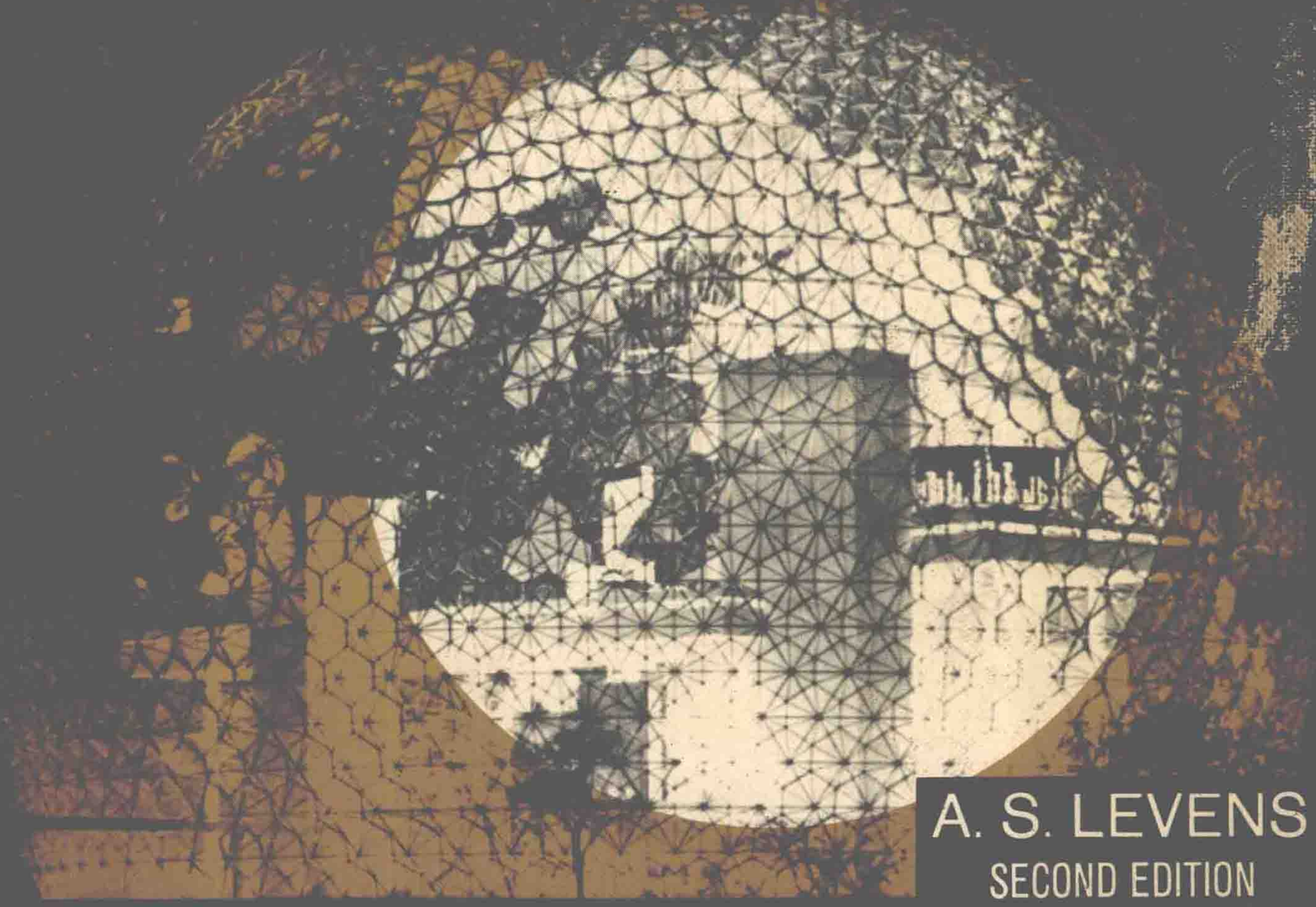
# GRAPHICS

## ANALYSIS AND CONCEPTUAL DESIGN



A. S. LEVENS

SECOND EDITION

# GRAPHICS

## ANALYSIS AND CONCEPTUAL DESIGN

*Other Books by A. S. Levens:*

Nomography, Second Edition
Also translated into a Japanese Edition

Graphical Methods in Research

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# PREFACE

Engineering as a profession is concerned primarily with design. The core of engineering is design, in a broad sense, of machines, processes, structures, and circuits, and combinations of these components, into plants and systems. The professional engineer must be capable of predicting the costs and performances of the components, plants, and systems to meet specific requirements. The scientist is primarily concerned with the discovery of new knowledge and the development of new scientific principles, whereas the engineer is concerned with the implementation of these principles. The professional engineer deals with the applications of science, tempered by judgment based on experience, to the solution of engineering problems.

The late Dr. Theodor von Kármán stated it very nicely when he said: "The scientists explore what is, and the engineers create what has never been." In the development of solutions to real engineering problems, the creative art of conceiving a physical means of achieving an objective is the first and most important step. Analysis of the possible solutions is the next step. Stated simply, synthesis in conception precedes the analysis required to refine the conception.

Graphics plays a very significant role in the conceptual design phase; and in many cases is most effective in the analysis stage. Surely, the study of analytical courses is essential because it is difficult, without analysis, to predict performance and costs of a conceptual design while it is in the paper stage.

Designing is a conceptual process which is done largely in the mind, and the making of sketches is a recording process, a reliable memory system, which the engineer uses for self-communication—talking to himself—to help him "think-through" the various aspects of his project. Graphics is an integral part of the conceptual phase because, more often than not, the making of a simple sketch to express a design conception does of itself suggest further ideas of a conceptual nature.

Engineers who have developed the ability to form a visual image of geometrical and physical configurations and to "think graphically" have a tremendous advantage in creating a physical means of achieving a technological objective.

