CHRISTOPHER ALEXANDER

FROM A SET OF FORCES TO A FORM

There are more and more man-made objects in our environment. Each one is made to meet certain needs, but unfortunately they often fail to meet the needs. This raises the question: "Given a set of needs, how can we generate a form which meets those needs?"

In this paper I shall describe three fundamentally different ways of doing this: by numerical methods, by analog methods, and by relational methods. Numerical methods and analog methods are in common use. Indeed, most of the research now being done on "systematic" methods of design is based on these methods. However, I believe that they are almost entirely unsuited to environmental design: they are far too simple. The complexity of the needs which enter into the design of an object like a house demands much more general, and more powerful, methods.

In the last section I shall deal with a class of methods which I call relational methods. I believe they are, in principle, capable of generating form even in answer to the great complexity of human needs. But they are so far almost unexplored. I have written this paper in the hope that it may persuade some of the people now working on numerical and analog methods to shift their attention to relational methods.

Let us begin by extending the concept of a "need."

The concept of a need has several faults. It can easily be unobjective, it gives no indication of the kind of form which satisfies the need and, worst of all, it is too narrow. It leaves out many other factors which must influence the form of buildings: the force of gravity, the tendency for heat to flow across a temperature gradient, the fact that people tend to walk in straight lines, the social forces which make it necessary for a housewife to keep a "tidy room" for visiting strangers, the economic forces which cause a steady drift of population from rural into urban areas, the processes of production and distribution which force builders to use pre-assembled factory components, and the deeper psychological demands of human nature.

I shall therefore replace the concept of need, by the concept of "force." A force is an invention. It is an invented motive power which summarizes some recurrent and inexorable tendency which we observe in nature.

All systems, whether they are individual human organisms, or social systems, or mechanical systems, share the following property: when in certain states, they have inexorable tendencies to seek certain other states. If the system is human, we summarize these tendencies in terms of needs. If the system is mechanical, we summarize the tendencies in terms of Newtonian forces. If the system is thermodynamic, we summarize the tendencies in terms of thermodynamic potential. If the system is social, we summarize the tendencies in terms of social forces. Etc., etc.

The fact that people need a certain light level for reading, summarizes the fact that, if they have the opportunity, they tend to switch the light on, or to dim the lights, or to move toward the window, when they find it hard to read.[1]

The force of gravity summarizes the inexorable tendency for two large masses to move toward each other.

Thermodynamic potential summarizes the inexorable tendency for heat to flow across a temperature gradient (like that between the inside of a building and the outside).[2]

The fact that people walk in straight lines, summarizes their inexorable tendency to take the shortest path between two points.[3]

When we speak of a woman's need to protect herself symbolically against invasion, we mean to summarize the fact that she tends to enclose herself—for instance, with elaborate window curtains.[4]

These kinds of tendency, and many many other kinds, all play their part in shaping the environment. We must therefore choose a single word to summarize them. I have chosen the word *force*.

In order to define a tendency we must define:

1. The exact circumstances under which the force arises.
2. The exact conditions which the force is seeking.

Forces generate form. In the case of certain simple natural systems, this is literally true. In the case of complex, man-made systems, it is a metaphor. Let us look at a simple system first.

When a constant wind blows across a sandy surface, it forms wave-like ripples in the sand (Fig. 1). There are five forces at work.[5]

Fig. 1. Sand ripples. Reproduced from Vaughan Cornish, *Ocean Waves*, Cambridge University Press (1934).

1. If there is any irregularity in the surface, the number of grains arriving on its windward slope (the slope facing the wind) is greater than the number arriving on the leeward slope (the slope facing away from the wind). The windward slope therefore tends to "catch" grains, and to grow.
2. The wind picks up grains and carries them a certain distance. For a given wind speed, this distance tends to be approximately constant.
3. The wind picks up more grains on a windward slope than on a leeward slope, and since it carries the majority of grains the same distance, any irregularity tends to be repeated one "path length" downwind.
4. When the grains land, their impact pushes other grains forward, causing creep. The impact is usually not enough to carry a large grain beyond the crest of a ripple, but it will carry small grains beyond the crest, so that the larger grains tend to accumulate at the crests.
5. On the crests, where the wind velocity is higher than in the dips, small grains tend to get blown off, and only heavy grains stay put.

These five forces make any level surface or any unevenly spaced pattern of bumps unstable. The slightest bump will grow into a ripple; and the ripples will repeat at regular intervals downwind, so that gradually a "wave-like" pattern of ripples is built up. With the wind blowing, the level sand surface is an unstable form because it gives rise to forces which ultimately destroy it. The rippled form is stable because the forces which it gives rise to maintain the form.

Let us now contrast this simple system with a complex system in the man-made world—a family and the house it lives in.

Although its evolution has made it partially stable, this system is still, in a larger sense, unstable. Periodically, it gives rise to forces whose repercussions threaten to destroy the harmony and stability of the whole.[6)]

People in the house will tend to try and escape from neighbor noise. But the house may not allow them to escape it, so the tendency has repercussions. People close bedroom windows and make the bedroom stuffy. They turn up the volume of the radio to drown the noise, making more noise in the neighborhood. Or the tendency goes underground altogether, until it finds an outlet in bad temper.

Again, people tend to try and store things on open level surfaces at about waist height. When there is no provision for this tendency, things get put on the kitchen stove and start a fire; or they get stored in a forgotten place and cannot be found when wanted; or, they get left on narrow window sills, and then knocked down and broken.

The forces which are not provided for do not disappear. They always find an outlet in an unexpected way. The deeper psychological and social forces, if not provided for, can easily have repercussions which lead to drastic kinds of instability. They do not, of their own accord, create a stable state.

Unlike the forces in a simple system, which always steer the system to a stable state, the forces in a complex man-made system are often impotent. The tendency to escape neighbor noise does not, of its own accord, create a quiet building. The tendency to store things on open level surfaces does not provide a house with large amounts of open level surface.

