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A Tale of Two Cities: Architecture and the Digital Revolution

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The scientific and technological advances of the industrial revolution radically transformed construction. New materials and systems transcended previously critical constraints on building size and complexity, allowing architects to create skyscrapers, long-span structures, and mechanically and electrically serviced interiors. By providing new intellectual tools, the digital revolution is now producing a similar revolution in design, allowing architects to imagine, develop, and explore innovative concepts that would have proved impossibly difficult in the past.

The curved surfaces of the Sydney Opera House presented an extraordinary structural challenge.

Before a large and complex building can be constructed, architects first need to produce drawings or some other precise and detailed representation of it. Furthermore, architects and engineers need to predict its performance under expected conditions of use: They must establish acceptable levels of confidence that it will be structurally adequate, that it will provide the necessary thermal, lighting, and acoustic conditions, that it can be built on time and on budget, and so on. Thus the architectural design process is largely one of creating and analyzing representations of alternative proposals, and then translating the completed representation of a selected proposal into full-scale, physical reality. This extended, highly collaborative process proceeds partly through flashes of inspiration, but mostly through dogged trial and error.

In the past, the geometric and material possibilities that an architect could explore in this process were severely constrained by the limitations of available representation and analysis tools. Traditional drafting instruments—parallel bars, triangles, compasses, scales, and protractors—largely restricted designers to a world of straight lines, parallels and perpendiculars, arcs of circles, and Euclidean geometric constructions. The limitations of analysis techniques based on precedent and rule of thumb meant that the range of designs with predictable performances was even narrower.

As a result, architects frequently found that they could sketch configurations that they could not describe sufficiently precisely or analyze sufficiently reliably, and therefore could not build. Of course, it was still possible to create wonderful works under these constraints, just as poets can create masterpieces within the severe constraints of the sonnet form, but the fact remained that many interesting design possibilities could never even be given serious consideration.

Today, computer technology has changed all that. Modern CAD (Computer Aided Design) systems allow designers to create very complex three-dimensional (3D) geometric models with ease. In addition, the availability of inexpensive computing power facilitates the application of sophisticated analysis and simulation algorithms to predict performance. These procedures need not rely on unsubstantiated assumptions and rough approximations as in the past, and the simulations can model the performances of structural and environmental systems much more reliably. CAD/CAM technology—the use of CAD models to drive numerically controlled fabrication and assembly machinery—also allows the timely and economical realization of designs that would once have proved impossibly slow and costly.

To illustrate the extraordinary transformation that has taken place in the digital decades, let us compare two architectural masterpieces of the latter half of the 20th century: Jørn Utzon's Sydney Opera House and Frank Gehry's Guggenheim Museum in Bilbao. Both were regarded as breakthrough buildings of their time, both caught the public imagination, and both became instantly emblematic of the cities in which they were built.

The Sydney Opera House was the outcome of an international competition held in 1956.* Utzon's winning entry featured curved concrete shell vaults which, the jury commented, "relate as naturally to the harbor as the sails of its yachts." However, these spectacular vaults obviously presented an extraordinary structural challenge, and the London engineering firm of Ove Arup and Partners was therefore immediately engaged to help figure out how to build them.

Utzon's very schematic competition

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*The story of this project is told in detail, with numerous illustrations, in Francoise Fromonot, *Jørn Utzon: The Sydney Opera House* (Electa/Gingko, Milan, 1998).

†Quoted in Fromonot, p. 65.

‡Francesco Dal Co, Kurt W. Forster, and Hadley Arnold, *Frank O. Gehry: The Complete Works* (Monacelli Press, New York, 1998).

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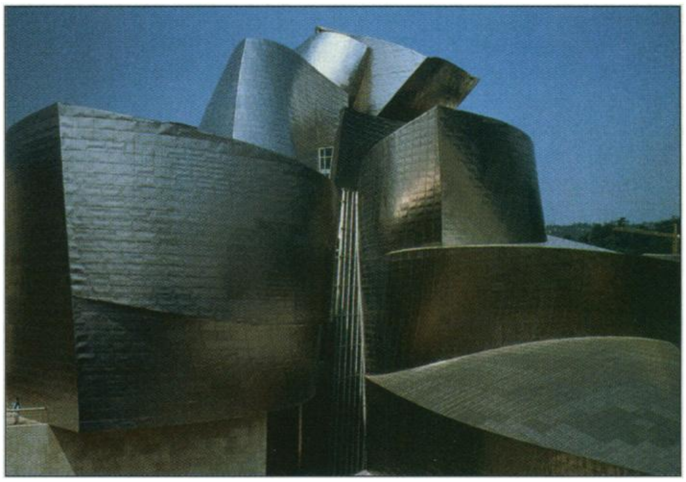
drawings had depicted free-form curved surfaces. The first task was thus to find a precise and useful mathematical description. Arup commented: "Each of the main shells consists of two symmetrical halves meeting in a ridge in the vertical plane going through the longitudinal axis of the hall. The ridge is part of a parabola. The two symmetrical surfaces meeting in this ridge are roughly triangular in shape and descend on each side to a point which forms a support for the shells.... By thus defining the surface of the shells geometrically each point of the surfaces can be given spatial coordinates and a basis has been created for the calculation of the forces acting on the shells and the stresses created in the shells."[†]

