The Mystery of the Master Builders

Robert Mark

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Series Foreword

The Alfred P. Sloan Foundation's New Liberal Arts (NLA) Program stems from the belief that a liberal education for our time should involve undergraduates in meaningful experiences with technology and with quantitative approaches to problem solving in a wide range of subjects and fields. Students should understand not only the fundamental concepts of technology and how structures and machines function, but also the scientific and cultural settings within which engineers work, and the impacts (positive and negative) of technology on individuals and society. They should be much more comfortable than they are with making calculations, reasoning with numbers and symbols, and applying mathematical and physical models. These methods of learning about nature are increasingly important in more and more fields. They also underlie the process by which engineers create the technologies that exercise such vast influence over all our lives.

The program is closely associated with the names of Stephen White and James D. Koerner, both vice-presidents (retired) of the foundation. Mr. White wrote an internal memorandum in 1980 that led to the launching of the program two years later. In it he argued for quantitative reasoning and technology as "new" liberal arts, not as replacements for the liberal arts as customarily identified, but as liberating modes of thought needed for understanding the technological world in which we now live. Mr. Koerner administered the program for the foundation, successfully leading it through its crucial first four years.

The foundation's grants to 36 undergraduate colleges and 12 universities have supported a large number of seminars, workshops, and symposia on topics in technology and applied mathematics. Many new courses have been developed and existing courses modified at these colleges. Some minors or concentrations in technology studies have been organized. A Resource Center for the NLA Program, located at the State University of New York at Stony Brook, publishes and distributes a monthly newsletter, collects and disseminates syllabi, teaching modules, and other materials prepared at the colleges and universities taking part in the program, and serves in a variety of ways to bring news of NLA activities to all who express interest and request information.

As the program progressed, faculty members who had developed successful new liberal arts courses began to prepare textbooks. Also, a number of the foundation's grants to universities were used to support writing projects of professors—often from engineering departments—who had taught well-attended courses in technology and applied mathematics that had been designed to be accessible to liberal arts undergraduates. It seemed appropriate not only to encourage the preparation of books for such courses, but also to find a way to publish and thereby make available to the widest possible audience the best products of these teaching experiences and writing projects. This is the background with which the foundation approached The MIT Press and the McGraw-Hill Publishing Company about publishing a series of books on the new liberal arts. Their enthusiastic response led to the launching of the New Liberal Arts Series.

The publishers and the Alfred P. Sloan Foundation express their appreciation to the members of the Editorial Advisory Board for the New Liberal Arts Series: John G. Truxal, Distinguished Teaching Professor, Department of Technology and Society, State University of New York, Stony Brook, Chairman; Joseph Bordogna, Alfred Fitler Moore Professor and Dean, School of Engineering and Applied Science, University of Pennsylvania; Robert W. Mann, Whitaker Professor of Biomedical Engineering, Massachusetts Institute of Technology; Merritt Roe Smith, Professor of the History of Technology, Massachusetts Institute of Technology; J. Ronald Spencer, Associate Academic Dean and

Lecturer in History, Trinity College; and Allen B. Tucker, Jr., Professor of Computer Science, Bowdoin College. In developing this new publication program, The MIT Press has been represented by Frank P. Satlow and the McGraw-Hill Publishing Company by Eric M. Munson.

Samuel Goldberg
Program Officer
Alfred P. Sloan Foundation

Preface

Paul Goldberger, the architecture critic of the *New York Times,* has observed in several recent articles that "our culture has shown more interest in the field of architecture than ever before." That interest is reflected by the publication in just two years (1985 and 1986) of four major texts devoted to the general history of architecture and intended for use in college-level survey courses. The authors of these texts recognize the central role of technology in large-scale architecture. Yet, with their traditional emphasis on formal stylistic development, symbolism, and iconography, they fail to maintain a consistent focus on building technology or on the crucial *interaction* of structure and style in historic architecture.

The present work is not intended to supplant these general texts, nor for that matter does it attempt to present a coherent account of the sweep of Western architectural history. Rather, it deals mainly with three historic eras that witnessed the development of new large-scale building types that retain great influence in architectural planning up to the present day. The application of modern engineering tools has clarified the technological underpinning of these developments and provided new insights into the design techniques employed by the early builders. Hence, another theme of the present work is the reinterpretation of technological precedents that are often misunderstood in contemporary architecture. It is hoped that this book, when used together with the general texts, will provide a stronger technological focus on all of architectural history as well as a basis for more rational criticism of contemporary design.

