ANALOGICAL REPRESENTATION IN MODELLING NAIVE PHYSICS

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ABSTRACT

Ideas and experimental results are presented on the use of analogical representations of knowledge, in Sloman's sense, that is, ones which bear a structural similarity to what is represented. This has been done for the qualitative modelling of the everyday behaviour of objects and substances like strings, liquids and gases, represented by pixel sets built up from base elements of pixel aggregates. The global physical behaviour results from message-passing between adjacent base elements. These messages embody a very small number of local constraints derived from naive observation such as material continuity and non-copenetrability.

Based as they are on fundamental phenomenological properties of the physical world, these programs turn out to have capacities for solving other problems than those for which they were designed.

The use of such programs in integrated reasoning and problem-solving systems, and the relationship of the present approach to those of classical physics and current AI ones in qualitative physics, are also discussed.

"You can pull with a string but not push with it"
M.Minsky, quoted in K.Forbus, "Qualitative process theory", Artificial Intelligence, Vol. 24, 142 (1984)

1.Introduction

Current research in naive physics (cf. Bobrow [1]) has concerned itself with qualitative models of the behaviour of physical systems and devices. The construction of these has been motivated by various aims, such as providing epistemologically adequate axiomatiozations, or as instruments for diagnosis of faults, or as valid mental models. But central to the whole enterprise is the issue of <u>simulation</u> (or, more generaly, envisionment) of the behaviour of such systems, and much of the published work (cf. Bobrow [1]) has been principally concerned with this.

However, the representation of knowledge and processes in all this work has been, to use Sloman's terminology [2], Fregean, so that the representation bore no structural similarity to the system represented. For instance it might use logical axioms and rules of inference or qualitative versions of differential equations. Following Sloman, we shall use the term "analogical" for schemes of representation which predominantly are structurally similar to what is represented; examples are maps, diagrams, flow-charts. The ideas and experiments described started in the context of work on the design of emergency diagnostic systems for nuclear reactor plant, when it became clear that much of the knowledge an operator of such plant must have, especially of the more "commonsense" type, is most naturally, and simply, expressible in analogical form. That is to say, he employs visualization, not only of the physical structure and layout of the plant but also of many of the processes taking place in it.

While visualization is a ubiquitous component of mental functioning, used for example in problem-solving in abstract as well as concrete domains, the studies reported here are principally concerned with analogical simulations of the everyday behaviour of objects like strings and substances like water and vapour, which it would be difficult to model in heuristically adequate ways either with classical mathematical physics or current qualitative reasoning approaches. What is claimed for the present approach is that the representation is simple and natural (compare the treatment of liquids by Hayes [3] and Forbus [1]) ; that it has psychological plausibility (cf. Kosslyn et al. [4]) ; that it yields unique solutions, which is the exception rather than the rule for qualitative reasoning systems; that it does not have to face the frame problem (McCarthy et al. [5]) ; and that it is characterised by much weaker ontological commitments than the Fregean systems (cf. Sloman [6]) .

In the initial work reported here two-dimensional models of physical objects took the form of sets of pixels of the two-dimensional array of a computer graphics system, so that spatial properties and relations of objects are implicit in the representation itself. The programs deal directly with these pixel sets rather than with numerical or other representations of the objects. The basic structure of the programs consists of message-passing between actors ; this choice of programming style was made not only because of its convenience (availability of a Symbolics 3600 Lisp machine), but because of its architectural similarity to the operation of massively parallel computers [7] which, when they become available, would be the ones most suitable for implementing analogical representations. The issues of three-dimensional modelling have not yet been studied, although they do not appear to be fundamentally different.

As unexpected fall-out from the work, analogical programs can sometimes solve, or provide the basis for a solution of, problems other than those for which they were designed; for example the string program solves automatically the maze problem, and suggests an analogical solution of the robotics problem of navigation in a cluttered environment. They can also suggest new types of heuristics for problem-solving.

The issues of interpretation and the representation of generality are discussed, and a suggestion made of a symmetrical unified architecture of the analogical and Fregean components of an integrated reasoning system.

Finally some aspects of the relation of analogical naive physics to physics in general are presented.

2. The use of decomposition

The most significant predecessor of this work is in Funt's program WHISPER [8]. This is a reasoning system in the domain of stability of "blocks-world" structures. A diagram (a two-dimensional picture raster) is used to answer questions put by the reasoning program, such as : "What will be the position of such and such a block, rotating about such and such a point, when it hits the first block it may contact ?" The representation of the kinematics of rotating and sliding is genuinely analogical : it uses no classical (mathematical) mechanics but only picture transformations derived from naive observation.

Our programs too are based on naive observations such as : inelastic objects do not shorten or lengthen when moved; gravity forces a body downward unless otherwise constrained ; solid objects move continuously in general; a liquid poured into a container distributes itself so that its top surface is horizontal ; a strong enough wind lifts an object; etc.,etc.

However, when one needs to represent more complicated transformations than Funt's rotations and slidings of blocks (for example ones involved in the behaviour of strings and liquids) it becomes necessary, in order to avoid an indefinite multiplication of such global analogical procedures, to resort to a representation of <u>local</u> behaviour of the parts of a body or substance, so that their joint operation gives rise to the global behaviour. It turns out that the local rules required to give qualitatively correct representations of even very complex behaviours are in general both few and simple.

We illustrate this "molecular" approach for cases of solid objects including strings, flexible rods and composite objects., though we do not dogmatically exclude the use of global rules;

one can foresee - in applications to engineering structures - that it may be convenient and computationally economical to resort to particular global rules for specific purposes.

The base elements are represented on the graphics screen as pixel aggregates of some fixed shape (e.g. circular or square); computationally speaking, they are actors, each one an instance of a so-called flavor (named Element) of the Lisp system used. Physical objects are represented as structures composed of base elements; computationally they are also actors, instances of the flavor named Object. The computational unity of the representation is preserved by representing composite objects also as instances of the flavor Object. In general the representation of physical movement and behaviour is effected entirely by exchange of messages between neighbouring base elements. The fixed environment of the physical systems (walls, fixed containers, etc.) are represented by means of the usual graphics facilities, and are instances of the flavor Window ; the pixels of which they are composed can exchange messages with the other actors. The only external action allowed is the use of the system's mouse to move or fix a base element.

3. Strings and derived solid objects

In the experiments strings were modelled as one-dimensional aggregates of base elements with exchange of messages governed only by the maintenance of the following constraints :

1 There is a fixed distance parameter (e.g. zero) between each element and its two neighbours, or its single neighbour in the case of the two terminal elements (Continuity)

2 There is a fixed angle parameter, which is an upper bound to the amount the line joining the centres of two neighbouring elements may rotate

(Flexibility)
3 The set intersection between the pixels of an element with the pixel elements of environmental objects is zero (Non-copenetrability). For the purposes of the present experiments it was not necessary to impose the copenetrability constraint also for other objects.
4 Forces like gravity, or wind, or viscous drag, are stored in the Element flavor; for example gravity as a tendency for an element to move in a certain direction a number of steps determined by a force intensity parameter (Fields of force).

These four constraints turn out to be sufficient to give qualitatively correct behaviour of strings in a variety of situations, for example : falling in free space, falling on to a floor with protuberances, being used to pull or (unsuccessfully) to push, being uncoiled, being dragged over protuberances or through narrow channels. It should be noted that some basic properties of the string are assured by the mode of representation, e.g. the conservation of length and thickness.

