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► To cite this version:

Jamel Nouiri, Claude Cadoz, Annie Luciani. The physical modelling of complex physical structures. The mechanical clockwork / ESQUISSES Programme. Fith Eurographics Workshop on Animation and Simulation, 1994, Oslo, Norway. pp.14. hal-00910600

HAL Id: hal-00910600

<https://hal.science/hal-00910600>

Submitted on 27 May 2014

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The physical modelling of complex physical structures The mechanical clockwork

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Introduction

This paper deals with physical modelling and more particularly with the particle-based modelling technique used by the Cordis-Anima modeller-simulator designed by the ACROE. Our goal is to show that it is possible to model a rigid articulate system with a complex geometry thanks to this technique. We chose an example of this category that seemed to us to be the most significant (complex and complete) of this problem : a clockwork.

The achieved model is the result of different analysis levels of a real clockwork (functional, structural and phenomenological). The result of the clockwork's structure enabled us to identify and to dissociate the different mechanisms at work and their relative dispositions. Functional analysis brought out the principles of the functioning of a clock and the interactions between the various mechanisms. The observation of the running of a clock enabled us to adjust and to refine the characteristics of our model.

The paper is structured as follows :

1. A non-exhaustive overview of the system of physical object modelling and simulation that we used in this work.
2. The description of the functioning and the main mechanisms of a clockwork.
3. From the real clock to the physical model : the description of the final model and the techniques used for the various adjustments and refinements of the model.
4. The generation of sound from the physical model of the clockwork
5. Conclusions
6. A video tape is available in the ACROE laboratory

1. The Cordis-Anima system

1.1. The principles

CORDIS - ANIMA is a computer tool for the modelling and the digital real-time simulation of physical objects. CORDIS-ANIMA is the outcome of fundamental research activity to choose the modelling principles simultaneously adapted to obtain the best motion realism, the best genericity for a physically-based modeller, and the real time simulation of the generated physically-based models. The design of this modelling and simulating system began [CLF84], [LC84], and today CORDIS-ANIMA is [CLF90], [LJCFR91] :

- a formal representation system for the specification of physical modelling
- a computer language for the description of physically-based models
- a simulation language to commute these models in real time.

Originally dedicated to musical creation and animated image synthesis, it has been used to generate physically based models for Robotics [JLL91], for the mechanics of the terrain and soils [JLL92], to model living behaviours [DLC93] and to model complex physical phenomena [HLM94].

Its basic characteristics are :

1. The underlying Physics is that of material point systems. It allows to model physical systems having a very complex geometry and to calculate very complex physical interactions between physical bodies whatever the geometry of these bodies.
2. CORDIS -ANIMA is a physically consistent language. It guarantees that whatever the models generated with it, they are physically correct, this means that it always satisfies the basic principles of physics such as energy conservation and the action - reaction principle.
3. the user who designs a physically based model with Cordis-Anima never writes mathematical equations. But he must be able to have correct physically based reasoning to assembly basic fundamental physical elements to find the model which is able to produce the complex physical phenomena he aims. This property leads the user to learn what is a good physical reasoning. For example on simulate turbulence in gas, it is not sufficient to reproduce the Navier -Stokes formula found in Physics book, but the user seeks to understand, by means of Cordis-Anima how and why matter can be turbulent.
4. In return, any object, system of objects or physical phenomenon is learned, specified, programmed and simulated according to a same formalism.

1.2. The basic elements

Physical discretized objects communicate by two dual physical variables, intensive variables (forces ...) and extensive variables (positions ...). For this reason, only two dual elementary formal components are sufficient to describe physical object or phenomena : the <MAT> component which produces an extensive variable from a intensive one; and the <LIA> component which produces two opposite intensive variables from two extensive variables (figure 1).

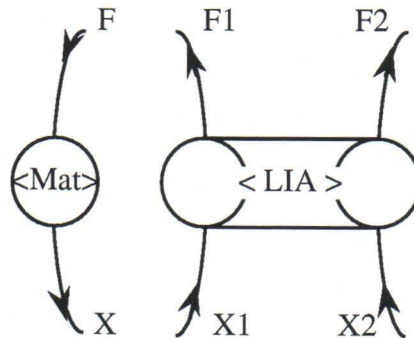


Figure 1 - The basic components of the Cordis-Anima formalism

Thus, any physical object can be described by a network of these two elementary formal components (figure 2). This is why, all the parts and subparts parts of this network are interacting in guarantee of the physical action- reaction principle. On the left of figure 2, the explicit representation is described : the grey component is the matter component and the white component is the interaction-without-mass component. On the right of the figure, there is the reduced representation, which will be used in the sequel : the grey spheres are matter components and the black line segments are interaction components.

