INTRODUCTION
TO
MODEST MORPHOLOGY

by John D. Strong

Modern technology is constantly faced with problems for which it is of transcendent importance to get timely solutions. Many of these problems are so complex that they cannot be solved by conventional methods, but the Morphological Research Method developed by Fritz Zwicky, Caltech professor of astrophysics, provides formal procedures suitable to the solution of such problems. These procedures have much in common with those used informally and intuitively by our scientific giants – especially Faraday and Mendéléeff. In their application, however, Zwicky's procedures have the new feature of explicit formality, so that they can be consciously practiced.

Zwicky's morphology arranges the progress toward the solution of a problem into four phases:

1. Formulation of the problem
2. Analysis of the problem
3. Synthesis of valid solutions
4. Judgment of these solutions

The real inner purpose of separating and formally arranging these phases, and of formally arranging the application of talents to them, is to *remove restrictions* which would otherwise preclude optimum solutions. A completely rigorous and full response to these four phases, as it applies to almost any technical problem, requires the devoted application of several competent scientists for a matter of years. As in an imperfect practice of the Christian Ethic, which can be practiced rigorously and fully only by saints, there is merit in an imperfect, or less than rigorous and full application of the morphological method.

A problem must be a strategic one to be worthy of the extensive effort of giants. In contrast, I describe the applications of "modest morphology" to problems of experimental physics, particularly instrument design, and, specifically, problems whose solution is subject to severely modifying, prescribed restrictions.

The prescribed restrictions relate to the fact that our problems come under established, defined programs with fixed budgets and definite performance dates. We apply morphology to the many small, unanticipated, ancillary problems that come up in our research. Most of them could be solved by straightforward engineering; only occasionally one requires invention. These tactical problems, however, must be solved for so-and-so-much money, and within such-and-such a time limit. Also, we work under many other restrictions. It is a mistake to complain, for all of these restrictions are a proper condition on our work. Fortunately, they do not preclude the restricted use of Zwicky's morphological method.

This restricted application is most effectively applied by a properly indoctrinated group, working together. And it is part of the indoctrination for members of the group to learn that the formality of the method may appear, at first, to be an unnecessary distraction. They will soon learn, however, that the distraction is worthwhile because, in the end, by practicing modest morphology they will require less time to meet their goals, and they will achieve their goals more effectively and enjoy more personal satisfaction.

Here, then, are the four phases of modest morphology as we practice it.

Phase I. The Problem. I have often visited groups, busy at research, that have not formulated an explicit definition of their problem. Such a definition is important.

Phase II. The Analysis of the Problem. The purpose of the second phase, analysis, is to enumerate and organize *all* the parameters that are pertinent to valid solutions of the problem.

In our modest practice we state our problem, list the *main* parameters and begin forthwith to synthesize solutions. We take the parameters as being either obvious to all concerned, or we develop the parameters more formally as we go, by feedback from the various solutions that come up. Thus, in our less formal practices we are fluid, the parameters being changed as we progress. Even the definition of the problem may be changed by the synthesis of solutions for it.

Phase III. Synthesis of Solutions. In an extensive morphology it is necessary to make every possible combination of the parameters, and thus to derive *all* of the valid solutions. In our restricted practice of morphology there is a tacit understanding that we must get at least two valid solutions. The second solution is often more satisfactory in elegance, in cost, or in time of realization than the first, even when the first was completely adequate. The first solutions, as in the example I give later, may be conventional ones, widely practiced. And in the rare case when no improvement is made over an adequate first solution, a confidence factor is obtained, from getting a second, that is worth the trouble it costs.

Combinations of parameters frequently produce inventions. The law defines invention as an act of the creative imagination lying beyond that which is possible to the mind of those who are simply skilled in the art. A creative combination of parameters is referred to in the law as the so-called "flash of genius." Inventions arrived at by the practice of the morphological approach are sometimes, but usually not, of this sporadic flash type; they ordinarily come from the deliberate application of the imagination to the parameters analyzed. *The fact that "inventions" can be deliberately induced is a main value of the morphological approach.* Zwicky's morphology teaches the "secret" of sparking this induction.

