A Natatorium for M.I.T. a spatial experience defined by a roof structure, light and movement

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B.A. Drama
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May, 1986

February 1998

Submitted to the Department of Architecture
in Partial Fulfillment of the Requirements for
the degree of Master of Architecture
at the Massachusetts Institute of Technology

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This thesis articulates the design of a Natatorium through both the use of computational methods of visualization and through traditional methods of representing architectural space and form. Computer visualization is used as a primary exploratory method for understanding the relationships of light, movement and the structure of a roof, to defining a spatial experience. The design for the facility serves as an exploration of spatial experience analogous to nature; and it intends to evoke the visual sensation of being underwater on a bright sunny day. Within the context of a Natatorium, this thesis explores the relationships of: branched construction to light and shadow; water to an undulating roof form; and swimming and diving to movement. The site selected for this project is based upon a facility currently being planned for the MIT campus.

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Submitted to the Department of Architecture on January 16, 1998 in partial fulfillment of the requirements for the degree Master of Architecture at the Massachusetts Institute of Technology.
I would like to thank many people for their help and support during my time at MIT and throughout the course of my thesis:

My parents, Helen and Joseph, who have supported me throughout my education. Bill Mitchell for providing me with an atmosphere of freedom to explore and find a vision for this project. Chris Luebkeman for his inspiration, thoughtful direction and understanding. Jose Duarte and Megan Yakeley for their skilled assistance with computer related issues and algorithmic coding. Tom Fitzgerald and Doritt Schuchter for their help with computer related issues. Adrian Smith for his willingness to help edit text. Dale Clifford, Lisa Makuku, Scott Merchel, Daniel Hernandez and Leonardo Rastelli for lending a helping hand when it was most needed.
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Water Polo, Swimming and Diving.
The primary goal of this project was to establish the roof of the Natatorium to define the experience of light and movement. This proved to be an engaging exploration that continued throughout the design process. In order to realize the vision for the Natatorium, a variety of advanced computational visualization methods and tools were employed to represent and communicate the design. The foundation of the thesis stemmed from the use of an algorithm written especially to generate tree-like structures, to various studies of "movable" roof structures. The overall vision and inspiration was driven by the author's experiences in the water as a competitive swimmer.

The purpose of this facility is to increase M.I.T's competitive ability to attract national and international swimming events, as well as to provide a recreational and sports facility accessible to the community at large. The program provides for a fully equipped, state of the art swimming and diving facility. It is described in further detail in the section entitled: Natatorium.
**Site**
The site is situated in the west portion of the MIT campus. Massachusetts Avenue, splits the campus as it runs north and south, perpendicular to the Charles River. Massachusetts Avenue divides the campus from west to east, which in turn defines the western half as the location for most Athletic facilities. The proposed building site is tightly nestled amongst the neighboring buildings. The buildings of the West Campus are all distinct structures. This stands in clear contrast to the inter-connected buildings of East Campus. Each West Campus building maintains its own identity, while varying in scale and form: from the monolithic brick blocks of the Johnson Athletic Center, to the elegant eighth of a sphere, known as Kresge Auditorium. The design challenge of introducing this new structure to an "Institute of Technology", is to orient it to the sun, organize the program in terms of use and function, and create a design which fulfills the vision described earlier.

Site location within MIT's campus.

Site context: Natatorium within surroundings.
Site analysis

Several studies of the effects of shadows on the site generated results that influenced important aspects of the project's design. Through computer modeling, simulated shadows were cast onto the site during the key periods of use; water polo and swimming season. This study helped develop options for maximizing the potential of an open roof system, a system which would provide direct sunlight between the overbearing presence of the adjacent buildings. The problem was that the length of the shadows cast by the Johnson Athletic Center increased as the season progressed. This resulted in a heavily shaded site in the month of January which is a problem for the use of the site at grade during Water polo championships. With the intentions of maximizing sun, the shadow study aided in determining the arrangement of the various pools within the Natatorium complex: they were situated on terraces high above grade. Depending on the programmatic function of each pool, a hierarchy of their position was determined relative to the shadow cast. This was to bring the sun in during the winter and perhaps utilize the shade during the summer.

