Architecture and Evolution

In the debate over adaptation, which view is best served by the metaphors of the "spandrels" of San Marco and the bosses of King's College?

Robert Mark

To support their criticism of the evolutionary precept of *adaptationism,* biologists Stephen Jay Gould and Richard Lewontin in 1979 devised an analogy rooted in historical architecture. In a paper that soon became famous, they asserted that in designing a building, it is absurd to accept decoration applied to the interior as the determinant of the form of its structural elements. By analogy, Gould and Lewontin criticized arguments about evolution that emphasize immediate biological utility and pay little attention to other attributes of form. They decry, for example, the various "untestable speculations based on secondary utility" offered to explain the stunted front legs of a *Tyrannosaurus*; it makes far more sense, they contend, to accept its abnormal form as "the reduced product of conventionally functional homologues in ancestors." In other words, adaptationsim places so much faith in natural selection as an optimizing agent that an organism "is broken into unitary 'traits' and an adaptive story for each is proposed separately." In some cases, a viable explanation based on adaptation cannot be devised and should not be, Gould and Lewontin wrote.

Gould and Lewontin's principal metaphor, based on the so-called decorated spandrels of Saint Mark's Cathedral (Basilica de San Marco) in Venice, has come to pervade evolutionary discourse. For example, in his 1992 text on evolution George Williams categorically states "New structures arise in evolution in one of two ultimate ways, as redundancies or *spandrels.*" Gould himself recounted how a colleague asserted "We have all been spandrelized." This mindset, however, is not shared by every commentator on evolutionary theory. The analogy came under heavy fire during the past year from philosopher Daniel C. Dennett, as part of a general assessment of Gould's beliefs. Gould, he notes in his book *Darwin's Dangerous Idea,* "needs to have a term for the (presumably many) biological features that are not adaptations." Yet, according to Dennett, there are problems with the analogous architectural elements chosen by Gould and Lewontin, as well as with Gould's biological speculations.

I leave it to others to pursue the evolutionary side of the argument; the function of the historical architectural elements, however, *can* be clarified. By considering the structural mechanics of ancient buildings and by following the historical path of development that led to the adoption of architectural elements in the buildings cited by Gould and Lewontin, we can analyze the suitability of the architectural metaphors they used.

Robert Mark, professor of civil engineering and architecture at Princeton University, has pioneered the application of modern engineering modeling for the study of historical buildings. Several of these studies, which have brought new focus to architectural history as well as to the conservation of historic buildings, have been reported on previously in American Scientist *(Winter 1968, September–October 1978 and March–April 1987). Address: School of Architecture, Princeton University, Princeton, NJ 08544-5264.*

The Evolution of Building Technology

A thorough understanding of the structural mechanics of ancient buildings has become possible only in recent decades, with the development of experimental and numerical modeling techniques capable of reliably analyzing complex historical architectural forms. These techniques, particularly when applied in the context of information available from primary documents and from archaeological examination, have greatly enhanced our understanding of architectural innovation. They have also helped illuminate the methods used by prescientific builders to achieve remarkable success in erecting large-scale structures. Although primary geometric forms—particularly those that could be simply laid out using common instruments such as a straight edge and a compass—were extensively used in conceptual design, they were modified as needed to assure structural stability. Realizing that confidence in a new building's ability to resist collapse could never have been gained merely from applying simple geometric rules, I have sought to identify other sources of the early builders' structural knowledge.

Chief among these is the fact that building technology itself follows an evolutionary pattern. Practical experience with earlier buildings once furnished much of the information about building performance that today comes from engineering modeling. In effect, an earlier building served as a "model" for a new design. The technological elegance of many early structural solutions led me also to discern that during construction the master builder used a technique that, although available to today's designers, is rarely employed, because of the usual separation of the modern design office from the construction site (and sometimes, too, because of misplaced confidence in modern analysis methods). During construction the builder made detailed observations of any undesirable behavior—particularly cracking in the building fabric. Steps taken to remedy these shortcomings then led to refinements in the design.

