# ALGORITHMIC MODELING; PARAMETRIC THINKING: COMPUTATIONAL SOLUTIONS TO DESIGN PROBLEMS

*Conceptual Explorations and Practical Applications*

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**Abstract.** Architects and designers have often used computational design techniques in their design process, even without "computers", from designing spaces which activate at the instant of the solstice sunrise, to creating geometrically complex and structurally innovative cathedrals. Designing with rules and variables can lead to solutions which satisfy the design criteria and may result in interesting and unanticipated models. Computational design is a process of designing and a way of thinking; contemporary tools can promote and enhance this process.

## 1. Introduction

Architects and designers use many techniques and tools in creating, analysing, and documenting a design. Contemporary practices are using sophisticated computational tools, this use driven by many factors, including: competitive and economic requirements to work faster and with fewer resources; new construction and fabrication processes; collaborative opportunities among people in various disciplines involved in a project (for example: those specializing in developing forms and those who study structural and environmental considerations); requirements to create deliverables in electronic extremely specific formats; skills of young professionals eager to implement techniques and tools used in academic environments.

Although tools are allowing and mainstreaming techniques and processes which may have been tedious previously, and fabrication and construction processes allowing designs to be built which may have been impossible or prohibitively expensive or time-consuming previously, some of these concepts and design paradigms have existed for many years, even before computers, and have recently become more recognized and tools facilitating these ways of working becoming popular. Additionally, these tools and techniques allow great flexibility and freedom in developing work, and even inspiring work processes and forms.

I often use as an example of algorithmic design the work of Antonio Gaudi, whose methods of exploring design possibilities and geometric rigor in these explorations allowed unique and innovative forms which satisfied his diverse (playful, geometrically innovative) and very real (and structurally innovative) criteria.

Another example, my own firm, Skidmore, Owings & Merrill, was an early innovator in developing and using computational tools for architectural design. A large interdisciplinary firm whose work consists typically of large and complex projects, SOM began developing tools in-house as early as the 1970s to facilitate a more efficient design process (which includes design, analysis, and documentation). Our process is an extremely collaborative one, and we have been fortunate enough to have so many project participants – architects and various types of engineers – under one roof. Our integrated tools were developed primarily by architects and engineers, some of whom were recent graduates from academic programs which were beginning to experiment with the new field of computer graphics [1].

In the work presented here, I have combined my interests in geometry and in a process of design which uses a rigorous and consistent exploration method which can be employed in an extremely diverse range of situations with a variety of software tools (off-the-shelf, and some simple customized applications [2] and a work environment in which this way of working is helpful to our work and encouraged by the people and teams I work with.

## 1.1. SOME DEFINITIONS

I tend to use the terms "algorithmic" and "parametric" interchangeably, and following these terms by one of: "modeling", "design", or "thinking". Although there is a distinction between these, their use is often inter-related and overlapping. Another term, which in my mind is related as well, and which has become an important buzzword in architecture, is "building information modeling".

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[1] Programs such as Cornell's, under the direction of Don Greenberg, were leaders in the field of computer graphics, and attracted many architects to this specialty within the field of architecture.

[2] I wouldn't consider myself a "programmer", but I'm able to create my own tools (in a (small) variety of software and languages) when I need to.

*Parametric modeling* might best be characterized by creating a model which can be controlled or “driven” by variables or parameters. In building a parametric model, in addition to describing these parameters, one also describes relationships between components of the model; manipulating a parameter (which can also be referred to as “flexing” the model or component) will have an effect on the entire model, not just the one part to which the parameter is connected.

*Algorithmic modeling* allows us to create a model based on a set of rules. These rules may describe a process, which when used once or multiple times will always create the identical result, or may include some variable parameters (such as environmental conditions) (and even some randomness) which can create condition-specific and visually and performatively diverse models. The rules can be iterative and recursive, and may cause an “emergent” model to result. Sometimes this technique can create models which are unanticipated and surprising.

“Building a model” (as in “parametric modeling” and “algorithmic modeling”) is an important and somewhat defined activity in the design process. Using computers and software to build a model results in a virtual abstraction of a design idea. This abstraction can be visualized to give feedback to the modeler about the model, and also to communicate the design idea to others who are not so directly involved in the model-building process.

“Designing” (as in “parametric design” and “algorithmic design”) implies a process beyond just building the model, but perhaps also collecting feedback and using that feedback to further develop the design (and the model). Feedback may be in the form of analysis results. A loop in which feedback results are used to modify the model, and perhaps create a better-performing model, can be a way of “optimizing” a design.