Invention (the discovery of a hidden valid solution) is not inhibited when one follows the rule that, during the synthesis phase, it is only proper to pass judgment as to whether or not combinations form valid solutions. It is improper to judge these combinations initially on any other basis. If this rule is obeyed, garnering valid solutions to a problem becomes straightforward.

One can best understand the compromises of modest morphology, as contrasted with the uncompromising thoroughness and rigidity of Zwicky's teaching, by extending our analogy to the Christian Ethic. Like a man who acts like a Christian on Sundays but is "practical" during the week, we apply the commandment to get *all* the valid solutions, each without prejudice, only as far as we can afford to within the frame of our restrictions. It is our practice to sustain the morphological attack until we get two or more valid solutions to a problem, or until we have made a sincere try for a second solution.

In modest morphology the valid rule that certain spontaneous, premature evaluations of valid solutions must be suppressed until *all* the valid solutions (or at least two, in our case) are garnered is all but impossible to adhere to. It is difficult to follow this rule because one must suppress much impulsive judgment; each successive solution, or invention, as it is garnered, will be spontaneously judged "good" or "bad." For example, a particular solution may be impulsively and prematurely judged "bad" because it requires materials for reduction to practice that are not available, or it requires skills that are not attainable, or it involves expense that is unsupportable. During the synthesis stage, only the judgment that a solution is a valid one, or not, is proper.

And yet, after the climate of modest morphology has matured in a group, these spontaneous, premature evaluations of "good" and "bad" are gracefully handled; and they serve a valuable function.

In a properly indoctrinated group, if a solution is valid, but is spontaneously declared by anyone in the group to be "bad," then the inventor will be

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A graduate of the University of Kansas, he got his PhD from the University of Michigan in 1930, and came to Caltech as a research fellow. He was in charge of the research and development work which resulted in the optical systems of the Palomar Observatory. In 1937 he became assistant professor of physics and astrophysics here.

While at Caltech, Dr. Strong evolved the first practical technique for evaporating aluminum directly to mirrors, now a standard practice. At Johns Hopkins, his interest in infrared spectroscopy has led to a unique and highly specialized design of ruling engines for diffraction gratings, and further, to the application of experimental physics to meteorology and astrophysics.

The morphological method which Dr. Strong discusses in the accompanying article is nothing more than an orderly way of looking at things. Its aim is to achieve a schematic perspective over all of the possible solutions of a given large-scale program. The method was developed by Fritz Zwicky – professor of astrophysics at Caltech, and staff member of the Mount Wilson and Palomar Observatories – with whom John Strong worked while he was on the Caltech faculty.

especially proud of it. Or he may secretly have judged it "bad" himself, and he will be proud of having suppressed his prejudice. He will admonish his critics for their prejudice – and then look for some "good," knowing that "bad" solutions are valuable for the following reasons:

1) Some "bad" solutions actually produce results which "good" ones do not, and thus may amplify or alter the statement of the problem.
2) A "bad" solution may induce a "good" one.
3) Two "bad" solutions may combine to produce a "good" one.
4) A "bad" solution may point out the need for more analysis.

Phase IV. The Judgment. The choice of the particular solution that is to be reduced to practice, and tested, from among all those that have evolved, can now properly be made with open consideration of values which have heretofore been suppressed, such as available materials, attainable skills, supportable cost, achievable deadlines.

Since our practices fall far short of the ideal, how, then, is our modest morphology different from standard engineering practice in which alternate solutions or alternate designs are also evolved? The main difference lies in our attitude about, and treatment of, "bad" solutions. Experience has taught us their value. We seek them out and treat them with respect.

Many examples of the application of modest morphology are not as crisp and black-and-white as my exposition might imply. In many instances the fruit of this application, like all good solutions, seems, in retrospect, to be trivial and obvious.

