Fractals and the birth of Gothic: reflections on the biologic basis of creativity.

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PERSPECTIVE

Fractals and the birth of Gothic: reflections on the biologic basis of creativity

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We can pinpoint the origin of no previous [architectural] style as exactly as that of Gothic. It was born between 1137 and 1144 in the rebuilding, by the Abbot Suger, of the Royal Abbey Church of St Denis just outside the city of Paris.
What distinguishes this interior immediately from its predecessors is its lightness, in both senses; the architectural forms seen graceful, almost weightless as against the massive solidity of the Romanesque....

HW Janson, *History of Art*, 2nd edn[1]

The great, storied, stained-glass windows, the fan vaults, the decorative borders of narrative sculpture and the enormous dimensions of the cathedral cancel out surfaces and planes, and reduce the entire figurative vocabulary to a dialectic of dynamic lines stretched almost to the breaking point.

B Zevi, *Architecture as Space*[2]

The birth of Gothic, one of the great triumphs of human spiritual and artistic expression, would appear to be a topic remote from the enterprise of contemporary neurobiology. The intent of this brief essay is to explore the possibility that this singular architectural movement may have important implications for understanding the nonlinear dynamics of the brain. We explore the hypothesis that the Gothic cathedral, with its porous, scale-free structures, may represent an externalization of the fractal properties of our physiology in general, and of our neural architectures and neuro-dynamics, in particular.

Keywords: creativity; fractals; Gothic art; neurobiology; nonlinear dynamics

Nonlinear transitions

A remarkable aspect of the Gothic style was its abrupt appearance. As described in the introductory citation, Gothic architecture did not so much evolve as erupt—a revolutionary 12th century movement originating at the northern outskirts of Paris.[1–4] The Royal Abbey Church of St Denis represented a dramatic break with the prevailing Romanesque tradition; and this new architectural dynamic quickly percolated throughout Europe over the ensuing decades, becoming the dominant style for the next three centuries. The sudden emergence of a new style is reminiscent of a ubiquitous family of transformations called *phase transitions*, part of the more general class of *critical phenomena*.[5] Familiar examples in nature include freezing or boiling of water at a critical temperature. Other examples include geometric transformations of macromolecules in solution and the onset of turbulent flow. Phase-like transitions may also occur in biologic systems, possibly exemplified by abrupt shifts in mood or sleep stage. The Romanesque→Gothic phase-like transition appears, remarkably, to have been realized primarily through the creative efforts of a single individual, the Abbot Suger who, singlehandedly, conceived and directed the rebuilding of the Royal Abbey Church.[3] This transition can be further characterized topologically as a *dimensional* alteration, with the Gothic* style representing the emergence of an artistic form

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* According to Erlande-Brandenburg[4] the term 'Gothic' first appeared in Vasari's *Lives of the Most Excellent Painters, Sculptors, and Architects* (1550). 'Sharing the distaste of his fellow humanists for a style that failed to achieve lasting success in Italy, Vasari summarily dismissed the 'art' of the Middle Ages as *monstrous* [italics added] and attributed it to the Goths on the basis of its 'barbaric' qualities.' In a notable parallelism, Dyson[6] describes how the fractal 'revolution was forced by the discovery of mathematical structures that did not fit the patterns of Euclid and Newton. These new structures were regarded... as 'pathological'... as a gallery of 'monsters' ' by the mathematicians of the late 19th century.

