American Journal of Applied Psychology
2016; 5(6): 98-103
http://www.sciencepublishinggroup.com/j/ajap
doi: 10.11648/j.ajap.20160506.19
ISSN: 2328-5664 (Print); ISSN: 2328-5672 (Online)

Artificial and Biological Intelligence: Hardware vs Wetware

Piero Chiarelli

National Council of Research of Italy, Pisa, Italy

Email address:
pchiare@ifc.cnr.it

To cite this article:
Piero Chiarelli. Artificial and Biological Intelligence: Hardware vs Wetware. *American Journal of Applied Psychology*. Vol. 5, No. 6. 2016, pp. 98-103. doi: 10.11648/j.ajap.20160506.19

Received: December 9, 2016; **Accepted**: December 22, 2016; **Published**: December 30, 2016

Abstract: By starting from physical principles, the paper formulates the basis of the biological intelligence and coscience formation. The work shows that far from equilibrium, the principle of maximum energy dissipation, in a fluid phase, brings the molecules to organize themselves in living systems (ordered stationary states) that sustain energy-matter fluxes that determine the architecture of the dissipative system. The driver of the process is the energy; the matter is the substrate. On this base, and thanks to a "selection rule", the living systems developed a bi-phasic structure consisting of a solid network permeated by a liquid where fluxes of ions and molecules can be maintained. In this way they realize a "wetware" where the energy and the organization/information are handled, and where a high specialization of functions can be obtained by using the spatial delocalization leading to the development of the complexity of the shape. The outputs of a living system can be divided in two categories: 1) macroscopic outputs: Movements, definition of an organized reaction or plan of action, and 2) microscopic ones: Plastic rearrangement of structures, migration of chemical species and electrochemical dynamics (transportation of matter, rearrangement, sensing, storage and information handling). The biological intelligence is a product of these basic processes where the wetware (matter substrate) is continuously modified by the energy-matter fluxes. On this base, the artificial intelligence of computers can be seen as a subclass of intelligent processes since it owns some limitations due to the invariance of the material substrate (that is not self-modified by the energy fluxes) and by the unique form of the flux of matter that is given by the electron current. Finally, the definition of a bio-inspired artificial intelligence is discussed.

Keywords: Generation of Life, Living Systems, Biological Intelligence, Biological Conscience, Artificial Intelligence, Matter Self-Organization, Maximum Free Energy Dissipation

1. Introduction

The lack of a physical theory that can explain the generation of order at the base of biological systems is a big obstacle for the physical explanation of the expression of life.

The second law of thermodynamics expresses the tendency of systems toward the maximum disorder and conceptually forbids self-organizing processes of matter.

Starting by the thirties of the last century, physicists and chemists were convinced that the tendency to the increase of entropy happens near the thermodynamic equilibrium, and that the generation of order is possible far from it [1-8].

In 1945 Prigogine [1, 2] proposed the "Theorem of minimum entropy production" which applies only to stationary states near-equilibrium. Šilhavý and others [3-4] have shown that the variational principle of (near-equilibrium) thermodynamics does not have any counterpart in steady states far from-equilibrium despite many claims in the literature.

Sawada postulated the principle of maximum entropy production [5]. He started by the work given by Malkus and Veronis [6] about the earth's atmospheric turbulence where the principle of maximum heat current, holding in fluid mechanics, has been proven to drive the energy transport process. Sawada showed that this law corresponds to the maximum entropy production, but this inference is not ever valid.

Sawada and Suzuki showed that the maximum production of entropy leads, in electro-convective phenomena, to the maximum rate of free energy dissipation. This principle was confirmed, both by numerical simulations and by experiments [8]. Moreover, they showed that ordered metastable states are visited by the system with a life-time proportional to the rate of energy dissipation.

An extensive discussion of the possible principles of maximum entropy production and/or of dissipation of energy is given by Grandy [9]. He finds difficulty in defining the rate of internal entropy production in the general case, showing that sometimes, for the prediction of the course of a process, the maximum rate of dissipation of free energy may be more useful than that of the rate of entropy production.

