Fortunato Tito Arecchi

Present positions: Emeritus of Physics, University of Firenze
and Scientific Associate of Istituto Nazionale di Ottica (INO)

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Date and place of birth: 11/12/1933, Reggio Calabria, Italy

Education:

1957: PhD in Electrical Engineering at Politecnico di Milano

Curricular activity

1957-60: Researcher in Nuclear Electronics at CISE, Milano,
1960-62: Research Associate on Lasers, Dept. EE, Stanford University,
1962-70: Leader Research Group on Lasers at CISE Milano,
1963-70: Associate Professor of Physics, Milan University,
Visiting scientist:
1968-69: IBM Res. Lab. Ruschlikon (CH);
1978 and 1985: IBM Res. Lab. San Jose, (CA);
1969-70: Visiting Professor, Dept. of Phys., MIT;
1970-77: Chair of Physics, University of Pavia;
1977- 2009: Chair of Physics, University of Firenze;
2009-present: Professor Emeritus of Physics, University of Firenze
1975 -2000 : President of Istituto Nazionale di Ottica (INO) ,

2001-present: Scientific Associate of INO

Affiliations

- Member of: - Italian Physical Society;
  - Academia Europaea;
  - Academie Internationale de Philosophie des Sciences (AIPS) -Bruxelles
  - Accademia Colombaria (Firenze)
- Fellow of - Optical Society of America (OSA)

Main scientific contributions:

1) Cooperative effects in quantum optics
2) Photon statistics and laser fluctuations
3) Deterministic chaos in optics
4) Pattern formation in extended media
5) Complex phenomena and cognitive processes

(see the enclosed comment and selected list of papers)

Recent Awards

Max Born 1995 Medal of OSA
Enrico Fermi 2007 Prize SIF (Italian Physical Society)
Honorary Editor : Chaos (American Institute of Physics)
Honorary Member: Scientific Committee for Physics of Solvay Institute (Bruxelles)

Editorial

- Vice-Director: Nuovo Cimento (Italy) (1976-1998);
- Editor in Chief: European Physical Journal –D (1999-2004);
- Editor: Chaos (AIP -U.S.A.)(1991-2016)
- Formerly Editorial Board: Optics Communications, (North Holland); Int. J. Bifurcation and Chaos (World Scientific); J. Phys. B (IOP- U.K.); Int. J. Nonlinear Optical Physics (World Scientific); Cognitive Processing (Pabst) and.
  Member of: -Commissions de Publications Francaises de Physique;
  - Acta Physica Polonica

Publications

- Scientific papers: more than 450.
- Communications to scientific meetings: more than 300.
- Books:

Laser Handbook, vol. 1 and 2. (with E. Schulz Du Bois), North Holland 1972; Instabilities and Chaos in Quantum Optics (with R.G. Harrison), Springer 1987;
I simboli e la realtà, Jaca Book, (with I. Arecchi), Milano 1990;
Optical chaos (selected papers on) (with R.G. Harrison), SPIE Opt. Eng. Press 1994;
Lexicon of Complexity (with A. Farini), Firenze 1996;
Coerenza, Complessità, Creatività, S. Di Renzo, Roma,2007
also Co-Editor of several Proceedings of International Conferences and Schools.

ARECCHI'S MAIN SCIENTIFIC CONTRIBUTIONS

(numbers refer to the selected list of papers)

1) **Cooperative effects in quantum optics**

1964: Theory of a laser amplifier [1] which extended Lamb theory to account for space dependence. This was the first formulation of the coupled field-matter equations with space dependence (later called "Maxwell-Bloch equations"). It predicted invariant pulses propagating at the light speed (the nonlinearity compensating for dispersion). These results were later applied to absorbing media (self induced transparency).
1969: Introduced a fundamental parameter of the resonant interaction [8] that is, the correlation length in the cooperative spontaneous emission of atoms prepared incoherently in an excited state. It does not depend on boundary conditions (as the mirrors in a laser), nor on an external field (as in coherent spectroscopy), but it is an intrinsic parameter of many body optical interactions.
1970: Theory of the atomic coherent states [9] as a basis for a statistical description of coherent phenomena in resonant spectroscopy.
1978: Theory of the two photon optical bistability, observed four years later.

