The Ad Hoc Collective Work of Building Gothic Cathedrals with Templates, String, and Geometry

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Gothic cathedrals like Chartres were built in a discontinuous process by groups of masons using their own local knowledge, measures, and techniques. They had neither plans nor knowledge of structural mechanics. The success of the masons in building such large complex innovative structures lies in the use of templates, string, constructive geometry, and social organization to assemble a coherent whole from the messy heterogeneous practices of diverse groups of workers. Chartres resulted from the ad hoc accumulation of the work of many men.

The construction of the Gothic cathedrals, such as Chartres, poses a number of questions. How were large numbers of undifferentiated stones assembled into an organized structure? How were the labor and skill of large numbers of men and women coordinated? What was the role of the architect, of drawings, and of scientific knowledge? How were innovations like flying buttresses possible in the absence of a theory of structural mechanics? As a consequence of their presuppositions about distinctions between science and technology and the nature of theory and practice, many authors answer these questions in a way that makes the process seem mysterious and radically different from "modern" construction and design.

The accounts of medieval architecture given, for example, by Jantzen, a historian of art, Bernal, a historian of science, and Heyman, an architectural and engineering historian, create a great divide between then and now. They portray science as an abstract and entirely modern phenomenon and cathedral building as mere technical craft unguided by theoretical or scientific under-

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standing. Hence they are drawn to make an inexplicable mystery out of the Gothic cathedrals. Thus Jantzen writes "an insuperable barrier indeed separates [the medieval] approach to building from ours."[1] Correspondingly, Bernal argues that

> architecture was indeed the greatest and most characteristic expression of medieval thought and technique. It was, however, a purely technical rather than a scientific achievement. The marvellous construction of vault and buttress, far more daring than anything the Romans or the Greeks attempted, was the result of a series of *ad hoc* solutions to practical difficulties. Theory did not enter into them at all, nor could it, for the theory of the arch, apart from working knowledge of it, was only discovered in our time. For the same reason medieval architecture contributed little, directly or indirectly, to the advance of science.[2]

Likewise, Heyman claims that

> it is almost certain that the builders [of Gothic cathedrals] were incapable of even the simplest structural analysis. One of the classic medieval problems was that of the parallelogram of forces, not solved until the end of the sixteenth century; without any rules for the composition of forces, or, indeed, any clear formulation of the notion of a force and of its line of action, it is difficult to see how any calculations can have been done to determine for example the line of thrust in a buttress.
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> There can, however be no doubt of the practical abilities of the masterbuilders; a cathedral which survives almost intact for 800 years is clearly a work of genius. Equally clearly, the structural system employed, measured by almost any yardstick is almost perfect. Certainly advances must have been made by trial and error, by experiments with the actual structure as well as with models. But, looking at, for example, the complete glass curtain-walls of the Sainte Chappelle in Paris, one is tempted to sense a mastery of building technique greater than any that can be ascribed to mere trial and error.[3]

In this article, I reexamine the dichotomies that such authors create between technology and science, between the medieval and the modern, and between the *ad hoc* and the theoretical. The assumption of these seemingly self-evident distinctions makes the construction of the cathedrals into a mystery requiring the invocation of such imponderables as "insuperable barrier" or "genius."

These dichotomies can be resolved and the construction of the cathedrals can be demystified if the Gothic cathedrals are conceived as sites of experimental practice: literally as "laboratories." Arguably, the power of laboratories derives from their potential for assimilating the diverse, but amorphous, phenomena of nature into data that can be assembled, manipulated, and transmitted beyond the laboratory as texts. Laboratory-based procedures for the transformation of nature into accounts can be generally described as *manipulable system*.[4] A key element in the creation of a manipulable system with respect to the construction of the Gothic cathedrals is the template. A template is a pattern or mold, usually outlined on a thin piece of wood, that a stonemason uses to cut a stone to a particular shape. This small item of representational technology has much of the power of a scientific theory; it manifests the integration of science and technology and theory and practice, and it is a solution to the central problem of how knowledge was transmitted. It was the use of templates, along with constructional geometry and a relatively small range of simple tools—compasses, straightedge, and string—that, in an experimental context, enabled the construction of extremely high, radically innovative buildings without a common system of measurement and, in the early Gothic period, perhaps without drawn plans and without continuity of architects or design. In the later part of the cathedral-building period, the use of plans became commonplace, and the role of master mason changed to that of architect. Both of these transitions have served to reinforce a distinction between science and technology and have, I believe, resulted in the modern overemphasis on the role of theory at the expense of practice. This distinction and this overemphasis characterize the traditional view of scientific knowledge and derive from epistemological presuppositions that conceal the local and "messy" practices that characterize the production of technoscientific knowledge in all eras. The differences between the building of Chartres cathedral, for example, and modern technoscientific practice lie not in the possession of some secret or mysterious skill nor in some essential difference between science and technology on the one hand or between theory and practice on the other.[5] Both science and technology, now and in the past, are the product of local and tacit knowledge.[6] The differences between them lie in the social and technical means by which local and messy knowledge and practices are made robust, coherent, and mobile, that is, in the ways in which the site-specific or even problem-specific products are added to the work of previous individuals or groups of workers or transmitted to another site.

Chartres Revisited

After a disastrous fire, Chartres cathedral was rebuilt between 1194 and 1230, with a spire 345 feet high, the equivalent of a 30-story skyscraper.[7] It has stood for nearly 800 years and to modern eyes is a breathtakingly beautiful example of Gothic architecture. Yet, in the 17th century, the period when the major positivistic myths about science had their beginnings, such buildings were abhorred as "congestions of heavy dark melancholic and monkish piles without any just proportion, use or beauty," hence Vasari's dismissive term *Gothic*, literally meaning the product of uncivilized tribal barbarians.[8]

The question of how Chartres was built becomes more acute when the enormous volume of construction in the period is taken into account. So massive a transformation did all this building produce in Europe that it has been called the 13th-century industrial revolution, of which the central dynamic was the "cathedral crusade."[9] Over one and a half centuries, a population of 2.5 million people built 50 major religious buildings, 3,500 churches, numerous abbeys and retreats, military works, palaces, and houses.[10] But not only were the Gothic cathedrals huge, complex, and ubiquitous, they were structurally radical and innovative, combining great height with thin walls and huge windows. In fact, masonry buildings, with rare exceptions such as St. Peter's in Rome and St. Paul's in London, were never to reach such heights again. It was not until the use of iron framing in the 19th century that they could be emulated and surpassed.[11] Inside the Gothic cathedrals, walls were transformed into curtains of glass, pillars became slender columns, and ceilings became delicate traceries of stone. Outside, they reached prodigious heights, seeming to be simultaneously supported and restrained by dramatic flying buttresses. How was all this possible in the early 13th century?

