Ship design differs from the creation of poetry only in its numerate content.
— J. E. Gordon, Structures

We tend to think of art and technology as having no important connection. What starker opposition than between the artist and the engineer—the irrational dreamer and the rigorous realist, the indulgent devotee of subjectivity and the austere technician? We tend not to think that engineering might be enhanced by the love of beauty, nor that it is impossible to be a really good engineer without understanding art. Yet we depend on essentially artistic skills in engineers, the capacity to feel technically and construct aesthetically. The invention of a seriously new alternative is an aesthetic moment in art and technology alike. No design is ever determined by calculations or technical necessity. Choice pervades technological design and is made, ultimately, on the basis of aesthetic invention (supplemented, of course, by careful testing). Engineering design is the analytical and imaginative synthesis of perception and technique, which is also the ideal, the point, the idea of art. There is art in good engineering and good engineering in art. To stand up and last, an artwork has to be no less well put together than a bridge.
Engineering Art

Engineering and technological design may be said to have a significant aesthetic dimension because they cannot fail to involve aesthetic choices: good engineering requires good aesthetic judgment. That aesthetics is integral to engineering has been affirmed a number of times by reflective engineers.¹ Othmar H. Ammann (1879–1965), the designer of New York’s George Washington Bridge (1931), made this point throughout his career. Writing in 1918, in a report on Gustav Lindenthal’s recently completed Hell Gate Bridge (fig. 1), Ammann, who was “first assistant” on the project, pronounces the bridge “one of the finest creations of engineering art of great size which this century has produced,” and adds: “A great bridge in a great city, although primarily utilitarian in its purpose, should nevertheless be a work of art to which Science lends its aid. . . . It is only with a broad sense for beauty and harmony, coupled with wide experience in the scientific and technical field, that a monumental bridge can be created.” Three decades and half a dozen major New York bridges later, Ammann felt the same way: “Mere size and proportion are not the outstanding merit of a bridge; a bridge should be handed down to posterity as a truly monumental structure which will

cast credit on the aesthetic sense of present generations.” “It is a crime,” he once said, “to build an ugly bridge.”

This thought is complemented by the words of Felix Candela, a highly accomplished Mexican designer of thin-shell concrete structures: “Beauty has no price tag and there is never one single solution to an engineering problem. Therefore it is always possible to modify the whole or the parts until the ugliness disappears.” I think Candela’s remark touches the heart of the matter: the availability and necessity of choice. Every technological problem has alternative solutions; and the more engineering there is, the more alternatives there are to choose from. One might say that modern engineering does not exist until there is a relative density of technical alternatives and an art of technological choice.

“Engineering design,” as one engineer has written, “is essentially a matter of thinking of a number of alternative solutions to each problem.” The designer’s skill and experience are most artful in choosing the best alternative. Concurring that technical design is “a sequence of comparative choices,” another engineer has argued that “there can be no optimum in structures, but only many reasonable choices.” A specification of the intended function of a new device or structure leaves the design problem (“form”) practically wide open. “The topography of a new thing,” an engineer-historian has told us, “is astonishingly unconstrained.” Yet another engineer has written of bridge design: “Almost every conceivable way in which a bridge could possibly be made has actually been tried, at one time or another, for making real bridges. One might have supposed that one approach to the problem would have turned out to be the ‘best’ of all and would have come to be generally accepted, but this is not the case; and the number of structural systems which are in common use seems to increase as time goes on.”

Two examples may suggest the scope of engineering choice. In planning the Hell Gate Bridge, Lindenthal’s team developed plans for several bridges at the site, making detailed analytic comparisons among such varied forms as cantilever, suspension, and continuous truss, as well as three different arches. Ammann reports “little if any difference in cost between the several types mentioned” and says that the form eventually selected, called a spandrel arch, was favored on aesthetic grounds. Thus the preliminary planning generated a remarkably wide choice among designs, any one of which would “work” and all at about the same

5. Billington, Tower and the Bridge, 265, 142.
7. Gordon, Structures, 199.
price. These were ideal conditions, then, for something other than economy or efficiency to step in and finish the design. The more choices Lindenthal had, the freer his hand to take more and more into consideration, widening his design problem into the domain of public art.

To shift from this grand scale to the minute but realistic and unavoidable, we might for instance survey the options for putting a floor on the deck of a bridge. As Ammann writes in a 1940 article on developments in structural design:

> There is a very definite trend toward the use of light-weight bridge floors as a means of effecting economies in the entire bridge structure. Many types of such floors are now available, including steel plate floors, usually with a surfacing material; floors of interlocked steel panels with fillers and a surfacing material; composite steel grid and concrete floors; open grating steel floors; light concrete slab construction; and aluminum alloy types.9

Each alternative has systematic implications for a host of other choices that compose the bridge. Ammann goes on to say that the proliferation of technical choice gives welcome prominence to aesthetic judgment in engineering design:

> The more thorough knowledge of the character and actual behavior of structures has led to greater confidence and freedom on the part of the designer. He is encouraged to depart from conventional practice and to try uncommon forms and types. In this process he has been aided by the growing demand for consideration of esthetics in structural design, and he has found that this demand is not in conflict with a broad interpretation of the technical and economic requirements.10

Engineering’s dependence on alternatives generates engineering alternatives in a self-advancing technological ratchet upon which humanity’s future now depends. The more engineering we do, the more technological choices there are and the greater design’s freedom to be art. Thus one office of aesthetics in engineering is to help in making good choices. What is this “good”? Not the good of pure reason or of economic rationality; apparently not the moral good. It seems a matter of realizing an aesthetic quality in a structure (or other design). It means taking perception as well as force into account, making something that anticipates its perception and works when we look at it as well as when we use it.