2) **Photon statistics and laser fluctuations** (reviewed in [R1-R2])

1965: First experimental evidence of the statistical difference between a laser and a random field [2,3]. It was obtained by photon statistics, and it included evidence of the bunching phenomenon for Gaussian sources already explored by Hanbury-Brown and Twiss, but also of the absence of such a bunching for a laser field [4]. These experiments provided a physical ground for Glauber's theory of coherence.
1966-67: Application of the above methods to laser fluctuations at threshold, providing the first experimental evidence of critical fluctuations [5] and slowing down [6] in a "phase transition out of equilibrium", as called later.
1967: Transient statistics of a laser switched from below to above threshold [7]: a new phenomenon was discovered, i.e. a transient enhancement of the photon variance.
1989: The time statistics permits an accurate calibration of the initial photon number giving rise to the amplified chain in a laser. This method has been called "statistical microscope" [14] because it provides measurement of a small photon number <u>not</u> by electron multiplication (as in usual photomultipliers) but by photon multiplication.

Recently, this research line has been recently revisited in two directions, aiming at

i) providing evidence of quantum interference between macroscopic distinct states,
ii) exploring the coherence properties of the Bose Einstein condensate and the atom laser.

3) **Deterministic chaos in optics**

1978: Theoretical introduction of a mechanism of laser turbulence[10], consisting of a cavity including a lasing medium and a second harmonic crystal. A pair of laser photons are converted to a second harmonic photon and this photon is reconverted into a pair of laser photons of different frequencies, thus inducing a type of chaos observed later (in 1986).

1982: First experimental evidence of deterministic chaos in a laser [11], starting a research line the main results of which are:

i) 1982-87: characterization of low dimensional laser chaos by different means, that is, loss modulation, injection of an external field, two counter propagating fields in a ring cavity, and feedback [12].
ii) 1984: classification of lasers in classes A,B,C depending on the time scales of their dynamical variables. This classification has now become of general use.
iii) 1982: first evidence of generalized multistability, which is the coexistence of many attractors.
iv) 1987: evidence of the mechanism of competing instabilities [12] leading to homoclinic chaos (Shil'nikov chaos) characterized by the statistics of the return times to a given reference point in phase space [13]. Characterizing chaos by times rather than by geometry is conceptually similar to what done in transient statistics [11] and it is an essential tool whenever chaos does not induce appreciable geometric irregularities, as in most heteroclinic connections; synchronization of homoclinic chaos appears as a universal avenue for biological clocks and biological communication [23].
v) 1993: adaptive recognition of chaos and its control [20].
vi) 2004: Mixed Mode Oscillations = coexistence of two temporal regimes in chaotic semiconductor lasers [27]

4) **Pattern formation** (reviewed in [R3-R4])