This question has been given a variety of answers by architectural historians, art historians, and economic historians, although, curiously, few historians of technology and virtually no historians of science have addressed the problem.[12] Yet a brief consideration of the analysis of Chartres cathedral[13] by the architectural historian John James makes it apparent that many important issues are at stake. The question "How were they built?" is not a simple technical matter but complex and multifaceted, with political, social, religious, geometrical, economic, aesthetic, organizational, communicational, educational, and constructional aspects, only some of which can be discussed here.

For those raised on the traditional accounts, James's analysis of Chartres is full of surprises. He finds that "the design is not a well controlled and harmonious entity, but a mess."[14] The building has a bewildering variety of buttresses, fliers, roofs, doors, and windows. The bays and, more important, the axes in the nave and transepts are completely irregular, the only regularity being in the interior elevation.[15] According to James, Chartres's style cannot be explained as the result of a coherent Gothic aesthetic or even in terms of gradual transition from Romanesque to Gothic. Altogether there were nine different contractors or master masons[16] who took between 25 and 30 years to build the cathedral in 30 distinct campaigns.[17] There were 13 major design and structural changes in that 30-year period, but there was no overall designer, just a succession of builders.[18] "Chartres was the *ad hoc* accumulation of the work of many men."[19]

Nonetheless, despite being *ad hoc* and a mess and despite lacking a design or coherent aesthetic, Chartres is typically perceived as a unified whole—as a Gothic cathedral. Moreover, Chartres continues to stand without major structural problems, despite the lack of a method of analyzing structure and despite the destabilizing effects of high wind loading, settlement of the foundations, and weak mortar.

"Reconstructing" Chartres with Templates Rather Than Plans

James's account is indeed provocative; it is not surprising that many analysts have taken exception to it. The principal objections leveled against it are rational or logical ones based on the supposition that a building as complex as Chartres could not have been built without a plan or a designer. To the modern mind, the design argument in architecture seems self-evident, just as an analogous argument in biology used to seem self-evident until its displacement by evolutionary theory: The world is a very complex place, full of intricate mechanisms like the eye; therefore, it had to have had a designer. Arguably, the design argument derived its self-evidence from what is popularly still believed about science and architectural practice. Science is held to be the product of great thinkers and designers using laws and theories or plans, and all large buildings are designed by architects and require detailed plans, so that the intentions of the architect can be passed on to the builder. Just as the self-evidential character of the argument from design for the existence of God has been displaced by alternative explanations, so the necessity for an architect for Charters may also become less self-evident in the light of a plausible explanation of how it was built. Concomitantly, the preeminent role of theory and genius in science may also be called into doubt.

All analysts agree that there are no extant plans for Chartres and the architect is unknown, but it is anachronistic to assume, as some historians have, that they *had* to exist.[20] The nature of plans and the role of the architect have changed over time and might well have undergone a transition in the very process of building the cathedrals. Apart from the plan of the monastery at St. Gall dated 820 AD, there are no extant plans from the Western medieval period before 1225.[21] Obviously, absence of evidence is not evidence of absence. Indeed there are good reasons *not* to expect plans to survive. All site plans are subject to the vicissitudes of wind, rain, and wear. They are essentially ephemeral documents that no one would have tried to preserve as such, except possibly the client, as evidence of the worthiness of the project.

Architectural plans did not become art objects until much later. Another plausible explanation for the apparent lack of evidence is that they were drawn on velum, a commodity of some scarcity. Even when heavily degraded through reuse, velum was still sought after for making glue.[22]

The assumption that the essential requirement for the construction of organized complex structures, like Chartres, is a design, a plan, a set of rules, or even a genetic code to specify the whole and its parts by making the process algorithmic explains too little and too much. It does not explain how the cathedrals were structurally achieved and attributes powers to rules that they cannot have. I want to argue that a plan is too strong a requirement and that a minimum requirement is some means of transporting knowledge to and within the structural site and between sites. Can such an explanation be developed for the Gothic cathedrals? The achievement of the order of complexity and structural innovation involved in the construction of the cathedrals required a high degree of precision in the production of the stones and larger numbers of workers as well as types of workers. These factors create organizational difficulties that turn crucially on a fundamental problem: communication. Knowledge and instructions had to move among many participants. For a given building, there had to be clear communication between the ecclesiastical client and the master mason and between the master and other masons on and off site, because some stones were cut at the quarry. Masons also had to communicate with other teams of masons and other workers, principally carpenters who were responsible for the invisible, but nonetheless essential, scaffolding and form work as well as the roof and all the heavy lifting equipment. In addition, knowledge had to be transmitted between sites and across successive generations of masons.

However, these requirements have to be seen against the background of the discontinuous character of the cathedral-building process. The building of all the churches and cathedrals in the Paris basin in this period tended to be conducted in short campaigns.[23] The mortar they used was slow setting and possibly subject to shrinkage. Work may have had to stop whenever a certain number of wall courses had been laid or when the form work for an arch was removed to allow the mortar to dry and the stonework to settle, although major fortresses were raised in single rushed campaigns. The erection of scaffolding, centering, and roofs made for delays in the cutting and laying of stone. The cycle of fund-raising through donation and tithing followed by expenditure also made financing a discontinuous process. Hence James concludes that "the essential reality behind the inventiveness of [the 13th] century resides in the short term campaign."[24]

