

Chapter 1

Resonances Everywhere

Alien View of Earth

If an alien visitor from a distant planet came to visit the Earth, there are certain prominent features of life on Earth that would immediately strike the alien as significant characteristics of terrestrial life, but that pass almost completely unnoticed to human eyes due to their overwhelming familiarity and ubiquity. First of these is a fundamental symmetry and periodicity seen in virtually all life forms, like the examples in Figure 1. We see symmetry in the starfish, the octopus, pine trees, palm trees, and in the splendid diversity of flowers. We see periodicity in the segments of a worm, the ribs and vertebrae of a snake, the scales on fish, feathers on birds, the periodic pores and hairs on a mammal's hide, and in the patterns of veins in leaves and stems of plants. What is the origin of this symmetry and periodicity in nature? What is the pattern or template that nature uses to sculpt these symmetrical and periodic patterns in living tissue?



Figure 1. Symmetry and periodicity abound in the forms of plant and animal bodies on earth.

We now know the reason for this pervasive principle of periodicity and symmetry in living things. The mechanism behind it is a *chemical harmonic resonance* known as *reaction diffusion*, a continuous, circular reaction that produces a periodic pattern of chemical concentration, and it is the natural periodicity and

symmetry of reaction diffusion that explains the pervasive symmetry and periodicity in nature.

The principle of reaction diffusion is demonstrated most clearly in the Belousov-Zhabotinsky reaction. This involves a continuous chemical reaction in which some reagent A is continuously catalyzed into a different reagent B, while at the same time reagent B is being continuously transformed into reagent A. The net result depends on the relative concentrations (and diffusion rates) of the two reagents, a high concentration of A produces more reagent B, whereas a high concentration of B produces more A. The chemical state is thus unstable, and will cycle endlessly between high concentrations of A and B alternating over time, and this is visible in the Belousov-Zhabotinsky reaction as a cyclical change in color from light to dark and back again, as the reaction proceeds.

Chemical diffusion keeps the chemical state uniform throughout a small sample of the Belousov-Zhabotinsky reagents, thus all of the molecules within that sample tend to change state in lock step. In a larger vessel, chemical diffusion takes time to propagate through the volume of the chemical bath, so the synchrony to more remote parts of the chemical is phase lagged by the time it takes for diffusion to propagate between those points. So reaction-diffusion strikes a dynamic balance between the competing constraints of cyclical reaction at every point in the fluid, and local chemical synchrony enforced by diffusion, which propagates at some fixed rate. The dynamic solution to these constraints appears as a periodic spatiotemporal pattern of chemical waves that emerge spontaneously from the chemical brew, and propagate in parallel fronts through the volume of the liquid in such a way that each point in the fluid cycles endlessly between concentrations of A and B as the chemical wave fronts pass through that point. Figure 2 A shows the patterns obtained by the Belousov-Zhabotinsky reaction evolving over time in a beaker, and Figure 2 B shows the reaction confined in a test tube.

The pattern of chemical waves in the beaker in Figure 2 A is largely a feed-forward phenomenon of waves propagating outward in concentric rings from spontaneous ignition points. In the test tube in Figure 2 B, where the reaction is more tightly constrained in a cylindrical vessel, the reaction-diffusion tends to form a periodic pattern of stripes along the length of the tube, the only direction that diffusion is free to propagate any significant distance. If the height of the column of chemical liquid is contrived to be an integer multiple of the natural wavelength of the Belousov-Zhabotinsky reaction, it is possible to establish standing waves of chemical harmonic resonance, in which each point in the liquid cycles endlessly,

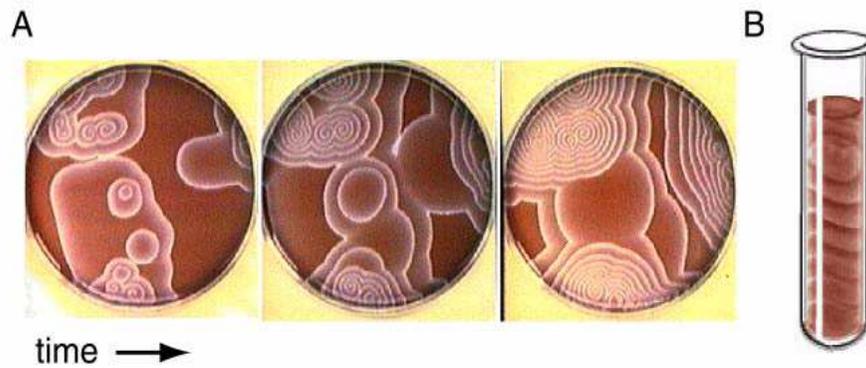


Figure 2. A: The Belousov-Zhabotinsky reaction evolving over time in a beaker, and B: defining a striped pattern in a test tube.

but the pattern as a whole remains stationary, oscillating about a set of fixed nodes disposed at periodic intervals along the tube. It is by this kind of chemical standing waves that nature defines the periodic patterns of tissue in the geometrical designs of plant and animal forms.

Figure 4 A shows an embryo of the fruit fly *Drosophila* at an early stage of development when the periodic pattern of its segmented body is first being laid down, as revealed by appropriate staining techniques that render the pattern visible. These patterns of alternating chemical concentration fix the fate of the underlying tissue, transforming the initially undifferentiated tissue into layers of specific tissue types. Tissue that is surgically transplanted from one part of the embryo to another *before* this critical period, takes on the character of the destination tissue into which it is transplanted, whereas tissue that is transplanted *after* this critical period, retains its original tissue identity at the transplanted location. The template for the periodic striped pattern is a *chemical harmonic resonance* whose standing waves define the stripes in the pattern.

There are actually several sets of such stripes defined by several different reaction-diffusion processes occurring in the embryo, that together define different hierarchical levels of the pattern template for the insect's body, as shown in Figure 4 B. The highest level of the hierarchy is defined by the so-called *maternal* genes, (whose chemistry is supplied by the pre-natal maternal environment) that distinguish the head end from the tail end of the embryo, or anterior from posterior. The corresponding *morphogens*, (chemicals that determine the morphology of the embryo) which are produced by specialized cells in the head and tail, diffuse passively through the tissue of the embryo, creating a gradient of chemical concentration for each morphogen as shown by the colored shading in the figure.

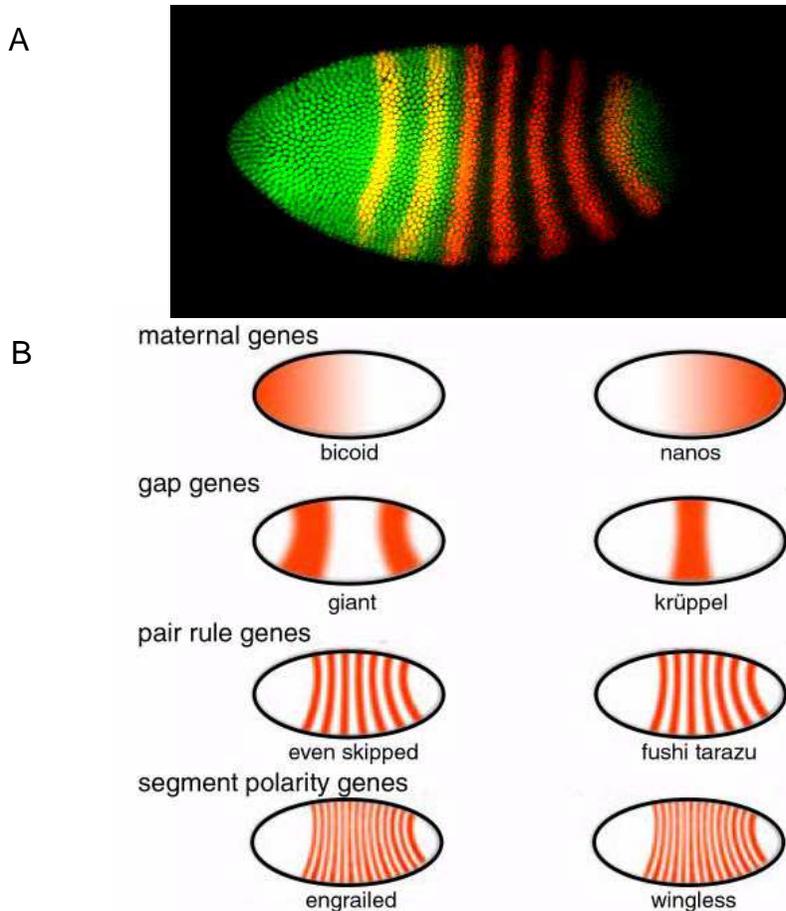


Figure 3. Chemical harmonic resonance in embryological morphogenesis. A: A pattern of chemical concentration in the developing embryo, defined by B: a hierarchical series of component morphogens, each defined by a different standing wave pattern across the embryo.

