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Author(s): Rabun Taylor
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A Literary and Structural Analysis of the First Dome on Justinian’s Hagia Sophia, Constantinople

Rabun Taylor, University of Minnesota

The first dome of Hagia Sophia in Constantinople, perhaps the greatest structural and artistic innovation in Justinian’s church, is lost to us forever. Its precise shape and size are not recorded in the written or visual records; nor does an approximation of it survive in architectural filiations. Completed sometime in 537 C.E., the dome lasted just over twenty years before a series of earthquakes in 557 led to the collapse of the eastern main arch in May 558. Deprived of this support, portions of the dome and eastern semidome fell with the arch, and the rest of the dome was cleared away for rebuilding. In his ekphrasis written for the second consecration of the building in 563, Paul the Silentiary describes the collapse this way:

Now the wondrous curve of the half-sphere, although resting on powerful foundations, collapsed and threw down the entire precinct of the sacred house…. Yet, the broad-breasted fane did not sink to the foundations…but the curve of the eastern arch slipped off and a portion of the dome was mingled with the dust: part of it lay on the floor, and part—a wonder to behold—hung in mid-air as if unsupported….1

According to the sixth-century historians Procopius and Agathias, the first dome was an object of reverential astonishment. Apparently Justinian’s contemporaries considered the replacement dome—large parts of which survive in today’s dome—a less subtle achievement, admirable in its own right but conveying less of the former magic. Agathias remarked that “it did not strike spectators with as much amazement as before, but it was far more securely set up.” This testimony must be taken seriously, since Agathias is likely to have seen both domes personally.2

The current dome is justly famous for its subtle visual effects [Figure 1], and so one cannot fail to be intrigued by these brief reports of lost grandeur. A number of scholars have ventured to speculate on the shape of the original dome, but few have approached the problem in a systematic way, synthesizing the literary testimony and structural possibilities to arrive at a reasonable reconstruction of this ephemeral experiment by Justinian’s master architects, Anthemius of Tralles and Isidorus of Miletus. All have been satisfied to envision a dome that in its essentials is similar to the surviving dome, only shallower. R. L. Van Nice even went so far as to claim that “the original structural scheme was…intrinsically so unalterable that all later repairs were obliged essentially to reduplicate the forms that had fallen. Thus, although reconstruction brought changes in detail, the principles at work were affected only in a matter of degree.”3 This article offers a respectful challenge to Van Nice’s assumption. Whereas the existing dome is fenestrated and springs directly from the marble cornice resting atop the main arches, a close reading of Procopius, who offers the most reliable eyewitness description, suggests that the original dome had no windows, and instead rested upon a fenestrated drum.

The Main Structure and Its Limits
To attempt a reconstruction of the early dome, one must turn first to the information inherent in the present building.4 The following describes the dome and the primary structural components supporting it and cites some of the structural movements that have taken place over the years [Figure 2].

Of a broad, rectangular basilican plan, Hagia Sophia is oriented roughly on an east-west axis. The crown of the present dome (A), which is just over 100 Byzantine feet in diameter, hangs 178.3 feet (55.6 m) above the floor.5 Four main piers (B), made mostly of limestone and greenstone ashlars, define the corners of the central 100-foot square of floor that lies beneath the dome. They rise 74.17 feet (23.14 m)6 and are spanned by four thick semicircular arches of brick (C), which are bound together by brick pendentives (D). These culminate at 133 feet (41.5 m) in a somewhat deformed circle of flat marble blocks upon which the dome rests (E). The blocks jut out several feet into the central space, forming a cornice used as an inner walkway around the dome’s base.

The main east and west arches serve as the terminations of the two main semidomes (F) which, being roughly full quaterspheres, have a slightly smaller surface radius than the main dome. The semidomes extend the nave to nearly its full length, and are each supported by the main piers and two secondary piers toward each end of the nave (G). The semidomes and secondary piers serve as the principal east-west buttresses to the dome, main arches, and main piers.7 To the north and south,
FIGURE 1: The central dome and eastern semidome of Hagia Sophia, as engraved by the architects Gaspare and Giuseppe Fossati in 1846.
FIGURE 2: Isometric cutaway view of Hagia Sophia as it is today (modified from Mainstone, Hagia Sophia). The dome (A) rests upon the cornice (E), which forms a ring at the top of the pendentives (D). The main arches (C) spring from massive stone piers (B), which rise from the corners of the central 100-foot square. The secondary piers (G) help to support the semidomes (F). Mainstone shows that these latter elements effectively buttress the dome and the east and west main arches. The buttresses to the north and south (H) have been somewhat less successful in countering the lateral thrusts of the dome and main arches.

external buttresses (H), rising nearly to the height of the main arch crowns, are joined by arches and walls to the main piers and the superstructure above them.

The present dome, parts of which have survived for 1,400 years, rises 48 feet (15.0 m) from the level of the upper cornice, just slightly short of a hemisphere. It is made of brick and pozzolanic mortar. Anchored to the cornice, and thus indirectly to the arches, it is pierced at the base by forty arched windows. Between the windows thick radial ribs rise to the crown; the webs, well integrated with the ribs, are somewhat recessed, with an average thickness of about 2½ feet. On the outside, the ribs broaden into equally spaced spurs extending out about 7 feet, which serve as radial buttresses for the dome.

