Constructing Complexity

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**Abstract:** Buildings were once materialized drawings, but now, increasingly, they are materialized digital information – designed and documented on computer-aided design systems, fabricated with digitally controlled machinery, and assembled on site with the assistance of digital positioning and placement equipment. Within the framework of digitally mediated design and construction we can precisely quantify the design content and the construction content of a project, and go on to define complexity as the ratio of added design content to added construction content. This paper develops the definitions of design content, construction content, and complexity, and explores the formal, functional, and economic consequences of varying the levels of complexity of projects. It argues that the emerging architecture of the digital era is characterized by high levels of complexity, and that this enables more sensitive and inflected response to the exigencies of site, program, and expressive intention than was generally possible within the framework of industrial modernism.

Perhaps you have wondered why the shapes of buildings seem to be getting more complex. Conceivably, it could be nothing more profound than an arbitrary flicker of architectural fashion. But it is worth asking whether the difference between, say, Frank Gehry’s Bilbao Guggenheim and the characteristically rectangular slabs and towers of the late twentieth century is due to something more fundamental? Does the curved shape of London’s Swiss Re Building, the twisted profile of New York’s proposed Freedom Tower, or the non-repetitive roof structure of the British Museum courtyard represent some significant change in the conditions of production of architecture?

The shift, I suggest, is a direct outcome of new conditions created by the digital revolution. Buildings were once materialized drawings, but now, increasingly, they are materialized digital information – designed with the help of computer-aided design systems, fabricated by means of digitally controlled machinery, put together on site with the assistance of digital layout and positioning devices, and generally inseparable from flows of information through global computer networks. Many architects have simply exploited digital technology to reduce the time and cost of
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producing buildings in the conventionally modernist mode, much as architects of the early industrial revolution took advantage of mass-production to inexpensively proliferate the ornament that had previously been created by craftsmen. But others have recognized that the digital revolution has opened up new domains of architectural form for exploration, and they have seized the opportunity to produce projects that break the old rules.

To see precisely how new formal possibilities emerge from the interplay of information and materiality, we need to do some numbers. It will be helpful to begin with a homely example that should be familiar to anyone who has ever operated a computer graphics or computer-aided design system. Consider the task of inputting a circle. You need to give a circle command and specify three numbers – usually an $x$-coordinate, a $y$-coordinate, and a radius, though Euclid tells us that there are other, equivalent ways to convey the same information. You can enter the circle’s three parameter values by typing the numbers, or by graphically selecting and sizing a circle with a mouse, but the result is the same in any case. Now consider the task of inputting an irregular, jagged polygon with, say, fifty vertices. It is a lot more work. You need to explicitly enter the $x$-coordinate and the $y$-coordinate for each vertex – a polygon command, plus a total of one hundred parameter values. Let us say, then, that the design content of a shape entered and stored in the system is the number of discrete items of information (that is, command words and parameter values) required to specify it. (A little more strictly, it is the number of bits in the input stream.) It is easy to see that design content of the circular shape is approximately three percent of that of the irregular, jagged shape.

The difference is not just a technicality. The higher the design content of a shape, the more opportunities it provides for adaptation to a specific context. If a designer needs to fit a circular shape into a tight space, for example, she can only shift its center point and vary its radius. But if she needs to fit the jagged shape, she can shift any combination of vertices to accommodate arbitrary nooks and crannies. This added flexibility comes at a price, however. There are more decisions to make with the jagged shape – more for the designer to think about.

To refine this definition of design content a little further, we can establish it relative to particular computer-aided design systems. Any such system has a set of input commands – enabling the user to specify a straight line, a circle, a rectangular box, a spline, and so on. Some systems have more specialized commands to facilitate the entry of objects like columns, walls, doors, windows, and the like. In interpreting a command, the system makes use of built-in design content – knowledge, expressed in computer code, of how to display a straight line defined by its end points, how to display a circle specified by three parameters, how to display a column proportioned as desired, and in general how to display anything in the system’s shape vocabulary. Some systems encode very little predefined design content in this way, and have correspondingly restricted sets of input commands, while others encode a great deal, and provide extensive repertoires of commands for users to learn and utilize. Thus, when a designer inputs a shape using the commands of a particular system, the input that she provides is the added design content. This can be defined as the smallest number of discrete items of information (shortest string of bits, if you want to be
precise) required to specify the shape fully. This modified definition allows for the fact that there will usually be efficient and inefficient ways to enter the same geometric information, and stipulates that we are only concerned here with the most efficient.