The next hierarchical level is defined by the *gap* genes, *giant* and *krüppel*. (named for the embryonic deformations produced by mutations that disrupt each morphogen individually) The sharp boundaries between adjacent regions of each morphogen shows evidence of a chemical standing wave like the Belousov-Zhabotinsky reaction, since these boundaries would quickly blur if they were driven by passive diffusion alone, as in the maternal genes. Besides, passive diffusion is an interpolative function that can only generate continuous gradient patterns, it cannot in principle generate the alternating striped patterns of the chemical standing wave. Similar patterns of even finer stripes are defined by the *pair rule*, and the *segment polarity* genes. Considered in combination, these various patterns of chemical concentration uniquely identify or address every point in the embryo as to which segment it is located in. For example the *maternal* and *gap* genes together divide the embryo into five segments each uniquely identified by a specific pattern of concentration of the corresponding morphogens. The *pair*

rule genes further subdivide those zones into the regular pattern of insect segments, and the *segment polarity* genes divide each segment into anterior and posterior halves. This creates something like a Boolean addressing scheme, in which the relative concentrations of a small number of morphogens determines the specific tissue type required in each segment of the embryo. Figure 4 A is a multiple exposure that superimposes the patterns of three of the morphogens in one picture to show how they work in combination to create a compound pattern of embryonic architecture. This chemical harmonic resonance by way of chemical standing waves is the code used by nature to determine the morphology of the developing embryo, and it is the fundamental periodicity of the phenomenon of standing waves that accounts for the pervasive symmetries and periodicities of plant and animal forms. The fact that nature both *can* and *does* make use of chemical harmonic resonance as a template for defining the spatial patterns of the body in morphogenesis is significant.

At one glance at our bodies, the alien visitor to earth would immediately recognize that we and our fellow fauna and flora are sculpted by harmonic resonance. Besides the linear periodicity clearly evident in the pattern of our segmented vertebrae and ribs, there is a further periodicity in the segments along our limbs, fingers, and toes, with chains of similar bones linked by cartilagenous joints along each individual finger and toe. There is also a radial periodicity evident in the pattern of bones along each limb, that begins with a single bone proximal to the body, (the humerus in the upper arm, and femur in the upper leg), followed by a pair of bones more distally, (radius and ulna in the lower arm, tibia and fibula in the lower leg), and the number of bones continues to increase in stages towards our distal fingers and toes, as suggested schematically in Figure 4 A. This basic pattern is common across a wide variety of species, seen most clearly in early limbed creatures like the Plesiosaurus shown in Figure 4 B. This pattern of radial periodicity has been explained by a chemical harmonic resonance in the embryonic limb bud, that jumps to successively higher harmonics as the limb bud grows in physical size, as suggested schematically in Figure 4 C. (Newman & Frisch 1979) In the human and other mammalian forms, the triple and quadruple bones in the foot and ankle are clumped together into a bony mass due to non-uniform growth rates in different parts of the limb after the initial tissue imprinting during the critical formative period, thus demonstrating that the geometrical regularity of the morphogenic resonance is only present or significant during the critical period in the embryonic limb bud. And the bilateral symmetry of the mammalian body, as well as the four-fold symmetry of a box jellyfish, and the five-

fold symmetry of a starfish, are all manifestations of the principles of harmonic resonance in morphogenesis.

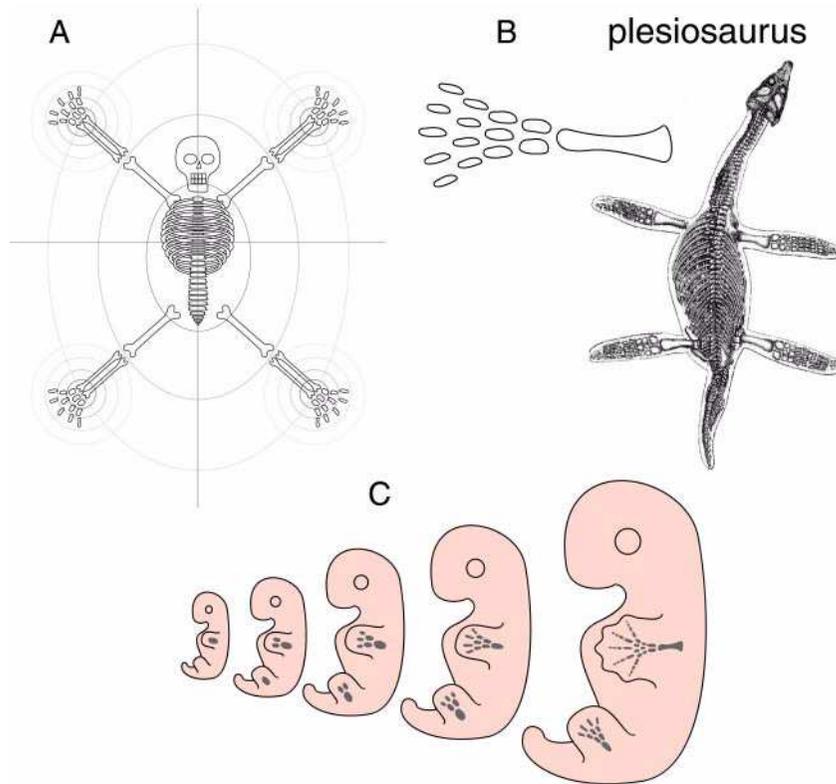


Figure 4. A: A pattern of progressive increase in the number of bones in each limb from proximal to distal, B: seen most clearly in early limbed creatures like the plesiosaurus. C: This pattern is explained by a successive jumping to higher harmonics of chemical harmonic resonance in the embryonic limb bud as it grows to larger size.

There are many more examples of chemical harmonic resonance in morphogenesis, evident just about everywhere that symmetry and periodicity are in evidence. Murray (1981, 1988) shows how the patterns of markings seen on animal skins, such as the spots of a leopard and giraffe, and the stripes of a tiger and zebra, shown in Figure 5 A through D, can all be explained as parametric variations on a single reaction-diffusion mechanism, computer simulations of which are shown in Figure 5 E through H. Murray clinches the argument by showing how the same parameters that produce spots, like those on a leopard, will naturally tend to form rings at the tip of the tail, as is observed for many spotted creatures, due to the long and thin geometry of the tail, by the same principle that the concentric rings in the Belousov-Zhabotinsky reaction in Figure 2 A becomes a striped pattern in the test tube in Figure 2 B. This phenomenon is replicated in the computer simulations of Figure 5 E. Of course the geometry of the tail is only influential during the critical period when the reaction-diffusion

pattern is being permanently fixed in the embryonic tissue. Murray also showed how the triangular pattern of stripes on a zebra where the foreleg meets the body, seen in Figure 5 B, can also be explained by the same reaction-diffusion process that creates the more regular pattern of stripes on the leg and the body, as shown in the computer simulation in Figure 5 F.