The "thinking-through" process is an exercise of the mental powers of judgment, conception, and reflection for the purpose of reaching a conclusion, i.e., a design which is the "best compromise" solution to a given project.

The technological explosion in the present era has brought about the need for much closer working relations between engineers and scientists. For effective communication both must be proficient in mathematics, physics, chemistry, graphics, and certainly in a common form of oral and written expression.

Engineering education must contribute, significantly, to the development of young, well-qualified persons who can and will face challenging engineering situations with imagination and confidence.

The student who undertakes preparation for the stimulating and exciting profession of engineering must have adequate education in mathematics, physics, chemistry, graphics, the engineering sciences, and a good background in the humanities and social sciences. With respect to graphics this means good facility in freehand sketching; thorough knowledge of (*a*) the fundamental principles of orthogonal projection and experience in applying the principles to the solution of space problems that arise in both engineering and science; (*b*) knowledge and use of graphical methods of computation; and (*c*) the development of the design process and the capability of coping with the "many-solutions" type of problems that are so characteristic of professional engineering.

It is the objective of this book to give the student an up-to-date treatment of graphics and an introduction to design that will help him become "graphically literate," so that he can apply graphics, with confidence, to synthesis, analysis, and solutions of problems that arise in the fields of design, development, and research, whenever appropriate. In contrast to the first edition, this new edition lays much more stress on the design process and includes several industrial examples which serve to provide the student a vicarious design experience. In addition, the very latest standards are used throughout the book. Moreover, many new examples and figures pervade the entire text.

Part 1, Fundamental Principles and Applications of Orthogonal Projection, lays *stress on principles and concepts.* Thorough grasp of the few basic principles greatly enhances the student's ability to analyze and solve various space problems that arise in both engineering and science. Use of *freehand sketches* in recording the student's thought process and in planning a suitable arrangement of views in solving problems is stressed. *The emphasis is on thinking, not on draftsmanship.* A variety of thought-provoking space problems is available in this part of the text and in the accompanying workbooks.