Designers can re-use not only content that they find pre-encoded in a system at the start of a design process, but also content that they have input themselves, at some earlier stage in that process. A common strategy in design of office towers, for example, is to lay out a standard floor then repeatedly translate vertically and copy to describe the entire building. Depending upon the specific circumstances, we might regard this either as elegant economy of means or as lazy self-plagiarism.

A fully displayed design, then, is the joint product of the information already encoded in the system and the information added, in response to particular conditions and requirements of the context at hand, by the designer. The system automatically does the work of expanding the added design content into a complete display.

Another way to express this point, using more traditional terminology, is to say that any computer-aided design system encodes stylistic conventions. Many systems support a style derived directly from Euclid’s Elements – one characterized by straight lines, arcs of circles, parallels, perpendiculars, and tangents. Some encode the vocabularies and layout rules of particular industrialized component building systems. It would be a provocative but technically trivial exercise to implement a neoclassical system that encoded the vocabulary and syntax of the style specified by, say, Palladio’s *Four Books*, or Durand’s *Précis*. A designer working within the established intellectual framework of a strong tradition, as expressed in the commands of a computer-aided design system, needs to add only a small amount of content to specify a complete design, while a designer working within a more general tradition typically needs to add more. A designer who is content to operate within the bounds of encoded tradition needs to add relatively little, while a designer who wants to break radically with tradition needs to work harder. In design innovation, as in other domains, there are no free lunches.

Investment in computer-aided design software privileges the associated style. Early computer-aided architectural design systems mostly privileged a very conventional style of walls, columns, doors, windows, extruded floor plans, floor slabs, and so on, laid out with the help of grids, construction planes, and skeletons of construction lines. In the 1980s and 1990s, though, the software industry invested in computer-aided design systems that encoded knowledge about the calculation and display of free-form curved shapes specified by a few parameters. As a result, these became widely and inexpensively available. They were mostly intended for use in the automobile, aerospace, and animation industries, but were quickly appropriated by architects. They established and enforced the rules of a new style – one of splines, blobs and twisted surfaces. Before these systems, creation and display of an architectural composition consisting of free-form curved surfaces would have required a huge amount of added design content – impractically large in most practical contexts. After these systems, the same composition could be specified with a much smaller amount of added design content. Under these new conditions, it
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was hardly surprising that schools and avant-garde practices happily embraced curved surfaces – much as the schools, in previous eras, had followed Palladio and Durand. It was a matter of the shifting economics of information work.

But it is one thing to specify and render a curved-surface shape on a computer-aided design system, and quite another to materialize it, at large scale, on a construction site. Successful materialization requires some sort of construction machine that can efficiently translate the digital description of the shape into a tangible realization. (The process is analogous to that of performing a digitally encoded score on an electronic musical instrument.) It might, in principle, be a sophisticated CAD/CAM fabrication device such as a laser cutter or a multi-axis milling machine, or it might be an organized team of construction workers with the skills and tools needed to do the job. Let us, for the moment, make the simplifying assumption that it is just a black box that accepts a digital description as input and produces a material realization as output.

Now, like a computer-aided design system, a construction machine will have some set of commands that it can execute. A simple laser cutter, for example, might execute commands to move the laser from one specified point to another, and to cut from one point to another. To connect to such a device, a computer-aided design system needs driver software that translates an internally stored description of a shape into a corresponding sequence of move and cut commands. The construction content of a shape may be defined as the length of this sequence. (More strictly, it is the number of bits in the sequence.) A rectangle, for example, has little construction content; it can be generated by one move command followed by four cut commands. But a fifty-sided polygon requires a move command followed by fifty cut commands, so it has much greater construction content. In each case, an additional locate command must be executed – by fingers, a robot, or a construction crane – to place the fabricated piece within an assembly of pieces.

The translation of a shape description into a sequence of commands to a construction machine is one of converting a state description, which specifies a desired end condition, into a process description, which tells how get there. The translation task may be quite trivial, as in generation of move and cut commands for a laser cutter. The translation of a complex three-dimensional shape into tool paths for a multi-axis milling machine is, however, much less trivial. In general, state-to-process translation algorithms encode knowledge of construction materials and processes.

