Physics in Automation and Biomechanics

M. Paul Asir

Lodz University of Technology, Lodz , Poland.

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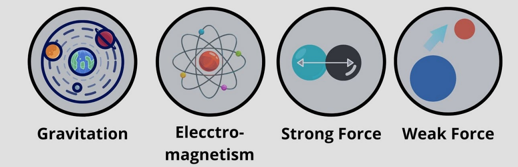
Plan

Fizika

"Machines are the imprints of Nature"

- Paul.

- Physics is the way to observe, analyse and quantify nature through experiments and mathematics.
- The nature can be broadly perceived as **Matter** and **Radiation** and the forces acting on them.
- Primarily the forces are to bind, create and annihilate matter.
- Fundamental forces are gravity, electromagnetic , strong and weak nuclear forces.



Forces and Fields

- $Fields/Manifolds/Space - time\ \ fabric$ are often used to study the **dynamics**.
- Interacting particles exchanges energies between particles gives us an perception of fields.
- Gravitons, Mesons, Pions, Quarks, Photons , gluons are some interacting particles.

Quark potential

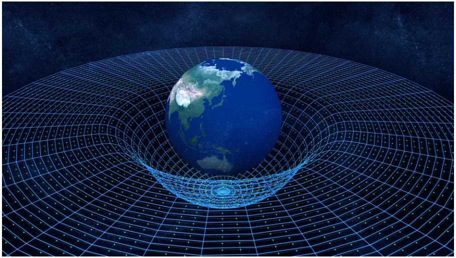
$$V(r) = -\frac{4}{3}\frac{\alpha(r)\hbar c}{r} + k\ r$$

Forces and Fields

Einstein Field equations [1917]

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{C^4} T_{\mu\nu}$$

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu}$$



Principia of Dynamics Formalism

Newtonian

$$\sum F_i = m_i \frac{d\mathbf{p}}{dt}$$

Lagrangian

$$\frac{\partial \mathcal{L}}{\partial q_i} - \frac{\partial \mathcal{L}}{\partial \dot{q}_i} = 0$$

Hamiltonian

$$-\dot{p}_i = \frac{\partial H}{\partial q_i}$$
$$\dot{q}_i = \frac{\partial H}{\partial p_i}$$

Manifestations of Physics

Manifestations of Physics

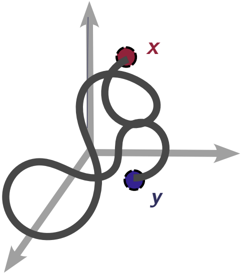
- Optics
- *Mechanics : Classical , Quantum , Statistical*
- *Electronics*
- High Energy Physics
- Astrophysics
- Electromagnetism
- Nonlinear Physics

Perceptions of Physics

Macroworld: Space-Time continuum [1]

- Discretization of integration. (Calculus)

$$\mathcal{U}(x,t) := \sum_{i=-\infty}^{\infty} m\,\frac{d\mathcal{U}^2}{dt^2}.\frac{dt}{d\mathcal{U}^2} := \frac{\partial\mathcal{U}^{\mu}\partial\mathcal{U}^{\nu}}{\partial t^2}.\frac{\partial t^2}{\partial\mathcal{U}^{\mu}.\partial\mathcal{U}^{\nu}\quad\partial\mathcal{U}^{\mu}}$$

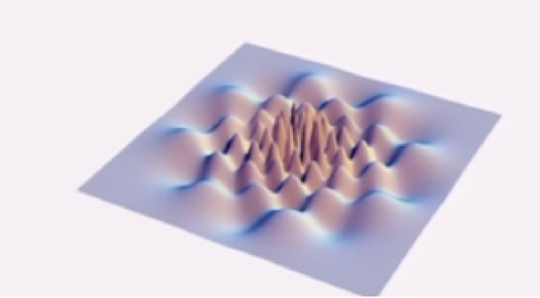


[1]Yuming Zhang., On continuity equations in space-time

Perceptions of Physics

Microworld : Quantum Mechanics

$$-i\hbar\frac{\partial\psi}{\partial t} = \left[-\frac{-\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + V(x,y)\right]\psi(x,t)$$

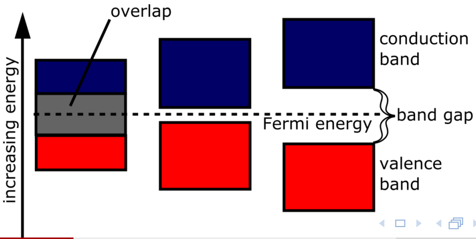


Physics in Automation

' Needs are the inception of Invention' –Anonymous

Automation

- *Automation* : Performance of sequence of events to accomplish a task without human intervention.
- Control of machinaries through electronics - Mechatronics
- Often performed with the *physics of semiconductors*, that controls the machines to perform specific tasks.



Energy Conversion

When electrons flows...

Transducers

A device that converts one form of energy (particularly due to the movement of electrons) into a detectable signal.

