Architecture and Engineering: asymptotic paths

> *There are things that intelligence alone is able to seek, but which, by itself, it will never find. These things instinct alone could find; but it will never seek them.*

> Henri Bergson[1]

My acquaintance with Peter McCleary dates back to 1969, when I came to the University of Pennsylvania to attend Louis I. Kahn's "Masters Studio." The last stirrings and social ferment of the 60's were still part of the campus drama in the warm humid days of a lingering Philadelphia summer. I remember clearly my first studio session: it was one o'clock in the afternoon, up the stairs I went to the penthouse of the Furness Library, Kahn's bastion and overlook — he refused to meet with his class in Meyerson Hall, the Architecture building, which unlike the Furness he considered to be a building without merit.

After twelve years of rehearsal, the ritual of the Master's Studio was well established. There was a group of three, Kahn, Robert le Ricolais, and Norman Rice, sitting at the ubiquitous oak table at the west end of the long room, opposite the east end's rotunda. Rice attended to administrative aspects of the class and occasionally engaged in distracting platitudes. Le Ricolais was taciturn, yet when he spoke he was precise, poetic, and even in silence his presence was positive and had a sense of scrutiny. Although the studio had three afternoons in the school's calendar, Kahn only came on Mondays and Fridays.

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[1] Bergson, Henri, *Creative Evolution*. New York: Holt, 1911.

There were three kinds of events, and we (the twenty-four odd students) spontaneously learned the order and rhythm of things as time elapsed and our work progressed. One was what can be best described as Kahn's soliloquies on architecture, which with minor distractions and a short break at mid-afternoon normally lasted until the early evening. Of a different sort were the meetings that had the group still congregated around the table, and those students who wished, voluntarily brought their work forward to be examined in quorum, seeking comments — and perhaps the blessing — of the master. The third kind was that when all students put their work on vertical boards, along the perimeter of the room, a few feet away from the walls and windows, and a procession began with Kahn bearing the standard. A peculiar ceremony was enacted in front of each board, with the student in one side, the work in the middle open to the view of the group, and Kahn with his two colleagues on the other side, sitting on high stools, speaking of the work as if it was common property. Even when his observations were particular and focusing on detail, their precision hit the target of everybody's mind. In all three kinds of meetings, an omnipresent chalkboard was by Kahn's side, waiting for his mark.

I sensed that his validity as a teacher was even more persuasive when, after belaboring for days, you put your work up on the board in spite of the intellectual discomfort, which comes about from the act that the Russian writer of fairy tales Alexander Afanasyev calls ''burning the frogskin.'' Kahn and the procession stopped at your board, an with what appeared to be effortless facility and unexpected revelation, he would uncover the cause of your discomfort with the precision of a surgeon and bring your mind back to the state that Aristotle called ''wonder'' — back to the fold of architecture.

It was customary that most of the students in Kahn's Master's Studio also enrolled in Robert le Ricolais ''Laboratory of Experimental Structures'' — it was in the grape-vine's explicit knowledge that it was the best thing to do. Perhaps less preoccupied with the quality of the building, Le Ricolais was satisfied to set up quarters in the top floor of Meyerson Hall. The room was approximately 30 by 40 feet and had plenty of natural light coming down from a roof monitor. On the north end was a long table with a select display of structural models, mostly made out of steel, which had been built and tested by students in-house during a period of fifteen years. On the south end was the stationary heavy equipment: a Bridgeport milling machine, a six-foot lathe, a bench top drill presses, a band

saw, and a wet metal saw for cutting heavy stock. There was also acetylene and arc welding equipment, an air compressor, a complete array of portable power and hand tools, and a more than sufficient supply of raw stock — assorted gauges of rods, tubes, cables and plate metals. Everything was kept in good order under the vigilant eye and stern hand of "Blackie," a no non-sense master mechanic that promptly instilled in us the ethic of shop equipment maintenance, by hail or brimstone.