There are, however, supply chains for construction elements, and the definition of construction content should be established relative to position within a supply chain. If, for example, a designer has at her disposal a pre-cut rectangle of the right size for use in her project, then no further cutting operations are required; the only construction operation is to locate it in the desired position. This locate operation represents the added construction content at this step in the supply chain. In general, construction machines that start with elementary raw materials add a lot of construction content in the process of realizing elaborate designs, while construction machines that assemble sophisticated, highly finished, prefabricated components add relatively little. This, of course, relates closely to the economist’s concept of added value at each step in a supply chain.
Generally, construction operations can usefully be subdivided into fabrication operations (cutting, milling, stamping, etc.) that produce discrete elements and assembly operations that combine discrete elements to produce systems. Since ancient times, for example, builders have fabricated discrete bricks by shaping and drying or firing clay, and then assembled bricks into walls, arches, and other structures. Similarly, in modern electronics, solid-state devices – very sophisticated building blocks – are fabricated in expensive and technologically sophisticated plants, and then robotically assembled into devices. A designer may assume prefabricated elements, or even pre-assembled complete subsystems. In doing so, she not only establishes a starting point for addition of construction content, she also inherits design content. This inherited design content may be represented explicitly and in detail in a computer-aided design system, as when selection of a component from a menu results in insertion of a detailed description of that element into the design, or it may be represented by an abstraction, as when an element is represented simply by its outline.

![Figure 1 The Bush Building at MIT, designed by Walter Netsch in the early 1960s – an elegant example of industrial modernism. The design content is low, since the entire form is generated by a few key decisions. Construction economies were achieved through extensive repetition.](image)

The ratio of fabrication operations to assembly operations may shift from project to project. When a cave is carved directly out of the living rock, or an adobe building is created from mud, the task is entirely one of in-situ fabrication. Conversely, when a
factory is assembled from precast concrete elements, or when a child creates a composition of Lego blocks, the task is entirely one of assembly. A standard strategy of industrial modernism has been to minimize in-situ fabrication, and to do as much pre-fabrication and pre-assembly as possible, under controlled factory conditions.

Execution of a command by a construction machine has an associated time and a cost. Obviously the total time to fabricate a component is the sum of the times for the individual commands in the sequence, while the total cost is given by the cost of raw materials plus the sum of the costs for the individual commands. Similarly, the total time to assemble a subsystem is the sum of the times for the individual assembly steps, and the total cost is the sum of the individual costs. Thus the times and costs of executing a design rise with construction content, but can be reduced by machines that execute commands quickly and inexpensively.

In practice, this analysis is complicated by the fact that errors occur in fabrication and assembly processes. They must, therefore, incorporate strategies for error detection and correction. Net efficiency depends upon reducing error rates, and upon effective detection and correction.

It follows from all this that fast, reliable, efficient construction machines allow designers more construction content within the same schedule and budget constraints. Industrial-era machinery typically achieved such efficiency through repetition, mass-production, and economies of scale. In the digital era, numerically controlled machines have allowed similar efficiencies with non-repetitive operations.

With the concepts of design content and construction content in hand, we can now formalize the intuitive idea of the complexity of a designed and constructed shape, an assembly of shapes, or a complete architectural project. Roughly speaking, it is the number of design decisions relative to the scale of the project. We can measure it as the ratio of added design content to added construction content. If the entry of a few command words and parameter values to a computer-aided design system suffices to generate a great deal of construction content, then the project is of low complexity. If many parameter values are required, as in the case of a fifty-sided irregular polygon to be produced by a laser cutter, the complexity approaches one hundred percent. Differences in complexity arise because a command given to a computer-aided design system may imply more construction content than immediately meets the eye.

The difference between building designs of low complexity and those of higher complexity is economically and culturally significant, and its implications have played out differently in different eras. This can conveniently be demonstrated by means of the following two-by-two table.
Along one axis there is a distinct distinction between projects of low complexity and those of high complexity, and along the other the distinction is between repetitive construction and non-repetitive. The entries list examples of each combination.

The condition of low-complexity, repetitive design and construction is illustrated by the industrialized component building systems that were popular in Postwar Europe. These radically reduced the time and cost of construction through efficient mass-production of standardized elements. Architects working within the frameworks of such systems could select and specify the positions of standard elements – adding relatively little design content as they did so. If the elements were available from stock at construction time, there was also little added construction content. So large buildings could be designed and built very quickly and economically, but the process provided little opportunity to adapt buildings sensitively to local site and climatic conditions, programmatic requirements, and cultures.