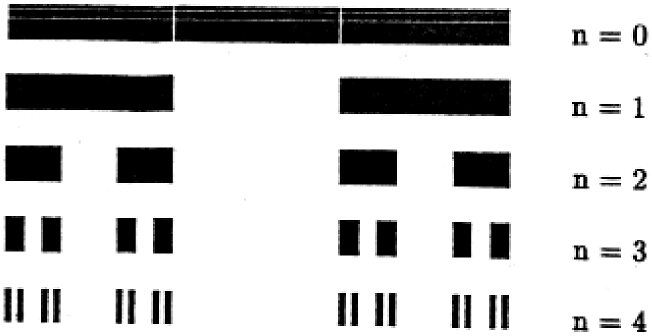

Figure 1 The first four iterations (n) of the triadic Cantor set, a 'porous' structure with a fractional dimension d = log 2/log 3 = 0.6309.

embodying a non-integer or fractional dimensionality referred to as *fractal*.[7–12]

Fractal dimensionality

The classical concept of dimensionality is firmly rooted in our recognition of Euclidean forms having dimension = 1 (line), 2 (plane) or 3 (solid). Over the past few decades there has been growing appreciation that the irregular, rough shapes that predominate in nature typically do not possess integer dimensionality, but instead have a fractal dimension. As stated by Benoit B Mandelbrot, the mathematician who pre-eminently developed this new geometry: 'Clouds are not spheres, mountains are not cones, coastlines are not circles, and bark is not smooth, nor does lightning travel in a straight line'.[7]

An important example of a fractal, called the Cantor set, with potential relevance to understanding the porosity of Gothic structures, is obtained by the following procedure (Figure 1). Start with a line segment and remove the middle third, leaving two shorter line segments. Repeat this operation (resection of the middle third) on the two sub-segments; then iterate this excision process again and again. The result is a fragmented dust-like residue having dimension less than 1 (less structure than a line) but greater than 0. A second fractal creation, reminiscent of Gothic crenelations, is the Koch 'coastline' shown in Figure 2, which can be

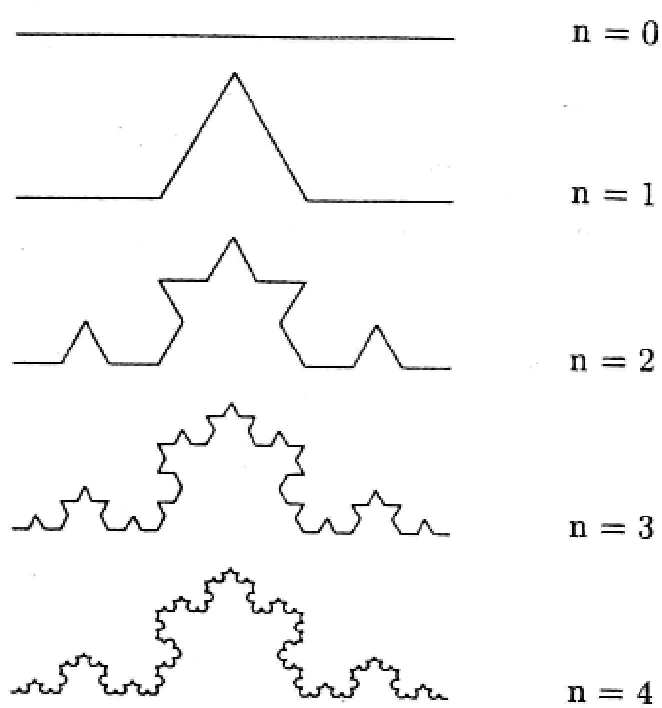

Figure 2 The first 4 iterations (n) of the Koch coastline curve. The fractional dimension is d = log4/log3 = 1.2618.