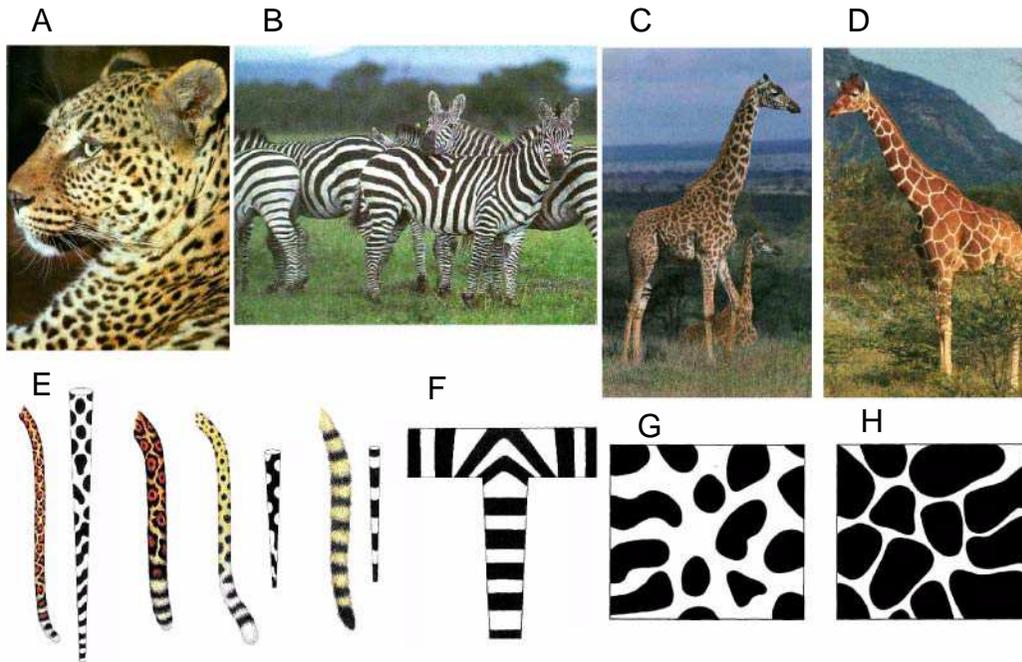


Figure 5. A through D: The great variety of spots and stripes seen on animal hides can be explained by parametric variations of a reaction-diffusion as shown in computer simulations E through H that replicate observed phenomena like the way that E: spots often turn to rings at the tip of the tail, and F: the way the stripes from the forelegs and torso of a zebra merge, and G and H: variations in the spots of different species of giraffes can be produced by parametric variations of the reaction-diffusion.

The patterns on animal hides, which are generally for the purpose of camouflage, demonstrate that reaction-diffusion can generate random, or quasi-random patterns as well as more regular periodic and symmetrical patterns, although the principles of periodicity and symmetry are nevertheless evident as the foundational basis of even these irregular patterns. More regular geometrical patterns are seen on animals whose markings are not intended for camouflage, but as a warning. For example many poisonous snakes and caterpillars, among other creatures, advertise their danger to predators by more prominent geometrical patterns such as stark stripes or rings or diamond patterns.

Why Standing Waves?

Why did nature pick the phenomenon of chemical standing waves as the operational principle behind the pattern formation mechanism of embryological morphogenesis? The answer to this question turns out to be of great significance not only for theories of morphogenesis, but also for other applications in biology where spatial representations are needed, that is, in perception, cognition, and motor control, and one day spatial representation by harmonic resonance will also be a significant human technology once we have figured out how to replicate the central computational principle behind the brain. What makes standing waves so useful as a pattern formation principle is the flexibility or adaptability of the generated patterns. Unlike a template or blueprint that defines a rigid inflexible pattern, standing waves represent a *multipotential* pattern formation principle that can potentially generate an infinite variety of different patterns that all conform to certain general rules, as seen for example in the infinite variety of leopard spots on individual leopards, all of which exhibit the familiar characteristic pattern for that particular species, and yet each individual exemplar of that infinite variety of leopard patterns is distinct from the infinite variety of giraffe spots on individual giraffes. The secret behind the adaptability of standing waves is that they are an *emergent feedback* phenomenon that continuously reconfigures itself (during the critical period) to adapt to ambient conditions, like an elastic template or blueprint that can be stretched or squeezed in a number of different directions, while retaining its relative proportions.

For example the segments of the morphogenic patterns in Figure 3 are defined not in terms of a rigid periodic template, but the boundaries between segments automatically shift and distort to create segments of equal *volume* rather than of identical geometry, because it is the volume of each segment that determines its rate of production of morphogen, rather than its geometrical shape. This results in a *topological* rather than *topographical* pattern template, one that automatically adapts to any irregularities or deformations in the embryo to produce geometrically warped segments that conform to the deformation of the embryo. That is why plant and animal bodies, even of the same species, exhibit an astonishing range of sizes, shapes, and varying proportions, while each body is complete with its pattern of limbs, bones, and internal organs all neatly re-proportioned to exactly match the proportions of the given individual. Although the principle of reaction diffusion in embryological morphogenesis is no longer controversial, and is well known within that specialist field, there is little

recognition of the profound implications of this highly flexible and adaptive pattern formation principle in nature.

The real power and flexibility of morphogenesis can be seen in the great variety of conjoined twins, whose bodies can fork or branch at any of a number of different locations, as shown in Figure 6, and yet in each case, at the point where the body branches, every bone, muscle, organ, nerve, sinew, and blood vessel, branches neatly at that point, as if that were part of the original plan. This is a remarkable property for a pattern formation template, quite unlike any other spatial patterning principle devised by man, and certainly unlike the plans or blueprints commonly used in architecture and engineering, where the size, shape, and location of every component is rigidly specified to the minutest detail. This remarkable adaptability of the body plan to variations in body topography is a necessary prerequisite for evolution, if random mutations that modify the body plan in any way are to have any chance of viability.

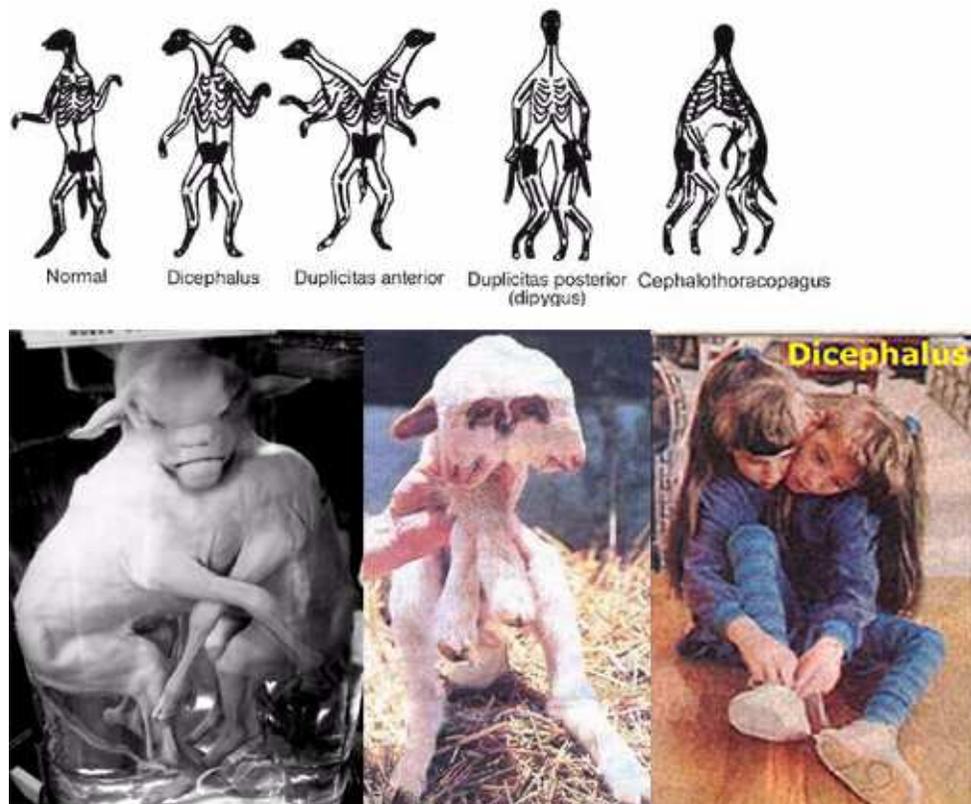


Figure 6. The phenomenon of conjoined twins demonstrates the remarkable flexibility and adaptability of the biological body plan. Wherever the body plan splits or branches, every bone, muscle, organ, nerve, sinew, and blood vessel, branches neatly at that point, as if that were part of the original plan.

