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PHYSICAL MODELING AND ANIMATION
at GRENOBLE - FRANCE

ACROE - LIFIA

THE CORDIS ANIMA SYSTEM

TOWARDS A MODULAR AND INSTRUMENTAL APPROACH

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EUROGRAPHICS ANIMATION WORKSHOP

T1

We have been working on Computer Animation, and on Computer Animation with Physical Modeling since 1978. At this time, Computers were not enough powerful for large simulations required by physical models and the main part of our work was to develop principles and concepts which are simultaneously,

- * general, i.e., able to simulate a large variety of objects and systems of objects,
- * reliable for computer evolution
- * well adapted to real time simulation

For this, we were forced to place different representations of physical universe in relation and to confront them with computer representation capabilities.

We will speak about this point, explain and justify the chosen principles, which are now implemented in the CORDIS-ANIMA System.

The second determinant of our work was the choice of artistic creation as the more complete and demanding human activity. To build an artistic creation tool requires careful considerations of:

- * general cognitive processes
- * general perception processes
- * general physical and conceptual action processes

We will not speak here at length about this point, but I will only ask the fundamental question: why is physical modeling necessary for artistic creation and animation ¹

The third determinant of our approach is the concern to design more a creation tool with physical models rather than only specific algorithms or simulations of physical knowledge. This aim requires finding a balance between:

- * theoretical and practical points of view in physical designing and simulation
- * quality of perceptual phenomena produced by simulations and their variety

T2

Now, the first fundamental question is? Why physical modeling for Animation?
Animation is movement and the true question for us is rather How is Computer Animation possible without dynamics and physics?
It is simple but not trivial. What ?

For us, Animation are not only the frame by frame drawings technique.

If you look at the creation process, you can remark that there are two major modes of conventional animation creation

- * the drawing process, which is the process usually considered, animation by cells for example.
- * The manipulating process, in which objects are manipulated by animators directly and in front of the camera. This process conveys the expressivity in movements more easily.

To reconstitute the second process with the computer requires immediate physical models of physical objects and gestural control.

At contrast, the first process is, in fact, less obvious. In this, if we observe, not the production process - the drawing process for example, but the creation process - what drawings are made? - we see that the deformations and displacements of objects are made according to the physical laws, as shown here.

There is a physical model. There is a physical simulation. But in the mind of the animator. The animator develops an expertise that is a mental representation of physical processes which govern movements, a mental dynamic simulation capability and the ability to draw immediately and quickly some results from these mental processes in terms of frame by frame drawings.

If we want to give a computer creation tool to the animator, we can integrate this kind of physical knowledge into the computer. This is also "Physical Modeling".

I will not speak anymore about these cognitive aspects in animation but it is an important guide of our ideas.

T3

Now for the second point of my talk: What physics for animation? What physical Models? What Algorithms for Physical representation?

The problem is to give a computer representation of a large variety of physical objects and physical systems with which the animator can interact to experiment, search and control non a priori defined movements. The representation must serve to discover as well as to produce movements.

Physics gave rise to multiple representations and for choosing, it is fundamental to recall the hypothesis which underlies each representation and each specific domain.

I briefly examine these main hypothesis.

T4

Firstly:

There are two basic formalisms in Physics, which are totally equivalent but fundamentally different:

* Newtonian formalism, described by the fundamental law of dynamics $d^2r/dt^2 = F$, which defines the force notion and its associated notion of mass

* The formalism of Maupertuis or "principe de moindre action", (I don't know the english term) described by a Calculus of Variations, which had been the first step to the definition of Energy.

The former defines the movement locally and step by step. The latter considers the movement globally, in comparison to an infinity of possible movements called virtual movements.

We can say that the first formalism is a "concrete", a constructivist formalism with a representation of the physical universe by another, composed of a set of punctual masses pulled by forces, and the second, rather more abstract, has a vision of movement spaces and it attempts to provide an analytical description of these spaces.

The first enables us to construct a physical representation of physical space. It defines a kind of "synthetic physics". The second is the basis of analytical mechanics and has developed the major part of formal calculus in physics.

Don't forget that the two formalisms have the same domain of expressivity (expressivity means as in informatics, domain of representation).