This is the basic difference between a natural object and a man-made object. A natural object is formed directly by the forces which act upon it and arise within it. A man-made object is also formed by certain forces; but there are many other latent forces which have no opportunity to influence the form directly, with the result that the system in which the object plays a part may be unstable. The form can be made stable with respect to all these forces only by artificial means. The most usual artificial method is that known as "design," in which an individual designer tries to generate the form intuitively. But "design" is only a particular way of doing this; there are other ways. We may state the problem of design, in its most general form, in two parts:

1. Given a system, how can we assess the forces which act upon it and arise within it?
2. Given a set of forces, how can we generate a form which will be stable with respect to them?

I shall not deal with the difficult problem of assessing forces here. Let us assume that they have been established by some reliable and objective means.[7)] There are then various ways of generating form from them. I shall now describe three ways of generating form.

I. NUMERICAL METHODS

All numerical methods of generating form rely on three essentials:

1. Each "force" can be represented by the variation of a one-dimensional numerical variable. One of these seeks minimization (or maximization). The others are held constant, and are called constraints.
2. Equations or inequalities relate the values of the different variables to the configuration of the system and to one another.
3. There exists a theorem, or an algorithm, which defines the configuration in which the chosen force reaches its minimum (or maximum) value, under the constraints provided by the others.

Here are three examples of numerical methods:

The calculus of variations. The calculus of variations defines curves and surfaces on which some chosen integral reaches a maximum or minimum.[8)]

Suppose, for instance, we have a system in which material slides down a chute, from one point to another, and suppose there is a tendency to minimize the time it takes the material to slide down the chute. The time can be expressed as an integral along the curve. The calculus of variations then shows that in order to minimize time, the chute must have the form of a cycloid.

Plant layout analysis and linear programing. Given any organization in which there is a lot of movement, like a hospital or an industrial plant, there will be certain tendencies for people and materials to move from one department to another; there will also be a tendency to try and cut down the total amount of daily movement in the organization as a whole.

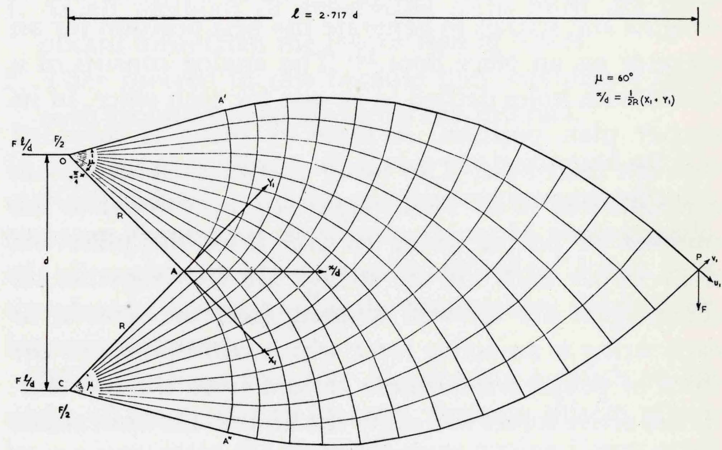
The (nearly) best layout for such an organization can be generated by a simple algorithm. This algorithm is based on the idea that you can compute the total daily movement, for any given layout, and then make successive improvements in the layout, by exchanging departments, until no exchange of departments leads to an improvement. This method has been widely used for laying out of both industrial plants and hospitals.[9]

The Michell Theorem. In the design of a load-bearing frame structure, the principle forces are the loads themselves (with their magnitude, position, and direction specified), and the tendency to try and reduce the weight of the structure to a minimum.

A theorem by A. G. M. Michell makes it possible to generate the form of the least-weight structure almost uniquely, from a specification of the loads. The theorem shows that all the members of the least-weight structure must lie on one of two families of orthogonal curves (the compression members on one family, the tension members on the other), and places strong restrictions on these families of curves.[10]

For example, in the case of a simple cantilever, carrying a single load, the families of curves are near spirals, as shown in Fig. 2; and the least-weight cantilever which they generate is the fish-like structure illustrated in Fig. 3.[11]

These kinds of methods are beautiful as far as they go. But they are very limited. There is no guarantee that the forms they generate are stable, since it is likely, indeed, almost certain, that there will be other forces in the system which have not been represented. The Michell theorem, though it minimizes the weight of the structure, does not take into account the need to use steel sections which can easily be transported, or the fact that the cantilever will need periodic repainting. The hospital layout, though it minimizes movement, does not take into account the patients' need to feel secure in the hospital, or the need for conditions which speed up cure. We must remember that numerical methods only work for forces which can be represented by the optimization of a single one-dimensional numerical variable. Most of the subtler human forces cannot be.



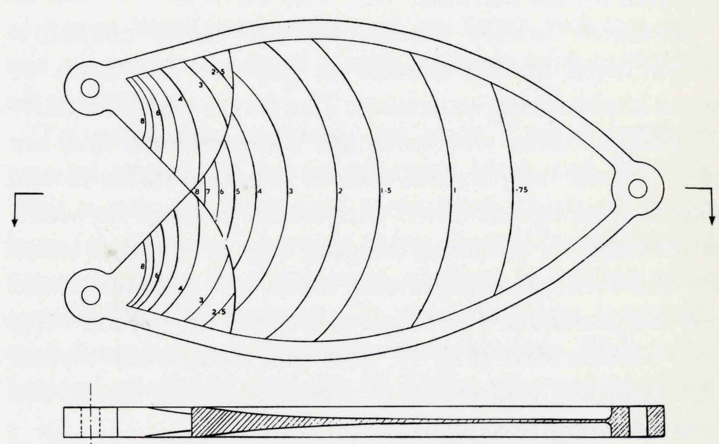


Fig. 2. Drawing for a simple cantilever.

Fig. 3. Drawing for a least-weight cantilever.

II. ANALOG METHODS

Analog methods actually generate form physically. As we know, the forces which occur in a system are often too weak to take the system to a stable state, of their own accord. It is sometimes possible to find a second system, which is a model or analog of the first, in which the forces model the forces of the first system, but are this time strong enough to take the system to a stable state. If the analog is well chosen, the form of this stable state will also be a stable form for the original system.

Analog methods rely on one essential: each force can be represented by some "active" force in the analog.