Emergence, Holism, and Gestalt Theory

There is something truly magical about the holistic emergent nature of the pattern formation principle observed in embryological morphogenesis. And a similar holistic emergent principle is observed in many aspects of visual perception and of motor control. This was the principal thesis of the *Gestalt* movement of the early nineteenth century, as espoused by the founders of Gestalt theory, Max Wertheimer, Kurt Koffka, and Wolfgang Köhler. The most significant general property of perception identified by Gestalt theory was a holistic, or global-first character in which the global configuration of a stimulus is often perceived before its local component features. Figure 7 shows a picture that is familiar in vision circles, that reveals the principle of emergence in a most compelling form. For those who have never seen this picture before, it appears initially as a random pattern of irregular blotches. A remarkable transformation is observed in this percept as soon as one recognizes the subject of the picture as a Dalmation dog in patchy sunlight in the shade of overhanging trees. The outlines of the dog are defined by a large number of apparently chance alignments of irregular edges. What is remarkable about this percept is that the dog is perceived so vividly despite the fact that much of its perimeter is missing. Furthermore, visual edges that form a part of the perimeter of the dog are locally indistinguishable from other less significant edges. Therefore any local portion of this image does not contain the information necessary to distinguish significant from insignificant edges. This figure therefore reveals a kind of processing in which global features are detected as a whole, rather than as an assembly of local parts.

The principle of emergence, sometimes expressed as the Platonic motto "*The whole is more than the mere sum of its parts,*" seems to suggest some kind of magical mystical process whereby perceptual structure appears out of nowhere. However, Wolfgang Köhler (1924) argued that there is no magic in emergence; the principle of emergence is seen in many physical systems, including the way that electric charge distributes itself throughout a conductor, or water seeks its own level in a vessel, where the final position of every particle in the system depends immediately on the positions of every other particle. Perhaps the most familiar Gestalt example of emergence in a physical system is the soap bubble (Koffka, 1935). The spherical shape of a soap bubble is not encoded in the form of a spherical template or abstract mathematical code, but rather the form emerges from the parallel action of innumerable local forces of surface tension acting in unison.



Figure 7. The dog picture is familiar in vision circles, because it demonstrates the principle of emergence in perception. The local regions of the image do not contain sufficient information to distinguish significant form contours from insignificant noisy edges. As soon as the image is recognized as that of a dog in dappled sunshine in the dappled sunshine under overhanging trees, the contours of the dog pop out perceptually, filling in visual edges even in regions where no edges are present in the stimulus.

Principles of Harmonic Resonance

The principle behind the emergent pattern formation mechanism of reaction diffusion can be better understood by examining the properties of other kinds of standing wave resonances, such as vibrational resonances in elastic solids, electrical resonances in electric circuits, and laser and maser systems that operate by standing waves in light and microwaves respectively. It turns out that many of the properties of chemical standing waves are expressed by the same mathematics that describes the behavior of those other resonances. In fact, harmonic resonance and standing wave phenomena represent a higher order organizational principle of physical matter, that transcends any particular implementation of it.

Murray (1981, 1988) demonstrated the link between reaction diffusion and standing wave vibrations of solid objects. Figure 8 (from Murray 1988) shows a

thin sheet of steel cut in the approximate shape of an animal hide, that is subjected to vibrations of various frequencies and waveforms to induce vibrational standing waves in the steel, showing how the patterns of standing waves replicate the same kinds of spotted and striped patterns observed in animal markings. Like the Belousov-Zhabotinsky reaction, each point in the vibrating steel sheet cycles endlessly between deflections in alternate directions, like a guitar string when it is plucked. Immediately adjacent points in the vibrating surface are constrained to vibrate in synchrony, whereas the synchrony between more distant points in the sheet are systematically phase-lagged by the time it takes for the vibrational wave to propagate between those points. Normally the vibration pattern of a steel plate is virtually invisible, since the actual deflections are so minute in magnitude, and fleeting in duration. The standing wave patterns in Figure 6 A were made visible by constructive and destructive interference between coherent laser light illuminating the plate, and the light reflected back from the plate, showing deflection in one direction as dark, and in the other direction as light. The dark/light pattern reverses many times each second along with the vibration of the plate, so to capture the pattern photographically, the illuminating light must be strobed in synch with the vibration of the plate, to capture only one phase of the pattern and not the other.

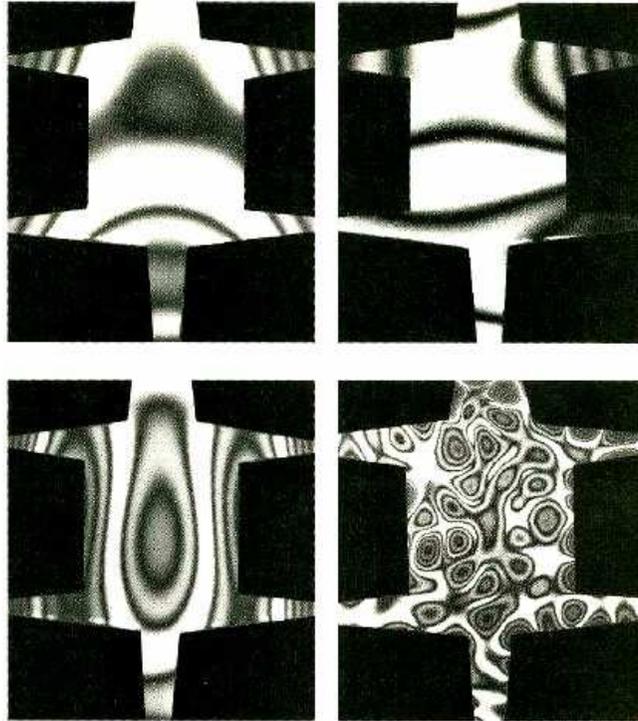


Figure 8. Murray (1988) showed the connection between chemical and vibrational standing waves by replicating the patterns of leopard spots and zebra stripes in the standing wave resonances in a vibrating steel sheet cut in the approximate shape of an animal skin.

Another way to record the patterns of standing waves on a steel plate was devised by Ernst Chladni, back in 1787, illustrated in Figure 9. Chladni sprinkled dry sand or powder on steel plates set into vibration using a violin bow. The sand dances around randomly on the vibrating surface, but eventually settles along the nodes of vibration, the lines of zero vibration that separate patches of the plate that are vibrating in counterphase to each other, thus rendering those node lines visible. Unlike the forced, or driven vibrations of Murray's steel plate, Chladni's bowing with a violin bow energizes the vibration without imposing any particular frequency or waveform on it, so that like a violin string, the plate will automatically resonate at its natural modes of harmonic vibration. This principle of energizing vibrations without imposing a vibration pattern on them, is seen in a wide variety of musical instruments. Different patterns are obtained by touching the plate with a finger at some point, as shown in the figure, which creates a node of vibration at the damped location.

Mary Waller (1961) refined Chladni's technique for producing standing waves in steel plates. Instead of bowing the plate with a violin bow, Waller pressed a piece of dry ice against the plate. As a child she had noticed how a piece of dry ice from

her neighborhood ice cream vendor would make the bell of her bicycle ring with a continuous tone or squeal when the dry ice was pressed against it. The carbon dioxide gas that sublimates from the dry ice in direct contact with the steel, opens a tiny gap between the ice and the steel for the gas to escape, which then slams closed again for each tiny bubble of escaping gas, creating a continuous ringing or vibration in the steel. Different standing wave patterns can be generated on a Chladni plate in this manner by applying the dry ice to different points on the steel plate, by pressing harder to generate higher frequency tones, and by touching parts of the plate with a finger to damp the oscillations at various points. Figure 9 shows three plates, one square, one round, and a third one cut in the shape of a guitar soundboard.

