset, the focus on 'graphs' is one in terms of a centre of gravity rather than a hermetically sealed 'class'. The centre of gravity of graphing is the *activity* of producing inscriptions. Thus it is not surprising that engines that bear the suffix 'graph' in their names tend to have automatic capacities. Through their design they embody the graphic agencies that would otherwise be confined to the living skills of a human being.

Graphing is powerful, but it is less the inscription in its singularity that identifies science, than the manner through which it is specialized and engineered into the practice with other engine forms. As Lynch and Woolgar put it, 'how scientists articulate experimental designs and use specialized equipment turns the opposition between bricoleur and engineer [Lévi-Strauss] into a genealogy'.[75] The relationship between the pragmatics of engine practice and the graphic representations generated is dynamic, ongoing and embedded in 'socio-material' interactions.[76] There is no compelling reason to speak of all the engines of science in the singular vocabulary of inscriptions. Latour's 'binocular' scope of the mental and material, the symbol and the paper, the semiotics of meaning and the mobilizations of power, ironically arrives in a monist world where not only every representation, but every 'thing' is (or at least looks like) an inscription.[77] All engines look like graph engines, and the significance of engineering seems less connected to material craft than it does to 'industrial drawing'.[78] It is what 'draws things together', not what engineers them together, that is important for Latour: if you 'grasp [the inscriptions of] thermodynamics you grasp all engines (past, present and future)'; Carnot, by this reading, is a great diagram-scientist, rather than a great engine-scientist.[79]

Chambers: The World Subject to Ingenious Force

If a *differential* analysis of epistemic engines is desired, it is particularly important that chamber engines like the pump or steam engine should not be made homologous with inscription devices. Doing so skews understanding towards the abstract and overly mind/theory centred conceptualizations that Latour and others suggest we avoid. Paper is crucial, but overemphasis on it leads away from the specificity of science. Instead of a social and cultural cartography of the continuities and discontinuities between science and non-science, the image becomes one of a single actor-network of power both 'drawn together' and 'held together' by inscriptions. Science seems not so different from non-science, and social science not so different from natural science – at least, the differences stem primarily from their inscription capacities. The power of chambers, however, is different from the power of graphing. For instance, it is the very special power of the steam engine, its capacity effectively to transform heat into mechanical motion, that not only distinguishes it from all previous technologies, but explains in significant measure how England and Europe came to dominate the world.[80]

Chambers, which are closest to what Hackmann calls 'active instruments', might justifiably be given the eponym 'Baconian'. Boyle's pneumatic engine, for instance, physically captured and restrained natural phenomena, often bringing great force to bear upon it. Seals and valves blew, parts imploded, and birds suffocated. Chamber engines, more than any other kind of engine, facilitate the vexing of phenomena, their systematic physical manipulation. This is one of the reasons why the humble pump is so emblematic of late 17th-century experimental philosophy. In the Baconian sense, knowledge is gained not simply by contemplation, but as Ian Hacking has put it, by intervention, by putting nature out of its natural course. Chamber engines include steam, internal combustion, pneumatic, hydraulic and jet engines. Their defining component is a space within which phenomena can be materially secured and manipulated. In the case of the steam engine (and many chamber engines), 'valves' are crucial components permitting manipulation. The space in which manipulation takes place, however, is sometimes secured by the configuration of the forces themselves, rather than by a sealed physical chamber. For instance, electromagnetic force in the case of accelerators, electric motors,[81] and free electron lasers, or balanced pressures in the case of jet propulsion engines. Chambers make it possible materially to manipulate phenomena with great force. They are the quintessential modern engine – the power generating engine.

Given their character, it is not surprising that the first enormously powerful chamber engine in history was crucially active in the modern conceptualization of 'energy'.[82] Norton Wise, Crosbie Smith and Timothy Lenoir have demonstrated how the steam engine generated epistemic innovation in physics.[83] Carnot's *Essai sur les machines en général*, Whewell's *Mechanics of Engineering*, Willis's *Principles of Mechanism*, and published work by Thomson, Maxwell and Helmholtz, all show how the workings of different steam engines, vortex turbines and electromagnetic engines raised issues that were central to the conceptualization of thermodynamics and electromagnetism. Wise and Smith's collaboration has been very fruitful, showing the intricate connections between Thomson's work in field theory/energy physics, matter theory/cosmology and electromagnetism, and the material operations of steam engines, vortex turbines and electric telegraphs.[84] Engine science – the integration in practice of theory, mathematics and engineering – is deployed in the second half of the 19th century with stunning clarity and success.

Wise traces the crucial 'mediating' rôle the steam engine played in linking Thomson's concept of 'work' in engineering mechanics, with his understanding of 'labour value' in political economy; he and Smith show how energy and empire were connected in the most detailed and convincing way, without the need for talk of science 'reflecting social relations'. The steam engine was not only symbol, metaphor and model, it was a 'material system' embedded in both the micro-world of research and the macro-world of an industrializing power-house:

> The steam engine connotated the moving force of industry, the power of an empire, personal wealth, and the wealth of the nation. Thus Thomson saw in his favored material system a set of concepts upon which he placed great value, concepts realized and articulated as an operating system. On the other hand, the engine could transfer these valued societal concepts to dynamics only because he perceived them, through the engine, as natural, as constitutive of the economy of nature. From a steam engine one cannot read off a theory of measurement, unless the engine already is taken to represent something worth measuring, something valuable; nor does a

> steam engine help to solve mathematical problems of natural philosophy by extremum methods, unless it is conceived as an interpreted algebra of optimization within nature; similarly for the theoretical structure of dynamics. The engine in this scheme is not the economy of nature, nor is it the political economy, but it is embedded in both and embeds them both.[85]

The engine concepts Wise identifies fit a matrix of values of work, ingenuity and power that orbit the philosophical fascination with chamber engines at least as far back as the 17th century.[86] The importance of chamber engines lies in their material capacity to bring force to bear upon phenomena in ways that graphs, meters and scopes cannot. Unsurprisingly, their centrality in physics expands in the 20th century with the development, for example, of bubble, cloud, drift, ionization, jet and plasma chambers, and of course the extremely complex hybrids of chamber, meter, scope, and graph commonly referred to as 'accelerators' or 'colliders'.

The Scope of the Analysis in the Sciences and Society

These four engines do not exhaust the range of tools and instruments in modern science, but they do encompass, both quantitatively and qualitatively, a vast number of complex and crucial pieces of material culture active in the practice. They are isomorphic with the integrated practices of scoping out the world so as to make it available to the senses, of transducing the world into number so that it can be handled mathematically, of representing the world by methodologically writing it, and of intervening in the world in forceful ways that materially manipulate phenomena with powerful and revealing effect. They are engines of sensing-perceiving, measuring-mathematizing, writing-representing and forcing-controlling. Engine science is sustained by its cognitive culture of ingenuity, its metric, inscriptions and engineering praxis. It is crucially powered by its epistemic engines.

Peter Galison's account of the first big hydrogen bubble chamber provides a gripping image of the cultural forces brought to bear on natural phenomena in 20th-century engine science.[87] Hydrogen, captured in a chamber, subjected to high pressure and reduced in temperature to over 400°F degrees below freezing, was finally made to liquefy and yield the sought-after bubbles. The vexing was so great that elaborate emergency procedures were required in case any of the valves, gaskets, or the structural integrity of the chamber itself were compromised. The character of the forceful practice, and the dangers of engine failure, are not in principle different from those faced by Boyle, whose vacuum chamber imploded, and whose valves and gaskets gave up under the force exerted by the pressurized air.[88] Similarly, the imaging dimensions of the engine express the culture of a scoping practice, of probing and detecting and rendering to the senses, and the logical and statistical representations the transducing of natural phenomena into number so they can be handled mathematically.