My affection for machines and equipment was aroused in my high-school days when during the summers I became the self-appointed mechanic who kept things running in a sugar cane plantation and rum distillery that my father owned in South America. But the experience at le Ricolais' laboratory was an induction into a higher order of workmanship, putting manual dexterity on an equal footing with logical precision. The laboratory was scheduled on Tuesday and Thursday mornings, but as we became engrossed in model fabrication, we began to log in hours well in excess, perhaps five-fold the time allotted in the calendar.

The funicular polygon of revolution

After working for three weeks in minor variations of a couple of models, which I chose from the existing repertoire of structural concepts, I felt confident with the fine points of operation and calibration of the machines, particularly the Bridgeport mill, which was new in my experience and induced the greatest appeal in my imagination as an instrument of three-dimensional metal milling. So I began work on a new variant of the lemniscate, or funicular polygon of revolution. Having no current access to the physical object or to my shop log, which I have searched for in vain, I will reconstruct the model from memory. The stock materials used in fabrication were: 3/4 inch diameter aluminum tubing for the central compression post, 3/16 inch thick aluminum plate for the circular diaphragms, 1/32 inch stainless steel aircraft cable for the funicular tensile strands, and 3/4 diameter stainless steel ball bearings for the ends.
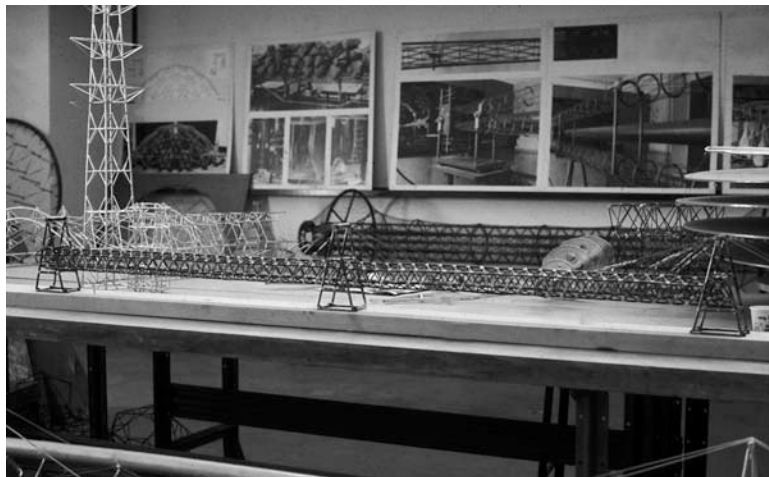
With sporadic assistance from Blackie, I managed to finish the model in six weeks — it was by all accounts a well-run laboratory, balancing tacit and explicit knowledge.[2] The contour of the spatial volume was the revolution of a parabolic segment, intentionally adjusted by
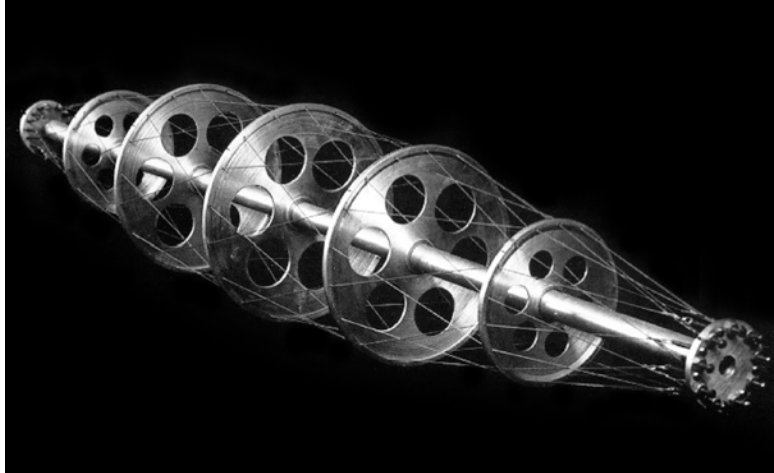
[2] Sennett, Richard, *The Craftsman*. New Haven: Yale U. Press, 2008.

