### CHEMICAL ARTIFICIAL INTELLIGENCE:

**NATURAL COMPUTING AND FUZZY LOGIC TO FACE THE CHALLENGES OF COMPLEXITY AND CHAOS.**

### Books

<table>
<thead>
<tr>
<th>Number</th>
<th>Author</th>
<th>Title</th>
<th>Publisher</th>
<th>URL</th>
</tr>
</thead>
</table>

### Papers in Journals

<table>
<thead>
<tr>
<th>Number</th>
<th>Author</th>
<th>Title</th>
<th>Journal</th>
<th>Year</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>(24)</td>
<td>Alessio Cesaretti, Irene Di Guida, Naishka E. Caldero-Rodríguez, Catia Clementi, Raimondo Germani, Pier Luigi Gentili.</td>
<td>Mimicking the Secretory Action of a Gland by a Composite System Made of a pH-Responsive Surfactant-Based Hydrogel and a Dialysis Membrane.</td>
<td>ACS Omega</td>
<td>2018, 3, 12</td>
<td>16777-16783</td>
</tr>
<tr>
<td>(23)</td>
<td>Pier Luigi Gentili</td>
<td>The Fuzziness of the Molecular World and its Perspective.</td>
<td>Molecules</td>
<td>2018, 23</td>
<td>2074</td>
</tr>
<tr>
<td>(22)</td>
<td>Pier Luigi Gentili, Maria Sole Giubila, Raimondo Germani, B. Mark Heron.</td>
<td>Photochromic and luminescent compounds as artificial neuron models.</td>
<td>Dyes and Pigments</td>
<td>2018, 156</td>
<td>149-159</td>
</tr>
</tbody>
</table>
| (21) | Pier Luigi Gentili, Maria Sole Giubila, Raimondo Germani, Aldo Romani, Andrea Nicoziani, Anna Spalletti, B. Mark Heron.  
| (20) | Pier Luigi Gentili, Maria Sole Giubila, B. Mark Heron  
*Processing Binary and Fuzzy Logic by Chaotic Time Series Generated by a Hydrodynamic Photochemical Oscillator.*  
**Invited contribution.** |
| (19) | Pier Luigi Gentili  
*A Contribution to the Development of Chemical Artificial Intelligence: The Implementation of Biologically Inspired Photochromic Fuzzy Logic (BIPFUL) Systems that Extend Human Vision to UV.*  
**Invited contribution.** |
| (18) | Pier Luigi Gentili, Amanda L. Rightler, B. Mark Heron, Christopher D. Gabbutt  
*Discriminating between the UV-A, UV-B and UV-C regions by novel Biologically Inspired Photochromic Fuzzy Logic (BIPFUL) systems: A detailed comparative study.*  
| (17) | Kenta Hayashi, Hiroshi Gotoda, Pier Luigi Gentili  
*Probing and exploiting the chaotic dynamics of a hydrodynamic photochemical oscillator to implement all the basic binary logic functions.*  
Chaos, 2016, 26, 053102 (1-8) |
|---|---|
| (16) | Pier Luigi Gentili, Amanda L. Rightler, B. Mark Heron, Christopher D. Gabbutt  
*Extending human perception of electromagnetic radiation to the UV region through biologically inspired photochromic fuzzy logic (BIPFUL) systems.*  
Chem. Comm., 2016, 52, 1474-1477 |
| (15) | Pier Luigi Gentili, Hiroshi Gotoda, Milos Dolnik, Irving R. Epstein  
*Analysis and prediction of aperiodic hydrodynamic oscillatory time series by feed-forward neural networks, fuzzy logic, and a local nonlinear predictor.*  
Chaos, 2015, 25, 13104 (1-14) |
| (14) | Pier Luigi Gentili  
*“The human sensory system as a collection of specialized fuzzifiers: A conceptual framework to inspire new artificial intelligent systems computing with words.”*  
J. of Intel. & Fuzzy Sys., 2014, 27, 2137-2151 |
| (13) | Pier Luigi Gentili  
*“The Fuzziness of a Chromogenic Spirooxazine.”*  
| (12) | Pier Luigi Gentili  
“Le sfide della complessità e il contributo dell'intelligenza artificiale chimica”  
100news-Scienza, raccolta del 15 gennaio 2014, 3-4. | ![Image](image1.png) |
| (11) | Pier Luigi Gentili, Milos Dolnik, Irving R. Epstein  
“Photochemical Oscillator”: Colored Hydrodynamic Oscillations and Waves in a Photochromic System.  
J. Phys. Chem. C, 2014, 118, 598-608. | ![Image](image2.png) |
| (10) | P. L. Gentili  
Small steps towards the development of chemical artificial intelligent systems  
RSC Advances 3, 2013, 25523-25549 | ![Image](image3.png) |
| (9) | **VIP: Very Important Paper**  
V. Horvath, P. L. Gentili, V. K. Vanag, I. R. Epstein  
*Pulse-Coupled Chemical Oscillators with Time Delay*  
Angew. Chem. Int. Ed. 51, 2012, 6878-6881 | ![Image](image4.png) |
| (8) | P. L. Gentili, V. Horvath, V. K. Vanag, I. R. Epstein  
Belousov-Zhabotinsky “chemical neuron” as a binary and fuzzy logic processor.  
Int. J. of Unconventional Computing, 8, 2012, 177-192. | ![Image](image5.png) |
| (7) | P. L. Gentili  
The fundamental Fuzzy logic operators and some complex Boolean logic circuits | ![Image](image6.png) |
implemented by the chromogenism of a spirooxazine.