The freedom of choice of the parameters in the above four rules (effectable of course by a special menu on the graphics display) also permits the representation of other solid objects:

The flexibility limit angle set to 180° yields a string, but set to 0° it gives a rigid bar, and set to angles in between it gives rods with various degrees of flexibility. A ring can be represented by joining the terminal elements of a string or rod.

Figure 1 shows some examples.

Figure 2 shows, respectively, a string, a flexible rod and a rigid bar, held at one end and allowed to drop on to a floor.

Figure 3 shows a string under gravity in various environmental situations, including one under the "table" where it has been pushed against a solid object.

Figure 4 shows the comparable behaviour of a flexible rod, and Figure 5 that of a rigid bar.

Figure 6 shows the sequence of movements of a string, a flexible rod and a rigid bar, held at one end and falling under gravity.

By fixing the positions of the two terminal elements of a flexible bar under gravity one obtains a catenary, and by fixing that of one internal element of a rigid bar one obtains a lever.

It is interesting that although the basic representations are of inextensible objects, they can be used for representing elasticity. For example Figure 7 shows the pulling of an elastically deformable ring through a constricting channel. This is achieved by modifying the flexibility constraint : If n is the number of base elements of the ring, the flexibility limit angle chosen is 180/n, and this is also the preferred angle between between any two neighbouring elements, being decreased only if forced by the other constraints of the model.

As mentioned earlier, the uniformity of representation mediated by instantiation of the flavor Object means that no extra difficulties are encountered in the representation of the behaviour of composite objects. Figure 8 shows a lever supporting a ring on one arm and a moveable rod or string attached to the other arm. Figure 9 shows a more complicated system composed of pulleys,lever, ring and strings.

4. Problem-solving applications

Perhaps it is not surprising that these programs, based as they are on representations of fundamental properties of physical objects such as continuity, conservation of spatial extension and non-copenetrability, appear to have the capability of solving also problems for which they were not specifically designed.

For instance, the string program automatically solves maze problems of any degree of complexity, as illustrated in Figures 10,11 and12. All that needs to be done is to join the starting and target points by a rectilinear string, and then switch on the message-exchanges between its base elements. The resulting configuration of the string is a solution path. It is interesting to compare the solution of Figure 11 with that of Figure 12 employing a thinner string : the former because it cannot pass through as narrow passages as the latter has to find a different (and longer) path. (The shortest-path problem will be referred to below). This obviously suggests applications to the robotics problem characterized by Brady [9] as one of the most difficult, namely, navigation in a cluttered environment. It seems very likely also that flexible rod and rigid bar programs could be used to simulate robot arms and hands in the planning of assembly and similar tasks, as well as parts being manipulated.

5. Discussion

Only some of the issues of naive physics have been tackled so far. For instance, a rigid bar, suspended from a fixed point and allowed to fall under gravity, would not execute a pendulum motion, but come to rest in a vertical position. This is because we have not yet developed a satisfying model of the effects of momentum. It is an open question how far the essentially kinematical approach adopted so far can be used for dealing with such dynamical questions.(In this regard it is interesting to note that in advanced physics dynamic phenomena are often represented in kinematical, "geometric" ways; for instance in general relativity the motion of a body is represented as a geodesic in four-dimensional space-time). An associated open question is the degree of explicitness with which time should be represented.

There is a rather subtle issue connected with the uniqueness of solutions previously claimed as characteristic of the analogical approach. It might be argued that this is more apparent than real, since differences in the algorithms chosen to realize the local constraints could produce differences in behaviour. For instance, the precise way the flexibility constraint is programmed might determine whether the angle between two particular base elements of a string is, say, 60° or 70°, both being compatible with the constraint. The evidence so far is that the qualitative behaviour is independent of the algorithm design. This raises an interesting question : is it perhaps the case that this is a common property of the intuitive insights about the workings of the physical world that we all acquire ?

Applications of the analogical approach to liquids and gases are also being developed with some success : existing programs demonstrate adequately phenomena like the filling of any shaped container with liquid, the effect of holes in walls, the homogenization of a gas between two connected chambers initially at different pressures, etc. These studies will be reported elsewhere.

6. Beyond simulation

A number of interesting issues arise when we consider how analogue simulation programs might be used in computational models of problem-solving and reasoning systems. The most immediate ones are those of interpretation, of the representation of heuristics, and of generality.

In regard to interpretation, it might at first sight seem as if the whole AI armoury of vision processing might be needed to interpret the graphics pictures. In fact, however, naive physics shares with traditional physics the use of idealized schemata, so much less will be required; in fact, one suspects that not much more than set-operations on pixel aggregates will be needed. For instance, whether an object is above or below a table could be determined by intersecting the object aggregate with pixel aggregates representing respectively the spaces above and below the table.

Similarly, set-operations on pixel aggregates might be used in the representation of problem-solving heuristics. For example, suppose we wanted the <u>shortest-path</u> solution of the maze problem mentioned previously. One could let the string program operate with the maze masked by successively wider passageways directed from the starting position to the target point; then the first path found will be the solution.

The issue of generality is crucial for integrated problem-solving systems. An analogical representation is by its nature particular : a particular string, a particular lever, or whatever. If one wanted at all costs to stay within the the analogical paradigm, one might perhaps think in terms of approximate extensional representations, for example a set of graphic instances of a lever to represent the general notion of a lever, but such an approach would be clumsy and quite soon run into insuperable difficulties when one has to deal with not only general concepts but also general propositions. It seems inevitable that one will have to have recourse to supplementation of the presentations. There appear to be two ways of doing this.

Consider the graphics program for representing an object, say some particular lever. It will have embedded in it numbers or sets of numbers determining properties of the object, such as length of the arms, thickness, position of pivot, gravitational force, etc. If these numbers are replaced by "slots", each slot being provided with a numerical range for possible fillers of the slot (chosen to preserve the lever-character of the representation), the result would be the representation of a lever up to a certain degree of generality. It is interesting that quite sophisticated use has already been made of representations of this type in the Stanford ACRONYM vision system (cf. Brooks [10]).

An alternative would be representation by prototype, that is, an analogical representation of a particular lever, say, together with a set of procedures for transforming the representation while preserving its lever-character. This mode may be particularly suitable in cases where the major part of the simulation and reasoning would concern the prototype.

The first method described above suggests an appealing general architecture for integrated reasoning systems. For, slots in graphics programs might also be filled by other data than numbers, e.g. by arbitrary graphics programs. So, for instance, an analogical representation could even call itself recursively, which might be a suitable way of representing Russian dolls ! More interestingly, such a facility could be very useful in the representation of a complex physical system simultaneously at various levels of abstraction or detail. But when one goes on to notice that slots may be filled by arbitrary programs, not necessarily only graphics ones, the possibility of a symmetrical unified reasoning system presents itself. For the Fregean part of such a system might be composed of Minskyan frames provided with their statutory slots, which in turn may also be filled with arbitrary programs including graphics ones. The whole will thus consist of a collection of interacting frames, some analogical and others Fregean.

7. Comparison with classical and qualitative physics

The representations of classical (mathematical) physics in engineering or other real-world applications involve in general the provision of too much information in one sense and too little in another. Too much, because the specification of variables and functions as real numbers requires a strictly infinite amount of information; too little, because they neglect a great amount of ("assumed") commonsense knowledge actually used by engineers and people generally.

The introduction by Hayes [11] of the notion of quantity space has been a first and important step in providing a means of cutting down the "explosion" of information to a reasonable size, though we still have no guiding theory on the relationship between what we may want to know about the behaviour of a physical system and the amount (as well as the nature) of the information about the system required to derive that knowledge.