Isidorus the Younger, nephew of one of the original architects, designed the second dome. He decided to demolish the remainder of the first dome and start afresh, attacking the structural problem at the level of the arches. Agathias provides a few interesting facts about the rebuilding:

Since Anthemius had long been dead, Isidore the younger and the other engineers reviewed among themselves the former design and, by reference to what had remained, they judged the part that had fallen down, i.e., its nature and its faults. They left the east and west arches as they were in their former places, but in the case of the north and south ones they extended inward that part of the construction which lies on a curve and gradually increased its width so as to make them [the north and south arches] agree more closely with the others and observe the harmony of equal sides. In this way they were able to reduce the unevenness of the void and to gain a little on the extent of the space, i.e., that part of it which produced a rectangular figure. Upon these [new]
arcs they set up once again that circle or hemisphere (or whatever else they call it) which dominates the centre of the building. As a result, the dome naturally became more even and well-curved, conforming altogether to the [correct geometrical] figure. It was narrower and steeper so that it did not strike spectators with as much amazement as before, but it was far more securely set up.\footnote{11}

The most pronounced distortions in the building then, as now, were in the outward leaning of the northeastern and southeastern main piers caused by spreading of the eastern arch. Similar distortions are visible to the west. Spreading began immediately after the arches were built. Left alone, it would have continued at a steadily declining rate until the mortar dried. But when the first dome was added, its weight compounded the spreading until the collapse, by which time the central “square” at the tops of the arches had become a rectangle, gaining several feet on its north-south axis over its relatively stable east-west dimensions.\footnote{12} This concerned the younger Isidorus enough so that once he had demolished the remainder of the old dome and repaired the eastern arch, he thickened the outward-leaning north and south arches toward the crown, bringing their inside faces nearer to vertical, so that the rectangle upon which he was to build would be closer to a square.\footnote{13}

By examining the written descriptions and the building itself, Rowland Mainstone has traced some of the inherent weaknesses in the building of 537.\footnote{14} According to his calculations, the weight and lateral thrusts of the first dome upon the arches were not in themselves manifestly excessive. Nor were the arches directly at fault. The Achilles' heel of the structure then, as now, he believes, was the insufficient buttressing to the north and south of the main piers.\footnote{15} As we shall see, Mainstone's analysis may underestimate the weight and instability of the first dome.

**Procopius on the First Dome**

Every study of the original form of Justinian's Hagia Sophia must inevitably take stock of Procopius's description of the church in Book 1 of his panegyric *The Buildings*—a work of uncertain date, and fraught with distortions, both intentional and accidental.\footnote{16} A source of proven mendacity and unproven date is never a good starting place for an inquiry, but we need not scrutinize Procopius's motives in the brief passages of *The Buildings* that concern us. While Procopius might safely exaggerate Justinian's achievements on the empire's periphery, he could hardly misrepresent the physical appearance of buildings in the capital, which were in plain view to many of his readers.

A more vexing problem involves the date of completion of *The Buildings*, or at least of Book 1. Many dates have been proposed, but those most commonly encountered in the current debate are 554, before the collapse of the first dome, and 559–560, a couple of years after the collapse. Since the second dome was not completed until 562, there is no question that the dome Procopius described was the first one. But was he writing from direct observation in 554, or from memory in 560, when the remnants of the old dome had been demolished and construction of the new dome was well under way? The answer may have a bearing on the precision of his description.\footnote{17}

A number of scholars endorse the earlier date, arguing that even a panegyric could not ignore so monumental an event as a collapse. Cyril Mango's recent assessment points out that, in *The Buildings* 1.1.69, Procopius ascribes to Justinian's genius the completion of the very arch that collapsed in 558.\footnote{18} This is reason enough to accept 554 as the year of composition, as Justinian surely would not have allowed such an indiscretion after the collapse. But there are broader arguments for the earlier date as well. "Procopius' work is a celebration of imperial glory," Averil Cameron writes—"relevant enough in 554 when Italy had just been finally won, and when a good part of the ambitious building programme in Africa had just been carried out, but very out of place in 559 when the darkness of plots and disillusion was settling round the aged Justinian."\footnote{19}

Procopius's description of the dome from inside Hagia Sophia is not in itself precise or detailed enough to justify the conclusion that he is writing from direct observation. But his use of the present tense to describe the glories of the great dome would have seemed gratuitous hypocrisy in 559 or 560, when the growing ranks of Justinian's local detractors were faced daily with the ruined profile of Hagia Sophia. Describing finished buildings as if they are in the process of construction is "a standard ekphrastic technique," one scholar claims. But no ekphrastic poet to my knowledge wrote a paean to a partly destroyed building—much less to a building that he knew would look different when reconstructed, and thus render the old description obsolete. Common sense must prevail over the arguments for the later date, which depend largely on the evidence of a single reference in a chronology written centuries after the fact.\footnote{20}

It is well to be mindful of Mango's distinction between Procopius's reliability as a witness of the building itself, with which he was quite familiar, and of its construction, with which he was not. Procopius was abroad from 533 to 540, and his account of the original construction of Hagia Sophia is plainly confused. But he spent many of his subsequent years in the capital, and was certainly in Constantinople while writing *The Buildings*; otherwise he could not have had access to the government records that he so plainly consulted.\footnote{21} We can therefore say with some confidence that aside from a few brief comments from Agathias and Paul the Silentiary, Procopius alone among the sources provides a reliable eyewitness description of Justinian's Hagia Sophia in its original form. Here, then, is a literal translation of the relevant passage in *The Buildings*:
And upon them [sc., the arches] hangs a rounded structure (kykloteres oikodomia) in the shape of a ring, from which the day always smiles first. For I am convinced that it rises above the whole earth; and the structure is discontinued every little while, purposely omitted at enough intervals that the places to which the gaps in the structure correspond might give admittance to adequate light. . . . As [each pendente] rises the rest of the way and is broadened by the intervening space, it culminates at the ring (kyklo teres) which it thus supports, and forms the remaining angles there. And rising upon this ring, an immensely large spherical dome renders it surpassingly beautiful. It appears not to rest upon the solid structure, but to cover the space [as if] suspended from the golden chain of heaven.22