Recently, the author has shown [10-13] that it is possible to define, in the phase space, a Wigner type distribution function [3-15] that can lead to the definition of an energy function (named hydrodynamic free energy (HFE)) whose dissipation, generally speaking, has a part that is maximum during the relaxation processes far from equilibrium. As shown in reference [14], it is possible describe a gas or a Marcovian fluid by mean of the distribution function of a single particle derived by the stochastic approach of the quantum mechanics in the hydrodynamic representation that leads to a Fokker-Plank form of the Maxwell equation [16]

$$\partial_t \rho + \nabla \bullet (\rho(< \dot{x}_{\overline{H}} > + < \dot{x}_s >)) = 0 \tag{1}$$

where the brackets $< ... >$ stand for the local mean, where

$$\dot{x}_{\overline{H}} = (\frac{\partial \overline{H}}{\partial p}, -\frac{\partial \overline{H}}{\partial q}), \tag{2}$$

where $\overline{H}$ is the mean-field Hamiltonian, and where $< \dot{x}_s >$ is defined by the relation [14]

$$< \dot{x}_s > = -D \nabla \phi \tag{3}$$

where the HFE ϕ (that in the limit of local equilibrium converges to the free energy, normalized to kT [14] where T is the temperature) is given by the formula

$$< \Delta V_m > = h^3 \exp[-\phi]. \tag{4}$$

where $< \Delta V_m >$ is the mean volume of the molecular distribution function in the phase and h is the Planck constant.

Moreover, by introducing (3) into the FPE (1) the kinetic equation

$$\partial_t \rho + \nabla \bullet \rho < \dot{x}_{\overline{H}} > = \nabla \bullet \rho D \nabla \phi \tag{5}$$

is obtained where D is a local diffusion coefficient [14].

Far from equilibrium, the HFE φ allows the definition of a formal criterion of evolution in terms of its "*stochastic differential*" [14]

$$d_s \phi = [< \dot{x}_s > \bullet \nabla \phi] \delta t \tag{6}$$

that is minimum with respect the choice of $< \dot{x}_s >$ and, since $< \dot{x}_s >$ is anti-parallel to $\nabla \varphi$, that the "stochastic" dissipation of the HFE

$$| \frac{d_s \phi}{\delta t} | = -\frac{d_s \phi}{\delta t} \tag{7}$$

is maximum with respect the choice of $< \dot{x}_s >$.

By using (7), in quasi-isothermal condition (and elastic molecular collisions) it is possible to show that the flux of entropy $S_{\sup}$ at the boundary surface of the system reaches the maximum rate of variation [14]. Moreover, by assuming, without lack of generality, that the energetic reservoirs work reversibly onto the system and that the heat generated into the system is reversibly exchanged with the environment it follows that

$$-\frac{dF_{tot}}{dt} = \iiint_V \{ \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} kT \frac{(\phi - 1)}{\phi} \rho^s (\frac{d_s \phi}{dt}) d^3 p \} \, d^3 q > 0 = \text{Max} \tag{8}$$

where F_{tot} is the total free energy. Sawada and Suzuki [17] proved that (8) is verified in the electro-convective instability very far from equilibrium.

By applying (8) to a system far from equilibrium that makes a transition from a metastable state (1) to another one (2) and vice versa, it is possible to show [15] that always we have both $\delta F_{tot\,(1 \to 2)} < 0$ and $\delta F_{tot\,(2 \to 1)} < 0$, but we must also have $\delta F_{sys\,(1 \to 2)} < 0$ and $\delta F_{sys\,(2 \to 1)} > 0$ or $\delta F_{sys\,(1 \to 2)} > 0$ and $\delta F_{sys\,(2 \to 1)} < 0$, from where it follows that, even if the total free energy always decreases, in one of the transitions there is an increase of free energy of the system. This is warranted by the fact that transition between metastable states can happen in both directions.