There is a second office of aesthetics in engineering design, which relates to what are called statically indeterminate structures. These are structures for which it is not possible to calculate internal stresses and breaking points. The

conditions of their static equilibrium (why they do not fall down) are therefore unknown. Even computer-assisted calculations are imprecise and incomplete, but engineers have designed and built such structures anyway. It may well be the case that most of the notable engineering of modern times has built indeterminate structures. Science has not caught up with what the engineers are accomplishing. Engineering is not groping blindly for want of a theory.

One reason there are more indeterminate structures than ever in humanity’s built environment is that we use more reinforced concrete than ever. It is not difficult to understand why. This material, which came into modern use after 1894, has been described as “the most fertile, ductile, and complete construction process that mankind has yet found.” It is “technically the most nearly perfect material,” an artificial superstone that can be produced in a semifluid state and molded into any form. No stone can do what reinforced concrete does: resist force in tension—a force trying to pull it apart.\(^{11}\) Reinforced concrete is cement and aggregate laced with embedded steel, either as rods or wire mesh. The advantage of the combination is that concrete is strong in compression but weak in tension, while steel rods are the opposite. By a wonderful contingency, materials this different have nearly the same coefficient of expansion, tending to change size with temperature at the same rate—a contingency crucial to their working together. Otherwise the combined material would tear itself apart. By bringing the two materials together, we get the best of each, the strength of one canceling the weakness of the other.

The structural properties of reinforced concrete stubbornly resist mathematical analysis. Apart from the simplest cases long since transcended in practice, it is not possible to calculate that a given form in reinforced concrete will have the strength required for a given application. The root of the problem is that reinforced concrete does not follow what engineers call Hooke’s Law. There is no proportion between stress and deformation.\(^{12}\) So subversive is this lawlessness that, after a century of modern experience with the material, “the primary uncertainties in reinforced concrete behavior have never been removed by mathematical analysis. . . . Stresses in concrete (pounds per square inch of compression), for example, are mere guesses—even when computed following the most rigorous formulations of theoretical mechanics.”\(^{13}\)

The Italian engineer Pier Luigi Nervi, master of the thin-shell concrete dome, says of calculation that “reinforced concrete presents hidden deficiencies and specific characteristics which make its structural behavior difficult, if not altogether impossible, to foresee exactly. Its high thermal sensitivity, its shrink-

---


\(^{13}\) Billington, *Tower and the Bridge*, 215, 216.
age, and above all its plasticity . . . shatter our hope of investigating or knowing either before or after construction the real conditions of equilibrium of any statically indeterminate structure.”

Candela concurs and generalizes: “All calculations, no matter how sophisticated and complex, cannot be more than rough approximations of the natural phenomena they try to represent . . . There is no such a thing as an exact method of structural analysis and, notwithstanding the popular belief in the letter of the codes, the accuracy of any calculation is still a question of personal judgment”—an observation that, according to David Billington, “summarizes the view of every great structural designer from [Thomas] Telford on.”

A prominent example of an indeterminate structure, in this case not due to the use of reinforced concrete but simply to the inordinate complexity of the design, is New York’s Brooklyn Bridge (1883). Ammann, who described the Brooklyn Bridge as “the most fascinating and outstanding structure of its kind,”

writes of the radical indeterminacy introduced deliberately into the bridge by its designers:

The system adopted for the Brooklyn Bridge is an extremely complex and highly indeterminate one, so that it is impossible even today to determine the stresses with any degree of accuracy. . . . The stiffening system is a complex combination of trusses along the floor and diagonal stay ropes attached to the tops of the towers. The latter, together with the trusses, which are also fixed to the towers, form cantilever arms and thus relieve in part the loads carried by the cables. The interaction between cables, stays and trusses is thus very uncertain.

Far from inadequate, outdated, or otherwise technically objectionable, the system that John Roebling designed, though complex, is also exceptionally sound engineering. The primary point of the complexities Ammann describes is to prevent the bridge deck from beginning to sway in the wind (it was wind-induced twisting that tore down the Tacoma Narrows Bridge in 1940). The Roebling design dampens wind-induced oscillation with Daedalian geometry rather than brute stiffening and protects the deck from probably its greatest structural danger. Moreover, the Brooklyn Bridge does so without adding the weight, cost, and unsightly bulk of rigid stiffeners along its length that make the Williamsburg Bridge (1909) seem inferior.

15. Billington, Tower and the Bridge, 219. Thomas Telford, the greatest bridge designer of his generation, is remembered for a groundbreaking early suspension bridge (1826) over the Menai Straits in Wales.
The nimbus of theoretical uncertainty surrounding indeterminate structures has not deterred engineers from designing them, yet how can an engineer make a considered choice among forms whose stresses and breaking points are incalculable? Swiss engineer Robert Maillart (1872–1940), probably the twentieth century’s outstanding structural artist in reinforced concrete, was convinced that reliance on calculations is an insidious danger. Maillart took structural indeterminacy into the stratosphere. Apart from one bridge sacrificed to an avalanche, nothing failed; and forty-five of his forty-seven career bridges remain in service. Full-scale testing was for him the only path to engineering knowledge and guaranteed safety. “Experiments and the measuring of deflection in existing buildings are of the greatest importance,” he wrote: “It cannot be overestimated in any way.”

Full-scale testing is part of the way to design indeterminate structures; but before you can perform a test, something testable has to be designed. This inventive moment of the design is as indeterminate as anything else about the structure, and to some extent we are giving a name to our ignorance in saying that aesthetic perception and feeling play a role in guiding the drafting hand. However, aesthetic perception is also the name for a freedom we recognize. The designer seeking beauty steps into a free realm where what feels right, complete, and expressive motivates choice among alternatives. The more indeterminate the structure, the freer the designer’s hand, and the more everything depends on a technical coherence that design translates into aesthetic coherence. Maillart offers this observation on the relationship between aesthetic and technical coherence:

Reinforced concrete does not grow like wood, it is not rolled like steel, and it has no joints as masonry. It is most easily compared with cast iron as a material cast in forms. Perhaps we can learn something directly from the slowly discovered cast iron forms regarding the avoidance of rigidity by a fluid continuity between the members that serve different functions. The condition of this beautiful continuity is the conception of the structure as a whole. . . . It is not only the feeling for beauty which makes desirable the conception of the whole primary to that of the single elements. Seeing the structure as a whole nearly always brings economic advantages as well.