Part 2, Graphical Solutions and Computations, includes: (*a*) graphical presentation of data; (*b*) graphical mathematics, including arithmetic, algebra, and calculus; (*c*) empirical equations—forms frequently used in engineering; (*d*) functional scales; and (*e*) an introduction to nomography. The student will find this part both stimulating and very useful. His experience with the material on graphical calculus will greatly enhance his understanding of integration and differentiation. He will see that, in several cases, it is not convenient to express the relation between two variables algebraically, and that a graphical solution is best suited to the problem. This is very often true in dealing with experimental data.

When the material on graphical, numerical, and grapho-numerical methods of integration and differentiation is presented, it is appropriate to introduce *computer solutions.* For example, a computer solution of the application of Simpson's rule could be demonstrated. Also, Cal-comp or Gerber plot-outs could be shown if equipment is available. Included in this part are several examples of the use of graphical methods in the solution of problems that have arisen in research projects.

The material on nomography will be found most interesting. Nomograms play an important role in the repeated solution of formulas and also in *studying the interrelationships among four or more variables for which an explicit or implicit relation exists.* Further study of the fascinating field of nomography is provided for in the author's book, *Nomography.**

Part 3, Introduction to Design, provides an opportunity for the student "to be on his own" to a large degree. The experience in facing up to projects that have several solutions will enable the student to approach, with much greater confidence, real engineering situations that will confront him in his professional career.

*We cannot start too early to give the student the experience of confronting and solving the "open-ended" type of problem. The first year in engineering education is not too soon!* We recognize that the student's background is quite limited at this stage of his career, and therefore the proposed projects are relatively simple. Nevertheless, in principle, they are of the same character as some of the more involved projects that arise in engineering practice. The student's experience in coping with open-ended projects will be found to be stimulating, challenging, and most rewarding. He will find a good spirit of competition among his classmates, especially with regard to who has developed the "best" design solution. In this part of the text he will learn to understand the design process and its employment in undertaking a project.

The chapters on pictorial drawing, sections and conventional practices, fasteners, dimensions and specifications for precision and reliability, constitute additional background material for the chapter on conceptual design. It is presumed that the student has already developed a reasonable degree of proficiency in manual dexterity with respect to use of drawing instruments, lettering, geometric constructions, etc., in high school courses. When the student has had such experience in the above areas, including freehand pictorial sketching, more time can be devoted to conceptual design. This text and the two workbooks will also serve the needs of those high school seniors and junior college students who are committed to study engineering in preparation for an engineering career.

It is strongly recommended that some time be

**Nomography,* 2nd ed., John Wiley and Sons.

devoted to the chapter on dimensioning for precision and reliability so that students will be aware of the *important role* of this material in present day design and manufacture.

As the student progresses in his engineering education and enters upon the study of mechanics, strength of materials, design (in the broad sense), and research, he should continue to employ, whenever appropriate, graphical methods to solve problems that arise in these areas.

*Graphics, Analysis and Conceptual Design,* as presented in this text, reflects today's thinking and our continual effort to develop a meaningful and worthwhile treatment, which, we believe, is consistent with the needs of a scientific and engineering era. The experience with our students continues to be most gratifying. *Students are stimulated to learn and to apply fundamental principles; to "think-through" a problem, rather than depend upon rote learning;* to learn and use graphical methods of computation; and to appreciate, through their own experience with conceptual design, that the qualified engineer must have the necessary education and experience to cope with real engineering situations that arise, and will continue to arise, in an ever-growing, dynamic technological era.

I am deeply appreciative of the cooperation received from the following organizations and editors of a number of journals and periodicals, for permission to use certain photographs, charts, and drawings: Automobile Manufacturing Association, The Bendix Corporation, The Boeing Company, *Experimental Mechanics Engineering,* Falk Corporation, General Motors Corporation, *Industrial Fasteners Institute,* Librascope, Inc., Lockheed-Georgia Company, *Machine Design,* Mattel, Inc., Mobil Oil Corporation, National Safety Council, *Plant Engineering, Product Engineering,* Republic Steel, Sandia Corporation, San Francisco Naval Shipyard, TRW Systems, Inc., and U.S. Weather Bureau.

