Some Aspects of Synergetics. From Laser Light to Cognition

Hermann Haken

Abstract While the study of the selforganized formation of spatial, temporal or even functional structures has a long history in *individual* scientific disciplines, ranging from physics over medicine till economy, the goal of synergetics is to unearth the underlying principles of selforganization. The explicit example of a physical device, the laser, allows the development and illustration of general concepts such as order parameters, the slaving principle and circular causality. I show how these concepts and the related mathematical approach can be applied to brain processes connected with visual perception. At the level of order parameters, hysteresis in perception and ambivalent figures are dealt with. A bridge between this phenomenological level and that of real neurons is provided by the Synergetic Computer based on the analogy between pattern formation and pattern recognition. A more recently established link with information theory is outlined,—including a brief discussion of Shannon-, pragmatic and semantic information.

1 Introduction. The Aim of Synergetics

In my contribution, I want to elucidate the scope of Synergetics, an interdisciplinary endeavor that I initiated in 1969 (for some historical aspects (Kröger [1] and Haken [2])). Synergetics is a search for unifying principles for the selforganized formation of spatial, temporal or functional structures in complex systems. The exploration of such structures has a long history. A few hints may suffice:

Chemistry (cf. the nice contribution by P. Plath in this issue)
Fluid dynamics (Bénard [3])
Psychology/Gestalt theory (Köhler [4])
Medicine, Synergy of muscles (Sherrington [5])
Economy (Nash [6]).

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So why Synergetics? My late Russian friend Yuri Klimontovich (who was also the thesis advisor of Werner Ebeling, a pioneer of complexity research) brought it to the point: He said, present days'science resembles a situation where miners working in *different* mines are digging deeper and deeper, while they are not aware of what is found in other mines. So Klimontovich considered Synergetics as an enterprise to foster interdisciplinary cooperation. I stress right at the beginning that Synergetics is a *system* science that not only refers to the "hard sciences" such as physics and chemistry, but also to the "soft sciences" such as sociology or even epistemology. Synergetics focusses its attention on a widespread phenomenon that has marvelled scientists since the antique: the formation of structures by *selforganization,* i.e. without interference by means of any kind of "sculptor" [7]. By fortunate circumstances I came across such a phenomenon not in biology, where selforganization happens all the time, but in physics, i.e. the inanimated world.

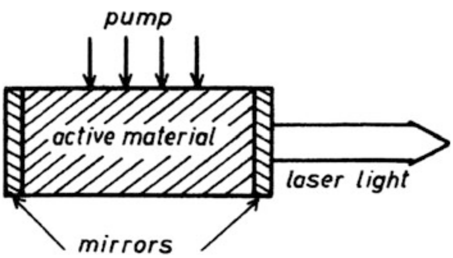
Because a detailed study of the concrete physical system, the then novel light source has revealed so many basic insights into the "mechanism" of selforganization, you surely will forgive me, when I briefly recapitulate basic aspects.

2 The Laser Paradigm

The ruby laser is a nice example of a laser device (Maiman [8]). Ions embedded in a crystal of the shape of a rod may emit light. At the end faces of the rod mirrors are mounted, one of them semitransparent. Thus light emitted in axial direction is reflected several times and can interact with the ions more strongly than light emitted in other directions (Fig. 1).

The electrons of the ions are excited from the outside by *pumplight* so strongly that more electrons are in the upper, excited state than in the lower state (ground state). Denoting the occupation numbers by N_2, N_1, respectively, a positive *inversion* $D = N_2 - N_1$ results. The predominant reason for the construction of a laser was to produce a light source with high spectral purity (Prochorov [9], Schawlow and Townes [10]). They based their suggestion on the process of *stimulated emission* that had been invoked by Einstein 1915 to derive Planck's formula for black body radiation. This process had been used in masers ("*M*icrowave *A*mplification by *S*timulated *E*mission of *R*adiation"). There were, however, two essential

Fig. 1 Scheme of a laser



obstacles for the extension into the *optical* region with its much shorter wavelengths: In the laser rod, many axial waves (called "modes") can coexist, and the emission line is very broad so that many modes can be excited. We (Haken and Sauermann [11], as well as Tang et al. [12]) could show that in a ring laser a competition between modes leads to the amplification of only a *single mode* according to the principle: "winner takes all" or, using an expression of the evolution theory of biological species "survival of the fittest". Actually, later we found a close analogy between our equations and those of Eigen [13]. So my story could have ended here, weren't there a real suprise. As I could show in 1964 [14], laser light has a further fundamental property besides spectral purity (which had been considered by the experts as the only typical feature of laser light). To explain this and to show why all this has to do with selforgnization, I have to consider the laser process in more detail, but invoking a simple model for visualization (Fig. 2).