From our modern vantage point, the construction time constraints and the unequivocal transmission of instructions could only be achieved with drawing.[25] The introduction of site drawings did not occur overnight but was the result of a developmental process. Experimentation with more sophisticated and demanding construction techniques brought with it a need for more detailed modes of representing the parts of the building. One could imagine that the first full-scale drawing of Chartres, like that of Reims Cathedral, was the ground plan that the master mason laid out on the ground. Prior to that, he might only have had a rough model produced as the result of discussion with church authorities.[26] Drawing of some kind is a necessity for instructing the other masons how to cut the stones and where to lay them. Indeed, the beginnings of the technology of representation that is involved in the modern system of architectural drawings may have come about in conjunction with the development of cathedral building. The first reference made to a tracing house attached to a construction site is in an English text of 1274.[27] It is thus at the zenith of the Gothic period that there is evidence of the use of architectural project plans from which site drawings could be traced or derived. However, the use of site drawings in the modern sense is only possible through the use of measurement, and, as we have seen, the 13th-century masons did not have a common measure. Moreover, of 5,000 medieval drawings that have been examined, only 10 have measurements on them at all.[28] Drawings were used, but at full scale like those still extant incised into the stone in the ambulatory at Clermont Ferrand.[29] More commonly, they would have been laid out on sheets of plaster or wood. But regardless of whether there were plans in the modern sense or full-scale drawings, a key device is the template, a pattern or mold that permits both the accurate cutting and replication of shaped stone and the transmission of knowledge between workers.[30]

Cathedrals as Laboratories

How the cathedrals were built becomes understandable if we recognize that the cathedrals were comparable to modern laboratories in three important ways.[31] First, their very construction constituted a series of full-scale experiments. Close observation of the drying mortar enabled the builders to detect areas of stress in the fabric and to take appropriate remedial measures through the placement of buttresses, pinnacles, or reinforcement.[32] (Intuitively, it may seem that one needs laboratories to perform experiments rather than the other way around. However, laboratories are not simply built by architects; they are constituted through the performance of experiments.) Second, laboratories are the spaces in which the local, the tacit, and the messy knowledge and practices of groups of practitioners are transformed through collective work into a coherent tradition. Third, cathedrals, just like 20th-century laboratories, are powerful loci of social transformation, absorbing large amounts of capital and concentrating resources, skills, and labor.[33] Through this process of heterogeneous engineering, machinery, instruments, skill, techniques, theory, raw materials, and social relations are interrelated.[34] This combination of social and material factors constitutes a manipulable system, the establishment and maintenance of which may be considered an essential function of modern laboratories.[35] Such a system in a modern laboratory enables two orders of manipulation: first, of natural phenomena to generate data and, second, of that data into the literature. Similarly, the "cathedral laboratory" provides for the manipulation of unshaped rocks into precision-cut stones and their subsequent assemblage into a stable whole. In both cases, the focus is on getting the experiment to "work" through the process of collective practice.[36]

On this view, answering the question "How were the cathedrals built?" involves seeing them as experimental laboratories in which the key elements were the template, geometry, and skill. The power of the template lies not only in the way it facilitates accurate mass production but also in the fact that simple geometrical rules of thumb will often suffice for the template itself to be accurately reproduced as often as required.[37] The template helps to make possible the unified organization of large numbers of men with varied training and skill over considerable periods of time.

> On them were encapsulated every design decision that had to be passed down to the men doing the carving in shop and quarry. Through them the work of all the masons on the site was controlled and coordinated. With them dozens, and in some cases hundreds, of men were guided to a common purpose. They were the "primary instruments" of the trade.[38]

In addition to the power to organize large numbers of workers, templates have the power to allow for great exactness of stone cutting and enabled a stable, enduring, and coherent structure, despite a discontinuous process and radical design and structural changes. Three major "reversals of force,"[39] are achieved with this one small piece of representational technology: One person can get large numbers of others to work in concert, large numbers of stones can be erected without the benefit of a fully articulated theory of structural mechanics or a detailed plan, and incommensurable pieces of work can be made accumulative.

The template makes possible the transformation of amorphous masses of stone into an enduring, stable structure. It provides a structure whose stability is achieved despite the lack of what we would take to be the basic essentials for producing the specifications for a particular element in a building, a common and precise mode of measurement, a knowledge of structural mechanics, and a detailed scale plan. James's analysis shows that no consistent unit of measure was used and that successive contractors had their own individual measure.[40] Masonry buildings like Chartres are dependent on stability rather than strength to stand. It is possible to achieve stability through proportional rather than structural analysis; hence, in large part, structural analysis was not required.[41] According to Pacey, although the masons

> lacked the knowledge of a modern engineer . . . it is clear that [they] usually knew very precisely where the buttresses ought to be and at what height their counter pressures were needed. To this extent, then, their experiments were guided by knowledge. Their trial and error was not just groping in the dark for they had a considerable insight into what shape a building should be, insight which was aided by geometrical rules of design. . . . As it turns out, the successful design of masonry structures depended more on getting the shape, that is, the geometry, than on calculating the magnitude of forces in the modern way.[42]

Thus an essential ingredient is geometry. In the absence of rules for construction derived from structural laws, problems could be resolved by practical geometry using compasses, a straightedge, ruler, and string. The kind of structural knowledge that is passed on from master to apprentice related sizes to spaces and heights by ratios, such as half the number of feet in a span expressed in inches plus one inch will give the depth of a hardwood joist. These rules of thumb were stated as, and learned as, ratios; for, as the span gets larger, the depth of the joist will too.[43] This sort of geometry is extremely powerful. It enables the transportation and transmission of structural experience, it makes possible the successful replication of a specific arrangement in different places and different circumstances, it reduces a wide variety of problems to a comparatively compact series of solutions, and it allows for a flexible rather than rigidly rule-bound response to differing problems.[44]

The sort of geometry that is required is not that of Euclid; rather, it is a set of rules for deriving ratios and proportions through the division of squares and circles using compasses, what Shelby has usefully called "constructive geometry."[45] Essentially, it enables a dimensionless analysis precluding the need for a common measure. Geometrical techniques in this case are a powerful mode of communication that dissolve the potentially incommensurable use of individual measurement systems.