It would be simplistic to think that the “personal judgments” without which engineering cannot be practiced are arbitrary or indifferent. They are aesthetic—and while their aesthetic character makes them the all-too-human work of all-too-human heads, being human is no disgrace. Good judgments are no easier to come by if they are aesthetic. And the aesthetic quality of the judgments that an engineer makes can elevate their outcome (a technological artifact, like a bridge) to the level of great art.

**Do Not Accuse Engineers of Functionalism!**

The idea that design is or can be purely technical, a calculation or deduction, inspires the inane nostrum “form follows function.” There is just nothing right about it. The emphasis on form is misguided. What sets design problems are intended results, which are more independent of form or shape than may be supposed. Technical form is never literally entailed or derived from anything, the most exact specification of “function” least of all. Nothing designed has rationally to be made one way rather than another. There is no such thing as the “one best way” in technical design, though there often is a cheapest way. There is no eliminating the choice, preference, selection, artistic sensibility, and style of the designer. We have no idea what a purely functional artifact would look like. No such thing can be made. All useful devices do unwanted, useless, even counter-productive things; and practically anything we make has qualities given to it by useless, easily avoidable work. Doing useless work on useful things is a basic pattern of human artifice.

If form should follow function, why do seriously functional artifacts—aircraft or bridges—not all look alike? What is the function of a bridge? Let us say, to convey traffic across a natural barrier. Anything that does so is a bridge, and the form of those bridges that do it most efficiently is the best, the most rational, the technically correct form for the job. Fine. Now, in order to fulfill this function, the bridge must resist the forces to which it is predictably subject, the forces that pull it down or try to twist it. But exactly what are these forces? Where do they act? How do they combine and resolve? You can hardly make a bridge that efficiently deals with such forces unless you know where they act and with what magnitude. I hope no one thinks that “science” holds the answer to such questions—that engineers can consult some scientific theory and find the laws and equations required to determine the forces to which a bridge would be subject. Nothing remotely like that is possible.

A designer does not first consider what forces a bridge will be subject to, then design an appropriate structure. Choosing a structure determines what forces its parts are subject to. The same load generates entirely different profiles of force depending on the structure. Consider some common structural forms (fig. 2):
(a) A beam suspended at two ends, like a lintel over columns or a tree trunk over a stream. A constant load at midpoint bends the beam, generating a compressive force across the upper portion and a tensile force across the lower part. Should it fail, the cause will be horizontal sheer beginning at the point where these two opposite vectors of force meet.

(b) The same load on a truss resolves quite differently. The system of triangles creates a rigid structure. Provided the load stays within limits, the truss cannot deform. The effect of this geometrically induced rigidity is to convert the load to purely vertical compression acting at the two ends, where it is safely and efficiently transferred into the foundations.

(c) In a suspension system, the load generates tension in the cables (transferred to anchorages at either end) and compression on the towers, glorified wedges jacked under the cables to create the elegant catenary droop.

(d) In a Roman or semicircular arch, the load is converted into a lateral thrust that pushes the voussoirs against each other, channeling the force down
into the foundation. Besides the vertical (compressive) force taken by the foundations, there is an oblique force that would flatten the arch unless it is retained by massive buttressing—prompting Eduardo Torroja Miret’s comment that “an arch is a gamble, a jugglery with structural functions that are passed to elements external to the structure proper.”

The genius of the so-called Norman, Gothic, or pointed arch is that a simple modification of geometry—this form is two semicircular arches on their sides—eliminates the horizontal kick of the Roman form, leaving vertical compression as the only structural force, which the new arch carries straight down to the foundations. The twelfth-century shift in European construction from Romanesque to Gothic arches was more than a new symbolism. The new arch makes walls structurally superfluous. Europeans finally surpassed Roman engineering.

What force a load generates thus depends entirely on the structure, which depends entirely on the designer’s choice. It is not the function of the form to respond to potentially destructive forces, to meet them and stand up. There is no saying what those forces are until the bridge is designed; and after it has been built and has passed into service, theory may remain mute and uncomprehending. The form not only controls but actually generates the major structural forces to which it is subject. In the case of a bridge, the structurally most important source of load is simply the dead weight of the bridge itself. If it can hold itself up, the live traffic load is insignificant. For example, in Ammann’s George Washington Bridge (fig. 3), the weight of cables and deck alone (not including the towers) is five times the heaviest potential live load.

Science has never told an engineer how to put anything together. Any device could have been made differently and still worked (technically, if not economically or politically). That is why not all bridges look the same and why their differences cannot be dismissed as the invasion of technical rationality by arbitrary social representations. We must expect every work to have its style, whether it is mass-produced (a jar) or handmade (a carpet), symbolic (a painting or treatise) or structural (a bridge). Style is deeply implicated in any work of human hands because the intended result of artifice never determines shape or form. Style steps in to delimit possible designs in ways that neither function nor economy can do.

---

21. Viollet-le-Duc writes that with the pointed arch coming into use in the new architecture of the twelfth century, especially in the Ile-de-France, “walls became merely enclosures or partitions . . . if need be, they could be constructed after the basic structure of the building was completed; indeed, they could be eliminated entirely.” Eugène-Emmanuel Viollet-le-Duc, *The Foundations of Architecture: Four Essays from the Dictionnaire Raisonné*, trans. Kenneth D. Whitehead (New York: George Braziller, 1990), 134.
Anything *made to work* is always at the same time a *work*, and there is more to any device than the intended use necessarily requires. A technical form, to be functional, has to be more than functional, has to have qualities acquired not by design—not because of how the artifact works but because of the artifice, fabrication, craft, or workmanship that actually brings it into existence.