In an atom (or impurity ion in a crystal), a negatively charged electron is bound to a positively charged nucleus so that at atom j a dipole moment p_j results. When an atom is excited so that $d_j > 0$, p_j begins to oscillate spontaneously and emits a light wave (for a survey, cf. Table 1 and following text)

1. When the $p_j s$ oscillate independently, the fields E_j are uncorrelated. This happens in all conventional lamps. But in the laser, something new happens:

$$\text{stimulated emission.} \tag{1}$$

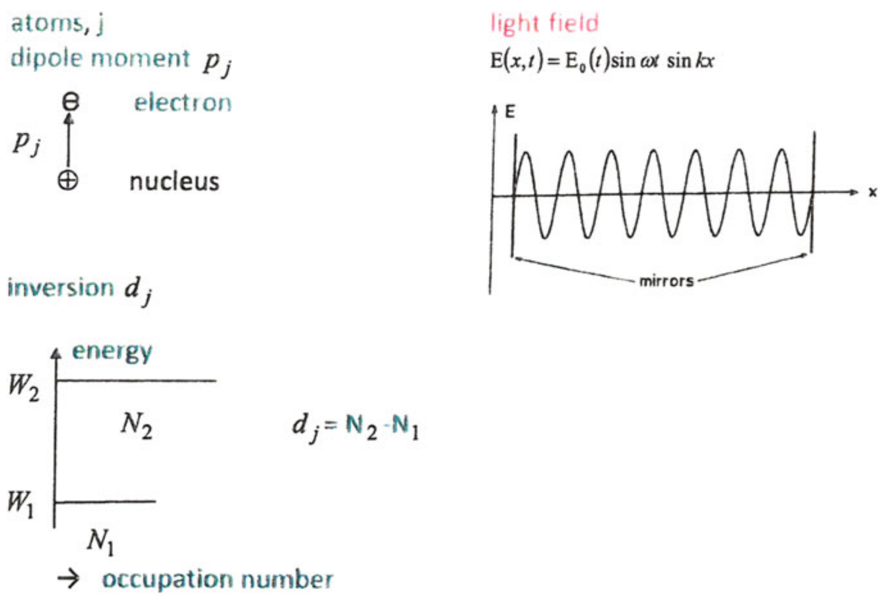
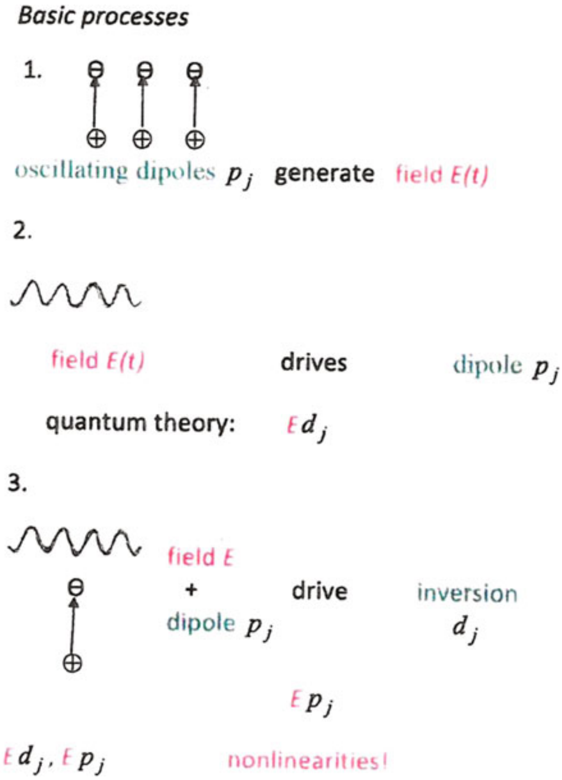