However, geometry alone is not enough: It has to have a material manifestation—the template. Templates could either be derived from an exposed section of earlier work or set out directly by the master masons using their knowledge of geometry. They were then used by a mason to cut stones to specification. Although simple stones could be cut without them, complex irregular stones would require several templates, and many hundreds would have to be cut in the course of construction. Templates, in their more durable form, were a valuable possession; master masons may have taken them from job to job. Different geometrical techniques could be used to make them. This fact allowed for the possibility of individual stylistic variation. The techniques themselves were relatively simple and enabled master masons to show ordinary masons how to prepare them for particular tasks.[46]

Templates are models or patterns, that is, accepted, concrete, local, or indexical solutions that can be applied to other problems. Thus they perform the role of exemplars, the more restricted sense of Kuhn's paradigms. This use of portable solutions as opposed to fully articulated and consistent plans to build cathedrals and transmit knowledge is reflected in the "model books" of the time, like that of Villard de Honnecourt. Printing not yet having been invented, the only way to compile and transport knowledge, in addition to the tacit knowledge of the master masons and their templates, was in the collections of drawings of model solutions known as model books. These books have some interesting characteristics: They seem to our modern eye completely unsystematic, putting together drawings of human figures with machines and architectural details, and they also never show anything in its totality, only partial views or, at best, particular elevations.[47] Hence it seems that they do not presuppose the kind of ordering we take for granted. Instead they assume that order can be created out of the aggregation of model solutions or paradigms.

The point of this extended examination of the role of plans, geometry, and templates is twofold. It shows that the building of the cathedrals is not mysterious, nor is it a merely practical matter. What it takes is the establishment of a laboratory and the joint deployment within it of a mode of proportional analysis and a small innovation in the technology of representation, the template. By analogy, modern technoscience, which is a large complex structure requiring the integration of the local knowledge and skills of a wide range of people, may also succeed in constructing a unified edifice without the benefit of anything so intangible as the scientific method or fully articulated theory. The local, contingent, and theory-independent nature of modern technoscientific practice is illustrated by the remark of Peter Brookes, the architect of a 39-story skyscraper in Melbourne, who commented:

> The principles of the shape and structure are well known, but the detailed solutions always vary. Actually building it is rather like a gigantic experiment and you are never really sure what it will end up looking like.[48]

Form and Function

Contemporary technoscience is often portrayed as being governed solely by the dictates of its own internal logic. An aphoristic version of this technoscientific determinism is "form follows function." It was Pugin's articulation of this principle in his precipitation of the Gothic revival that has led to the virtual equation of modernity and good design with the idea that function and technology have aesthetic and social primacy.[49] Because Pugin derived the concept from his understanding of Gothic architecture, we can now go back to the Gothic cathedrals and reexamine the question: Is the structural form of the Gothic cathedrals dictated by the requirements of high stone buildings? The rationalists, like Viollet-le-Duc, who was responsible for much of the restoration of the French cathedrals in the mid-19th century, argued that such characteristic Gothic features as flying buttresses, ribbed vaulting, and pointed arches are the consequence of functionalist minimalism, that they are the optimal structural bones. The illusionists, on the other hand, would have it that they are dictated by stylistic considerations rather than by necessity.[50] Recent evaluation of Gothic structures suggests that neither of these understandings hold true but that a degree of rational functionalism is employed in the service of a higher aesthetic.[51] Buildings of that height would not be feasible economically, nor would the foundations take the weight unless they used techniques that optimized the use of stone, hence the functional and economic necessity of the slim "misshapen" pillars abhorred by Evelyn. Equally, such tall buildings had to be able to resist high wind loading; hence the flying buttresses were functionally required as props. In turn, the vertical buttresses on which the fliers depended had to be able to resist the shear loading, hence the otherwise apparently redundant pinnacles. In contrast, the much-vaunted ribs serve no structural function, the thickness of the walls is deliberately concealed, and the flying buttresses are not always maximally effective. In the case of Laon Cathedral, the buttresses were added later to conform to the 13th-century aesthetic, and some of the Gothic cathedrals, like Beauvais, may even exceed the structural limits.[52] Simson has argued that "we find it necessary to suppress the symbolic instinct if we are to understand the world as it is rather than as it seems. Medieval man conceived the symbolic instinct as the only reliable guide to such an understanding."[53] Medieval man integrated form, function, and geometry as a "graphic functionalism" in the attempt to create a literal "image of heaven."[54]

Thus, in the case of the Gothic cathedrals, the idea that form follows function only has cogency when abstracted from the interests of the builders and from the "technoscience world" in which it is embedded.[55] The ogival arch, the flying buttress, and the ribbed vault—all make possible certain forms that the limits of material reality make difficult or impossible without them, but these technically functional elements can only constrain rather than determine the actual outcome, the realized form. There is no deterministic internal logic of function or of form. The structure of the cathedrals results from the combined forces of religious beliefs and aesthetic values, a developing, but limited, set of building practices, economic opportunities, modes of communication, and the work of others. These factors all interact as a whole to produce a particular form. The "Gothic style," as such, was not in the minds of the cathedral builders. They had no theory of the Gothic, nor could they have. The notion of a particular style implying a unifying set of rules or principles is a construct of contemporary analysts and critics. The enduring existence of the Gothic cathedrals creates an impression of an irreversible process driven by a determinate logic. That impression serves to deny the contingent and the accidental way in which the cathedrals were actually built.[56]

Theory, Collective Practice, and Technoscience

This contextualization of the relationship between form and function also opens up the question of the relationship between theory and practice and between science, technology, and design. If form rigorously followed function, it would imply that the form of a building is determined by the physical laws governing the behavior of the structure, that the builder had some understanding of the forces at work, and that technology follows science as applied knowledge, tacit or otherwise. On the face of it, this seems unlikely in the case of the Gothic cathedrals. There are two kinds of reasons for thinking this to be the case. One is historical, and the other derives from an analysis of contemporary structural practice, which throws fresh light on this fundamental issue.