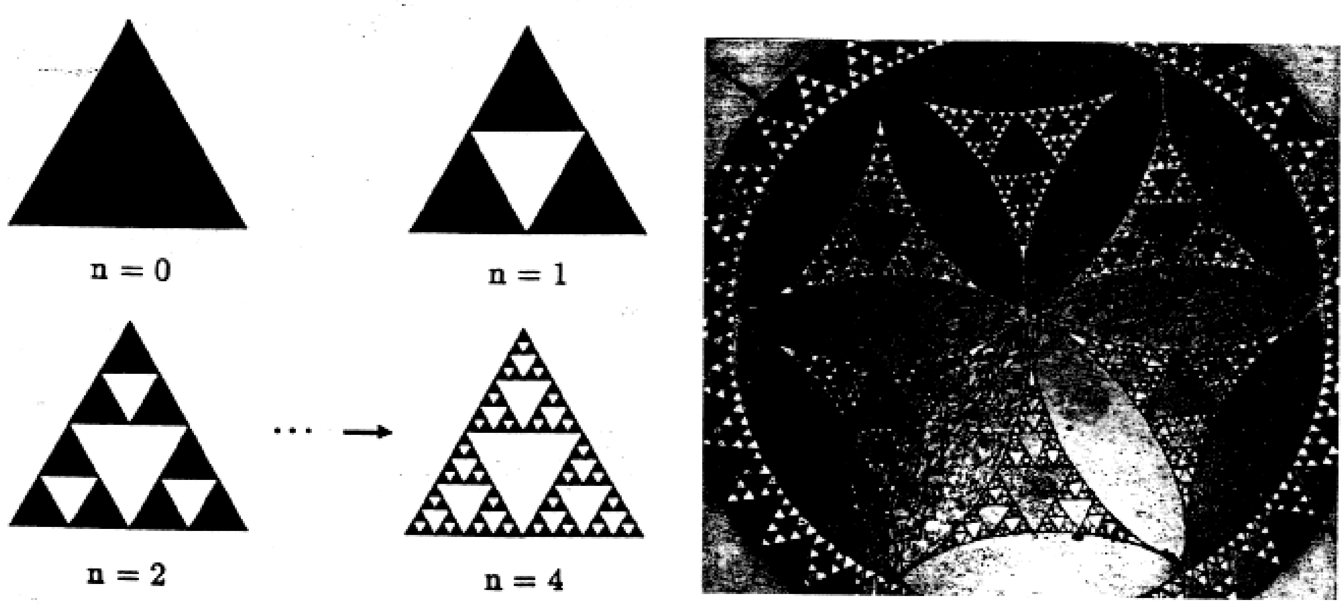

Figure 3 (Left panel) Construction of the Sierpiński gasket with dimension d = log3/log2 = 1.5850. (Right panel) Photograph (by R Stanley) of a floor mosaic of the cathedral in Anagni, Italy (1104 AD) showing Sierpiński gasket at the fourth stage of iteration. This early 12th century fractal prefigures the explosion of scale-free forms in Gothic architecture. (Reproduced with permission from Ref 10.)

viewed as the addition of triangulated forms upon triangulated forms. Such a wrinkly structure has a dimension between 1 and 2: ie it occupies more space than a straight line, but does not fill the plane. A third illustrative fractal construction is the Sierpiński gasket, which is made by excavating triangles of different scale (Figure 3).

Gothic fractals

These fractals capture several key features of Gothic architecture: its porous 'holeyness' or carved-out appearance, its wrinkled, crenelated surfaces, and its overall *self-similarity*. The latter is a defining feature of fractals, which are objects composed of smaller units that closely resemble the larger scale structure. The fractal nature of the Gothic cathedral can be appreciated by viewing it (both from without and within) at progressively greater magnifications (Figure 4). From a distance, the sharp spires are the dominant feature. Closer proximity reveals that these spires are not smooth, but have spiny outgrowths. Yet closer inspection reveals even more pointed detail superimposed on these ornaments. The repetition of different shapes (arches, windows, spires) on different scales yields a combination of complexity and order. The carved-out, fenestrated nature of the buildings, particularly when supported by flying buttresses, gives them a remarkably skeletal appearance and accounts for their luminosity.[1–4]

Romanesque structures, in contrast, are notable for their solidity, their filled-in appearance.[1] Further, the surfaces of Romanesque buildings tend to be smoother and less irregular and spiky than their Gothic counterparts. The inside of a Romanesque church does not convey the same skeletal sense as the interior of a Gothic structure. The organic nature of Gothic forms is noteworthy because of recent evidence indicating that many anatomic structures, and certain features of physiologic dynamics, are fractal.[8,9,11,12] Self-similar structures include the branching dendrites of neurons, and the multiple enfoldings of the cerebral cortex. Such