Mainstream architectural modernism more generally – particularly in its developer-driven manifestations – has frequently served as a strategy for simultaneously meeting challenges of scale, budget, and schedule by reducing complexity. A typical modern office tower, for example, might have a modular layout, symmetry about one or more axes, a repetitive structural frame and curtain wall, and a standard floor plan that repeats vertically. An urban complex might even be composed of repeating towers, as in the case of the ill-fated World Trade Center. At the design stage, replication of a floor or an entire tower by a translate-and-copy command is an operation that adds very little design content, but eventually generates a great deal of construction content. But you get what you pay for; this simplification of design (typically under budget and time pressure) reduces an architect’s ability to respond thoughtfully to the exigencies of particular moments and spaces.

Typically, modernists have minimized complexity not only by standardizing components and subassemblies, but also by standardizing the spatial relationships

Table 1 Interrelationship between type of construction and level of complexity

<table>
<thead>
<tr>
<th>Repetitive construction</th>
<th>Non-repetitive</th>
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<tbody>
<tr>
<td><strong>Low complexity</strong></td>
<td></td>
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<tr>
<td>Industrialized component building</td>
<td>British Museum roof</td>
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<td>systems</td>
<td>Swiss Re</td>
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<tr>
<td><strong>High complexity</strong></td>
<td></td>
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<tr>
<td>Habitat, Montreal</td>
<td>Craft construction</td>
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<td></td>
<td>Stata Center, MIT</td>
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among them – laying them out in repetitive arrays and grids. An alternative strategy was famously demonstrated by Moshe Safdie’s Habitat in Montreal, where the box-like units were highly standardized, but the spaces and masses that they produced were varied. The efficiencies of mass production could still be achieved, but the resulting level of complexity was higher.

Habitat and the British Museum courtyard combine standardization and variability in different ways – putting the capacity for responsive variation in different places.

Figure 2  The roof of the British Museum courtyard, London, by Norman Foster. Non-repetitive construction is enabled by efficient numerically controlled fabrication, but design content remains fairly low, since the varied shapes of the roof panels, structural members, and joints are controlled by simple rules and a few parameter values.

Norman Foster’s designs for the British Museum courtyard and the Swiss Re tower in London illustrate the condition of non-repetitive geometry with relatively low complexity. In each case, the structural frame and skin system is topologically uniform but geometrically varied. The metal structural members are connected together in a standardized way, but the lengths of the members, the joint angles, and the dimensions of the glass panels that they support are varied. The variation is controlled by simple formulas and a few parameters, so the added design content is not much higher than for fully repetitive designs. This is variety, cleverly achieved through exploitation of numerically controlled fabrication, but without resulting in great complexity.
In Habitat it is in the spatial relationships among standard physical elements, while in the British Museum roof it is in the lengths and connection angles of the physical elements themselves.

Under conditions of craft production, the versatility of craft workers makes it possible to produce buildings that contain very little repetition anywhere. But the operations performed by craft workers tend to be slow and expensive, so craft production does not scale – as illustrated by projects like Gaudi’s Sagrada Familia, which has been in construction, at great cost, for many decades. Non-repetitive construction at large scale requires digitally controlled fabrication, positioning, and placement machinery that combines versatility approaching that of craft workers with efficiency approaching that of mass-production techniques.

Frank Gehry’s projects for the Bilbao Guggenheim, the Disney Concert Hall in Los Angeles, and the Stata Center at MIT, vividly demonstrate this new possibility of scaling up variety. Both the shapes of the material components and their spatial relationships are non-uniform. Efficient construction required both numerically controlled fabrication and use of advanced electronic surveying and positioning techniques to assemble fabricated elements on site. Added design content is very high, since each space, element, and detail had to be considered individually. This gave the architect enormous scope to respond to the demands of complex programs.
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and surrounding urban conditions, and provided a great deal of expressive freedom. The result is correspondingly complex form, at large scale, achieved through clever exploitation of the possibilities of non-repetitive but efficient construction.

It does not follow that buildings with very high design content, produced under conditions that allow varied construction at large scale, will always be spectacularly irregular in their forms. It is logically possible for many carefully considered design decisions to add up to an elegantly minimal, tightly disciplined response. But this is now a deliberate design choice, not a side effect of industrial-era construction technology and inherited design content.

Figure 4 The Stata Center at MIT, designed by Frank Gehry. The architect made many explicit choices in response to the demands of a very complex program and urban context, so the form has a corresponding level of complexity. Form follows function in a new sense.

New technological capabilities are not always wisely used. Our new capacity for digitally enabled variety and construction of strange and irregular shapes has sometimes been deployed merely for its sensational effect. But thoughtful architects are beginning to see beyond the short-lived seduction of the surprising, and to find new ways of responding – without the compromise of Procrustean simplification – to the demands of the complex conditions they engage. As they do so, an authentic architecture of the digital era is emerging.