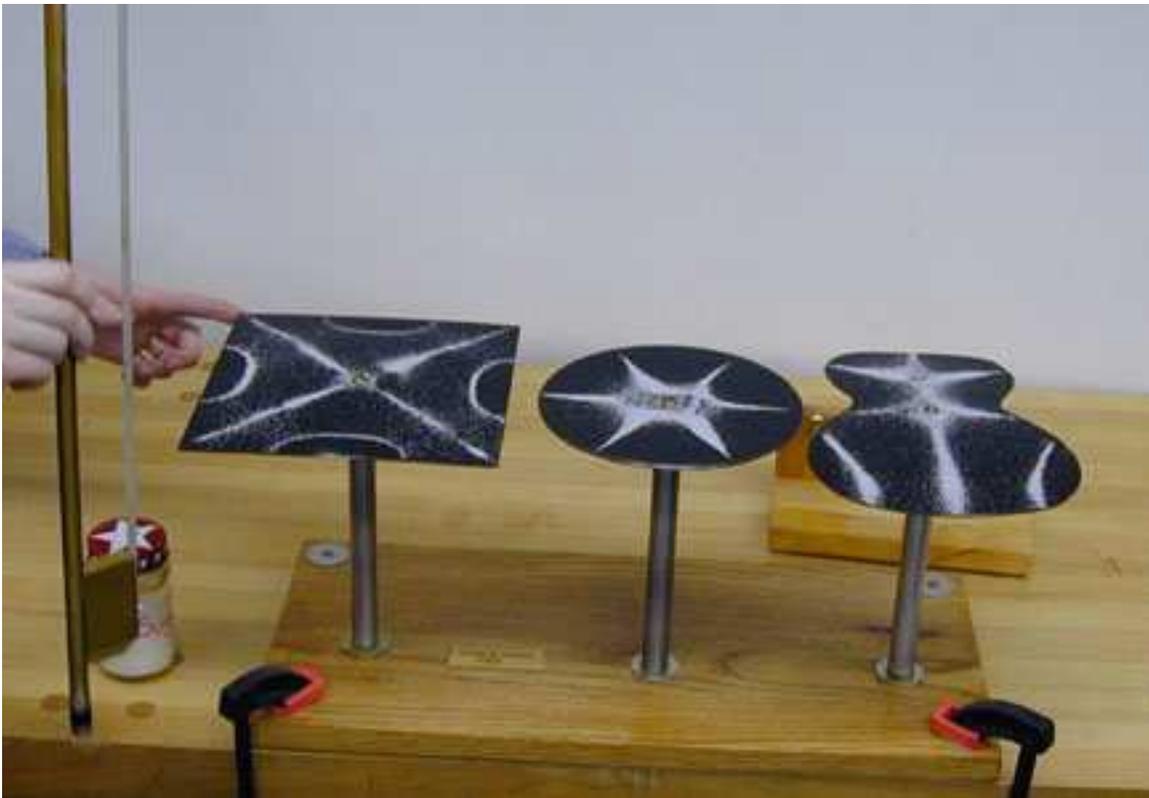


Figure 9. Chladni figures produced by bowing a steel plate while damping the plate with a touch of a finger. The patterns of standing waves are revealed by a sprinkling of salt that settles along the nodes where the vibration is minimal. Three plates are shown, one square, one circular, and a third shaped like the body of a guitar.

Figure 10 (adapted from Waller 1961) shows a variety of standing wave patterns obtained for a square plate that is clamped at its midpoint. The patterns toward the upper-left correspond to lower frequencies of vibration of the plate, whereas the patterns toward the lower right in the figure correspond to ever higher frequencies

of vibration of the standing waves, which requires higher energies of vibration. Every distinct pattern of vibration of the plate shown in Figure 7 corresponds to a distinct and unique frequency of vibration, that can range from a low baritone note, to a high pitched squeal, emanating from the plate as each standing wave pattern appears.

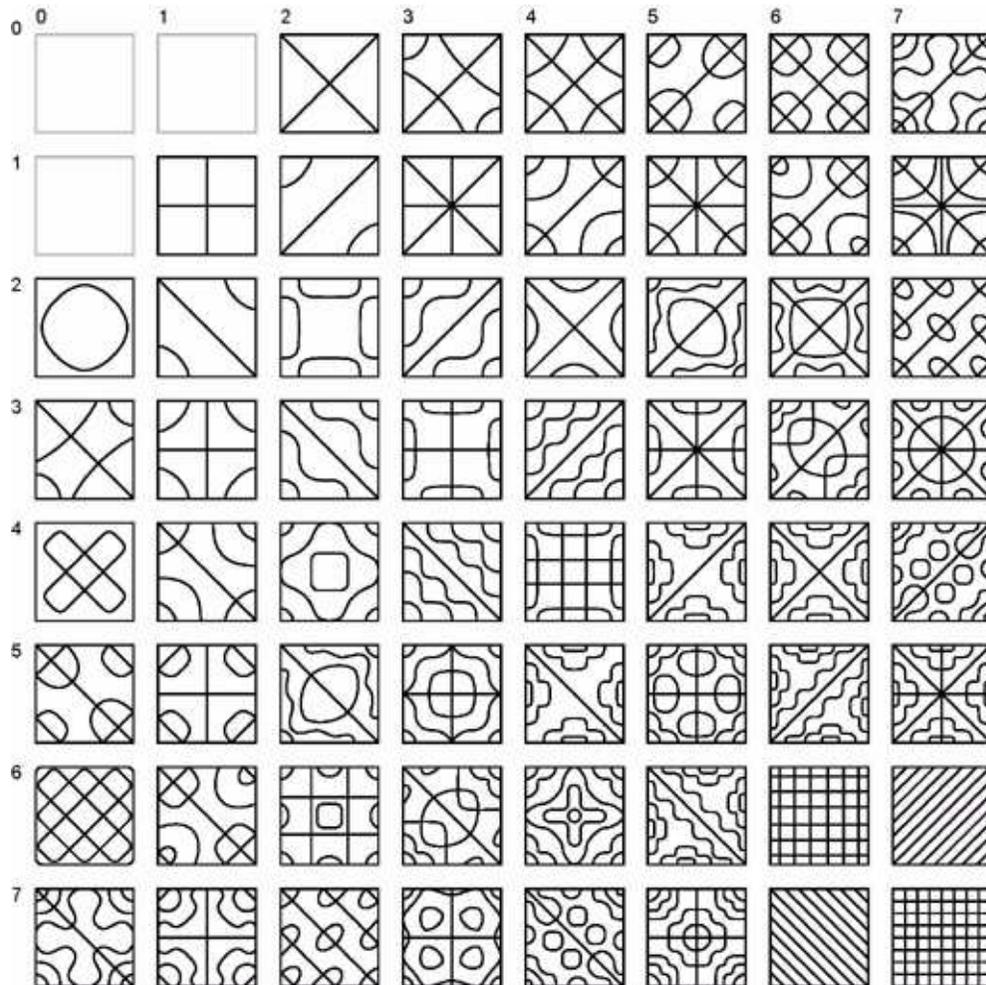


Figure 10. Chladni figures for a square steel plate (adapted from Waller 1961) demonstrate the fantastic variety of standing wave patterns that can arise from a simple resonating system.

The range of patterns observed in Chladni figures depends on the shape of the vibrating plate. Figure 11 shows Chladni figures obtained for a circular plate, with radial and concentric node lines that subdivide the circle into periodic segments.