Newtonian formalism, because of its numerical calculability and its constructive and local aspects is more adapted to step by step simulation with the computer. It is better to create a representation of the physical universe by another physical space, which can be properly called a physical model of the physical universe. This formulation, we can even say, this model, with its specific approximations, is widely used in some chapters of Physics as constructive domains, non-linear systems, vibrations ...etc

->For these reasons, We have chosen for our computer tool of physical universe representation, Newtonian formalism. More generally, We will reason, not in terms of movements but in terms of matter elements pulled by forces, to constitute objects or systems of objects.

T5

Another demarcation line in Physics is in the choice of this minimal element of matter. We want to point out here the contrast between particles' physics and solids' physics.

The first chooses, for the minimal matter element, a material punctual particle and the second chooses an infinitesimal solid. In the first case, we constitute a piece of matter or any system of objects by aggregation of particles. In the second, we can constitute a piece of matter by an integration process of the infinitesimal solid.

The first enables the representation of micro and macrostructures, homogeneous or not, with the same formalism. It can calculate the physical variables (forces and positions) also on the boundaries and it can solve boundary and non linear problems. In practice, we have a finite number of points, and the virtual object presents a more or less rough granularity. The second allows a thinner granularity. But it is generally limited to homogeneous objects and it is unwieldy to solve boundary problems.

For example, The Elasticity theory is only interested in the intrinsic behavior of homogeneous and isotropic objects in their continuous, reversible and small deformations.

These are very restrictive hypotheses for us because the major parts of systems we must simulate are highly non linear and dissipative.

In conclusion to this point :

* punctual matter representation and solid matter representation are equivalent to represent homogeneous objects. For thin granularity, in practice, the first demands more points and the second demands integrale calculations. Therefore, for us, we consider that with computers the first one is more convenient: no matrix, no tensors, only centered forces.

* for interaction problems and non linearity phenomena, only the particle formalism is practicable. We choose it ,with its derivative concepts: the discrete components "mass - spring - damper" linked under non linear conditions. The underly model is a lumped network of mechanical low order filters,

T6

We can now give the general structural model of a physical system.

Don't forget that a physical system is not only an object but a set of object in physical interaction:

(let us mention for example road or tracker vehicles with many degrees of freedom and necessary dry friction with ground for locomotion • or the striking of • plasticine piece or more simply collisions between rigid or deformable objects).

This general structural model has a form of a finite set of material points in Euclidian space interconnected one to one by non linear dampers and springs. The points represent masses and the chains represent the forces acting and reacting to the particular lumped masses. The chain of dampers represent the dissipation forces and the springs the potential forces, restitutive forces acting in parallel. Each point of the model can be a boundary point or not, and all boundary conditions are imposed on these points. The internal and external interactions (dissipative or potential) are described in the same manner. From a formal point of view, every physical system may be considered as a chain of these elements. These can be interconnected in parallel, in series, in parallel-series, with or without feedback, with or without external actions.

Let us now focus on interactions and non linear interactions.

we have already defined linear interactions, described by springs and dampers. They enable a representation of the quality of material, (called rheologic behavior). Therefore, building a linear material consists in ordering distribution of springs and dampers between masses, until obtaining the correct mechanical transfert function onto each mass. Here, we want to point out what we call "the necessary modelisation activity", that is more depending on the designer ingenuity.

In general, a non linear system may constitute a very complicated set of interconnected linear and non linear elements. We can make the hypothesis that non linearities can be conveyed only by springs and dampers and not by masses. It is not a very risky hypothesis because it means that there are no "quantitative mass transformations" within the entire system and this is the more frequent case.

Look at this figure: let a body M located between two yielding walls with a play between the two faces of the body and the walls. You can represent it by this model.

It is a simple case of strong non linear interaction. Suppose that you have only one access to the behavior of this system by measuring the position of the mass, we obtain the characteristic in the form of this diagram. In this way, we can consider that the mass and the walls are always connected by a non linear spring having this characteristic.

T7

This diagram shows typical non linearity on positions, described as non linear springs
We can reason in the same manner for non-linearity on speed with non linear dampers.
The major interest of this kind of reasoning is that, we can build complex and composite non linearities from elementary non linear systems.

Video tape will demonstrate some cases of these interactions made with our system, from the simplest case of "visco-elastic collision" to cohesion forces, fractures and plasticity.

T8

In the interactions previously described, the non linearity concerns only one variable and then, the relation between the univariable input and the univariable output can be represented by piecewise linear functions as in the next table.