Here are three examples of analog methods:

The use of weights and strings to locate an elevator. Perhaps the simplest analog device of all is the use of weights and strings to generate the best position for an elevator on an office floor.[12] The analog consists of a board with holes drilled in it, one for each office, in its proper plan position. A piece of string is threaded through each hole. The lower end of each string has a weight tied to it. This weight is proportional to the number of people going to and from the office. At their upper ends all the strings are tied together. If the weights are allowed to hang free, the tension in each string is an active force which corresponds to the force of people's movement to and from the elevator. These active forces will move the knot to the most stable position for the elevator.

Antonio Gaudi's models for the Guell chapel.[13] Gaudi used analog devices to generate the form of stone load-bearing structures. The forces which actually operate in these structures are compressions, and are not, of their own accord, able to generate stable forms. Gaudi used upside-down wire-model analogs in which wires stand for columns, hanging bags of lead shot stand for the eventual compressing loads, and tensions stand for compressions. The tensions are able to pull the wires into a stable form (Fig. 4). This wire form, when turned upside-down, and made of stone, is stable under the original compressions (Fig. 5).

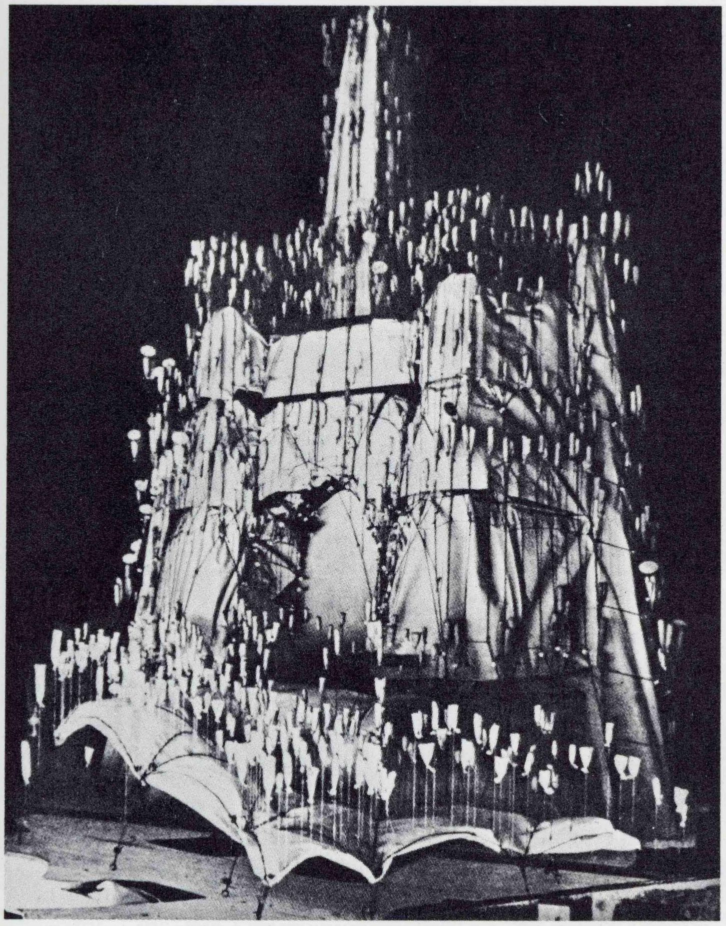
The experimental use of lightweight furniture. My third example of an analog is an actual living room. The forces at work within a living room are complex: tendencies for people to move through the room on certain paths, tendencies for people talking to sit close together, tendencies for people to move into positions where the draft is least, and to where the light is best, and to where they face the fire...

Under normal circumstances the furniture in a room is so heavy that these forces are powerless to move it. However, they can be made temporarily active. When I recently bought a house, instead of starting with permanent furniture in the living room, I started with lightweight bamboo stools for seats and tables. With these bamboo pieces in it, the room itself became an analog, the forces became temporarily active, and could push and kick the system from one state to another. After a few weeks, as people used them, the pieces fell into a stable pattern. This pattern defined the best configuration for the permanent furniture.

Again, these kinds of methods are beautiful as far as they go. But, like numerical methods, they are very limited. The wire model contains no force which represents the need for adequate light. The furniture analog contains no force which represents the need for easy cleaning. Analog methods only work for forces which can be represented by some "active" counterpart. Most of the subtler human forces cannot be.

Fig. 4. Canvas and wire model for Guell chapel. The photograph of the model, which is actually suspended from the ceiling, is here reproduced upside down.

Fig. 5. Interior view of vaulting and supports of Guell chapel.



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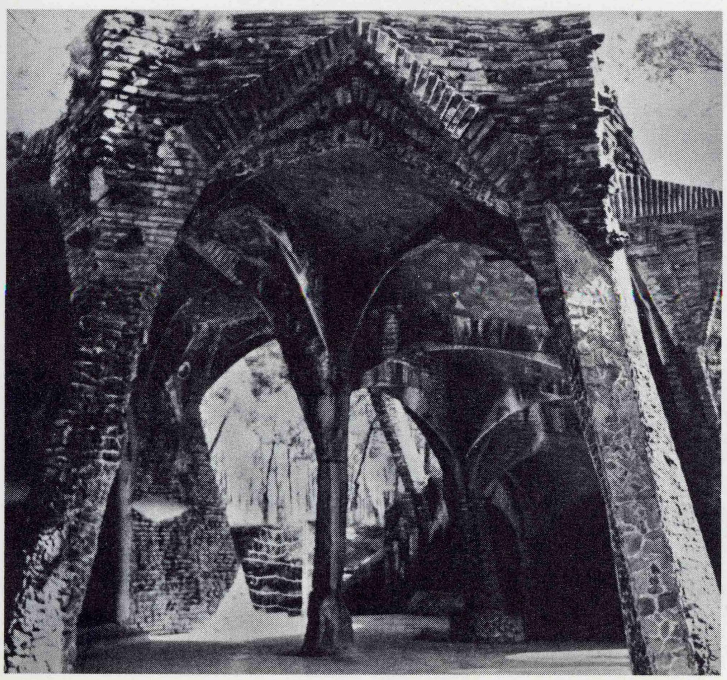

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III. RELATIONAL METHODS

I have tried to give the reader some sense of the limits of numerical and analog methods. Though they are rich and valuable for problems in engineering and economics, they are almost useless in designing houses, or any piece of the environment where people are. The reason is simple: no more than a handful of the practical, psychological, and social forces which have the most profound effect on human life can be represented by these methods. Most forces cannot be represented by the variation of any one-dimensional numerical variable. Most forces cannot be represented by "active" forces in an analog.