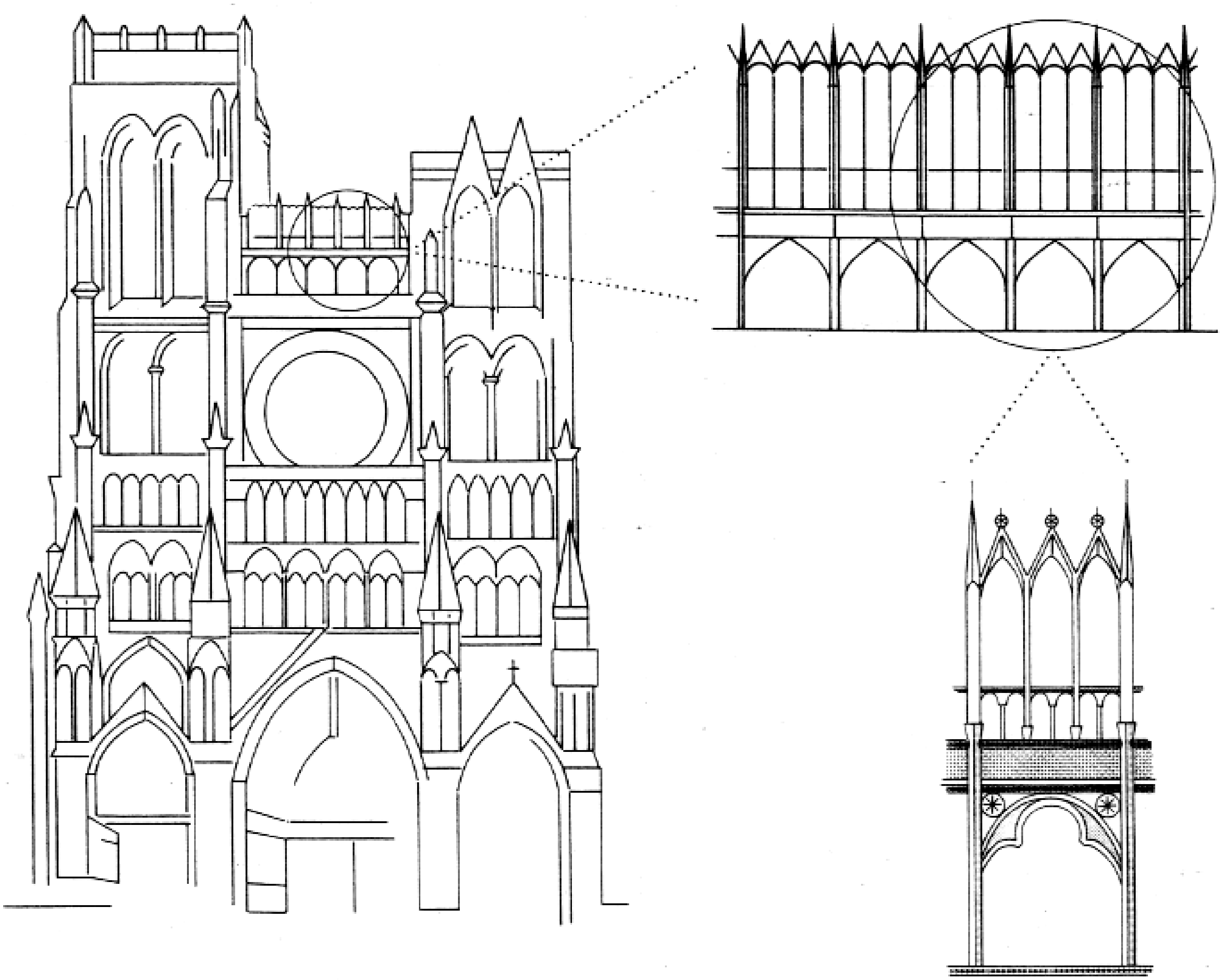

Figure 4 Schematic drawing to illustrate fractal appearance of Gothic cathedrals which show self-similar (but not identical) features on multiple scales of magnification. (Drawings by A Brass.)