There is no written evidence of an adequate understanding of basic structural mechanics until Galileo's *Two New Sciences* in 1638, but this does not imply, as some commentators have suggested, that the cathedral builders had *no* knowledge of structural mechanics.[57] Galileo did not create his laws out of whole cloth. In the very period when the cathedral builders had to resolve some profound structural problems, Jordanus Nemorarius and others were starting to develop theoretical statics.[58] Hence it seems highly likely that the development of the theoretical laws of structural mechanics had its beginnings in the very process of their application, in building the cathedrals and schools in which scholars, monks, and masons were trained. This historical observation contradicts the old orthodoxy that technology is a derivative of science, which has also been challenged by the claim that science and technology are largely autonomous practices and owe little to each other until they become fully entwined in the late part of the 20th century.[59]

Both of these historical accounts are arguably based on a conception of science as written lawlike knowledge and its transmission through texts. There are, I suggest, three reasons to reject both views of the relationship between science and technology. First, physical laws, although having great explanatory power, are, by virtue of their abstraction, nonetheless false when it comes to the description of particular circumstances. Second, the role of theories and laws in the building of large contemporary structures has often been misconstrued, and hence their role in the past has also been misconstrued. Third, the issue at stake is not one of understanding the development of general theory but, rather, one of how knowledge created in one circumstance is made to work in another.[60] In other words, the problem, in both science and technology, is not one of putting theory into practice but one of the transmission of practices. It is small social and technical variations in effecting that transmission that account for differences in knowledge systems. These differences between knowledge systems have been misconstrued as evidence of a great divide between the pretheoretical period and the present and between Western and traditional cultures.[61]

The received view of contemporary physics is that it consists in large part of an accumulated body of true, or at least highly confirmed, theories and laws, much of the evidence for which consists in the effectiveness of the technology derived from them: Bombs go bang on command, television sets show pictures, and men have landed on the moon. However, strictly speaking, the laws of physics are false.[62] They have explanatory power, but this, and the fact that they work, is no guarantee of their truth. To generate solvable equations with usable solutions in particular circumstances, the laws have to be so modified through the process of simplification and inclusion of specification of those circumstances that they are no longer general laws, but empirical generalizations.

The issue of knowledge transmission and the site-specific character of scientific knowledge are reflected in the actual practice of engineers. David Billington in an analysis of the "new art of structural engineering" argues that science tries to produce general unifying theories, whereas engineering aims for solutions with a limited range of application. He cites the case of

> Robert Maillart, the Swiss bridge designer, [who] developed in 1923 a limited theory for one of his arched bridge types that violated in principle the general

> mathematical theory of structures and thereby infuriated many Swiss academics between the wars. But Maillart's limited theory worked well for that special type of form. Within that category type Maillart's theory was useful and had the virtue of great simplicity; he developed the theory to suit the form, not the form to suit the theory.

In contrast, Billington claims, the American bridge designers of the early 20th century were convinced that effective bridge design should be derived from general theory. This obscured their familiarity with the tradition, that is, their knowledge of the success and failure of particular bridges in the past, as is shown by the defective design of many major bridges in the 1930s and the Tacoma Narrows Bridge collapse of 1940.[63]

Thus it seems reasonable to suppose that the Gothic cathedral builders, like the builders of today, did not need a generalized theory to achieve successful practice. Instead, they needed case-specific solutions, or exemplars. So the question then is how those solutions were transmitted.

Knowledge can be transmitted in a variety of ways. It can, as Bachelard suggests,[64] be "frozen" into the technique, in this case the technique of using geometry and compasses, being materialized in the form of portable templates. It can also be transmitted through education and the establishment of a tradition. A tradition may or may not include theories and texts but always includes training, development of skills, and the knowledge of previous structures and solutions. As Billington has argued, a "tradition" is essential in engineering, that is, a historical awareness of previous successes and failures.[65] This is, of course, exactly what Mark and James have argued for the Gothic cathedrals.

Building on the work of others sounds like a recipe for dogmatism and stasis. How can you use the work of your predecessors or peers to build things that the world has never seen before? Further, how can you do it without theory or plan, without an overseer, and without a common measure? The answer in the case of cathedrals is that it is done with precision-cut stones, geometry, and experiment. Provided that the stones are sufficiently well cut according to a system of proportion and are assembled in a way that contains all the thrusts within vertical columns of stone as revealed in previous building, then accumulation and innovation is possible, given one other factor, namely, motivation or interest—in this case, the religious and aesthetic urge to create heaven on earth.

This characterization of cathedral building resonates very strongly with Holton's description of modern science

> The scientists' chief duty [is] not the production of the flawlessly carved block, one more in the construction of the final Temple of Science. Rather it is more like participating in a building project that has no central planning authority,

> where no proposal is guaranteed to last very long before being modified or overtaken, and where one's best contribution may be one that furnishes a plausible base and useful materials for the next stage of development.[66]

The "Technoscientific World" of the Cathedral Builders

The cathedrals were both the focus and the motor of the 13th-century industrial revolution. They were a direct expression of the resurgent integration of the commercial and religious life that accompanied the development of cities and the influx of capital in Europe following the crusades and the transformation of agriculture produced by the horse collar, the mold board plow, the horseshoe, and the three-field rotation system.[67] Although the cathedrals were dependent on the availability of finance and the growth of cities, they in their turn produced a massive transformation of the organization of labor, resources, and knowledge. Groups of tradesmen, masons, sculptors, carpenters, glaziers, smiths, and tilers began to develop. As White has pointed out, the Gothic cathedrals "are the first vast monuments in all history to be built by free- nay unionized-labor."[68] A massive development of resources and trades took place; quarries opened up, roads and transport expanded, and glass making and window making were transformed, as were metal working, stone working, and carpentry.

> At Chartres, the building of the cathedral attracted numerous artisans. Work on this enterprise . . . undoubtedly transformed the upper part of the town into one immense building site that occupied, directly or indirectly, an entire population of workers.[69]

But the biggest transformations were in the organization and integration of all this money, resource, skill, and religious fervor. These were principally changes in the way knowledge was produced, used, and transmitted. Along with the cathedral came not only the emergence of the role of the master mason, the master carpenter, the glazier, and the sculptor but also the lodge or guild and the itinerant tradesman who took the whole of Europe as his workshop. The lodge was originally a temporary building on the construction site to shelter the masons while they carved the stones. Eventually, it became the cooperative institution whereby knowledge and skills were transmitted through apprenticeship, mutual exchange, and accumulation as manifested, for example, in the lodgebooks.