But there are two valuable lessons to be learned from numerical and analog methods:

1. As all methods of generating form must do, they obtain form from the *interaction* of forces.
2. They succeed in this because they establish a common ground where the forces can interact.

In numerical methods all forces are expressed as numerical variables, and the number system provides the common ground for their interaction. In analog methods all tendencies are expressed as "active" forces, and the physical analog itself is the arena where these active forces can interact.

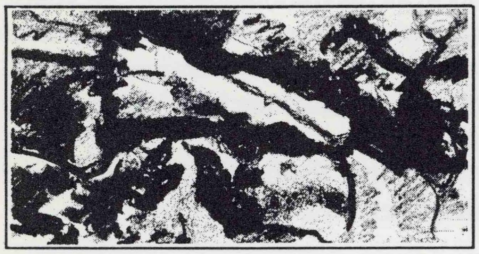
What we need is a way of allowing a much wider range of tendencies to interact. Bearing this in mind, let me now state the problem once again: *Given a set of forces,* WITH NO RESTRICTION ON THEIR VARIETY, *how can we generate a form which is stable with respect to all of them?*

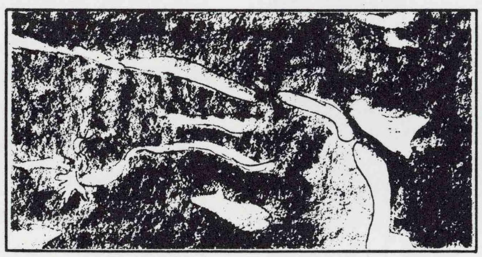
To solve this problem, we must find a common ground where all forces, of every kind, can interact. This means we must find something which all forces have in common. The only thing that all forces have in common is the fact that each of them is seeking some specific kind of end-state. In more familiar language, each force has certain physical implications. This is the basis of relational methods.[14] There are two key ideas:

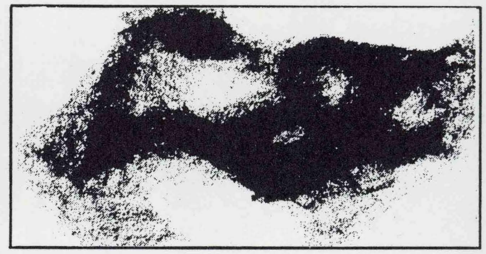
1. We try to determine, as abstractly as possible, the physical relation which each individual tendency is seeking.
2. We try to combine these individual abstract relational implications, by fusion, to generate the form.

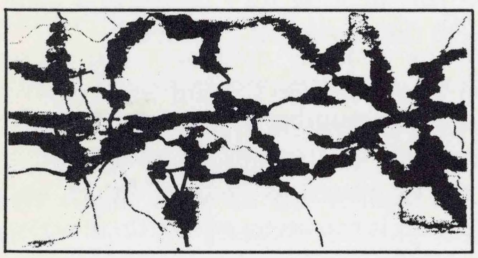
We may begin to see how the relational implications of forces can be stated, and combined by fusion, in the following example taken from work done several years ago at the Massachusetts Institute of Technology.[15)]

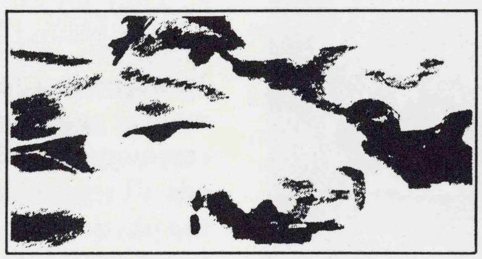
The problem was to locate a twenty-mile stretch of highway in Massachusetts, starting from Springfield and ending somewhere near Northampton. We defined twenty-six forces which would influence the location. Each force seeks a certain kind of location for the highway. For example, force number 1, the need to reduce earthwork cost, seeks a location through the areas where the land is flat. The full relational implication of each force is represented as a pattern of grays over the terrain: each point in this pattern is dark if the force is likely to generate a highway through that point, and lighter if it is less likely to do so. All twenty-six individual relational implications are shown here. Each corresponds to the entire terrain from Springfield to Northampton.