Chladni figures are the pre-eminent example of emergence. From totally homogeneous medium emerges not one, but a whole family of periodic and symmetrical patterns that are related by integer harmonic relations into a

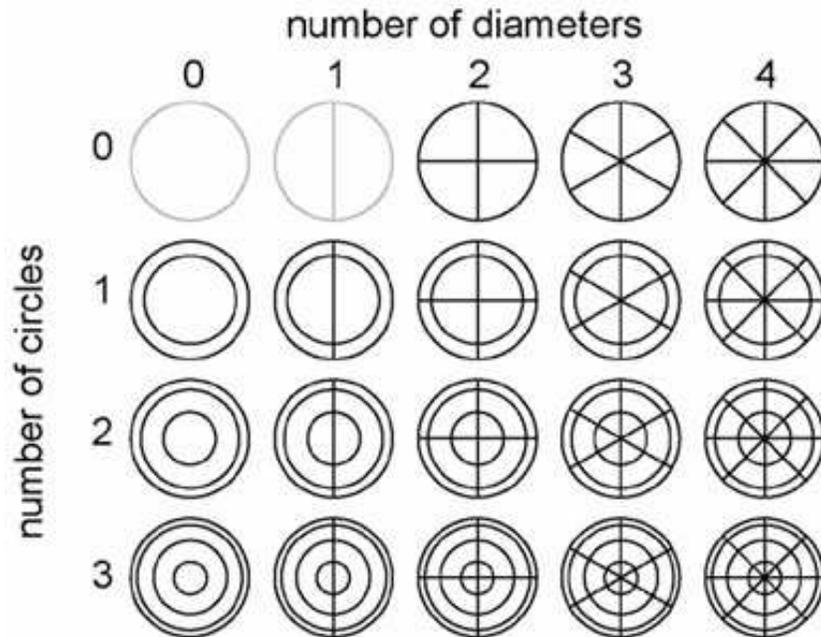


Figure 11. Chladni figures for a circular plate, sorted by number of [diameters, circles] in each pattern. These patterns can appear at any orientation on the plate.

hierarchical family tree, and the geometry of those patterns is not determined so much by the local properties of the resonating medium, as by the global configuration of the resonating system as a whole.

Entrainment and Coupling of Resonances

One of the most remarkable properties of the phenomenon of harmonic resonance is the tendency of resonating systems to couple or synchronize with each other, even when the coupling forces between individual resonances are weaker by orders of magnitude, than the internal forces within each resonator. Christiaan Huygens, who perfected the pendulum clock, discovered the phenomenon in 1665 when he was running two pendulum clocks in parallel for comparison of their timekeeping. Huygens discovered that if one clock ran only slightly faster or slower than the other when hung on opposite walls of a room, those same clocks would run at exactly the same speed when hung two feet apart on the same wall. Not only would they keep the same time, but he found that their pendulums would swing in synchrony, in perfect counterphase, like mirror images of each other alternately approaching and withdrawing. Apparently the tiny vibration caused by the oscillations in each clock was transmitted through the wall sufficient to establish the synchrony between the oscillations through this miniscule synchronizing force. This is the phenomenon of *entrainment*, a central principle of harmonic resonance seen in countless forms throughout the universe.

We see resonance in the way an electron orbits its atom, and how it reacts with different frequencies of light, absorbing and emitting only at a wavelength that harmonizes with its own resonant frequency, imprinting a complex harmonic signature in the emission and transmission spectra of clouds of gas, stars, and galaxies based on their elemental composition. It is a resonance phenomenon that different wavelengths are absorbed very differently by material substances. Low frequency infra-red radiation are absorbed by whole molecules, whereas higher frequency x-rays are absorbed by the atoms of those molecules, and gamma rays are absorbed by the nuclei of those atoms. Resonance is the principle by which radio and television signals which are broadcast at many different frequencies, can be tuned for individually by a radio receiver whose resonant frequency can be tuned to receive only a single channel at a time. And it is a resonance principle that sorts Saturn's rings into patterns of bands, and that distributed our planetary orbits to follow Kepler's law, whereby the *squares* of the periods of the planets are proportional to the *cubes* of their semimajor axes. In all of these examples of entrainment of oscillations, we see a miniscule force, applied repeatedly at just the right frequency to an oscillator system, to produce a quite considerable response.

Resonance also comes in more complex compound form with coupled oscillators. For example if two or more pendulums are hung from a horizontal cross-string, then their motions will be weakly coupled by the cross-string. If one pendulum is set to swinging, then the tiny coupling force will slowly set the next pendulum to swinging faster and faster, even as the first one goes ever slower and slower, until eventually the second pendulum will be swinging at full amplitude and the first one has been brought to a complete standstill, at which point the situation reverses, and the first pendulum gradually robs energy from the second until the original condition is restored. This pattern can continue indefinitely, each pendulum taking turns in a cyclic sequence. If there are four pendulums hanging from the cross-string, then there are several different characteristic modes at which they can oscillate. They can all swing in unison, like a single virtual pendulum. Or they can swing in pairs, with the first two in phase with each other, and in counterphase to the last two. Or they can swing in alternate pairs, the first and third swinging against the second and forth. These are the natural modes of four coupled oscillators, each of these patterns is stable, that is, it will continue indefinitely if once set in motion, at least in the absence of frictional losses, or if the oscillation is amplified. So again, we see emergent complexity arising from a very simple system of identical oscillators, natural patterns of complex behavior in the

absence of any explicit pattern generation mechanism. In mechanical systems like a car engine, this kind of pattern of sequenced motion is often enforced by cams and push rods, like those that control the valves to open and close at the proper time for each cylinder. In computer algorithms patterned sequences of this sort are usually achieved by loops and counters and logical IF statements. In either case, the complexity of the sequencing mechanism or algorithm is of the same order as the complexity of the pattern of motions that it generates. Emergence is a natural property of harmonic resonance, whereby a very simple homogeneous mechanism composed of identical units can generate patterns whose complexity far exceeds the complexity of the mechanism that generates them. And it is that property of emergence which explains why nature makes use of harmonic resonance as its central pattern formation mechanism in space and time.

I propose that it is harmonic resonance that couples the electrical activation across the whole brain into a single synchronized harmonic oscillation, in which individual specialized brain areas each contribute their component of the oscillation. But the resonance in every brain area is instantly and immediately influenced by the resonance in every other brain area simultaneously, like the different parts of a musical instrument sharing the vibration of a note being played. The vibration is like a ghostly pattern superimposed on the tissue of the cortex, although moving somewhat independently of that tissue, so as to be near invisible to a tissue-anchored electrode, manifesting itself only as an otherwise mysterious synchrony between distant cortical regions. It is this synchrony, the holistic emergent intercoupling of innumerable parts into an integrated whole, that is the explanation for the unity of conscious experience, for the simultaneous and parallel experience of our visual field, our body field, and the space around us, all at once and in fixed relation to each other in a single space. This is how the unity of experience can be resolved with the apparently fragmentary architecture of the cortex, with its specialized areas tuned to individual modes and modalities. Specialized cortical areas do not process their data independently in an input-output fashion, and then transmit the result back to Central Control, as in a computer algorithm, but rather, each cortical area is like a resonator tuned to enhance or amplify the particular feature for which it is tuned, whether a spatial pattern in vision, or a temporal pattern in music or audition, or a spatiotemporal pattern in somatosensory and motor representations. When that area resonates with a recognized feature, an echo of that resonance is felt in every other cortical area, each of which resonates with their own contribution to the global resonance shared by them all, in the same way that the vibrational resonance at every point

in a guitar is influenced by a finger pressed against a single string as it vibrates. This was the principal message of Gestalt theory: that the unity and coherence of experience implicates a unitary and coherent principle of perceptual computation in the brain, and harmonic resonance is that principle of organization in the brain.

The spatiotemporal coupling between cortical areas in the brain is analogous to the coupling between various parts of a Chladni plate. For example pattern [0, 7] (expressed as [row, column]) in Figure 10 appears as two copies of the same pattern reflected across a diagonal symmetry axis, and that is because the standing waves of those two portions of the steel plate are exactly in this kind of symmetrical counterphase, exactly mirroring and thus balancing each move of the other, like two mirror-image copies of the same dynamic pattern.

Computational Function Served by Neural Standing Waves

How can harmonic resonant standing waves serve a computational function in the brain? What kind of things can resonance compute? The answer to this question can be found in one of the simplest single-celled organisms from the lowest branches of the evolutionary tree, the *paramecium*. The single-celled Paramecium has little hairlike cilia around its tiny cigar-shaped body, and it waves those cilia in synchronized waves from the head toward the tail, as shown in Figure 12 A, in order to propel itself forward through the water. This global synchronized pattern reveals the presence of global waves of energy propagating down the body of the Paramecium, as suggested in Figure 12 B, and those waves perform a vital integrative control function that synchronizes the motions of the many individual cilia to a globally coherent motor plan. The paramecium is capable of swimming faster or slower, steering in different directions, and when it gets stuck in a blind alley, it can reverse its swimming movements and back out, and turn aside to set off in a new direction. The integrated lawful behavior of this dynamic travelling wave structure is the living soul that animates lifeless tissue with patterns of willful motion. It is a dynamic spatial structure that appears as if out of nowhere, is composed of nothing but patterns of energy, and it disappears without a trace when the tiny creature dies, leaving a lifeless corpse that is not even the tiniest microgram lighter for the loss of its living soul. And yet while the creature is alive, it fairly pulses and throbs with vibrant energy in regular structured patterns of coherent motion under a kind of intelligent or directed control.