David Pye was the most technically accomplished philosopher of design since William Morris (a comparison that extends no further). Pye’s book *The Nature and Aesthetics of Design* is wise on every page, and at least one remark that he makes there deserves the attention of every philosopher of technology:

> When any useful thing is designed the shape of it is in no way imposed on the designer, or determined by any influence outside him, or entailed. His freedom in choosing the shape is a limited freedom, it is true, but there are no limitations so close as to relieve him or the maker of responsibility for the appearance of whatever they have done. The ability of our devices to “work” and get results depends much less exactly on their shape than we are apt to think. The limitations arise only in small part from the physical nature of the world, but in a very large measure from considerations of economy and of style. Both are
matters purely of choice. All the works of man look as they do from his choice, and not from necessity.  

Technology is not a name for Being. The appearance of inevitability in technology is an illusion to which contemplative nonpractitioners (the majority among philosophers of technology) are highly susceptible. What is inevitable in technological design is style.

Two Bridges

Two New York City bridges in particular demonstrate the inevitability of style and aesthetic choice in technological design. One I have already mentioned, Gustav Lindenthal’s Hell Gate Bridge of 1917 (fig. 1). A railway bridge carrying four sets of tracks over the East River, its span is 977 feet, a world record when built. The second bridge is Ammann’s Bayonne Bridge of 1931, linking Bayonne, New Jersey, with Staten Island (fig. 4). Its 1675-foot span was another world record on opening.  

Technically, both bridges are arches composed of a parabolic steel truss and loaded from below by the suspended deck rather than over the crown of the arch. By making the arch parabolic (rather than semicircular) and building it from a steel truss (rather than stone blocks), the oblique thrust usually taken up by massive abutments is eliminated. The rigid truss in the arch ensures that loads resolve entirely into two moments of vertical compression at either end. Look again at Hell Gate, especially the ends, and compare the Bayonne Bridge. Those massive masonry piers in the older bridge are not structural. They carry no load. You could dismantle them and it would not make any difference to the bridge, at least from the point of view of structure; it would not fail. Ammann’s bridge—a Hell Gate stripped of nonstructural piers and made 700 feet longer into the bargain—should remove all doubt.

Ammann’s design is also 40 percent lighter than Hell Gate, despite the considerably greater length of the Bayonne Bridge. Part of its lightness comes from the material, a high-magnesium steel that imparts a lustrous sheen.  

23. David Pye, The Nature and Aesthetics of Design (Bethel, CT: Cambium, 1978), 14. It was either ignorance or mendacity that led Le Corbusier to write, “Engineers employ a mathematical calculation which derives from natural law. . . . Guided by the results of calculation (derived from the principles which govern our universe) . . . engineers . . . make the work of man ring in unison with the universal order.” Le Corbusier, Towards a New Architecture, trans. Frederick Etchells (New York: Payson and Clarke, 1927), 15, 31.

24. Ammann’s bridge resembles the Sydney Harbor Bridge, which was completed only months before Bayonne, though Ammann’s clear span is twenty-five feet longer.

25. The Bayonne Bridge was in fact the first significant use of manganese steel. Ammann, “Structural Design,” 23. Technically, only the lower chord, which carries practically all of the load, is made of the manganese alloy. The top chord, whose role is stiffness, is made of silicon steel. Rastorfer, Six Bridges, 85.
is stronger for its weight than usual steels, and it will not rust, making unnecessary the nearly continuous painting that other bridges require. Then again, magnesium steel is expensive, and a big bridge like this one uses a lot of it. That is one reason a design that cut a lot of weight was attractive, and here Ammann was brilliant. His bridge uses 37 million pounds of steel compared to 87.8 million pounds for Hell Gate (which has only 30 percent of the span).26

However, doing away with monumentally superfluous piers in Ammann’s bridge is not a triumph of functional rationality over romantic whimsy. Ammann’s approved design called for monumental stonework over the foundations of the arch. An architectural design was created by the office of Cass Gilbert, architect of New York’s Woolworth Building (1913). The indifferent box frame visible around the two ends was designed to hold masonry cladding. Speaking at the opening ceremony, Ammann said that “the huge abutments of the arch, which are yet exposed in their crude construction, are eventually to be marked by massive pylons, and will thus further enhance the appearance of the structure in its setting in the landscape.” Despite finishing the work on time and 14 percent under budget, the New York Port Authority, owners of the bridge, never took action on the pylons and never dismantled the boxy armature designed to hold

26. Billington, Tower and the Bridge, 138. Live loads (mainly traffic) for the two bridges are very different. Bayonne, an automobile bridge, is designed for a live load of 7,000 pounds per foot of bridge; Hell Gate, a railway bridge with four lines of track, has a carrying capacity of 75,000 pounds per foot of bridge, a value that has never been exceeded. Rastorfer, Six Bridges, 8.
the stone. Ironically, Ammann had earlier praised the aesthetic sensibility of the bridge's commissioners: “The Port Authority recognized the fact that its structures must not only be useful, but they must also conform to the aesthetic sense. This was one of the motives for the selection of an arch spanning the entire river in one sweeping graceful curve.”

David Billington, a professor of engineering, calls Lindenthal’s “reliance on masonry for monumentality” an irrational inheritance from days before the Industrial Revolution: “When a designer builds nonfunctional stone towers to visually contain arch forces, which do not in fact exist where they appear to exist, then the design is not an indissoluble union of structure and form but rather a massive frill.”