Engines are particularly suited to the analysis of 'boundary objects', since they almost always occupy the borders between different communities of practitioners. From at least the 17th century, engines made possible the integration of natural philosophy, mathematics and engineering in practice, even as each domain remained or became more differentiated through the division of labour, specialization, professionalization and economies of class and status.[89] The heterogeneity of accelerators illustrates the integrative dynamics of epistemic engines, both in relation to the differential character (by definition) of engineered forms, and the social interfacing of relatively distinct and autonomous cultures of scientific practice. Engineering almost always involves the integration of diverse designs associated with discrete sets of ideas and concepts, sometimes organized as theories or expressed in models, in a single material form. Engines always materialize geometry. Engine science is thus highly differentiated and poses, in Galison's terms, an ongoing challenge to the coordination of action and belief, the difficulty often arising precisely at the interface of differentiated cultures. As Shapin and Schaffer argue, the problem of managing that difficulty is a problem of social order, and its solution is integral rather than peripheral to the successful production of scientific knowledge.

Though the analysis of engine science appears particularly well-suited to the physical sciences, it also works well for the life sciences. In biology, for instance, the microscope is an obvious and powerful engine of inquiry. But biology also has its chamber engines. The centrifuge, at the heart of which is a rotating chamber (or series of chambers), is used to bring force to bear upon organic materials such as cells, sub-cellular organelles and viruses, as well as proteins and nucleic acids.[90] Molecules are variously sedimented – forced asunder – according to their size, shape, density and viscosity. 'Preparative centrifugation' yields purified concentrations of materials that in turn become new epistemic things subject to further manipulation and study. The balance between the sedimenting force of the centrifuge and the counteracting forces of the material (for example, density) is expressed in various formulae and equations. Preparative investigations calculate the time required to sediment a particle to the bottom of the chamber, while 'analytic centrifugation' is used to determine sedimentation coefficients and the masses of dissolved macromolecules. As well as plugging the data into mathematical formulae, a range of graphic strategies are adopted for rendering the material in literary or visual form. Thus, in biology as in physics, the integrated practices of metering, graphing, scoping and forcing are crucially generative in the construction of knowledge. Biology, though far from the same, is more like physics than is sometimes suggested. And given that biology is an engine science, it is not surprising that modern bio-medicine also has its graphs, meters, chambers and scopes, and that they are integrated in the practice in respect to both research and diagnosis, from the humble but revolutionary stethoscope, through the crucial sphygmomanometer, to the contemporary world of PET scanners and MRIs.

Liminal and Hybrid Forms

Most modern engines of scientific practice are integrated hybrids of the forms identified. For instance, while Boyle's pump was crucially a chamber-engine, it could also be engineered to scope by fitting it with a transparent evacuation chamber. Similarly, the barometer both scopes out atmospheric pressure and transduces it into number. Thus Hooke gave it the name 'baroscope', later changed to 'barometer' by Boyle. This is not a case, however, of the distinctions simply dissolving in the face of a messy empirical world. Rather, it is a recognition by an actor, in this case Boyle, that with the inscription of numbers on the mercury-tube, and its employment in the service of measuring changes in the atmosphere (rather than establishing its weight), the importance of the engine in the practice shifts. Sensing atmospheric pressure is now important in the practice to the extent that the natural condition is rendered in an on-going and a scalable way. This is the sense in which to meter is actively to regulate, and thus the materials used in the manufacture of the engine (as in the case of the thermometer) become subject to metrologies, so that the numbers can be reliably compared. Indeed, the shift from a scope to a meter forces the development of standardized precision as an issue in itself. Two different barometers in the same place cannot be permitted to yield significantly different metrics. Engines must be artfully contrived in a standardized form if they are to serve as they are advertised.

Engines are heterogeneous, bearing a holistic character by virtue of the way they are engineered into a singular form. An engine can have more than one capacity even though only one is emphasized in its name. Scoping, graphing and metering are closely related in practice, so one often sees a terminological shift as an engine develops, for instance, from spectroscopes (the simple prism to quite complex 19th-century engines) that make the spectra of different light sources sensible, to spectrometers which directly measure the spectra. Again, this is not a case of the same item moving from one category to another. The spectrometer is materially different from the spectroscope because of its direct metering capacity. It remains a scope, but one designed for rendering the phenomena (relatively continuously) in number.

Similarly, something need not be formally called a meter in order to be a meter. This is because history is layered, one period or era never entirely overwriting another. Old idioms continue in new contexts. The word 'gauge' is a simple but illustrative case. The origin of the term seems directly connected to the standardization of measures in law. In 14th-century England, for instance, a royal edict ordered that standard weights and measures be made of brass and sent to every city and town. The oldest surviving 'gauges' of this sort date from the late 15th century. The method was quite effective, the gauge of a yard from this period differing by only two-hundredths of an inch from the modern imperial measure.[91]

As an instrument, a gauge might be an object without numeric display. A 'horseshoe gauge' and most other 'fixed gauges' once used in machining, for instance, need not have any numbers inscribed on them. Rather, they provided fixed 'go' and 'not go' measures cast in iron or steel, the distance between which established the 'tolerance' permissible in the part being manufactured. A gauge might be variable, however, as in the case of a needle dial indicating high or low, hot or cold, and so on. Gauges of this sort are *like* scopes, they allow one to get a sense of something: is the temperature in the danger zone? On the other hand, they are akin to meters in that they can gauge a number: the tank is 1/2 full. Boyle designed and fitted a 'gage' of this kind to his pump, allowing him to 'estimate how the Receiver is exhausted'.[92] From the centre of gravity of the meter, however, gauges of this sort orbit rather than occupy the centre, since they do not have scalability and thus cannot render phenomena in a way that facilitates precise mathematical integration. Most, if not all, 'gauges' used in contemporary science do, however, incorporate scaled numeric readings. For this reason they occupy the centre of gravity of the meter, even though they do not bear the name.[93]

Foregrounding liminal forms is not at odds with the desire to make stable distinctions. It is in keeping with the 'flexible' approach to sorting things out suggested by Bowker and Star. Though committed to a conceptual explanatory framework that cannot be reduced to the empirical (what is considered empirical is itself a conceptual question), it seems overly contrived to treat the empirical as being so malleable that it can be reduced to a rigid abstraction. Trying to unite an empirical with a conceptual strategy is an on-going process unlikely to provide the hermetic closure desired by purists.[94] The liminality of many things within science should not, however, be confused with the hybrid character of many engines. Liminality is a condition of being between worlds, hybridity a condition of being of more than one. Engines, as the products of engineering cultures, necessarily incline towards hybridity because engineering inherently means to fit heterogeneous parts together. Modern computers are a particularly illustrative example of this hybridity.

The 'Automatic Computing Engine': A Qualitatively Different Engine?

Charles Babbage's design for an automatic computing engine was unrealized on the scale he conceived,[95] but in the 20th century computers have become powerful engines of scientific research. Conceived as a calculator, the computer can be and has been linked to the abacus, the origins of which are obscure, versions found in Babylonia, China, Japan and Rome. Despite variations in design, all facilitated arithmetical processing. Babbage's engines mark a significant departure, not simply because of their engineering complexity, the designs of which are ingenious, but because they were able *automatically* to perform the four basic arithmetic functions.[96] His first design, the 'Difference Engine', could only mechanically perform additions, achieving multiplication operations through the principle of finite differences. Hence the name. The design of his 'Analytical Engine' departed from previous mechanical calculators in that it envisioned, in his words, 'an engine embodying in itself the whole of the executive department of mathematical analysis'.[97] It could 'store' data (memory), and in response to input instructions from punch cards, automatically retrieve it and deliver it to the 'mill' (CPU).[98] Importantly, it had a secondary storage capacity such that numbers could be held in the mill for more immediate retrieval (the *time* required to perform an operation was central to the entire design). If 'memory' is viewed as being at the heart of the automatic computer, then Babbage's design is a qualitative break with all earlier 'calculators'. Indeed, Babbage was less interested in its capacity to replace competing mechanical calculators than in its capacity to replace human 'computers'.[99] Babbage, it might be said, found an elaborate engineering solution to the problem of securing numbers in anticipation of further operations. His central engine problem, in this respect, was that of *control.* The store and mill, and the manner in which they operated together, in principle solved the problem. Thus his Analytical Engine, by capturing mathematical operations in mechanical gears, provided the basic requirements of a chamber, the capacity to take hold of something and manipulate it.