The issue of "assumed" knowledge is an interesting one. In the representations of mathematical physics some of it is implicit in the formalisms used. For instance the fact that a body does not change its mass when moving is assured by using a constant as the symbol for its mass; or the fact that most physical phenomena have a continuous character is implied by the ubiquitous use of mathematically continuous functions (even sometimes for essentially non-continuous events like quantum jumps !). But when one examines the application of formalisms like differential and other equations to the real world, one finds essential steps of the reasoning not represented in any way in the formalism. A simple paradigmatic example is provided by a billiard ball A moving with speed v and impacting a stationary ball B : what are the subsequent motions ? If one writes down the energy and momentum equations, one obtains two solutions : the first brings A to rest and projects B with speed v; the second keeps B stationary while A continues with speed v. Why is the second immediately rejected ? - simply because it contradicts the commonsense non-copenetrability constraint (embodied in the analogical physics programs described above).

In one respect the present analogical approach is identical with that of mathematical physics, namely in the use of local constraints. For local constraint is exactly what a differential equation is, and the integration of such an equation is a well-defined procedure to obtain the global from the local behaviour; our graphics systems perform the corresponding "integrations" automatically by message-passing.

But the local constraints used in analogical naive physics are of a different character from those of classical physics. They express rather immediate, "phenomenological", commonly observed characteristics of the physical world, rather than highly abstract notions such as Newton's second law. In this respect they differ also from those of most of the Fregean systems of qualitative physics so far developed. For instance both de Kleer and Brown, and Kuipers [1] use abstract differential equations but ranging over quantity spaces instead of the real number continuum. Such systems are appropriately characterised as being qualitative rather than naive physics.

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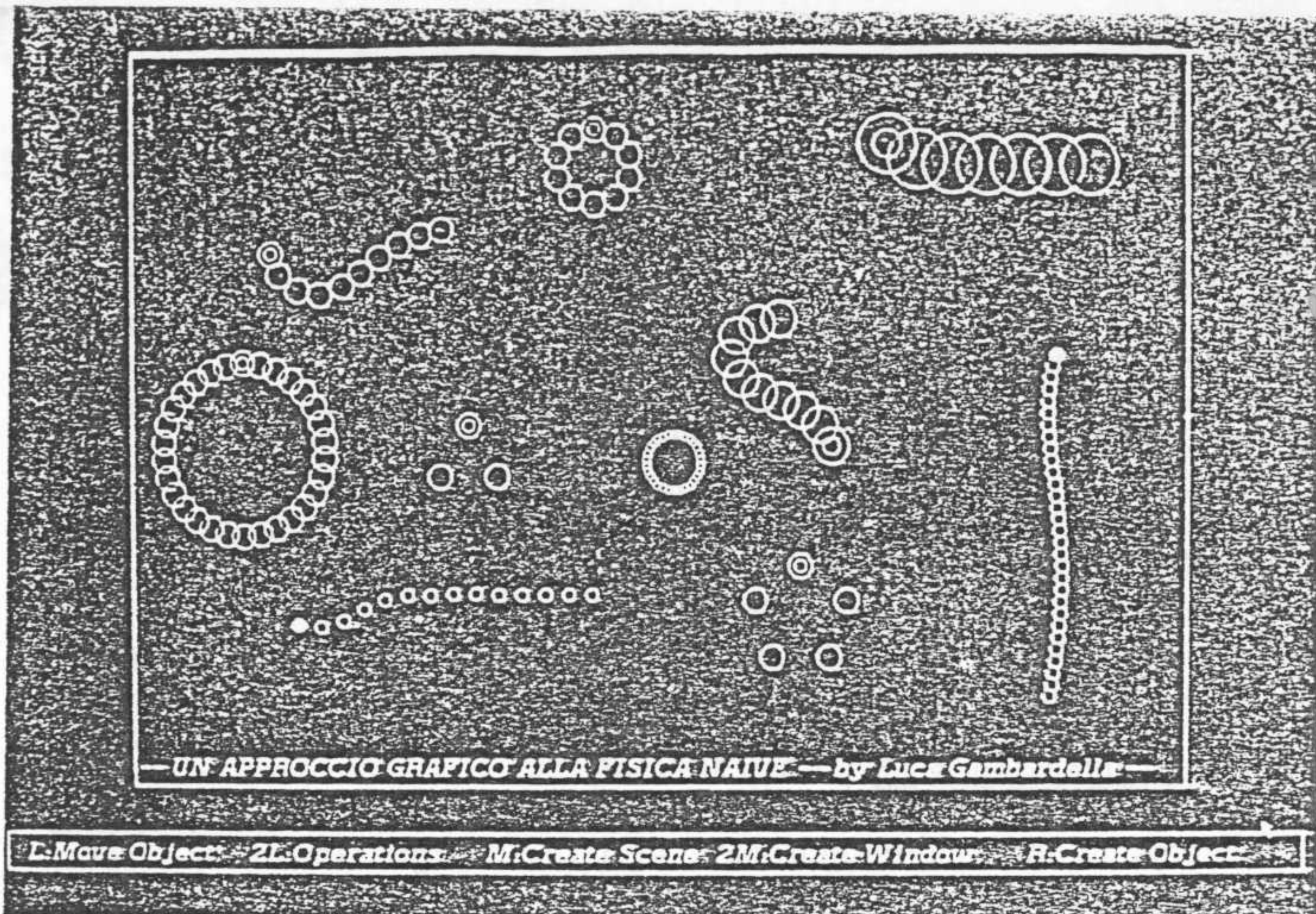
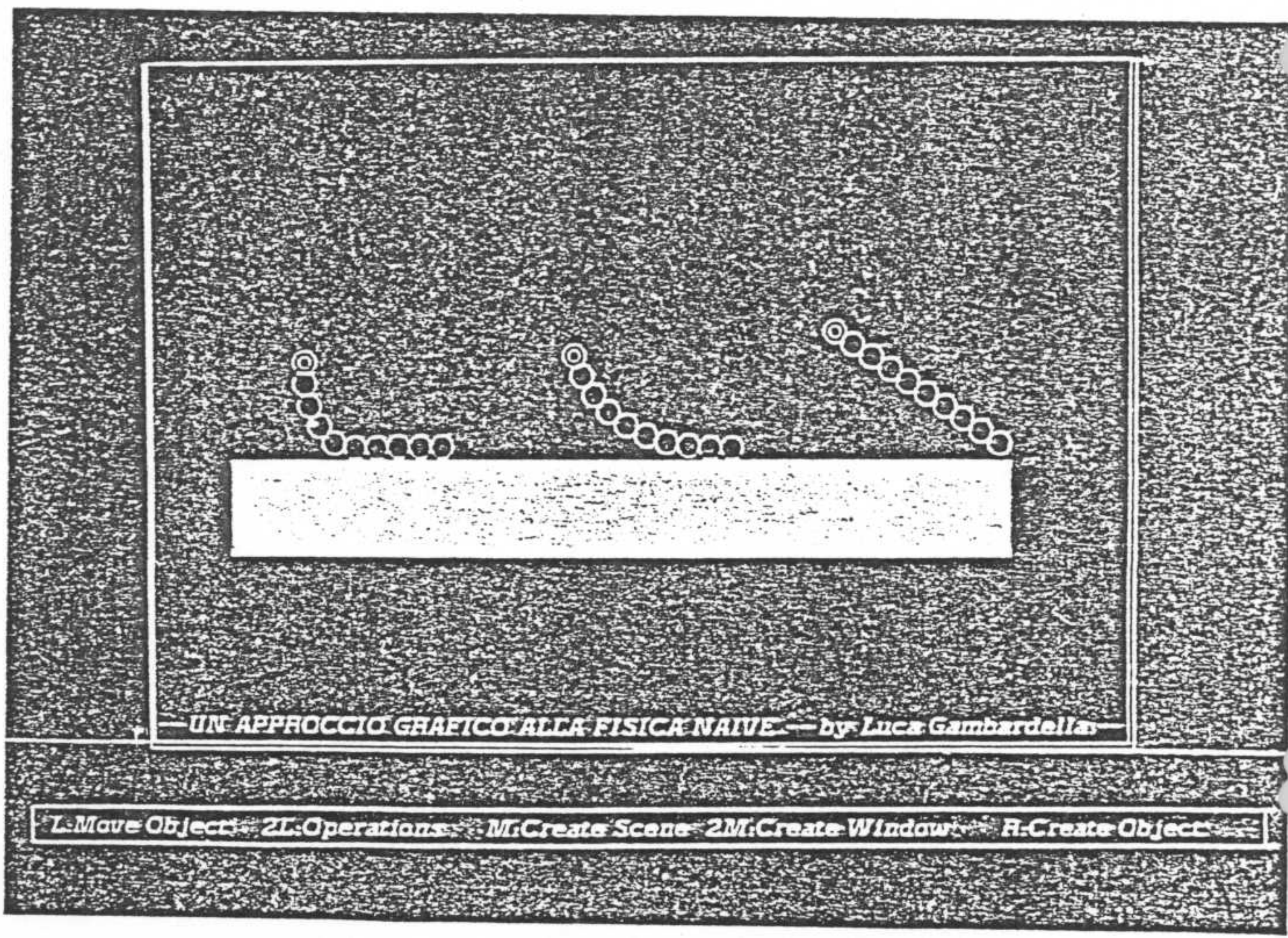