At the same time, cathedral schools and universities began to develop. The close integration of commerce, trade skills, religion, and classical education appears not only in the fabric of Chartres, which has windows and chapels devoted to the guilds and the seven liberal arts as well as the major religious figures, but also in the social institution it housed. It was at Chartres that Bishop Thierry set up the cathedral school that was one of the first in the West to study natural phenomena. It was also where many master masons received their education, in keeping with the school's policy of bringing together men of the liberal arts and men of the mechanical arts, the intellectuals and the highly skilled workmen, science and technology.[70] This attitude is reflected in some of the founders of experimental science writing in this period: Robert Grosseteste, Roger Bacon, and Peter of Maricourt, who, for example, said in his treatise on magnetism *Epistolae de Magnete*

> You must realise, dearest friend that while the investigator in this subject must understand nature and not be ignorant of the celestial motions, he must also be very diligent in the use of his own hands, so that through the operation of the stone he may show wonderful effects. For by his industry he will then in a short time be able to correct an error which he would never do in eternity by his knowledge of natural philosophy and mathematics alone if he lacked carefulness with his hands. For in investigating the unknown we greatly need manual industry without which we can usually accomplish nothing perfectly. Yet there are many things subject to the rule of reason which we cannot completely investigate by the hand.[71]

The cathedrals were thus dependent on a range of social, religious, and technical roles and activities that the cathedral building at the same time served to create. They were constitutive of a "technoscientific world."

Master Mason to Architect: Theory Splits from Practice

At this point in the middle of the 13th century, the acme of the Gothic period, science and technology were one in Chartres cathedral, and theory and practice were uniquely synthesized in the knowledge and skills of the master mason. However, as the role of the master mason evolved into that of the architect, so theory became divorced from practice, and skill became expertise. Eventually, the structural principles of Gothic architecture were lost, never to be recaptured. In 1568, Philibert de l'Orme could still describe the Gothic as "the modern way of vaulting," but, by 1711, it had been forgotten, when the clock tower that Louis XIV tired to have built collapsed and was abandoned after the efforts of five architects. In the end, tie bars and supplementary arches and floors had to be used, exactly the kind of prop the Gothic technique eschewed.[72]

Most commentators agree that the role of the mason began to change about the middle of the 13th-century.[73] The transition seems to have begun after the completion of Chartres and about the time when the masons' lodges started up.[74] Whether there is a causal connection is debatable, but it is in this period that the preacher Nicholas de Biard complains

> The masters of the masons, carrying a baguette [measuring rod] and gloves, ordered others to "cut it there for me," and worked not at all, although they received a larger payment; it is this way with many prelates.[75]

By the 16th century, a fundamental shift had occurred in the role of the masons' craft in the art of building. As the social and professional status of the architect rose, the mason dropped gradually into the role of serving merely as a builder for the architect. As execution and design became separate, the education and training of the mason and the architect became distinct. A new-style gentleman architect emerged who did not serve an apprenticeship but learned from books and thereby avoided the taint of being, or associating with, craftsmen.[76]

The split between theory and practice, an essential characteristic of the process of the division of labor, had been rather atypically disavowed by Vitruvius, the Roman architect and military engineer, whose text *De Architectura* was one of the very few to be available throughout the Middle Ages, although it was unlikely that it was read by or known to any masons. Vitruvius defined architecture as a discipline consisting of *both* practice (*fabrica*) and reason (*ratiocinatio*).[77] In antiquity, it had been commonplace to deprecate handiwork and separate it from theory and mathematics.[78] It was again commonplace by the 15th century, as can be seen in the work of Alberti, the first Renaissance architectural writer, who separated design from construction; and it has remained so until now. Interestingly, contemporary bridge building may, like the Maillart example, show a countervailing trend. The most recent advances in which cable-stayed bridges are being built across unprecedented spans are not due to any breakthrough in materials or design. Rather,

> the construction industry . . . has been able to extend the boundaries of bridge technology by getting its designers, builders and computer specialists to work together more closely.[79]

At the height of the Gothic cathedral-building crusade, theory and practice were firmly integrated in the activities of the master masons, in their training, and in their texts. But, as theory became divorced from practice, the master masons became architectural "experts," and it was experts who were commonly consulted whenever difficulties arose. The building of Milan Cathedral begun in the late 14th century is an example of the decline associated with these transitions. Following the laying of the foundations, the Italians became uncertain of how to proceed and called in a succession of foreign experts to resolve a fundamental dispute over what system of proportion to use, the square or the triangle, and what should be the basic units of measurement. After the French expert Jean Mignot arrived, the consultative process degenerated into an acrimonious debate in which the Italians claimed,"*scientia est unum et ars est aliud*" (theory is one thing, practice another). To which Mignot gave his famous retort, "*ars sine scientia nihil est*" (practice is nothing without theory).[80] Although this may sound like a scientific expert scoring a blow for rationality over dogmatic traditionalists, the discredits are about evenly distributed. Mignot, under the guise of *scientia*, was in fact trying to impose on the Milanese the system of proportion based on the square more familiar to his northern colleagues, but without any real understanding of its use in practice, whereas the Milanese were so removed from the principles of Gothic architecture that they claimed that the pointed arch exerts no thrust on the buttresses.[81] In the end, the Milanese viewpoint prevailed and the cathedral stands to this day. By this, time theory had become completely sterile and almost totally divorced from practice.

Conclusion

The Gothic cathedrals constitute a potent and illuminating example of the ways in which technoscientific knowledge was produced in the 12th and 13th centuries. They were large-scale laboratories, sites of experimental practice where the collective work of skilled specialists was aggregated, producing a manipulable system—a working experiment consisting of the cathedral itself. This was possible in the absence of fully articulated structural theory, specified design or plans, or common measure, because the builders developed ways in which their local and tacit knowledge and their messy practices could be combined and transmitted to other sites in the form of skills, geometric method, and templates. This constituted a tradition of shared solutions and skills in which theory and practice were integrated and no strong distinctions were made between science and technology.

The example of the Gothic cathedrals undermines some of the great myths about science and technology. There is no great divide between the past and the present or between science and technology. Technoscience then and now results from site-specific, contingent, and messy practices. It can be and often has been *ad hoc*, un-unified, atheoretical, and lacking a common measure, yet still result in robust structures and traditions. Fundamentally, like the cathedrals, technoscience is the product of collective practice based on the earlier work of others.[82]

Notes

1. Jantzen (1962, viii)

2. Bernal (1965, 310)

3. Heyman (1966, 249)

4. Turnbull and Stokes (1990). See also Latour (1986).

5. Science and technology are being increasingly recognized as interactive rather than as derivative one from the other. See, for example, Barnes (1982), Layton (1987), and Staudenmaier (1985). However, although science and technology may take place in different social contexts, at the cognitive and instrumental level, they are inextricably interwoven and are only analytically distinct. Hence I use the term *technoscience* wherever possible, following the suggestion of Latour (1987, 174). See also Turnbull (1991).