Despite the many similarities between Babbage's designs and subsequent electronic computers, for a variety of reasons there is little direct historical connection between them. Yet if controlling 'bits' or 'packages' of information was a central problem for Babbage, it might be said that he lacked only the right kind of engine. Electronics can be viewed as providing the solution in the form of a chamber that overcomes the limitations of mechanical engines by virtue of the way it secures and manipulates electric current.[100] All chambers crucially depend upon valves, and in this respect the invention of the transistor (1947) was revolutionary. Operating as a miniature valve for controlling the flow of electricity, the transistor announced a major technical advance, permitting energy-efficient and compact computers. The transistor was to electrical engines what brass or machined valves were to mechanical engines. The integrated circuit, and the incorporation of the essential computing functions in a central processing microchip, completed the hardware revolution. But it was with 'software engineering', the 'point and click' graphic interface, long-distance networking and the crucial 'hypertext',[101] that the power of this complex engine was realized. The microelectronic automatic computing engine integrates every other engine ever devised while at the same time going qualitatively beyond them. As well as being a material hybrid, it makes possible a complete range of 'virtual' meters, graphs, chambers and scopes. Virtual experiments and complex modelling place simulation at the heart of scientific practice.[102] As well as permitting simulations in the sense of abstract models, computers are mobilized to simulate some of the most forceful conditions in the material world. Perhaps the most incredible is that currently being attempted at the 'National Ignition Facility' in Livermore, California. An array of powerful lasers, located at the heart of an equally powerful computational infrastructure, will be used to blast a relatively tiny spot at the centre of a 'target chamber'. The aim is to 'simulate' the interior of a thermonuclear bomb.[103]

Computers make possible a seemingly unlimited range of engineering hybrids, both representational and material. In this sense they seem destined to become the nodal engine that connects all other engines together. It is not surprising that the idiom of engines in computer science has survived since the invention of the Difference Engine. The language of 'RISC engines',[104] 'parsing engine', 'search engines', and 'software engineering' all point to the computer as a creation of engine science. It is difficult to understand these developments without a conceptualization of the character of 'engineering cultures'.[105]

Engine Science and Engineering Cultures

The power, and thus the political significance, of engine science, derive directly from the specificity of the practice rather than the uses to which it might be put by particular political constituencies. Rather than simply being a 'tool of power', it is generative of power.[106] It is precisely its character as a metrology, a sensing engine, inscription device, and vexing and transformative praxis, that creates the affinity between engine science and other powerful cultural forms. The centrality of engineering in modern science, the craftiness of its engagement with the forces of nature, makes it possible to transform those forces into forms of social power. Thus the epistemological success of modern scientific knowledge need not be conceived in terms of a consensus reached through 'methods' that can short-circuit the social domain in which they are embedded. Once the demarcation between science and society is itself socialized, it is clear that the epistemological success of science is not unrelated to its success for power (though this is not to suggest that reference to power can provide a sufficient explanation for that success).

From the perspective of engine science, the oppositions between the internal and external, science and technology, the local and supra-local (overly abstracted to 'universal'), which have caused so much mischief in the past, are not issues. Rather than asking how they might be connected back together, the point is to refrain from wrenching them apart in the first place. Analysis of the engines of science suggests that the local practice of the laboratory is in crucial respects continuous with the broader engineering culture of which it is a dynamic and generative part. Engine science drives the development of engineering capacities – military, civil, mechanical, sanitary, thermodynamic, electrical/electronic, bio/genetic – and these activities in turn generate new conceptual challenges and theoretical problems. And while engines are distributed in localized space, they are bound together through the supra-local networks of governing metrologies, component industries and common knowledges.

Knorr Cetina's conceptualization of the relations between micro 'epistemic cultures' and macro 'knowledge societies' can be understood in terms of the engineering cultures that straddle micro and macro contexts, the laboratory and 'the state'.[107] Viewed in this way, the affinity of engine science to industry and government appears both immediate and generalized. Governments that have historically networked with science in order to identify and exploit resources, and know and govern land and people (as both natural and political objects), have crafted the most powerful states in history, states that may justifiably be called 'engineering states'. Sociotechnical analyses, advocated by Wiebe Bijker and John Law, can be mobilized to map, naturalistically, the 'rhizome',[108] the connections which link the powers of engine science in the laboratory with other powerful cultural forms such as agriculture, industry and government, all of which in the modern period become infused with engine science.[109] From this perspective, social engineering is not a special and 'evil' case, but one more manifestation of a broader engineering culture in which knowing is inseparable from building, including the building of 'society'.[110]

When social science is viewed in terms of its historical relationship to modern government, and thus to social engineering, the analysis seems to apply here also. The bills of mortality and the censuses can be analysed as graphic meters. Surveys and panopticons might be viewed as socio-scopes. The detail of map-making reveals an array of graphic strategies and technologies that were crucial to modern state craft. And schools, hospitals and prisons were similar to chambers in that they were not simply buildings, but controlled spaces designed to permit the material manipulation of bodies. The idea of an engineering culture and practice recognizable at local, national and international levels thus provides one angle by which to approach the question of the character of modern state formation, as does the idea of an 'engineering governmentality' that links engine science to practices of governing and projects of social engineering.[111]

The praxis of engine science is thus a forcing house for culture as well as nature, materially engineering the two together such that it is sometimes difficult to determine where the one begins and the other ends. Engineering cultures generate a 'technoculture' that marvels, from America's 'Popular Science' to England's 'Tomorrow's World', upon each new engineering achievement. In England, we find friendly father/son teams entering their engines in 'Robot Wars' while, in the California desert, families gather picnic-style to launch home-engineered rockets up to 50,000 feet into the air.[112] Yet the wonder is countered by suspicions of malengine, and by recurrent dreams of natural purity and freedom from artificiality. Contemporary engineering cultures are almost schizophrenic concerning their own achievements, sometimes dogged by ambivalence towards the process of cyborgization, often searching for solace in imagined boundaries between 'pure' (human and intellectual) science and 'mere' (thing) technology.

Conclusion

'Epistemic engines' – 'meters', 'scopes', 'graphs' and 'chambers' – have been elaborated as analytic categories crafted from empirical material but on the basis of theoretical and explanatory considerations. The integrated practice of graphing, measuring, sensing and forcing has been linked to a cognitive culture of ingenuity and an array of material technologies that together indicate the specificity of engine science. The method helps circumvent many dualisms, such as science and technology, theory and practice, nature and culture, and science and society, dualisms that obscure more than they reveal. It indicates a way to follow the multiple paths that link discrete communities of practitioners, experimental researches, theoretical conceptualizations, social negotiations, material engines and cultural powers. From this perspective, the political significance of engine science lies in the character of the practice itself. Yet it is within the wider context of engineering culture that such significance is recognized and acted upon by governments.

Much effort has been expended trying to establish the specificity of science by reference to asocial and ahistorical epistemological or methodological criteria. Such efforts tend to give slight notice to the fact that data always can be, and frequently are, questioned in terms of how they were generated – how they were engineered. Scientists regularly disagree about what the numbers mean, how they should be handled, what is being perceived, and how it should be understood. Each new rendering of the world raises new difficulties about what exactly is being perceived and what can be said to be known about it. New engine strategies offer no escape from the 'experimenter's regress'.[113] Thus an analysis of the engines of science offers a gauge of the difference between science and non-science that does not revolve around the axis of method or epistemology as commonly understood. The specificity of science is conceived by reference to the practice and material culture of metering, scoping, graphing and manipulating without, in the first instance, making special epistemological claims. The praxis of ingenious inquiry, with its material culture of meters, scopes, graphs and chambers, points to a particular form of practice and culture that can readily be recognized, specifically, as 'engine science'.