But in most cases, the output signal depends on several input signals, for example depends simultaneously on position and velocity, and this according to a complex sequence of conditions. We see "the bowed string" - the friction of a "collophaned bow on a violin string" as the typical and the more complex example of this case. We have implemented this and you will see its real time simulation on the video. Other cases are similar: the interaction "snow - ski" by the means of felt or wax on the ski, or the interaction between a track vehicle and a textured ground ... In general, interactions are composed of numerous, but finite, states : for example, bowed string interaction or track locomotion interaction combine "dry friction and visco-elastic interaction".

T9

The ABSTRACT PHYSICAL MACHINE

Now let us examine these two points: matter and interactions, from the point of view of computer design and simulation

On a formal and conceptual level:

From whatever point you consider the system - a macroscopic point of view for a complex scene or a microscopic point of view for a piece of matter - the computer model of a physical system has a form of network where nodes are material components and lines "linking components".

Material components and linking components are built from the elementary components "mass - non linear spring, non linear damper".

The minimal material component is the mass

The minimal linking components are the spring and the damper.

You can define the degree of granularity as you want

On the simulation level, the computer model is composed of two dual algorithms:

- * One producing extensive variables (positions for example) from intensive variables (forces for example)

- * the other, producing intensive variables from extensive variables.

The smaller element of each one is a first or second order difference equation, that is very easy to calculate. All the system is composed of a great number of this smaller components which have a very simple dynamic behavior, and this vision in terms of network of simple interconnected components is very well adapted to the present and future computer technology.

We can group elements into blocks of the same kind. And, by successive "components integration", we obtain only two dual blocks, one which produces forces and the other positions.

Let us now consider temporal determinations. When it is a machine which makes the calculus, for example by an algorithm that is a list of arithmetic instructions, this algorithm must be seen, in contrast with a physical block, as an oriented block with an input and an output, and there is necessarily a delay between the input and the output. This defines a concept of "computer bandwidth".

As regards these temporal determinations, the proposed formalism, with its two dual blocks, is optimal. The algorithmic system is a kind of a "flip-flop looped systolic system". Blocks run in parallel. At each step, in one block, positions are calculated with the next-step forces. Simultaneously, in the other block, current forces are calculated with current positions according to non linear conditions on variables. Then, variables are transferred.

This reasoning shows us that it is impossible to simulate objects which have a bandwidth greater than the "computer bandwidth". This is an important conclusion, and it points, in its principles, to the limits of pure physical simulation in contrast to pure geometrical representation.

Now let us examine in this machine the important case of non linear interactions representation.

We have developed a general formalism which is able to describe and simulate all the interactions described below, and which is consistent with the desired modularity and real time determinations of our system.

When the output depends on only one variable, as explained below, the interaction function can be represented by piecewise linear functions. It is easy to define a generic algorithm to design piecewise linear functions. More. if we remember that, because of the formalism of punctual representation, the forces are summed on masses, we can put several interaction functions in parallel and then we obtain complex interaction functions. According to this, it is not necessary to have more than two or three pieces in the interaction primitives.

In the Cordis - Anima system, this case is only a particular case, more precisely, a kind of optimization for efficient simulations. The general process is the following.

Non linear dampers and springs are considered in Cordis-Anima system as conditional links between masses and they are described by a finite state automata.

A non linear link is defined by a state and by state change conditions. A state describer provides the values of the physical parameters (stiffness, viscosities, thresholds ...) associated to the state and state change conditions are logical operations (increase, greater than ...) on any physical variables (forces, positions, speeds). We have defined here an "interaction is algebra and interaction is langage".

It is easy to see that piecewise linear functions can be described by this formalism and to see that you can combine interaction functions, by putting them in parallel.

Several examples, Visco-elastic collisions, grasping, plucking ..Cohesion interaction, plasticity and fractures, Adherence ...are shown in the video tape that I am going to present now:

VIDEOTAPE

1. in the First example we will see numerous rigid particles in interaction and with stationary obstacles and under gravity. Because of the physical interaction between themselves, they can constitute stacks.

2. Here rigid particles in a box. The box is also described by masse-spring-damper network

3 There is The minimal solid element with this formalism :Four masses with cohesion forces generate a quasi rigid solid that can move and rotate.

4. deformable objects: It is possible to take into account a certain locality of the deformation. It is attractive as regards calculation cost.

6. This shows interaction with an animator. The interaction between the animator and the virtual objects is in the same way of interaction between objects. The animator and the objects exchange forces and positions. The device is a special device that we have built ourselves. It is a gestual transducer with force feedback and many degrees of freedom, up to sixteen. By means of these devices, that are an important part of our work and research, the animator can feel, by gesture, the physical behavior of simulated objects.