6. On tacit knowledge, see Polanyi (1958), Collins (1985), Cambrosio and Keating (1988), Hindle (1981), and Vincenti (1990). On the local and messy practices of science, see Knorr-Cetina (1979, 1981, and 1983). On the achievement of robustness, see Star (1989, 1990). On moving local knowledge, see Turnbull (1992), Latour (1986, 1987), and Rouse (1987).

7. Gimpel (1961, 5). This comparison was first drawn by Henry Adams, one of the early celebrants of modernism in architecture as technology and has been frequently repeated ever since (Adams [1931, 342ff]; see also Branner [1965, 25]).

8. "Goths, Vandals and other barbarous tribes subverted and demolished their Greek and Roman art introducing in their stead a certain fantastical and licentious manner of building which we have since called modern or Gothic: congestions of heavy dark melancholic and monkish piles without any just proportion, use or beauty, compared with the truly ancient.

"They set up these slender and misshapen pillars, or rather bundles of staves and other incongruous props to support incumbent weights and ponderous arched roofs without entablature.

"For proof of this I dare report myself to any man of judgement, after he has looked awhile upon King Henry VII's Chapel at Westminster, gazed on its sharp angles, narrow lights, lame statues, lace and other cutwork and crinkle-crankle and then shall turn his eyes on the Banqueting House built at Whitehall by Inigo Jones after the ancient manner" (Wren [1750] 1903, 174-75).

"Then new architects arose who created that style of building for their barbarous nations which we call Gothic and produced some works which are ridiculous to our modern eyes but appeared admirable to theirs" (Vasari [1550] 1963, 1:12).

9. Gimpel (1961).

10. James (1979, 11) and James (1984).

11. Condit (1964, 79).

12. An exception is Crombie (1959, 205-6), who allows that "thirteenth century architects must have had a greater ability to generalise the problems of stress and weight lifting involved than the poverty of theoretical writings might suggest."

13. James (1985).

14. James (1985, 9).

15. According to Kostof (1977, 91) the slight irregularities, which accurate surveys reveal, can be accounted for by the fact that the cords used to lay out the building were stretched bay by bay.

16. James (1985, 26).

17. James (1985, 60).

18. James (1985, 60).

19. James (1985, 123), Harvey (1974, 32-33) comes to a similar conclusion about English cathedrals. "There is not a single English cathedral, except the Renaissance St. Paul's, which

was built from start to finish under the supervision of its original architect. Nor is there any medieval cathedral save the last, Bath, which was in essentials finished according to the intentions of its designer, and still retains those essentials unchanged. Most of our cathedrals resemble that other homely product of England, the patch work quilt."

However, many analysts have taken issue with James's account. For example, Mark (1982, 16, n. 10) disagrees with James about the lack of an overall scheme, as does Kostof (1977, v), who argues that "buildings of substantial scale or a certain degree of complexity must be conceived by someone before construction of them can begin" and, again, that "the notion that Gothic cathedrals were the triumph of anonymous team work or the conjuring of scholarly churchmen cannot be seriously entertained" (p. 77). Similarly, Shelby (1981) rejects James's thesis that there was a succession of contractual crews and no overall architect. See also Murray (1981).

There is, however, no clear agreement about how the cathedral was built. See Van der Muelen (1967). But the analysis in Murray (1987, 5-7) broadly confirms James's account of cathedral building as a discontinuous process.

20. See, for example, Harvey (1975, 120): "No building of any size, or of high quality was ever produced by simply 'having a bash' without some drawing as a vital prerequisite." Or see Bucher (1968, 70): "The large number of Gothic plans makes it likely that extensive careful and detailed planning accompanied the erection of large structures at least from the beginning of the thirteenth century."

21. The issue of the existence of plans and their role is extremely controversial. According to Branner (1963, 129) "It was Gothic Architecture with its emphasis on linearity that seems to have called modern architectural drawing into being. . . . [And] Project drawings—those from which buildings could be constructed—were made by Roman and Byzantine architects, but contrary to current belief, it is highly questionable whether they were used in the early medieval west." According to Mark and Clark (1984, 251), the earliest evidence of the use of drawings to record and transmit architectural ideas dates from about 1225, almost at the time when Gothic construction began to decline. Although Scheller (1963, 1) argues rather conservatively that there are "few if any drawings pre 1350," Shelby (1981, 175) argues that "architectural drawings were only just coming into use as controlling documents in the design process when Chartres was built." Shelby (1965, 242) also points out that "in medieval building practice, plans and elevations did not possess the supreme importance they do in modern times, but during the later Middle Ages drawings came to be more and more widely used." According to an anonymous referee, "the earliest extant Gothic plans and elevations are in Villard de Honnecourt and date circa 1225. There is clear evidence of their earlier existence in Picardie and Champagne," a conclusion that is accepted by Harvey (1975, 119): "The mere fact that surviving drawings in England are extremely rare has led to the sweeping conclusion that technical *working* drawings were not made. This is countered by the continental material." Study of the continental drawings . . . [confirms] that detailed drawings were usual—and indeed essential—for the execution of all major works from about the middle of the 13C if not before. However earlier writers have taken a different view. Andrews (1925, 2) writes, "That the mediaeval builder frequently began operations with little else pre-arranged than the general scheme of the building, may be quite safely affirmed. They appear to have had but few drawings of any sort, and those that they had, when compared with the work they allege to have forecast, are difficult to reconcile or even understand because of their crudity and incompleteness." And (p. 8) "no individual designer *qua* architect was existent and *per se* he was not necessary." Blomfield (1912, 13-18) doubted "that the necessity for working drawings was seriously felt by the Gothic builders." Kostof (1985, 4) confirms the view of Andrews and Blomfield despite his claim that "there are extant architectural drawings from as far back as Ancient Egypt and Mesopotamia. Indeed, it is hard to see how any structure but the simplest and most traditional could be built without the

benefit of such preliminaries." He goes on to argue that "a cursory sketch plan was enough to record these [initial geometric] choices. All details would be designed on site and executed individually. The architect supervised every step; he provided templates for every twist of tracery. Improvisation and on-the-spot reversal during the building process were not uncommon" (p. 405).