Notes

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1. Thomas Shadwell's satire of the members of the original Royal Society, in his *The Virtuoso. A Comedy, Acted at the Duke's Theatre* (London: Herringman, 1676), 36.
2. Charles Dickens, speaking of the engine powered by steam, made locomotive by rail, and everything that it projected in its stay: quoted in Simon Schaffer, 'Modernity and Metrology', in Luca Guzzetti (ed.), *Science and Power: The Historical Foundations of Research Policies in Europe* (Luxembourg: European Union Publication, 2000), 71–91, at 86.
3. See, for instance: Michael Mulkay, 'Some Aspects of Cultural Growth in the Natural Sciences', *Social Research*, Vol. 36, No. 1 (1969), 22–52; David Edge and Michael Mulkay, *Astronomy Transformed* (New York: Wiley, 1976); Bruno Latour and Steve Woolgar, *Laboratory Life: The Social Construction of Scientific Facts* (Beverly Hills, CA:

Sage, 1979); John Law, 'Theories and Methods in the Sociology of Science: An Interpretive Approach', *Social Science Information*, Vol. 13 (1974), 163–71; Michael Lynch, *Art and Artifact in Laboratory Science* (London: Routledge & Kegan Paul, 1986); Sharon Traweek, *Beamtimes and Lifetimes: The World of High Energy Physicists* (Cambridge, MA: Harvard University Press, 1988); Andrew Pickering (ed.), *Science as Practice and Culture* (Chicago, IL: The University of Chicago Press, 1992); Karin Knorr Cetina, *Epistemic Cultures: How the Sciences Make Knowledge* (Cambridge, MA: Harvard University Press, 1999).

4. A Conference was recently dedicated to this question: 'Demarcation Socialised: or, Can We Recognize Science When We See It?' (Centre for the Study of Knowledge, Expertise, and Science [KES], Cardiff University, Wales/UK, 25–28 August 2000).
5. See, for instance: Chandra Mukerji, 'Toward a Sociology of Material Culture: Science Studies, Cultural Studies, and the Meanings of Things', in Diana Crane (ed.), *The Sociology of Culture* (Cambridge, MA: Blackwell, 1994), 143–62; Mukerji, *Territorial Ambitions and the Gardens of Versailles* (Cambridge: Cambridge University Press, 1997); Peter Galison, *Image and Logic: A Material Culture of Microphysics* (Chicago, IL: The University of Chicago Press, 1997). Though not expressed in the idiom of material culture, see also: Hans-Jörg Rheinberger, *Towards a History of Epistemic Things: Synthesizing Proteins in the Test Tube* (Stanford, CA: Stanford University Press, 1997); Adele E. Clarke and Joan H. Fujimura (eds), *The Right Tools for the Job: At Work in Twentieth-Century Life Sciences* (Princeton, NJ: Princeton University Press, 1992); M. Norton Wise, 'Mediating Machines', *Science in Context* Vol. 2, No. 1 (1988), 77–113; Andrew Pickering, *The Mangle of Practice: Time, Agency, and Science* (Chicago, IL: The University of Chicago Press, 1995); Robert Bud and Susan E. Cozzens (eds), *Invisible Connections: Instruments, Institutions, and Science* (Bellingham, WA: SPIE Optical Engineering Press, 1992).
6. See, for instance: Steven Shapin and Simon Schaffer, *Leviathan and the Air-Pump: Hobbes, Boyle, and the Experimental Life* (Chicago, IL: The University of Chicago Press, 1985); David Gooding, Trevor Pinch and Simon Schaffer (eds), *The Uses of Experiment: Studies in the Natural Sciences* (Cambridge: Cambridge University Press, 1989); Timothy Lenoir, 'Practice, Reason, Context: The Dialogue Between Theory and Experiment', *Science in Context*, Vol. 2, No. 1 (1988), 3–22.
7. See, for instance: Thomas L. Hankins and Robert J. Silverman, *Instruments and the Imagination* (Princeton, NJ: Princeton University Press, 1995); John Burke (ed.), *The Uses of Science in the Age of Newton* (Berkeley: University of California Press, 1983), esp. Albert Van Helden's piece, 'The Birth of the Modern Scientific Instrument, 1550–1700', 49–84. For a discussion and examples of recent work, see Albert Van Helden and Thomas L. Hankins (eds), 'Scientific Instruments', Special Issue of *Osiris*, Second Series, Vol. 9 (1994).
8. A crucial exception is Deborah Jean Warner, 'What is a Scientific Instrument, When did it Become One, and Why?', *British Journal for the History of Science*, Vol. 23 (1990), 83–93.
9. John Hall, *Cultures of Inquiry: From Epistemology to Discourse in Sociohistorical Research* (Cambridge: Cambridge University Press, 2000).
10. Rheinberger, op. cit. note 5, esp. Prologue & Chapter 2.
11. Most of the empirical research informing this paper was conducted in archives in Ireland, the United States, England and Scotland, and focussed on the period 1650–1880. The paper is also informed by a number of years of informal participant observation in a start-up R&D engineering firm (see *www.flometrics.com*), a short study of a cancer research laboratory in San Diego, observational tours of physics research sites such as Rocketdyne International in Los Angeles and the UCLA plasma research facility, and informal interviews with physicists with respect to the research and development of free electron lasers (FELs). I have also relied upon studies of secondary literature too numerous to cite here, and also encyclopedias of scientific instruments, such as Robert Bud and Deborah Warner (eds), *Instruments of Science: An Historical Encyclopedia* (New York & London: The Science Museum [London] and The

National Museum of American History [Smithsonian Institution] in association with Garland Publishing, 1998).

12. As discussed in, for example, Pickering (ed.), op. cit. note 3.
13. Geoffrey C. Bowker and Susan Leigh Star, *Sorting Things Out: Classification and Its Consequences* (Cambridge, MA: MIT Press, 1999), 325–26; see also Chapters 9 & 10.
14. J.A. Bennett, 'A Viol of Water or a Wedge of Glass', in Gooding, Pinch & Schaffer (eds), op. cit. note 6, 105–14, at 105. See also: Jan Golinski, 'Barometers of Change: Meteorological Instruments as Machines of Enlightenment', in William Clark, Jan Golinski and Simon Schaffer (eds), *The Sciences of Enlightened Europe* (Chicago, IL: The University of Chicago Press, 1999), 69–93.
15. Willem D. Hackmann, 'Scientific Instruments: Models of Brass and Aids to Discovery', in Gooding, Pinch & Schaffer (eds), op. cit. note 6, 31–65.
16. Warner, op. cit. note 8.
17. The notion of an engineered natural entity immediately appears a contradiction in terms. The problem has a long history in engine science, Boyle confronting those who claimed that the 'artificial' effects of his engine could not provide the basis for a 'natural' philosophy. His reply is instructive:

> Nor will it suffice to justify learned men in the neglect and contempt of this part [mechanical trades] of natural history, that the men, from whom it must be learned, are illiterate mechanicks, and the things that are exhibited are works of art, and not of nature. For the first part of the apology is indeed childish, and too unworthy of a philosopher, to be worthy of a solemn answer. And as for the latter part, I desire that you would consider, what we elsewhere expresly [*sic*] discourse against, the unreasonable difference that the generality of learned men have seemed to fancy betwixt all natural things and factitious ones. For besides, that many of those productions that are called artificial, do differ from those that are confessedly natural, not in essence, but in efficients; there are many things made by tradesmen, wherein nature appears manifestly to do the main parts of the work: as in malting, brewing, baking, making of raisins, currants, and other dried fruits; as also hydromel, vinegar, lime, &c. . . . and scarce any man will think, that when a pear is grafted upon a white thorn, the fruit it bears is not a natural one, though it be produced by a coalition of two bodies of distant natures put together by the industry of man, and would not have been produced without the manual and artificial operation of the gardener.