“Parametric thinking” and “algorithmic thinking” place the processes which one typically associates with computers and software in one’s mind. This isn’t to say that one does all the modeling and algorithmic or parametric computation in one’s head without a computer, but that this process has become one’s way of designing. If I’m thinking algorithmically, I’m not necessarily thinking of a form which will meet my design criteria (and I might use clay, or a software application which allows me to manipulate virtual form as I would clay), but instead thinking of the rules which will meet my design criteria, and accepting the possibility that a form might result which was not pre-conceived, or a set of forms might result from which I can choose or subject to additional criteria.

These processes (<parametric/algorithmic> <modeling/design/thinking>) can be used, in addition to creating forms and designs, to analyze and visualize/document an already-existing model. An example of this might be a view study or a sun study. (While this analysis or visualization can provide valuable feedback and documentation, it can also be fed back into the model, as an optimization technique.)

"Building information modeling" is a recent term [3] used to describe a process in which a model of an architectural project is able to provide to a variety of people who access that model the information they need from it. The model is developed and used from the design phase of the building (where the people who interact with the model (adding, extracting, and changing information) might be architects and engineers), through the construction phase (where the people who interact with the model might be contractors and fabricators), and throughout the life of the building (owners, maintainers, and occupants). For this to be successful, there needs to be agreement on the format(s) of a model which so many participants will interact with, as well as responsibility for that information.

My introduction to parametric and algorithmic design stems from an intense interest in geometry, studying with an inspiring professor in college (Haresh Lalvani) whose interest and teaching in geometric forms and relationships among them, which coincided with architects at the school just beginning to explore using computers, and finally to working in a professional environment where these ideas and skills can be implemented on projects.

Just as I believe that algorithmic and parametric "thinking" is an important part of using this technique – that one must understand this process and not just "let the computer do what it does" – I also think that architects need a fairly intense and intuitive sense of geometry, to be fluent in the language of form. To use a parametric controller to manipulate a form, one should understand the ways in which that form (whether it's a complex three-dimensional doubly-curved surface or a simple two-dimensional polygon) is able to be manipulated.

## 2. Developing software for architects

Skidmore, Owings & Merrill is an interdisciplinary design firm, well known for designing very large and complex projects. Founded in 1936, SOM is internationally recognized as a leader in the design of skyscrapers and other building types, and for the development of technological innovations in structural design, building systems, curtainwalls, as well as design software, all of which are integral to the buildings we design. In the 1970s and 1980s SOM developed their own software tools specifically to meet the needs of

[3] Although the term is recent, computer aided design applications have implemented concepts of BIM for many years, including SOM in their own software.

their practice: able to model (design, analyse, document) large and complex projects (like skyscrapers, hospitals, airports, …) and to enable large interdisciplinary teams to collaborate on these projects, sharing the same set of data. This software was a collection of several modules, (the modelling module was called "DRAFT" (an unfortunate name, I think, because it was much more than a drafting tool, but a full three-dimensional modelling environment), with some interesting features even lacking in today's more sophisticated software; other modules were for rendering, printing, and various types of engineering modelling and analysis), it was eventually further developed in collaboration with IBM to become a commercially available tool for the building industry called "AES" (Architecture and Engineering Series).

The hardware we had in the office in the mid-1980s, when I joined the firm, seems ancient today. We were using "mini-computers" – not as powerful as mainframes, but similar conceptually in that they were large computers in their own specially conditioned rooms, to which many terminals and devices (like plotters) were connected. Each computer could only support a limited number of "users" – when this number was exceeded, everyone suffered a decrease in performance until a new computer was acquired. Plotting slowed down the entire system, so plots were done overnight.

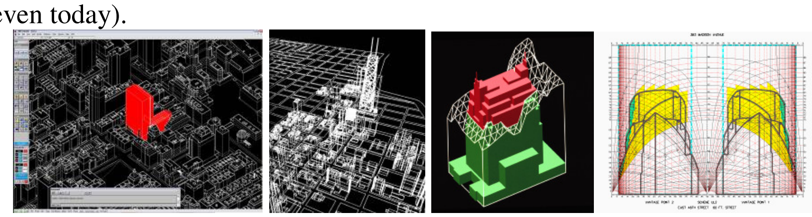

*Figures 1,2.* "Computer Room", mid 1980's, show Digital Equipment Corp's VAX mini-computer, including CPU, disk drives, backup tapes, printer, and console; Tektronix 4014 terminal "green screen" (with thumbwheels just to the right of the keyboard).