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I am grateful to my colleagues at the University of California: Professor H. D. Eberhart for the use of the material from the Prosthetic Devices Research Project; Professors D. M. Cunningham, F. E. Hauser, and H. W. Iversen, for experimental data used in connection with several examples in the chapters on empirical equations and graphical calculus.

And to my wife, Ethel, whose continuous encouragement, patience, and understanding made this work possible, my heartfelt and everlasting appreciation.

*A. S. Levens*

*Berkeley, California*

# PREFACE TO THE FIRST EDITION

The well-qualified engineer must be proficient in mathematics, graphics, physics, chemistry, and the engineering sciences. In addition, he should have a good background in the humanities and social sciences.

In developing solutions to real engineering problems, the creative art of conceiving a physical means of achieving an objective is the first and most important step. Analysis of the possible solutions is the second step. Stated simply, synthesis in conception precedes the analysis required to refine the conception.

Graphics plays a most important role in the conceptual design phase; and in many cases it is also most effective in the analysis stage. Of course, the study of analytical courses is very necessary because it is difficult without analysis to predict performance of a conceptual design while it is still on paper.

The technological demands of our scientific era have brought about much closer working relations between engineers and scientists. For effective communication both must be proficient, not only in mathematics, physics, and chemistry, but also in engineering graphics; and certainly in a common form of oral and written expression.

Engineering education must contribute, significantly, to the development of young, well-qualified persons who can and will face new and challenging engineering situations with imagination and confidence.

With respect to graphics and its important role in engineering, it is essential to provide programs of study that are pertinent to the students' preparation for the engineering profession. Certainly, development of facility in freehand sketching—both pictorial and orthographic—is most important for both engineering and science students in order to provide an effective *graphic extension of the mind.*

Engineering as a profession is concerned primarily with design. In fact, the core of engineering is design which, in the broadest sense, includes circuits, machines, structures, processes, and combinations of these components into systems and plants. The professional engineer must be capable of predicting the performance and cost of the components, systems, and plants to meet specified requirements. We must not overlook the fact that the theoretical scientist is primarily concerned with the discovery of new knowledge and the development of new scientific principles, whereas the engineer is concerned with the implementation of these principles. The professional engineer deals with the applications of science, tempered by judgment based on experience, to the solution of real engineering problems.

Designing is a conceptual process which is done largely in the mind, and the making of sketches is a recording process, a reliable memory system, which the engineer uses for self-communication to help him "think-through" the various aspects of his project. Graphics is an integral part of the conceptual phase because, more often than not, the making of a simple sketch to express a design conception does of itself suggest further ideas of a conceptual nature. Engineers who have developed their ability to visualize geometrical and physical configurations and to "think graphically" have a decided advantage in creating a physical means of achieving an objective.

The student who undertakes preparation for the exciting and stimulating profession of engineering must have adequate education in graphics. This means not only facility in freehand sketching, but also thorough knowledge of (*a*) the fundamental principles of orthogonal projection and experience in the application of those principles to the solution of space problems that arise in both engineering and science; (*b*) knowledge and use of graphical solutions and methods of computation; and (*c*) the development of capability to cope with the "many-solutions" type of problems that are so characteristic of engineering.

The principal objective of this book is to provide for the student a modern treatment of graphics and an introduction to conceptual design that will help him become "graphically literate," so that with confidence he can employ graphics—a powerful mode of expression—to the synthesis, analysis, and solution of problems that arise in the fields of design, development, and research.

It is presumed that the student has already developed a reasonable degree of proficiency in manual dexterity with respect to lettering, use of drawing instruments, geometric constructions, etc., in high school or, if feasible, in noncredit prerequisite work in a college. The material in Appendix A of this text, and the problems in the appendix of the workbook, number one, provide ample subject matter for this purpose.