None of the results of these new architectural studies has informed any of

The Royal Collection, Her Majesty Queen Elizabeth II

Figure 1. Domes of Saint Mark's Cathedral in Venice, painted by Canaletto in the early 18th century, have become the unlikely subjects of a continuing debate concerning the role of adaptation in evolutionary theory. Evolutionists Stephen Jay Gould and Richard Lewontin proposed in 1979 an architectural metaphor to elucidate their view that not all aspects of form have immediate biological utility. They cited the decoration of the "spandrels"—the triangular areas between Saint Mark's arches and the domes—as well as the embellished bosses in the vaults of King's College Chapel in Cambridge, as architectural by-products, analogous to the nose furnishing support to spectacles. Critics, most notably philosopher Daniel Dennett, have taken Gould and Lewontin to task for both the architectural elements chosen and their biological speculations. Meanwhile, experimental and numerical modeling techniques have recently made it possible to structurally analyze the complex elements of historical architecture. The author applies such knowledge to the function of spandrels, bosses and similar architectural elements, judging their metaphoric suitability to the evolutionary debate.

the arguments for or against the evolutionary metaphor. Considering how recently these results were published, it is not surprising that Gould and Lewontin made no reference to them—although, as part of a more general discussion of evolution, one could have expected at least a passing reference to the evolutionary aspect of architectural design. Dennett, writing much later and focusing more on architectural matters, opens himself up to stronger criticism on this score. But before I go further into all of this, we should examine the architectural issues raised by both sides.

The Birth of a Metaphor

Gould and Lewontin begin their paper with the observation that:

> The great dome of St. Mark's Cathedral in Venice *[see Figure 1]* presents in its mosaic design a detailed iconography expressing the mainstays of Christian faith. Three circles of figures radiate out from a central image of Christ: angels, disciples and virtues. Each circle is divided into quadrants, even though the dome itself is radially symmetrical in structure. Each quadrant meets one of four spandrels in the arches below the dome. Spandrels—the tapering triangular spaces formed by the intersection of two rounded arches at right angles—are necessary architectural by-products of mounting a dome on rounded arches. Each spandrel contains a design admirably fitted into its tapering space.... The design is so elaborate, harmonious, and purposeful that we are tempted to view it as the starting point of any analysis, as the cause in some sense of the surrounding architecture. But this would invert the analysis. The system begins with the architectural constraint: the necessary four spandrels and their tapering triangular form. They provide a space in which the mosaicists worked; they set the quadripartite symmetry of the dome above.
>
> Such architectural constraints abound and we find them easy to understand because we do not impose our biological biases upon them. Every fan vaulted ceiling must have a series of open spaces along the midline of the vault, where the sides of the fan intersect between the pillars. Since the spaces must exist, they are often used for ingenious ornamental effect. In King's College Chapel in Cambridge, for example, the spaces contain bosses alternately embellished with the Tudor rose and portcullis *[see Figure 2]*. In a sense, this design represents an "adaptation," but the architectural constraint is clearly primary. The spaces arise as a necessary by-product of fan vaulting; their appropriate use is a secondary effect. Anyone who tried to argue that the structure exists because the alteration of rose and portcullis makes so much sense in a Tudor chapel would be inviting the same ridicule that Voltaire heaped on Dr. Panglos: "Things cannot be other than they are.... Everything is made for the best purpose. Our noses were made to carry spectacles...." Yet evolutionary biologists, in their tendency to focus exclusively on immediate adaptation to local conditions, do tend to ignore architectural constraints and perform just such an inversion of explanation.