Our early graphic terminals were nick-named "green-screens". They were analog screens, and worked liked an oscilloscope – a single beam excited a layer of phosphor on the viewing surface of the "tube". The excited phosphor was a bright green. Instead of using a mouse, the cursor was controlled by two thumbwheels near the keyboard – one thumbwheel moved the cursor left and right, and the other up and down. These became as fast and intuitive to use as we use a mouse today.

In 1980, even as development of our software continued, SOM published a booklet called "Computer Capability". It was a brochure highlighting some of the features of Draft and how it was being used at the office. Intended as a marketing tool, it addressed how our projects were benefiting from using these tools that we had developed – how we were able to create better designs, and analyze and document them more thoroughly and efficiently than could be done without such tools. One quote from this publication reads: “Information from a single data base is used to draw a variety of graphic illustrations.” The same data was used for far more than to draw a variety of graphic illustrations – the same data was used also to perform many analyses, including structural analysis, environmental (particularly shadows) analysis, schedules (doors, furniture, equipment, …), etc.

With our collaboration with IBM, AES became available on workstations that could be at someone’s desk instead of in a computer room. At first these were very powerful (and expensive) UNIX workstations, but eventually AES became available on standard PCs.

One aspect that made Draft so successful was the following: at the time it was developed and used, sharing of electronic information was an issue only internally; SOM had just about all the disciplines required to design and engineer the projects that we work on in-house. Anyone outside of the office we needed to share our information with (consultants, clients) could not use the electronic information (because they were not using computers), so they required paper documents, which we were easily able to provide, either as backgrounds or as final documents. When other entities began requiring from us electronic data in a different format than it was created, we began dealing with issues that were frustrating and had little to do with our design process. We did build translators into our software, but they are never perfect, and rarely even acceptable (and that has not improved much, even today).



*Figures 3-6.* 3: a screen-shot of AES Model running on a PC in Windows, the image is of Memorial Sloan Kettering Research Center as a massing model set in context in Manhattan; 4: still from an animation (entitled "Nine Cities") of fly-throughs of the nine cities in which SOM had offices, about 1980, the image is from the fly-through of Chicago; 5: an analysis for a project in Boston, where, at the time of the study, they were anticipating passing a law preventing new buildings from casting any additional shadow onto the Boston Commons, the image shows an in-progress design clipped with the "no-shadow envelope" which we computed for the site, taking into account geographic and map data and existing surrounding buildings, the volume colored green within the no-shadow envelope but the volume colored red casting a shadow for at least an instant over the analysis period (the building was re-designed to fit within the envelope); 6: a "waldram" zoning analysis for a building in mid-town Manhattan (this type of analysis is one of two methods that the New York City zoning code allows for measuring massing compliance).

## 3. Project examples

I have been involved in literally hundreds of projects in the office. My involvement on projects has been a result of various circumstances, from being asked by a project team member for help with a small aspect on the project or even to write a small program to automate some tedious task – sometimes this takes less than a day – to becoming a member of the project team, where I participate in many facets of the project, and can identify and define aspects of the project which can be addressed computationally, and be free to devote more time exploring these aspects. There's a trade-off between these ways of working: when I'm asked to write a program to make a task easier (usually by someone who is frustrated with their task and realizes there must be a better way), although I never mind doing that and usually enjoy it and also try to generalize the program so it can later be used by other teams and people, I always wonder what tasks the team is not asking me to help with, which might allow them to explore more design options more quickly or address some issue on the project which they might not even have considered; when I'm a dedicated team member on a project, I can identify aspects of the project which would benefit from algorithmic and parametric design techniques – aspects which most team members would overlook, although in addition to that, I'm often doing things which are unrelated to my expertise (like all team members, doing everything we need to do to get the project done). In either case, I often talk with project team members throughout the office about what they happen to be working on, and try to suggest computational techniques.

When I began working at SOM, in the New York office in the mid-1980s, there were between ten and twenty workstations in the office. These were not located in one area, but distributed throughout the office. They were being used by project team members who were interested in learning and using these tools on their projects. I was a member of the "computer department", and my responsibilities included helping teams use "Draft" and later "AES" on their projects (and even then, sometimes spending a very short time helping with specific tasks and sometimes being a member of a project team) and also teaching people how to use these applications (we had a two-week training session). Our "computer department" was made up of people who managed the hardware and the network, people who wrote programs (most of the programmers who were developing the core applications, Draft and AES, were in our Chicago office, but there were people in all offices who were writing applications and tools to address needs of the New York office and specific projects), and people like me who helped people and teams become comfortable with this new technology. While the people who were using computers on their project teams were not part of an official group or department, they created an informal community and often discussed how they were using the tools and some of the frustrations they were facing.