Robert Boyle, 'Some Considerations Touching the Usefulness of Experimental Natural Philosophy. The Second Tome, containing the latter Section of the Second Part' [1772], in Thomas Birch (ed.) *Robert Boyle: The Works*, 6 Vols (Hildesheim: Georg Olms Verlagsbuchhandlung, 1965), Vol. III, 392–494, at 442–43.

18. On the politics of representation, see Hugh Mehan, 'Beneath the Skin and Between the Ears: A Case Study in the Politics of Representation', in Seth Chaiklin and Jean Lave (eds), *Understanding Practice: Perspectives on Activity and Context* (Cambridge & New York: Cambridge University Press, 1993), 241–68, esp. 263–64.
19. Steven Shapin, 'The Invisible Technician', *American Scientist*, Vol. 77, No. 6 (November-December 1989), 554–63; Shapin, *A Social History of Truth: Civility and Science in Seventeenth-Century England* (Chicago, IL: The University of Chicago Press, 1995), Chapter 8, 'Invisible Technicians', 355–407.
20. Mukerji (1997), op. cit. note 5, 241–47, 260–62.
21. For pictures of instruments as examples of fine art, including Watt's engine in the form of a gentle model, see Gerard L'E. Turner, *Scientific Instruments 1500–1900: An Introduction* (Berkeley: University of California Press, 1998). For rough engines juxtaposed with fine instruments, see Jim Bennett and Steven Johnson, *The Geometry of War* (Oxford: Museum of the History of Science, 1996).

22. The military was a crucial space in which European engineering culture developed. The idiom of engines was so deeply embedded in military discourse that even the discipline of drill was described as an engine:

    > Words cannot express the power, beauty, and facility of the operations . . . Repeated views of the operating Engine, give the idea which I cannot. The ranks are worked in these positions . . . [and] . . . two months practice enables the Engine to complete sixty operations in one minute . . . Their practice [the soldiers] . . . is in strict conformity to the laws of gravity, and powers of the lever, regardless of the theory a stranger to them.

    Anthony Gordon, *A Letter on the Bayonett Exercise, submitted to the Right Hon. General Burgoyne, Commander in Chief of His Majesty's Forces in Ireland, &c.* (Dublin Barracks, 1783), 13–16.
23. Shapin & Schaffer, op. cit. note 6, 130–31.
24. Simon Schaffer, 'Enlightened Automata', in Clark, Golinski & Schaffer (eds), op. cit. note 14, 126–65.
25. Quoted in ibid., 129.
26. Quoted in ibid., 163.
27. Ken Alder, 'French Engineers Become Professional: or, How Meritocracy Made Knowledge Objective', in Clark, Golinski & Schaffer (eds), op. cit. note 14, 94–125, at 117.
28. Thomas F. Gieryn, *Cultural Boundaries of Science: Credibility on the Line* (Chicago, IL: The University of Chicago Press, 1999), Chapter 1, 'John Tyndall's Double Boundary-Work: Science, Religion, and Mechanics in Victorian England', 37–64. For evidence of how engine science forged ahead despite the representational efforts to divide it between labour and intellect, see Graeme Gooday, 'Teaching Telegraphy and Electronics in the Physics Laboratory: William Ayrton and the Creation of an Academic Space for Electrical Engineering in Britain, 1873–1884', *History of Technology*, Vol. 13 (1991), 73–111. For a discussion of how the ranking of science and engineering was institutionalized, see W.J. Reader, ' "The Engineer Must Be a Scientific Man": The Origins of the Society of Telegraph Engineers', ibid., 112–18.
29. Warner, op. cit. note 8, 89–90. See also: Ronald Kline, 'Construing "Technology" as "Applied Science": Public Rhetoric of Scientists and Engineers in the United States, 1880–1945', *Isis*, Vol. 86 (1995), 194–221.
30. William King, 'Of Hydraulic Engines', TCD. MSS I.4.18, ff. 105–12; John Locke, 'The Towing Engine', Bodleian, Locke MSS c. 31 fol. 48.
31. Shapin & Schaffer, op. cit. note 6, 30–31; Shadwell, op. cit. note 1, 72–79.
32. Shapin & Schaffer, op. cit. note 6, 30.
33. Boyle, op. cit. note 17, 435. The term could also mean 'the science of machines': Peter Dear, *Discipline and Experience: The Mathematical Way in the Scientific Revolution* (Chicago, IL: The University of Chicago Press, 1995), 169.
34. In relation to the 15th century, see Pamela O. Long, 'Power, Patronage, and the Authorship of *Ars*: From Mechanical Know-how to Mechanical Knowledge in the Last Scribal Age', *Isis*, Vol. 88 (1997), 1–41.
35. Shapin & Schaffer, op. cit. note 6, 129–30.
36. Ibid., esp. 128–30. Also see: Steven Shapin and Barry Barnes, 'Science, Nature and Control: Interpreting Mechanics' Institutes', *Social Studies of Science*, Vol. 7, No. 1 (February 1977), 31–74.
37. Steven Shapin, *The Scientific Revolution* (Chicago, IL: The University of Chicago Press, 1996), esp. 30–57.
38. Shapin & Schaffer, op. cit. note 6, 128–29, 140–43. Petty, though in many respects bridging the philosophies of Boyle and Hobbes, took quite the opposite view from the latter on this issue. Hence he distinguished between 'nature free', which is the domain of the history of nature, and 'nature vexed and disturbed', which pertained to nature subject to 'experiment'. Both were required for a sound natural philosophy. William

Petty, *The Advice of W.P. to Mr. Samuel Hartlib for the Advancement of some particular parts of Learning* (London, 1648), 26.

39. Shapin & Schaffer, op. cit. note 6, 129, 145–50.
40. Shapin, op. cit. note 37, 111–17.
41. Ian Hacking, *Representing and Intervening: Introductory Topics in the Philosophy of Science* (Cambridge: Cambridge University Press, 1983). Boyle (op. cit. note 17, 446) states: 'some of these occurring phenomena being produced by nature, when she is as it were vexed by art, and roughly handled by ways unusual, and sometimes extravagant enough, may discover to a heedful and rational man divers luciferous things not to be met with in books'.
42. This integration was first detected by Zilsel, and has more recently been identified by Bennett: Edgar Zilsel, 'The Sociological Roots of Science', *American Journal of Sociology*, Vol. 47 (1942), 544–62, reprinted in *Social Studies of Science*, Vol. 30, No. 6 (December 2000), 935–49; J.A. Bennett, 'The Mechanics' Philosophy and the Mechanical Philosophy', *History of Science*, Vol. 24 (1986), 1–28. Shapin and Schaffer, however, point out that there was no levelling in terms of the status of the different constituencies.
43. The notion of 'laws of nature' has recently been subject to sustained philosophical critique: Nancy A. Cartwright, *How the Laws of Physics Lie* (Oxford: Clarendon Press, 1983); Ronald N. Giere, *Science Without Laws* (Chicago, IL: The University of Chicago Press, 1999).
44. David Gooding, Trevor Pinch and Simon Schaffer, 'Preface', in Gooding, Pinch & Schaffer (eds), op. cit. note 6, xiii-xvii, at xiii.
45. Lenoir, op. cit. note 6, 3. However, this problem has begun to be addressed in the past decade.
46. Quoted in Wise, op. cit. note 5, 108.
47. See Kline, op. cit. note 29, esp. 198–201, 220–22.
48. The mischief caused by the science-technology pair continues to assert itself: a second edition of a classic in 'technology studies' fails to correct the widely-held view that 'before the latter part of the nineteenth century the contribution of activities we would now think of as science to what we would call technology was often marginal': Donald Mackenzie and Judy Wajcman (eds), *The Social Shaping of Technology* (Milton Keynes, Bucks, UK: Open University Press, 2nd edn, 1999), 7. But see the essays by Albert Van Helden, Robert Westfall and others in Burke (ed.), op. cit. note 7. For an example of the continued deployment of the language of 'pure science' and technology, see Michael Hunter, *Science and the Shape of Orthodoxy* (Woodbridge, Suffolk, UK: Boydell Press, 1995).
49. In this sense, all engine scientists are 'heterogeneous engineers': see John Law, 'Introduction: Monsters, Machines and Sociotechnical Relations', in Law (ed.), *A Sociology of Monsters: Essays on Power, Technology and Domination* (London: Routledge, 1991), 1–23, at 9.
50. The distinction was first drawn by Gilbert Ryle, who argued that *knowledge how* depended upon a complex of abilities while *knowledge that* had no connection to ability and depended only upon a relationship between a thinker and a true proposition. The opposition maps directly on to that between 'science' and 'engineering'. While this paper rejects the opposition from a sociologically naturalistic perspective, it is also weak from a purely philosophical perspective. See Jason Stanley (University of Michigan) and Timothy Williamson, 'Knowing How' (unpublished paper presented to the UC Davis Department of Philosophy Colloquium Series, 27 April 2001).
51. Leigh Star and James R. Griesemer, 'Institutional Ecology, "Translations" and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907–39', *Social Studies of Science*, Vol. 19, No. 3 (August 1989), 387–420.
52. And pH meter, penetrometer, viscometer, watt meter, voltmeter, thermometer, pyrometer, porometer, insulation meter, manometer, eudiometer, electrometer, photometer, ammeter, gasometer, spectrophotometer, ellipsometer, turbidimeter,