The upper chord of the truss forming the arch in a bridge like Hell Gate or Bayonne is for stiffening only and does not carry the load per se; it makes the load-bearing lower chord stiffer. The business of the upper chord is therefore concluded at the point where the lower chord transfers its load vertically into the foundations. At that point the upper chord can just stop and hang in midair. And so it does in Ammann’s bridge, and in Lindenthal’s too, except that in the latter the upper chord is masked (from most approaches) by the pylons. A different solution was found by Gustave Eiffel for his Garabit Viaduct (1884), a so-called crescent arch whose upper and lower chords gracefully meet at the foundation. Yet Lindenthal specifically considered the crescent arch form of Eiffel’s bridge and rejected it for his project: “The spandrel arch, owing to its height increasing from the center toward the ends, is more expressive of rigidity than the crescent arch.”

Lindenthal’s peers in the American Society of Civil Engineers tended to think well of the design, including the nonstructural towers (it is prejudicial to call them nonfunctional; if they do something for the eyes, might that not be an intended result or “function”?). Senior American bridge designers invited to comment on Ammann’s technical report on the recently opened bridge were undivided in their praise. One called Lindenthal’s bridge “the largest, most scientific, and, it is believed, the most artistic bridge yet constructed.” Commenting specifically on the towers, another found them “plain and simple in design, but in every way appropriate and in harmony with the great arch. . . . The whole structure may be said to be the most complete lesson in bridge esthetics in America, and one of the best in the world.” A generation later, Carl Condit, an authority on American engineering, wrote of “the power and dignity” of Lindenthal’s form: “The slender arch rib, with its massive but simply articulated stiffening truss [the upper chord], is the very expression of combined stability and

27. Ammann, cited in Rastorfer, Six Bridges, 92, 77.
28. Billington, Tower and the Bridge, 128.
energy; its enormous thrust is perfectly contained, in a visual sense, by the heavy masonry towers.”

The most eloquent defense of Lindenthal’s choice comes from Ammann himself in his official account of the design and construction of the Hell Gate Bridge:

Mr. Lindenthal conceived the bridge as a monumental portal for the steamers which enter New York Harbor from Long Island Sound. He also realized that this bridge, forming a conspicuous object which can be seen from both shores of the river and from almost every elevated point of the city, and will be observed daily by thousands of passengers, should be an impressive structure. The arch, flanked by massive masonry towers, was most favorably adapted to that purpose. The massive masonry towers which flank the steel arch greatly enhance the appearance of the bridge and give it its monumental character. They also give expression to the solidity of the abutments to resist the great thrust of the arch. Without the towers, the statically trained eye would want that expression of stability, because of the comparative flatness of the shores.

Here Ammann defends the towers as a visual need for the trained (that is, the engineer’s) eye. One commentator thought that Ammann was saying the opposite—that only the untrained eye feels the want of a visual counterpart to the thrust inconspicuously channeled down to the foundations at the two ends of the truss. “It is desirable,” Henry Quimby wrote, “to make a structure appear not only graceful but satisfyingly stable to the miscellaneous eye as well as to the trained and understanding scientific eye.” But both observations demonstrate the felt visual need for a vertical force at the arch’s foundation. It is a perceptual need, not a structural one, but Ammann calls the designer’s sensitive response to it “an architectural necessity.”

Having defended the towers as a need for the trained eye, Ammann went on to imply that they are not altogether nonstructural. The “static requirement” of the towers, he said, “is not merely an apparent one.” In other words, the towers do some work. Of course, structural or not, these towers are heavy. Between the two, and including their foundations, they contain 110,000 cubic yards of cement. It is those foundations, remember, that do the work the towers seem to do: receiving the thrust of the load. The structural situation is this: the weight of the bridge loads the arch, whose rigid truss channels the force into a purely compressive


thrust at either end. The foundations obviously must be deep and strong enough to carry this load down to bedrock. The thicker the foundations are, the more expensive to build. It would therefore be desirable to minimize their volume.

This situation is structurally similar to one that cropped up in medieval European building after the eleventh century. This so-called Gothic architecture is justly famous for two qualities: the soaring height of its enclosed spaces and the intricately ribbed vaults for ceilings over those heights. Ceilings had never been either so high or so heavy, for those elegant vaults are, of course, 100 percent stone. A heavy weight from a great height is a tricky thing to support on relatively slim piers embedded in a relatively unstressed wall. The higher the ceilings got, the more precarious. Hence another notable quality of this architecture: the flying buttress, an arch boosted against the outer surface of the piers supporting the vaulting.

The distal end of the flying-buttress arch receives a thrust from the load of the pier against which it rests, and it has to convey this force to its foundations, usually down a column under the springing of the arch. In order that this column be as thin as possible, these architect-masons made a sophisticated reading of the forces in the buttress and an innovative application of what engineers call the rule of the middle third. “The basic condition for the safety of masonry,” J. E. Gordon (an engineer) writes, “is that the thrust line should always be kept well inside the surface of a wall or column.” How far is “well inside”? The tried and tested rule is to keep the line of thrust in the middle third of the width of the wall or column. The Gothic architects understood that adding more weight to the top of the column makes it stronger, by more precisely channeling load thrusts to well within the middle third (fig. 5). “Contrary to what one might suppose,” Gordon adds, “weight at the top is likely to make a wall more, not less, stable and will bring an erring thrust line back, more or less, to where it ought to be”—namely, well inside the middle third. Therefore, the distal end of a flying buttress, where the arch transfers its load to an external column, is usually festooned with pinnacles and statuary. They do structural work. Remove them and the buttress no longer functions as designed and may fail: “They really are up there to say ‘boo’ to the functionalists and to all the dreary people who bleat too much about ‘efficiency’.”

I have reviewed some basics of Gothic architecture because Ammann in effect offers the same defense of his Hell Gate Towers. He never explicitly makes the comparison to cathedral statuary, but the structural situation is analogous.