Now everyone has a computer at their desk. Just about everyone is quite comfortable with our standard tools (including tools designed to facilitate "building information modeling"), and some are willing to explore more sophisticated tools (which facilitate parametric and algorithmic modeling). We now also have an informal community within the office of people who are exploring these new tools in much the same way as we did decades ago. In our Chicago office, we have also created a group called the "BlackBox group", which focuses on research in advanced computational tools and new ways of working which can be facilitated by these tools.

Each of the projects described here could be an entire paper, and the list of projects that have included aspects which relate to this topic would fill many pages. To give an indication of the variety of applications of these design methodologies, I will briefly describe six projects – three of which will include a brief description of the algorithmic process used.

In addition to project work, I often explore new ideas using more theoretical applications, though many of these have found their way into projects as well. These independent research explorations often include studies in geometry and tiles, and have been inspired by: nature, music, the sidewalks of Prague, and either directly or indirectly the work of so many people, including Haresh Lalvani, Ron Resch, Bridget Riley, Antonio Gaudi, Erwin Hauer, M.C. Escher, Buckminster Fuller, Ernst Haeckel, …

### 3.1. REFLECTION STUDY

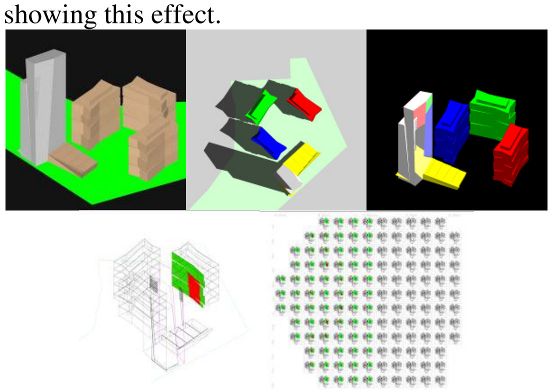
For this design of several residential buildings and a hotel building, we were asked to study reflections of sunlight from the reflective hotel facades and their effect on the residential buildings. We initially assumed we could use rendering tools to model and document this effect, but although (at the time) the tools could reflect objects, we were not able to model the reflected light.

#### *3.1.1. description of the algorithmic process*

An initial idea to study this was to use the capabilities of our tools (able to reflect objects), and, for various instances, place our eye-point at the location of the sun for each instant, look towards the hotel building, and determine which residential buildings were visible as a reflection. If a residential building was visible as a reflected object in the hotel facade, then that part of the residential building would get reflected sunlight at that instant. We color-coded the three residential buildings to help us identify the effect, as shown in the diagrams.

Although this method demonstrated the effect of the reflected sunlight, our team thought it would be too confusing to understand.

We ultimately created a method to show the effect in a clear way, by creating an analysis algorithm. First we divided the residential building facades into a set of panels. We would determine, for a series of instances, whether the centerpoint of each panel would be hit (or "lit") by reflected sunlight. At a particular instant we compute the direction vector to the sun. We then compute the direction of a vector representing the reflected ray through the facade of the hotel. From each panel centerpoint, we place a vector parallel to the reflection-direction-vector, and determine if that vector intersects the hotel facade for which that vector was computed. If yes, then that point would get hit, and we color that panel red. If no, the reflection-direction-vector did not intersect the hotel facade, then that point would not get hit, and we color that panel green. So looping through each panel, and also through many instances, we generate a very simple easy-to-understand set of images showing this effect.



*Figures 7-11.* 7: a model of the project, showing the three residential buildings in beige ad the hotel building in gray; 8: a plan view, with buildings color-coded; 9: in this "view from the sun" we can see in the hotel building reflections of the residential buildings -- those buildings will get reflected sunlight at this instant (it's difficult, however, to identify exactly which parts or how much of the residential buildings will be affected); 10: an analysis using a custom "ray-tracing" algorithm -- panels colored red on the residential building analyzed will get reflected light from the hotel at this instant, panels colored green will not; 11: a grid of analysis results for many instances.

## 3.2. SKYLIGHT DESIGN

Another project also involved an interesting solar analysis, but in a very different way. For Deerfield Academy, in Deerfield, Connecticut, USA, we designed a school building, the "Science Math Technology" Building, officially named the Koch Center. For several school projects, we collaborated with artists, and for this project (and others) we collaborated with James Turrell, an artist particularly known for his work with light and space.