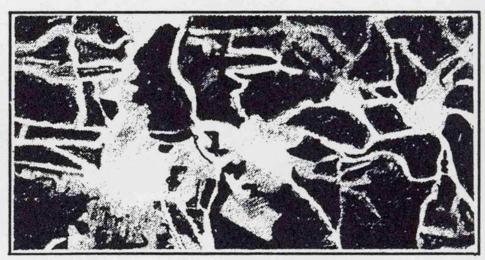

1. Earthwork Costs

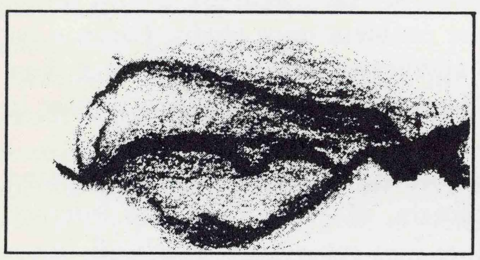

2. Comfort and Safety

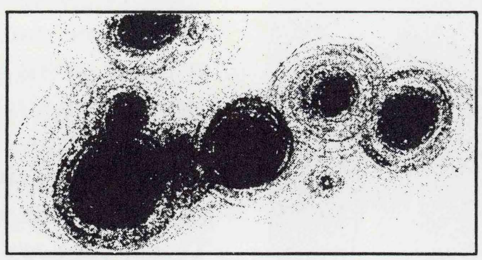

3. Regional Development

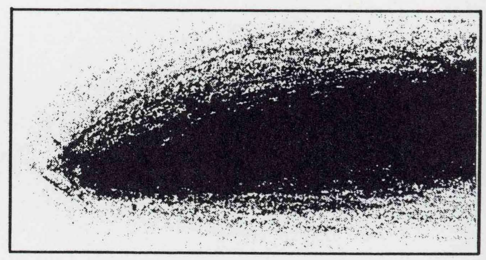

4. Local Land Development

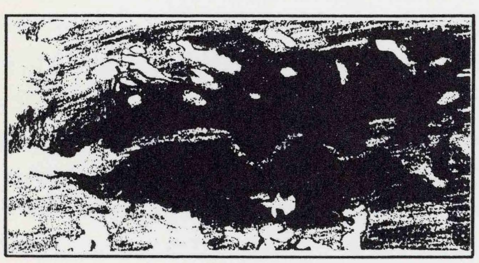

5. Obsolescence


6. Interference During Construction

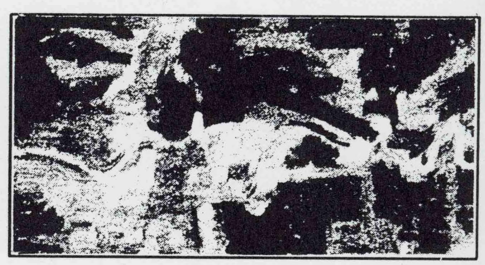

7. User Costs


8. Services

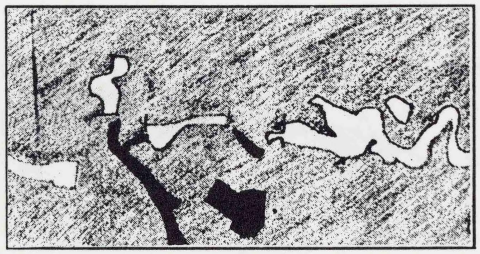

9. Travel Time


10. Pavement and Subgrade Costs

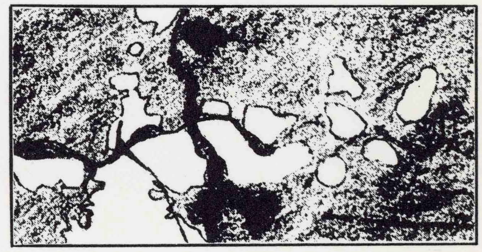

11. Drainage Patterns


12. Bridge Costs

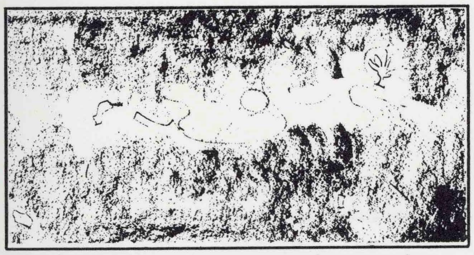
13. Land Costs



14. Eyesores

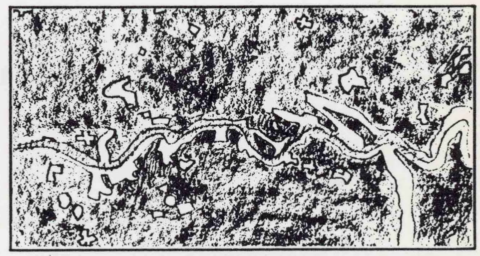


15. Noise

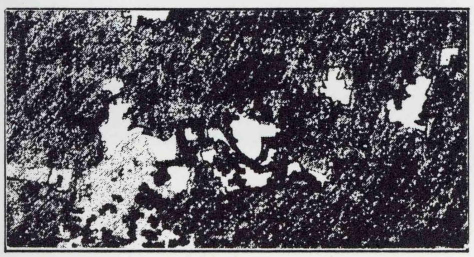


16. Air Pollution

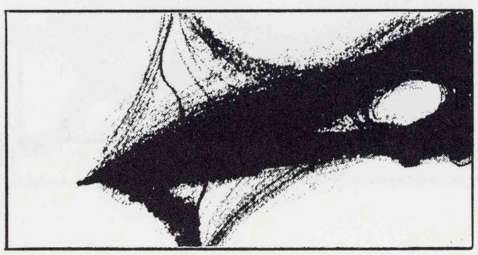
17. Weather Effects



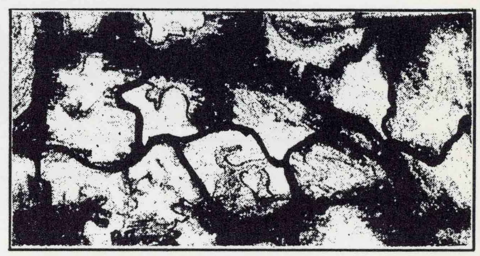
18. Non-recompensable Public and Private Losses