There is one other relevant scrap of testimony from a near-contemporary, the historian John Malalas:

In the same year, when the dome of the Great Church was being restored—for it had been cracked in some places by the earthquakes which had occurred through God’s Providence—. . . . the eastern part of the vaulting (prohypostole) fell down. . . . The remaining part that had stayed in place was taken down, including the arches (elema ta).23 The dome was rebuilt 20 (Roman) feet higher.24 Procopius’s brief description, along with Malalas’s claim that the second dome rises 20 feet higher than the first, has led at least four scholars in this century to venture theories about the shape of the original dome.25 If Malalas’s figure is accurate—and most scholars have concluded that from an engineering standpoint it is quite feasible—then the dome must have been shallower than it is now, perhaps shallow enough to share the curvature of the pendentives [Figure 3].

Twentieth-Century Theories

Mainstone’s proposed profile of the first dome is the most current and physically plausible [Figure 4, A]. Judging from the placement of some apparently original cornice blocks to the north and south, he concludes that they were set all around the tops of the pendentives, with a uniform overhang corresponding to the two lower nave cornices.26 This means that these blocks—and thus the first dome—did not correct the deformities of the circle inscribed in the 100-foot square, which was distorted by the movements of the piers and arches. Mainstone proposes a shallow dome that would have risen 28 feet from springing to crown (i.e., 20 feet lower than the present crown, as Malalas says), a bit elongated on the north-south axis because of the square’s deformity, “lifted somewhat above the cornice [about two feet] by a low drum-like section at the foot to afford reasonable passage around it.”

The only clues to its possible precise form are what we are told about the height of the crown in relation to that of the reconstructed dome, and what we can deduce about the precise forms of the pendentives and cornice. In following up these clues, it soon becomes apparent that the radius of curvature of the main curved surface cannot have differed much from that of the pendentives themselves, which makes it highly probable that the same radius was adopted for both. In effect, construction of the notional continuous hemispherical dome—of which the pendentives were the only parts that had so far been built—would simply have been resumed a little higher up, after being cut off by the cornice.27

Kenneth J. Conant proposed a three-point dome profile, but such a dome, rising steeply from its springings and then abruptly altering its curvature into a flattened crown, even if it rested on unmoving foundations, would suffer extreme tensile stress toward the bottom, causing radial cracking as the flat central area pushed out on the steep peripheral area.28 It is highly doubtful that the main dome of Hagia Sophia, with the added complications of unprecedented size and a less stable base, could possibly have had this profile.

Mainstone’s proposed shallow “saucer dome” has been universally accepted since he proposed it, and I too have no quarrel with the proportions he assigns to the dome itself. But I must raise one major objection: Mainstone does not account for Procopius’s clear indication that a rounded structure (kyklo teres oikodomia), pierced by windows, separated the dome from the arches and pendentives below. He dismisses the implications of this statement, as he dismisses Conant’s theory, on physical grounds: given that the crown of the second dome is fully 20
feet higher than that of the first, as Malalas attests, a drum under the first dome would render it impossibly shallow, more like an overturned platter than a saucer.29 The crown would remain at the same level, while the drum would raise the springings [Figure 4, B].

Mainstone apparently prefers to interpret the rounded structure as his low “drum-like section” described above, surmounted by the windows piercing the proposed dome. Apart from the fact that a drum this low simply could not provide head clearance for a person standing on the cornice as Mainstone claims, his reconstruction again misconstrues the placement of the windows (Figure 4, A).30 And a drum less than a meter high, set back from the cornice as it must have been, could not even be seen from the floor or the gallery; so how would Procopius have seen it? Even if he had ventured up to dome level, such a minor feature would hardly have merited mention in his sketchy description of the building. Procopius's kykloteres must have been a drum. But how can it be reconciled with the reportedly low profile of the first dome?

A NEW PROPOSAL
Thanks to Malalas, both Mainstone and Conant labor to justify an original dome whose crown was 20 feet lower than the present dome—Conant at the expense of sound engineering, and Mainstone at the expense of Procopius’s credibility. Malalas was clearly not an eyewitness to the reconstruction, whether or not he confused the pendentives (which were dismantled) with the arches (which were not). He was probably a resident of Antioch at the time he wrote this part of his chronicle, and would have relied on secondhand reports from the capital for his information. There is no good reason to assume that Malalas’s reported 20-foot differential is as reliable as Procopius’s eyewitness testimony of a “rounded structure”; yet there is still a way to reconcile these accounts.31 Rather than represent the absolute difference in height of the two dome crowns above the floor, i.e., the elevation, Malalas’s 20 feet may refer only to the relative heights of the domes from their springings, ignoring any change in the relative positions of the springings themselves. In other words, by a “lower” first dome Malalas’s source may simply have meant “shallower,” while any mention of a drum under the shallower dome was lost in the transmission. This drum, though it would decrease the disparity in elevations, may have been deemed part of the substructure and consequently discarded from the account.32

I am satisfied to join the chorus of agreement that the earlier dome would indeed have been about 20 feet shallower than the rebuilt dome, thus having a height from springings to crown of about 28 feet and the same radius of curvature as the pendentives.33 But the dome did not spring directly or almost directly from cornice level, as modern theories contend. It rested upon a drum of modest height—though much less modest than Mainstone’s two Byzantine feet—which was vertical or near-vertical on the inside. This drum accommodated most or all of each window embrasure, and was distinguishable on the inside from the dome above by the geometric juncture of the sphere segment with the cylinder. With the drum, the crown of the first dome was perhaps about 10 feet lower in elevation than the existing dome, rising 38 feet from cornice level [Figure 5].