P. L. Gentili
*Molecular Processors: From Qubits to Fuzzy Logic.*

Chemical intelligence: Different types of logic can be implemented with molecules. In absence of decoherent effects, quantum logic can be carried out. Otherwise crisp logics can be processed (see flowchart). In case of collections of molecules, there are conditions favourable for building fuzzy logic systems which are playing an increasingly important role in the development of artificial intelligence.

Future Information Technology Systems will hinge on logic gates implemented at the molecular level. To expand the intelligence quotient of next artificial machines, it is necessary to find out how to process Fuzzy logic at the molecular level. Fuzzy logic allows certain and uncertain information, objective and subjective knowledge to be dealt with.

If the logic gates, sculpted from bulk semiconductors, are based exclusively on electrical signals, those based on single molecules can be extended to chemical, optical and other physical inputs and outputs. Purpose of the chemist is to find out always new powerful molecular systems that can carry out the logic operations required for computer circuitry. If the compound behaves as a versatile molecular switch, it can be adopted to process Boolean binary logic. On the other hand, if a chemical species responds to external inputs with a continuously variable output signal and the relation between inputs and output can be rationalized in terms of IF-THEN statements, it can be employed to process Fuzzy logic.

If the logic gates are based on single molecules, those based on single molecules can be extended to chemical, optical and other physical inputs and outputs. Purpose of the chemist is to find out always new powerful molecular systems that can carry out the logic operations required for computer circuitry. If the compound behaves as a versatile molecular switch, it can be adopted to process Boolean binary logic. On the other hand, if a chemical species responds to external inputs with a continuously variable output signal and the relation between inputs and output can be rationalized in terms of IF-THEN statements, it can be employed to process Fuzzy logic.
The Sun is an energy source of utmost importance for the Earth. Solar energy has been crucial for the emergence of Life and is still fundamental for its support. In this paper, the role fulfilled by the Sun’s energy toward the terrestrial evolutionary processes and the current action performed toward the living beings are presented. Life on Earth employs the solar radiation as both energy source and information spring for its spatial and temporal orientation.