Fig. 2 Upper part, l.h.s.: dipole moment of atom j, *upper part*, r.h.s.: standing wave between two mirrors. ω: frequency, k: wave number. $E_0(t)$ envelope, *lower part* energy levels and inversion

Table 1 Basic elementary processes



2. The resulting field $E = \sum E_j$ acts on the individual dipoles by a driving force Ed_j.

$$E \rightarrow p_j \tag{2}$$

3. E jointly with p_j causes also a change of the inversion d_j of each atom.

$$E \rightarrow d_j \tag{3}$$

Putting (1), (2), and (3) together, we obtain a loop

$$\swarrow \overset{\mathrm{E}}{(p_j, d_j)} \nwarrow \tag{4}$$

that I have called circular causality. At this stage of our approach (4) results in a complete mess concerning the temporal behavior of E. However, our laser device is coupled to its surround: the atoms (ions) are embedded in a matrix that perturbs the dipole oscillations leading to their damping and fluctuations. In addition, the pump light tries to restore the inversion within a typical relaxation time, or, equivalently, with a specific damping. In analogy to the notation of spin resonance two types of damping constants come into play, inversion: γ_1, dipole: γ_2. Furthermore, the lightfield is damped also, because it can escape through the semitransparent mirror. I denote the corresponding damping constant by κ. In typical lasers we have a time scale separation.

$$\kappa \ll \gamma_1 < \gamma_2 \tag{5}$$

This means that the atoms react quickly to the rather slowly decaying field E_0 after splitting off the rapidly oscillating factor exp($i\omega t$), ω light frequency.

$$E = E_0 \sin \omega t \, \sin \, kx$$

This allowed me to express the dipole moments p_j and in the quantum mechanical approach the inversion d_j by the amplitude of the field strength E_0. Thus, I found a simple equation for E_0

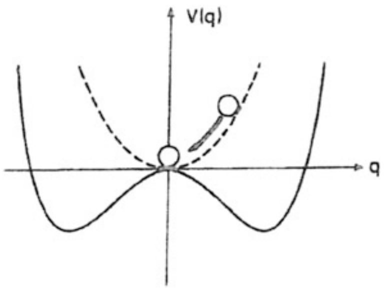
$$\frac{dE_0(t)}{dt} = (g - \kappa)E_0(t) - sE_0(t)^3 + F(t) \tag{6}$$

Actually, for my presentation, (6) is somewhat simplified but captures the most essential features of laser light. In (6) g is the “gain” that results from the continuous excitation of the atoms by means of pumplight. K is the just introduced damping constant. The next nonlinear term sE_0^3 is most important and serves for the stabilization of the laser light amplitude. The last term $F(t)$ describes the impact of fluctuations. This effect becomes very small if $g - \kappa > 0$. The meaning of (6) can be easily explained when we realize that it can be expressed by means of a potential $V(E_0)$:

$$\frac{dE_0}{dt} = -\frac{\partial V}{\partial E_0} + F(t) \tag{7}$$

$V(E_0)$ is plotted in Fig. 3. For $g < \kappa$, i.e. weak excitations, the parabola with only one minimum of V applies: The field amplitude is mainly zero and fluctuates due to the random “kicks” of $F(t)$.