Fig. 1. Examples of object models : strings, flexible rods, flexible rings.



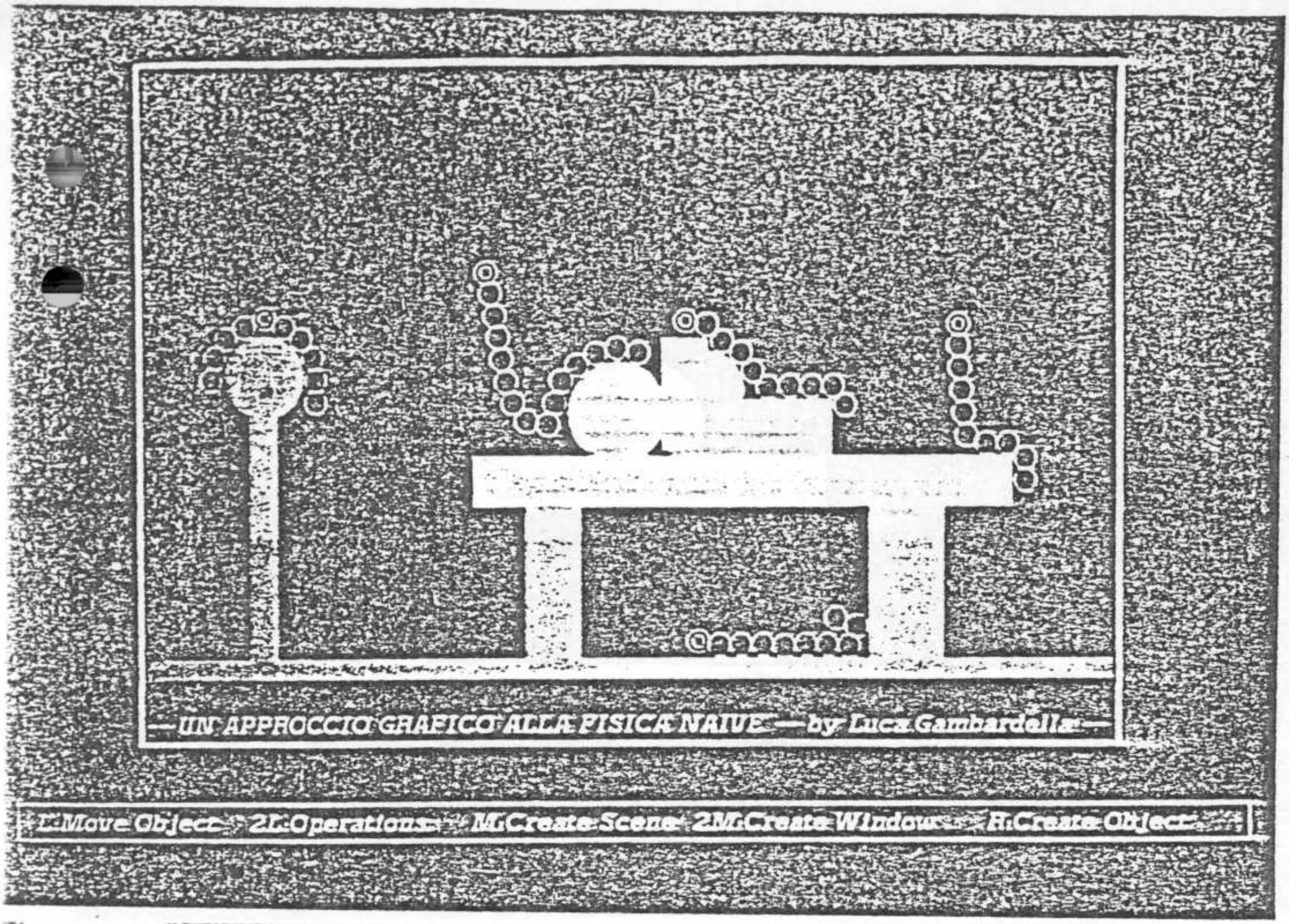
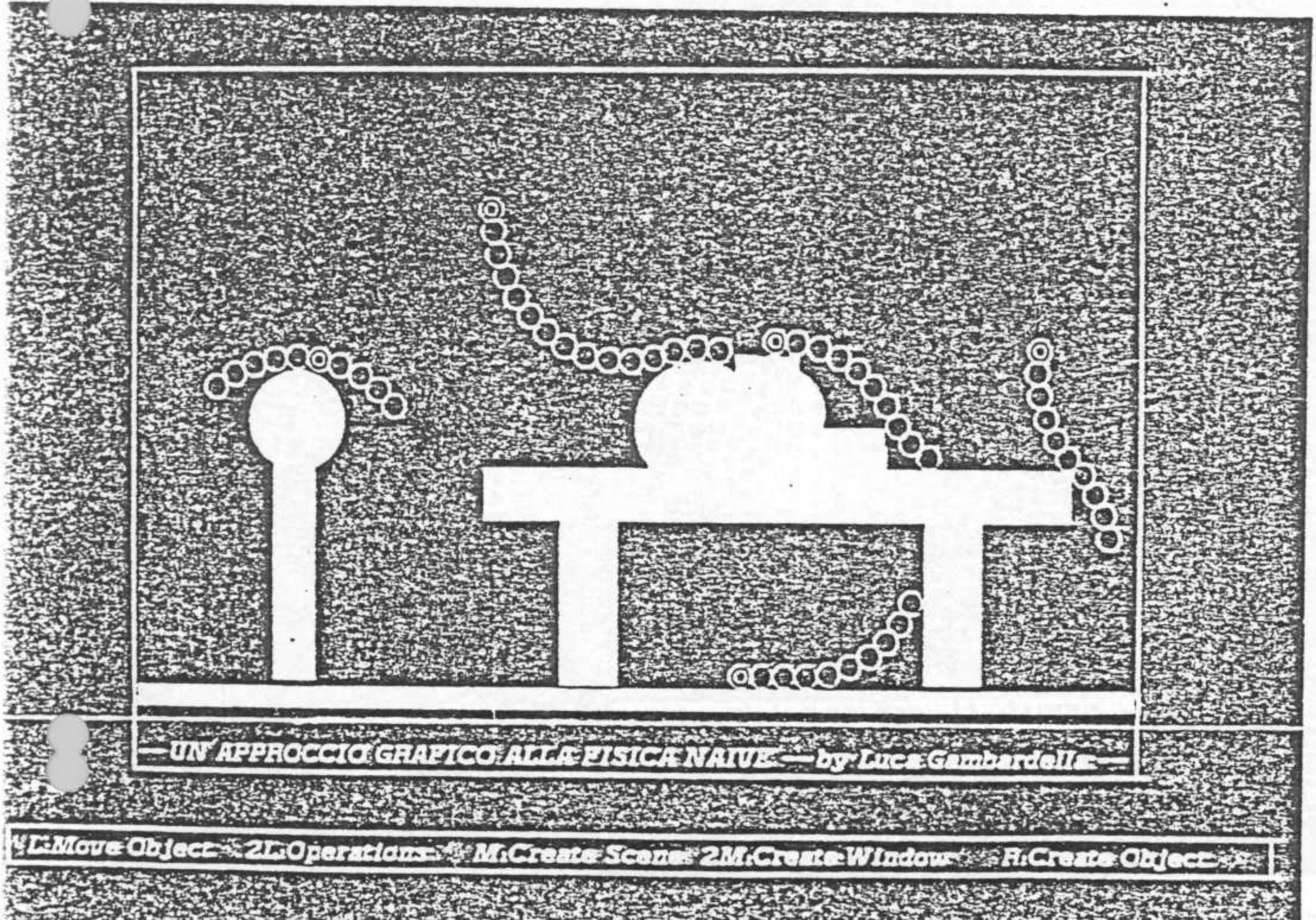