33. Gordon, Structures, 184, 182, 184. The buttress itself works in a similar way. It exerts a force against the pier that has the effect of channeling into vertical (middle third) the oblique thrust of the supported vaulting. Viollet-le-Duc, Foundations of Architecture, 181.
By adding weight to the bridge's foundation, which is in effect a column down to bedrock receiving the compressive thrust of the arch's truss, the towers permit the designer to minimize the volume of the foundation while keeping thrusts well within the safety zone of the middle third. In his report, Ammann twice claims that the towers are structural. The first time, he says: “with their great weight, they steepen the resultant arch thrust and thereby limit the size of the deep foundations to a minimum. They also facilitated and cheapened the erection of the arch to a considerable extent.” Later, he reiterates and invokes the rule of the middle third: “To restrict the size of the foundations to a minimum, it was necessary to provide above the ground a mass of masonry, the weight of which, combined with the inclined reaction of the arch, would give a steep resultant, passing well within the middle third of the foundation area, so that the edge pressure could be kept within permissible limits”—like the pinnacles atop a flying buttress.34

Among the peers invited to comment on Ammann’s report was Leon Moisseiff, future designer of the failed Tacoma Narrows Bridge. Moisseiff questioned Ammann’s claim to a structural (or more precisely, an economic) justification for the towers. Moisseiff admitted the less than ideal conditions at one abutment and granted that they might have required foundations of unwieldy dimensions. But he concluded that it was not serious to suggest this as a technical justification for the cost of building the towers. In reply, Ammann agreed with Moisseiff that the towers are not an economic feature if intended for the exclusive purpose of keeping the resultant reaction within the middle third of the foundation area, because, if it is a mere question of a sufficient weight of masonry, such weight can be provided more cheaply by extending the foundation in the direction of the axis of the bridge. Where it is a question of providing towers for architectural reasons, however, such towers constitute at the same time a considerable saving in the foundation masonry and are then not entirely for architectural purposes.\(^3\)

Fifteen years later, reporting on the construction of his George Washington Bridge, Ammann returned to the question of this “architectural necessity.” The case is again ironic. The towers of the George Washington Bridge as we have it (fig. 3) are a complex high-tech web of exposed structural steel. But as it was not Amman’s original idea to leave the abutments of the Bayonne Bridge without a visually forceful response to the thrust they receive from the truss, so the George Washington towers were supposed to be clad in concrete and faced in granite. Ammann was surprised at their agreeable appearance without cladding, finding that “they lend the entire structure a much more satisfactory appearance than [I] (and perhaps any one connected with the design) had anticipated.” Nevertheless, he said, “the appearance of the towers would be materially enhanced by an encasement with an architectural treatment.”\(^4\)

Billington called Lindenthal’s towers a massive frill. They appeared to him to respond to forces that do not exist. It would be more fair and precise, however, to say that the towers offer a visual complement to the horizontal visual force of the arch and its deck. It is true that physical forces do not require the towers, but visual forces do; and it is not a frill, but intelligent and satisfying engineering, to find the freedom to address visual as well as physical needs. Ammann seems to have anticipated the sort of criticism Billington levels at Lindenthal and replies to it in his report on the George Washington Bridge. Ammann says he “is not impressed by the criticism, based solely on theoretical and utilitarian grounds, that the encasement [of the towers] would constitute a camouflage which would hide the true structure and its function”:

\(^3\) Ammann, “Hell Gate Arch Bridge,” 1036; Moisseiff’s comment appears on 1007.  
The covering of the steel frames does not alter or deny their purpose any more than the exterior walls and architectural trimmings destroy the function of the hidden steel skeleton of a modern skyscraper, except to the uninitiated. Camouflage in this sense would condemn many of the creations in private and public life. It is an essential manifestation of civilization and is not incompatible with sincerity and honesty of endeavor, because an essential part of human effort is to create an aesthetic atmosphere, the value of which cannot be expressed in economic terms. . . . Why should not a supreme effort be made in that respect in engineering structures, especially those that are viewed daily by thousands or millions of people? 37

Twenty-five years later, Ammann’s conviction was the same: “Economy and utility are not the engineer’s only concerns. He must temper his practicality with aesthetic sensitivity. His structures should please the eye. In fact, an engineer designing a bridge is justified in using a more expensive design for beauty’s sake alone. After all, many people will have to look at the bridge for the rest of their lives.” 38

One has to be pretty crass to think that Ammann has no point. But it matters what point we think it is that he has. Lindenthal’s towers do not say, as it were, I know that you, technical illiterate, think that some prodigious mass must receive the weight of my arch, but that is false, as I, being scientific, know. Nevertheless, I shall cater to your vulgar error and give you something big and powerful where you, in your ignorance, think you need it. Instead, it were as if Lindenthal, as designer, said to his public: When people see a forcefully horizontal shape like my bridge, they see that it is very heavy, very horizontal, and very suspended over thin air. This creates a visual need for a balancing vertical moment. That is not a false belief of the ignorant about physical forces. It is a true belief of us all, engineers and others, about the visual need for a visually vertical moment in order better to see the bridge, to stabilize its perception, to enable us equitably to see it as a bridge. 39

Several of the engineers who have discussed Lindenthal’s design, pro or con, claim that technically untrained people see the towers as required to receive the oblique thrust of the arch. Supposedly the untrained do not know about trusses or structural rigidity. As we have seen, some engineers think that indulging this technically illiterate whimsy is “a massive frill.” Others think that since ordinary people have to live with the bridge, their feelings, technically irrational as they may be, should be taken into account. I think these terms misconstrue the situa-

39. The towers do their visual work at a certain distance and from certain views, which is probably why Lindenthal was not averse to having the upper chord of his truss stop a few feet short of the towers. There would be few and inaccessible views from which the towers would have impinged on the visual coherence of the perception.
tion. It takes a trained eye to look at a structure and see the conditions of its real, physical equilibrium. But that does not mean that when an untrained eye looks at a structure, it makes mistakes and forms false beliefs about those same conditions. The engineer has learned that there are directed physical forces like compression, tension, and shear, and that their correct visualization and estimate is crucial to the static equilibrium of a structure. Without such training, most people do not concern themselves with the static equilibrium of structures, as engineers must. Most of us are, however, spontaneously concerned with the visual, psychological equilibrium of our own perception, and visual equilibrium depends on principles other than engineering statics.