Part 1, Fundamental Principles and Applications of Orthogonal Projection, *lays stress on principles. Rote learning is discouraged. Thorough grasp* of the few fundamental principles will greatly enhance the students' ability to "think through" and solve various space problems that arise in both engineering and science. The student is encouraged to use freehand sketches in planning the arrangement of views that may be necessary for the solutions and in recording his thought process in evolving the solutions. *Emphasis is on thinking, not on draftsmanship.* Interesting examples of the application of the fundamental principles of orthogonal projection to problems that have arisen in the field of research are included.

The diligent student will be able to apply the principles to the solution of many problems that "appear" to be different, but are *basically* the same.

The treatment of vector quantities and vector diagrams with applications to three-dimensional force systems affords the student another opportunity to apply the fundamental principles of orthogonal projection to the solution of concurrent, non-coplanar force problems.

Chapter 11, the final chapter of Part 1, is intended to strengthen the students' ability in analysis. It is suggested that reference to this chapter be made whenever appropriate.

Part 2, Graphical Solutions and Computations, includes the graphical presentation of data; graphical mathematics—arithmetic, algebra, calculus; empirical equations (forms most frequently encountered in engineering); functional scales; and an introduction to nomography. The student will find this part most interesting and stimulating. His understanding of integration and differentiation will be enhanced by his experience with the material on graphical calculus. The student will realize that many problems cannot be conveniently expressed in the symbolic language of mathematics and that a graphical (which is also mathematical in the broad sense) method may be better suited to the solution of the problem.

At the time when the material on graphical, numerical, and grapho-numerical methods of integration and differentiation is presented, it has been found appropriate to *introduce computer solutions.* A number of examples are included to demonstrate the employment of graphical methods in the solution of problems that have arisen in research projects at the University of California at Berkeley.

The material on nomography is an adequate introduction to this most useful and fascinating field. The student will dicover that nomograms play an important roll in the repeated solution of formulas and also in analyzing the relations among three or more variables for which an explicit or an implicit relation exists. (In very recent years a nomographic method has been developed to test the validity of a family of experimental data curves.*)

Part 3, Introduction to Conceptual Design, affords the student an opportunity "to be on his own." His background in graphics—based on the material in the first two parts—coupled with his course work in mathematics, chemistry, physics, and perhaps some actual job experience will have a direct bearing on his progress in dealing with *projects that have many solutions.* The experience in facing up to such problems will enable the student to approach, with greater confidence, real engineering situations that will confront him later. *We cannot start too early to give the student the experience of confronting and solving, reasonably well, the "open-ended" type of problem. The freshman year is not too soon!* It is recognized that the student's background is quite limited at this stage of his career, and because of this the proposed problems are relatively simple and limited in scope. *Nevertheless, in principle* they are of the same character as some of the most advanced problems in engineering practice. The student will find his experience in conceptual design stimulating, challenging,

*In the author's 2nd edition of *Nomography,* John Wiley and Sons.

and rewarding. A good spirit of competition is generated among the students—especially with regard to who has the "best" design.

The chapters on pictorial drawing, sections and conventional practices, fasteners, dimensions and specifications, dimensioning for precision and reliability, constitute additional background material for the chapter on conceptual design. Where the student has had good experience in the above areas, more time can be devoted to conceptual design.

An appreciation of some of the problems that confront the engineer is the matter of "dimensioning for precision and reliability." It is strongly recommended that some time be devoted to this chapter so that students will understand the importance of this subject, especially today in connection with the design of various space vehicles.

As the student progresses in his engineering education and enters upon the study of mechanics, strength of materials, design (in the broad sense), and research, he should continue to employ, whenever appropriate, graphical methods to solve problems that arise in these areas.

Graphics, with an introduction to conceptual design, as presented in this text, reflects our continual effort to develop a meaningful and worthwhile treatment which, we believe, is consistent with the needs of a scientific era. The experience with our students continues to be most gratifying. *Students are stimulated to learn and to apply fundamental principles; to "think-through" a problem, rather than depend upon rote learning;* to learn and use graphical methods of computation; and to appreciate, through their own experience with conceptual design, that the qualified engineer must have the necessary education and experience to cope with real engineering situations that arise, and will continue to arise, in an ever-growing, dynamic technological era.