CORROBORATION FROM THE SOURCES
Agathias is silent on the subject of a drum, although his contention that the second dome was “more securely set up”
FIGURE 5: Proposed dome arrangement with a fenestrated drum. The combined height of drum and dome would leave the crown 10 Byzantine feet lower in elevation than that of the present dome.

than the first may owe its self-assurance to more than just the thickening of the north and south arch crowns. There is no other direct written or architectural evidence of a fenestrated drum under the first dome of Hagia Sophia. Because there are no existing filiations of this arrangement on so large a scale, and because it seems an unnecessary risk on so novel a building project, we are tempted to question Procopius’s technical competence. Since he was a layman, we tell ourselves, this is surely one of the numerous cases where a panegyrist is not equal to his subject matter. But as it happens there is a strikingly similar descriptive passage in Book 1 of The Buildings, where the structure in question is better attested. It describes the domes on the cruciform Church of the Holy Apostles in Constantinople, completed around 550, and demolished in 1469.34

The part of the roof above the so-called sanctuary, at least in the middle, is built in a way similar to the church of Sophia, except that it happens to be smaller in size. For the arches, four in number, rise up and are bound to each other after the same fashion [as Hagia Sophia, i.e., by pendentives]; and the rounded form [kykloteres] standing upon them is divided by windows, and the spherical shape arching above seems somehow to hover on air and not rest upon the solid structure, although it is quite secure. In this way, then, was the central part of the roof constructed. As for the sides [i.e., cross arms], which are four in number, as I have said, they have been built on the same scale as the central one, but missing this one thing: below the dome the structure [oikodomia] is not divided by windows.35

So the church had five domes, one in the middle and one over each of the four arms. Certainly the central dome, and probably the others as well (the word oikodomia, “structure,” is ambiguous) rested on drums; the central drum had windows, while the others did not. Most significant, the entire description of the central space—arches, pendentives, drum, windows, and dome—is meant to draw a direct parallel with Hagia Sophia. Curiously, many scholars have ignored this reference to a drum in both passages of Procopius; and those who have acknowledged it in the case of the Holy Apostles have disregarded the direct parallel Procopius draws with Hagia Sophia. Only Mainstone calls attention to the drum mentioned in the Hagia Sophia passage, but he minimizes its visual and structural importance. This passage rather weakens any suspicions that Procopius was describing the early Hagia Sophia from errant memory: whatever it is that the Holy Apostles has under its dome, he is saying, Hagia Sophia has it too.

There are, in fact, other descriptions of the Church of the Holy Apostles, one from the tenth century and one from the twelfth. Both are ekphrasis, but they were not written to commemorate a remodeling or rebuilding. In fact, it seems that the tenth-century poem, by Constantine of Rhodes, represents the building’s fabric (if not decoration) much as it was when Procopius saw it four centuries earlier.36 The poet goes along with the popular belief that the wonders he is describing are all the work of Anthemius, an original architect of Hagia Sophia, and Isidorus the Younger, who replaced its first dome (lines 550–552). There is less agreement about the testimonial value of the second ekphrasis, written in the twelfth century by Nikolaos Mesarites.

We turn then to relevant passages in Constantine’s description:

And he [i.e., the architect] likewise constructed piers, four in number ... which are allotted the task of carrying the central dome and the arches securely set [beneath it]. Constructing these [i.e., arches] against
just as many flanks of the single central part [i.e., the central square defined by the four main piers], all arranged doubly like a cross, and then constructing this same wondrous form to the east, west, south, and north [more arches, this time atop the piers of the four cross arms], he assembled, extended, unfolded a great building in five parts, enshrouding the edifice, which bears the hallowed shape of the cross, in domes as great as the slings [i.e., pendentives] he had unfurled into a circle. He wove one arch to its mate, wove cylinder again to cylinder; he tied pier to pier, one to another; and he bound [each] sphere, cut in half like a hill, to another spherical construction.

As if towering giants had come forth and extended their hands into the air, weaving together fingers to fingers, right hand up against its neighbor, in the form of well-rounded, much-turned cylinders, they [i.e., the builders] constructed circular wheels, extending to them four well-fitting curves which the builders call slings [pendentives]; and they [the wheels] likewise received five domes; but the architect arranged the middle dome in a reverent way, so it would project and reign over all and be the great throne of the Lord and shelter to the most-revered image rendered in the middle of the renowned building. You might say that they [the domes] fashion a heaven from bronze-turned, fiery cylinders, and then, as they descend, that they converge handsomely and marvelously, like heads, with the shoulders of the bronze-columned vaults...

Here we have remarkable confirmation that a drum supported not only the central dome of the Holy Apostles, but apparently each of the other four as well. The central dome, being "higher" than the others, presumably had a taller drum—tall enough, undoubtedly, to contain windows. The original Church of the Holy Apostles, dedicated in the fourth century, probably had a fenestrated drum over the center, surmounted by some sort of dome. We may reasonably assume that this feature was copied in the church's later manifestation under Justinian. Unfortunately, the tenth-century poet says nothing about the placement of windows, although his apostrophe to Christ Pantokrator, depicted in the dome's intrados, refers to the Crucifixion and the Second Coming as sunset and sunrise—times of day that were (and still are) rendered especially magical through Hagia Sophia's crown of windows.