High-dimensional optical dynamics results from the competition of many degrees of freedom, either space-like as in extended media, or time-like as in delayed dynamics. In both cases competition gives rise to patterns similar to those observed in fluids, hence the name of "dry hydrodynamics".
1990: The gradual transition from a small to a high number of competing modes is denoted by the passage from periodic and chaotic alternation (PA, CA) where one single mode per time is present, to space time chaos (STC) where many modes coexist at the same time. These phenomena, first observed in [15], have been explained in terms of cavity symmetries in [18].
1991: A heterodyne method introduced to detect phase singularities or vortices of the optical field [16] allows the description of optical pattern formation in terms of vortex statistics. The different scaling of the vortex statistics with the cavity size provides a discrimination between two regimes, one in which patterns are imposed by the boundary and one where patterns are intrinsic of the medium, as in chemical Turing morphogenesis [17].
1992: A different way to study high dimensional chaotic systems is to still refer to a strongly confined medium as a single mode laser cavity, but introducing a feedback with a delay longer than the intrinsic correlation time of the laser dynamics [17].
1995-1997: Morphogenetic mechanisms analogous to those of fluid mechanics, are shown by the onset of different crystal and quasi-crystal symmetries, depending on the boundary constraints [21]. As the system is driven far away from threshold, many of these "pure" symmetries are excited simultaneously, but rather than quenching each other, they coexist in different regions, giving rise to a multidomain structure or they lock into a single super-structure.
1999: Ref. [22] reports the scaling behaviour of defects after a rapid passage from below to above threshold in a nonlinear optical system. This corresponds to the rapid passage from many uncorrelated domains to an asymptotic single coherence area; however the asymptotic state is reached for long times, and immediately at the end of the switch pulse one finds a collection of

frozen defects, due to the critical slowing down at the transition point. Such a feature is common to all extended critical phenomena; it had been hypothesized for cosmological defects and observed in liquid helium, however here we provided the first quantitative evidence of the scaling.
2009. First evidence of Rogue Waves in a nonlinear optical cavity[27]

5- Physics of cognitive processes (reviewed in [R5])

The methods developed to recognize and control chaos and patterns can be extended to biological phenomena as e.g. cardiac and brain signals. The adaptive methods can not only be extended from discrete to continuous dynamical systems, but they can also control a delayed system. Now, the delayed feedback method corresponds to embedding a physical system with a small number of degrees of freedom into a space with a larger number of dimensions.
Hence, this appears as a good analogy of the cognitive strategy used in any perceptual task, whereby we build holistic perceptions upon partial information (think e.g. of a deteriorated photography).
2004-2009. A new type of chaotic behaviour, called HC (homoclinic chaos) consisting of spike trains separated by chaotic time intervals ,first observed in CO_2 lasers, displays features common to brain neurons [26]. It has been demonstrated to display a high propensity to organise in large synchronized networks, hence it appears as the most plausible dynamical model for the build up of *"feature binding"* through the synchronization of large neuron arrays in the brain .

Rather than tracing the individual neuron behavior, a collective way of describing cognitive tasks is by Bayes inference [28]. Bayes inference characterizes perceptual processes, whereby a sensorial input elicites an adequate motor reaction; it requires a pre-assigned algorithm. On the contrary, in linguistic tasks, humans compare a piece of a text with a previous one, recalled by the short-term memory. The comparison gives rise to a new algorithm, via a process called *inverse Bayes* [29].
The role of language vs perception in decision tasks is being actively explored, as reported in the review R5.

OVERVIEW OF THE SCIENTIFIC ACTIVITY OF ARECCHI

Arecchi's research starts with the onset of the laser age (early sixties). Rather than looking for new materials and excitation techniques (spectroscopy) or new cavity configurations (optical engineering) Arecchi focuses on the coherence aspects, measured in terms of photon statistics (research lines #1 and #2). Thus the coherent interaction of matter (atoms, molecules) and electromagnetic radiations which is the basis of the laser action does not need a description in

terms of each microscopic component, but it can be epitomized in terms of a small number of collective variables.
This leads to the discovery that the laser threshold is like the critical point of a thermodynamic phase transition, marking the onset of a new type of order; however, the laser threshold occurs far from thermal equilibrium. Furthermore, the laser threshold is just the first of many possible bifurcation phenomena to qualitatively new states.
Two concepts play a crucial role in these phenomena. The first is nonlinear dynamics, which gives rise to different bifurcations as a control parameter is changed; the second one is that of open system, which means that the dynamics is non conservative and influenced by the environment.
As said, dynamics of the single mode laser is epitomized by a very small number of degrees of freedom. If this small number is equal to, or larger than, three, then deterministic chaos arises as shown in the research line # 3.
The standard use of laser systems in the research laboratory and in applications is based on single, or a few, mode operation plus some modulation or feedback, amounting to a small number of coupled variables sufficient to induce chaos. For this reason chaos has been a crucial topics of laser research since 1982.
Increasing the number of modes or introducing a delayed feedback brings a large number of degrees of freedom, thus giving rise to problems of pattern formation and competition, already explored in other areas of physics, as fluid dynamics or chemical reactions. Doing it in optics implies a careful control of the operating conditions, thus it has put in evidence fundamental phenomena such as the role of symmetries and the competition between the bulk dynamics and the driving due to the boundary effects (research line #4).