5. Structured objects

6. Fluids, as a limit to consistant objects.

7. Pieces of material named agglomerates, that can be homogeneous or heterogeneous.

8. Agglomerate with plastic behavior: The piece of matter remains in the mouldable shape. The operator kneads the paste with the gestual transducer. It is a special case of cohesion forces obtained by specific choice of parameters in the interaction characteristic. Because of its parameters, the paste can break into several pieces. The animator stretches the paste and he can also re-sticks it.

All these examples are in real time.

Now an example in which the same physical model produces animation and sound.

And now the bowed string with natural force feedback manipulation

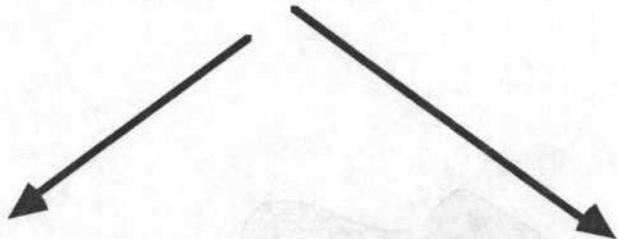
I would like to conclude with one point often considered as an intrinsic computer representation limit, I want to speak on the notion of rigidity and deformability.

Deformability and rigidity are relative notions that depend on the point of view. A rigid object can be deformable on one scale, and rigid on another scale, and vice-versa. On a macroscopic scale, Physics has studied the two cases independently. And the respective models are orthogonal. If we adopt a geometrical definition for rigid objects, for example, the definition which says that the shapes don't change over time, and if we implement geometrical and cinematic calculus, we can really obtain with the computer absolutely rigid objects, but they cannot interact. If we implement physical calculus with physical interactions, we don't have infinite forces, or infinite masses, and we don't have strictly speaking a rigid object. But, it is not in itself a limit because it is evident that only atomic physics proposes the same formalism for the two phenomena and, for this Physics, all the objects are deformable objects. More, an object is only a relative notion: an object exists only if the cohesion forces are greater than the external forces applied to it. This is the point of view we have adopted.

Then, the rigid object is a limit to the general object, that is deformable in itself. Fractures is a special case of deformations and they can happen when some objects' parts are less robust.

The major interest of this definition is, in comprehending the transient and dynamic phenomena as bandwidth, resonance, instability, which are very important for the elaborate correct simulations. It is perhaps the major difficulty in physical simulation.

T4

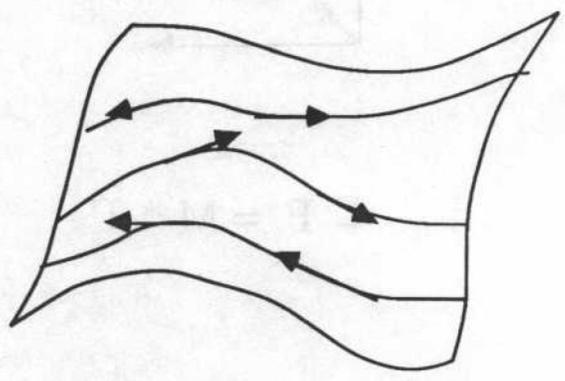
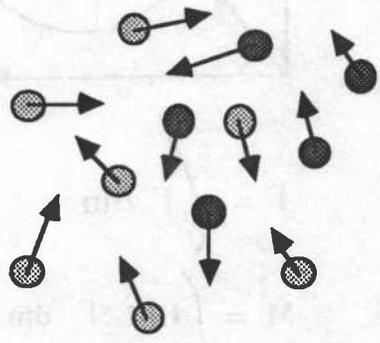


NEWTONIAN FORMALISM

MAUPERTUIS FORMALISM

$$F = M * \frac{d^2 R}{d T^2}$$

$$A = \int P * dR$$



PHYSICAL NEWTONIAN UNIVERSE

PHYSICAL MAUPERTUIS UNIVERSE

Concrete
Construtive

Abstract
Formal Developments

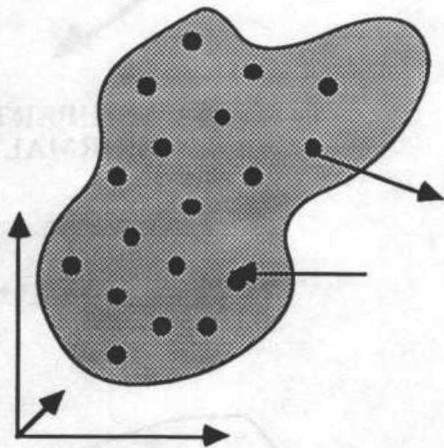
"SYNTHETIC PHYSICS"