So in Constantine of Rhodes's *ekphrasis* we have written confirmation of Procopius's description of the central vaulting of the Church of the Holy Apostles. It is hard to avoid the conclusion that in this church we have the only attested filiation of the great experiment atop Hagia Sophia. At the very least, we must conclude that the central domes of the two churches were highly similar on account of the identical visual effect they had on Procopius; for the drums surely contributed to the illusion that the domes were levitating. This effect would have been especially dramatic from the floor of the nave directly below the dome, where most or all of the drum and its windows would be hidden from view by the cornice. The dome would seem to be "hovering" several meters above the cornice, flooded by light emanating from the unseen interval. Such an arrangement would make rather more sense of Agathias's contention that the second dome, in which the windows are visible from all angles, did not "strike the spectators with as much amazement as before."

**The Physical Nature of the Dome**

Large diameter and shallow profile are the two bugbears of dome builders, and the first dome on Hagia Sophia carried both to an extreme. The dome was far larger than any ever attempted in the East; this, combined with its shallowness (the radius of curvature at the intrados would be 68 to 70 feet, as opposed to 53 feet for the present dome), imparted severe thrusts upon the substructure. In cross-section, the vector of a dome's combined lateral and downward thrusts is tangential to the dome's slope at its periphery; so the shallower the dome, the greater its lateral thrusts upon its supports *[Figure 6, A and B]*. The lateral thrusts of the proposed dome would quickly...
have peeled apart an unbuttressed drum. Although well-integrated ribs would have minimized radial cracking in the dome, the drum itself was extremely vulnerable to cracking—especially above the window embrasures, the points of least resistance to the expansive tendencies of the dome. Therefore, the drum would have had substantial buttressing on the outside in the form of spurs between the windows similar to those on the dome today, but probably higher and heavier. Perhaps the space above the windows between the spurs was heavily clamped. The heavier the buttresses, the more they would absorb the lateral thrusts, thereby deflecting the thrust lines downward into the arches and pendentives [Figure 6, C]. If the thrust lines had remained too flat to angle into the arches, the drum probably would have collapsed almost immediately. This constraint limits the drum’s viable height to about 10 feet on the inside. This would furnish more than enough headroom around the cornice, while retaining enough visible presence to attract Procopius’s attention and convey the remarkable illusion of a lid hovering just over the pot (Figure 5).

In recent years a great deal of energy has been devoted to modeling the structural characteristics of Hagia Sophia’s main vaulting system. To my knowledge, all of the models of the original dome to date have started from the assumption that it sprang directly from cornice level, following Mainstone’s reconstruction. Obviously, the present proposal offers a significantly different profile whose structural viability could be tested, at least in a preliminary fashion, using finite element modeling techniques.

The findings of Swan and Çakmak “tend to dispel the notion that the flatter original dome caused the excessive spreading observed in the structure, since the steeper present dome would have produced greater spreading, at least at the springing level of the main piers.” Likewise, Robert Mark and his colleagues find that “the changing of the first to the second dome configuration had only small effect on relieving the total outward thrusts on the main piers.” In fact, a more substantial structural such as the one I have described might account for the early pier spreading; the combined weight of the dome and drum would have borne down upon the half-dry, inadequately buttressed east and west arches, causing their springings—and thus the main piers—to spread to the north and south. Depending on various characteristics of the drum—stiffness, elasticity, plasticity, tensile strength—and the degree to which it was bonded to the arches and pendentives, the lateral thrusts of the dome, mostly absorbed by the drum buttresses above the level of the arch crowns, may have had considerably less effect upon the arches than at present. The drum would have offered less resistance to the inward thrust of the semidomes, and must have contributed to the seismic instability of the vaulting system.
semicircular profile; (2) assuming well-anchored springings, arches and domes of full semicircular profile tend to be inherently less stable than shallow ones, flattening at the crowns and spreading toward the bottom; (3) buttressing an arch or a dome at its lower levels will mitigate both of these problems; and (4) placing weight on top of an arch or a dome will exacerbate both problems.

These and other rules gave Byzantine buildings a chance for permanence; but the mathematical principles that made buildings stand in the first place were poorly understood. Byzantine architects probably lacked a precise understanding of the consequences of scale, a particularly relevant concern in the building of Hagia Sophia. Modern statics reveal that as the linear dimensions of objects increase at a steady rate, their inherent thrusts and counterthrusts increase exponentially. But in Justinian's time this principle could be understood only in the vaguest terms, perhaps as an empirical assessment of the countermeasures necessary for doubling the span of an arch or a dome.

Still, by the year 537, having observed the movements of the nearly completed building and attending to the rules of thumb mentioned above, the architects must have known that the semidomes were providing more effective buttressing against spreading of the arches than were the north-south buttresses, and hence the critical problem was with the north-south axis. Despite the structural benefits of a dome continuous with the pendentives, and the architects' empirical knowledge of this fact (persuasively argued by Curcic), they probably knew that a shallow dome anchored directly to the arch crowns, with its radial horizontal thrusts, would have aggravated the tilting of the north and south arches and their piers, whereas the dead weight of a full half-sphere with its necessary panoply of radial or stepped ring buttresses (the staple of classical and contemporary architects) would threaten to overwhelm the spreading eastern arch.