Applications

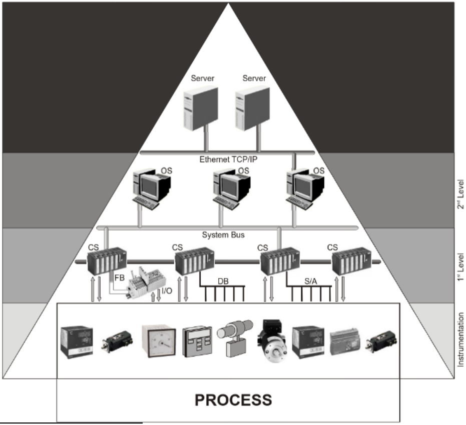
- Superconductors : Josephson junctions : Quantum mechanical circuits, SQUID, QuBits sensing.
- Remote sensing : Antennae for long range communication
- quantum computing : Applying the principles of superposition and entanglement for Qubits generation and computing.

Thermodynamic Limit

No engine is 100 percent efficient - *Carnot Engine*

Recent trends in Automation [1]

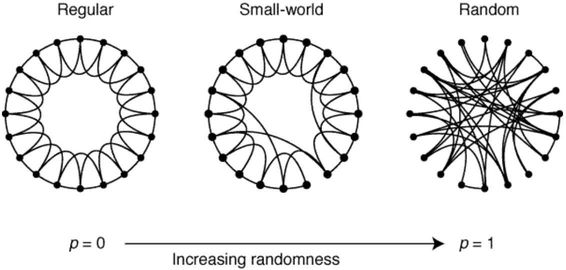
Networked control systems : Sensor Networks



[1] Zezulka, F., et.al (2010). Trends in automation-investigation in network control systems and sensor networks. IFAC Proceedings Volumes, 43(24), 109-113.

Addressing the network failures...

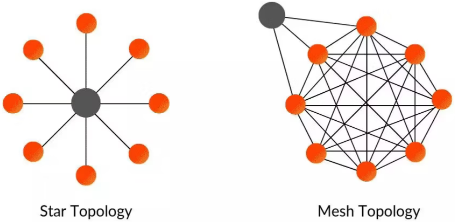
Small-world network [1]



[1] Watts, D. J., & Strogatz, S. H. (1998). Collective dynamics of 'small-world'networks. nature, 393(6684), 440-442.

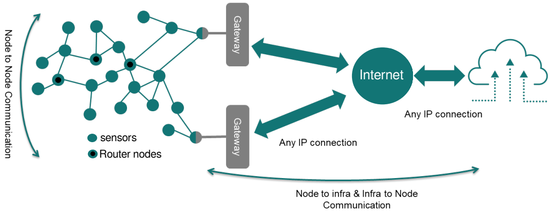
Addressing the network failures...

Star Networks : Network–Hub



- Connecting the control network in a *star topology* with small world rewiring bring out resilience from network failures.
- otherwise a control network in a *star topology* with complete network can enhance the network performance and stability.
- Further more, lag in network communications can be largely- reduced in such configuration.

Wireless sensor Networks



Future of wireless networks

- Self-organisation
- Adaptation
- Self-healing

Physics in Biomechanics

- The collective dynamics of Ion transport in membrane [1]

$$\Phi = \frac{p}{q} \frac{\{1 - exp\left[zF(V_m - E)\right]\}}{k_B T}$$

- The fluid dynamics of blood flow [2]

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} - \mathbf{v}_G)\nabla_x \mathbf{v}\right) = -\nabla_x \mathbf{P} + \nabla_x . \tau_f + b$$

[1] Lauger P. Physiol Rev. 1987, 67(4).

[2] Figueroa, et al., 2017. In Encyclopedia of Computational Mechanics.

Physics in Biomechanics

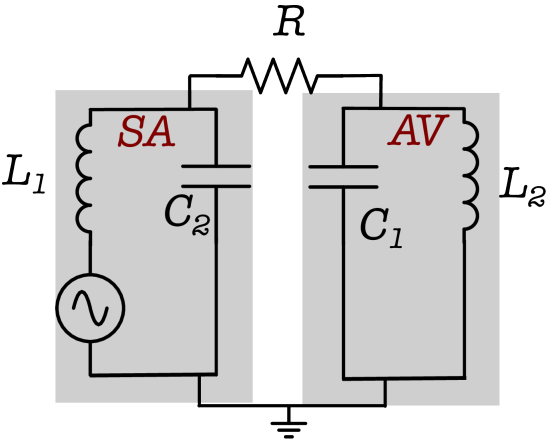
- The dynamics of Heart beat [1]

$$
\begin{aligned}
\dot{x_1} &= \frac{1}{C_1}x_2 \\
\dot{x_2} &= -\frac{1}{L_1}\left[x_1 + g(x_2) + R(x_2 + x_4)\right] + Acos(2\pi f t) \\
\dot{x_3} &= \frac{1}{C_2}x_4 \\
\dot{x_4} &= -\frac{1}{L_2}\left[x_3 + f(x_4) + R(x_2 + x_4)\right]
\end{aligned} \tag{1}
$$

[1] Signorini, M. G.,et. al (1998).IJBC, 8(08).