Perceived shapes are dynamic, animated with tension and tendency: this is not poetic rhapsody but a robustly confirmed result of experimental psychology. What we perceive is not a static arrangement of objects, surfaces, or shapes, but the interplay of directed tensions. These are not added to a static image but are rather the primary data of visual perception. “Our senses,” Rudolf Arnheim, the psychologist of vision, writes, “are not self-contained recording devices operating for their own sake. They have been developed by the organism as an aid in reacting to the environment, and the organism is primarily interested in the forces active around it— their place, strength, and direction.” As a result of this evolution, that is what we see: not shapes or lines but dynamic shapes and expressive lines, pregnant with movement, or what Arnheim calls directed tension, which, he says, “is as genuine a property of visual objects as size, shape, and color. The nervous system of the observer generates it at the same time that it produces the experience of size, shape, and color from the stimulus input.”

“The very percept of the bridge,” Arnheim writes elsewhere, “in order to be complete and correct, must include the presence of the absent bridge-crosser. Otherwise it is an enigmatic ornament.” I believe Arnheim is saying that to see a bridge and not an enigma requires a perceptual equilibrium, an equilibrium of visual, not static, physical forces. And with a bridge like Hell Gate, where the arch is notably expressive of heaviness, to see the form as a bridge requires a visual vertical reply. This requirement is visual rather than structural, but it responds to a common human need as much as the static equilibrium responds to the need for a functional bridge.

I would say that Ammann’s Bayonne Bridge (as built) suffers from visual enigma. Longer and thinner than Hell Gate, it is even more horizontal, a visual quality further exaggerated by the long, straight approaches at either end. A crucial point, symmetrical at each end— where the arch stops, the bridge meets the


approaches, and the water reaches the foundations—is visually tangled, busy, and confusingly articulated by the pointless boxy frame that was supposed to hold stone cladding. Ammann’s piers were to have been much lower than those at Hell Gate and apparently were intended to reach only to the height of the guardrail of the road deck; but they would have been thick and rusticated. Visual mass at that point would acknowledge and respond to the vectors of visual force that meet there. The curve of the arch in brilliant metal would be enhanced by massive shapes of strikingly contrasting material at exactly those two points. Were it made just that much more of an arch for the eyes as well as for the traffic, a poet might sing of Bayonne Bridge as Hart Crane did of the Brooklyn Bridge:

Accolade thou dost bestow
Of anonymity time cannot raise:
Vibrant reprieve and pardon thou dost show

... And of curveship lend a myth to God.42

Art Is a Technical Idea
Art is not an essence, for essences do not exist. And art is not human nature, for it first emerged about 40,000 years ago, which was 50,000 or more years after the evolutionary consolidation of our species. In other words, art did not appear until well after evolutionary natural selection was done with us, and we had long since become as fit as we were going to get, genetically speaking. Anatomically, genetically, neurologically, linguistically modern human beings existed without art of any distinction for longer than the time since we cottoned on.43 The same is true of technology. It took anatomically modern humans at least 50,000 years to surpass Neanderthal in the number, complexity, and virtuosity of their stone tools.

Art began not as a discrete thing, an originally new thing to do, but as a new synthesis of things we had long been doing. We had to discover the possibility of cultivated coordination between visual perception and manual technique.44 It was


43. For a recent overview of human evolution, stressing the remarkable gap between the biological emergence of modern Homo sapiens about 150,000 years ago and the complete absence of a complementary modern human culture until about 40,000 years ago, see Richard G. Klein and Blake Edgar, The Dawn of Human Culture (New York: Wiley, 2002). For discussion of this point and its philosophical implications, see Barry Allen, Knowledge and Civilization (Boulder, CO: Westview, 2004), chap. 6.

44. It is important to understand that visual perception is a form of agency, not a passive process of registration. “In looking at an object,” Arnheim writes, “we reach out for it. With an invisible finger we move through the space around us, go out to the distant places where things are found, touch them, catch them, scan their surfaces, trace their borders, explore their texture. Perceiving shapes is an eminently active occupation.” Arnheim, Art and Visual Perception, 43.
not a biological but a historical event when these two forms of agency began to come under cultural control. We had always enjoyed vision but had not perceived our perception, been shown it and made to think about it, until the first visual art made it happen. To perceive perception takes more than perception; it takes art, artifice, the skillful translation of perception into a medium. Art began in this coupling of perceptual and manual cognition. Getting the idea of art means thinking about art technically and about technique artistically, whether on the walls of Altamira or in elegantly knapped laurel-leaf blades. Visual art is a synergy of manual technique and visual perception in a form that is perceptually and aesthetically coherent (an appealing presence) because of how it is put together technically.