Fig. 3 cf. text, $q \equiv E_0$



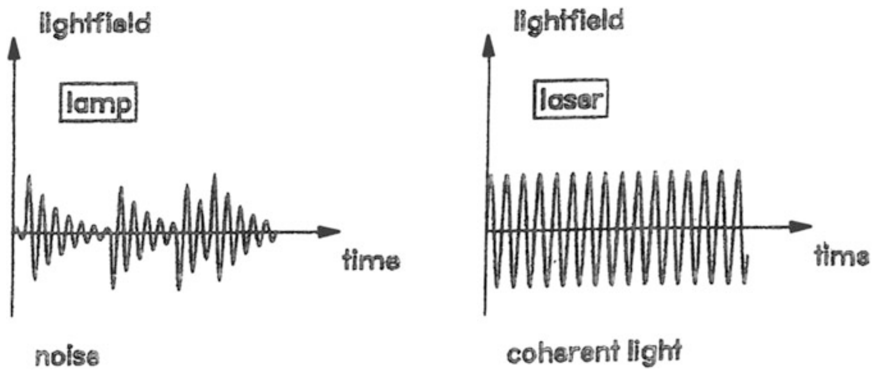


Fig. 4 L.h.s.: light of a lamp; r.h.s.: laser light

For g > κ evidently stable minima result indicating a stable field amplitude. Figure 3 is, of course, familiar to all those scientists who have been concerned with phase transitions of systems in thermal equilibrium such as freezing of water, ferromagnetism, superconducting a.s.o. Thus, the highly ordered laser light emerges from the (chaotic) light of conventional lamps by a phase transition! But here we are dealing with a driven system far from thermal equilibrium. Furthermore, we are dealing with a macroscopic quantum system subject to quantum noise $F(t)$ (actually in my original paper (6) is an *operator* equation). Laser light is brought about by the *selforganization* of the dipoles that must oscillate in phase. The many individual wave tracks of the light of lamps are replaced by a single, practically infinitely long laser wave (Fig. 4).

3 The Road to Selforganization

My laser example allows us to gain insight into basic features of selforganization that can be generalized to far more complicated systems. First of all, we deal with a system composed of many elements that interact with each other (the laser atoms interacting via the light field) and the system is coupled to its surround (Fig. 5).

The system receives inputs of energy, matter and/or information (e.g., pump light) and may dispose of "waste", e.g., heat (entropy). The coupling(s) of the system is (are) described by control parameter(s), e.g., pump strength.

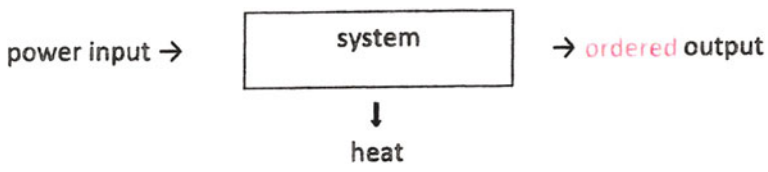


Fig. 5 Scheme of an open system

At a critical value of a control parameter, the system changes its state qualitatively. Its state becomes unstable.

In such a situation, one (or several) new collective variables appear, e.g. in the laser: the coherent field E. Generalizing Landau's notion we call these variables *order parameters*. These order parameters *enslave* the individual parts (the field E fixes the behavior of p_j, d_j). (The slaving principle is more general than the center manifold or inertial manifold theorem by the inclusion of fluctuations). Order parameters and enslaved parts condition each other by

$$''\text{circular causality}''(\text{cf.}4)).$$

The concept of order parameters and the slaving principle lead to a remarkable

complexity reduction.

Instead of dealing with the numerous variables of the parts (e.g. p_j, d_j), their behavior is determined and described by only few order parameters (in the single mode laser described above by *only one*). By use of dynamic systems theory, a number of order parameter equations can be classified leading to fixed points, limit cycles, tori and deterministic chaos.

How far can we go when we try to apply these concepts (and the underlying mathematical tools that I haven't presented here) to really complex systems? Probably the most complex system we know is the human brain. So let's try!

4 The Brain as a Synergetic System

Figure 6 shows the human brain as seen from above. Its white-gray matter of about 1.5 kg has the shape of a walnut. When studying it under a microscope, we observe small, complicated structures, the neurons of which Fig. 7 shows two examples. There are about 10^{11} neurons in the brain, and a neuron can receive inputs from up to 10^4 other neurons. Figure 8 shows a typical structure of a neuron. Its center is the cell body. Synapses receive (usually) voltage "spikes" from other neurons, convert them into electric currents in dendrites. The cell body sums them up and "fires" if the sum is beyond a threshold (This model picture forms the basis of many neural network approaches since McCulloch and Pitts [15]). The cell body then sends out a sequence of short pulses using pulse code modulation. The great challenge to neuroscience is the question: Who or what steers the neurons so that the brain may recognize objects, steer our movements, and may produce so many of its other complex activities. The answer I have proposed in 1983 (Haken [16]) is: The brain is a synergetic system, i.e. in particular, that it is selforganizing. To be concrete, I suggest an analogy:

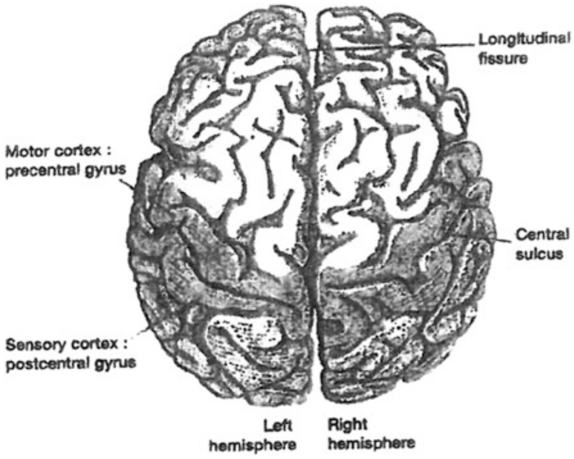


Fig. 6 The brain seen from above

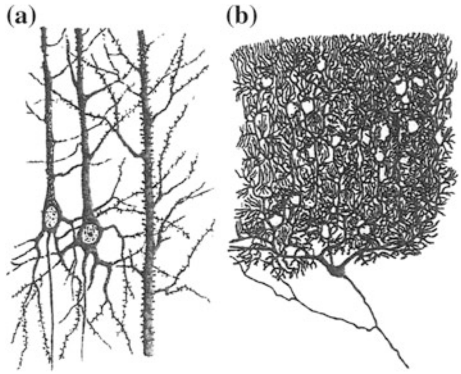


Fig. 7 **a** Pyramidal cells, **b** Purkinje cells

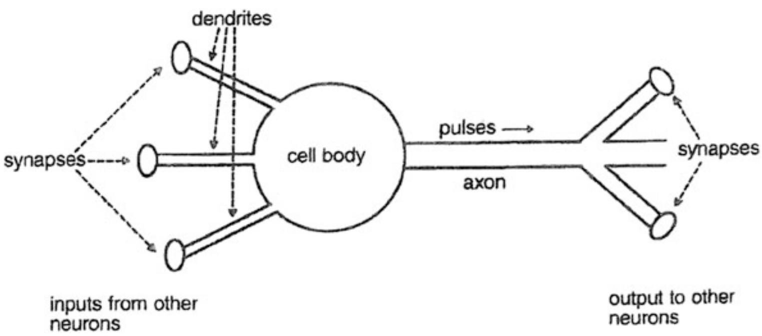


Fig. 8 Scheme of a neuron

	laser		brain
macro:	laser light	order parameters	percepts
	↕	↕	↕
micro:	atoms	parts	neurons

Over the past decades, I have devoted one line of my activities to the relation between neurons and percepts, or in other words, to pattern recognition. To this end, I proceeded in three steps which I can discuss here only briefly.

(4.1) phenomenological approach based on order parameters
(4.2) mesocopic approach based on the synergetic computer in which model neurons produce order parameters
(4.3) microscopic approach that treats the dynamics of neurons

4.1 Phenomenological Approach

If there is only 1 order parameter, ξ, the dynamics is prescribed by a potential $V(\xi)$, where V depends on a control parameter that causes deformations of V such as in Fig. 9. We ascribe to the minima of V specific percepts. We start with the upper row from the left. When the control parameter is increased (middle part), the system is still in its original state. But finally, a new minimum will be occupied. Now follow the lower part in the reverse direction. In the middle part the system is still kept in the right minimum. Though the control parameter is the same as before in the middle part of Fig. 9, the states occupying the minima are different. Clearly, here I have

visualized the hysteresis effect. But the reader may verify this effect in visual perception, when in Fig. 10 s/he first looks at the upper row from the left to the right and then at the lower row from the right to the left. Did you notice that your perception switches at different positions depending on what you have seen before?

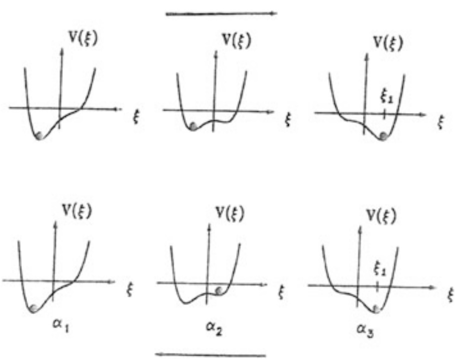


Fig. 9 cf. text

I have "invented" a further example shown in Fig. 11. First look at the upper line, hiding the other lines. Then proceed step by step to the lower lines. Then do the same in the opposite direction. Could you notice the hysteresis?