calorimeter, polarimeter, magnetometer, interferometer, tachometer, spherometer, microdensitometer, hydrometer, geometer, hemoglobinometer, and so on.

53. While a conceptualization of 'material agency' is helpful, I restrict my sense of it to material culture forms, that is, to forms that have agency precisely because they embody human designs. I do not believe that it is either useful or necessary to conceive of the weather as a form of material agency (cf. Pickering, op. cit. note 5, 6). Mere force, or 'material resistance', is not 'agency'. However, since the forces Pickering describes only emerge in the context of human activities, they can be considered agential.
54. Petty made comments of this sort in many of his publications. For example, he advises the Fellows of the Royal Society to 'apply your mathematics to matter', and discusses 19 different areas of research, from the 'shapes of ships' to the 'lives of men and their duration': William Petty, *The Discourse made before the Royal Society concerning the use of Duplicate Proportion in sundry important particulars: Together with a New Hypothesis of Springing or Elastique Motions* (London: John Martyn, 1674), 5, 9. And in his 'Advertisements to the Dublin Society' (1684), he instructs new members to 'provide themselves with the Rules of number, weight and measure; not onely how to measure the plus & minus of the quality and Schemes of matter, but do provide themselves with Scales and Tables, whereby to measure and compute such qualitys and Schemes in their exact proportions': in William Petty, *The Petty Papers*, Vol. II, edited from the *Bowood Papers* by the Marquis of Lansdowne (London: Constable, 1929), 91.
55. Schaffer, op. cit. note 2. See also: Ian Hacking, *The Taming of Chance* (Cambridge: Cambridge University Press, 1990); Joseph O'Connell, 'Metrology: The Creation of Universality by the Circulation of Particulars', *Social Studies of Science*, Vol. 23, No. 1 (February 1993), 129–73; Andrew Barry, 'The History of Measurement and the Engineers of Space', *British Journal for the History of Science*, Vol. 26 (1993), 459–68; Theodore M. Porter, *Trust in Numbers: The Pursuit of Objectivity in Science and Public Life* (Princeton, NJ: Princeton University Press, 1995); Mary Poovey, *A History of the Modern Fact: Problems of Knowledge in the Sciences of Wealth and Society* (Chicago, IL: The University of Chicago Press, 1998); Patrick Carroll, *Engineering Ireland: The Material Constitution of the Technoscientific State*, esp. Chapter 3, 'Meter Engines and the Data State' (unpublished PhD dissertation, University of California, San Diego, 1999).
56. Schaffer, op. cit. note 2, 78.
57. Bruce Curtis, 'From Moral Thermometer to Money: Metrological Reform in Pre-Confederation Canada', *Social Studies of Science*, Vol. 28, No. 4 (August 1998), 547–70.
58. 'The end and aim of all units is to make all contracts and other statements involving quantities intelligible and precise... It has always been the care of wise governments to provide national standards and to make use of other standards punishable... The man of business requires these standards for the sake of justice, the man of science requires them for the sake of truth, and it is the business of the state to see that our... measures are maintained uniform': Maxwell, quoted in Schaffer, op. cit. note 2, 85.
50. And also the x-ray, spinthariscope, gastroscope, electroscope, polariscope, hygroscope, helioscope, baroscope, chronoscope, seismoscope, cystoscope, glucose sensor, nephelescope, gyrocompass, opthalmoscope, tachistoscope, otheoscope, stereoscope, and the like, and a range of 'probes' and 'detectors'.
60. Research into visual representation has constituted one of the most fruitful areas of science studies during the past couple of decades. See, for instance: Martin Rudwick, 'The Emergence of a Visual Language for Geological Science, 1760–1840', *History of Science*, Vol. 14 (1976), 149–95; Michael Lynch, 'Discipline and the Material Form of Images: An Analysis of Scientific Visibility', *Social Studies of Science*, Vol. 15, No. 1 (February 1985), 37–66; Michael Lynch and Steve Woolgar (eds), *Representation in Scientific Practice* (Cambridge, MA: MIT Press, 1990); James R. Griesemer, 'Must Scientific Diagrams Be Eliminable? The Case of Path Analysis', *Biology and Philosophy*, Vol. 6, No. 2 (1991), 155–80; Jane R. Camerini, 'Evolution, Biogeography, and Maps:

An Early History of Wallace's Line', *Isis*, Vol. 84 (1993), 1–28; Ludmilla Jordanova, 'Gender, Generation, and Science: William Hunter's Obstetrical Atlas', in William F. Bynum and Roy Porter (eds), *William Hunter and the Eighteenth-Century Medical World* (New York: Cambridge University Press, 1985), 385–412; Howard E. Gruber, 'Darwin's "Tree of Nature" and Other Images of Wide Scope', in Judith Wechsler (ed.), *On Aesthetics in Science* (Cambridge, MA: MIT Press, 1978), 121–40; Mary G. Winkler and Albert Van Helden, 'Representing the Heavens: Galileo and Visual Astronomy', *Isis*, Vol. 83, No. 2 (1992), 195–217.