One aspect of the project is called the "analemma skylight". An analemma is a term in astronomy for a particular curve created by tracking one astronomical body from another. For example, from a location on the earth, if every day at precisely the same time (say, noon) we record the position of the sun in the sky from our point-of-view, and create a curve by connecting those positions, we will create an analemma, which will be in the shape of a figure-eight. For different locations on earth, and for tracking different objects and from different objects we will get different analemmas (which may not necessarily be in the shape of a figure-eight). Similarly, if we create a sundial (which can either use direct sunlight or shadow (of course they are related) to indicate the time), and record the position of the indicator, we will see the same analemma.

For the Deerfield project, we designed a skylight which will allow a shaft of light into the space below through a six inch (15.25 cm) hole in the ceiling. There is an interior brick wall in the space below - the hole is located so that the circle of light will be projected onto that wall. Every day at noon, if we record the position of the center of that circle, at the end of a year, we will have drawn an analemma on the wall [4]. (We can also record the position at any time (as long as we are consistent from day to day) and create different analemmas -- a 10:00am analemma, an 1:00pm analemma, a 3:15pm analemma, etc. (always “standard time”, not “daylight saving time”)).

Our original intention was that the spot of light would be visible in the space (on the wall) at sunrise or shortly after, and until sunset or almost sunset. From morning until evening it would move across the wall. During the summer when the sun is high in the sky, the spot will appear low on the wall. During the winter when the sun is low in the sky, the spot will appear high on the wall. If we have an analemma etched onto the wall, each day at noon, the spot will cross the analemma.

*3.2.1. description of the algorithmic process*

The roof structure in which the skylight is placed is fairly substantial. The distance between the plane of the ceiling and the plane of the roof is a bit over three feet, or just under a meter. If the opening in the ceiling surface is a six-inch hole (15cm), in order for the spot to be projected into the space below, the opening in the roof surface needs to be much larger. If the hole

[4] This was intended to be an activity in which the students can participate – they would in fact physically record the position of the spot of light on the wall at noon every day for a year, after which the path – the analemma – would be permanently recorded.

in the ceiling was the bottom of a perfect vertical cylinder, the spot would enter the space only when the sun was directly overhead (this never happens in Deerfield, Connecticut), and the spot would be cast for an instant (perhaps a "long" instant, because the hole has some size) onto the floor directly below. If the opening on the roof surface is larger, then the spot will be projected even with the sun is not directly overhead. For the spot to be projected from sunrise to sunset each day of the year, the opening on roof surface would be enormous. So we decided to limit the time that the spot would be visible. Taking into consideration both a reasonable time period each day for the sunspot projection to track across the wall and a reasonable size of opening on the roof surface, we concluded that we should allow direct sunlight to enter the space for the precise two-hour period each day from 11:00am until 1:00pm (always standard time).

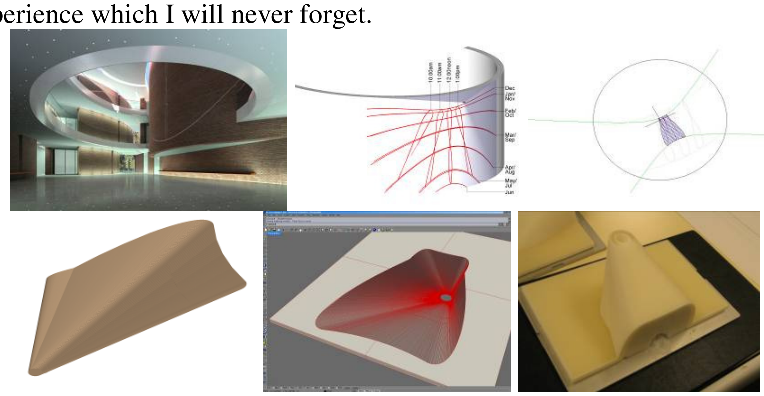
We then modeled the shape of the skylight that would cause this effect. The shape would be different for different locations on earth (or on other planets, or for other light-giving stars), and would be different for different time or date criteria. To create the shape, we computed the analemmas for 11:00am and 1:00pm, and also the path of the sun on the solstice dates, 21 December and 21 June; these were used to determine the boundary edges of the roof-surface opening. [5]

The skylight is about three feet (about one meter) wide, and almost ten feet (over three meters) long. In designing the shape of the skylight ("designing" by identifying the criteria -- we didn't say "this is the shape we want") we did want to see and feel this form, and even test a prototype before the large skylight was fabricated. At about the same time we were working on these studies, our office just got a rapid-prototyping machine, which "prints" physical three-dimensional models from virtual computer models. This was a perfect first-test of this machine. We printed a scale model, and brought it to the site (the test must be done there, since the form is site-specific).