fractality greatly enhances the surface area for information exchange, just as the fractal foldings of the bowel and lung greatly amplify surface area for nutrient absorption and gas exchange, respectively. We[13–16] and others[17,18] have also recently reported a fractal type of organization of nucleotides in non-coding DNA from a wide variety of species, indicating that this scale-free architecture extends to submicroscopic levels (Figure 5).

Of equal interest are the fractal dynamics (temporal architecture) of the nervous system. Fractal processes, analogous to fractal structures (which do not have a single length scale), lack a characteristic or single scale of time. Instead, such complex processes generate fluctuations on multiple time scales. This multi-scaled fractal property has obvious adaptive advantages. A system with multi-scale variability is more capable of coping with an inherently unpredictable environment.[8] Fractal dynamics have been reported in a number of important facets of neural function, from the level of ion-channel openings[12] to auditory nerve train spikes,[19] fluctuations in cardiac interbeat intervals under healthy conditions[20–22] (Figure 6), and step-to-step variability in human gait[23] (Figure 6). Of related interest is the finding that a wide class of pathologic (ie non-adaptive) dynamics are associated with the emergence of highly periodic behavior dominated by a single time scale or characteristic frequency. Examples of this loss of multi-scaled fractal variability include the periodic type of tremors observed in a wide range of neural diseases, regular oscillations of the EEG during generalized epilepsy, and perseverative behavior observed in obsessive-compulsive disorder as well as with various types of organic brain disease.

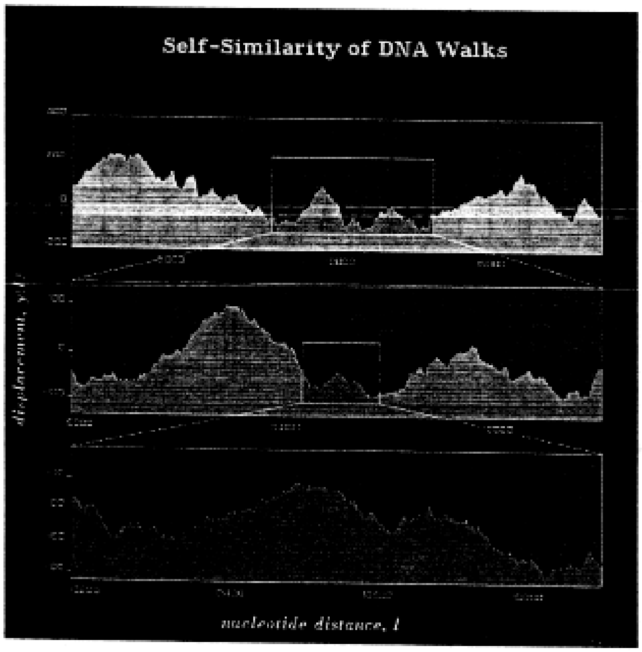

Figure 5 The DNA walk representation (see Refs 13 and 15 for details) for the rat embryonic skeletal myosin heavy chain gene. These plots are generated by mapping the nucleotide sequence onto a two-dimensional walk such that the walker takes a step-up if the nucleotide at any position is a pyrimidine and a step-down if it is a purine. (Top) The entire sequence. (Middle) The magnification of the solid box at top. (Bottom) The magnification of the solid box in the middle. The statistical self-affinity of these plots is consistent with the existence of a scale-free or fractal phenomenon termed a fractal landscape. In order to observe statistically similar fluctuations within successive enlargement, the magnification factor along the vertical direction (M_V) and horizontal direction (M_H) follows a simple relation: $\log M_V / \log M_H = \alpha$. Here $\alpha = 0.63$, indicating long-range power-law correlations.[13–16] Note that these DNA walk representations are plotted so that the end point has the same vertical displacement as the starting point. (Adapted from Ref 13.)