"ANALYTIC PHYSICS"

PARTICLES ' PHYSICS

versus

SOLIDS' PHYSICS



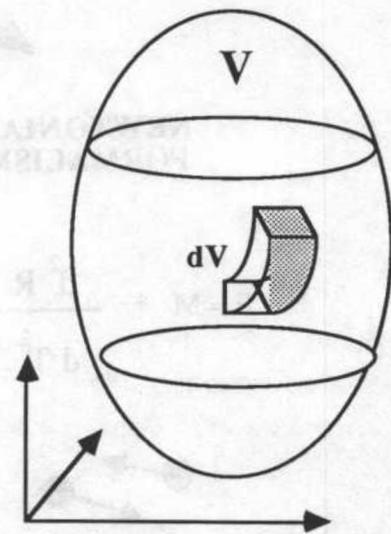
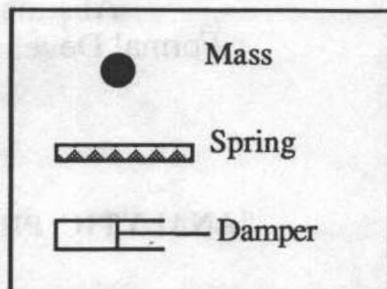
$$\Sigma F = M * \Gamma$$

Centered forces

Heterogenous Objects

No Boundary Problems

Non linearities



$$F = \int_V \Gamma \, dm$$

$$M = \int_V OM \wedge \Gamma \, dm$$

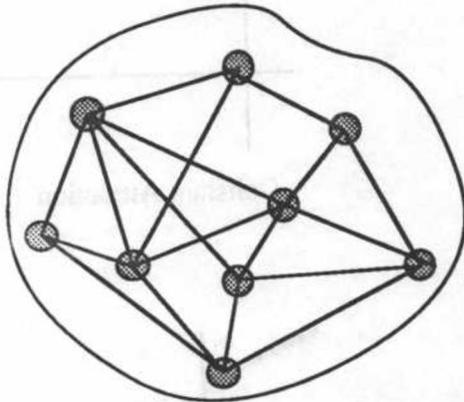
Tensors

Only Homogeneous Objects

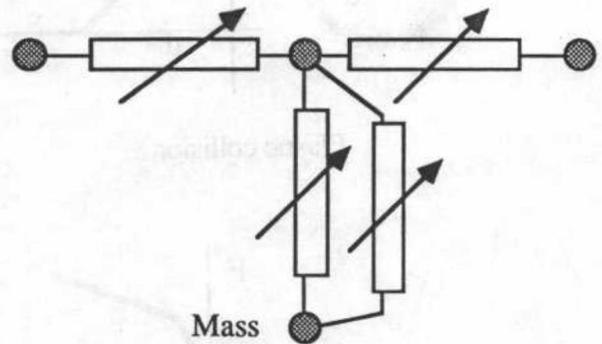
Boundary Problems

Only Linear Systems

GENERAL STRUCTURAL MODEL

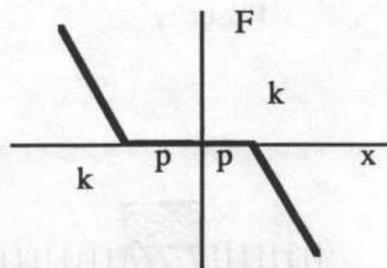
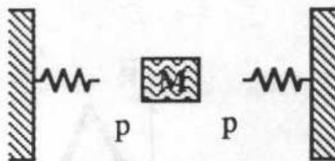
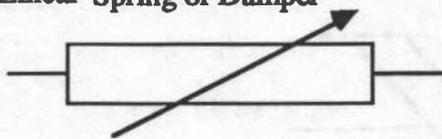


Non Linear Damper - Spring



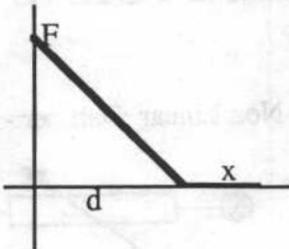
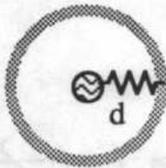
LINEAR and NON LINEAR INTERACTIONS