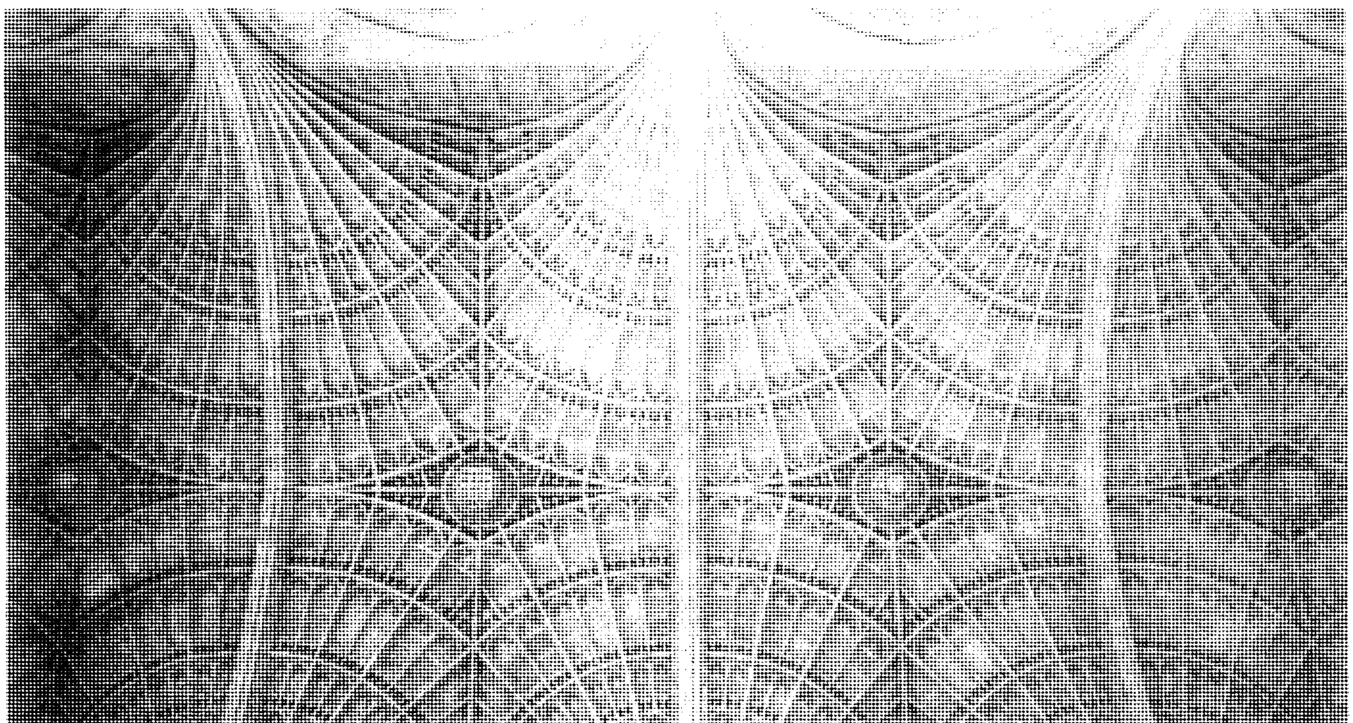

Figure 2. Ceiling of King's College Chapel in Cambridge, England, is formed by fan vaulting, a structure of ribs radiating from piers along the building's periphery. As a result, opening are created at the perimeters of the conoid tops. Gould and Lewontin suggested that the ornate bosses within these spaces are a secondary design element. In a recent book, Dennett argued that the metaphor is inappropriate, because it cannot be determined whether the bosses are secondary or primary—perhaps fan vaulting was chosen to make possible the beautiful bosses. He suggests, in any event, that they have no function other than visual. In fact, though, these spaces need to be filled for structural surety, to prevent the spread of fire, to improve acoustics and to exclude birds in the roof from entering the chapel. (Photograph courtesy of E. C. Robison.)

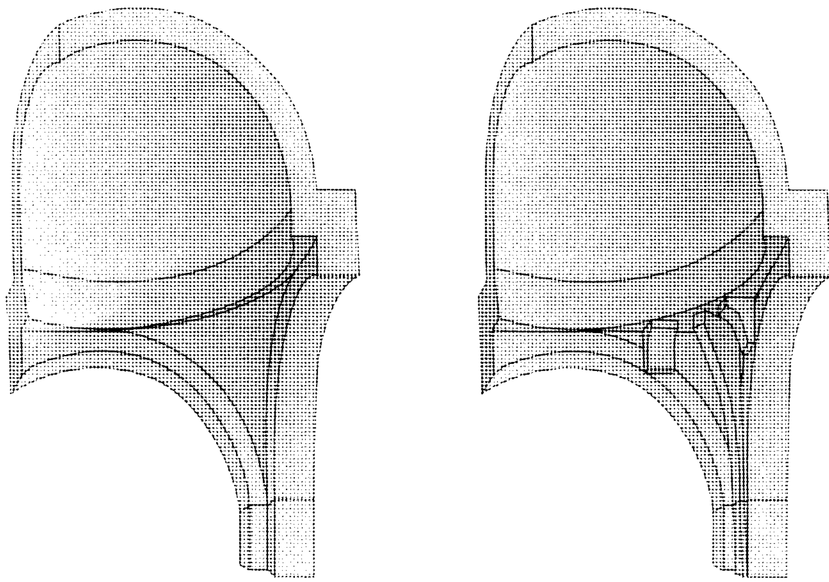

Figure 3. Domes mounted on arches create roughly triangular spaces in the corners, between the upper sides of the arches and the base of the dome. Gould and Lewontin called these spaces spandrels, whereas Dennett (correctly) identified them as pendentives. The former saw these spaces as opportunities for decoration left by the choice of structure, whereas the latter suggested that the structure was chosen to make possible the spaces for the display of mosaics. In fact, the pendentives *(left)*, which are but the visual surfaces in front of a heavy surcharge, are necessary structural elements. Brackets *(right)*, suggested by Dennett as substitutes for pendentives, are not "equivalent" because of they lack such surcharge as well as support from any other massive structure.