Our experience in the design of a dividing head for a new diffraction grating ruling engine will illustrate the value of modest morphology.

Man's most powerful tool

Albert Ingalls, in an article on ruling engines in *Scientific American* for June 1952, states that it is no exaggeration to say that the splitting of light into its colors by means of spectrographs is man's most powerful tool for investigating the universe. Astronomers use spectrographs to study the stars, physicists to probe the atom, chemists to identify molecules, biologists to explore living substances, food processors to test food, detectives to analyse blood stains.

A prism may be used to sort out the colors of the light, but modern spectrographs require the use of the much more powerful diffraction grating.

The ruling of diffraction gratings is an art that has been practiced for more than 80 years by American physicists – notably, in the beginning, H. A. Rowland, J. A. Anderson, and R. W. Wood at The Johns Hopkins University, and A. A. Michelson at the University of Chicago.

Nowadays, a diffraction grating is made in a thin uniform aluminum film deposited on a polished plane or concave spherical glass surface. Several tens of thousands of grooves of a specified profile (or shape) must be embossed (or ruled) in it by the diamond tool of a ruling engine. The power of the grating depends not only on the precision of shape of the plane or spherical surface, but also on having the embossed grooves straight and parallel to one another, and equidistant – all within a small fraction of the wavelength of the light which we wish to analyse with the grating.

Two basic approaches

The generation of precise shapes can be achieved, in principle, by two basic approaches – either by a *construction procedure* that is inherently adapted to generate the desired surface automatically; or by a *correction procedure* that eliminates local imperfections after they are revealed by a suitable test.

I can illustrate and contrast these procedures by describing the construction of a concave polished grating blank. Two similar pieces of glass are rubbed together with an abrasive between them. This rubbing produces mating spherical surfaces (one converse and the other concave) automatically. Subsequently, after polish, the concave surface may not be precise enough for a grating blank. But it can be made precise by "figuring" – that is, by local polishing, guided optically by the Foucault knife-edge test. This is a correction procedure.

As far as the ruling of optical gratings is concerned, the problems of procurement of spherical and flat blanks have been fairly well solved during the past 60 years. Actually, it seems that the ancient Egyptians knew and used the sophisticated and inherently precise procedure of lapping three surfaces together to make them flat. But there are other instances where inherently automatic procedures may be used in the construction of a ruling engine.

By the application of modest morphology we developed a new method whereby we made a straight rod for our ruling engine. It was made straight to a millionth of an inch by an automatic, inherently precise, procedure. I mention this application here only as introduction to another equally effective automatic procedure that we developed, and that I shall use to illustrate the application of modest morphology.

The morphologist, when doing total research, is not only interested in how to produce straight lines, flats, spherical surfaces, and so on, by one or the other of the intrinsically accurate methods, or by one or the other of the methods of successive approximations; he will actually want to know the totality of mechanical, optical, electrical, or chemical methods that there are, by which he could produce the required geometrical figures. The importance of such knowledge of all the possible methods is evident when it is realized that the best method of producing straight grooves on a grating blank may not at all be the best method to achieve straightness in other cases where it is vital – as for the seven-mile-long rocket test sleigh track at the Holloman Air Force Base at Alamogordo, N. M., or the two-mile-long linear particle accelerator at Stanford University. Failure to choose the best method of producing a straight line may in some cases actually result in losses of millions of dollars.

Two main difficult problems

In the development of a ruling engine there have been two main difficult problems: one is the problem of shaping of the grooves, for blazed gratings; and the other is the control of the diamond's motion, to get straight and accurately spaced parallel grooves.

The first problem requires a suitable metal film into which to form the grooves, and skill in adjustment of a precisely shaped diamond ruling edge. My own introduction of aluminum films, when I was at Caltech, provided the suitable film, and the skillful adaptations of the ancient art of cutting and polishing diamonds provided the tool.