The effect of ambivalent figures (in German: Kippfiguren) on perception has been modelled by means of the oscillatory dynamics of two order parameters (cf. Figures 12 and 13) (Ditzinger and Haken [17]).

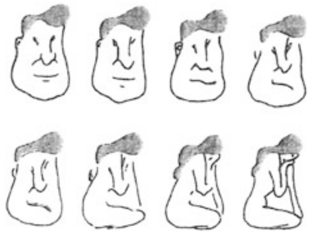


Fig. 10 Hysteresis in visual perception

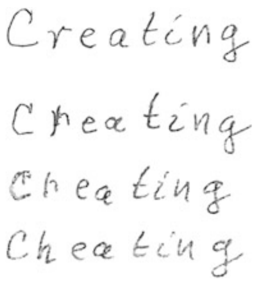


Fig. 11 Hysteresis in understanding (cf. text)

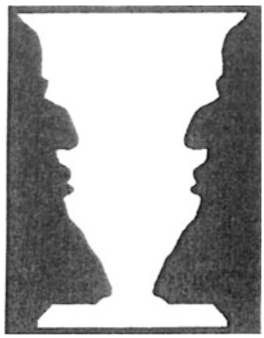


Fig. 12 Vase or faces?

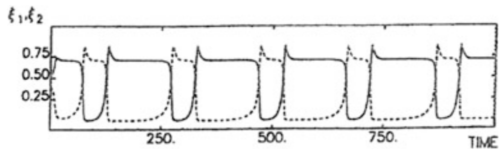


Fig. 13 Plot of the order parameters ξ_1, ξ_2 corresponding to two interpretations, for instance vase/faces, versus time [17]

4.2 Mesoscopic Approach

Here I modelled perception by means of the Synergetic Computer. (My algorithm was implemented on a computer by my Ph.D. student Armin Fuchs). The basic concept is based on the analogy between pattern formation (e.g. in fluids) and pattern recognition by humans or computers. A main ingredient of pattern is associative memory. A telephone book is an example: a person's name is supplemented by his/her telephone number. Thus, based on memory, incomplete data are complemented. This is achieved in the Synergetic Computer by a specific dynamics using order parameters (Fig. 14).

In pattern formation an initially only partly ordered pattern calls up several order parameters which compete with each other. Eventually one order parameter wins and enslaves the total system so that it is now in its fully ordered state. A similar process happens in pattern recognition. An only partly offered picture is calling up several order parameters that compete with each other. Again, the winning order parameter restores the complete picture Fig. 15 (face recognition).

More recently, we (Haken and Portugali, to be published) found a nice new application of the Synergetic Computer. Some time ago, so-called hybrid images were "constructed" by Oliva and Schyns [18]. A typical example is shown in Fig. 16.

When you look at it from a short distance, you will recognize Einstein, but when looking from a larger distance, or with half-closed eyes, you will recognize Marílyn Monroe. The "secret" of the construction principle is as follows: the total picture consists of a superposition of two pictures, Einstein and Monroe. While Einstein's face is composed of fine lines (i.e. high band pass filtered) that of Monroe is based on smooth shades. To see, how the Synergetic Computer can deal with hybrid images, we first stored the corresponding *unfiltered* images in the computer. Then

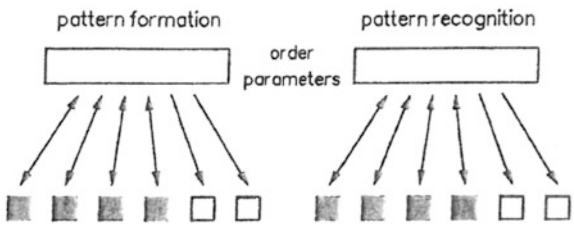


Fig. 14 Analogy between pattern formation and pattern recognition

Fig. 15 Example of a recognition process where part of a face is prescribed as initial state