### Chapters in Books

| (1) | P. L. Gentili  
*Fotorecettori Biologici. Il sole e la vita sul pianeta terra.*  
| --- | --- |
| (7) | Pier Luigi Gentili  
*I complessi interrogativi bioetici: dove cercare risposte?*  
| (8) | Pier Luigi Gentili  
*Le sfide della Complessità Naturale e Computazionale: come vincerele? Il contributo della Chimica.*  
In “Fare scienza oggi”, pag. 539-548, Morlacchi Editore U. P., Perugia 2018. |

L’umanità è chiamata a vincere le sfide della Complessità. Vi sono tre tipi di Complessità e quindi vi sono tre tipi di sfide. Vi sono le sfide della Complessità Naturale che coinvolgono tutto il sapere scientifico. Vi sono, poi, le sfide della Complessità Computazionale che coinvolgono, in primo luogo, le scienze matematiche ed informatiche. Tuttavia per poter affrontare le sfide della Complessità Computazionale in maniera efficace, è necessario anche il contributo delle altre discipline scientifiche. Infine esistono le sfide della Complessità Etica e Bioetica. Quest’ultime richiedono il contributo di tutto il sapere umano; non solo quello scientifico, ma anche quello umanistico. Ho già proposto una strategia per poter affrontare le sfide della Complessità Bioetica nel volume dedicato al I Convegno Interdipartimentale dell’Ateneo perugino. La strategia proposta prevede l’uso del messaggio cristiano come chiave di lettura e codice morale per trovare risposte ai complessi interrogativi bioetici (cfr. Gentili, 2017). In questo capitolo intendo parlare di come la chimica può contribuire a vincere le sfide della Complessità Naturale e Computazionale.

Questo contributo si pone due obiettivi. Il primo consiste nel far capire perché è giusto definire complessi gli interrogativi bioetici. A tale scopo, si presentano le sfide della Complessità Naturale e quelle della Complessità Computazionale che la scienza contemporanea è chiamata ad affrontare. Il secondo obiettivo consiste nel proporre degli ambiti disciplinari dove cercare risposte ai complessi interrogativi bioetici. Secondo l’autore non è sufficiente un approccio puramente scientifico, ma è necessario coinvolgere il sapere giuridico, umanistico ed anche teologico. In particolare la teologia è l’unica disciplina che può fornire risposte cariche di speranza agli interrogativi esistenziali che sono coinvolti nelle questioni bioetiche.
| (6) | Pier Luigi Gentili  
*A strategy to face complexity: The development of chemical artificial intelligence*  
Communications in Computer and Information Science  
Volume 708, 2017, Pages 151-160  
11th Italian Workshop on Artificial Life and Evolutionary Computation, WIVACE 2016; Fisciano; Italy; 4 October 2016 through 6 October 2016;  
Code 191279 |
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nowadays, science is spurred to win the Complexity Challenges. There are challenges regarding Natural Complexity. But there are also challenges regarding Computational Complexity. A strategy to face both of them consists in developing Chemical Artificial Intelligence. Its development requires an analysis of the Human Nervous System and Human Intelligence at three levels; at the (i) Computational, (ii) Algorithmic, and (iii) Implementation levels, respectively. The effectiveness of this approach is demonstrated by showing three ways for implementing Fuzzy logic at the molecular level.</td>
<td></td>
</tr>
</tbody>
</table>

| (5) | Pier Luigi Gentili  
*The Development of Chemical Artificial Intelligence Processing Fuzzy Logic*  
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>The Human Nervous System is an outstanding example of natural complex system. Its hierarchical architecture and its basic nonlinear working principles store the secrets of Complexity. Of course, a scrutiny of the Human Nervous System is going to have a profound impact on the challenges to Complexity. In this contribution, we present the first results in our analysis of the human nervous system at the “computational”, “algorithmic” and “implementation” levels. Such analysis will probably bring to the development of a new generation of computing machines imitating the human intelligence that computes with words and solves quite easily computational problems like the recognition of variable patterns.</td>
<td></td>
</tr>
</tbody>
</table>