Physics in Biomechanics

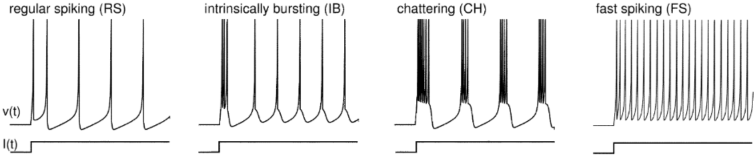
Dynamics of Heart beat



Physics in Biomechanics [1]

Neuron Spiking

- $$\begin{aligned} v' &= 0.04v^2 + 5v + 140 - u + I \\ u' &= a(bv - u) \end{aligned}$$

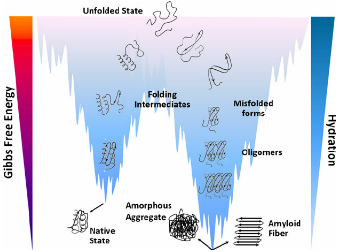


[1] Izhikevich, E. M. (2003). IEEE trans. on neural networks,14(6),

Bio-molecular machines

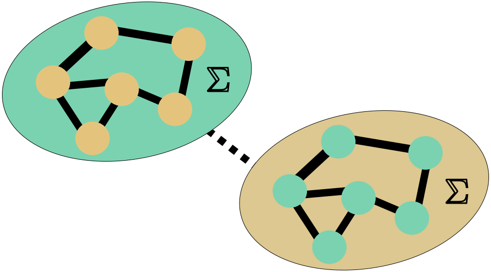
Proteins

- A polymer macromolecule that forms the strands of DNA often made up of amino-acid chains
- Protein folding incurs nolinear energy landscape.
- During protein folding , the movement of ions to their respective sites are modelled by random walks/ nonlinear chaotic dynamics.



Protein folding: A Nonlinear dynamic perspective

Interdependent random network



[1] Paul Asir., 2024, *submitted to* European Biophysical Journal

Protein folding: A Nonlinear dynamic perspective

Interdependent random network

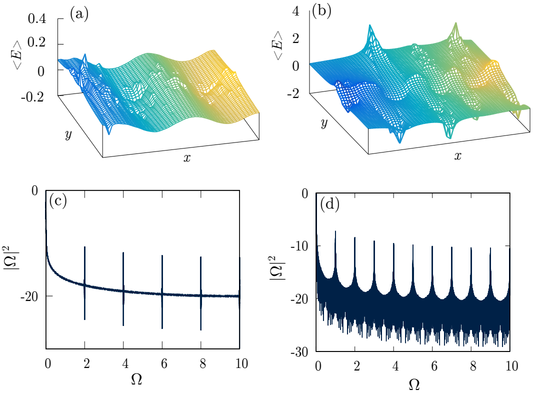
$$
\begin{aligned}
\dot{\mathbf{X}}_l &= F(x_i^1, ...x_i^n) + \epsilon_1 A_{ij}(x_i - x_j) + \epsilon_2(\bar{Y}_m - \bar{X}_l) + \lambda\gamma_l + \eta(t) \\
\dot{\gamma}_l &= -\bar{X}_l - \bar{Y}_m - \gamma_l \\
\dot{\mathbf{Y}}_m &= F(y_i^1, ...y_i^n) + \epsilon_1 A_{ij}(y_i - y_j) + \epsilon_2(\bar{X}_l - \bar{Y}_m) + \lambda\gamma_m + \eta(t) \\
\dot{\gamma}_m &= -\bar{X}_l - \bar{Y}_m - \gamma_m
\end{aligned}
\tag{2}
$$

Van-der Pol oscillators

$$
\begin{aligned}
\dot{x}_i^l &= y_i^l + \epsilon_1 A_{ij}(x_j^l - x_i^l) + \epsilon_2(\bar{X}_i^l - \bar{X}_k^m) + \lambda\gamma^l - \eta(t) \\
\dot{y}_i^l &= -\mu \; y_i^l(x_i^l \times x_i^l - 1) - x_i^l \\
\dot{\gamma}^l &= -\bar{X}_i^l - \bar{X}_k^m - \gamma^l \\
\dot{x}_k^m &= y_k^m + \epsilon_1 A_{ij}(x_h^m - x_k^m) + \epsilon_2(\bar{X}_i^l - \bar{X}_k^m) + \lambda\gamma^m - \eta(t) \\
\dot{y}_k^m &= -\mu \; y_k^m(x_k^m \times x_k^m - 1) - x_k^m \\
\dot{\gamma}^m &= -\bar{X}_k^m - \bar{X}_i^l - \gamma^m
\end{aligned}
\tag{3}
$$

Protein folding dynamics

Frustrated Energy landscape



Conclusion

- An intriguing model for protein-protein interaction dynamics is introduced.
- A multi-layer relaxation oscillators coupled by dynamic mean-field manifesting various energy landscapes has been utilized.
- By varying the magnitude of interaction strength, different regimes of synchronization (conformational states) are obtained.
- Note that the model has the spatio-temporal domain with an ability of tuneable parameters.
- The output of this model can be corroborated with the protein databank.