In addition to James Turrell, another person critical to the process of creating this skylight was Dick Walker. Because so many of his projects

[5] The “focal point” in this analysis (as if we were building a pinhole camera or camera obscura) is the center of the hole in the ceiling. We could have located the focal point on the roof surface, and then have a large opening on the ceiling surface (although the skylight shape would have been similar – just inverted) – we thought the effect on the viewers in the space would be greatest if a small hole was the only visible part of the skylight. The focal point, in fact, could have been located at some point between the ceiling and roof surfaces – this could have been a parameter in our model (we did have a version of our model in which this was the case). This parameter might vary from 0 to 1 as the focal point moves from one surface to the other, and can even go beyond these extremes.

deal with light and often relate to astronomy, Mr. Turrell consults with an astronomer, and for many years that was Mr. Walker. Dick Walker worked closely with me during the process of computing the skylight, helping me (and our team) to understand analemmas and other astronomical phenomena that would be used in our design. I've worked with many "consultants", but to work with an astronomer (and Dick Walker in particular) was a great experience which I will never forget.



*Figures 12-17.* 12: a rendering of the space, the inscribed analemma can be seen in the curved brick wall, the six-inch hole of the skylight in the ceiling of the three-story space is blocked in this view by the curved ceiling edge of the first level; 13: paths of the sun on the 21st day of each month (horizontal curves) and analemmas for 10am, 11am, 12noon, and 1pm, all projected onto a model of the curved wall; 14: an image showing how the edge of the top surface of the skylight was computed; 15: a computer model of the skylight, seen from below; 16: a computer model of the skylight, seen from above; 17: half of the skylight as a 3d-printed prototype.

## 3.3. FRIT PATTERNS

Memorial Sloan Kettering Research Center is a laboratory building in east midtown Manhattan. This building (and many others) want to have as much glass as possible, maximizing views out and daylight into the interior spaces. There's an environmental trade-off for this, in solar heat gain - sun streaming into a space tends to significantly increase the temperature and require additional air conditioning to offset this effect. Glare is another undesirable affect.

One way to alleviate the effect of solar heat gain (and glare) is to make some of the glass partially opaque, but without compromising views or daylight. Frit patterns on the glass are one way to accomplish this.

Frit patterns are typically white ceramic circular dots applied to the glass using a silk-screening process. We can vary the density of the dot pattern, and control the opaque/transparent percentage. Two aspects can vary to control the density: the size of the dots, and the spacing. [6,7]

In this project, the pattern of dots to create the frit patterns on the glass is very much an integral part of the architectural design of the building. On each glass panel, the frit density varies vertically in one of two ways: a. the pattern on the glass is most transparent near the center of the pane, at the vision area of the glass allowing clear views out, and gradually becoming more dense and opaque at the top and bottom of the pane; and b. the pattern is most opaque near the center of the pane, and becoming less dense and more transparent at the top and bottom.

The interior spaces of this project are organized in such a way that there are alternating bays, perpendicular to the exterior wall: an aisle bay where people walk and sit at their lab stations, and an equipment bay. The aisle bays end in panel type "a", where the vision area is most transparent, and the equipment bays end in panel type "b". These alternating panels on the exterior of the building create an interesting effect of "weaving".

We experimented with many variations and subtle changes in the density patterns, using several factors to evaluate them: the effect of the frit on the performance of the glass (we had an opaque percentage that the patterns were designed to comply with), the architectural and visual effect on both the exterior of the building and the interior spaces, and people's reactions to and comfort with these patterns (we were concerned that the varying patterns might make people uncomfortable ... we printed full-size mock-ups of several variations and hung them in front of windows in our office, and found they had no negative effects).

*3.3.1. description of the algorithmic process*

There are two aspects which affect the density of the pattern, as previously mentioned: dot size and dot spacing. Typically these dots are located on a square grid, and the dots can change in size smoothly as we move in one

[6] Another aspect we explored on other projects where frit was used was to place the dots on more than one surface of the glass. The effect (how much direct sunlight is blocked) would vary depending on the orientation of the glass, the direction of the sun (affected by the location of the project, and date/time), and the distance between the surfaces. In many glass applications where one or two air spaces separate two or three panes of glass, there can be four or six surfaces on which it is possible to apply frit.