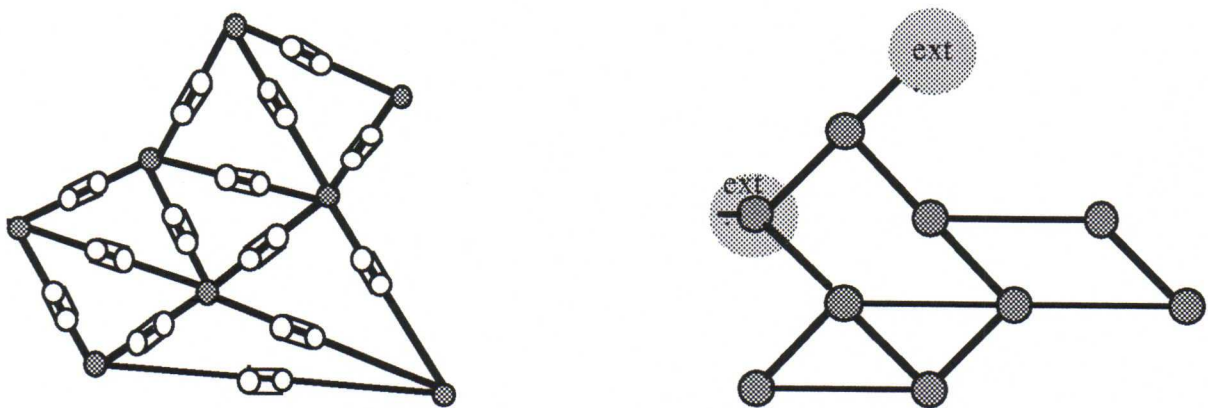


Figure 2 - A Cordis-Anima network.

1.3. Some usual CORDIS - ANIMA algorithms

We give here three algorithms amongst the CORDIS - ANIMA usual ones, we used in the model described in this paper.

A first usual algorithmic instance of the <MAT> element is the punctual mass. One specific implementation of it can be that using finite differences equations with delayed velocity. The algorithm is given below :

$$\text{MAS : } X(n) := 2X(n-1) - X(n-2) + T^2/MF(n-1)$$

where :

$X(n)$	is the position computed at instant n
$X(n-1)$	is a position memory i.e. the position at instant $n-1$
$X(n-2)$	is a position memory i.e. the position at instant $n-2$
$F(n-1)$	the input force at instant $n-1$
M	the algorithmic mass parameter
T	the constant calculation time step

An another usual algorithmic instance for the interaction element <LIA> is the parallel elasticity / viscosity given below :

$$\text{RES/FRO : } F_1(n) = -F_2(n) = -K(X_2(n) - X_1(n)) + Z/T ((X_2(n) - X_1(n)) - (X_2(n-1) - X_1(n-1)))$$

where :

$F_i(n)$	the forces computed at instant n , $i = 1, 2$.
$X_i(n)$	the positions of the two matter points on each side of the link element at instant n .
K	the algorithmic stiffness parameter
Z	the algorithmic viscosity parameter
T	the constant calculation time step

As before, the velocity is computed according to the "delayed velocity discretization scheme".

Finally, a last usual algorithm is that of collision interaction. With CORDIS - ANIMA, we obtain very complex non linear interactions by combining the visco-elastic component with finite state automata processes driving the values of the parameters according to conditions on physical state variables. By these means, we can create any kind of deformable materials (rigid, elastic, plastic, friable...), of complex materials (pastes, soils, woods, metals, sand, muds ...) and of complex object assemblies (articulate objects, collisions, dry friction, adherence, sticking...)[LJRCF91].

The simplest of these non-linear interactions is the non penetration interaction (also called the collision interaction) between two matter points or two groups of matter points. This interaction can be interpreted as a spring added between the two sets of matter points, as soon as they get close enough i.e. as soon as their distance gets smaller than a threshold value d_0 . (figure 3).