Dennett's Controversion

Dennett begins his rebuttal by acknowledging the now wide spread use of the term "spandrels" by evolutionists, and then he goes on to appraise the architectural side of the metaphor:

> The spandrels of San Marco, we are told, "are necessary architectural by-products of mounting a dome on rounded arches." In what sense necessary? It might appear at first as if there were no alternatives to smooth tapering triangular surfaces in between the dome and the four rounded arches, but there are in fact indefinitely many ways that these spaces could be filled with masonry *[see Figure 3]*, all of them about equal in structural soundness and ease of building....
>
> Here [too] there is a terminological confusion that seriously impedes discussion.... Strictly speaking, the tapering, roughly spherical surface [in between the dome and the four round arches] is called a *pendentive*, not a *spandrel*. Strictly speaking, spandrels are what remains of a wall once you punch an arch through it *[see Figure 4]*.... Speaking more loosely, spandrels are places-to-be-dealt-with, and in that looser sense ... another variety of spandrel would be a *squinch [see Figure 5]*.
>
> Now, why does all this matter? Because, when Gould and Lewontin say that spandrels are "necessary architectural by-products," what they say is false if they are using "spandrel" in the narrow sense (synonymous with "pendentive") and true only if we understand the term in the loose, all-inclusive sense. But in that sense of the term, spandrels are design *problems*, not *features* that might either be designed (adaptations) or not. Spandrels in the loose sense are indeed "geometrically necessary" in one regard: if you place a dome over four arches, you have what you might call an *obligatory design opportunity*: You have to put something there to hold up the dome—some shape or other, you decide which. But if we interpret spandrels as obligatory places for one adaptation or another, they are hardly a challenge to adaptationism.
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> But is there nevertheless some other way in which spandrels in the narrow sense—pendentives—truly are nonoptional features of San Marco? That is what Gould and Lewontin seem to be asserting.... Not only were the pendentives just one among many *imaginable* options; they were just one among the readily *available* options. [According to Richard Krautheimer] squinches had been a well-known solution to the problem of a dome over arches in Byzantine architecture since about the seventh century.
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> What the actual design of San Marco—that is, pendentives—has going for it are mainly two things. First, it is (approximately) a minimum "energy-surface" (what you would get if you stretched soap film in a wire model of the corner), and

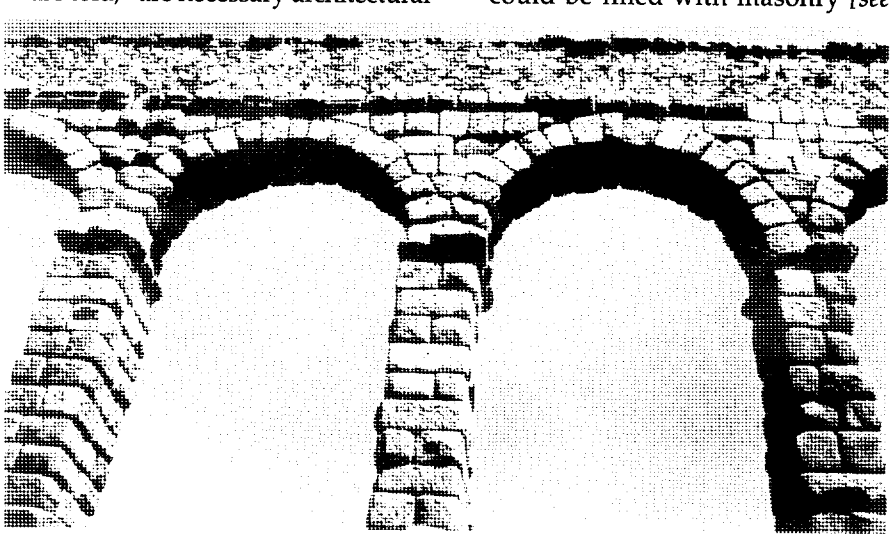

Figure 4. Arches based on half-circles, such as these supporting the Segovia Aqueduct (first century A.D.), are not optimal structural forms. The surcharge placed in the triangular spaces, or spandrels, prevents the arch from deflecting laterally at its haunches. Pendentives, with their heavy surcharge behind, serve the same function in San Mark's. (Photograph by the author.)