The free energy difference between two assigned stationary states depends by the kinetic characteristics of the system and can be sensibly higher than the small amount that can come by the presence of the external fluctuations.

Even if a large fluctuation may displace the system from a metastable stationary state, this fact will not be enough to bring the system toward the new stationary state. It is the tendency to the maximum stochastic dissipation of the hydrodynamic free energy that makes it possible.

As shown by Sawada and Suzuki in electro-convective instabilities [8, 17], the tendency to maximize the free energy is a real force that attracts the system toward the new stationary condition. In fact, they showed that: 1) The stationary state with higher free energy dissipation is the more stable (i.e., it owns a longer life-time before the transition to another metastable state takes place); 2) In reaching the fully stationary condition, the free energy dissipation of the system increases and reaches the top at the establishing of final stationary configuration.

The maximum free energy dissipation generates the basin of attraction for each metastable state (basically larger, higher is the dissipation rate of the metastable state) and the fluctuations allow the system to jump between them.

Generally speaking, the increase of free energy does not mean that the entropy of the system has to decrease. This depends by how much is the energy change in the transition.

Nevertheless, given that, in a transition between metastable states, the macroscopic kinetic energy of the molecules does not appreciably increases (as showed by Sawada and Suzuki [17] in electro-convective instability) and that the internal energy is just a function of the temperature; due to the incompressibility of the fluid phase that makes quite small the energy variations coming from the specific volume variation, in isothermal transitions in fluids (as the electro-convective ones) the free energy increase is almost due to the entropy decrease.

The ability of a system in making back and forth transitions between metastable states (as the consequence of both the presence of fluctuations and of the tendency to the maximum stochastic dissipation of free energy) allows the spontaneous increase of order in incompressible fluids far from equilibrium.

For sake of completeness, it must be observed that, in principle, is possible to have self-assembling of matter in fluids other than water such as for instance in the methane of the ocean of the moon of Saturn, Titan [18-19].

The present paper is organized as following: in section 2 the characteristics of organized structures are analyzed and the evolutionary pathway is derived; in section 3 the functions-structure relationship of living system is investigated and the basis of the biological intelligence is outlined.

2. General Characteristics of Stationary Ordered Systems

The fact that self-assembled structures that maintain their ordered structure (i.e., are stable, or thermodynamically speaking stationary (on the observing time scale)) must dissipate energy, comes from the fact that the dissipation (5, 7, 8) becomes null only at thermodynamic equilibrium when it holds that

$$\partial_t \rho + \nabla \bullet \rho < \dot{x}_{\overline{H}} >= 0 \tag{9}$$

and that

$$< \dot{x}_s >= -D\nabla\phi = 0 \cdot \tag{10}$$

Generally speaking, hence, in the other stationary states we have that

$$\partial_t \rho + \nabla \bullet \rho < \dot{x}_{\overline{H}} >= \nabla \bullet \rho < \dot{x}_s >= \nabla \bullet \rho D \nabla\phi \neq 0 \tag{11}$$

and since ρ is not null over all the phase space, it follows that

$$\nabla\phi \neq 0 \tag{12}$$

and the related matter-energy fluxes

$$\rho < \dot{x}_s >= -\rho D\nabla\phi \neq 0 \tag{13}$$

are present into the system.

The thermodynamic forces, due to the energetic and entropic gradients (contained in the explicit form of $\nabla\phi$), generate the fluxes $\rho < \dot{x}_s >$, that bring matter and charges moving through the system, and concur to the realization and maintenance of the ordered structure.

2.1. Basic Characters and Components of a Living System

At this stage of analysis, by using the results of the preceding section, we can outline some basic features owned by systems that undergo self-assembling:

1. a material substrate;
2. an ordered structure;
3. energy dissipation (with fluxes of molecules, energy, entropy and charges with gradients far from equilibrium);
4. a fluid component (e.g., water)

This is not new, what is new is the link between fluid, energy and order. The energy is the generator of order and it needs a fluid phase to do that.