The same kind of synchronized waving of cilia is seen also in multi-cellular creatures like jellyfish. Ctenophora, or comb jelly, is a simple creature with a decentralized nervous system, and the comb jelly uses the same synchronized

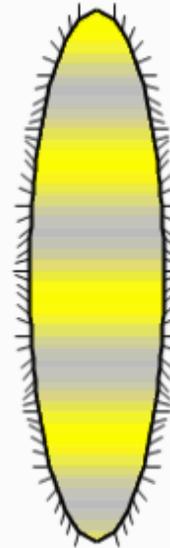


Figure 12. A: The paramecium is a single-celled organism covered with tiny microscopic hairs called cilia, that it uses for locomotion. B: The cilia beat in synchronized waves from head to tail, revealing waves of synchronized activation sweeping across the tiny creature's body.

waving of its cilia for propulsion as does the paramecium, only implemented at a very much larger multi-cellular scale. The waves of contraction sweep along the body of the creature as it swims, and in some species these waves of contraction are accompanied by waves of glowing bioluminescence that sweep over the creature's body, a visible trace of the electrochemical waves that control the propulsive undulations of the cilia, revealing the tiny creature's "motor thoughts", that stream endlessly like the moving letters on an old fashioned theater marquee. This same principle of synchronized waving of cilia exists also in the lining of our own trachea, where the cilia serve to waft mucus and trapped dirt upward from our lungs. The waves of contraction and extension of the cilia stream through the tissue that sustains it without respect to the boundaries of the cell wall.

Similar global patterns of alternating contraction and extension are seen in larger and more advanced animals, such as swimming snakes or eels, like the one shown in Figure 13 A. , The motor pattern of a swimming eel clearly appears as a travelling wave propagating continuously from head towards tail, periodic in space and time. At any one moment, the pattern is defined by a sinusoidal alternation between equally spaced regions of contraction and regions of extension, as shown in Figure 13 B, where the cylinder represents a map of the eel's quasi-cylindrical body, and the different shades represent regions of contraction and extension mapped to the body. Regions of contraction on one side of the body are balanced by regions of extension on the opposite side of the body, creating

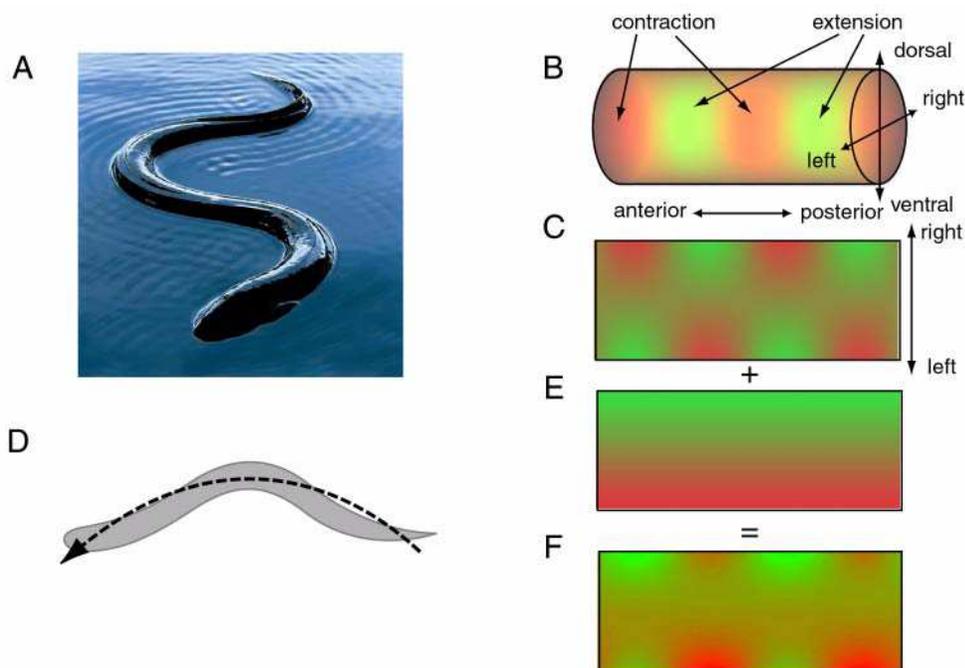


Figure 13. A: The motor pattern of a swimming eel takes the form of waves of contraction and extension on opposite sides of the body, and these waves stream continuously from anterior towards posterior.

polarity-reversed patterns of contraction and extension across the body midline, as shown in the top view of the motor pattern in Figure 13 C. The eel's motor pattern exhibits a perfect symmetry, or balance across the body midline, with a smooth and continuous change of body tension as a function of spatial location. And every instant this pattern translates continuously from anterior toward posterior, like the travelling waves in a rope when one end is shaken up and down vigorously. This dynamic sinusoidal symmetrical pattern is the required "output" of the motor computations of a swimming eel, in order to account for the observed sinusoidal flexion of the body.

The eel can also steer its body in smooth curves left or right, as suggested in Figure 13 D, and also up and down, while still maintaining its sinusoidal propulsive undulations. In order to achieve this, the eel's motor pattern must combine the propulsive undulations of Figure 13 C with a superimposed steering pattern as shown in Figure 13 E, where the motor pattern to steer left is expressed as a contraction along the entire left side of the body, and a symmetrically opposed extension on the right side. This uniform lateral gradient is combined with the propulsive undulations to produce a compound or combined motor pattern shown in Figure 13 F. Note how the periodic regions of contraction are amplified on the

left side and diminished on the right, and vice-versa for the regions of extension. More generally, each component of the motor pattern, propulsion faster or slower, steering left or right, and steering up or down, can be controlled independently, and yet they are all combined in such a way that each muscle knows exactly how much to contract or extend depending on its location within the global motor pattern at each instant in time. This poses a formidable computational challenge for any paradigm of motor control. It just so happens that standing waves in a cylindrical resonator or acoustical cavity, have exactly these kinds of periodic symmetrical patterns, and standing waves naturally tend to combine in exactly this manner to produce compound patterns. The ability of snakes and lizards to freeze in the middle of any serpentine motion, and to hold that posture rigidly, clearly demonstrates that the brain can sustain static motor patterns at will, a standing wave rather than a cyclic travelling wave phenomenon. Harmonic resonance has that property also, that is, a natural tendency to form patterns of standing waves, expressed in periodic and symmetrical primitives or basis set.

The necessity for a pattern generating function in motor control is nowhere more evident than in some of the surprisingly complex behaviors observed in creatures with the simplest unstructured nervous systems. For example consider the hydra, a tiny microscopic organism with a simple network for a nervous system, somewhat like a fishnet stocking that extends uniformly across the creature's body and around each tentacle. The primitive synapses that form between these neurons transmit activation in both directions, so that stimulating the tiny organism at one point creates waves of activation spreading outward from that point, like the rings in a pond when a stone is thrown in, as depicted in Figure 14 A. And yet, with this simple unstructured nervous system the hydra performs some pretty remarkable motor patterns. When it snags food with one of its tentacles, it knows which side of the tentacle to contract more, in order to steer the food toward its mouth, and it knows to open its mouth in anticipation, as suggested in Figure 14 B, and to close it again after engulfing the food. The hydra also performs peristaltic contractions that propel the food down toward the foot, and reverse contractions to expel the undigested remains back out of its mouth. The hydra is also capable of a kind of somersaulting locomotion depicted in Figure 14 C, where it contracts all the muscles on one side of its body and tentacles, leans over and grabs the ground, then it reverses its pattern of contraction and extension to flip upside-down overhead in a somersault, and it repeats this extension / contraction grab / release periodic cycle of motor pattern to travel along a solid surface. How, but for some kind of standing wave model, could a simple unstructured nervous