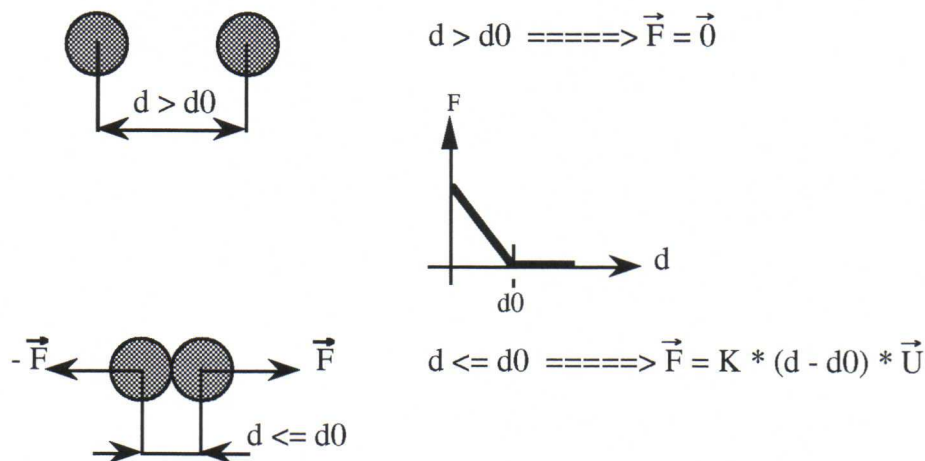


Figure 3 - The non penetration interaction

In figure 3, the circles represent the threshold of the elastic non penetration interaction, in other words the rest position of the non penetration area. In following drawings of our model, all the masses are linked by this kind of interaction, and the circular area surrounding each mass represents its relative non penetration area.

1.4. Other works and aims of the our current works

In Computer graphics, two kinds of works are usually distinguished : those seeking to model rigid and rigid articulated objects and those seeking to model deformable materials. The particle-based models have been introduced since the geometry became quite complex such as in the case of complex kinematics [Ree83], [Sim90], or since the deformations became quite large. There was the case with the modelling of solid-> fluid transition [TPF89], with breaking objects [Nor91], with surfaces having variable topology [ST91], with complex motions of objects immersing in turbulent velocity fields [WH91], with fluid pastes [DG94]. This is also the fundamental reason why we design CORDIS-ANIMA with which we have modelled several types of deformable objects (see above references).

But in a more general way, these different kinds of objects (rigid, articulate, deformable) or phenomena (turbulence, images, sounds, fusion, explosion ...) can coexist in a same natural context. Then authors

achieve to cohabit different kinds of models in some specific situations, such as the modelling of manufactured tissues falling on rigid solids with complex shape [HBG92], or the modelling of an elastic surface surrounding a articulated rigid skeleton [GVP91].

We try to model each kind of physical object and phenomenon with the same physical interacting particle-based system. We can remark that even articulate rigid objects are deformable systems and when the number of degrees of freedom is high, it is unwieldy to compute them with solid-physics-based models. Furthermore, adding the sound raises the same kind of question : specific models (such as modal or acoustical models) or general particles system. In its principle, the physical interacting particle based modelling allows models for all these cases. The question is then "Is this formalism quite general to model and simulate complex mechanisms, such as buffered articulations, slipper guides, driving belt, ..., with a small number of punctual masses and interactions between them?"

We have already developed several models of mechanisms, like complex vehicles moving on rigid grounds, on rigid soils covered by mobile rocks, and deformable soils [Jim93]. The clock, we proposed to model, is an object that is in its principles more complex than other kinds of articulate rigid objects such as for example the robotics vehicles we have previously developed. A clockwork mechanism have several kinds of mechanical liaisons and in addition, because it must count very regularly, needs very precise object shapes, very precise assembling and several feedback complex loops between all the components.

2. The mechanical clockwork : the mechanisms and the functioning

Clocks are used for the measure of time. The time base is generated by the oscillation of a *pendulum* in interaction with a source of energy necessary for the maintaining of the oscillations. The supply of kinetic energy of the oscillating element is provided by the transformation of either the elastic potential energy of a spring (strained during an initial rewinding) or a gravitational potential energy of a weight. This energy must be let out regularly. This is done by the *regulator* or *escapement/damper* mechanism. On the one hand, this mechanism provides the energy impulse necessary to compensate for the attenuation of the oscillation caused by mechanical imperfection and a damping environment, and on the other hand, it inhibits the energy supply until the next sequence. This is the level where time regulation is carried out. Time display is carried out by visual systems (clock hands) or sound systems (clock chimes) (figure 4).