Much of the material derives from a seminar offered annually at Princeton and usually co-taught by the author and an architectural historian. Begun a little more than a decade ago with a focus on Gothic structure, the seminar now treats issues of structure and style from the whole history of architecture. The results of related research have been published in a wide spectrum of journals, including the *Annals of the New York Academy of Science, American Scientist, Art Bulletin, Experimental Mechanics, Interdisciplinary Science Reviews,* the *Journal of the Society of Architectural Historians, Scientific American, The Sciences,* and *Technology and Culture,* which makes them difficult to collect by anyone working in a single field of scholarship. Some of these new materials have already found use in seminars for visiting faculty sponsored by the Alfred P. Sloan Foundation and the National Endowment for the Humanities and held at Princeton during the summers of 1985–1988. They were also used in a University of Michigan colloquium held during the spring of 1988 (the colloquium was jointly sponsored by departments of archaeology, architecture and planning, art history, and engineering), and they provided the basis for "The Mystery of the Master Builders," a "Nova" program first broadcast by PBS in March 1988.

The text is aimed at the general reader as well as at students of architecture and architectural history. An effort has been made to minimize jargon, but the nature of the subject demands that some technological ideas and terms be used. These are introduced in a simple manner in chapter 2. Sources of more detailed reference information are referred to in the notes. Architectural and technical terms are defined throughout the text, in illustrations, and in a glossary. Both the metric and the English system of units are generally used, but for the sake of clarity some of the drawings display units in only one system.

Important contributions to this work have been made by a number of my present and former colleagues at Princeton, including Kirk D. Alexander, David P. Billington, Slobodan Ćurčić, Michael Davis, Robert Gutman, Jean-Herve Prévost, Robert Scanlon, and Harry Titus, and by other scholars, including Sheila Bonde, William W. Clark, Lynn T. Courtenay, Harold Dorn, Joel Herschman, William Loerke, William L. MacDonald, Clark

Maines, Christopher Mark, Claudia Marchitiello Mark, Rowland Richards, Jr., Elwin Robison, and Leonard Van Gulick, to all of whom I am greatly indebted. Some of my former students (in architecture, art history, and engineering) also took part in these studies, including several with whom I have collaborated in publication: Yun-Sheng Huang, Paul Hutchinson, Anne Westagard Stokes, and William Taylor.

I wish to express my gratitude to the National Endowment for the Humanities, the Alfred P. Sloan Foundation, and the Andrew W. Mellon Foundation for sponsoring research and education programs of which this research was a part. I am indebted also to the John Simon Guggenheim Foundation for the granting of a fellowship in 1982–83 which enabled me to become familiar with and to photograph the fabric of many of the ancient sites, and to the National Science Foundation for a Scholar's Grant in 1983–84 which provided further assistance with these studies.

Finally, I am most grateful to the readers of The MIT Press and to William W. Clark, Lynn T. Courtenay, and Sergio Sanabria for editorial suggestions; to Robert Bork, Yun-Sheng Huang, David Lauer, Elizabeth Newman, and Valerio Simini for line drawings and computer-generated illustrations; and to J. Weyman Williams for producing print conversions from my color slides.