61. Worldly orientation could have a broad as well as narrow scope. Samuel Hartlib described his office of public address as an 'engine' through which to view the 'frame of a whole state', and as 'an Engine to reduce all into some Order which is confused': Samuel Hartlib, *A further Discoverie of The Office of Publick Addresse for Accommodations* (London, 1648), 26, 131.
62. Michael Aaron Dennis, 'Graphic Understanding: Instruments and Interpretation in Robert Hooke's *Micrographia*', *Science in Context*, Vol. 3, No. 2 (1989), 309–64, at 347.
63. The term 'virtual witnessing' is Shapin's: see Shapin & Schaffer, op. cit. note 6, 60–65, 225–26.
64. Understood in the narrow contemporary sense of an axial plot, graphing in science has been traced to the late 18th century: see Hankins & Silverman, op. cit. note 7, 117; cf. note 70, below.
65. Michel Foucault, *The Archaeology of Knowledge* (London: Tavistock, 1972); Jacques Derrida, *Writing and Difference* (Chicago, IL: The University of Chicago Press, 1978).
66. Patrick Carroll-Burke, 'Medical Police and the History of Public Health' (manuscript under review by *Medical History*); Galison, op. cit. note 5, esp. 48–52, 831–37.
67. Bruno Latour, 'Drawing Things Together', in Lynch & Woolgar (eds), op. cit. note 59, 19–68.
68. John Law and Michael Lynch, 'Lists, Field Guides, and the Descriptive Organization of Seeing: Birdwatching as an Exemplary Observational Activity', in Lynch & Woolgar (eds), op. cit. note 60, 267–99; Trevor J. Pinch, 'Towards an Analysis of Scientific Observation: The Externality and Evidential Significance of Observation Reports in Physics', *Social Studies of Science*, Vol. 15, No. 1 (February 1985), 3–36.
69. A revealing example is the 'orthography' of Ireland which formed part of the triangulated cartography known as the Ordnance Survey (carried out by the Royal Engineers). For a rich expression of the ambiguities and ambivalence generated by the English practice of translating and graphing Ireland, see Brian Friel's play, *Translations* (London: Faber & Faber, 1981).
70. Laurence D. Smith, Lisa A. Best, D. Alan Stubbs, John Johnston and Andrea Bastiani Archibald, 'Scientific Graphs and the Hierarchy of the Sciences: A Latourian Survey of Inscription Practices', *Social Studies of Science*, Vol. 30, No. 1 (February 2000), 73–94; Latour, op. cit. note 66.
71. William S. Cleveland, 'Graphs in Scientific Publications', *American Statistician*, Vol. 38 (1984), 261–69. Hankins and Silverman (op. cit. note 7) trace the origin of 'graphs' to images either directly inscribed by 'instruments', or plotted as axial diagrams: they call the former 'recording' or 'self-registering instruments'. Like Cleveland, they tie graphs to meters, particularly with respect to quantitative methods. The 'graphical method' is thus 'born' in the 19th century at the intersection of analytic geometry (in which relationships between pairs of variables are expressed in a curve) and 'automatic recording instruments' (ibid., 117). Though theirs is, in general, an historicist approach, it is actually teleological in terms of the nomenclature. Thus, while acknowledging that it is difficult to know what to count as a graph given the instability of the actors' categories, they adopt current nomenclature, explaining that one can unambiguously recognize the origin of 'graphs' in the 'indicator diagram of James Watt, in the lineal arithmetic of William Playfair, and the scientific writings of Johann Heinrich Lambert'. They re-label historical representations as 'graphs', that the historical actors labelled 'charts', 'diagrams' and 'figures'. Talk of the 'graphic

method', which they locate in the late 19th century (Étienne-Jules Marey), provides the idiom they use to translate earlier terminology. Yet they conclude that what was important about (at least some of) the new graphic 'language' was the 'shapes' it produced. Shapes, particularly in acoustics, were viewed not simply as relational measures, but as analogues of the phenomena (ibid., 128–30). Thus, whereas Hankins and Silverman locate the origins of graphs in the kind of quantitative plots that Cleveland equates with graphs, they shift to an emphasis on the *visual* qualities of graphs. What precisely constitutes a 'graph', in distinction to figures, charts, diagrams, drawings and so on, is not clear. In their first sense a photograph would not be a graph, though in the second it would. They do, however, provide examples from the 19th century that fit my more general usage. For instance, they note that Marey did view graphs as writing, though a particular kind of 'natural writing' (ibid., 139). As a kind of isomorphic correspondence with the natural, Marey viewed graphs like naturalistic pictures. Hankins and Silverman also note that the person believed to have coined the term 'graph' in English (J.J. Sylvester, in 1878) had a more specific understanding (abbreviation of 'graphic [chemical] formula') of the word than Playfair or Whewell. The result is a rich historical account of the various meanings the word had for different actors, but this is in tension with an unexplained imposition of just one of those meanings as an analytic category. More recently, Hankins has addressed the history of 'graphs' in more detail, but the same difficulties remain. The word is said to be coined in the late 19th century. It had a number of meanings, but one of those meanings is adopted as the master designation and is retrospectively fitted back to the late 18th century. This meaning, adopted from the late 19th century (and current statistical usage), leads to the conclusion that 'the entire Scientific Revolution of the seventeenth century took place without graphs': Thomas L. Hankins, 'Blood, Dirt, and Nomograms: A Particular History of Graphs', *Isis*, Vol. 90 (1999), 50–80, at 52. Though my own conceptualization of graphs in science is methodologically driven, such that I would include Petty's 'bills of mortality' as an important graphic moment in the history of public health, and certainly his map of Ireland in the history of cartography, there is no essential empirical justification for excluding earlier forms that bear the name: for instance, 'cosmography' and 'geography' (c. 1550), 'graphic art' (c. 1750s), and 'cartography', 'ethnography' and 'orthography' (c. 1850s). Note also the 'instrument' called a 'pantograph' (1603), which was used to copy, reduce, or enlarge maps. In any case, the approach developed here is conceptual as well as empirical; it views the experimental reports that Shapin and Schaffer call 'literary technologies' as important innovations in the history of graphing in science.

72. Griesemer, op. cit. note 59.
73. Brian Rotman, 'Thinking Dia-Grams: Mathematics and Writing', in Mario Biagioli (ed.), *The Science Studies Reader* (New York & London: Routledge, 1999), 430–41.
74. And the barograph, vitalograph, pantelgraph, meteorograph, polygraph, fultograph, bathythermograph, electrocardiograph, photograph, electroretinograph, plethysmograph, stereograph, polarograph, spectroheliograph, pentograph, etcetera, etcetera.
75. Michael Lynch and Steve Woolgar, 'Introduction: Sociological Orientations to Representational Practice in Science', in Lynch & Woolgar (eds), op. cit. note 59, 1–18, at 8.
76. Patrick Carroll, 'Science, Power, Bodies: The Mobilization of Nature as State Formation', *Journal of Historical Sociology*, Vol. 9, No. 2 (1996), 139–67, at 140–41.
77. Latour, op. cit. note 66, 24ff.
78. Ibid., 52–54. Important for Latour are drawings that make it possible to win in an 'agonistic field', to beat challengers and dominate the world. The best inscriptions are the ones that are most mobile and most immutable, that are flat and can be most easily collated, seriated and combined, that have scalability and can be reproduced and superimposed, and that can be integrated with 'written texts' and geometry (the best pictures have 'optical consistency'). The places where all these manipulations take

place are 'centres of calculation'. Thus, rather than many histories, or polygonal histories, Latour calls for 'a single history of these centers of calculation': ibid., 60.

79. Ibid., 62–63 (note 12).
80. Jack Goldstone, 'The Rise of the West – Or Not?: A Revision of Socio-Economic History', *Sociological Theory*, Vol. 18, No. 2 (2000), 175–94.
81. For a discussion of landmark achievements in the history of electromagnetic engines, see Brian Gee, 'Electromagnetic Engines: Pre-technology and Development Immediately Following Faraday's Discovery of Electromagnetic Rotations', *History of Technology*, Vol. 13 (1991), 41–72. It is unclear, however, what Gee means by 'pre-technology', since Faraday's demonstration of rotation by electromagnetic force is itself embodied in the technology of his apparatus. It may be the fact that Gee is relying upon the patent office definition of an 'electric motor', which leads him to conclude that 'Faraday's crude arrangement to show the compound rotation of a bar magnet and fly-wire does not constitute an electric motor and, therefore, its invention should not be attributed to him' (ibid., 43). I have no interest in priority of discovery disputes, but within my conceptual framework I would tend to class Faraday's invention as an electromagnetic engine because it captures a phenomenon and manipulates it in a material contrivance. The strength of the capture and the degree of manipulation are, however, quite minimal and rudimentary, so I would take a flexible approach (granted not of much value to patent law) and describe it as a 'threshold electromagnetic engine'. This approach does not detract from the ingenuity and engine successes of William Sturgeon, Francis Watkins, Joseph Henry, Jacob Green and others. From the sociological perspective of science as culture and practice, inventions are never entirely the property of single individuals.
82. Crosbie Smith, 'Energy', in Robert C. Olby, Geoffrey N. Cantor, John R.R. Christie and M.J.S. Hodge (eds), *Companion to the History of Modern Science* (London: Routledge, 1990), 326–41.
83. Smith, ibid.; M. Norton Wise, 'Electromagnetic Theory in the Nineteenth Century', in Olby et al. (eds), op. cit. note 81, 342–56; Wise, op. cit. note 5; Lenoir, op. cit. note 6.
84. Crosbie Smith and M. Norton Wise, *Energy and Empire: A Biographical Study of Lord Kelvin* (Cambridge: Cambridge University Press, 1989).
85. Wise, op. cit. note 5, 89.
86. On the link between work and virtue, and how this was impressed upon the young Robert Boyle, see Malcolm Oster, 'The Scholar and the Craftsman Revisited: Robert Boyle as Aristocrat and Artisan', *Annals of Science*, Vol. 49 (1992), 255–76.
87. Galison, op. cit. note 5, esp. 313–15, 352–62.
88. For a discussion of Bogle's engine problems, see Shapin & Schaffer, op. cit. note 6, esp. 27–30 & Chapter 7. In this context, Boyle advocated a 'history of valves'. Given the nodal character of valves, their history would form a crucial part of the history of engines more generally.
89. Zilsel, op. cit. note 42; Bennett, op. cit. note 42.
90. I'd like to thank James Griesemer for reminding me that the centrifuge is a chamber engine.
91. Edgar A. Griffiths, *Engineering Instruments and Meters* (London: George Routledge & Sons, 1920), 1–2.
92. Robert Boyle, 'A Continuation of New Experiments Physico-Mechanical [etc.]', *Philosophical Transactions: Giving some Accompt of the Present Undertakings, Studies and Labours of the Ingenious in many considerable parts of the World*, Vol. III (London: John Martyn, 1669), 845–50, at 847.
93. Similarly, there are instruments called meters that are in fact more like gauges. A 'conductometer', for instance, can consist of spokes of different metals extending from a centre hub attached to a wooden handle. It is designed to illustrate the variable conductivity of heat (and, by surrogate, electricity). Since the instrument does not give numeric readings, however, it is designated within my analytic nomenclature as 'liminal'. I am not, therefore, advocating a form of 'literalism'. While I look to words