Whatever has been explored in laser and nonlinear optics has a counterpart in any physical system which is driven away from thermal equilibrium through input/output channels; this includes not only meteorology, geophysics and oceanography, but also living systems and social phenomena.
We can speak of "complex systems", as distinguished from "composite systems", where this latter notion refers to system man made from a blueprint, such as an industrial product, whereas the former notion refers to natural systems whose scientific description is never complete, since we do not know the right amount of environmental perturbations.

The same formation of scientific theories is affected by the discovery that most phenomena are complex, thus any description is never complete. This means that in general different competing models are available for the same phenomenon. In such cases, the choice of the best strategy is the result of a "trial and error" search, which is common to all cognitive tasks. Hence, exploring complex phenomena and developing adaptive recognition strategies provides an insight into the language operations. The inverse Bayes inference yields novel algorithms, beyond the single algorithm approach of standard perceptual processes.

SELECTED LIST OF PAPERS BY F.T. ARECCHI

1. "Theory of optical maser amplifiers", J. of Quantum Electronics, 1, 169, (1965), (with R. Bonifacio).

2. "Measurements of the statistical distribution of Gaussian and Laser sources, Phys. Rev. Lett. 15, 912 (1965)

3. "High order fluctuations in a single mode laser field", Phys. Rev. Lett., 16, 32 (1966), (with A. Berné, P. Burlamacchi).

4. "Time distributions of photons from coherent and Gaussian sources", Phys. Rev. Lett., 20, 27 (1966), (with E. Gatti, A. Sona).

5. "Statistics of the laser radiation at threshold", Phys. Lett., 25A, 59 (1967), (with G.P. Rodari, A. Sona).

6. "Dynamics of the laser radiation at threshold", Phys. Lett., 25A, 341 (1967), (with M. Giglio, A. Sona).

7. "Time-dependent statistical properties of laser radiation", Phys. Rev. Lett., 19, 1168 (1967), (with V. Degiorgio, B. Querzola).

8. "Cooperative phenomena in resonant electromagnetic propagation", Phys. Rev. A2, 1730 (1970), (with E. Courtens).

9. "Atomic coherent states in quantum optics", in: Fundamental and applied laser physics, (Proc. of 1971 Esfahan Conference ed. by M.S. Feld et al.) J. Wiley, 1972, pp. 835-865, and Phys. Rev. A6, 2211 (1972), (with E. Courtens, R. Gilmore. H. Thomas).

10. "Quadratic nonlinearities and turbulence in a laser system", in: Coherent and Quantum Optics IV, (Proc. of Rochester Conf. on Coherence, 1977, ed. by L. Mandel and E. Wolf), Plenum Press 1978, (with A.M. Ricca).

11. "Experimental evidence of subharmonic bifurcations, multistability and turbulence in a Q-switched gas laser", Phys. Rev. Lett., 49, 1217 (1982), (with R. Meucci, G. Puccioni and J. Tredicce).

12 “Deterministic chaos in lasers with injected signal”, Opt. Comm., 51, 308 (1984). (with G.L. Lippi, G.P. Puccioni and J.R. Tredicce).

13. "Laser dynamics with competing instabilities", Phys. Rev. Lett., 58, 2205 (1987), (with R. Meucci, W. Gadomski).