Gothic creation as fractal re-creation

The apparent fractal nature of Gothic art viewed in light of important fractal features of our own anatomy and physiology, evident from macroscopic to macromolecular levels, raises the thematic issue of this essay. *Is artistic expression in some way an outworking or mapping of the mind's nonlinear processes?*[24] Since an intrinsic feature of the healthy nervous system appears to be its scale-free structure and function, the appearance of fractal representations might be anticipated as an output of the human imagination poised at the brink of self-organized criticality.[25] The process of creation realized in the minds of geniuses like Suger may be akin to re-creation in which the artwork externalizes and maps the internal brain-work of the architect. Conversely, the interaction of the viewer with the artform may be taken as an act of self-recognition. Standing inside a Gothic cathedral in the light of multi-paneled stained glass windows (Figure 7), we are able to look not only outward but also inward. The scale-free forms and complex patterns encountered are ultimately singular loci of self-discovery.*

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The author thanks Ellen Goldberger, C-K Peng, and Julio Licinio for helpful suggestions, Richard Nakamura for calling attention to origami art, Susan Spratt for discussions about quilting, and Joseph Mietus for locating a 'rose window' with 12-fold symmetry[33] in the Mandelbrot set. This essay is based on a lecture given by the author in the University Professors' Seminar Series, Boston University, March 21 1994.

* The focus in this essay on Gothic architecture as an externalization of scale-free physiology should not be taken to exclude or overlook the importance of other apparently fractal forms of art in both Western and non-Western cultures. These expressions may range from the self-similar features of origami folded art[26] to American quilt designs.[27] Mandelbrot[7] reproduces a number of paintings with fractal images, including Hokusai's famous depiction of waves. For examples of fractals in contemporary art see Refs 28 and 29. Finally, we note that scale-invariant properties of language[7,30] and music[24,31,32] may complement fractal forms in the visual arts.