the diameter and spacing of the five diaphragms. The diaphragms were milled to 1/16 inch thickness and perforated by six proportionately sized portholes — inadvertently heeding to le Ricolais' maxim, *The art of structure is where to put the holes* — to lighten their physical and visual weight, remaining thicker at the outer perimeter, as compression rings, and the inner circumference touching the center tube. The ball bearings, whose function was to eliminate torsion and to allow self-adjustment, were installed at both ends, over bushings that protected the tube walls from crushing. Two small diameter plates were installed over the ball bearings to allow the array of the tension strands, which were eighteen in total and rotated one full revolution from end-to-end, alternately clockwise and counterclockwise.
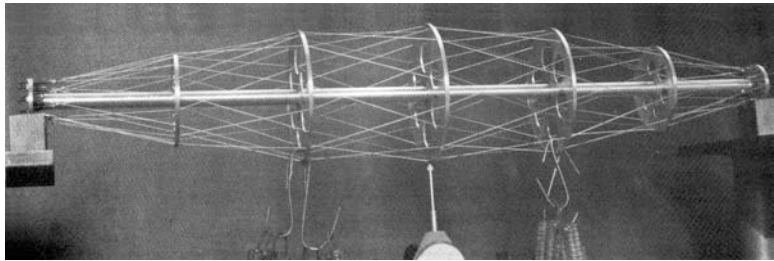
On judgment day, the mechanical performance of the model was more than satisfactory: its weight to span ratio was very economical, and the deflection under load was minimal, maximizing its dependence on the tensile network (funicular polygon) of revolution. Le Ricolais was quite pleased with the results — I remember his sober smile clearly. He made an intuitive assessment and jotted some numbers, which he probably knew by heart, on a piece of paper, and the test was finished. This model was still far from his dictum, *zero weight, infinite span*, nevertheless, it has stayed in my cerebral cortex as an example of what the Greek called "entelecheia" — or, entelechy: the actualization of form-giving cause and an inherent regulating and directing force in the development and functioning of a system.

1. Robert le Ricolais "Laboratory of Experimental Structures."
Philadelphia, 1969.

2. Lemniscate, funicular polygon of revolution (FPR), manufactured by Álvaro Malo. Philadelphia, 1969.

3. FPR, load test. Philadelphia, 1969.

The general run of inventions conforms to the following pattern: a series of progressive, almost continuous deformations of the raw material, and then — a step over a threshold — a sudden perception of the future of one of these states. "Future" here means a value that can be utilized; one that is significant and singular.[3]

The testing of the model also brings forth the recollection of my first formal encounter with Peter McCleary. He was present at the event and made some observations, which I probably disregarded, for I thought he was only an assistant to the master, better listen to the master himself. But, soon I found that he was also teaching some of the required courses in structures, from which I was exempt in Kahn's "Masters Studio" — I had already satisfied this requirement in my diploma studies in South America. Nevertheless, a

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[3] Valéry, Paul, *Analects*. Princeton: Bollingen Series, Princeton U. Press, 1970.

conversation began that has lasted almost forty years, perhaps our own version of Maurice Blanchot's *The Infinite Conversation*. Peter introduced me to two books: D'Arcy Thompson's *On Growth and Form* and Kenneth Boulding's *The Image: knowledge in life and society*. I suspect that he remembers well being the source of the first, but perhaps not of the latter. Thompson's work has been a font of inspiration and a model of precision in the geometric and poetic analysis of natural morphologies and specimens, providing clear methods of reference through analogy — similarity of function — and homology — similarity of structure. I have continuously brought it to light in my own teaching and have worn out several copies that have come apart at the spine. Once, when visiting the Rhode Island School of Design, I found that its "Foundation Program" had the "Nature Resource Room" in the heart of the building, better than a library I thought, there was Thompson's opus in full regalia.

Boulding's work has come back to my attention, after a long hiatus, particularly chapter 2, "The Image in the Theory of Organization," where he identifies seven levels of complexity: the jig-saw puzzle, the clockwork, the thermostat, the cell, the plant, the animal, and the human being. In my current research in "emerging material technologies," I find it necessary to challenge the exaggerated claims of "biomimetism" and "intelligent buildings." For thousands of years buildings have been designed to function as jigsaw puzzles, even some of exquisite intricacy, such as the Alhambra. One may find clockwork attributes in the building methods of Brunelleschi, one of the foremost architects and engineers of the Italian Renaissance — considering that his construction machines are fundamental to his architecture. Later, the thermostat as a device has been part of the mechanical equipment of buildings, as the governor is a regulating part of the operation of an engine; but buildings as whole thermodynamic systems are still experimental and rare. All claims above this level, even if well intentioned, are theoretical self-indulgence.