hence it is close to a minimum surface area.... Second, the smooth surface is *ideal* for the mounting of mosaic images—and that is why the Basilica of San Marco was built: to provide a showcase for mosaic images. The conclusion is inescapable: the spandrels of San Marco aren't spandrels even in Gould's extended sense. They are adaptations chosen from a set of equipossible alternatives for largely aesthetic reasons.... Their primary function [was] to provide a showcase for [Christian] symbols.... The Byzantine style of mosaic decoration had provoked the admiration of powerful Venetians who wanted to create a local example. Otto Demus, the great authority on San Marco mosaics, shows ... that the mosaics are the *raison d'être* of San Marco, and hence of many of its architectural details....

Gould and Lewontin's other example from architecture was also ill chosen, as it turns out, since we simply don't know whether the King's College bosses alternating rose and portcullis are the *raison d'être* of the fan vaulting or vice versa.... The purpose of the bosses is probably entirely to provide focal points for ornament. Did the bosses have to be there anyway? No. From an engineering point of view, there could have been neat round holes there, "lanterns" letting in daylight from above if it wasn't for the [timber roof above the fan vaults]. Maybe fan vaulting *was* chosen by the builders so that the ceiling could carry Tudor symbols!

These architectural issues can best be dealt with first by augmenting the ordinary definitions of the elements to include their technological functions, and then by reviewing the course of architectural development that led to their employment in San Marco and in the chapel of King's College.

Saint Mark's, Venice

Spandrel: Triangular wall areas over the haunches of an arch or, in multi-story buildings, the area of wall between the vertical supports and upper and lower windows.

Pendentive: Triangular segment of vaulting at the base of a dome used for transition from a round- to a square-planned space.

Squinch: An arch, or corbeling, at the base of a dome or cloister vault commonly used for transition to a square-planned space below.

Conventional architectural definitions, unfortunately, rarely touch on technical function. The description of a spandrel indeed seems to indicate only geometric necessity. When the spandrel is applied with semicircular masonry arches, however, it also takes on a crucial structural function. An arch can span relatively long distances (compared with a simple beam) because its rise generates horizontal as well as vertical forces within the arch that confine the individual stones (or *voussoirs*) comprising it. Yet arches may prove unstable and collapse unless their form approaches an optimal shape that induces resultant internal forces to act along the axis of the arch: a *catenary* for an arch of uniform depth supporting its own dead weight. (For most practical applications, a catenary is closely enough approximated by a parabola, or for shallow arches, even by a circular arc.) Semicircular, or "Roman," arches, used well into the Middle Ages because they are relatively simple to lay out and construct, are *not* an optimal arch form. Hence they require heavy, solid fill (surcharge) to prevent outward displacement at the haunches of the arch that could lead to failure. Such a surcharge, as illustrated in Figure 4, is ubiquitous in all but decorative Roman arches and constitutes what is normally referred to in the architectural literature as a spandrel.

The conventional definition of the pendentive also indicates only a geometric transition. Yet, as I have demonstrated from structural modeling of Imperial Roman and Byzantine monuments, the pendentive is actually a translation of the surcharge, or the so-called "step rings" typically found above large Roman domed buildings (including the Pantheon constructed in Rome between 118 and 128 A.D.). The step rings are, in turn, a translation of the *planar* arch spandrel to a three-dimensional dome. The solid-fill surcharge behind the pendentive surface (shown in the section through the dome of Justinian's Hagia Sophia, in juxtaposition with the Roman Pantheon, in Figure 6) prevents outward displacement of the lower portion of the dome (and of the four supporting arches as well) that could engender structural failure of the type experienced by a planar semicircular arch wanting surcharge.