14. "Experimental characterization of Shil'nikov chaos by return time", Europhys. Lett., 6, 677 (1988), (with A. Lapucci, R. Meucci, J.A. Roversi and P. Coullet)

15. "Determination of a small photon number by transient statistics", Europhys. Lett., 8, 225 (1989), (with R. Meucci and J.A. Roversi).

16. "Experimental evidence of chaotic itinerancy and spatiotemporal chaos in optics", Phys. Rev. Lett., 65, 2531-2534 (1990), (with G. Giacomelli, P.L. Ramazza and S. Residori).

17. "Vortices and defect statistics in two dimensional optical chaos", Phys. Rev. Lett., 67, 3749 (1991), (with G. Giacomelli, P.L. Ramazza and S. Residori).

18. "Two dimensional representatin of a delayed dynamical system", Phys. Rev. A45, 4225 (1992), (with G. Giacomelli, A. Lapucci and R. Meucci).

19. "Periodic and chaotic alternation in systems with imperfect 0(2) symmetry", Phys. Rev. Lett., 69, 3723 (1992), (with S. Boccaletti, G.B. Mindlin, C. Perez-Garcia).

20. "Transition from boundary-to-bulk controlled regimes in optical pattern formation", Phys. Rev. Lett., 70, 2277, (1993), (with S. Boccaletti, P.L. Ramazza and S. Residori).

21. "Adaptive recognition of a chaotic dynamics", Europhys. Lett., 26, 327 (1994), (with G.F. Basti, S. Boccaletti and A. Perrone).

22. "Two-dimensional crystals and quasicrystals in nonlinear optics", Phys. Rev. Lett., 74, 258 (1995), (with E. Pampaloni, P.L. Ramazza and S. Residori).

23. "Order parameter fragmentation after a symmetry – breaking transition", Phys. Rev.Lett., 83, 5220 (1999), (with S. Ducci, P.L. Ramazza and W. Gonzales-Vinas).

24. "Synchronization of homoclinic chaos", Phys. Rev. Lett., 86, 791 (2001), (with E. Allaria, A. Di Garbo and R. Meucci).

25. "Autonomous bursting in homoclinic system", Phys. Rev. Lett. 88, 144101 (2002), (with R. Meucci, A. Di Garbo and E. Allaria).

26 "Chaotic neuron dynamics, synchronization and feature binding", Physica A 338 218-237 (2004).

27 "Non Gaussian statistics and extreme waves in a nonlinear optical cavity" , Phys.Rev Lett. 103,173901 (2009) (with A.Montina,U.Bortolozzo and S. Residori).

28. "Physics of cognition: complexity and creativity". *Eur.Phys.J. Special Topics 46,*205(2007)

29 "Dynamics of consciousness: complexity and creativity." *The Journal of psychophysiology 24 (2),*141-148(2009)

REVIEWS

R1 "Photocount distribution and field statistics", in Quantum Optics (Proc. E. Fermi 1967 School ed. by R.J. Glauber), Academic Press, 1969, pp. 57-110.

R2 "Experimental aspects of transition phenomena in quantum optics", in: *Order and fluctuations in equilibrium and non-equilibrium statistical mechanics, (Proc. XVII Solvay Conf. in Physics*, Ed. by G. Nicolis et al.), J. Wiley 1981, pp. 107-157.

R3. "Pattern formation and competition in nonlinear optics", Physics Reports, 318 pp. 1-83 (1999), (with S. Boccaletti and P.L. Ramazza).

R4. "Rogue waves and their generating mechanisms in different physical contexts" Physics Reports (2013) 528, pp.47-89 (With M. Onorato, S. Residori, U. Bortolozzo and A. Montina).

R5 "Cognition and language: from apprehension to judgment-Quantum conjectures, in *Chaos,Information Processing and Paradoxical Games* (Eds. G. Nicolis and V. Basios),World Scientific (2015), Chapter 15 (pp.319-344).