Moreover, since the matter-energy fluxes are maintained by the energy dissipation, any ordered system needs a power source with an intake of energy and/or matter. This leads to the consequence that no life is possible in an isolated system.

For living systems, the isolation is harbinger of degradation and death: they are forced to reach the thermodynamic equilibrium with cessation both of matter-energy fluxes and of the maintenance of its ordered structure.

2.2. Life-Time of Ordered Systems and the Selection Rule

As shown by Sawada and Suzuki [17], the stability of stationary ordered states can be measured and defined by the duration of their life-time.

For simple ordered structures, the life-time is proportional to the dissipation rate of the state: higher is the dissipation rate longer is the life-time [17] of the stationary state. On the other hand, the permanence of the ordered structure is not due only to its ability to dissipate energy but also to its rheological characteristics: if the system is constituted by a fluid it can lose its shape very quickly (when the external sources are subject to a perturbation or they stop the energy supply) on the contrary, with a solid structure the ordered systems can maintain their shape (order) along the time and hence survive for a longer period of time.

The possibility of living structures of evolving toward more complex configurations increases with the improvement of their rheological characteristics. This can be conceived as the consequence of a selection rule: systems able to maintain and preserve longer and longer in time their shape (i.e., the acquired order) have higher probability of existence and completion.

The need of maintaining the acquired order (i.e., to have a longer life) has found the realization thanks to the development of bi-phasic structures made of a solid network whose pores are permeated by a fluid.

This because such structures can have the elasticity of a solid but they can also allow the flow of ions and molecules through the system with diffusivities typical of liquids [20-24] (the diffusivities of a solid material are of order of 10^3 to 10^6 times smaller than those of fluids, this means that, if the calcium ions diffusion and the following actin-myosin reaction can easily lead to a muscle contraction in 100 millisecond [25], in a “solid muscle” (if possible) it would require from 100 to 100 thousands seconds). The bi-phasic structure is widely common in living systems: skin [20], brain [26] and even bone [27] and cells are bi-phasic materials.

The richness of the polymeric networks, their variable porosity and elasticity, the degree of charge on their back-bone, the variety of molecular conformational shape have led to the development of a great variety of functions (e.g., tactile sensing in skin, or propagation of electric signal in nerve, streaming potential for reparation in bone and so on) and hence to the development of living systems with a variety of functions that in a pure liquid phase would not have been possible.

2.3. Transition to Living Structures: Synergies and Specialization of Functions

The transition to wet structures with a solid-like rheology is the successful move that has opened the way to more complex living systems.

The process is not immediate and the highly organized and complex functioning, that we can find in a living organism, is the result of a very long pathway of evolution. The biphasic structuring is the step that, thanks to spatial separation, has allowed the generation of specialized functions in different places of the living structure. In this way it is possible to have every single part devoted to a particular purpose whose output is useful for sustaining the processes in the other places, all in circle.

This has led to the establishment of a network of synergies: the real step that generates the transition from organized structures to living systems.

This can be well understood by the following thought experiment: if we take away, from their position, all cells of a living system and then we put them back reversibly in such a way to re-obtain the starting state, we will observe that when all the cells are far away each other, all living functions are suspended. Between those separated parts cannot be established both the energy-matter fluxes and the associated complexes functions. The life functions would be resumed only after the re-composition of the system.

Thence, the only possible answer the question “of what about is the life composed by?” is: The life realizes itself in the interrelations between the parts by the synergic functions developed among organized components.

In this way, the living systems are a sort of wetware where energy and organization/information are handled. The outputs of those systems can be divided in two categories:

1) macroscopic outputs: movements, decisions and/or plans of action,

2) microscopic ones: plasticity (ability of rearrangement either inside the cells for their functioning or for the system accretion and repairing) chemical reactions and electrochemical dynamics (sensing, generation of mechanical energy in muscle, transportation and storage of matter and information handling or transmission).