Process

Site context shadow study: Shadows cast at 3:00pm during Water Polo practice.
Branched construction

Ideas surrounding branched construction date back to ancient times. The author's interest in the subject begins with Frei Otto's research at the Institute of Lightweight Structures in Stuttgart 1964. According to Otto, "branched constructions are 3-dimensional supporting systems... which are stabilized by a system of braces." He continues to define different types of branching systems; "The tree-like branched structure is a materialized path network with minimum detours. It needs a relatively small amount of material and its load-bearing capacity can be increased by thin braces." The algorithm written for this project to draw parametric "trees" directly relates to Frei Otto's research. The algorithm, written by the author, draws "tree forms" in AutoCAD from the scripting language Autolisp. The algorithm is used as a tool shaped by the architect. In this case to aid in an exploration of isolating a specific spatial

experience, that of being under a canopy of trees. "Trees" that filter unique amounts of light and shadow.

These "tree forms" generated by the algorithm also establish a structure that people can readily identify and even understand as a form of architecture. More specifically a structural form of architecture, a structural form analogous to nature. This provides a method for people to draw a connection to the spaces they are experiencing. The "tree" structures are conceived as self contained free standing structural systems of spatial experience. Branches cantilever from the tree trunk in a fashion that is similar to the structure of an actual tree. The tree structure must be cross-braced at the canopy, then joined together as a unit in order to fully maintain its structural integrity. Perhaps more importantly, this structural necessity allows for a dynamic spatial experience from the human perspective, underneath.

The method in which the algorithm was scripted established the precise angle for every branch on the structure, and related it to the ground plane. Isolating the angles clarified the spatial experience, and established
structural integrity.

The tree structure was organized into three levels excluding the trunk. First, the "tree trunk" was drawn perpendicular to the ground plane, an angle designated by the user positioned a set of branches on the first level of the tree. By an increment written into the code, the next level of branches were generated and drawn but this time the angle of the branches increased. This broader angle then positioned the next set of branches shaping the entire form of the tree structure into three levels. All of the "branches" were set to fall between 25 and 60 degrees, thus maintaining structural integrity and tracking of angles.

The virtual prototype model seen on this page, denotes the structure of the tree canopy braced with trusses and peaked in the center. This "tree" form defined the spatial experience of light and shadow shown in the image on page 11. The use of the algorithm has proven to establish many possible spatial experiences.
To better visualize the spatial experience created by this branching effect, the model was set to have light pass through a glazed glass-like material. The reflective material was implemented for the roof at the top of the canopy. The placement of this material, simulated under direct sunlight, resulted in the dramatic pattern of shadows seen in the image on this page. The shadows produced suggest the need to further articulate the structure of the roof. At this point in the design process the question remained how to enclose this system of trees and still satisfy the Shadow experience rendered in Lightscape.
authors desire to design the experience of shadows underwater.

Roof Form
As the author visualized the underwater experience, the necessity to develop an understanding of complex three dimensional curves, or double-curved surfaces became apparent. The idea would be to relate the surface of the curve to the surface of water to achieve the spatial effect of being underwater. This form would also enhance the spatial experience of being under the tree forms.

The quality of an undulating form is challenging to grasp. The double-curved mesh pattern of vertices while complex, is essential to the location of sound structural connections. The position of each vertex needed to be understood in order to be realized in physical form. The images depict views of a skewed rectangular surface. Drawn by the use of the quadratic equation:

\[ y = -m^2x^2 + n^2x^4 + C. \]
The sine curve was manipulated to generate a mesh in Maple V (a numerical analysis and plotting application). By inserting different values to generate various forms, the results seemed to satisfy the aesthetic requirements for the project. However, this exploration raised many questions. How does the undulating surface enclose the existing spatial experience generated by the tree forms, without losing the drama of the shadows? Does the undulating surface enhance the volume of the Natatorium by expressing the form of water? In an attempt to answer these questions, research suggests that the Greeks symbolized water as being one of the five platonic polyhedra. "Water is represented by the icosahedra." Since the

1. Gabriel, Francois J., Beyond the Cube. Page 5

Tetrahedron in the form of an octatruccs traveling across an undulating surface.
tetrahedron is a polyhedra as well as one third the volume of a cube, it followed that the cubic volume of water required for the pools of Natatorium would relate to the volumes of tetrahedron. The images on the right are explorations with the tetrahedron in the form of an "octet truss."¹ The lateral stability for the undulating form was strengthened by the octet truss. This system could have included rotating joints connecting the octet truss, allowing enough freedom to completely open and close the entire roof top system thereby establishing an indoor outdoor Natatorium.