| (4) | Pier Luigi Gentili  
*Processing Fuzzy Logic by Molecules*  
Fuzzy Logic: Applications, Systems and Technologies, Editor Dinko Vukadinovic  
(ISBN: 978-1-62417-151-2) |
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Current computers process information based on transistors and electrical signals. The futuristic chemical computers will store, process, and convey information by using molecules, their assemblies, and physical-chemical signals. It is possible to compute by exploiting single molecules or large collections of them. Different kinds of logic can be processed. Since molecules obey the laws of quantum-mechanics, quantum logic can be implemented, as long as decoherent effects are avoided. If the collapse of superimposed or entangled wave-functions is inevitable, molecules can still be used to process either Boolean or discrete multi-valued or fuzzy logic. The conditions favourable to chemically process the infinite-valued fuzzy logic are presented in this text and few examples of its chemical implementation are reported. Fuzzy logic is particularly important for the development of artificial intelligence because it models pretty well human decision making. This property is due to the structural analogies existing between fuzzy logic systems and human nervous system.</td>
<td></td>
</tr>
</tbody>
</table>
There exists a worldwide race to make microprocessors of computers as much powerful as possible by shrinking electronic components and cramming logic gates onto smaller and smaller wafers of silicon. Over the past few years, some companies and several academic laboratories have started seriously entertaining the idea of constructing computers in which computations are performed by individual molecules. If the logic gates, sculpted from bulk semiconductors, are based exclusively on electrical signals, those based on single molecules can be extended to chemical, optical and other physical inputs and outputs. Purpose of the chemist is to find out always-new powerful molecular systems that can carry out the logic operations required for computer circuitry. If the compound behaves as a versatile molecular switch, it can be adopted to process Boolean binary logic. On the other hand, if a chemical species responds to external inputs with a continuously variable output signal and the relation between inputs and output can be rationalized in terms of IF-THEN statements, it can be employed to process Fuzzy logic. Organic compounds exhibiting “Proximity Effect” in their photophysics give an opportunity to implement Fuzzy Logic Engines at the molecular level. For these chemical species a quantum state, consisting of a superposition of two electronic levels, can be produced through excitation by UV-Visible radiation. The nature of the quantum state and its ability to emit light can be varied in a continuous manner by regulating environmental conditions such as temperature and hydrogen bonding donation ability of the solvent. This opens up a new avenue to implement Fuzzy logic at the molecular level.