The idea of an affinity between eye and hand is an old one that happens to be soundly based, as an intriguing experiment has confirmed. An experimental apparatus made it impossible for subjects to visually judge the size of two disks they saw. They were consistently wrong in their estimation. Then they were asked to reach for the disks, and experimenters measured the grip that the hand pre-forms as we reach for anything. The experimenters found that the configuration of the pre-contact grip accurately matched the actual size of the disk. The hands were making their own correct judgment of size, using the eyes in a way that bypassed conscious vision. This finding is supported in neurology: dedicated neurological channels have been identified that link visual input to the motor requirements of prehension (rather than vision).45

The work of the drawing hand is a method, a tool, a technique—at once manual, perceptual, artistic, and cognitive—for identifying, understanding, and defining things, investigating their relations, and creating order of increasing complexity.46 Because of his special relationship to drawing, Leonardo da Vinci, the ultimate artist-engineer, probably understood things that we still do not about hydrodynamics. Drawing was for him a cognitive tool, facilitating perception, extending perception, making perception more perceptive. David Rosand, a historian of drawing, writes of Leonardo’s “profound awareness of the act of drawing as an extension into the world, a process of seeing, knowing, and possessing, of that mutuality of hand and eye—and body.” With pen or chalk in hand, “Leonardo saw better. Through graphic gesture he could make visible those forces of nature that seemed to lie beyond the threshold of normal perception. Most impressively, he could see and record complex movements of water because he could impose upon the natural phenomena his own graphic formulae.”47

45. The experiments are recounted in Raymond Tallis, The Hand: A Philosophical Enquiry into Human Being (Edinburgh: University of Edinburgh Press, 2003), 59.


The paintings at Chauvet Cave date from more than 30,000 years ago. They easily stand artistic comparison with the famous paintings of Altamira or Lascaux, despite being from at least 15,000 years earlier (fig. 6). These paintings show that visual art did not begin “primitive” and slowly become more “advanced.” The first drawing, the first visual design, was already as good as it gets. We are not trying to get somewhere with art. The history of art is one of renewed accomplishment, renewing the origin of art in each work and each generation all over the world. The hand that drew the Chauvet tigers had a technical means, requiring skill at once visual and manual, of translating perception into a medium. The result is a work made to be perceived, a tool that works in being seen, in exciting and capturing our attention. And we should see drawing and stone-tool design as kindred gestures; both are inseparably visual and manual, perceptual and technical. The tigers and rhino of Chauvet are contemporary with carved human and animal forms in ivory and bone, and with elegantly sculpted laurel-leaf blades in flint.

At the same time, the human toolbox underwent a technical revolution. Stone tools that modern humans had shared with the Neanderthal (then still in existence) for 50,000 years were abruptly replaced by forms of unprecedented innovation: more complex, nuanced, elegant, and effective than anything in the history of technical culture to that point. It is difficult not to think that these two events, one technical, the other artistic, were connected. The connection, it
seems to me, is that the artistic event is a technical event, as the technical event is an artistic one. It is we, now, who insist that something belong either to art or to technology. Artistic perception was a technical breakthrough: finding ways to translate visual perception into a medium. And the innovations in stone-tool form are an artistic breakthrough: mastering purely visual values of equilibrium, balance, and expression in stone (as well as other materials), and making the crucial discovery that aesthetic coherence in artifacts pays returns in superior technical performance. In the words of Eduardo Torroja Miret: “Aesthetics, however much it depends on subjective personality, is nevertheless intimately linked to the geometric, analytic, mechanical, and strength properties pertaining to surfaces and lines that limit the masses of a structure.”

If we take a long view, if we appreciate humanity as an evolved species and accustom ourselves to a geological timescale, then there is no escaping the conclusion that, for most of Homo sapiens’ existence, art, innovation, and technical creativity were not needs and not conspicuous qualities in the astonishingly impoverished culture of people genetically and anatomically just like us. Art is an idea people got, a new ideal contingently discovered relatively late. Art has not always been with us, like an oxygen atmosphere. It is postevolutionary, a potential we had to discover as a cultural possibility and work to cultivate and master, just as we later did with agriculture and later still with cities. That is why I call art an idea: like agriculture or life in cities, art is a goal that people acquire, a practice they cultivate and may, in time, become irreversibly committed to.

We become committed to art because of what it does for us, an accomplishment we take for granted only because we have built so much on it and can scarcely imagine a time when we did not have traditions of arts to rely on. The technicalities of art are in service of both perception and cognition. They teach us to attend to our perception and let us ponder the relationships among shape, movement, and visual expression. In this service to what Arnheim calls “visual thinking,” the arts have, he says, become “the most powerful means of strengthening the perceptual component without which productive thinking is impossible in any field of endeavor.” “Vision,” as a philosopher of art puts this point, “is not a condition for art so much as art is the necessary condition for vision.”

Of course earlier humans, who lacked (visual) art, had vision, as do chimpanzees, birds, and fish. But these other species do not attend to their vision, and certainly do not have it called to their attention (which is what visual art does). Once we have the knack of thinking about our perception by translating it into various media, creating artifacts that work by being looked at, the vision


that other species have begins to seem deficient. Can they see lines or contours (without special training)? Do their colors have expressive qualities? Does their vision support any preference for things because of how they look? It is not likely. With us, perception itself has become artistic. We learn to see more expressively because that is how art presents perception to us, and we learn to cultivate visual expressiveness in practically anything we make. The birth of visual art was the birth of technical design and of what eventually became engineering. These are the same event, the cultivated synergy of perceptual and manual cognition and dexterity, under verbally different descriptions imposed by people who believe technology is governed by rationality while art is a subjective whimsy or arbitrary social representation.

Like sophistication in tools, art was originally a choice, a discovery, a contingency of history rather than a necessity of nature, but by now we could not survive without it. What art does for us is no different from what it has done for thousands of years, though art is immeasurably more important now because the stakes have become so much higher. With the dense technological network we have built around the planet and upon which more people rely every day, more than ever depends on the intelligence of our perception and on our freedom to envision seriously new technical alternatives. Both—perception and technique—are au fond aesthetic. We cannot flourish as a technological society without also flourishing as an artistic one. If we try to have one of these (technology) without the other (art), we endanger both, as well as everything that now depends on them; which is to say, human life itself. This conclusion might not need stating were it not for the nihilism that haunts art today.