¹ Fuller, R Buckminster, Inventions the patented works of R. Buckminster Fuller. Page 42

Model depicts an octet truss as part of a movable enclosure system on an undulating surface.
Diving and Movement
The path of movement that a diver follows when diving from a 10 meter platform provided inspiration for the form of the roof. The framed animation of simulated diving on this page depicts the still motion and movement that a diver takes when completing a three second dive. This element of time is key to both swimming and diving. The same concept of time would now also be key to the design of the roof structure. Theoretically the notion of time cannot be independent of space.¹

¹Hawking, Stephen, A Brief History of Time. Pages 15-34.
Building Form
The design for the Natatorium began to take shape. The images on this page are some of the first schematic designs that give the building its form as well as an organization to its spatial volume and program.
The program for the Natatorium is designed to take spectators and athletes through a progression of spacial experiences associated with materials as well as light and shadow. Examples of this can be seen in the images on pages 25-30. The experiences are enhanced by the quality of materials specified for each rendered image. Concrete was specified for the floor surface of each level. Steel was specified for the tree structure and roof system. PVC film coated polycarbonate was specified for the roof enclosure. White laminated glass and glass block were specified for the lockers. See the diagram on page 18.

The depth of water plays a major role in the transmission of light. The deeper one swims the darker the water; less light is visible. In order to design this experience for the Natatorium, each level of the building is organized by material density. At level one, the most dense materials are used; concrete, steel, tile and glass block. Level two is enhanced by the use of; concrete, steel, and white laminated glass. Level three, the most open, is surrounded by steel framing, laminated and clear glass.
ASSEMBLY

- PVC Polycarbonate or glass enclosure
- Skewed steel mesh cross bracing
- Coated and shaped steel tubing
- Irregular shaped steel tubing
- Reinforced concrete foundation

MATERIALS

Early diagram of building assembly and materials that were used in the rendered images.
As one passes through the massive concrete surrounding the building, the experiences abound from direct views into the swimming pool to transitional zones of light and shadow.

The roof filters and reflects light through the polycarbonate as if it were the surface of water.
The transparent roof plan shows the final surface pattern for the roof.
Natatorium

Plan

GROUND LEVEL ONE

1-ENTRANCE
2-LOBBY
3-ADMINISTRATION
4-LOCKERS
5-COACHES
6-TRAINING WELL
7-TRAINING POOL
8-SCUBA ROOM
9-SERVICES
10-PUMP ROOM/FILTER
11-EXIT

LEVEL TWO

12-MAIN SWIMMING POOL
13-LIFEGUARD TOWER
14-LOCKERS
15-COACHES

north
LEVEL THREE
16-MAIN DIVING WELL
17-WATER POLO POOL
18-SPECTATOR SEATING
20-COACHES
19-LOCKERS

ALL LEVELS
21-SPECTATOR SEATING
Natatorium

Light

Shadow

Experience

AutoCAD model
"De obre che mai so treminate."

"Quato il lume sara maggiore del corpo obroso, tanto li termini dell'onbre di tal corpo sara piu confusi."

"Of shadows which never come to an end."

"The greater the difference between a light and the body lighted by it, the light being the larger, the more vague will be the outlines of the shadow of that object."

Leonardo Da Vinci

Wire frame version of Natatorium
Natatorium

Divers experience
Credits

All works (sketches, drawings, physical models, computer models, renderings algorithm in this document are original works undertaken by the author during the course of this thesis.

Computer Modeling:
AutoCAD-v13 by Autodesk

Computer Rendering:
Lightscape-v2.0 Unix version used as the rendering and visualization system for the project.

Hardware:
An SGI-Indy 5000 with 128 megabytes of ram was used for the 3d modeling and rendering.

Photographs:
Images used were from Sporting Images at; www.espc.com.au/sporting

Images of Animation:
were from Animation lab; www.cc.gatech.edu/gvu/animation
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Gruffyd Bodfan, Tree Form Size and Colour; a guide to selection, planting and design, London. Page 3: "Tree Character", "Form", "Growth Rate", "Growth rate affects strength". "Growth rate and strength are affected by siting". "If trees are planted too close together, growth is drawn up. (in competition for light)"

Page 11: "Tree Shape", broad spread, narrow spread, conical spired, columnar, ovoid, weeping."


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Otto, Frei, Bodo Rasch: Finding Form, Towards an Architecture of the Minimal. by Sasabine Schanz Germany, 1992

Page 158: "Branched constructions are three-dimensional supporting systems used increasingly in steel, wood and concrete building. They are ancient and are derived from early pole building. Their heyday came as a result of medieval given distance (height), the direct path system in the form of vertical supports suggests itself." Page 159: "When looking for a form for compression loaded ceiling and roof plates knowledge of the minimum path system that can be investigated using soap films between plane-parallel glass plates is advantageous." Page 160: "The fan structure as used in timber and steel building, can be addressed as a materialized direct path network. The "braced fan construction" is more effective in many cases as the buckling lengths of compression members are reduced." "Tree-like branched structure is a materialized path network with
minimum detours. It needs a relatively small amount of material and its load-bearing capacity can be increased by thin braces. "Plant support structures are also branched constructions. They can be compared with engineering branched constructions."