for clues and guidance, the aim is to ground the distinctions in the actual character of the material culture.

94. The current controversy over whether Pluto can be classified as a planet would be easily solved if the antagonists recognized that classification schemes are not mirrors of the world. Relinquishing the realist 'all or nothing' view of classifications would make room for Pluto as a liminal form which, when looked at from one angle appears like a planet, but from another looks like a comet. For a demonstration that classifications are inventions as much as discoveries, see the much neglected paper by John Dean, 'Controversy over Classification: A Case Study from the History of Botany', in Barry Barnes and Steven Shapin (eds), *Natural Order: Historical Studies in Scientific Culture* (London & Beverly Hills, CA: Sage, 1979), 211–30.
95. Some fascinating connections are followed in Francis Spufford and Jenny Uglow (eds), *Cultural Babbage: Technology, Time and Invention* (London: Faber & Faber, 1996). See also the intriguing novel depicting an image of what the mid-Victorian world might have looked like had Babbage been successful: William Gibson and Bruce Sterling, *The Difference Engine* (New York: Bantam Books, 1991).
96. Earlier, more modest designs include the mechanical calculator built by Wilhelm Schickard (early 17th century), Blaise Pascal's device (mid-17th century), Leibniz' device (late 17th century), and Charles Thomas de Colmar's 'arithmometer', built in the 1820s: see Bruce Collier and James MacLachlan, *Charles Babbage and the Engines of Perfection* (Oxford: Oxford University Press, 1998).
97. Quoted in ibid., 106.
98. Ibid., 83.
99. William J. Ashworth, 'Memory, Efficiency, and Symbolic Analysis: Charles Babbage, John Herschel, and the Industrial Mind', *Isis*, Vol. 87 (1996), 629–53; Simon Schaffer, 'Babbage's Intelligence, Calculating Engines, and the Factory System', *Critical Inquiry*, Vol. 21, No. 1 (1994), 203–27.
100. Early electronic computers depended on mini vacuum chambers (cathode ray tubes), sensors (electric brushes for reading punch cards) and meters (crucially the 'potentiometer'): see the entry on 'Computers' in Bud & Warner (eds), op. cit. note 11, 138–40.
101. Paul N. Edwards, 'Hyper Text and Hypertension: Post-Structuralist Critical Theory, Social Studies of Science and Software', *Social Studies of Science*, Vol. 24, No. 2 (May 1994), 229–78.
102. See the special edition on simulations and models, edited by Sergio Sismondo and Snait Gissis, of *Science in Context*, Vol. 12, No. 2 (Summer 1999), esp. Sergio Sismondo's essay, 'Editor's Introduction: Models, Simulations and Their Objects', 247–60.
103. 192 beams are converged at the target chamber, which is 10 metres in diameter and 10 centimetres thick. The target is about a centimetre in diameter. See: <*www.llnl.gov/nif/index.html*>.
104. Reduced Instruction Set Computer (central processing unit).
105. For an extended discussion, see Patrick Carroll-Burke, 'Material Designs: Engineering Cultures and Engineering States – Ireland 1650–1990', *Theory and Society* (forthcoming, 2002).
106. This argument is central to Mukerji (1997), op. cit. note 5; see also Bruno Latour, 'Give Me a Laboratory and I will Raise the World', reprinted in Biagioli (ed.), op. cit. note 72, 258–75.
107. This argument is central to Knorr Cetina, op. cit. note 3, but see esp. Chapters 1, 2 & 10.
108. For an exposition of this concept, see Gilles Deleuze and Félix Guattari, *A Thousand Plateaus: Capitalism and Schizophrenia* (Minneapolis: University of Minnesota Press, 1987), esp. 'Introduction: Rhizome', 3–25.
109. One of the most vocal early opponents of the process was Edmund Burke, who railed against 'engines' and 'instruments' for the 'destruction of religion' and tradition embodied in 'artificial' political 'designs': see, for example, his *Reflections on the*

Revolution in France (1790), in Edmund Burke, *Reflections on the French Revolution and other Essays*, intro. A.J. Grieve, Everyman Series (London & New York: J.M. Dent & Sons and E.P. Dutton & Sons, 1935), esp. 168–81; Burke, *A Vindication of Natural Society, or, A View of the Miseries and Evils arising to mankind from Every Species of Artificial Society. In a letter to Lord* ****, ed. & intro. Frank N. Pagano (Indianapolis, IN: Liberty Fund Inc., 1982), esp. 4–6, 12–19, 39–45, 84–91.

110. See for instance, Law, op. cit. note 49; Bruno Latour, 'Technology is Society Made Durable', in Law (ed.), op. cit. note 49, 103–30; Wiebe E. Bijker and John Law (eds), *Shaping Technology/Building Society* (Cambridge, MA: MIT Press, 1992); John Law and Annemarie Mol, 'Notes on Materiality and Sociality', *Sociological Review*, Vol. 43 (1995), 274–94.
111. On governmentality, see Andrew Barry, Nikolas Rose and Thomas Osborne (eds), *Foucault and Political Reason: Liberalism, Neo-Liberalism and Rationalities of Government* (Chicago, IL: The University of Chicago Press, 1996).
112. See, for instance: <*www.rrs.org/Projects/Launches/Flowmetrics/.html*>; <*www.gt-electronics.freeserve.co.uk*>.
113. Harry Collins and Trevor Pinch, *The Golem: What Everyone Should Know about Science* (Cambridge: Cambridge University Press, 2nd edn, 1998), 97–106.

Patrick Carroll-Burke is assistant professor in the Department of Sociology, and a member of the Science and Technology Studies Program, at the University of California, Davis. He holds a Doctoral degree in Sociology and Science Studies from the University of California, San Diego, and a Masters degree in Modern History from the National University of Ireland, Maynooth. His current major research project, entitled 'The Science/State Plexus: Engineering Cultures and Modern State Formation, 1650–1900', applies the analysis of science presented here to the New English colonization of Ireland, and develops a new theory of the state that views the relations between government and science through a triangulated analysis of their shared ideas, practices and material culture.

Address: Department of Sociology, One Shields Avenue, University of California, Davis, California 95616–8701, USA; fax: +1 530 752 0783; email: pcarroll@ucdavis.edu