22. See Kostof (1977, 75) and Branner (1963, 135).

23. James (1989, 2-6).

24. James (1989, 6). James's conclusion may have to be qualified slightly in light of the possibility that mortar shrinkage may not have been a problem, as an anonymous referee points out in the case of fortresses.

25. See, for example, Harvey (1972, 101).

26. See Branner (1963, 130).

27. Branner (1963, 131).

28. Bucher (1979, 10).

29. Branner (1963, 131 and 134).

30. Harvey (1972, 119 and 174).

31. Wilson (1979, 29-30), an American physicist, has also drawn similar parallels: "As an accelerator builder, I have found great satisfaction in relating to the men who built cathedrals in the thirteenth century. When Ernest Lawrence built his cyclotrons with a dedicated passion he was not different from Suger, also with a dedicated passion, building the cathedral St Denis. The Abbot Suger was expressing a devotion to the church with his exalted structure, a structure that transcended all contemporary knowledge of strength of materials. And Lawrence too expressed, in his fashion, a devotion to the discovery of truth. He too transcended contemporary technology in attaining his dizzying heights of energy. I am sure that both the designers of the cathedrals and the designers of the nuclear accelerators proceeded almost entirely on educated intuition guided by aesthetic considerations (p. 30). Of course, building, even designing, a large accelerator is a complex team activity–just as it was for the cathedral.

32. Mark (1982, 56).

33. Touraine, *Production de la société* (1973), cited in Callon, Law, and Rip (1986, 4).

34. Law (1987).

35. Turnbull and Stokes (1990).

36. On the collective work required for robust results in science, see Star (1990).

37. See James (1985, 34), James (1979, 11:543), and Harvey (1974, 119 and 174).

38. James (1989, 2). See also Shelby (1971).

39. On the reversal of forces, see Latour (1987).

40. James (1985, 34 and 40). He argues that such measures were so precious as possessions that they could be willed to their successors and may have been talismans of authority. He claims that there were no universal foot units in the Middle Ages; each town had its own, often maintained in a metal replica set up in some public place so that strangers could equate the foot of their own region with the local one. Each trade also had its own unit.

41. Heyman (1966, 251).

42. Pacey (1974, 48).

43. James (1979, 11:543-49).

44. Bucher (1968, 71).

45. Shelby (1972). See also Sanabria (1989). Such geometry is also comparable to the "gauging" that merchants used in the 15th century to measure volumes of unstandardized barrels, sacks, and bales. See Baxandall (1972, 86).

46. Shelby (1981, 174) argues that it is this last factor that may explain the uniformity within sections of Chartres and the discontinuities between sections that James's analysis suggests,

without having to accept James's proposal that it was built by a series of completely unconnected contractors.

47. See Rosenberg (1936, 364) and Scheller (1963, 3): "In an age when no other reproduction methods were known it was the drawing book which transmitted iconographic and formal elements from place to place, from atelier to atelier, from generation to generation."

48. Watkins (1990, 7).

49. Pugin (1841, B) argued that all features should reflect the purpose and materials. "It is in pointed architecture alone that these principles have been carried out."

50. Mark (1982, 3).

51. Mark (1982), Heyman (1966), Rosenberg (1936), Billington and Mark (1984a), Condit (1984), Billington and Mark (1984b), and Mark and Billington (1989).

52. Mark (1982), Heyman (1966), Rosenberg (1936), and Stoddard (1972, 133).

53. Simson (1956, xix).

54. Simson (1956, 6-8).

55. A technoscience world is the constellation of social roles and collective practices that provide for the possibility of scientific and technical knowledge in a particular society. For a discussion of "science worlds," see Chambers and Turnbull (1989, 160). The concept owes much to Becker (1982).

56. "Medieval architecture followed no predetermined course and there was in the line of its development no immanent necessity. It is only the irreversibility of what has happened that, after the fact, turns accident into necessity" (Bony 1980, 29). This effect is called black-boxing by recent sociologists of technology; see, for example, Latour (1987).

57. See Mark (1982, 3).

58. Crombie (1959, 1:203).

59. See, for example, Mulkay (1979) who claims that "science seems to accumulate mainly on the basis of past science and technology on the basis of past technology." And again, White (1978) argues that "technological achievements and problems cannot be shown to have had much direct influence on the growth of medieval science, and scientific discoveries did not affect the growth of technology" (p. 83). Likewise Vincenti (1990) claims a "fundamental difference between engineering as the creation of artifacts and science as the pursuit of knowledge" (p. 112).

60. Rouse (1987) in his stimulating analysis of "local knowledge" argues, "Knowledge is extended outside the laboratory not by generalization to universal laws instantiable elsewhere, but by the adaptation of locally situated practice to new local contexts" (p. 125).

61. See Latour (1986, 4, Latour 1987, 211) and also Addis (1983, 1).

62. See the thorough analysis of this issue by Cartwright (1983).

63. Billington (1985, 8-10).

64. Bachelard (1985, 13).

65. Billington (1977).

66. Holton (1984).

67. Mark (1972, 90) and White (1978, 15-17).

68. White (1978, 63).

69. Simson (1956, 170).

70. Gimpel (1977, 141ff).

71. Quoted by Gimpel (1977, 176).

72. Rosenberg (1936, 274).

73. Simson (1956, 220).

74. Simson (1956, 222).

75. Gimpel (1961, 136).

76. Shelby (1977, 3ff).

77. Long (1985, 267).

78. See Burford (1972) and Geoghegan (1945, 229).

79. O'Neill (1991, 32). Hoch (1990) also argues the necessity of moving people together to achieve a "resynthesis of existing knowledges and techniques."

80. Frankl (1960, 79).

81. Frankl (1960, 72). See also Harvey (1972, 162) and Ackerman (1949).

82. This view of technoscience practice is consonant with the work of Suchman (1987), Star (1990), and Lave (1988), who have all found that individuals can make rational sense of the world without the guidance of plans, theories, or articulated mathematics.

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