Fig. 3. Strings under gravity, held at single points, in different environmental situations.



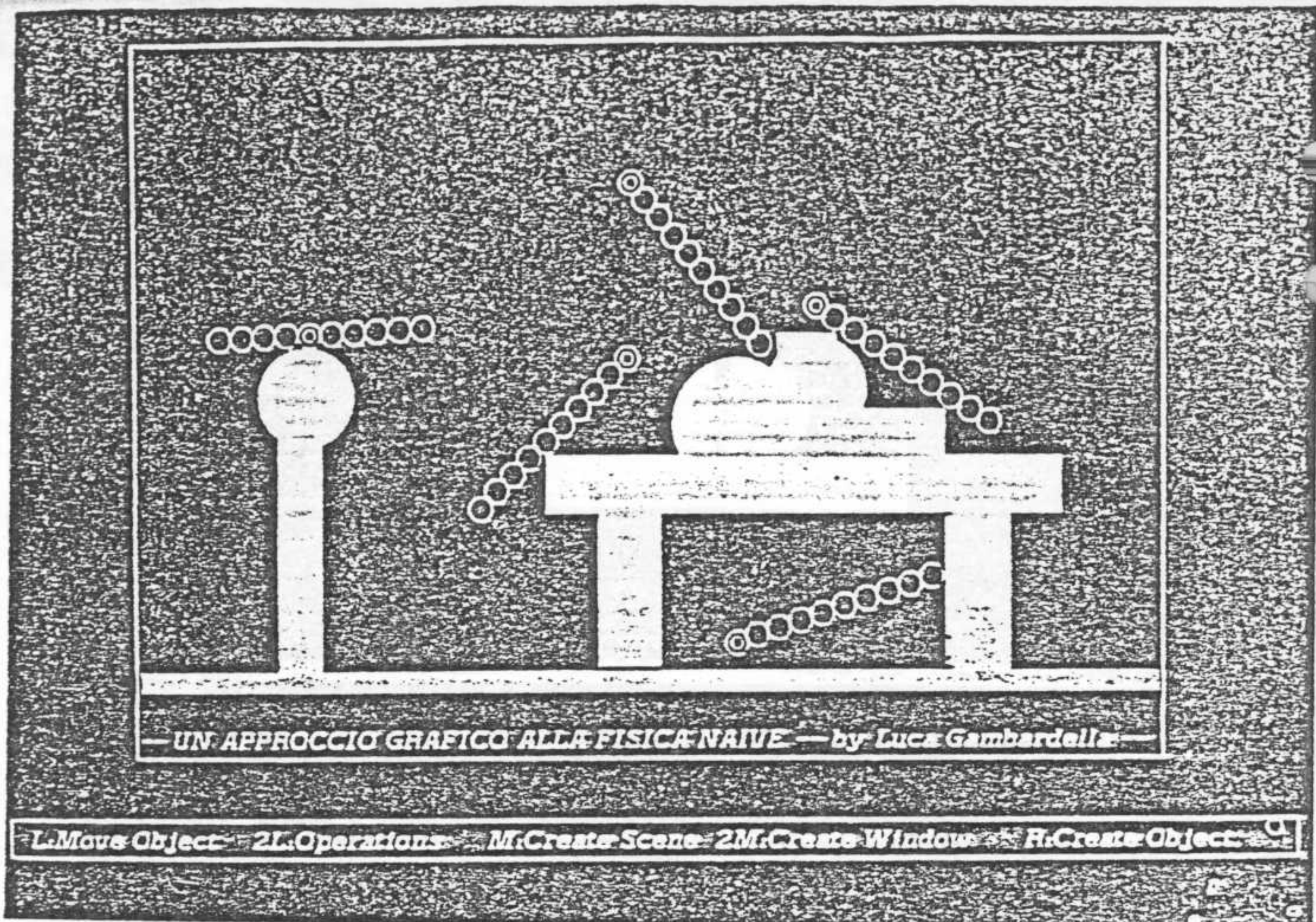
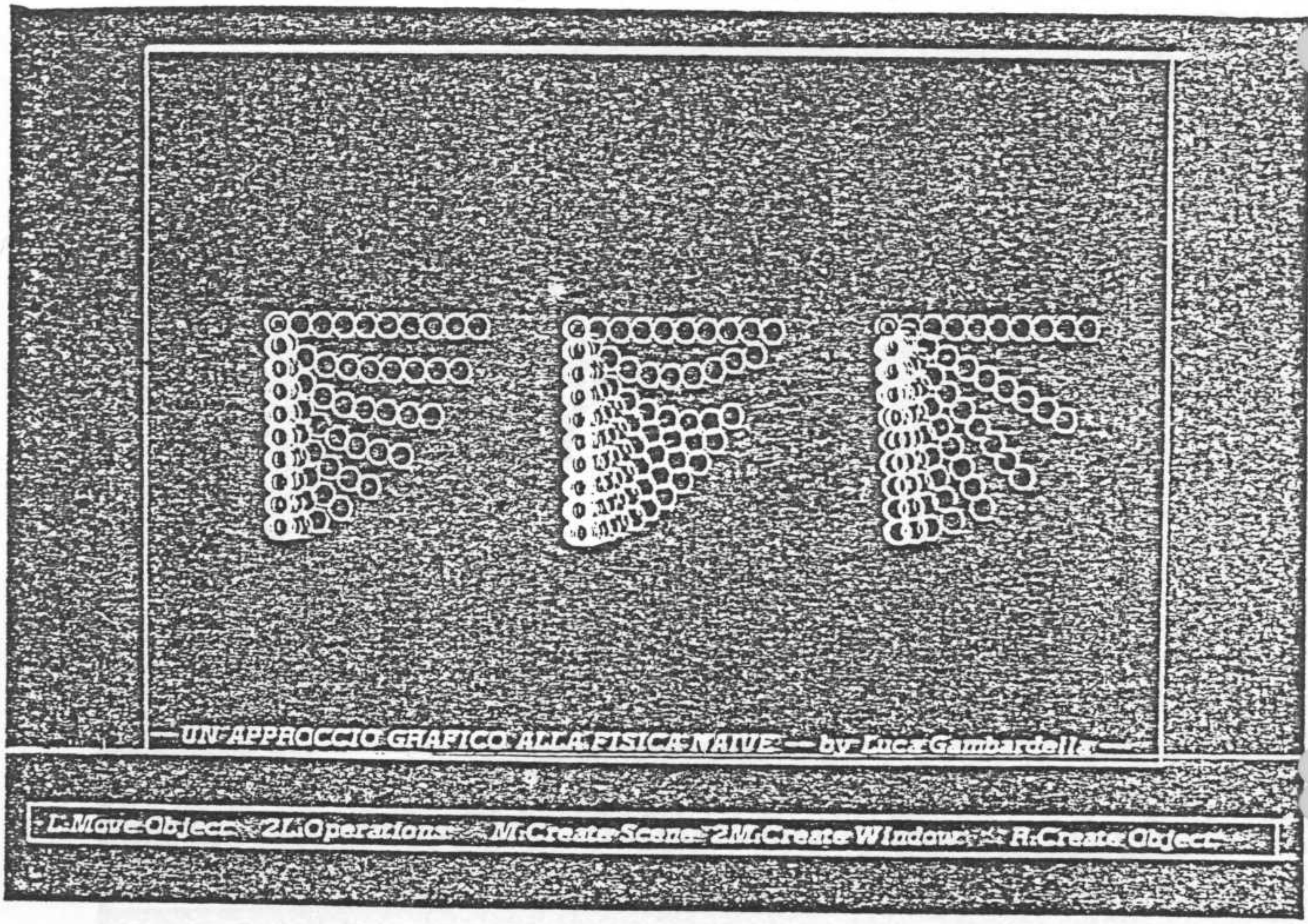