3. Energy Production and Matter Modelling

What we firstly observe in a living system is the material substrate and its production of energy, but actually exists also the inverse process: the shaping of the material substrate and its ordering by the energetic fluxes, where the last process is more important than the first one for the establishment of life.

This can be understood by observing that a young dead man remains with the shape of a young man (e.g., his skeleton) forever, while, if he would have survived, his body would undergo to accretion up to the final shape of maturity. The energy-matter fluxes act as a 3D printer that reshapes and builds up the living system. Many and perhaps the most important functions in a living system are generated by the inverse process of material modeling due to the energetic fluxes. For instance, we can evaluate the importance of the role of the energetic modeling of matter just observing a baby that is not able to speak and then, after a certain period of time, due to the nutrition and continuous energetic shaping and accretion, is able to speak. Analogously, the same happens to a person who lost his conscience following a trauma (and if the structural damage is not too large to deeply inhibit the energetic fluxes) after a period of time, he can heal and restart to speaking and regaining consciousness.

3.1. Intelligence and Conscience as a Product of Energy-Matter Modeling

The bi-phasic wetware of the material substrate allows the establishment of the energy-matter fluxes that modify and organize the matter. At each acquisition of information, it corresponds a new material state that is a re-writable imprint of it.

Moreover, since the numerous informational functions cannot be performed contemporaneously, all the processes are synchronized in steps and the timing of such steps leads to a sort of biological clock (characteristic of each living system). The first consequence is that the perception of the reality is not continuous and the time is discretized. The main demonstration of this fact is the realization of the cinemascope that is based upon this cerebral mechanism.

The intellective output is then the "reaction" produced by the changes of the brain state (due to its plasticity) to an external input, leading to evaluation of facts and to the plan of action.

At the base of the “decision making” process there is the so called "conscience" of what “I am” and what “I can do” that the system has acquired with the experience. This process is based upon the physical predictability of the reality in the sense that if I observe a behavior, following a certain event, I know that to a such premise it will follow a defined fact: The existence of the physical laws and the repeatability of the experiences are at the base of the formation of the conscience. In this sense "I know" what "I am" and what are my potentiality (so that I can understand where a chain of events can bring me). Moreover, given the experienced states written in our brain sequentially, the dynamics of our evolution is captured and a dynamical conscience is obtained by the comparison between the latest state and the new one at each step of the biological time.

The way the conscience works and how it is formed it is really important in the evaluation of the external experiences by a living system and, hence, in the formation of its cognitive heritage.

3.2. Artificial Intelligence

At this point it is possible to make a preliminary comparison between the biological intelligence and the artificial one: the artificial intelligence of computers can be seen as a subclass of intelligent process where limitations come from:

1. the invariance of the material substrate that is not modified by the matter-energy fluxes,
2. the material flux is exclusively made by electron current.

Thence, since the material substrate is static and does not change (like a fixed imprint) we have a sort of “frozen conscience”: the plasticity (due to the energy-matter shaping) that incorporates the informational state in body of the living system, is absent in a machine.

From these outputs we can understand how the power of calculation is just a (small) part of what we call intelligence while the conscience and the intelligence are based upon a larger set of properties among whose the plasticity is the basic one that lets the system to adapt itself to the external conditions and to evolve toward a more complex and sophisticated structure and functioning.

4. Discussion

In the present paper the author shows how from general basic physical laws, very important characetristics of the biological systems such as the bi-phase organization of tissues, intelligence and coscience derive. What it is also interesting is understand how some features of the intelligence and of the coscience are consequences of the characteristics of the physical world.

The picture that comes out is that a living organism is a system where the energy is the driver and the biological molecules constitute the substrate that is organized and continuously modelled. By using an analogy we can depict a living system like a “self 3D-printer” that continuosly rebuild itself.