Fig. 16 The same picture is interpreted in two different ways

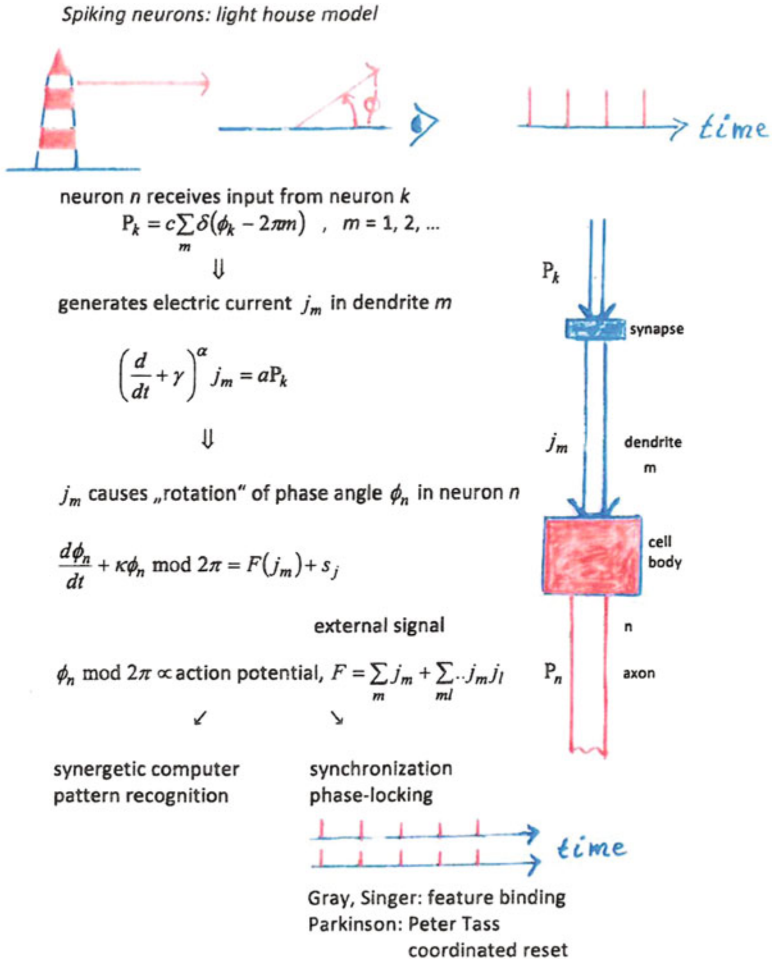
the hybrid image was offered to the computer which "recognized" Einstein. Then we studied the effect of *blurring* the hybrid image by forming its convolution with a Gaussian. We found that the fine lines were more affected ("smeared out") than the soft shades. So when the blurred hybrid image is offered to the Synergetic Computer, the "Monroe" interpretation wins. We expect that for a well-tuned blurring, a hybrid image may cause oscillations in perception as in the case of the "traditional" ambivalent figures.

4.3 Microscopic Approach—Spiking Neurons. Light House Model [19]

A survey is provided by Table 2 and an explanation on the next page.

As we know, the cell body of a neuron emits voltage spike trains along its axon. To model this effect, we consider a light house that emits a rotating light beam (upper part of Table 2, l.h.s.). Seen from above, (middle part): the light beams form an angle ϕ with respect to a fixed axis. Whenever $\phi = 0$, 2π, $l2\pi$, l: integer, an observer sees a flash. To apply this model to the action of a real neuron, we recall (cf. Fig. 8) that a neuron with label n receives its input from another neuron k in the form of pulses, where ϕ_k corresponds to ϕ in the upper middle part of Table 2, δ is Dirac's δ-function. These pulses p_k generate an electric current j_m in a dendrite m of neuron n. Note that according to measurements, the exponent α is a fraction in between 1 and 2. γ is a damping constant, and a a conversion factor. Finally, the cell body sums the incoming currents in a nonlinear fashion up (cf. F). The resulting F together with an incoming external signal s_n act as "driving force" for the overdamped rotation of the angle $\phi(t)$. κ is a damping constant, and the operation "mod 2π" serves the purpose that ϕ_n mod 2π remains restricted to $0 \leq {}_n < 2\pi$. It can be shown that ϕ_n mod 2π mod is just the action potential in suitable units. In my book [19], I have treated a network of such "light house" neurons and shown that it covers interesting special cases. On the one hand, it allows the

Table 2 Scheme of the light house model. For details cf. text



derivation of the equations of the synergetic computer for pattern recognition; on the other hand it captures synchronization between neurons, in particular phase locking between groups of neurons as observed by Gray and Singer [20], who invoke this effect to explain feature binding. Other synchronization effects play a fundamental role in Parkinson tremor, where Tass [21] has developed efficient methods of treatment by "coordinated reset".