The architects were taking other measures to address the crises developing in the substructure. Mainstone has demonstrated convincingly that before the dome was even begun, the north and south buttresses were modified to help them bear the unexpectedly great outward forces of the spreading east and west arches: the passageways between pier and buttress at the floor and gallery levels were narrowed, and the buttresses were heightened. This is evidence that Anthemius and Isidorus knew the risks of compounding the lateral thrusts on the piers, as would a shallow dome against the stiffening arches.

Second, Procopius gives a remarkable account of another emergency measure taken during construction, and it has the ring of truth:

But in the process of building the other arches, indeed, those namely which are turned toward the south and the north, the following chanced to take place. The so-called lori [the tympana lying directly below the north and south arches] had been raised up, carrying the masonry of the church, but everything underneath was labouring under the load, making the columns which stood there throw off tiny flakes, as if they had been planed. . . [Justinian] ordered them immediately to remove the upper parts of the masonry which came into contact with the arches, and to put them back much later, as soon as the dampness of the masonry should abate enough to bear them. This account accurately describes the effect the spreading north and south arches would have had on the underlying tympana and their supporting columns as the sagging crowns bore down upon the masonry below. This event must have alerted the architects to the risks of extreme downward thrusts, such as those that the massive weight of an entire hemisphere would exert upon the arches. So their solution was likely to reflect a conscious compromise entailing neither excessive weight nor excessive lateral pressure directly upon the arches.

But what would present a safe compromise? A vaulting system that worked on a different substructure was not guaranteed to work on Hagia Sophia's huge, undulating canopy. Contemporary brick-and-mortar domes had visible problems, and on a much smaller scale. The hollow ceramic tubes used in late antique African and Italian domes, such as the one on the fifth-century baptistery of Neon in Ravenna, were extremely lightweight; but would they have the tensile strength to resist cracking near the base of the huge dome, or the plasticity to survive an earthquake? The architects faced a bewildering array of problems in their choice of a dome shape and its materials.

The proposed dome-drum combination may have seemed an attractive middle road between dangerous extremes. The relative lightness of a shallow dome using low-density materials with high tensile strength was ballasted with a buttressing structure that would deflect the dome's thrust lines downward through the building's bulk. This road had its pitfalls, which may soon have become evident in radial cracking above the windows. But the architects could not have divined all the structural weaknesses of their formidably original (and brilliantly improvised) masterpiece. Had they done so, it probably would not have wound up such a masterpiece after all. Theirs was in fact a visually satisfying solution to a practical problem, and given their well-grounded fears of alternative options, an intellectually unexceptionable one as well. But surely the venture was not without a certain derring-do, a wish to crown a great achievement in truly exalted fashion.

Notes
2 We do not know when Agathias moved to Constantinople, but he was practicing law there as a fairly young man. The first dome collapsed when he was
twenty-five or twenty-six years old. Even if he did not see the first dome personally, his good friend Paul the Silentiary would have been a reliable witness to its splendors and weaknesses.


5 All measurements hereafter are in Byzantine feet. As Mainstone calculates it, the Byzantine foot used for Hagia Sophia is approximately 0.312 m, or 1.024 English feet. See R. Mainstone, Hagia Sophia: Architecture, Structure and Liturgy of Justinian's Great Church (New York, 1988), 6, 177. On the variability of Byzantine measures, see E. Schilbach, Byzantinische metrologische Quellen (Thessalonike, 1982).

6 This is the height of the top surface of the upper nave cornice as measured by L. Butler, "Hagia Sophia's Nave Cornices as Elements of Its Design and Structure," in Mark and Çakmak, Hagia Sophia from the Age of Justinian, 57–77, at 58.

7 Van Nice and Mainstone had a pointed disagreement on this issue. Van Nice claims that the semidomes have no buttressing effect ("The Structure of St. Sophia," 138, 210), whereas Mainstone argues that they do (Hagia Sophia, 94, 165, and figs. 114, 191, 192). The physical evidence seems to support Mainstone.

8 The eastern and western main arches have each fallen once in the meantime, causing partial collapses of the dome. The western portion, which fell in the tenth century, was sloppily reconstructed. The western arch was thickened by several feet, the ribs were made half again as thick as before, and two window embrasures were filled in under each join between the old section and the new. A collapse in the east, almost identical to the sixth-century collapse, took place in the tenth century, was sloppily reconstructed. The western arch was thickened by several feet, the ribs were made half again as thick as before, and two window embrasures were filled in under each join between the old section and the new. A collapse in the east, almost identical to the sixth-century collapse, took place in the tenth century, was sloppily reconstructed. 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10 In fact, the arches were not pulled down, except perhaps for remains of the fallen eastern arch. The cross sections of the north and south arches confirm that these arches were thickened on the inside without further tampering, as Agathias attests; see Mainstone, Hagia Sophia, 95–96. Malalas may be referring to the pendentives, which must have been dismantled to allow the north and south arches to be thickened.

11 On these latter cornices, see Butler, “Hagia Sophia’s Nave Cornices.”

Mainstone’s alternative proposal that the rounded structure is the “cornice around the tops of the pendentives and a ring of windows around this, both as in the rebuilt dome” (Hagia Sophia, 127) is baffling. As we have seen, Procopius clearly indicates that the structure itself, not the dome above it, contains the windows.

12 Conant, “The First Dome.” Lucid nontechnical explanations of masonry techniques are usually vague and perfunctory, would have taken notes describing any church—even Hagia Sophia—on his own initiative. Although Michael Whitby ("Justinian’s Bridge over the Sangarius and the Date of Procopius’ De Aedificiis," Journal of Hellenic Studies 105 (1985): 129–48) remarks that the description of Hagia Sophia is suspiciously brief, it is actually much more detailed than descriptions in the later books, which read like preparatory notes. Cameron charts Procopius’s growing disillusionment during his later years, which would explain his loss of zeal toward the end of the project. It is unlikely that the Procopius who wrote the scurrilous Secret History could have written the celebratory first book as late as Whitby believes.