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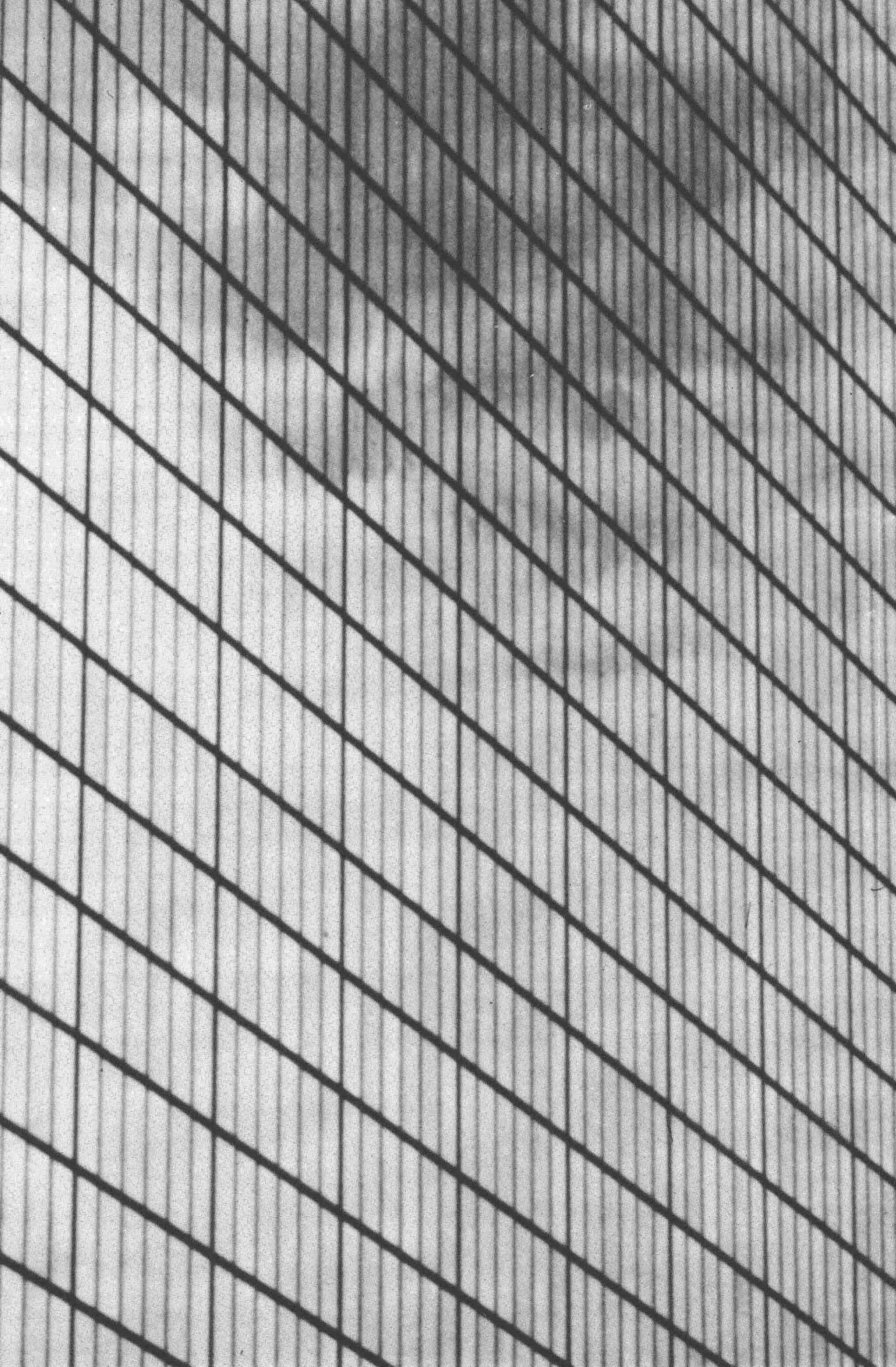


I

Problems of Technological Interpretation in Historic Architecture

The Opera House in Sydney stands high over the harbor like a great ship, its sail-like roof shells of concrete raised on a terraced platform. Yet its appearance betrays none of its ideological foundations. The project was begun in 1957 when the Danish architect Jorn Utzon submitted a series of freehand sketches of the roof shells to an international design competition and won the commission. The opera house finally opened in 1973, nine years behind schedule and at a cost that exceeded the original estimate of $10 million by more than $130 million—mostly because of an inappropriate notion of "honest" structural design.[1]

In the early stages of the project, Utzon and his structural engineer, Ove Arup, decided that the arching, pointed shells, which were to reach as high as 60 meters (197 feet) above their base and to be inlaid with ceramic panels, should be honestly self-supporting. In other words, the roof shells—whose form was determined primarily on the basis of aesthetic, sculptural considerations—would have to sustain the considerable forces of gravity and wind without support from any additional structural framing underneath. It would not be enough for the shells (composed of segments from a sphere 75 m [246 ft] in radius) to be aesthetically appealing; form would have to serve function. There would be no lazy, unworking shapes and no hidden supports.