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I am grateful to my colleagues at the University of California: Professor H. D. Eberhart, for the use of materials from the Prosthetic Devices Research Project; Professors L. J. Black, J. E. Dorn, F. E. Hauser, R. R. Hultgren, and H. W. Iversen, for experimental data used in connection with several illustrated examples in the chapters on empirical equations and graphical calculus; and to Mr. Paul Urtiew, graduate student, for the photograph and the delineation of the system used in connection with the research project on gas dynamics, shown as an example in the chapter on graphical calculus.

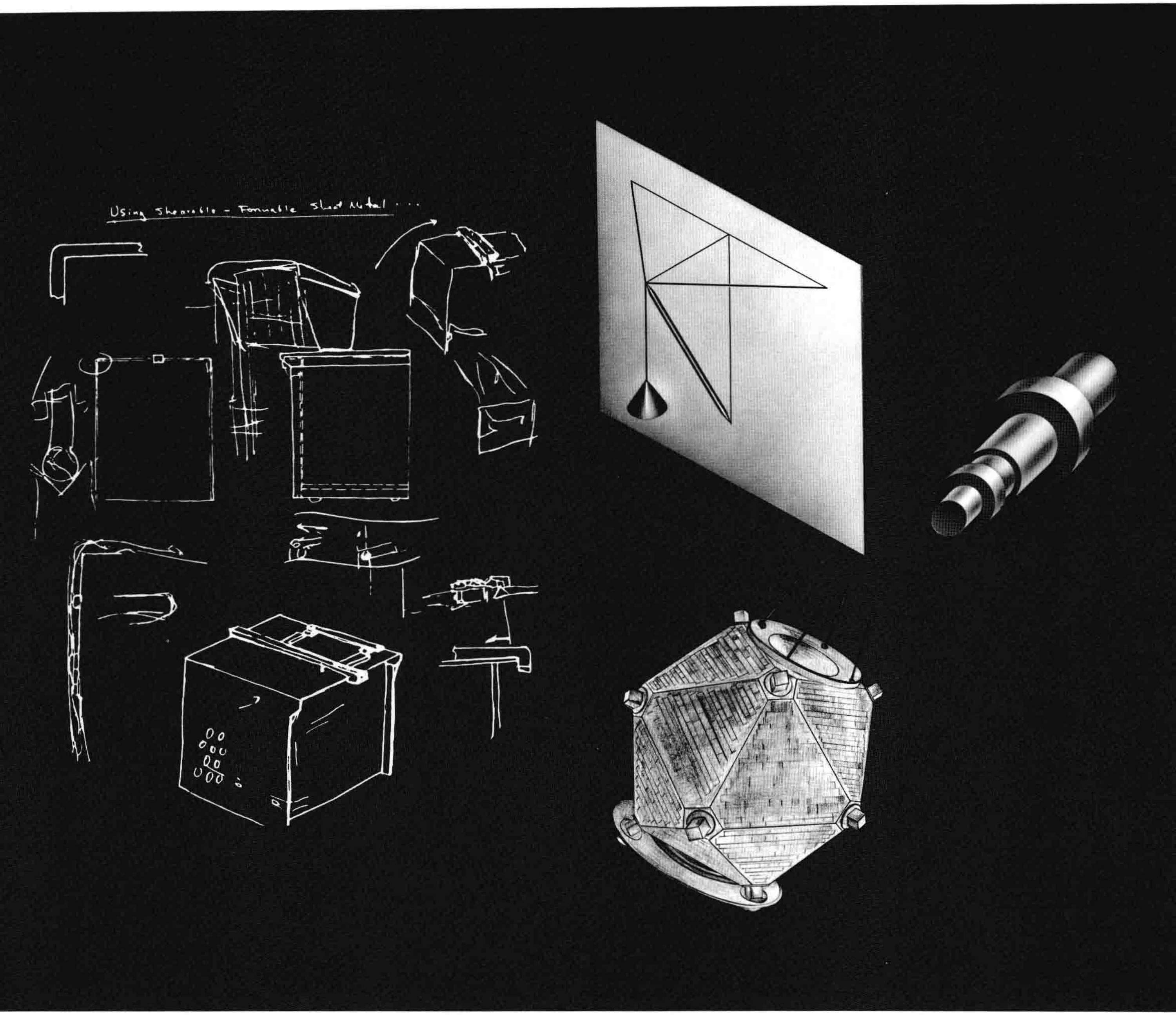
And to my wife, Ethel, whose patience and understanding made possible an environment which was conducive to productive writing, my ever-lasting and heartfelt appreciation.