14 Cameron, Procopius, 10.

15 Ibid. See G. Downey, “The Composition of Procopius’ De aedificiis,” Transactions of the American Philological Association 78 (1947): 171–83, and Whitby, “Justinian’s Bridge,” which endorse the later date. The basis of contention is Procopius’s statement in 5.3.10 that the bridge over the Sangarius River was unfinished at the time of writing, whereas Theophanes’s Chronographia (anno mundi 6052), written around the year 800, relates that it was begun in the year 560. Whitby does not insist that Book I was written after the collapse, but he prefers to think so.

16 Averil Cameron, Procopius and the Sixth Century (Berkeley and Los Angeles, 1985), 110.

17 Procopius could, of course, have possessed in 559 descriptive notes taken before the collapse. But The Buildings has the character of a hastily conceived and haphazardly compiled work; and it is unlikely that the author, whose descriptions of churches are usually vague and perfunctory, would have taken notes describing any church—even Hagia Sophia—on his own initiative.
aesthetic. Windows raking inward as much as 50 to 55 degrees from vertical would present to the eye a ring of large blocks of dazzling light, darkening everything near them by contrast. Viewers contemplating the dome and its mosaic cross would have to strain to see past the diffused corona of light formed by such a contrefour. Although this arrangement would no doubt be impressive, the indirect light from unseen (or barely seen) windows in upright embrasures recessed behind the cornice would have had a more subtle and ethereal effect.

31 The figure of 30 feet that appears later in Malalas (see Mango, "Byzantine Writers," 51) is "presumably a copyist’s slip, substituting 6 for 36" (Mainstone, Hagia Sophia, 264), but it may just as likely reflect the author’s own carelessness. Later chronologies that draw from the passage I cite preserve the figure of 20 feet; but only the one surviving Greek manuscript of Malalas (a condensation of the lost original history) actually includes the detail that the dome itself was raised 20 feet. Two later accounts that borrowed almost verbatim from this passage—Theophanes’ Chronographia and an anonymous fragment in J. A. Cramer’s Anecdota Graeca—replaced the word trollos (“dome”) with krisma (“building”) and hypsos (“web, structure”) respectively.

32 On a slightly more fanciful plane, the Narratio de S. Sophía, also called the Ducas, a semilegendary eighth- or ninth-century account of the building and rebuilding of the church, which claims the second dome was actually lowered (albeit by five fathom), may carry a grain of truth. For an eyewitness could just as easily have ignored the greater depth and pitch of the new dome, and fixed his attention where it was anchored—not up on a drum as before, but down on the crowns of the arches themselves. In fact, two of the three reasons given for the dome’s collapse in the Narratio sound quite plausible: the emperor “was too hasty in removing the wooden supports [i.e., centering] that were in the dome so as to cover it quickly with mosaic,” and “he made it [too] high [i.e., on a drum?] so as to be seen from everywhere” (Mango, Art of the Byzantine Empire, 102). A drum under the first dome would have seemed an obvious agent in the collapse and hence would be avoided in the rebuilding. So by dispensing with the drum, the dome would be “lowered.” Mango suggests that the Narratio’s strange blend of fact and fancy is the result of oral traditions (“Byzantine Writers,” 49).


39 My translation and emphasis from lines 562, 565–81 in Legrand’s edition.

40 Elif, οἱ γάνατοι ὁμοίοι εὐκνητοῖς καὶ γέφυρας ἔκτεινοντες εἰς τὸν ἄρχοντα καὶ διέκτεινος πλέοντας ὄλους διεκτεινός αὐτούς καθ’ αὐτοῦ διάδοχος πρὸς τὸν πέλαγον, τὸν κοίλον τοῦ βασιλείου, ἀνέθεσεν εὐχαριστῶν εὐκλονοῦσιν, εἰς τέταρτος τεινόντας κύκλων ἑκάστοτε, δεημαντών καλουνόν ἐργοναριθέταν, σφαιρὰς δέχοντα πενταερωμίσεις πλην τὴν μέσην προσέχοντας τὴν ἁλὸν ὁ τερνήτης ἐνεκείμεν τρόπον ἀλλοτριότους ἐν εὔκουνον μέχριν τῆς εἰκόνας τῆς ἱεραρχείας ἐν μέσῳ κελευνὸν δόμων ἐποίος ἀπὸ ἀνθρώπων καταρτίσατο ἐκ καλωσφερῶν ἔμφρων κυκλώματι κακέων αὐτοῖς κακοσκευασίας ἀμώοεος μιαίος καμάνιον υἱὸς καθαθεμβόλων.