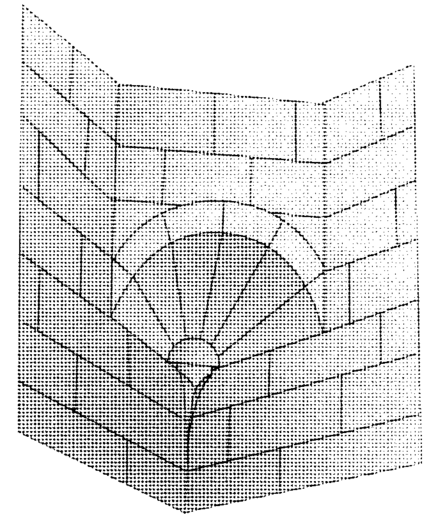

Figure 5. Squinches, Dennett suggested, could also be substituted for pendentives, making them one "among many imaginable options." In fact, squinches—shown here as arches placed across square corners to form an octagon—are structurally sufficient only for relatively small structures. Pendentives became the element of choice in the sixth century A.D. to provide support to large domes over arches springing from four piers. Since pre-scientific builders relied heavily on proven approaches in their designs, it is unlikely that the designer of St. Mark's would have considered other systems.

Unlike pendentives, needed for the support of large domes, squinches are appropriate only for relatively small-scale domes—a salient characteristic of Byzantine church domes after the seventh century—where outward-acting forces are also relatively slight. Both the conventional definition of the squinch and Richard Krautheimer's comment about its almost boundless use fail to account for building scale—although I have no doubt that the late Professor Krautheimer would have agreed with this limitation in use.

As to building history, San Marco, as the main church of Venice and the palatine chapel of the doge (the city's chief magistrate), was constructed between 1063 and about 1095 A.D. and was consciously based on the five-domed Greek cross sixth-century Church of the Holy Apostles in Constantinople, long ago destroyed. Pendentives, which may have been deployed as early as the late second century to provide necessary support for domes set above four piers, came to prominence with the completion in Constantinople in 537 of Justinian's Hagia Sophia. Not surprisingly, therefore, pendentives were used also in the Justinianic Church of the Holy Apostles and much later on in its replica, San Marco. Although the central dome of San Marco, just short of 13 meters in diameter, is much smaller than the 31-meter-diameter dome of Hagia Sophia, it is considerably larger than typical Byzantine domes constructed after the Justinian era. Without benefit of detailed stress analysis, it cannot be definitively argued that squinches—or, as suggested by Dennett, even an array of brackets—might suffice for supporting the San Marco central dome. But bear in mind that the process of structural design in the prescientific era was largely based on lessons learned from observing the behavior of earlier buildings. Hence I strongly doubt that a sixth- or an 11th-century builder would have dared consider any system other than pendentives to support a dome of San Marco's scale set over four piers.

Concerning the merit of Dennett's argument for the primacy of the (indeed truly splendid) mosaics of San Marcos, one must realize that all specialists tend to see their own discipline as being of greatest import to a large undertaking. The marked increase in the height of Gothic cathedrals at the beginning of the 13th century, for example, has been explained by stained-glass experts as resulting from the desire to increase the size of cathedral clerestories in order to display more glass. These explanations neglect the fact that High Gothic architecture was largely a phenomenon of extraordinary urban growth where mercantile and ecclesiastical centers vied with one another over height of building, as Chicago and New York were to do seven centuries later. Indeed, to fully understand the *raison d'être* of any monumental building, one must account for all the functions it was designed to meet, including the iconographic and symbolic associations of its forms and the cultural contexts of its patrons and users, as well as available technology. I. M. Pei's design of the East Wing addition to the National Gallery in Washington was far more directed to the single purpose of displaying art than was the main church of Venice, but all visitors to the building are made acutely aware that its design was affected by a host of other issue as well.

King's College Chapel, Cambridge

Fan Vaulting: A ceiling or roof structure formed of conoid surfaces of rotation about the axes of supporting piers from an array of uniform ribs.