[7] Frit patterns are not limited to dots, though these may be the most common implementation. Frit patterns may be lines, and a huge variety of other patterns. If ceramic frit is used (which uses a silk-screening process to apply the dots to the glass), there are some fabrication limitations. If laminated glass is used, it might be possible to “print” a pattern on the laminating layer, which would significantly increase the range of possible patterns.

direction through the grid (or in two directions), creating the varying density. (There are limits to the size of the dots, due to limits in the fabrication process: the dots cannot be too small (about 1/16 inch or 1.5mm), and the space between dots cannot be too small (also about 1/16 inch or 1.5mm); different fabricators probably have different limits (or might be more or less willing to experiment exceeding these limits) and processes might improve which ease limitations.) Ignoring these limitations, theoretically the dots can have a radius of 0 at one extreme, and touching each other at the other extreme. In our case, the dots are always present throughout the pane (so they never reach 0), and never quite touch each other.

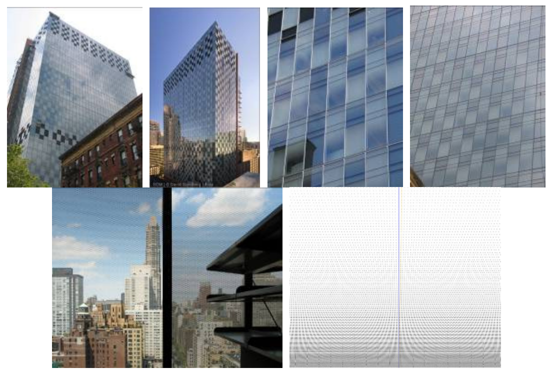
In our two panel types, we have varied both size and spacing to affect the density. This not only creates the large effect we planned on the exterior of the building, but also a very interesting pattern when a viewer is very close to the glass. Initially we were using mathematical formulas to set the size and spacing (for example, variations on an equation which included a sine or cosine function). To give ourselves even more control of the effect, we ultimately used a curve to set these, as follows:
we drew a vertical centerline through the panel; then we drew a curve (line, arc, spline, ...) to determine the dot size (as the program drew the dots horizontal row-by-row on the panel, it used the distance from the vertical line to the "size curve" as the size of the dots in that row - if the curve was closer to the vertical line at that point, the dots were smaller, if the curve was further from the vertical line at that point, the dots were larger); and another curve to determine the dot spacing (at the current row location, the distance between the "distance curve" to the vertical line determined the spacing between dots in that row, and also the distance to the next row).

Other designers on the project were able to manipulate these curves, and experiment with different variations. For each iteration, we could also compute the area of the dots to indicate the opacity percentage (making sure we met that requirement).

### 3.4. PERFORATIONS

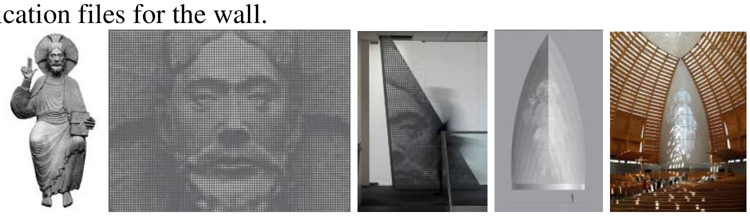
Dots, as described in the previous case study, can be used as frit patterns on glass. Dots can also be used as perforations in an opaque material, allowing light to come through the dots instead of the other way around. Patterns of dots for frit or perforations or other uses can be derived in several ways -- through some mathematical process, through a graphical process, as a result of processing an image, using a collection of data (for example, representing sunlight intensity over an area), etc.

The Cathedral of Christ the Light in Oakland, California, USA, completed in 2008, includes a sculptural element, integral to the architecture. The "Omega Wall" is made up of over 150 triangular metal panels, many of which have perforations of different sizes, which create an image of Jesus. The image is created by the light which penetrates the perforations.



*Figures 18-23.* 18-19: photographs of the tower, showing the visual effect of the fritted glass; 20-21: close-up views of this effect; 22: an interior view, showing the glass panel at the aisle bay on the left and the glass panel at the equipment bay on the right; 23: an example of the frit pattern, showing the vertical centerline and the change in both size and spacing of the frit dots..