Essentially, a clockwork is mainly composed of :

- (i) An oscillating mechanism that generates the time base : the counter
- (ii) A source of energy necessary for the maintaining of a stable movement : the motor
- (iii) A mechanism that regulates energy and time : the regulator.

(iv) A time display system which can be a visualisation (clock hands) or a sound representation of the time (clock chimes).

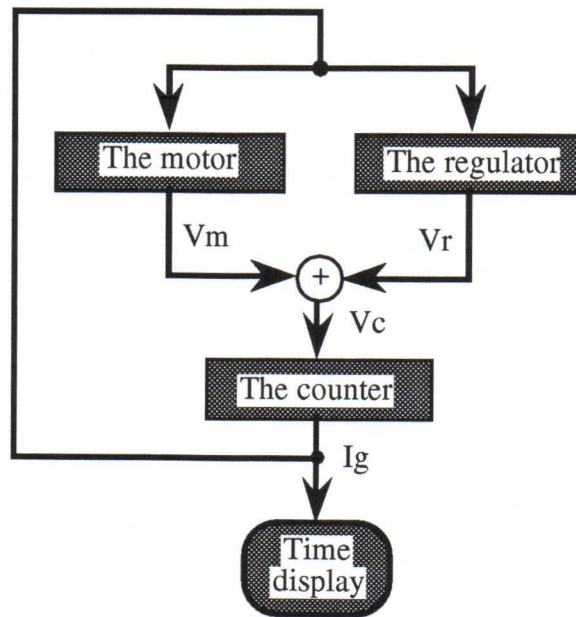


Figure 4 - The principle of the functioning of a clockwork with the electrical analogy V_m , V_r et V_c the potentials and I_g the electric current

One period of the oscillating element represents one time unit.

This is the way the sequence of the movements of all the mechanisms is organised : The oscillating element starts at rest, in a maximal amplitude position. When it is released it strikes the escapement system in order to free the source of potential energy and goes on until the opposite maximal amplitude position is reached. Then the oscillating element stops and returns back. At that moment, the kinetic energy regulator gives an energy impulse to the oscillating element. In this way, the oscillating element can carry on with the following sequence. Thus a continuous movement is achieved. It is only limited by the energy supply.

3. From the real clockwork to its simulated replica

Once the principle of the running of a real clock and its principal mechanisms are identified, we can tackle the description and the construction of these mechanisms in the Cordis-Anima formalism. This was carried out in three stages :

1. The definition and the description in the Cordis-Anima formalism of the different mechanisms of the clockwork, regardless of any mutual interaction.

2. The assembly of these different mechanisms in accordance with specific interactions.
3. The adjustment of the motion of the simulated clockwork in the virtual space.

3.1. The physical model of each mechanism

The analysis of the clockwork enabled us on the one hand to identify the four major mechanical components : the oscillating element (the counter) the motor, the regulator and the display system. On the other hand, the observation of the trajectory of the different components enabled to determine their relative size and to define the parameters of the different modules to simulate. In view of these results, this is the way we modelled the mechanisms.

a. The oscillating element

We have chosen a pendulum system with three mass elements : one pivot, one central point where kinetic energy from the motor is received and a third point representing the inertia and the weight of the pendulum. This structure is reinforced by two lateral mass elements which provide the stability of the model's shape and guarantee maximum rigidity for the whole structure (figure 5.).

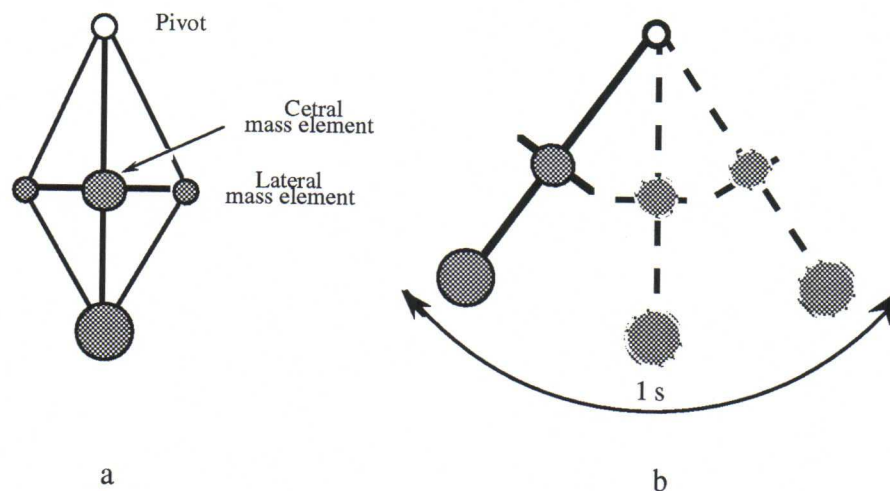


Figure 5 - The oscillating element model - a : structure of the built model, b : working.