From 1957 to 1961, Utzon and Arup struggled to find a feasible structural solution, while simultaneously experimenting with shape modifications intended to make the analysis and construction problems more tractable. They explored single-skin concrete shells, double concrete shells, systems of arches, and finally, ribs fanning out from the base of each shell. The ridge profile became a circular arc, then an elliptical one. Nothing worked, until the team eventually hit upon a brilliant simplification. The surfaces of all the shells could be defined, to a very close approximation of the original sketched forms, as triangular patches on the surface of a single sphere.



Computer-aided design facilitated modeling and construction of the Museo Guggenheim Bilboa.

The ridge profile and the ribs thus reduced to arcs of circles, and the uniformity of the surfaces now meant that they could be constructed from prefabricated repeating elements, achieving economies of scale and reducing the cost to a more acceptable level. The working drawings could be generated using traditional drafting instruments and standard techniques of descriptive geometry. Furthermore, even with the relatively primitive algorithms and minuscule computer power available at the time, the structural analysis problem was simplified to the point where the necessary calculations could be completed in a few months. By 1967, the beautiful shells that we see today on Bennelong Point were finished.

Meanwhile, Utzon turned his attention to the design of the auditorium ceilings, which he intended to be constructed from suspended plywood panels. These had to conform to the shape of the exterior shells, provide appropriate acoustic conditions, and create visually compelling interior spaces. After lengthy experimentation he proposed, in response to these demanding requirements, an elaborate system of plywood box-beams shaped as sequences of convex circular arcs.

To this second chapter of the story, though, there was to be no happy ending. Arup came to believe that the box-beam design was hopelessly impractical and should be replaced with a far more conventional one. Increasingly, the virulent Australian press pilloried Utzon for cost overruns and completion delays. Meanwhile, a newly elected conservative state government was after the architect's blood. (He was, after all, a foreigner, stubborn in defense of his apparently outlandish ideas, and an appointee of the previous Labor government.) In March 1966, Utzon was forced to resign; he left Australia in bitterness and secrecy and was not to return for decades. The interior project design was completed by others, and—apart from the magnificent shells—has little of the freshness and originality that Utzon and his supporters had hoped and struggled for.

The tale of Bilbao—four decades later—began similarly but turned out much more happily.[‡] Gehry's initial sketches and models for a museum beside the Puente de la Salve Bridge showed an even more audacious assemblage of free-form curved surfaces than Utzon's. But by this time, accurate modeling for analysis and construction purposes was no longer a problem. For development of the design, Gehry's office employed Catia—an advanced CAD system mostly used, until then, in aerospace and automobile design. Like other such systems available today, Catia provides a repertoire of spline surfaces, ruled surfaces, and other surface types that can be instantiated and assembled within a three-dimensional Cartesian coordinate system to model just about any form a designer might imagine. The Catia digital model, rather than a conventional set of drawings, thus served as Gehry's definitive design representation.

During development of the design, this digital model was put to many uses. Whereas Utzon had been forced to rely on laboriously handmade drawings and scale models in his explorations of visual and spatial effects, Gehry could employ visualization software to produce, almost instantaneously, whatever views he needed. He could also utilize rapid prototyping devices to generate physical models automatically. The digital model also provided input data needed for structural and other analyses. The complexity of these analyses no longer presented a difficulty either: the available algorithms had improved enormously in versatility and scientific accuracy since Utzon's day, and the computer power needed to execute them had become abundant and inexpensive.

Finally, at the construction stage, the digital model was used to control CAD/CAM fabrication processes. This greatly reduced the necessity for shape uniformity and component repetition. Gehry had no need to seek heroic simplifications, like Utzon's resort to spherical patches. The gap between what could be dreamed of and what could be produced had been narrowed dramatically. Budget and schedule were kept in close control, and the completed building—remarkably true to the architect's first visionary sketches—opened in 1997 to universal acclaim.

Bilbao illustrates a profound ongoing transformation of architectural thinking and construction practice, the greatest such shake-up since the industrial revolution. Replacement of drawings done by hand with 3D CAD models and computer visualizations has removed ancient constraints on architectural geometry and is allowing exciting new languages of architectural form to emerge. The use of sophisticated analysis and simulation algorithms, as well as accurate calculations that take advantage of abundant computer power, allows the behavior of these new forms to be understood and predicted. Finally, supplementing industrial-era mass-production with CAD/CAM mass-customization contributes to their speedy, accurate, and inexpensive fabrication. For architects, the gap between the imaginable and the feasible has narrowed dramatically.