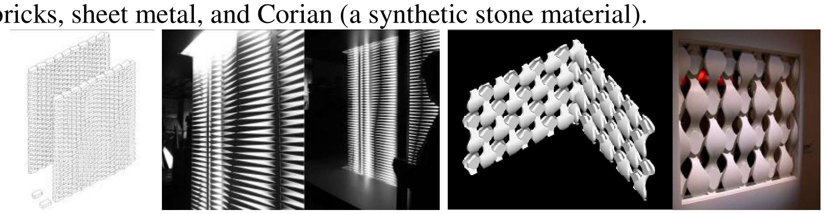
Cathedrals have always used images to inspire worshipers and to communicate biblical events, typically with stained-glass windows. In this case we used a very contemporary and innovative method to do this. Working very closely with our graphics designers in our San Francisco office (the project was done by our San Francisco office, and the graphics department was responsible for this particular part of the design (among others); I was then in the New York office), we took an image provided by the bishop of the cathedral and created the design, documentation, and fabrication files for the wall.



*Figures 24-28.* 24: the original image used for the wall; 25: a portion of the image, rendered with circular perforations of varying size; 26: a mock-up of a single panel (as an indication of its size, note that one of the ceiling panels needed to be removed in order to display it); 27: a model of the wall with the perforated image; 28: a photograph of the wall in the cathedral after completion.

### 3.5. SEMI-TRANSPARENT WALL

We designed a spa for a hotel complex in Kuwait. For the spa, we needed to create a set of interior walls which were generally opaque but had a small amount of transparency. We explored a range of materials and forms related to each particular material. The three materials we explored in detail were: bricks, sheet metal, and Corian (a synthetic stone material).

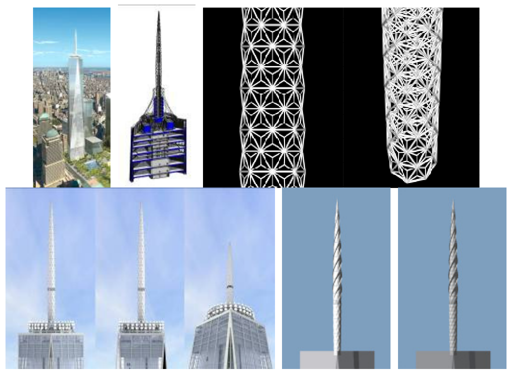


*Figures 29-33.* 29: a brick wall, with bricks rotated (using an algorithmic process) to create openings in the wall; 30-31: metal-panel wall, fabricated by Milgo-Bufkin; 32: model of "weaving wall" showing a corner condition; 33: Corian mock-up of "weaving wall" (displayed at SIGGRAPH 2008, photograph by Lira Nikolovska).

### 3.6. SPIRE

Tower One at the World Trade Center in New York, currently under construction, is a 1,368 foot (417 meter) tower, with a spire containing broadcasting equipment reaching a height of 1,776 feet (541 meter) (1368 is the height of the taller of the twin towers previously on the site, 1776 is the height identified in the master plan of the project, and representing the year of independence of the United States). Because the spire contains broadcasting equipment, it has size and structural requirements.

Our initial designs envisioned the spire as a lattice structure, and the equipment would have their own protective casing. Ultimately the spire became an enclosed structure, with the same shape and geometry of the previous version. The shape is defined by the height of the spire, required width to house equipment and allow for maintenance and servicing, and an architectural and iconic form clearly visible and growing from the architecture of the tower itself.



*Figures 34-42.* 34: rendering of World Trade Center Tower One; 35: sectional view of top of building including spire; 36-37: model of one (of many) version of a lattice enclosure for the spire; 38-40: three views of the spire as a fully-enclosed structure; 41-42: renderings of the spire with "helical strakes" for additional wind resistance (showing variation in light and shadow at different times of the day).

## Acknowledgements

Because of the nature of our practice, an interdisciplinary and team-based environment, working on large and complex projects, a single person cannot be responsible for a design, and often even aspects of a design are the result of a very collaborative effort. So I must acknowledge, for all the projects described here, and indeed for every project I work on at the office, my teams, from design partners to interns. As described in the text, the team often extends beyond our firm to include consultants and fabricators. Special mention and grateful acknowledgement to two people in particular for their vision regarding research in an architectural practice such as ours: **William Baker**, structural engineering partner; **Ross Wimer**, design partner. *Research* may differ slightly in our context from that of an academic institution or even a small practice, but is critical in maintaining innovation in the technology that goes into our designs, and our process of design.

I owe much gratitude as well to a couple of people who have had an immense impact on my education (and thinking process) and career:

**Haresh Lalvani**, my professor and mentor;

**Ron Resch**, who became a great friend several years ago, and has been a great inspiration through his work and our conversations; Ron passed away in November 2009, but continues to inspire me, and the many people who knew him or are familiar with his work.