Non Linear Spring or Damper

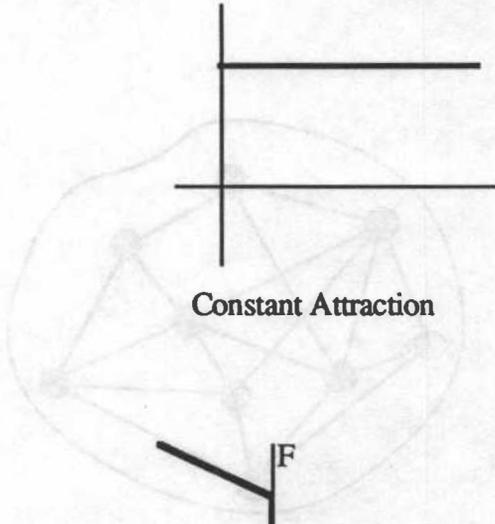


Elastic Buffer

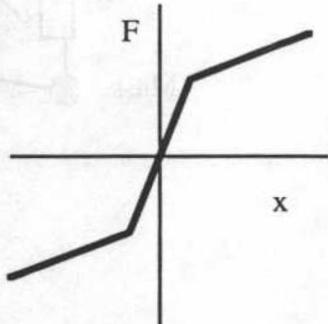
INTERACTIONS



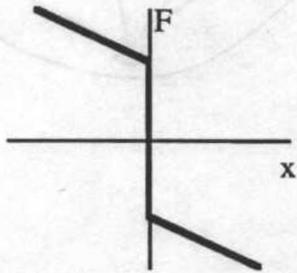
Elastic collision



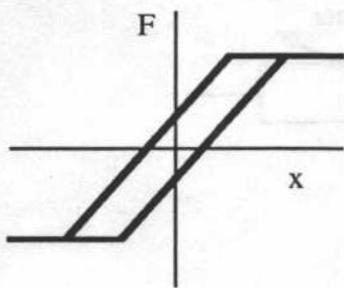
Constant Attraction



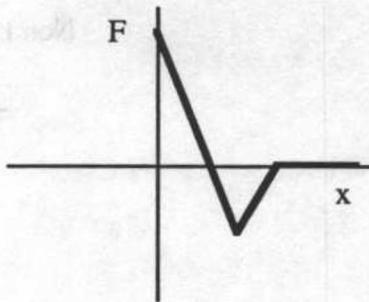
Spring Check



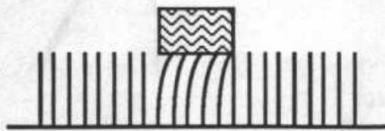
Preliminary Compression



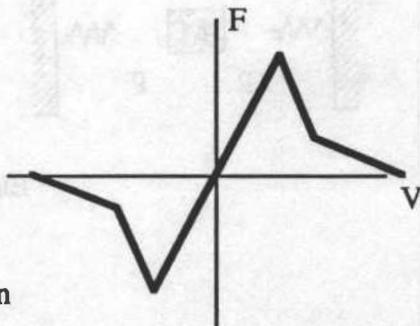
Plasticity



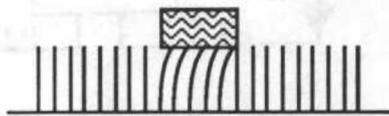
Cohesion Interaction



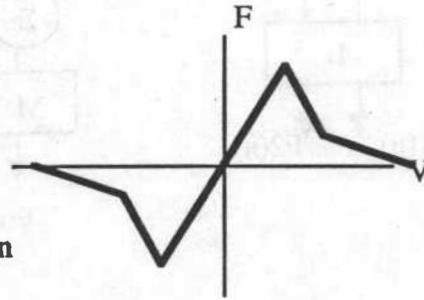
Dry Friction



COMPOSITE INTERACTIONS



Dry Friction



Bowed String Interaction

$$F_2 = -F_1 = -K * (LR) - Z * (V_1 - V_2)$$

$$LR = L - LA$$

Tangential interaction in relative Motion of 2 bodies

State 1 : Dry Friction

Condition : on Relative Speed

Dispositions : $K = 0$

$$Z = ZR$$

State 2 : Visco-elastic interaction

Condition : on the Relative positions
or on the force

Dispositions : $K = KR$

$$Z = ZR$$

$$LR = Lc - LA$$

T9

THE ABSTRACT PHYSICAL MACHINE