*A. S. Levens*

*Berkeley, California*
*April, 1962*

# CONTENTS

# PART 1
# FUNDAMENTAL PRINCIPLES AND APPLICATIONS OF ORTHOGONAL PROJECTION




# INTRODUCTION 1

The history of the development of engineering education reveals significant changes in engineering curricula. This is as it should be in the dynamic growth of the engineering profession. Changes have been necessary in order to keep pace with the accelerated growth in technology. This is especially true of the period since World War II. The importance of design, research, and development has increased the need for "science-oriented" curricula in engineering. There is now greater emphasis on mathematics, physics, chemistry, and the engineering sciences than on "the art of engineering." In recent years, however, there is the realization that *design* is the core of engineering and that a much greater effort must be made to enhance the engineering student's understanding of the design process and also to provide opportunities for design experiences. In the broadest sense design includes circuits, machines, structures, and processes, and their combinations. It is the responsibility of the professional engineer to use these components in the design of plants and systems; and also to predict their performance and costs to meet specified requirements. Engineers are often guided by the new-knowledge discoveries made by scientists, but the end products —hardware—are not the result of the physical facts alone. Many other factors must be considered. For example, the design of a space vehicle to meet certain environmental and performance specifications, or the design of a device to monitor blood pressure continuously without discomfort to the patient (or, for that matter, other useful products), requires of the engineer effective knowledge of the mathematical and physical sciences, of engineering graphics, of the engineering sciences, coupled with engineering experience which reflects good judgment in determining need, feasibility, reliability, marketability, etc. Engineering education must contribute, significantly, to the development of young men who can face new and challenging situations with imagination and confidence. Meeting such challenges invariably involves both professional and social responsibilities.

In the first stages of a technological project many ideas are presented in written form with accompanying "idea sketches," charts, models, and layouts, to provide means for studying such problems as feasibility, reliability, costs, etc. In some situations it may be necessary to carry on research, development, and design to resolve a number of technical problems. In these areas considerable use is made of mathematics, graphics, physics, chemistry, and the engineering sciences—mechanics, properties of materials, etc.

The role of graphics is very important in the "ideation stage"—the conceptual design phase. Conceptual design is a mental process. It is the creative process of conceiving a physical means of achieving a physical objective. The making of sketches is a very important recording process—a reliable memory system—which enables the design engineer to "talk to himself." The recording of the initial conceptual design sketches serves to suggest further items of a conceptual nature. Today much of the work associated with the preparation of detail drawings of components, assemblies of components, product design, and production illustration is done by well-trained technicians who are supervised by graduate engineers.

As a student who undertakes the study of engineering with the hope of becoming a competent professional engineer, you must have adequate education in the field of engineering graphics. This means thorough knowledge of the fundamental principles of orthogonal projection and experience in the application of these principles to the solution of three-dimensional problems that arise in the various fields of engineering and science; *proficiency in free-hand sketching*—a powerful tool for expressing ideas, for planning solutions, for recording analyses (the "thinking-through process") of space problems; and an understanding and use of graphical mathematics, including graphical calculus, empirical equations, functional scales, and elements of nomography.

In addition, experience in dealing with "open-ended" projects—the type of problems that have several solutions—is essential to your understanding of the "real" problems that continually face the engineer. You will develop, early in your career, a "feel" for the engineering approach to the solutions of project-type situations.