Fig. 5. Rigid rods in the same situations as those of Fig.3.



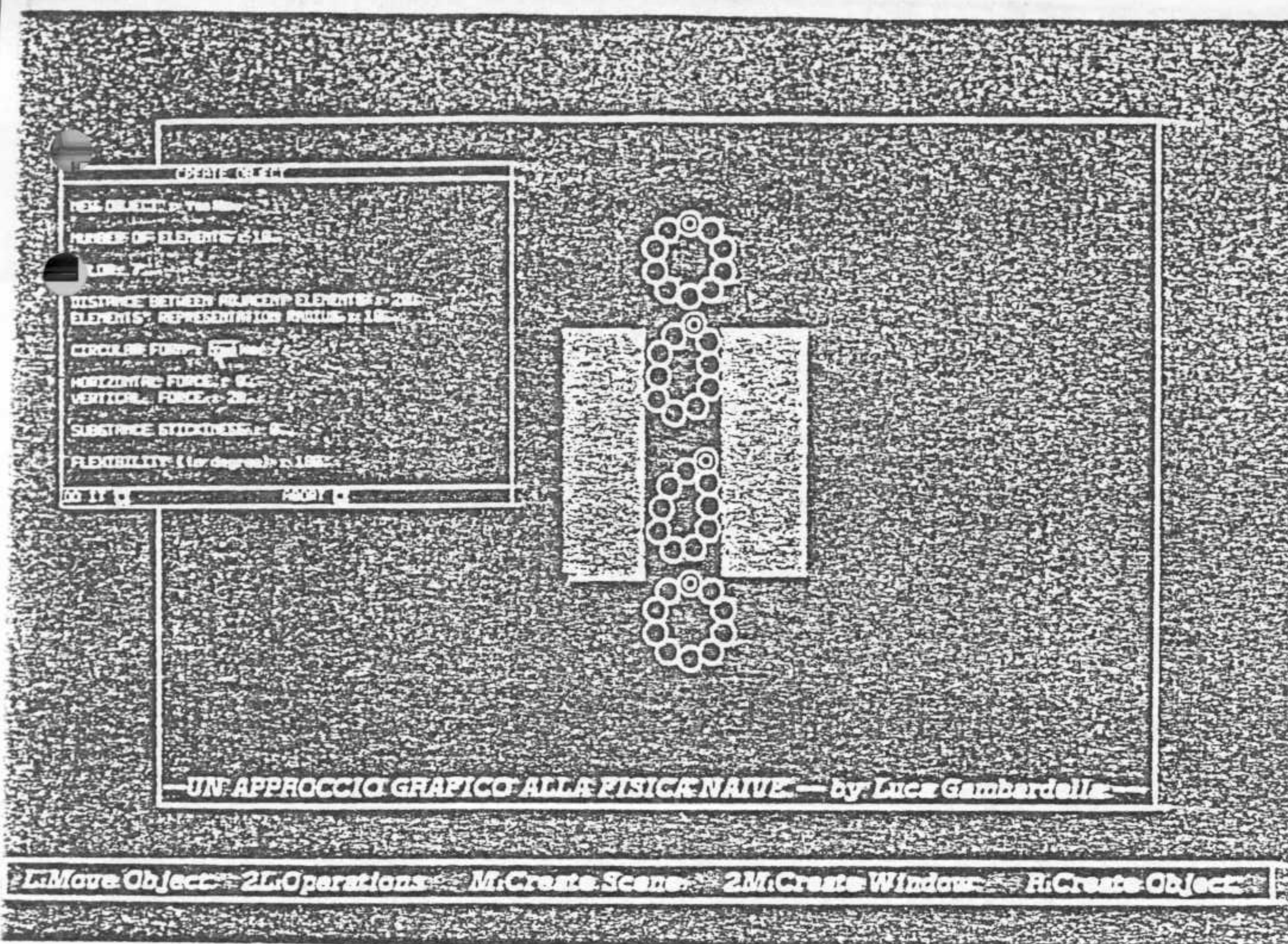
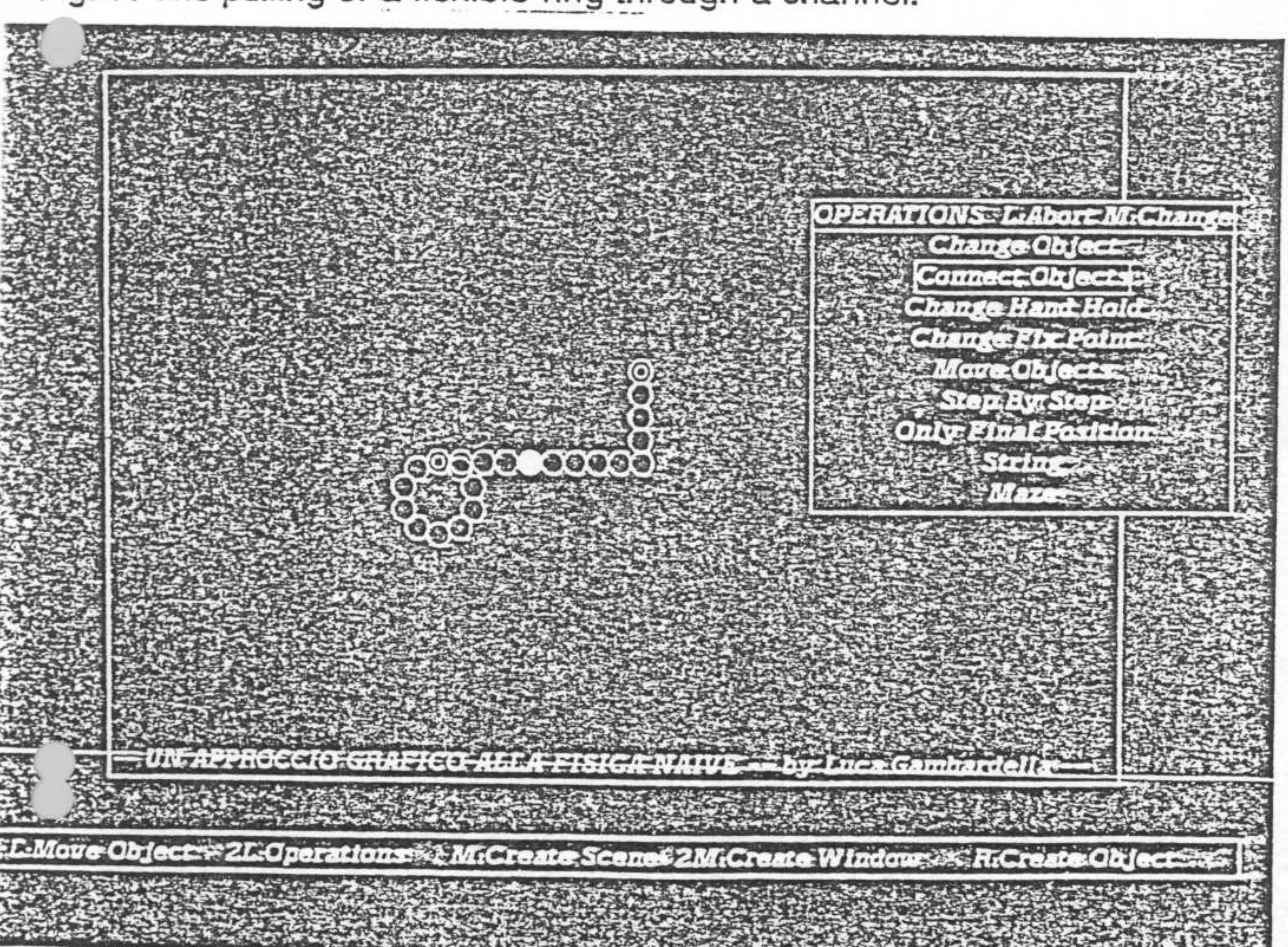