This model of living structures can help to deepen the understanding about the influence of the environment on the biological behavior vs the genetic one. The genetic basis in a living system determines the structure and the way how it (the “self 3D-printer”) “works”; the environment defines "what" the “self 3D-printer” writes; but since a 3D printer builds up the structure itself, it comes out that the environment can interfere with the genetic functions in determining the final biological structure and its behavior.

This knowledge can open new ways in finding comportamental pathways (training) that can repair disfunctioned organs (even brain) both by genetic deficiency and by environmental trauma.

The description reported in this paper is an innovation in the mental approach to the living organisms; the illuministic convincement that we are what we eat, is surpassed by a new one: we are what we do and we are influenced by the environment with which we interact.

From the physical approach of the present work, the "free willing" of an individual and the degree of objectivity of its conscience can be analitically defined and better evaluated (and will be matter of future work). Moreover, the common basis, and differences, of intelligence and coscience in animals respect to humans can be also recognized, being originated by the same physical laws.

Even if these results let the men pay the price to renounce to the convincement to be the only intelligent living organism with the conscience, they integrate the human race into a nature that manifests its creative power in many diversified ways: intelligent men in an intelligent nature.

5. Conclusion

Thanks to the principle of "maximum energy dissipation", in a fluid phase, the physical matter is able to organize itself in ordered stationary states with self-sustained energy-matter fluxes.

Through these fluxes, the energy shapes the architecture of living matter. Moreover, by the selection rule of “longest life-time”, the organized structures developed themselves into bi-phasic aggregations made of a solid network permeated by a liquid where fluxes of ions and molecules can be maintained.

In this way they realize a sort of wetware systems where energy and organization/information are handled, and where a high specialization of functions led to the development of the complexity of its shape.

The outputs of a living system can be divided in two categories: 1) macroscopic outputs: Movements, definition of an organized reaction or plan of actions, and 2) microscopic ones: material rearrangement, both chemical and electrochemical dynamics (transportation, sensing, storage and information handling).

The intellective output is the "reaction" produced by the changes of the brain state (due to its plasticity) following an external input, leading to evaluation of facts and to the plan of action. At the base of the “decision making” process there is the so called "conscience" of what “I am” and what “I can do” that the system has acquired with the experience. This process is based upon the physical predictability of the reality.

Moreover, since the imprints of the experiences take part to the arrangement of the structure where they are stored and handled, the dynamics of the evolution of the living system are captured with the formation of a dynamical conscience.

The work also gives the correct means to recognize the connections of the artificial intelligence with the biological one. To this end the paper helps to understand the limits of the artificial intelligence that can be seen as a subclass of the intelligent process since it owns the invariance of the material substrate (that is not self-modified by the energy fluxes) and a unique form of the material flux that is given by the current of electrons. This can help to improve the development of more sophisticated artificial intelligent machines but it can also help to understand better the biological intelligence by using the artificial one as a model of it.

References

[1] I. Prigogine, Bulletin de la Classe des Sciences, Academie Royale de Belgique 31: (1945) 600–606.

[2] I. Prigogine, *Étude thermodynamique des Phenomènes Irreversibles*, (Desoer, Liege 1947).

[3] B. H. Lavenda, *Thermodynamics of Irreversible Processes*, (Macmillan, London, 1978).

[4] M. Šilhavý, *The Mechanics and Thermodynamics of Continuous Media*, (Springer, Berlin, 1997) p. 209.

[5] Y. Sawada, Progr. Theor. Phys. 66, 68-76 (1981).

[6] W. V. R Malkus, and G. Veronis, J. Fluid Mech. 4 (3), 225–260 (1958).

[7] L. Onsager, Phys. Rev. 37 (4), 405–426 (1931).

[8] M. Suzuky and Y. Sawada, Phys. Rew. A, 27-1 (1983).

[9] W. T. Grandy, *Entropy and the Time Evolution of Macroscopic Systems*, (Oxford University Press2008).