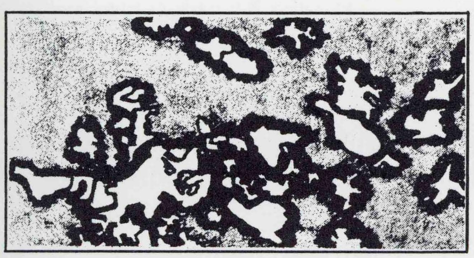
19. Public Financial Losses



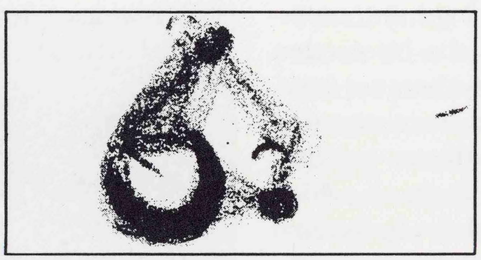
20. Major Current Traffic Desires



21. Catchment Areas



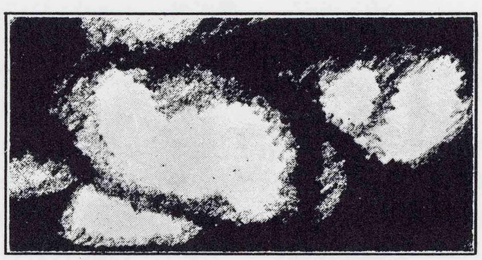
22. Local Accessibility and Integrity



23. Future Transportation Systems

24. Existing Transportation Systems

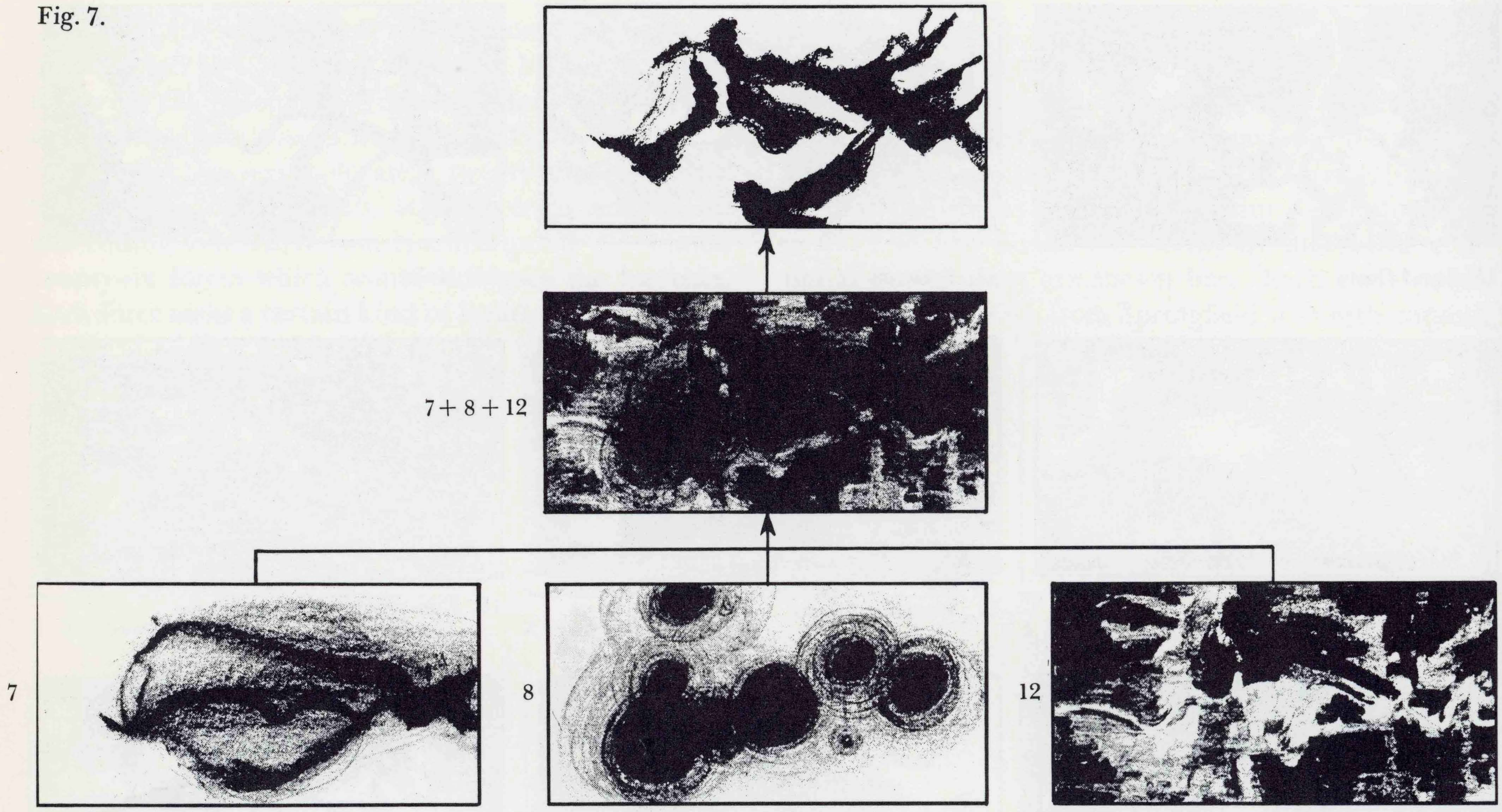
25. Duplication of Facilities



26. Self-induced Congestion

Fig. 6. Panels 1 through 26 are reproduced from the M. I. T. report, *The Use of Diagrams in Highway Route Location,* by Alexander and Manheim.

Fig. 7.



When two or more of these drawings are superimposed, a new pattern emerges from the interaction of the individual patterns. This happens because functionally, and visually, the patterns get their meaning from the continuity of density. Two patterns together may form certain continuous strands of darkness, which are not individually present in either of the individual patterns; and in the same way, patterns present in the individual drawings may be submerged in the combination of the two.

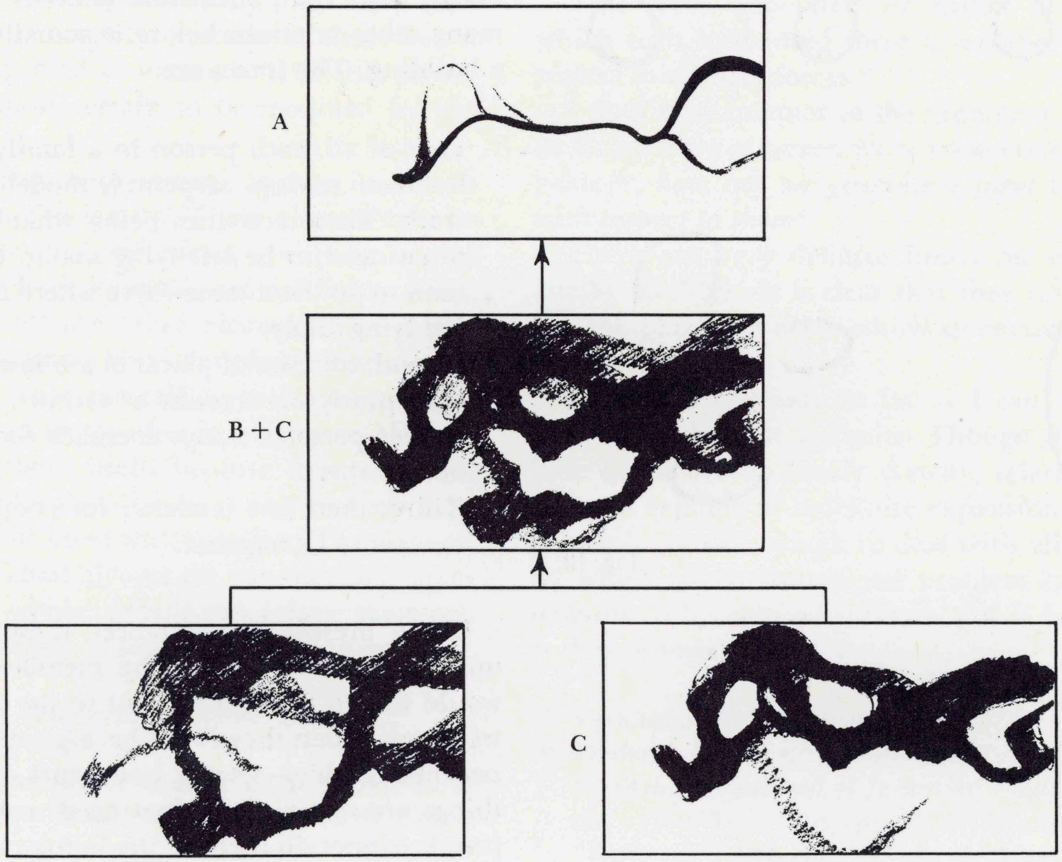
Fusion was carried out by superimposing several patterns photographically, and then, from the darkest, most continuous areas in the composite, generating a new pattern (Fig. 7). After a number of processes of fusion, the last fusion generated the pattern A shown in Fig. 8: nothing remains except a pair of lines, one darker than the other. The darkest line defines the best location for the highway (Fig. 9).