As to the latter problem, after we had developed new methods of generating, mounting, and using precision lead screws for our ruling engine, to produce proper spacing of the grooves, we needed means to accurately control the positions of the screws. For instance, in order to accurately effect the shift of 69 millionths of an inch from one groove ruling stroke to the next, we needed to rotate our lead screw (of 40 threads per inch) accurately by increments of angle of one degree of arc.

In the prior art, two methods were commonly practiced to get such incremental rotations. One method was to mount the wheel of a worm gear combination on the screw and turn its associated worm, repetitively. The other method was to use a dividing head – a wheel with, say, 360 triangular-shaped teeth around its rim. Then an associated pawl engaged a tooth of the head to locate the angular position of the head. The wheel might thus be rotated, repetitively, one tooth of angle at a time, and then held in each position by the pawl.

Following our policy for such cases we set ourselves the task of adding at least one new method to the prior art, before we would select a plan for execution. But all of the new methods that we garnered, when later judged, proved to suffer an intolerable accumulation of errors. In contrast, the dividing head or worm wheel with an integral number of teeth around its circumference is free of accumulated error.

New methods

We therefore elected to use a dividing head and moved on to the problem of finding new methods of doing this.

In connection with the application of modest morphology to this new problem, we began to look for methods to mount, and to use, the dividing head that would provide equal incremental rotations irrespective of its faulty construction. This was our definition of the problem.

Proceeding to find at least one new solution to add to the commonly practiced methods, first we considered angular positioning the dividing head with not one pawl but with a pair of pawls symmetrically disposed at opposite sides of the head's circumference. They were to be spring-mounted. It is well known by surveyors, and others, that by reading a precise transit circle twice, at points separated by 180°, and averaging these readings, one gets an angle value that is free of such errors as arise if it is mounted off-center. We considered achieving this effect automatically by means of the two spring-mounted pawls. This adaptation of an old trick provided a new valid solution to the first half of our problem; and it led us to realize that we could also average out, or ignore, the individual tooth errors of an imperfectly made wheel if we used 180 pairs of such spring-mounted pawls. And this "obvious" elaboration provided a new valid solution for both halves of our problem.

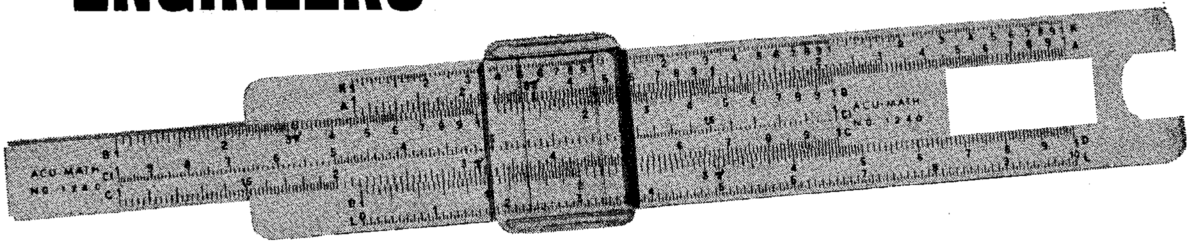
Going on from there, in consideration of various means by which we could use 360 spring-mounted pawls, such as opening up and closing them like the opening and closing of the petals of a flower, we came upon the terminal idea, which was to use the 360 spring-mounted pawls as 360 laps, and by this means generate a perfect dividing head.

The 360 laps were to take the form of short springs of steel, of triangular cross section. They were to be mounted for this purpose by fitting and fastening them in the teeth of a second dividing head. I call the dividing head that was intended to be perfected, the "work." I call the second head the "tool." We machined these two dividing heads so they were alike and as precise as possible.