1.1
Jorn Utzon and Ove Arup: Opera House, Sydney, 1973. (photo: WGBH/ Nova)

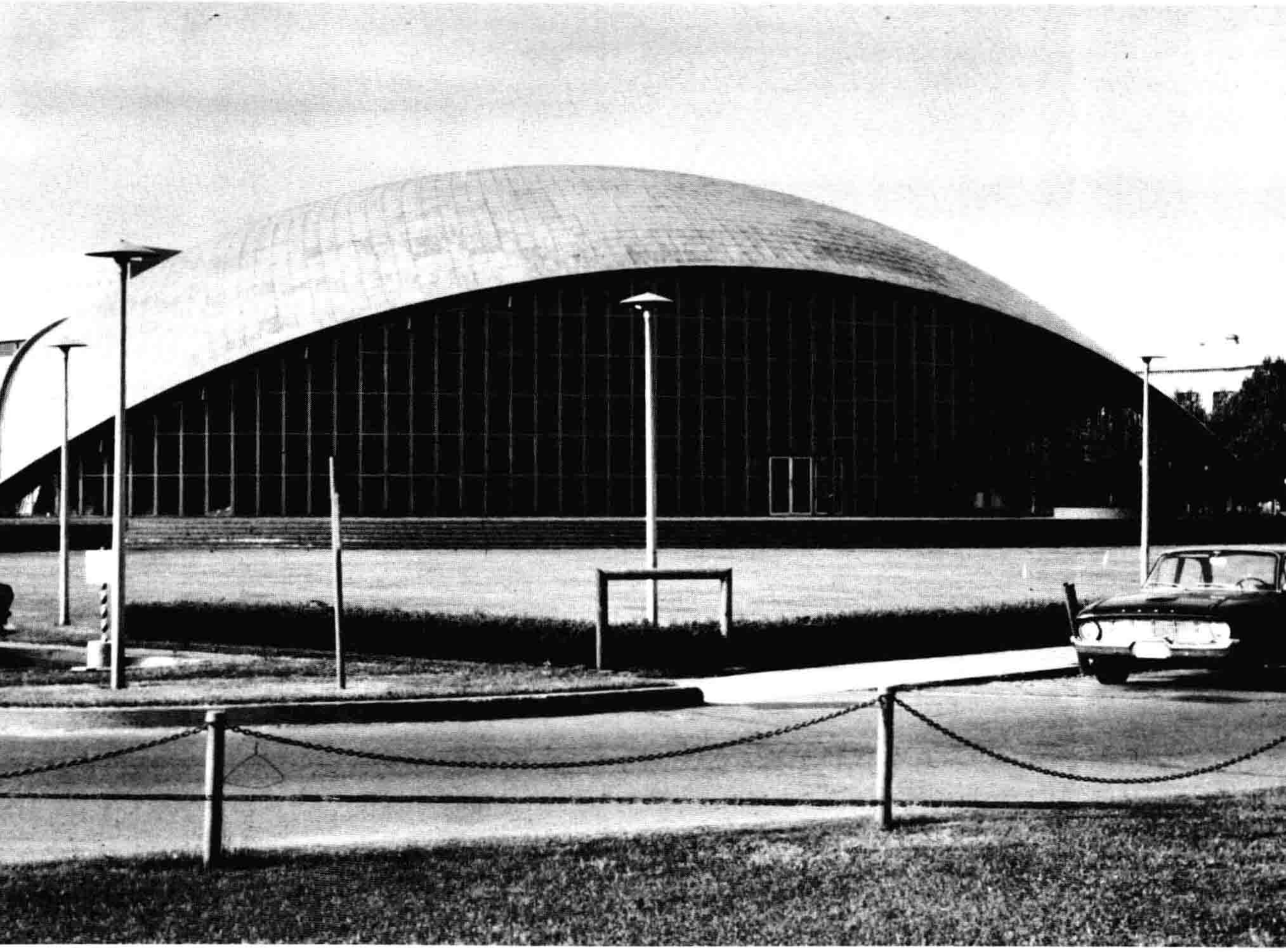
And so tens of millions of dollars were spent for years of engineering and computing time to produce a design for a vastly intricate, self-supporting, prestressed-concrete roof system.

