4.4 DOME

A **dome** (from Latin: *domus*) is an architectural element similar to the hollow upper half of a sphere; there is significant overlap with the term cupola, which may also refer to a dome or a structure on top of a dome. The precise definition of a dome has been a matter of controversy and there are a wide variety of forms and specialized terms to describe them. A dome can rest directly upon a rotunda wall, a drum, or a system of squinches or pendentives used to accommodate the transition in shape from a rectangular or square space to the round or polygonal base of the dome. A dome's apex may be closed or may be open in the form of an oculus, which may itself be covered with a roof lantern and cupola.

Domes have a long architectural lineage that extends back into prehistory. Domes were built in ancient Mesopotamia, and they have been found in Persian, Hellenistic, Roman, and Chinese architecture in the ancient world, as well as among a number of indigenous building traditions throughout the world. Dome structures were common in both Byzantine architecture and Sasanian architecture, which influenced that of the rest of Europe and Islam, respectively, in the Middle Ages. The domes of European Renaissance architecture spread from Italy in the early modern period, while domes were frequently employed in Ottoman architecture at the same time. Baroque and Neoclassical architecture took inspiration from Roman domes.

Advancements in mathematics, materials, and production techniques resulted in new dome types. Domes have been constructed over the centuries from mud, snow, stone, wood, brick, concrete, metal, glass, and plastic. The symbolism associated with domes includes mortuary, celestial, and governmental traditions that have likewise altered over time. The domes of the modern world can be found over religious buildings, legislative chambers, sports stadiums, and a variety of functional structures.

The English word "dome" ultimately derives from the ancient Greek and Latin *domus* ("house"), which, up through the Renaissance, labeled a revered house, such as a *Domus Dei*, or "House of God", regardless of the shape of its roof. This is reflected in the uses of the Italian word *duomo*, the German/Icelandic/Danish word *dom* ("cathedral"), and the English word *dome* as late as 1656, when it meant a "Town-House, Guild-Hall, State-House, and Meeting-House in a city." The French word *dosme* came to acquire the meaning of a cupola vault, specifically, by 1660. This French definition gradually became the standard usage of the English *dome* in the eighteenth century as many of the most impressive Houses of God were built with monumental domes, and in response to the scientific need for more technical terms.[1][a]

Definitions

Across the ancient world, curved-roof structures that would today be called domes had a number of different names reflecting a variety of shapes, traditions, and symbolic associations. The shapes were derived from traditions of pre-historic shelters made from various impermanent pliable materials and were only later reproduced as vaulting in more durable materials. The hemispherical shape often associated with domes today derives from Greek geometry and Roman standardization, but other shapes persisted, including a pointed and bulbous tradition inherited by some early Islamic mosques.

Modern academic study of the topic has been controversial and confused by inconsistent definitions, such as those for cloister vaults and domical vaults. Dictionary definitions of the term "dome" are often general and imprecise. Generally-speaking, it "is non-specific, a blanket-word to describe an hemispherical or similar spanning element." Published definitions include: hemispherical roofs alone; revolved arches; and vaults on a circular base alone, circular or polygonal base, circular, elliptical, or polygonal base, or an undefined area. Definitions specifying vertical sections include: semicircular, pointed, or bulbous; semicircular, segmental or pointed; semicircular, segmental, pointed, or bulbous; semicircular, segmental, elliptical, or bulbous; and high profile, hemispherical, or flattened.

Comparison of a generic "true" arch (left) and a corbel arch (right)

Sometimes called "false" domes, corbel domes achieve their shape by extending each horizontal layer of stones inward slightly farther than the lower one until they meet at the top. A "false" dome may also refer to a wooden dome. The Italian use of the term *finto*, meaning "false", can be traced back to the 17th century in the use of vaulting made of reed mats and gypsum mortar. "True" domes are said to be those whose structure is in a state of compression, with constituent elements of wedge-shaped voussoirs, the joints of which align with a central point. The validity of this is unclear, as domes built underground with corbelled stone layers are in compression from the surrounding earth.

The precise definition of "pendentive" has also been a source of academic contention, such as whether or not corbelling is permitted under the definition and whether or not the lower portions of a sail vault should be considered pendentives. Domes with pendentives can be divided into two kinds: *simple* and *compound*. In the case of the *simple dome*, the pendentives are part of the same sphere as the dome itself; however, such domes are rare. In the case of the more common *compound dome*, the pendentives are part of the surface of a larger sphere below that of the dome itself and form a circular base for either the dome or a drum section.

The fields of engineering and architecture have lacked common language for domes, with engineering focused on structural behavior and architecture focused on form and symbolism. Additionally, new materials and structural systems in the 20th century have allowed for large dome-shaped structures that deviate from the traditional compressive structural behavior of masonry domes and popular usage of the term has expanded to mean "almost any long-span roofing system".