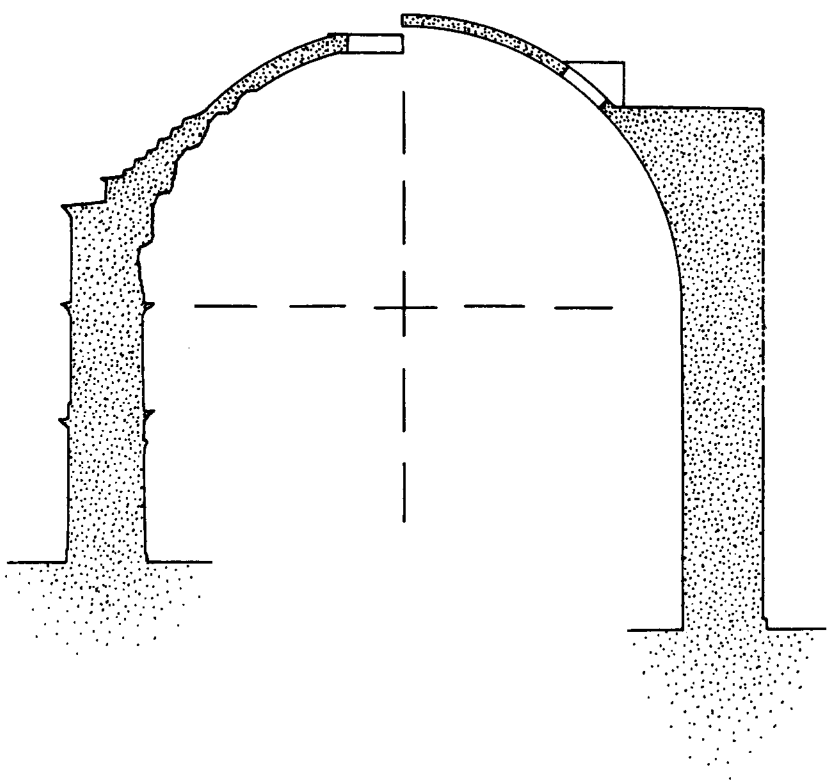

Figure 6. Sketches of comparative sections taken through the early second-century Pantheon in Rome *(left)* and along a diagonal of the sixth-century Hagia Sophia in Constantinople *(right)* reveal the vital stiffening surcharges around the exterior of the Pantheon dome and behind the pendentive in Hagia Sophia, a design element consciously used in St. Mark's.

This description of the type of vaulting that came into prominence in monumental English halls after the middle of the fourteenth century applies equally well to the central-pier-supported radial vaulting of polygonal English cathedral chapter houses that date from after the middle of the 13th century *(see Figure 7)*. Indeed, the dating suggests that the concept of fan vaulting derived from the chapter houses. Yet the adoption of radially ribbed vaulting from a central plan to a square- or rectangular-planned bay leaves an opening created by the perimeter of the conoid tops that requires closure *(see Figure 2)*—to provide horizontal restraint at the top of the vault ribs, to help prevent the spread of fire from the timber roof above the hall, to enhance the hall's acoustic ambience and, perhaps not at all least in importance, to provide a barrier against the ever-present avian community in the roof. This is most simply effected by the placement over the opening of a large, flat stone plate. The boss is actually only the ornament protruding from that plate.

In late Gothic architecture, particularly in England and in Germany, the classic quadripartite ribbed vault composed of diagonal and cross ribs was frequently supplanted by vaults displaying far more intricate rib patterns. In these later vaults, the closely spaced ribs effectively bear the weight of the vaulting, whereas the thin stone webbing (classically composed of voussoirs that function in three dimensions much like the load-bearing voussoirs of a two-dimensional arch) merely fills interstices between the ribs. The clustering of ribs also provides a strong decorative motif described as having "an atmosphere of heavy luxuriance"—hardly any vault surface remains available for applied decoration.

The 13-1/2-meter-span fan vaulting of King's College Chapel at Cambridge dates from between 1466 and 1515. Despite possible cost savings from the use of standardized, radial ribs, the building account gives the cost of constructing the fan vault as two-thirds more than that of a conventional quadripartite vault of equal span that could have displayed considerably more applied decoration. Rather than providing an appropriate "ceiling [to] carry the Tudor symbols," it is far more likely that fan vaulting was selected for the college hall in order to adopt an up-to-date, high architectural style.