[Cooperative effects in quantum optics](#)
[Photon statistics and laser fluctuations](#)
[Deterministic chaos in optics](#)
[Pattern formation in extended media](#)
[Complex phenomena and cognitive processes](#)

Cooperative effects in quantum optics

1964: Theory of a laser amplifier [22] that extended Lamb theory to account for space dependence. This was the first formulation of the coupled field-matter equations with space dependence (later called *"Maxwell-Bloch equations"*). It predicted invariant pulses propagating at the light speed (the nonlinearity compensating for dispersion). These results were later applied to absorbing media (self induced transparency).
1969: Introduced a fundamental parameter of the resonant interaction [41,44] that is, the correlation length in the *cooperative spontaneous emission* of atoms prepared incoherently in an excited state. It does not depend on boundary conditions (as the mirrors in a laser), nor on an external field (as in coherent spectroscopy), but it is an intrinsic parameter of many body optical interactions.
1970: Theory of the *atomic coherent states* [48,51,54] as a basis for a statistical description of coherent phenomena in resonant spectroscopy.
1978: Theory of the *two photon optical bistability* [65], observed four years later.
1998: *Quantum interference* of macroscopically distinct states in parametric optical generation [262].

2000: *Dissipative dynamics* of an open Bose-Einstein condensate (BEC): pattern formation[288,289].

2002:*Macroscopic quantum coherence in BEC*: attractive and repulsive interactions[306,307,312].

Photon statistics and laser fluctuations

1965: First experimental evidence of the statistical difference between a laser and a random field [23,28]. Obtained by *photon statistics*, and it included evidence of the bunching phenomenon for Gaussian sources already explored by Hanbury-Brown and Twiss, but also of the absence of such a bunching for a laser field [25]. These experiments provided a physical ground for Glauber's theory of coherence.
1966-67: Application of the above methods to *laser fluctuations at threshold*, yielding the first experimental evidence of critical fluctuations [34] and slowing down [37] in a *"phase transition out of equilibrium"*, as called later.
1967: *Transient statistics* of a laser switched from below to above threshold [33]: discovered a new phenomenon , namely, a transient enhancement of the photon variance.
1989: The time statistics permits an accurate calibration of the initial photon number giving rise to the amplified chain in a laser. This method has been

called "*statistical microscope*" [173] because it provides measurement of a small photon number not by electron multiplication (as in usual photomultipliers) but by photon multiplication.

2002: *Quantum state reconstruction* by tomography [299]

2003: *Nonlocal experiments on entangled photon pairs* [302]

Deterministic chaos in optics

1978: Theoretical introduction of a mechanism of *laser turbulence*[62], consisting in a cavity including a lasing medium and a second harmonic crystal. A pair of laser photons are converted to a second harmonic photon and this photon is reconverted into a pair of laser photons of different frequencies, thus inducing a type of chaos observed later (in 1986).
1982: First experimental evidence of *deterministic chaos in a laser*[92], starting a research line the main results of which are:

1. 1982-87: characterization of low dimensional laser chaos by different means, that is, loss modulation, injection of an external field, two counter propagating fields in a ring cavity, and feedback [112,122,135].

2. 1984: classification of lasers in *classes A,B,C* depending on the time scales of their dynamical variables [112]. This classification has now become of general use.

3. 1982: first evidence of *generalized multistability*, that is, the coexistence of many attractors [92].

4. 1987: evidence of the mechanism of competing instabilities [143] leading to *homoclinic chaos* (Shil'nikov chaos) characterized by the *statistics of the return times* to a given reference point in phase space[160]. Characterizing chaos by times rather than by geometry is conceptually similar to what done in transient statistics and it is an essential tool whenever chaos does not induce appreciable geometric irregularities, as in most heteroclinic connections; synchronization of homoclinic chaos appears as a universal avenue for biological clocks and biological communication[334].

5. 1993: adaptive recognition of chaos and its control [223].