Fig. 7. The pulling of a flexible ring through a channel.



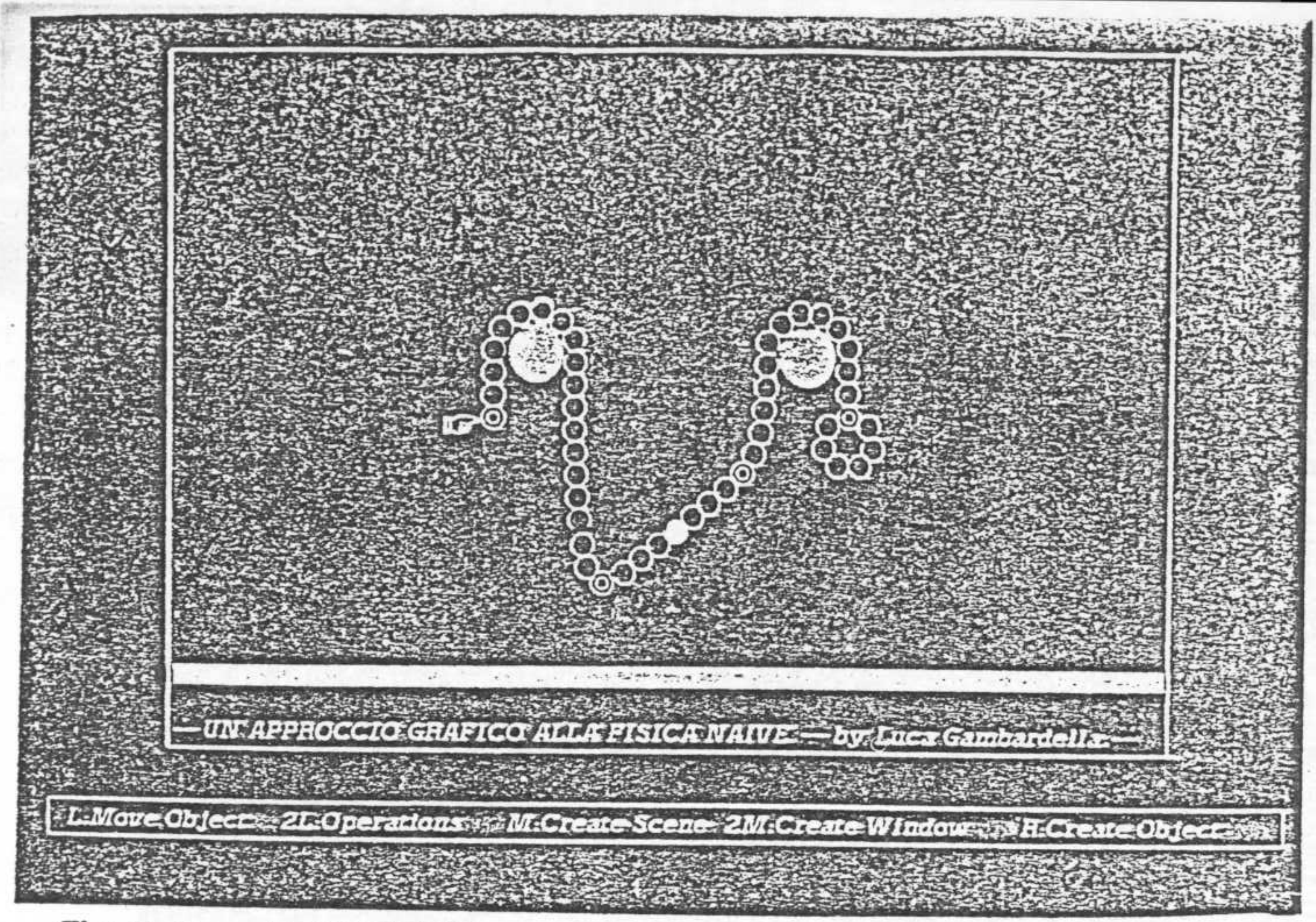
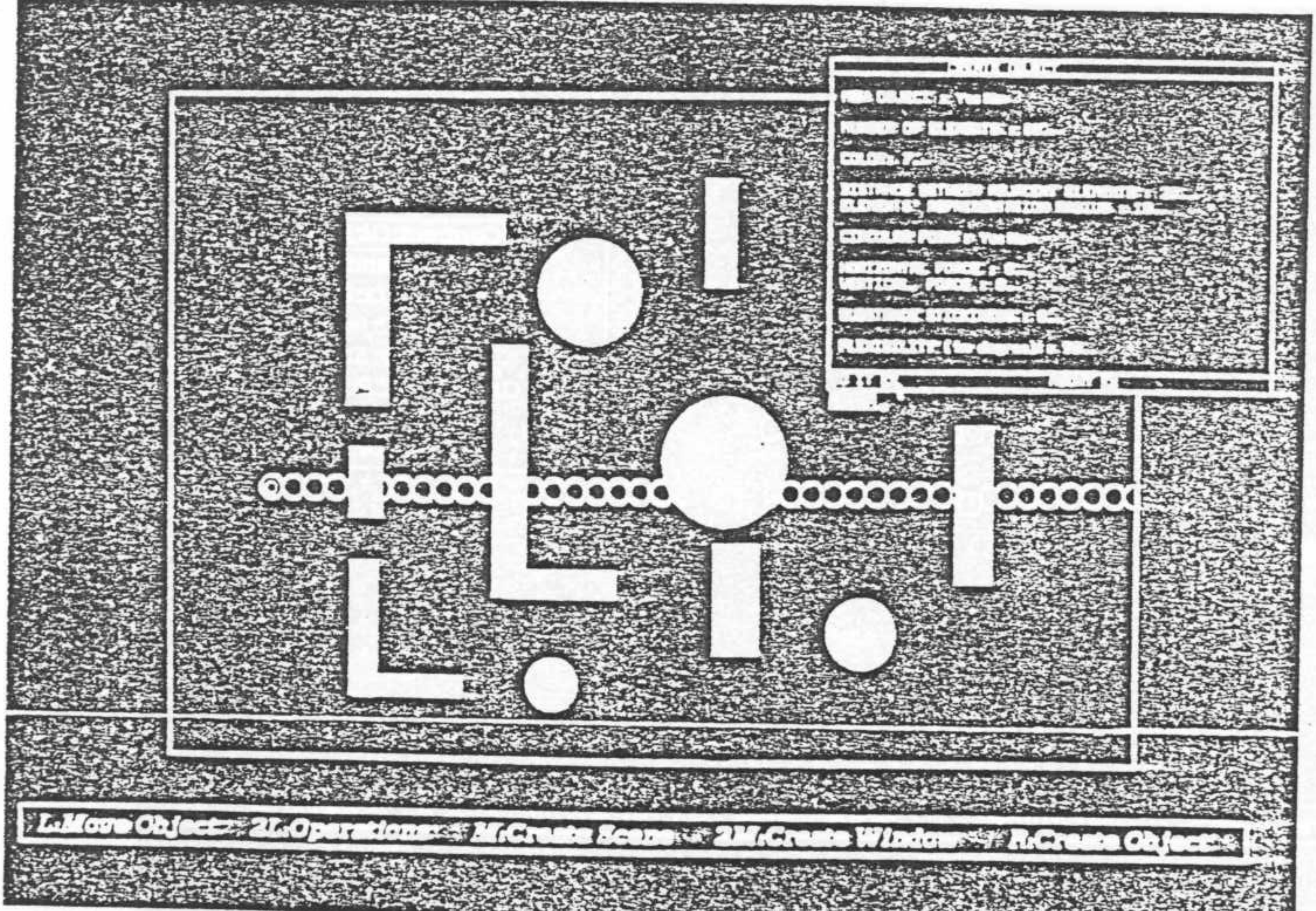