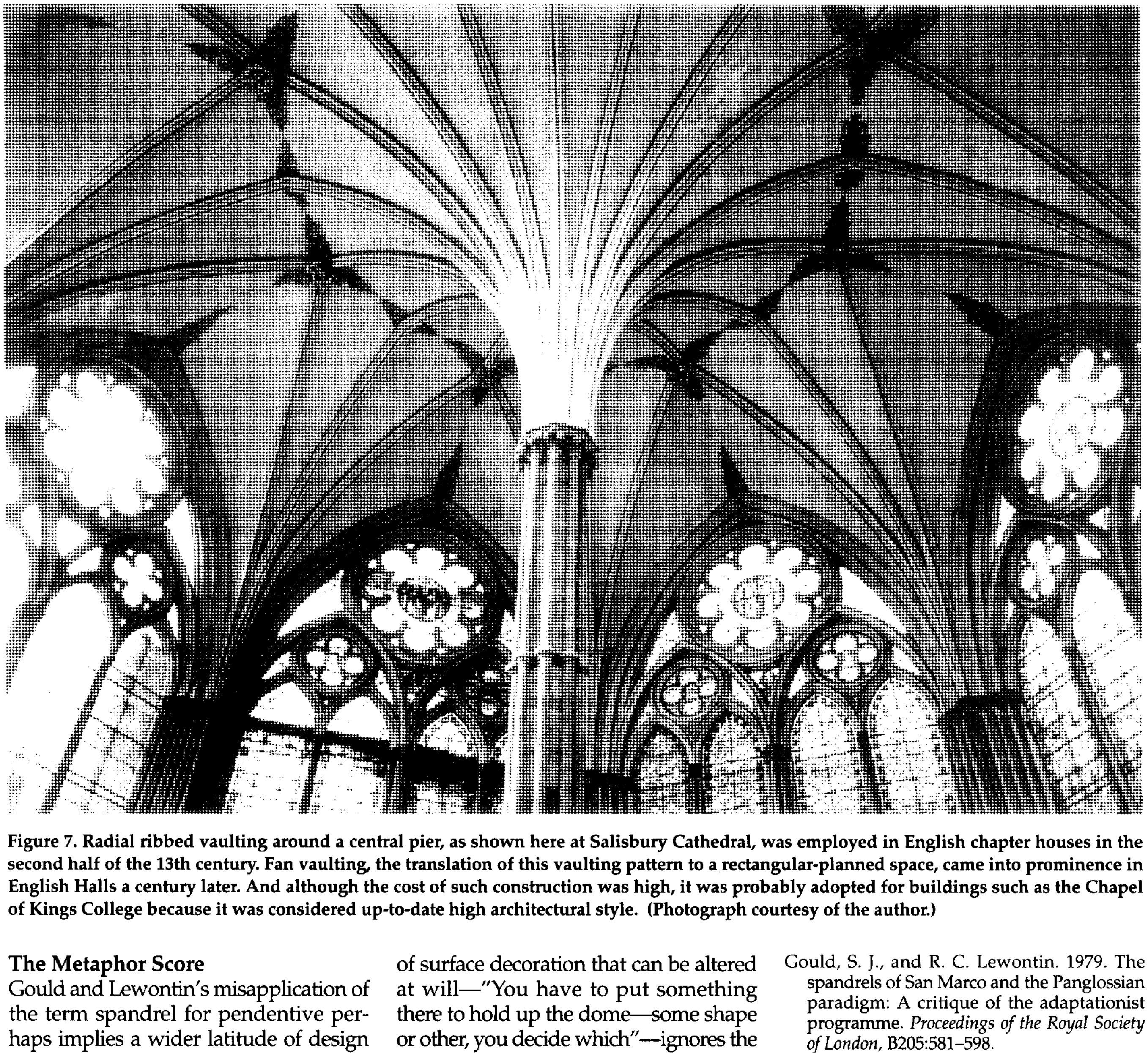

Figure 7. Radial ribbed vaulting around a central pier, as shown here at Salisbury Cathedral, was employed in English chapter houses in the second half of the 13th century. Fan vaulting, the translation of this vaulting pattern to a rectangular-planned space, came into prominence in English Halls a century later. And although the cost of such construction was high, it was probably adopted for buildings such as the Chapel of Kings College because it was considered up-to-date high architectural style. (Photograph courtesy of the author.)

The Metaphor Score

Gould and Lewontin's misapplication of the term spandrel for pendentive perhaps implies a wider latitude of design choice than they intended for their analogy. But Dennett's critique of the architectural basis of the analogy goes even further astray because he slights the technical rationale of the architectural elements in question. He is not alone in this. My colleague David Billington and I have pointed out that the problem is widespread both in historical analysis and in current architectural theory: "Following art history, contemporary writing on architecture tends to focus on formal analysis where visual ideas dominate the discussion of the origin and meaning of style. Technology is rarely touched upon, and structure, although generally understood as necessary, is hardly seen as a legitimate giver of form, even for large-scale building." To his credit, Dennett does not focus on style. But his treatment of crucial structural elements as a kind of surface decoration that can be altered at will—"You have to put something there to hold up the dome—some shape or other, you decide which"—ignores the years, or in some cases even centuries, of construction experience that led to their incorporation in historic buildings.

Acknowledgments

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