b. The escapement/damper mechanism

This is the major piece of the model. Three vital functions are concentrated in this single mechanism, in order to simplify the determination of the parameters of the model and the final adjustments. The model of the constructed object comprises three parts. The first part stops the falling chain. It is called the *damper*. The second part transmits the kinetic energy of the masses to the mechanism. It is called the

escapement. The third part transmits the kinetic energy acquired during the escapement, to the pendulum. The first parts are constructed by a set of mass elements arranged so as to obtain rigid curve shapes in order to facilitate collision and damping with the masses of the chain (see figure 6.).

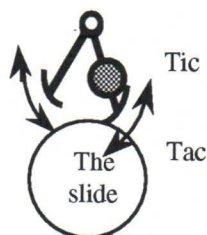


Figure 6 - Model of the regulator

c. The motor element

The motor element is modelled as a fine chain of masses guided by a round sliding channel. The maximal duration of the functioning is determined by the total number of masses on the chain (See figure 7) The movement of the pendulum is maintained by kinetic energy transfer from the masses to the pendulum, through collisions, firstly between the falling masses of the chain and the escapement/damper mechanism, and then between this mechanism and the pendulum.

d. Sound display mechanisms : the clock chimes

CORDIS - ANIMA is originally able to model objects producing sounds and musical sequences [FC91]. We have also imagined sound displays. They are represented by a set of gong models (4 in the case of this model). These gongs are struck by hammers moved by the falling masses of the chain through a gear system. (See figure 8.). The gongs are Cordis - Anima physical models of vibrating structures based on punctual physics. Vibrating objects are described by assembling of masses, dampers and stiffness according to a specific topology (line, surface ...). The physical parameters (M, K, Z) are chosen to obtain vibrating acoustical deformation modes. Because of the vibrating structures have usually linear behaviour, they can be modelled by modal models seen as more simplified masse-spring-damper models [Flo86], [Djo90]. The same process is used to add the tic-tac sound effects to the escapement -damper mechanism (figure 6).

The model of the gongs is composed of two parts : one part corresponding to the low frequency deformation modes, one other corresponding to the vibrating acoustical frequency deformation modes. The first part is simulated at the basic simulation rate that is 1050 Hz. All the mechanisms described before runs at this simulation rate. The hammers strike the gongs at the simulation basic frequency rate. The simulation of the second part runs at 44,1 kHz. Cordis - Anima integrates a physically based model

for the communication between several parts of the model which run at different frequencies. The visualisation of the clock runs at 25 Hz. The 1050 Hz basic frequency rate has been chosen according to the range of calculation step needed by the bandwidth of the simulated object in its low frequency deformation mode and because it is a multiple and sub-multiple of the standard time steps for numeric sounds and images.

This method allows the relation between the sounds and the images to be physically consistent. For example, the synchronisation is perfect and it appears sometimes micro-percussions. More, the dynamic of the percussions can have an effect on the sound.