Fig. 9. Composite object : moving a ring by means of strings over pulleys and a lever.



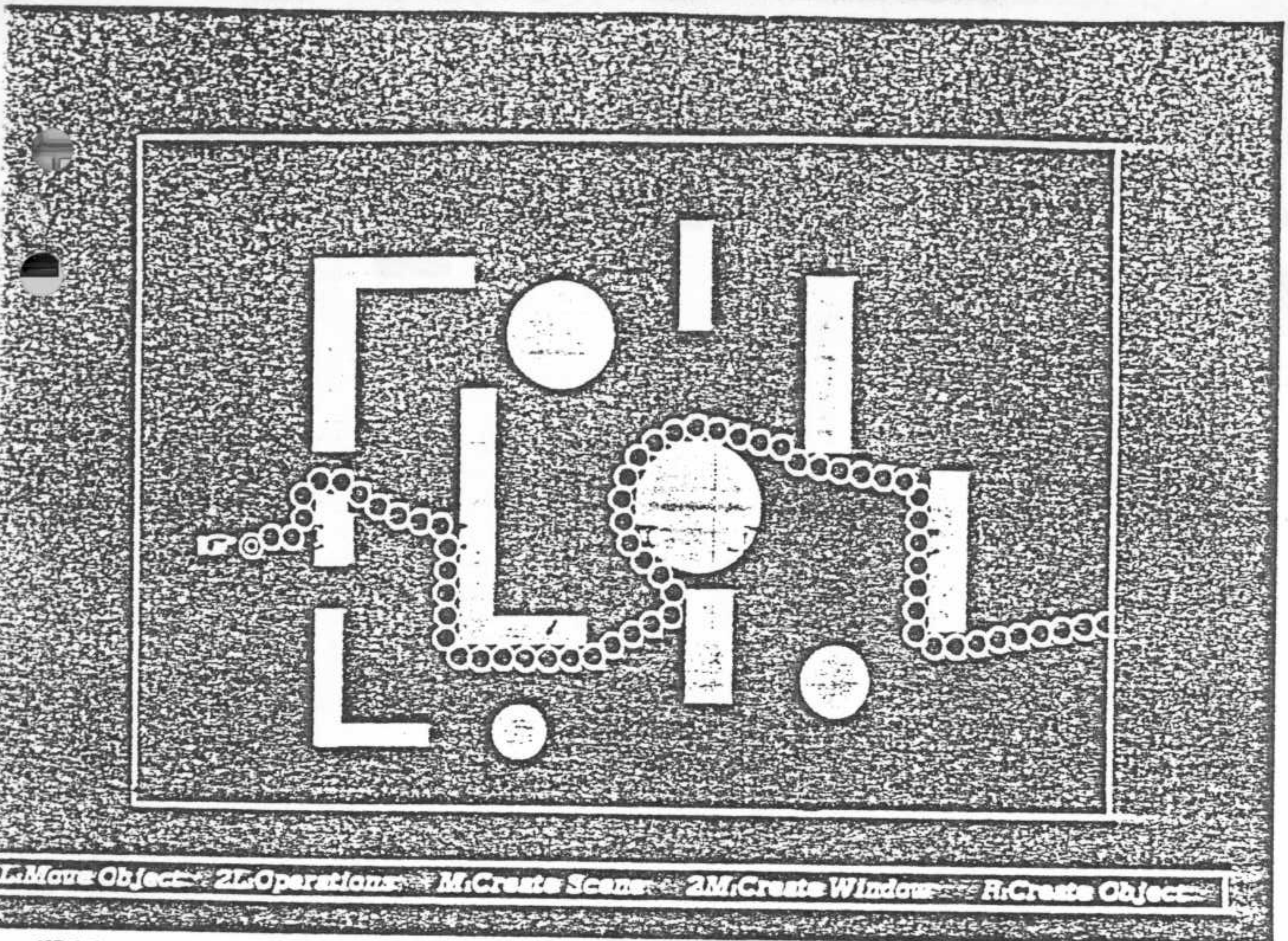


Fig. 11. Maze problem : solution state of string.