Materials

The earliest domes in the Middle East were built with mud-brick and, eventually, with baked brick and stone. Domes of wood allowed for wide spans due to the relatively light and flexible nature of the material and were the normal method for domed churches by the 7th century, although most domes were built with the other less flexible materials. Wooden domes were protected from the weather by roofing, such as copper or lead sheeting. Domes of cut stone were more expensive and never as large, and timber was used for large spans where brick was unavailable.

Roman concrete used an aggregate of stone with a powerful mortar. The aggregate transitioned over the centuries to pieces of fired clay, then to Roman bricks. By the sixth century, bricks with large amounts of mortar were the principle vaulting materials. Pozzolana appears to have only been used in central Italy. Brick domes were the favored choice for large-space monumental coverings until the Industrial Age, due to their convenience and dependability. Ties and chains of iron or wood could be used to resist stresses.

The new building materials of the 19th century and a better understanding of the forces within structures from the 20th century opened up new possibilities. Iron and steel beams, steel cables, and pre-stressed concrete eliminated the need for external buttressing and enabled much thinner domes. Whereas earlier masonry domes may have had a radius to thickness ratio of 50, the ratio for modern domes can be in excess of 800. The lighter weight of these domes not only permitted far greater spans, but also allowed for the creation of large movable domes over modern sports stadiums.

Experimental rammed earth domes were made as part of work on sustainable architecture at the University of Kassel in 1983.

Shapes and internal forces

A masonry dome produces thrusts downward and outward. They are thought of in terms of two kinds of forces at right angles from one another: meridional forces (like the meridians, or lines of longitude, on a globe) are compressive only, and increase towards the base, while hoop forces (like the lines of latitude on a globe) are in compression at the top and tension at the base, with the transition in a hemispherical dome occurring at an angle of 51.8 degrees from the top. The thrusts generated by a dome are directly proportional to the weight of its materials. Grounded hemispherical domes generate significant horizontal thrusts at their haunches.

The outward thrusts in the lower portion of a hemispherical masonry dome can be counteracted with the use of chains incorporated around the circumference or with external buttressing, although cracking along the meridians is natural. For small or tall domes with less horizontal thrust, the thickness of the supporting arches or walls can be enough to resist deformation, which is why drums tend to be much thicker than the domes they support.

Unlike voussoir arches, which require support for each element until the keystone is in place, domes are stable during construction as each level is made a complete and self-supporting ring. The upper portion of a masonry dome is always in compression and is supported laterally, so it does not collapse except as a whole unit and a range of deviations from the ideal in this shallow upper cap are equally stable. Because voussoir domes have lateral support, they can be made much thinner than corresponding arches of the same span. For example, a hemispherical dome can be 2.5 times thinner than a semicircular arch, and a dome with the profile of an equilateral arch can be thinner still.

The optimal shape for a masonry dome of equal thickness provides for perfect compression, with none of the tension or bending forces against which masonry is weak. For a particular material, the optimal dome geometry is called the funicular surface, the comparable shape in three dimensions to a catenary curve for a two-dimensional arch. Adding a weight to the top of a pointed dome, such as the heavy cupola at the top of Florence Cathedral, changes the optimal shape to more closely match the actual pointed shape of the dome. The pointed profiles of many Gothic domes more closely approximate the optimal dome shape than do hemispheres, which were favored by Roman and Byzantine architects due to the circle being considered the most perfect of forms.

Types

Beehive dome

Also called a *corbelled dome*, or *false dome*, these are different from a 'true dome' in that they consist of purely horizontal layers. As the layers get higher, each is slightly cantilevered, or corbeled, toward the center until meeting at the top. A monumental example is the Mycenaean Treasury of Atreus from the late Bronze Age.

Braced dome

A single or double layer space frame in the form of a dome, a *braced dome* is a generic term that includes *ribbed*, *Schwedler*, *three-way grid*, *lamella* or *Kiewitt*, *lattice*, and *geodesic domes*. The different terms reflect different arrangements in the surface members. Braced domes often have a very low weight and are usually used to cover spans of up to 150 meters. Often prefabricated, their component members can either lie on the dome's surface of revolution, or be straight lengths with the connecting points or nodes lying upon the surface of revolution. Single-layer structures are called *frame* or *skeleton* types and double-layer structures are *truss* types, which are used for large spans. When the covering also forms part of the structural system, it is called a *stressed skin* type. The *formed surface* type consists of sheets joined together at bent edges to form the structure.