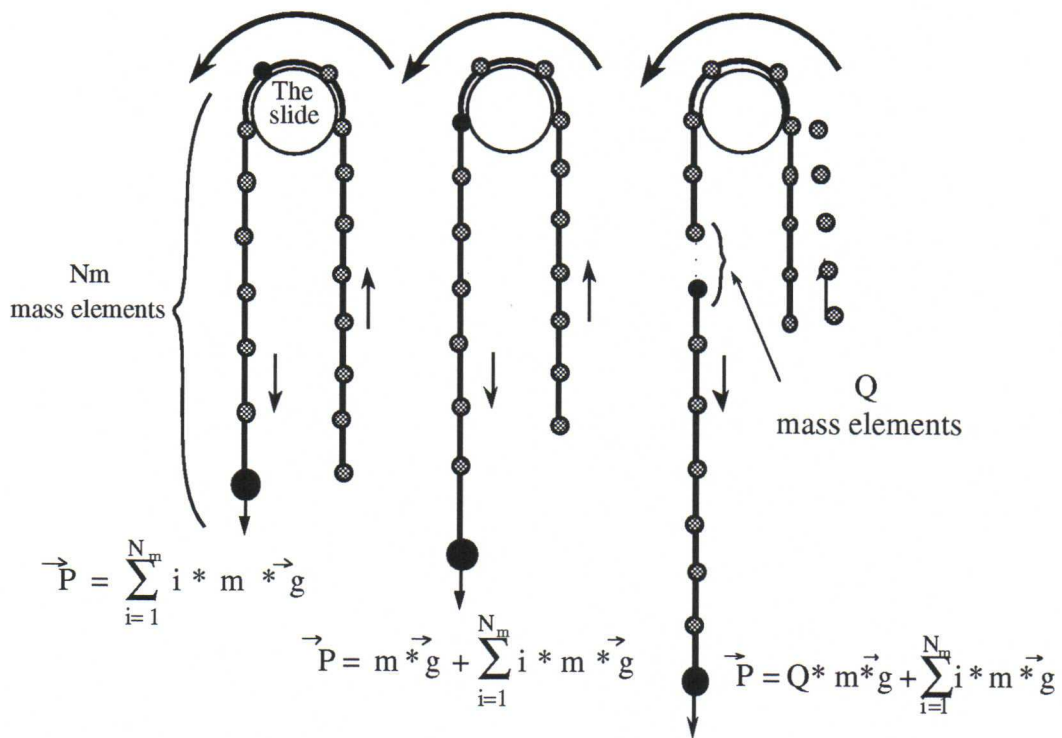


Figure 7 - Working principle of the motor element.

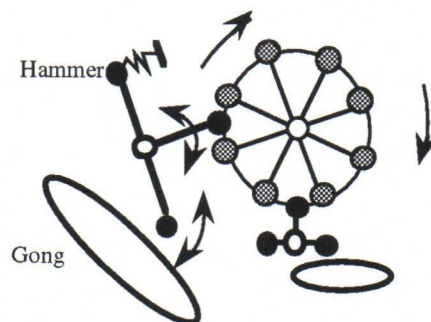


Figure 8 - The gear system and the clock gongs

3.2. The assembly of the mechanisms

In a first stage, the relative positions of the different mechanisms enabled us to determine the initial positions and afterwards to put each mechanism at its right place (see figure 9.). In a second stage, we defined the interactions between these mechanisms. These interactions are non penetration interactions previously defined (See figure 3).

3.3. The adjustment of the model

During the design of the model, we were firstly interested in the adjustment of the working and the interactions between the escapement/damper mechanism and the motor mechanism (the chain) This adjustment is truly a clock maker's work. It consists in the refinement of the weight of the chain's masses and the escapement/damper mechanism, in order to remedy the imperfection caused by the establishment of interactions between different modules. This work also consists in the adjustment of their relative trajectories. Afterwards we adjusted the initial positions of the pendulum and its trajectory. At last the transform rates between the chain masses to the display mechanism models are determined.