Otto, Free, IL-4, *Biology and Building*, preface by J-G Helmcke Information of the Institute for Lightweight Structures(IL); University Stuttgart, IL-4, printed in Germany, 1972 Page 6: "Here, we must not view analogy as slavish imitation, but rather as creative re-shaping toward "equivalents". It would be foolish to allow prejudice to reject perception and consideration of stimuli from nature - for in fact, living nature has produced a far greater variety of structures and forms than the human imagination."

Otto, Free, IL-5, *Convertible Roofs*, Information of the Institute for Lightweight Structures(IL); University Stuttgart, IL-5, printed in Germany, 19721. Page 13: "Convertible roofs are designed so that their form can be changed as often as desired and in a short period of time." "Mobility refers to variability of the location or situation of the building or building components. This means that whole buildings or building units can be moved without themselves changing their form. The location can be changed by simple assembly, disassembly and transport."

Otto, Frei, IL-6, *IL and Biology*, Information of the Institute for Lightweight Structures(IL); University Stuttgart, IL-6, printed in Germany, 1973 Page 5: "We are seeking the forms of lightweight structures, ie objects which can convey forces with minimum mass." "As with all material objects, every organic object is capable of conveying forces. In nearly every case the input of mass is minimal." "The observation of organic objects is also good training for Architects and Engineers in learning the infinite variety of forms and also those processes which produce forms while at the same time noting the process-like aspects of technology." "There are very few technical structures which have proven to be lightweight structures. We still lack the basic acumen to optimize form as regards minimal mass requirement for typical loads. Technical structures are manipulated for the most part by the will of the inventor, whereby the state
of the given technical acumen and creative aesthetic will have a direct or indirect influence."

Otto, Frei, IL-12, Convertible Pneumatic Membrane Structures, Information of the Institute for Lightweight Structures(IL); University Stuttgart, IL-12, printed in Germany, 1975

Otto, Frei, IL-14, Adaptable Architecture, Information of the Institute for Lightweight Structures(IL); University Stuttgart, IL-14, printed in Germany. Page: “Convertible Roofs and Adaptive Building.” “The constructional appearance of a room is particularly determined by the roof.” “opening and shutting of the roof calls for no reconstruction but a quickly performed alteration procedure that can be repeated as often as required.”

Otto, Free, IL-17, The Work of Frei Otto and his Teams 1955-1976, Information of the Institute for Lightweight Structures (IL) University Stuttgart, IL-17, printed in Germany. 1971

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Page 28: “In the problem of the tall tree we have to determine the point in which the tree will begin to bend under its own weight if it be ever so little displaced from the perpendicular. -we have to make certain assumptions—for instance that the trunk tapers uniformly, and that the sectional area of the branches varies according to some definite law, arras Ruskin assumed) tends to be constant in any horizontal plane.” Page 29: “In the tree, moreover, anchoring roots form powerful wind-struts, and are most developed opposite to the direction of the prevailing windiest. Pench, On buttress tree-roots). “the deciduous trees stop growing after the fall of the leaf, but evergreens all the year around, more or less. Page 239: “of the secular growth of trees.” Page 983: “On form and Mechanical Efficiency, of Shearing Stress, of Warrens Truss.” “(a metacarpal bone from a vultures wing), The Engineer sees in it a prefect warrens truss, just such a one as is often used for a main rib in an airplane. Not only so, but the bone is better than the truss; for the engineer has to be content to set his V-shaped struts all in one plane.” “A shearing stress is one in which produces “angular distortion” in a figure, which tends to cause its particles to slide over on another.” “When we submit a cubical block of iron to compression in the testing machine, it does not tend to give way by crumbling all to pieces, but always disrupts by shearing, and along some plane approximately at 45 degrees to the axis of compression; known as Coulombs Theory of Fracture.” “and the shearing stress is greatest in the “neutral zone” where neither tension nor compression is manifested.” “In short we see that, while shearing stresses can by no means be got rid of the danger of rupture or breaking-down under shearing stress is lessened the more we arrange the materials of our construction along the pressure-lines and tension-lines of the system; for along lines there is no shear.”

Turner, Paul Venable, Campus an american planning tradition, The MIT Press, 1984

Yakeley, Megan. Generative Modeling: An Architectural Process as an Object to Think With, MIT.