Cloister vault

Also called *domical vaults* (a term sometimes also applied to sail vaults), *polygonal domes*, *coved domes*, *gored domes*,[*segmental domes* (a term sometimes also used for saucer domes), *paneled vaults*, or *pavilion vaults*, these are domes that maintain a polygonal shape in their horizontal cross section. The earliest known examples date to the first century BC, such as the Tabularium of Rome from 78 BC. Others include the Baths of Antoninus in Carthage (145–160) and the Palatine Chapel at Aachen (13th – 14th century). The most famous example is the Renaissance octagonal dome of Filippo Brunelleschi over the Florence Cathedral. Thomas Jefferson, the third president of the United States, installed an octagonal dome above the West front of his plantation house, Monticello.

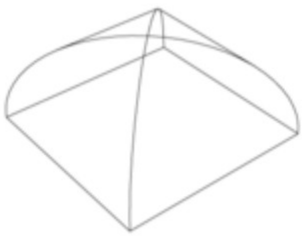
Compound dome

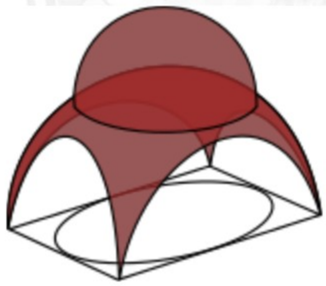
Also called *domes on pendentives* or *pendentive domes* (a term also applied to sail vaults), compound domes have pendentives that support a smaller diameter dome immediately above them, as in the Hagia Sophia, or a drum and dome, as in many Renaissance and post-Renaissance domes, with both forms resulting in greater height.

Crossed-arch dome

One of the earliest types of ribbed vault, the first known examples are found in the Great Mosque of Córdoba in the 10th century. Rather than meeting in the center of the dome, the ribs characteristically intersect one another off-center, forming an empty polygonal space in the center. Geometry is a key element of the designs, with the octagon being perhaps the most popular shape used. Whether the arches are structural or purely decorative remains a matter of debate. The type may have an eastern origin, although the issue is also unsettled. Examples are found in Spain, North Africa, Armenia, Iran, France, and Italy.

A corbel dome A domical vault A compound dome





Ellipsoidal dome

The ellipsoidal dome is a surface formed by the rotation around a vertical axis of a semi-ellipse. Like other "rotational domes" formed by the rotation of a curve around a vertical axis, ellipsoidal domes have circular bases and horizontal sections and are a type of "circular dome" for that reason.

Geodesic dome

Geodesic domes are the upper portion of geodesic spheres. They are composed of a framework of triangles in a polyhedron pattern. The structures are named for geodesics and are based upon geometric shapes such as icosahedrons, octahedrons or tetrahedrons. Such domes can be created using a limited number of simple elements and joints and efficiently resolve a dome's internal forces. Their efficiency is said to increase with size. Although not first invented by Buckminster Fuller, they are associated with him because he designed many geodesic domes and patented them in the United States.

Hemispherical dome

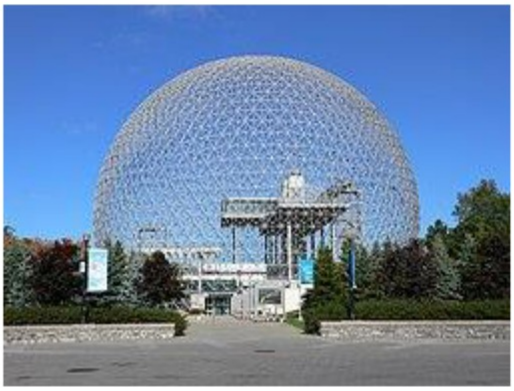
The *hemispherical dome* is a surface formed by the rotation around a vertical axis of a semicircle. Like other "rotational domes" formed by the rotation of a curve around a vertical axis, hemispherical domes have circular bases and horizontal sections and are a type of "circular dome" for that reason. They experience vertical compression along their meridians, but horizontally experience compression only in the portion above 51.8 degrees from the top. Below this point, hemispherical domes experience tension horizontally, and usually requires buttressing to counteract it. According to E. Baldwin Smith, it was a shape likely known to the Assyrians, defined by Greek theoretical mathematicians, and standardized by Roman builders.

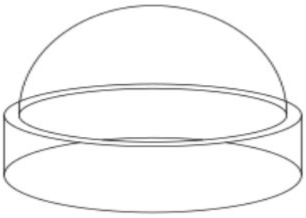
Onion dome

Bulbous domes bulge out beyond their base diameters, offering a profile greater than a hemisphere. An *onion dome* is a greater than hemispherical dome with a pointed top in an ogee profile. They are found in the Near East, Middle East, Persia, and India and may not have had a single point of origin. Their appearance in northern Russian architecture predates the Tatar occupation of Russia and so is not easily explained as the result of that influence. They became popular in the second half of the 15th century in the Low Countries of Northern Europe, possibly inspired by the finials of minarets in Egypt and Syria, and developed in the 16th and 17th centuries in the Netherlands before spreading to Germany, becoming a popular element of the baroque architecture of Central Europe. German bulbous domes were also influenced by Russian and Eastern European domes. The examples found in various European architectural styles are typically wooden. Examples include Kazan Church in Kolomenskoye and the Brighton Pavilion by John Nash. In Islamic architecture, they are typically made of masonry, rather than timber, with the thick and heavy bulging portion serving to buttress against the tendency of masonry domes to spread at their bases. The Taj Mahal is a famous example.