This example illustrates the two key ideas of all relational methods. Let me repeat them:

1. We try to determine, as abstractly as possible, the physical relation which each individual force is seeking.
2. We try to combine these individual abstract relational implications, by fusion, to generate the form.

However, the example is unusually simple. First, we know in advance that the highway will be a thin and gently curving line, and this makes the implications easy to state. Second, the underlying terrain provides a constant framework which makes fusion easy. It will usually be much harder to define the implications of individual forces; and much harder to state them in a universal framework, so that they can easily be fused.

Fig. 8.



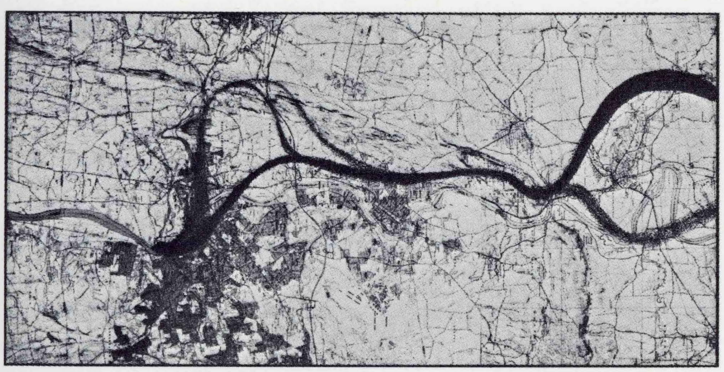


Fig. 9.

I shall finish by sketching a very simple example which shows these key ideas as they appear in a more general kind of problem. This example deals with the three-way interaction between three forces connected with the "living room" of a house.

I ask the reader to ignore the fact that these three forces are artificially isolated—in a real living room there are perhaps a hundred forces which must all be studied simultaneously. I ask also that he ignore the fact that the abstract relational implications of the individual forces are not clearly expressed; and that he ignore the fact that the process of fusion is not clearly explained. Neither the individual implications nor the fusion can be accurately defined, because at present we still lack any universal way of expressing them.

Lastly, I must ask the reader to remember that, since the example is based on three forces which have been arbitrarily picked out, the form they generate is itself

Fig. 10.

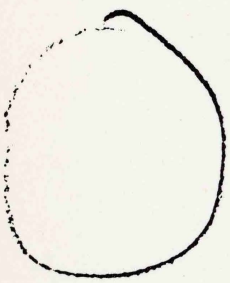


Fig. 11.

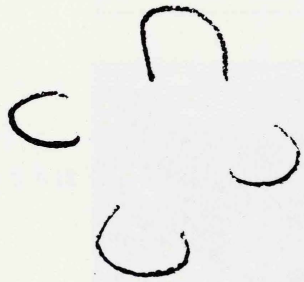
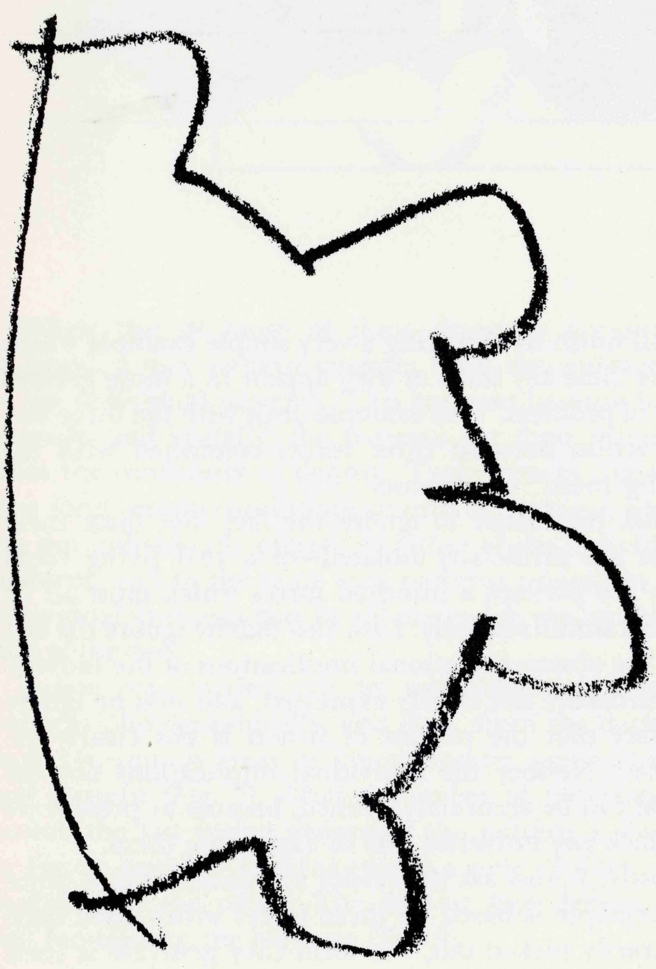


Fig. 12.