41 My translation and emphasis from lines 617–34 in Legrand’s edition.


45 My translation and emphasis from lines 974–78 in Legrand’s edition.
Krautheimer, “A Note on Justinian’s Church,” cites four depictions of the church in illuminated manuscripts, three from the Menologium of Basil II (c. 979–89) and one from the homilies of James Kokkinobaphos (twelfth century). All of these illustrations show the church—albeit much stylized—with several domes, the central one standing highest on a fenestrated drum. Krautheimer maintains that the multiple drums depicted in these illustrations, some with windows, attest a rebuilding of the church sometime between Procopius’s time and the illustration of Basil’s Menologium. This rebuilding included raising all the domes upon fenestrated drums. Epstein, “Rebuilding and Redemption,” gives ample evidence why this conclusion cannot be supported. I would add the following reasons: (1) Krautheimer’s premise that no drums existed on the original building is faulty; (2) he remarks that Constantin “strives . . . the lighting of only the main dome over the center bay,” an assertion I find unsupported in the text; (3) it is uncertain in the three earliest illustrations whether drums are being depicted, or simply the entire substructure of each cross-arm; and (4) small fenestrated drums were so common in Byzantine architecture by the tenth century that they had become a convention in illustrations of buildings, whether the subjects actually had them or not. Medieval depictions of buildings can almost never be taken at face value. Even Renaissance depictions can be grossly misleading: for example, the Nuremberg Chronicle panorama of Constantinople, dating from 1493, depicts not only the Nea Ekklesia (?) as a cluster of domed, faceted silos, but Hagia Sophia as Florence cathedral, with a huge hexagonal fenestrated drum and a Brunelleschian lantern sprouting from the crown of the dome.

Following a rule that seems to apply to vaulting throughout the building, Mainstone, Hagia Sophia, 210, suggests that the thickness of the first dome was about 5 percent of its radius of curvature, making it nearly a foot thicker than the present dome. This suggestion is highly speculative; more likely, strength was sacrificed to lightness in the dome, while the converse held true for the drum.

→ C. Swan and A. S. Çakmak, “Nonlinear Quasi-Static and Seismic Analysis of the Hagia Sophia Using an Effective Medium Approach,” Soil Dynamics and Earthquake Engineering 12 (1993): 259–71, at 264, calculate a force of between 200 and 375 meganewtons per rib for a dome model similar to the one proposed by Mainstone. They assume that the present dome is 26 percent heavier than the original; but under my proposal, the original dome (drum not included) may have been lighter even than this, thereby reducing the lateral thrust below the proposed magnitude. The vertical thrust, of course, would be substantially increased by the weight of the drum. A massive iron tie around the foot of the dome, similar to those applied to the present dome in the nineteenth century, could have reduced or even eliminated the lateral thrusts; however, there is no indication that this expedient was used in the sixth century. The technology to produce large iron chains certainly existed, as Procopius himself attests (Wars 5.19.24–26).

There were probably forty windows and spurs around the original dome, as now; for the rebuilders, concerned as they were with greater permanence, would not have increased the number of windows, clearly among the weakest features in the original structure.


Swan and Çakmak, “Nonlinear Quasi-Static and Seismic Analysis,” 265.


The Pantheon in Rome (c. 124 C.E.), the Rotunda of St. George in Thessalonike, built by Galerius (d. 311 C.E.), and the church of St. Costanza in Rome (c. 350 C.E.) are well-known extant examples of vaulted cylindrical precedents. J. B. Ward Perkins, “The Italian Element in Late Roman Architecture,” Proceedings of the British Academy 53 (1947): 163–94, offers instructive analogies with such buildings as the Basilica of Maxentius and S. Lorenzo in Milan, but in complexity Hagia Sophia far exceeds these buildings.


S. Ćurčić, “Design and Structural Innovation.” But for the intervening low drum, Mainstone’s proposal is identical.

See Mainstone, Hagia Sophia, 168–69. It is not my intent to enter the debate about the nature of architectural training during this period, but it seems foolish to claim, as Robert Browning does (Justinian and Theodore [London, 1987], 75), that Anthemius and Isidorus had little use for empirical models or for traditional training in the building craft; see A. Petronotis, “Der Architekt in Byzanz,” in Bauplanung und Bautechnik der Antike (Berlin, 1984), 329–43; H. A. Meek, “The Architect and His Profession in Byzantium,” Journal of the Royal Institute of British Architects 59 (1951–52): 216–20; G. Downey, “Byzantine Architects, Their Training and Methods,” Byzantium 18 (1946–48): 99–118. Even if they did not have much personal building experience, they would have consulted extensively with men who did, just as Brunelleschi did in Renaissance Italy; see Mainstone, Hagia Sophia, 157. “Anthemius and Isidorus could use only practical experience in building a guide to structural reliability,” writes Robert Mark. “Geometry did play a major role in their conceptual design; however as no less an observer than Galileo also commented, geometry alone can never ensure structural success.” See R. Mark, Light, Wind, and Structure: The Mystery of the Master Builders (Cambridge, Mass., 1990), 88–89.

In general, serious implications of increased scale arise because the forces associated with self-weight increase at a greater rate than the resistances opposed to them. Double all dimensions, and the forces increase eightfold, while the cross-sections, and hence the resistances, increase only fourfold.” Mainstone, Hagia Sophia, 166.


Procopius, The Buildings, 1.1.74–77; Loeb translation, p. 31.

These downward thrusts would add to the spreading of the arches, which in turn would compound the lateral thrusts upon the main piers.

There are excellent examples of radial cracking of domes due to circumferential tensions and thrusting apart of supports. . . . Similar evidence must have been visible in some of the earlier buildings of Constantinople: indeed SS. Sergius and Bacchus today exhibits much the same distortions in its galleries as can be seen in St. Sophia, and it is almost certain that the pronounced outward tilts of its piers and columns, for instance, were clearly apparent when St. Sophia was built.” Mainstone, “Justinian’s Church,” 43–44.

On the dome’s masonry, see R. A. Livingston, “Materials Analysis of the Masonry of Hagia Sophia Basilica, Istanbul,” in Çakmak and Brebbia, Soil Dynamics and Earthquake Engineering (see n. 17), 849–66.