### Communications at Congresses and Seminars

| (31) | 23rd Annual Conference of the International Society for the Philosophy of Chemistry (ISPC), Turin (Italy), July 15-17 July 2019. | Pier Luigi Gentili
The Complexity Challenges and the role of the Philosophy of Chemistry.
Proceedings pag. 27. **Invited Talk presented by Gentili** |
| (30) | Observatory for Astrochemical Kinetics and Related Aspects at the Accademia delle Scienze in Rome (Italy), 27-28 June 2019. | Pier Luigi Gentili
Astrochemistry and the theory of Complex Systems.
Proceedings pag. 29. **Invited Talk presented by Gentili.** |
| (29) | Statistical thermodynamics and chemical kinetics far away from equilibrium at the Accademia dei Lincei in Rome (Italy), 25-26 June 2019. | Pier Luigi Gentili
Out-of-equilibrium chemical reactions in neuromorphic engineering.
**Invited Talk presented by Gentili** |
<p>| (28) | | Pier Luigi Gentili |</p>
<table>
<thead>
<tr>
<th>No.</th>
<th>Event Description</th>
<th>Author(s)</th>
<th>Title</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>Complexity Summer School organized by the Italian Complexity Institute, at the Abano Terme (Italy), the 28th of August 2018.</td>
<td>Gentili</td>
<td>The Physical-Chemical Mind</td>
<td>Invited Lecture</td>
</tr>
<tr>
<td>23</td>
<td>Second International Caparica Christmas Conference on Translational Chemistry, Lisbon (Portugal), 4-7 December 2017</td>
<td>Gentili</td>
<td>A step forward to the development of Chemical Artificial Intelligence</td>
<td>Invited speaker</td>
</tr>
<tr>
<td>22</td>
<td>Institut Català de Nanociència i Nanotecnologia, Barcelona (Spain), the 8th of September 2017.</td>
<td>Gentili</td>
<td>“Tracing a new path in the field of Neuromorphic Engineering”</td>
<td>(Invited speaker)</td>
</tr>
<tr>
<td>20</td>
<td>XXXVII Dynamics Days Europe, 5-9 June 2017, Szeged (Hungary).</td>
<td>Gentili</td>
<td>Hydrodynamic Photochemical Oscillators Useful for Chaos Computing</td>
<td>(Invited speaker)</td>
</tr>
</tbody>
</table>
| (19) | 253rd American Chemical Society National Meeting & Exposition, 2-6 April 2017, San Francisco, CA (USA) | Naishka E. Caldero-Rodriguez, Pier Luigi Gentili
“P-dodecyloxybenzyldimethylamine oxide (pDoAO) gel as pH sensitive artificial gland”
Proceedings, CHED-1166. |
| (18) | II Convegno Interdipartimentale, “Fare scienza oggi”, 15-16 dicembre 2016, Perugia (Italia) | Pier Luigi Gentili
“The Challenges of Natural and Computational Complexities: how to win them? The contribution of Chemistry”.
Talk presented by Gentili |
| (17) | WIVACE/BIONAM 2016, 4-7 October 2016, Salerno (Italy) | Pier Luigi Gentili
“A Strategy to Face Complexity: The Development of Chemical Artificial Intelligence.”
Proceedings, page 5.
(Invited Plenary) |
| (16) | 2nd International Caparica Conference on Chromogenic and Emissive Materials held in Lisbon (Portugal), 5-8 September 2016. | Pier Luigi Gentili, Amanda L. Rightler, B. Mark Heron, Christopher D. Gabbutt
Implementation of Biologically Inspired Photochromic Fuzzy Logic (BIPFUL) Systems that extend human vision to UV.
(Invited Keynote speaker) |
| (15) | 251st American Chemical Society National Meeting & exposition, San Diego (CA, USA), March 13-17, 2016. | Amanda Rightler, Pier Luigi Gentili
Understanding research in Perugia, Italy: Extending cultural horizons and human vision through fuzzy logic photochromic systems.
Proceedings, page IAC-16. |
| (14) | 251st American Chemical Society National Meeting & exposition, San Diego (CA, USA), March 13-17, 2016. | Amanda Rightler, Pier Luigi Gentili
Expanding human perception of electromagnetic radiation to the ultraviolet region through fuzzy logic photochromic systems.
Proceedings, page CHED-1102. |
<p>| (12) | 1st Interdepartmental Congress, 3-4 December 2015, Perugia (Italy) | Pier Luigi Gentili | The Complex Bioethical Issues: Where Finding Answers? | Talk presented by Gentili |
| (9) | XLI Italian Congress of Physical Chemistry. 23-27 June 2013, Alessandria (Italy). | P. L. Gentili | “Fuzzy logic to tame the chaos” | Proceedings, pag. 154. | Poster presented by Gentili |
| (7) | Seminar taken at the Electrical and Information Engineering Department, University of Perugia, Perugia (PG). 19 December 2012. | P. L. Gentili | “The Challenges of Complexity and Molecular Computation” | Invited speaker |
| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th>Event Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Seminar taken at the Institute of Complex Systems (CNR), Sesto Fiorentino (FI), the 18th October 2012.</td>
<td>“Small steps towards a Chemical Artificial Intelligence” Invited speaker</td>
</tr>
</tbody>
</table>