The cycloid

After graduation in 1970, I went to work in Kahn's office. There were two active projects on the boards: the Kimbell Art Museum, in Forth Worth, Texas, and the Yale Center for British Art, in New Haven, Connecticut. Construction of the Kimbell had begun in 1969, but there were still construction documents and shop drawings being prepared. The Yale

Center was at the preliminary design stages, in its truly archaic beginnings. My affection for the Yale Center notwithstanding, it is the Kimbell and the lessons that issued from its conception, design, and construction that are more persuasive within the framework of this recollection.

The curator Richard F. Brown was entrusted in the mid 1960's with the task of developing the collection of the Kimbell Art Foundation and building a new public museum for what until then had been the private possession of the local entrepreneur Kay Kimbell, which was displayed in his home as a rotating exhibit. The story of Kahn's selection as the architect for the Kimbell is well recounted elsewhere in the museum's literature.[4] Of central concern to Brown was the desire to refine the quality of natural light as a condition of both visual perception and the potentially detrimental effects of direct sunlight on art objects. He stated this in an explicit note, "The creation of the ideal total visual situation, of course, involves the physics, physiology and psychology of it: i.e., all levels of perception."

This dealt the cards directly into Kahn's hand. I do not know whether his pronouncements concerning light, material, and structure — *Light is spent material* and *Structure is the giver of light* — predate, are contemporaneous, or came after the crafting of the Kimbell — I will leave the detective's work to historians. The transformation of the Kimbell's roof geometry from a folded plate, to a semi-circular vault, to a quasi-elliptical section, and finally to a half-cycloidal shell is also well documented on Kahn's own notebooks.[5] The technical work of refining, calculating, and making possible the construction of the structure as a post-tensioned thin-shell, working longitudinally as a beam, fell to the engineer August Komendant. Kahn and Komendant's collaboration, which lasted eighteen years, can be best described as a difficult love affair. During my time at the office, a young Swiss architect, who spoke German, was often sent out ahead of Kahn to speak with Komendant and smooth out the terms of their meetings.

Speculating on the pertinence of the Aristotelian "four causes" to the making of the structure of the Kimbell, I would say that the *formal* cause belongs mostly to Kahn, he shares the *material* cause with Komendant, the *efficient* cause, or technical implementation, belongs mostly to the latter, and the *final* cause is shared with Brown.

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[4] Loud, Patricia C., *In Pursuit of Quality: The Kimbell Art Museum*. Fort Worth: Kimbell Art Museum, 1987.
[5] Ronner, Heinz and Jhaveri, Sharad, *Louis I Kahn: Complete Work 1935-1974*. Basel: Birkhäuser, 1987.

However, the remaining question is, Why the cycloid? And here, I must relate the cycloid's own history and definition. The cycloid is the locus of a point on the rim of a circle rolling along a straight line. The cycloid was first studied by Nicholas of Cusa and later by Mersenne. It was named by Galileo in 1599. In 1634 G.P. de Roberval showed that the area under a cycloid is three times the area of its generating circle. In 1658 Christopher Wren showed that the length of a cycloid is four times the diameter of its generating circle.

The cycloid has been called "The Helen of Geometers" as it caused frequent quarrels among 17th century mathematicians.[6] In 1696, Johann Bernoulli challenged other mathematicians to find the curve that solves the "brachistochrone problem" (Greek: "brachistos" shortest, "chronos" time), knowing the solution to be a cycloid. Leibniz, Newton, Jakob Bernoulli and L'Hospital all solved Bernoulli's challenge. The cycloid also solves the "tautochrone problem," as alluded to in the following passage from *Moby Dick*: "The try-pot is also a place for profound mathematical meditation. It was in the left-hand try-pot of the *Pequod*, with the soapstone diligently circling round me, that I was first indirectly struck by the remarkable fact, that in geometry all bodies gliding along a cycloid, my soapstone, for example, will descend from any point in precisely the same time" (Melville 1851).