5 Concluding Remarks

I am very glad to see that the "Synergetics Endeavor" is still flourishing as is witnessed by this meeting at Herrenhausen Castle, by the proceedings of a meeting at Delmenhorst [22] (both meetings sponsered by the Volkswagen Foundation) as well as by numerous other publications. In a way, Synergetics rests on three columns:

dynamic systems theory dealing with deterministic processes

the theory of stochastic processes dealing with chance events

phase transition concepts of physics.

Needless to say, that Synergetics strongly profits from the Synergy between these columns as well as from the traditionally tight ties between experiment and theory. There is, however, a fourth colomn, that relates the topic *selforganization* with *information* (Haken [23]). More recently, jointly with Juval Portugali, I elaborated this relationship more closely [24]. Our starting point is Shannon's definition of information, $S = -\sum_j p_j log_2 p_j$, where p_j is the probability (or relative frequency in a different interpretation) of an event labeled by *j*. A well known "drawback" of this definition is that "meaning is exorcized". So there have been attempts to introduce concepts on "meaningful information". In my book [23] I defined it as such signals that have an effect on their receiver. For a historical account of the corresponding concepts of "pragmatic" and "semantic information" cf. [25]. Portugali and I have been intrigued by the question whether there is any relation between Shannonian information (SHI) on the one hand and pragmatic/semantic information (PI/SI) on the other. We found by the concrete example of visual perception based on the model of the Synergetic Computer, jointly with Jaynes' maximum (information) entropy principle, that SHI and PI/SI condition each other. Furthermore, we found that in cognition the human brain "deflates" or "inflates" SHI depending on the situation. While usually in pattern recognition the brain must select one specific percept out of many other interpretations ("deflation"), in other cases our brain "produces" several interpretations. An example is provided by Fig. 17 (from [24]). Its middle part shows a drawing by Picasso.

Lack of space does not allow me to present our results in more detail, but I can refer readers who are interested in this rather entertaining story to our book as well as to a forthcoming issue on Information and Selforganization in the journal "Entropy".

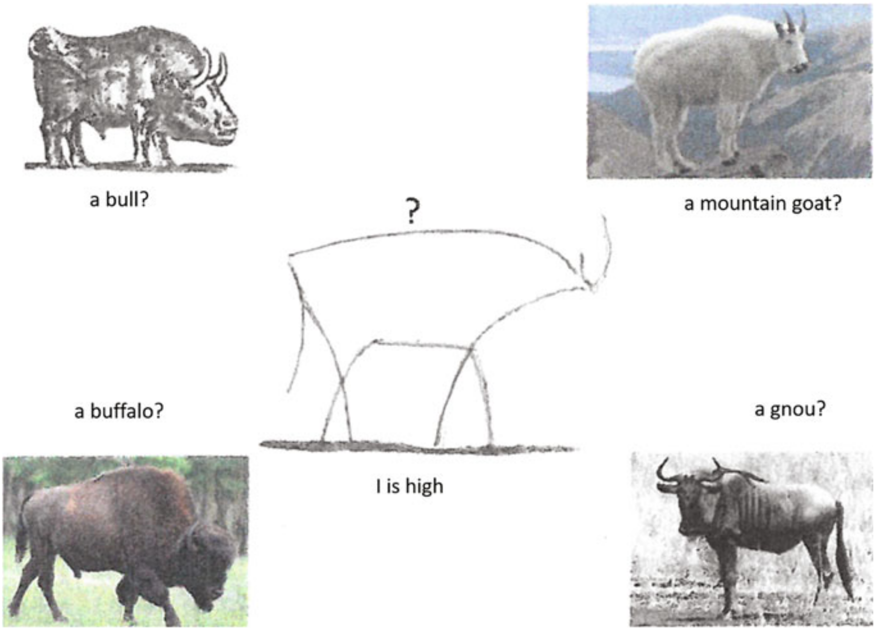


Fig. 17 Is the drawing at the center a bull? a mountain goat? a gnou? a buffalo?

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