The 360 steel springs of the "tool," when bent in slightly, and charged with a suitable abrasive compound, act as laps when they are lowered into the teeth of the "work." Consider any one of them as it rubs its way into contact with first one tooth, and then the adjacent one of the work, and so on. As this occurs, the other 359 springs will position the work, which is floated freely on an oil film. And, even if the 360th lap is not perfectly located where it should be, considering the other 359, it will, on its own favored side, still lap away more or less from any misplaced tooth in the work, according to the error of location of that tooth. Thus the teeth are all shifted, by lapping, into the positions that will yield greater uniformity of spacing. The result is that, as the lapping progresses, the teeth of the work are rapidly made free of error. And since we use hydraulic devices to control the stroke of the tool, automatically (that is, to raise the wheel with its laps, rotate it 1° between each stroke and lower it onto the floating work) this improvement of uniformity in location of the teeth, intrinsically precise, progresses automatically.

After 50 hours of unattended lapping, we found that the errors of our first wheel were reduced by an order of magnitude. Radial and tangential starting errors of a tenth of a thousandth of an inch, and a minute of arc, became, after lapping, final errors of only one or two hundredths of a thousandth of an inch, and a second of arc or two. Although this was more than adequately precise for us, there is no reason the process will not continue to far greater precision (without any exercise of skill) in instances where such greater precision will be required.

This example is typical of our experience. I doubt if we would have come upon this practical new



method that perfects a dividing head without any exercise of skill if we had not applied the principles of modest morphology, or at least we would not have marched straight to it, as we did.

One of the most important tasks before us, for the future, is the construction of large transparent gratings which will cover the whole aperture of wide angle telescopes.

Fritz Zwicky, (who, with the late Professor R. W. Wood, of Johns Hopkins University, many years ago assembled the first mosaic grating for the 18-inch Palomar Schmidt telescope) thinks that the 48-inch Schmidt telescope, equipped with an efficient full-aperture transparent grating, would be more effective than all other telescopes, as far as the discovery of new celestial objects is concerned. It also would make possible the wholesale spectral analysis of millions of stars and galaxies as faint as 1/100,000, the brightness of the faintest naked-eye stars. The solution of the problems involved in the construction of such large transparent gratings, with funds that can be properly made available, again calls for the use of the morphological method. In this case, in fact, the morphological method may even be indispensable.

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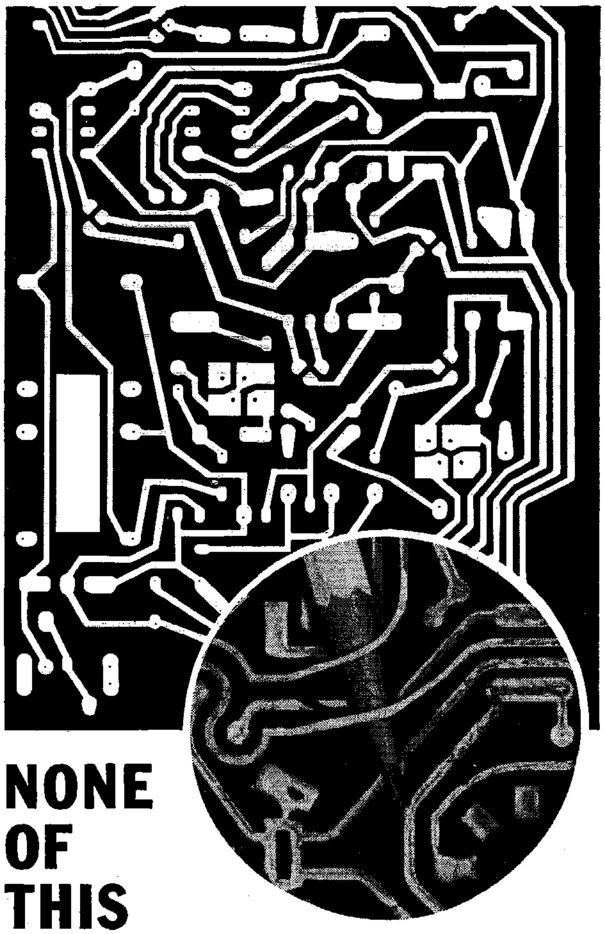

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