The brachistochrone problem asks for the shape of the curve down which a bead, starting from rest and accelerated by gravity, will slide (without friction) from one point to another in the least time. Fermat's principle states that light takes the path that requires the shortest time. Therefore, there is an analogy between the path taken by a particle under gravity and the path taken by a light ray, and the problem can be modeled by a set of media bounded by parallel planes, each with a different index of refraction (leading to a different speed of light). Consequently, the path taken by a light ray in these media where light propagates at variable speeds is the answer to the problem — the path taken by light approaches the cycloid, *quod erat demonstrandum*.

This comes back full cycle —better yet, full cycloid — to Brown's instructions regarding light, and Kahn's geometrical choice, which I think was not guided by analysis but rather by intuition — perhaps using intuition, in the Bergsonian sense, as a "method of precision."

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[6] Boyer, C. B. and Merzbach, U. C. *A History of Mathematics, 2nd ed.* New York: Wiley, 1991

This is yet another example of "entelecheia," a regulator of orderly activity causing things to do that which is natural to them when seeking their specific natural ends or completion — *a materialized idea* and *an idealized material*. In Kahn's words,
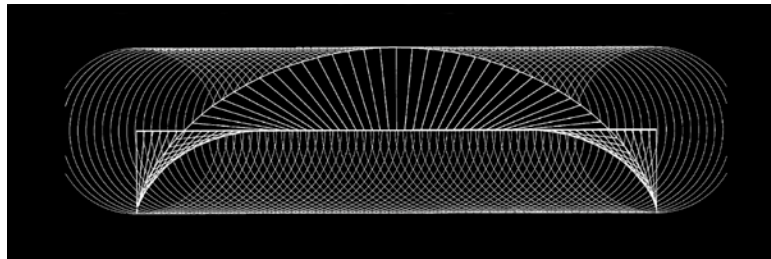
Order is
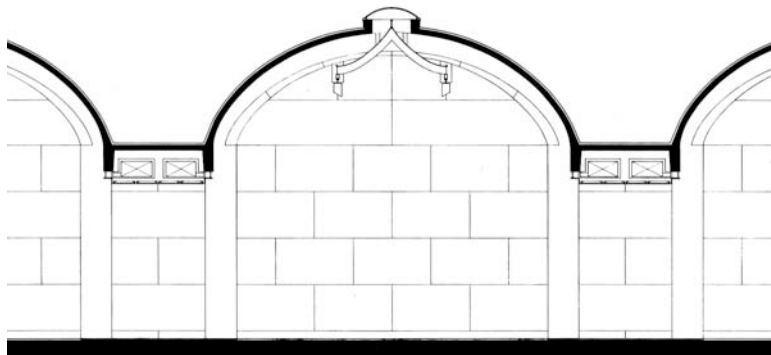
Design is form making in order

Form emerges out of a system of construction

Growth is a construction

In order is creative force[7]

6. Cycloid, student drawing at Á. Malo's seminar at Columbia University. New York City, 1987.

4. Kimbell Art Museum, section through cycloid shells. Philadelphia, 1968.

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[7] Scully, Vincent J., *Louis I. Kahn*. New York: G. Braziller, 1962.

5. Carpenters preparing formwork for cycloid shells. Forth Worth, 1969.

…matter is slow space and space is fast matter…matter and spirit are the same, they follow the same direction…Could spirit be such infinitely fast matter that to our eyes it disappears as matter?[8]

This desire to communicate with inanimate things may be at the end a form of poetic analysis, similar in its futility to the myth of Sisyphus, which the philosopher Guiles Deleuze defines as the adventure "of climbing from out of the depth of the body to the surface of words." Perhaps futile, but for the writer Maurice Blanchot it is a sign of the fundamental impulse to "make the obscurity of language respond to the clarity of things."

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[8] Ugarte, Luxio, *Chillida: dudas y preguntas*. Donostia: Erein, 2000.