Oval dome

An *oval dome* is a dome of oval shape in plan, profile, or both. The term comes from the Latin *ovum*, meaning "egg". The earliest oval domes were used by convenience in corbelled stone huts as rounded but geometrically undefined coverings, and the first examples in Asia Minor date to around 4000 B.C. The geometry was eventually defined using combinations of circular arcs, transitioning at points of tangency. If the Romans created oval domes, it was only in exceptional circumstances. The Roman foundations of the oval plan Church of St. Gereon in Cologne point to a possible example. Domes in the Middle Ages also tended to be circular, though the church of Santo Tomás de las Ollas in Spain has an oval dome over its oval plan. Other examples of medieval oval domes can be found covering rectangular bays in churches. Oval plan churches became a type in the Renaissance and popular in the Baroque style. The dome built for the basilica of Vicoforte by Francesco Gallo was one of the largest and most complex ever made. Although the ellipse was known, in practice, domes of this shape were created by combining segments of circles. Popular in the 16th and 17th centuries, oval and elliptical plan domes can vary their dimensions in three axes or two axes. A sub-type with the long axis having a semicircular section is called a Murcia dome, as in the Chapel of the Junterones at Murcia Cathedral. When the short axis has a semicircular section, it is called a Melon dome.





A geodesic dome A hemispherical dome

An oval dome

Paraboloid dome

A paraboloid dome is a surface formed by the rotation around a vertical axis of a sector of a parabola. Like other "rotational domes" formed by the rotation of a curve around a vertical axis, paraboloid domes have circular bases and horizontal sections and are a type of "circular dome" for that reason. Because of their shape, paraboloid domes experience only compression, both radially and horizontally.

Sail dome

Also called *sail vaults*, *handkerchief vaults*, *domical vaults* (a term sometimes also applied to cloister vaults), *pendentive domes* (a term that has also been applied to compound domes), *Bohemian vaults*, or *Byzantine domes*, this type can be thought of as pendentives that, rather than merely touching each other to form a circular base for a drum or compound dome, smoothly continue their curvature to form the dome itself. The dome gives the impression of a square sail pinned down at each corner and billowing upward. These can also be thought of as saucer domes upon pendentives. Sail domes are based upon the shape of a hemisphere and are not to be confused with elliptic parabolic vaults, which appear similar but have different characteristics. In addition to semicircular sail vaults there are variations in geometry such as a low rise to span ratio or covering a rectangular plan. Sail vaults of all types have a variety of thrust conditions along their borders, which can cause problems, but have been widely used from at least the sixteenth century. The second floor of the Llotja de la Seda is covered by a series of nine meter wide sail vaults.

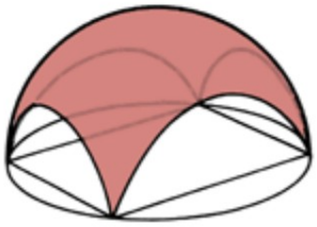
Saucer dome

Also called *segmental domes* (a term sometimes also used for cloister vaults), or *calottes*, these have profiles of less than half a circle. Because they reduce the portion of the dome in tension, these domes are strong but have increased radial thrust. Many of the largest existing domes are of this shape.

Masonry saucer domes, because they exist entirely in compression, can be built much thinner than other dome shapes without becoming unstable. The trade-off between the proportionately increased horizontal thrust at their abutments and their decreased weight and quantity of materials may make them more economical, but they are more vulnerable to damage from movement in their supports.

Umbrella dome

Also called *gadrooned*, *fluted*, *organpiped*, *pumpkin*, *melon*, *ribbed*, *parachute*, *scalloped*, or *lobed* domes, these are a type of dome divided at the base into curved segments, which follow the curve of the elevation. "Fluted" may refer specifically to this pattern as an external feature, such as was common in Mamluk Egypt. The "ribs" of a dome are the radial lines of masonry that extend from the crown down to the springing. The central dome of the Hagia Sophia uses the ribbed method, which accommodates a ring of windows between the ribs at the base of the dome. The central dome of St. Peter's Basilica also uses this method.



A sail vault

A saucer dome

An umbrella dome