Still more money went into reconstructing the terraced platform on which the shells were to rest after the designers found that the one originally constructed, in an attempt to make up for lost time and to schedule an even flow of work, would not hold up the roof. A simpler and far less expensive structural system, composed of hidden steel trusses, could have been used to support the sculptural shells, but the designers rejected this option and chased after their vision of technological morality—which Arup defended with a specious historical argument: "The cost, the length of time it is taking to complete, the use to which the building will be put, and so on have been discussed almost *ad nauseam*. As a consequence, the challenge, the excitement and the technical problems encountered in what must be one of the most complex structures ever built, have become obscured. Sydney Opera House is not the kind of building which often comes within the orbit of the structural engineer. It is an adventure in building. It is not really of this age and in concept is more appropriate to an autocratic rule of a former era."[2]

Although the Sydney Opera House has come to symbolize the tension between technology and art that exists in much of contemporary architecture,[3] Eero Saarinen—the architect who dominated the jury that awarded the Opera House commission to Utzon—had already been the author of a similar technological fiasco. His Kresge Auditorium, constructed on the campus of the Massachusetts Institute of Technology in 1955, was also conceived for visual effect without regard for structural imperatives—a fact that became painfully evident during its construction. Yet this was not the consensus of contemporary commentators. Even so astute a critic as Allan Temko thought the shell form attributable to "its absolute structural premise." "The auditorium," he went on, "can be recognized as closer to the 'correct' structural theory of Nervi . . . than to the structural rhetoric of [Wright's] Guggenheim Museum." And Saarinen himself did nothing to clarify the issue when he commented that "in developing the design of this building, we felt very strongly guided by Mies's principle of architecture—of consistent structure and a forthright expression of that structure."[4]

The cast-in-place concrete shell roof of the Kresge Auditorium, with its span of 49 m (160 ft) between supports, has the

1.2
Eero Saarinen: Kresge Auditorium, Massachusetts Institute of Technology, 1955. (photo: D. P. Billington)



form of an equilateral spherical triangle, comprising one-eighth of the full surface of a sphere with a radius of 34 m (112 ft).[5] The shell was originally intended to be of uniform thickness and to be supported only at its three corners by massive foundations. But deformation, caused by large bending forces along the outer edges after the removal of the temporary centering over which the concrete had been poured, demanded that reinforcement be added to the shell and that the window mullions be redesigned to provide edge support. Even with the modifications, additional long-time deformations, combined with the effect of movements caused by changes in temperature, hastened the deterioration of the roof and of the elaborate and costly lead covering that was applied to it when some of the problems first became apparent. With every heavy rain the auditorium flooded. More critically, the steel reinforcement within the shell corroded so badly from continual wetting that it began to lose strength. In 1979 the entire building had to be closed for more than a year to allow major reconstruction.

Tall office buildings are not immune to similar problems of design. With its great height, the form of the modern skyscraper might be expected to be influenced by the effect of wind. Indeed, as will be shown in chapter 4, even the external profile of the much lower and relatively heavy (compared with modern frame construction) High Gothic cathedral resulted in part from structural impairment caused by high winds. And although a response to wind forces is reflected in the form of at least some tall modern buildings (as exemplified by the John Hancock Center in Chicago, discussed in chapter 6), it does not appear to have been a primary consideration in the planning (by I. M. Pei and his chief designer, Henry N. Cobb) of the John Hancock Tower in Boston, an extremely slender 60-story steel-frame building clad in mirrored glass. The cladding was intended to reflect the downtown scene and to allow the tower, the tallest structure in the city, to fade into the background. In 1971, when the building was still under construction, the windows started to fall out; by the summer of 1973 almost a quarter of the glass had been lost. Occupancy had to be postponed for $3\frac{1}{2}$ years while extensive structural modifications were undertaken, which included stiffening the building's frame against twisting deformation. As a further palliative for excessive motion in high winds, tuned-mass dampers (huge moving weights high up in the structure, controlled by sophisticated electronic sensors) were installed. And all of the original windows needed to be replaced.