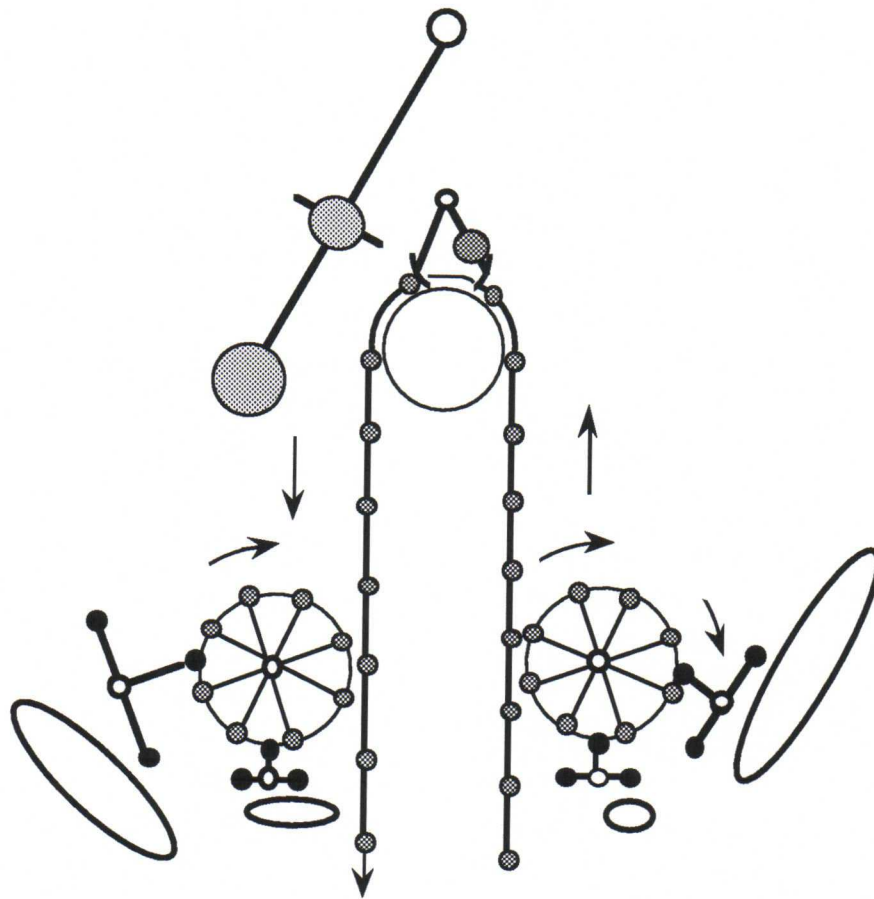
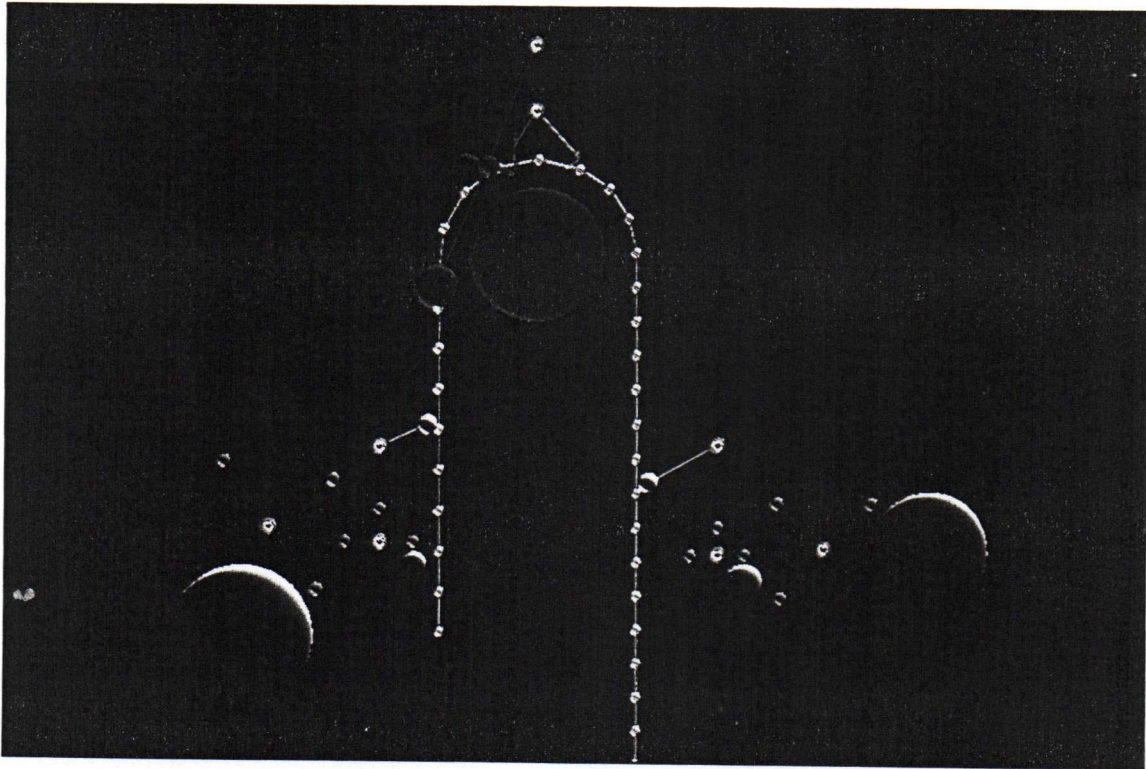


Figure 9 - All the mechanisms

4. Conclusion

The results of the modelling and simulations are more than satisfactory. We have been capable of simulating a clockwork that reproduces quite finely a clockwork's functions i.e. the measure and sequencing of time. Further, we can also reproduce some irregularities of a clockwork caused by its mechanics, for example the relative deformation of the chain. Photograph 1 shows the complete mechanism.