Many problems that arise in projects are best solved graphically. Graphical solutions, in many cases, are much quicker, more vivid, more practical, and less likely to incur accidental errors than solutions obtained algebraically. In some cases the problem cannot be adequately modeled mathematically. Technical problems in many situations are concerned with length, time, temperature, pressure, etc., quantities that can be measured only approximately. The reading of a voltmeter, for example, can be only as accurate as, among other things, the graduated scale (graphical) and the visual acuity of the observer. This is also true of lengths, whose measurement again depends on a graphical scale; or of pressure, whose measurements depend on a gage mechanism and a scale for reading numbers; or, of temperatures, currents, and many other quantities which are measured by devices that indicate values on a scale that is read by an individual. The *data are graphical* in nature. Certainly a graphical solution of a problem that inherently is based on graphical data can be arrived at by graphical methods with sufficient accuracy. The fact that we use numbers, obtained by reading various scales, in a mathematical solution of the problem does not, by any stretch of the imagination, make such a solution more accurate than a graphical one.

We know that thorough training in mathematics is essential to sound engineering and scientific activity. It is, however, important that you as a student do not get a *warped* view, so that your training will lead to *the intelligent use of several methods* and, it is hoped, to the *development of good judgment* in the choice of methods. In many cases a combination of algebraic, graphic, numerical, and electromechanical methods is best suited to the solution of technical problems.

In this treatment of graphics and conceptual design, Part 1 stresses the *fundamental principles* of orthogonal projection and the application of these principles to the solution of a variety of problems that arise in technology. Every effort is made to strengthen your ability to visualize and to analyze (the "thinking-through process") space problems, and then to record the solutions graphically. Many opportunities are given you to develop your *creative thinking* and "imagineering."

Included in Part 1 are problems dealing with the determination of true lengths of members (rods, pipes, cables, etc.); the determination of clearances, as in the case of a bomb-release cable and an aileron-control cable, or for that matter, in any case where specified clearances must be maintained between wires, pipes, or structural members; distance problems such as (*a*) from point to line, (*b*) from point to plane, (*c*) between parallel planes, etc.; angle problems such as (*a*) between lines, (*b*) between planes, (*c*) between line and plane; intersections, developments; vectors, and *graphic statics*, the treatment of which should enable the student to use the fundamental principles effectively in analyzing force problems and in solving such problems graphically. The first portion of graphic statics is concerned with two-dimensional systems, whereas the second portion deals with the determination of forces in three-dimensional frames. These problems afford the student an excellent opportunity to make use of the fundamental principles. Throughout Part 1—Fundamental Principles and Applications of Orthogonal Projection—the emphasis is on principles, analysis, and synthesis. Interesting examples of problems in the areas of design and research are demonstrated throughout Part 1. The development of power to visualize and analyze a space problem and then to solve it by employing the fundamental principles is an essential goal in educating the student to become self-reliant. The engineer who has the ability to "think graphically" has a decided advantage in conceiving a physical means of achieving an objective.

Reasonable proficiency in the use of drawing instruments is desirable, but *greater emphasis should be placed upon the development and use of good freehand techniques. The ability to make good free-hand sketches is an invaluable asset.* Engineers and scientists should be able to use the techniques of freehand sketching effectively in presenting ideas to their co-workers. Engineers can save much time, and thereby do a more economical job, by preparing good freehand sketches *for use by the draftsman* in making finished working drawings. While still an engineering or science student you should develop facility in making good freehand pictorials and orthographic drawings. You should take advantage of every opportunity—not only in graphics courses—to gain experience in technical sketching.

*Practice in making freehand sketches should become a hobby.* The full realization of the importance of developing skill in *"talking with a pencil"* will become increasingly evident after you have graduated from college and have entered upon the practice of engineering. You need not be an artist or have special talents to produce good freehand sketches. The essential requirement is to draw a reasonably straight line between two points. Of course, some training and practice are necessary. The skill required is, surprisingly, no greater than any student needs for good legible