Fig. 13.



hardly more than a relation: it needs to be fused with many other relations before it actually defines part of a building. The forces are:

1. First of all, each person in a family has his private hobbies: sewing, carpentry, model-building, homework. These activities being what they are, things often need to be left lying about. People therefore tend to do them somewhere where the things can be left lying safely.
2. Second, communal places in a house have to be kept tidy, partly on account of visitors, but also so that no one person's things encroach too heavily on any of the others.
3. Third, there is a tendency for people in the family to want to be together.

Under present circumstances, these three forces are mutually incompatible. The members of the family would like to be together; but in the evenings, and on weekends, when they could be, each one follows up his personal hobbies—sewing, homework, . . . Because these things are messy, and often need to be left standing, people cannot do them in the living room—they would be cleared away too soon. Instead, to do these things each person goes off to his private area—the kitchen, or the basement, or the bedroom—and the family cannot be together.

What are the relational implications of the individual forces?

The first one demands that each person have a private space, where he can do whatever he wants, and where he can leave things, knowing that they will be safe (Fig. 10).

The second one implies that any communal living space, where people come together, must be easy to keep tidy, and people's individual bits and pieces must not encroach on it: hence, that it will be a self-contained spatially integral unit (Fig. 11).

The third implies that when the individual members of the family are following their private interests, they should nevertheless still be with the family as a whole, still be able to see each other, still be within earshot and able to be together easily (Fig. 12).

I have shown these individual relations crudely in the drawings. Fusion of these three relations generates the form shown in the larger drawing (Fig. 13). I shall describe this form concretely, to make it clear. But it must not be interpreted as concrete. It is still an abstract relation—almost certain to be modified by further fusion.

It is a living room with several alcoves in it, one for each person in the family. These alcoves may be left untidy; private bits and pieces are quite safe in them. Each alcove looks into the central living room, and also looks at all the other alcoves. (The angles between alcoves are important.) People in these alcoves can see each other, they can talk to each other, and if they want to they can be together in a moment. Yet, the communal living room itself, because it is a convex whole which excludes the alcoves, is easy to keep tidy. (The alcoves might be fitted with curtains.) The bits and pieces in the individual alcoves do not encroach upon the tidiness of the whole: people can follow their private inclinations and yet be together, simultaneously.

This form, generated by fusion of the relations which each individual force is seeking, is stable with respect to all three forces.

I shall now summarize the argument. The question is: *Given a set of forces,* WITH NO RESTRICTION ON THEIR VARIETY, *how can we generate a form which is stable with respect to them?*

There are very definite limits on numerical and analog methods. It is clear that they cannot cover the full complexity of needs which an environmental problem can contain.

Relational methods, as far as I can see at present, have no such built-in limits. Though the examples I have given are obviously sketchy, relational methods do seem capable of indefinite expansion. They are, in principle, broad enough to deal with all the complexity which an environmental problem can contain. It remains to be seen whether they will be as powerful as they promise.

1. R. G. Hopkinson, *Architectural Physics: Lighting,* London, H.M.S.O. (1963), p. 15.
2. In the thermodynamics of irreversible processes, these tendencies are actually called "forces." S. R. de Groot, *Thermodynamics of Irreversible Processes,* Amsterdam (1961), p. 5.
3. Tyrus Porter, B. Arch. Thesis, Dept. of Architecture (1964), University of California, Berkeley.
4. Theodor Reik, *Of Love and Lust: On the Psychoanalysis of Romantic and Sexual Emotions,* New York (1957), pp. 476–491.
5. R. A. Bagnold, *The Physics of Blown Sand and Desert,* London (1941), pp. 144–153.
6. I have previously called this kind of runaway unaccommodated force a "misfit": *Notes on the Synthesis of Form,* Cambridge, Mass. (1964), Chapter 2.
7. For the problem of assessing forces, see Sim Van der Ryn, *The Ecology of College Housing,* Department of Architecture, University of California, Berkeley, 1965, and forthcoming publications from Barry Poyner and Ian Moore, *Directorate of Development,* Ministry of Works, London, 1966.
   See also Henry Murray, "Toward a classification of interactions" in *Toward a General Theory of Action,* (Talcott Parsons and Edward Shils, editors), Cambridge, Mass. (1962), pp. 434–464.
8. For a very simple account, see L. A. Lyusternik, *Shortest Paths,* New York (1964). For a more complete discussion, see Charles Fox, *An Introduction to the Calculus of Variations,* Oxford (1950).
9. Frederick S. Hiller, "*Quantitative Tools for Plant Layout Analysis,*" in *Journal of Industrial Engineering,* vol. 14, no. 1 (Jan.–Feb., 1963), pp. 33–40; Lynn Moseley, "Rational Design Theory," in *Architects Journal,* vol. 11, no. 9 (1963); J. J. Souder *et al., Planning for Hospitals: A Systems Approach Using Computer-aided Techniques,* American Hospital Association, Chicago (1964), pp. 113–162.
10. A. G. M. Michell, "The Limits of Economy of Material in Frame Structures," in *Philadelphia Magazine,* ser. 6, vol. 8 (1904), p. 589. H. L. Cox, *The Design of Structures of Least Weight,* New York (1965), p. 90.
11. W. S. Hemp and H. S. Y. Chan, *Optimum Structures,* College of Aeronautics Memo Areo, no. 70 (July, 1965). The cantilever was designed for the Machine Tool Industry Research Association, Macclesfield, Cheshire.
12. A. G. Shaw, *The Purpose and Practice of Motion Study,* Manchester (1960), pp. 116–120.
13. James Johnson Sweeney and Jose Luis Sert, *Antonio Gaudi,* New York (1960), pp. 74–91.
14. For a very sketchy discussion of the analysis of interacting forces, see *Notes on the Synthesis of Form, op. cit.* Chapters 8, 9, and Appendix 1.
15. Christopher Alexander and Marvin L. Manheim, *The Use of Diagrams in Highway Route Location.* Research Report R62–3, Civil Engineering Systems Laboratory, Massachusetts Institute of Technology (1962). In that report we called the forces "requirements."