Photograph 1 - The complete physical particle-based model of the clock

5. The illustration of the achieved results

The figure 10 illustrates one period of the functioning of the model.

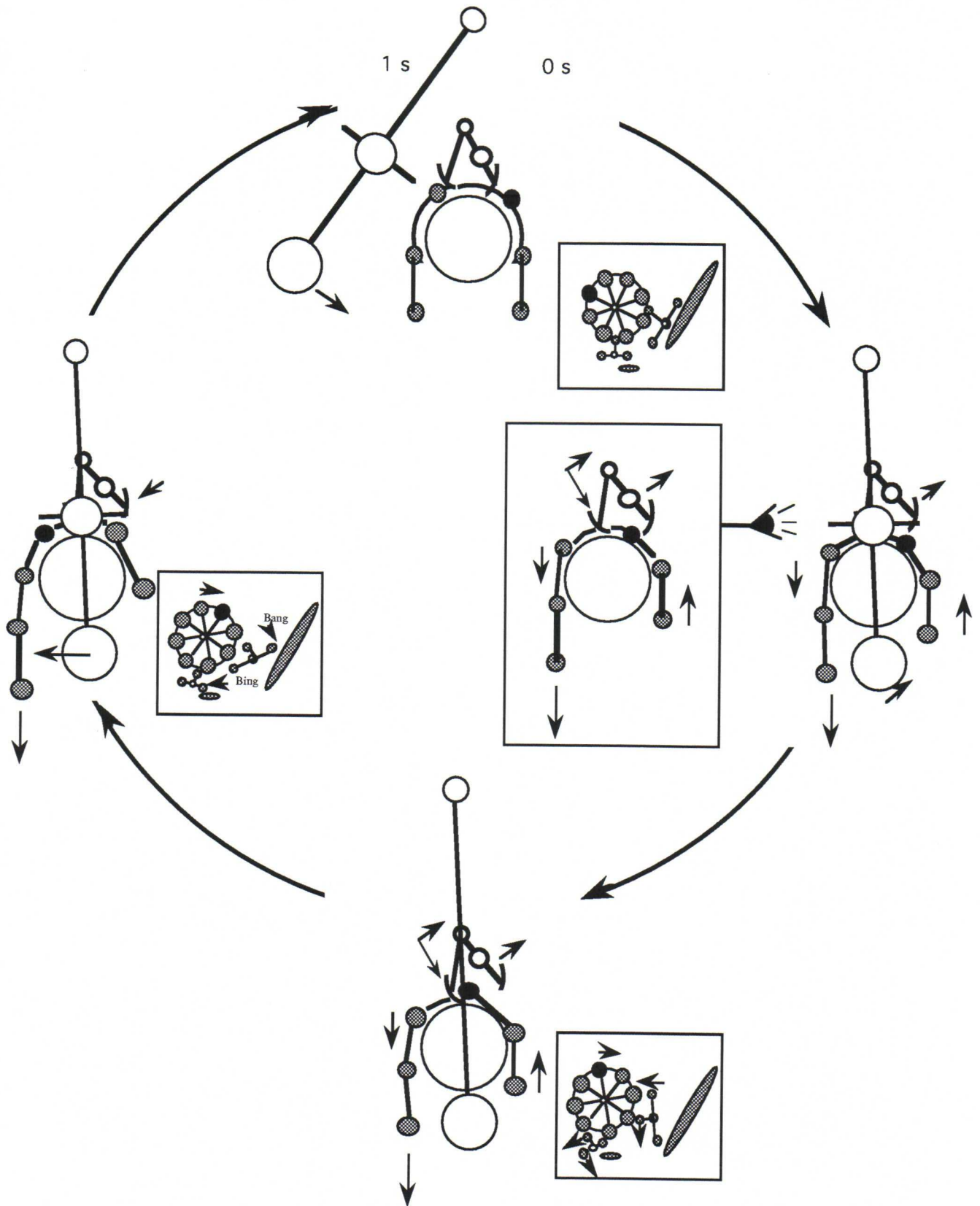


Figure 10 - One period of the functioning

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