[10] E. Madelung, Z. Phys. 40, 322-6, (1926).

[11] I. Bialynicki-Birula, M. Cieplak and J. Kaminski, *Theory of Quanta*, (Oxford University Press, Ny 1992).

[12] J. H. Weiner, *Statistical Mechanics of Elasticity* (John Wiley & Sons, New York, 1983), p. 316-317.

[13] Chiarelli, P., “Can fluctuating quantum states acquire the classical behavior on large scale?” J. Adv. Phys. 2013; 2, 139-163; arXiv: 1107.4198 [quantum-phys] 2012.

[14] Chiarelli, P., “Far from equilibrium maximal principle leading to matter self-organization” submitted to J. Adv. Chem., 5 (3) (2013) pp. 753-83.

[15] Chiarelli, P., Does life needs water or can be generated other fluids?, O. J. BioPhys., 4,. (2014) pp. 29-38.

[16] Y. B. Rumer, M. S. Ryvkin, *Thermodynamics, Statistical Physics, and Kinetics* (Mir Publishers, Moscow, 1980).

[17] Suzuki, M., Sawada, Y., “Relative stabilities of metastable states of convecting charged-fluid system by computer simulation”, Phys. Rev. A, 1-27, (1982).

[18] C. P. McKay, H. D. Smith, “Possibilities for methanogenic life in liquid methane on the surface of Titan”, Icarus 178 (2005) 274–276.

[19] Committee on the Limits of Organic Life in Planetary Systems, Committee on the Origins and Evolution of Life, National Research Council; The Limits of Organic Life in Planetary Systems; The National Academies Press, 2007; page 74.

[20] De Rossi, D., C. Domenici, Chiarelli, P.,: Analog of Biological Tissue for Mechanoelectrical Transduction: Tactile sensor and muscle-like actuators, in *Sensors and Sensory Systems for Advanced robots*, P. Dario Ed., 210-18, Nato ASi series, Springer Verlag, Berlin, 1988.

[21] Chiarelli, P., The pro-elastic behavior of a gel thin tube Materials Science and Engineering C 24 (4): 463-471·June 2004.

[22] Chiarelli, P., De Rossi, D., Modelling and Mechanical Characterization of Thin Fibres of Contractile Polymer Hydrogels, J. Int. Mat. Syst. & Struc., 3, 396-417, 1992.

[23] Chiarelli, P., De Rossi, Polyelectrolyte Intelligent Gels: design and Applications, Ionic Interactions in Natural and Synthetic Macromolecules, First Edition. Edited by Alberto Ciferri and Angelo Perico. 2012 John Wiley & Sons, Inc DOI: 10.1002/9781118165850. ch15

[24] Chiarelli, P., De Rossi, D., Basser, P.,: Hydrogel Stress-Relaxation, J. Int. Mat. Syst. & Struc., 4, 176-83, 1993.

[25] Grimby, L., Hannerz, J., Hedman, B., Contraction time and voluntary discharge properties of individual short toe extensor motor units in man. J. Pysiol. 1979 Apr; 289: 191–201.

[26] Chiarelli, P., Eng, J., Basser, P.,: "A Polymer-based method to measure contact stress", Proc. Symposium on Polymer Gels, Tsukuba, Japan, 1989

[27] A. J. Grodzinsky and N. A. Shoenfeld., Polymer, 18, 5 (1977).

[28] Clegg, J., Walker; J., A., Miller, J., F., et. al., Genetic Programming for prevention of cyber terrorism through dynamic and evolving intrusion, Decision Support Systems, 43 (4): (2007). 1362–1374.

[29] Jamil El-Ali1, Peter K., et al., Cells on chips, NATURE 442, 27 (2006).

[30] Huh, D., Matthews, B., D., Mammoto, A., et al., Reconstituting Organ-Level Lung Functions on a Chip, Science, 328 (5986) (2010) pp. 1662-1668.