Pattern formation

High-dimensional optical dynamics results from the competition of many degrees of freedom, either space-like as in extended media, or time-like as in delayed dynamics. In both cases competition gives rise to patterns similar to those observed in fluids, hence the name of "dry hydrodynamics".

1990: The gradual transition from a small to a high number of competing modes is characterized by the passage from *periodic and chaotic alternation*

(PA, CA) where one single mode per time is present, to *space time chaos* (STC) where many modes coexist at the same time. These phenomena, first observed in [179], are explained in terms of cavity symmetries.

1991: A heterodyne method introduced to detect phase singularities or *vortices of the optical field* [185] allows the description of optical pattern formation in terms of vortex statistics. The different scaling of the vortex statistics with the cavity size provides a discrimination between two regimes, one in which patterns are imposed by the boundary and one where patterns are intrinsic of the medium, as in chemical Turing morphogenesis [202].

1992: High dimensional chaos in a strongly confined medium, as a single mode laser cavity, results by introducing a feedback with a delay longer than the intrinsic correlation time of the laser dynamics [195].

1995-1997: Morphogenetic mechanisms analogous to those of fluid mechanics, are shown by the onset of different crystal and quasi-crystal symmetries, depending on the boundary constraints [224]. As the system is driven far away from threshold, many of these "pure" symmetries are excited simultaneously, but rather than quenching each other, they coexist in different regions, giving rise to a multi-domain structure [250] (later called *chimeras*) or they lock into a single super-structure.

1999: Ref. [274] reports the *scaling behaviour of defects after a rapid passage* from below to above threshold in a nonlinear optical system. This corresponds to the rapid passage from many uncorrelated domains to an asymptotic single coherence area; however the asymptotic state is reached for long times, and immediately at the end of the switch pulse one finds a collection of frozen defects, due to the critical slowing down at the transition point. Such a feature is common to all extended critical phenomena; it had been hypothesized for cosmological defects (Kibble-Zurek) and observed also in liquid helium.

2007-2009: Liquid crystal light oscillators provide evidence of spatio-temporal pulses [354] and of localized giant phenomena [385] called *Optical Rogue Waves* (reviewed in [426])

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Complex phenomena and cognitive processes

The methods developed to recognize and control chaos and patterns can be extended to biological phenomena as e.g. cardiac and brain signals. The adaptive methods can not only be extended from discrete to continuous dynamical systems, but they can also control a delayed system. Now, the delayed feedback method corresponds to embedding a physical system with a small number of degrees of freedom into a space with a larger number of dimensions.
Hence, this appears as a good analogy of the cognitive strategy used in any

perceptual task, whereby we build holistic perceptions upon partial information (think e.g. of a deteriorated photography).
2004-2009. A new type of chaotic behaviour, called HC (homoclinic chaos) consisting of spike trains separated by chaotic time intervals ,first observed in CO_2 lasers, displays features common to bain neurons [334]. It has been demonstrated to display a high propensity to organise in large synchronized networks, hence it appears as the most plausible dynamical model for a neuron and for the build up of *"feature binding"* through the synchronization of large neuron arrays in the brain [336].
The replacement of a conventional meter performing a local measurement with a time code which requires a given duration to access a reliable perception raises the question of the fuzziness of perceptions truncated to shorter times, and this introduces a quantum uncertainty which seems to hint to the possibility of parallel fast computation in brain processes.
Similar behavior has been observed in cell communications of plant roots [384].

2009-2017 Rather than tracing the individual neuron behavior, a collective way of describing cognitive tasks is by Bayes inference [357]. Bayes inference characterizes perceptual processes, whereby a sensorial input gives rise to an adequate motor reaction; it requires a pre-assigned algorithm. Perceptions occur in all brainy animals. On the contrary, in linguistic tasks, humans compare a piece of a text with a previous piece, recalled by the short-term memory. The comparison gives rise to a new algorithm, via a process called *inverse Bayes* [399].
The role of language vs. perception in decision tasks is being actively explored, as reported in the review [438].