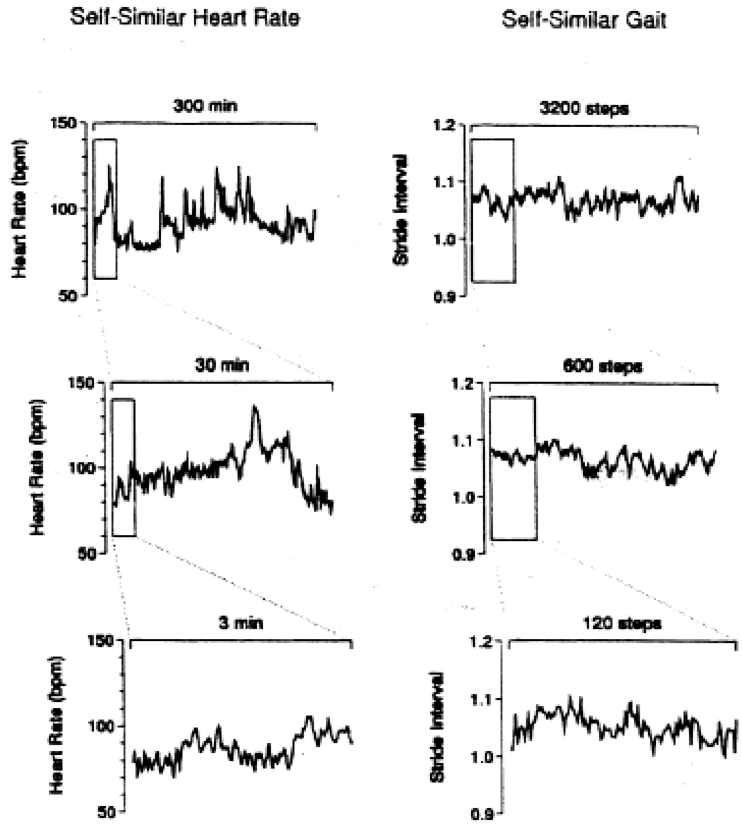

Figure 6 The temporal structure of both heart rate (regulated by the autonomic nervous system) and gait (regulated by the central nervous system) show a self-similar type of organization. Fluctuations on smaller scales (higher frequencies) are statistically similar to fluctuations on large scales (lower frequencies). Quantitative analysis confirms that both healthy heartbeat[18–20] and healthy gait[21] show long-range power-law correlations indicative of fractal dynamics. (Gait data provided courtesy of J Hausdorff.)

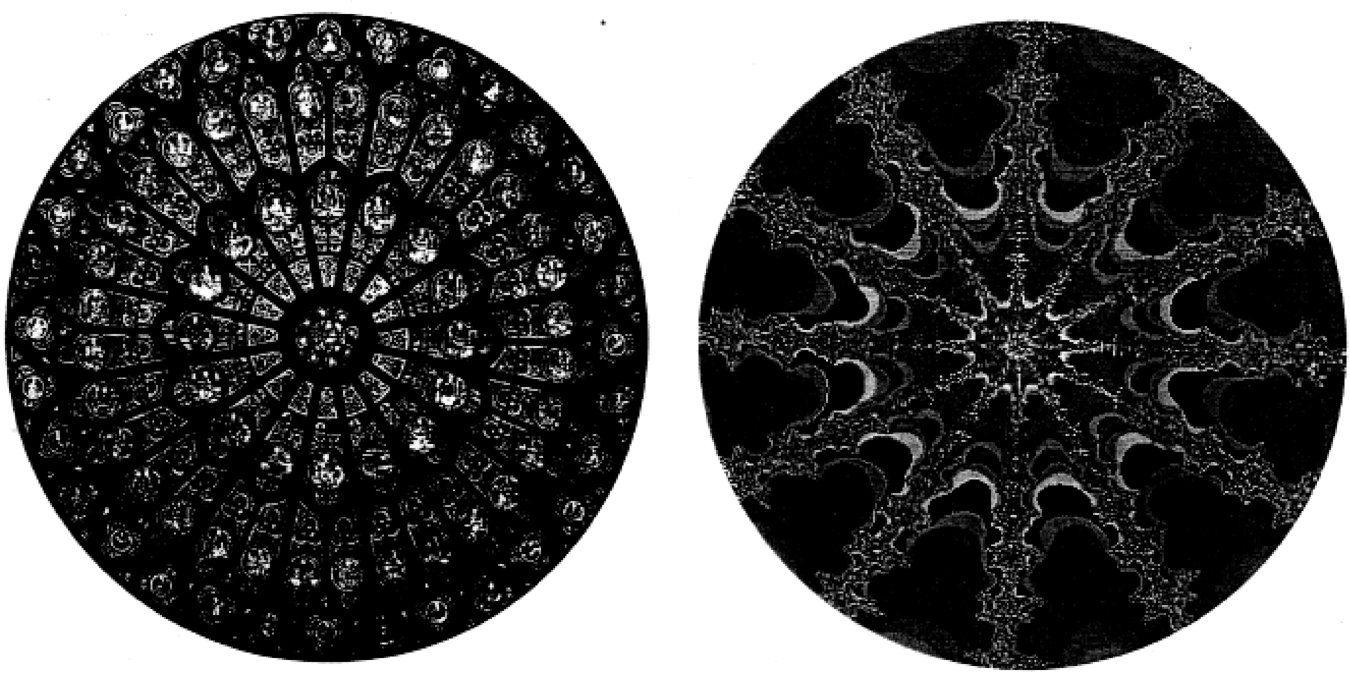

Figure 7 (Left panel) North transept rose window, Notre-Dame de Paris. (Right panel) 12-fold symmetry in portion of the Mandelbrot set,[6] magnified by a factor of 37 trillion.

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