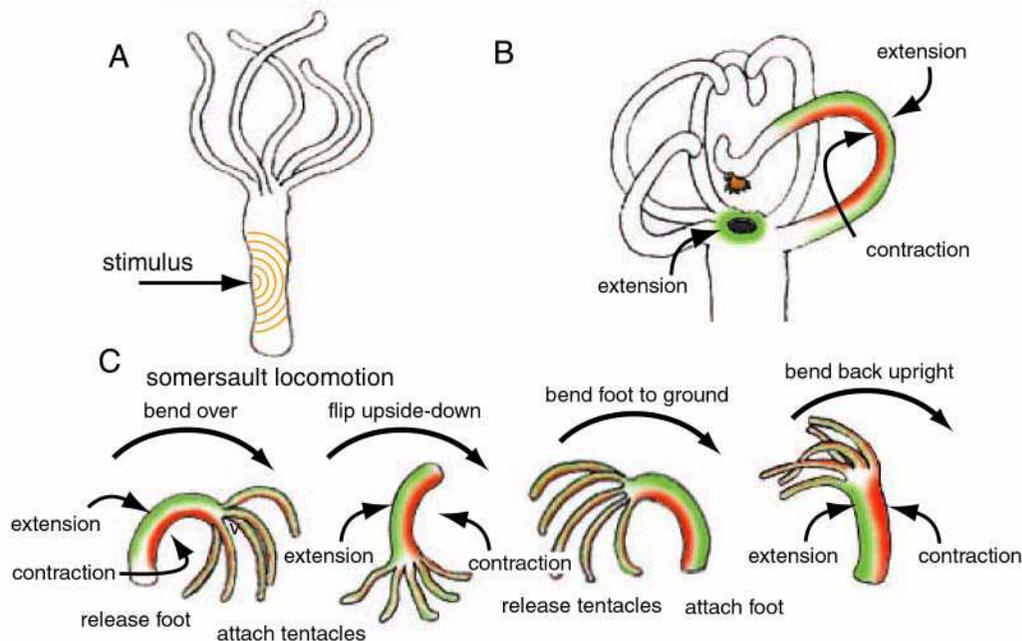


Figure 14. A: The uniform network of a hydra's nervous system propagates electrical activity out in all directions from a stimulation point, and yet this unstructured nervous system is capable of some rather sophisticated spatial behavior such as B: steering captured food from a tentacle into its mouth, which it opens in anticipation, and C: the hydra is capable of a somersaulting kind of locomotion that requires alternating regions of extension and contraction of its body.

system composed of a uniform network of undifferentiated cells, possibly generate such a rich repertoire of motor behavior? The synchronized waving of tentacles, so commonly seen in the simplest animate creatures, is a give-away clue to the wave-like nature of that computational principle. More clues to the harmonic resonance nature of motor patterns is seen in the periodic / symmetrical cycle of the legs of a walking centipede, and the periodic mirror-symmetric stepping motions of a six-legged insect. And evidence for harmonic resonance is seen even in the motor patterns of mammals. Strogatz & Stewart (1993) show that the various gaits of four-legged creatures, for example the trot, canter, and gallop of a horse, correspond to the various modes of oscillation of four coupled oscillators, while the gaits of bipedal creatures correspond to the modes of two coupled oscillators.

The alien visitor to earth, on seeing the rhythmic galloping of a horse, the periodic undulations of an eel, or the tiny waves of cilia on a paramecium, would immediately recognize that we and our fellow fauna employ a harmonic resonance principle of motor control. But then of course, that is what the alien

would probably have expected, given that it too is most likely controlled by a harmonic resonance motor principle.

Harmonic Resonance In Sensation and Perception

The powerful integrative capacity demonstrated by harmonic resonance in motor control is just as useful in sensation and perception too, where a spatial world is modeled using some kind of spatial representation. How are the individual sensory stimuli for example from the countless photosensitive cells of the retina, meaningfully integrated into a perceptual picture of the world? Hashemiyoon et al. (1993) have measured rapid electrical oscillations in the retina whose waveform is modulated by the visual input. I propose that these oscillations are a manifestation of standing and/or travelling waves across the retina which are an essential component of the mechanism that encodes the visual world in a meaningful code. I propose that the retina functions somewhat like a Chladni plate, with a natural tendency to sustain standing waves of electrochemical oscillation across the retinal surface to represent static patterns, and travelling waves to represent dynamically moving or cycling patterns. The visual input on the retina serves to modulate those standing waves so as to produce standing wave patterns that conform to the pattern of light projected on the retina, as a spatial effigy of that stimulus pattern constructed of standing or travelling waves. Unlike the individual sensory signals detected by the innumerable rods and cones, a standing wave is not a mere assembly of parts, but a highly integrated holistic Gestalt structure that cannot survive the elimination of any of its component parts without radically altering its form, because the structure of a standing wave is a continuing and sustained dynamic balance between mirror-image portions of the wave colliding and rebounding cyclically against each other.

The standing waves on a Chladni plate are controlled or modulated by damping the vibrations at different points with a touch of a finger. I propose that the visual input serves this damping function, damping the vibrations along the boundaries or contours detected in the image, dividing the image into contrasting regions of figure and ground, represented by regions of opposite polarity of the standing wave. For example an image of a white square on a black background would be represented by a standing wave of the same shape, with a positive square on a negative background, alternating cyclically with a negative square on a positive ground as a spatial standing wave. The nodal contour serves as the eigenfunction of the image pattern, the line along which the image is neither white nor black, just as in the standing wave it is neither positive nor negative, but serves as a pivot

about which the positive and negative regions alternate. As in the patterns of motor control seen in the cilia of the paramecium, the standing wave becomes a distinct spatial entity energized and sustained by the retina, but existing as if in a separate plane of existence than the physical mechanism that sustains it, with its own integral pattern of internal structure and dynamic logic. It is the dynamic logic of standing wave resonances that account for the Gestalt laws of perceptual grouping.

Sensation involves a mere recording or replication the pattern of the stimulus, whereas perception involves a recognition or understanding of the structure of that stimulus, an intelligent analytical function. The standing waves in the retina serve as the first stage of this analytical function, and it is for that reason that vision is particularly sensitive and responsive to periodic and symmetrical patterns, which is why we paint items in starkly contrasting periodic patterns when we want them to be most visible, like the stark barber-pole stripes on a railroad crossing barrier, or the black and white pattern of the “checker flag” used in auto racing, or the vertical stripes of an umpire’s uniform, and so forth.

The resonance seen in the Chladni figures also offers a clue as to how the standing wave patterns are recorded or registered in the brain in a meaningful code. Every unique Chladni plate figure is associated with a characteristic frequency and waveform, composed a fundamental frequency and a pattern of higher harmonics, and every time that pattern appears on the plate, its characteristic voice is also to be heard. Furthermore, if a pattern’s characteristic tone is played in the presence of the Chladni plate, it will have a tendency to vibrate the plate in sympathy with that tone, thus recreating the original standing wave pattern back on the plate. I propose that the relation between a Chladni figure and the harmonic waveform or musical chord heard whenever that figure is present on the plate, is the same relation seen in visual recognition between a pattern in our experience, and our perceptual or cognitive recognition of that form. If spatial experience is constructed of spatial standing waves in the brain, the presence of any recognizable shape in our experience will be accompanied by the characteristic tone of that pattern due to the vibration of the sensory standing wave, and it is by that tone that the shape is registered as a familiar shape in the brain.

Visual recognition is often described in neural network models as the “lighting up” of a node, or neuron in the brain, in response to the presence of its characteristic pattern in the visual stimulus. Although this “grandmother cell” or “feature

detector” concept of visual recognition is now largely discredited, at least in its most simplistic form, no clear alternative has been proposed for the essential principle behind visual recognition, and the neurophysiological literature is still replete with references to feature detector cells and their supposed receptive field profiles. The acoustical tones associated with the Chladni figures offers an alternative model of visual recognition. The “feature detector” nodes in the Chladni plate model can be conceived as a bank of tuned resonators set up near the plate. Like a “grandmother cell”, each resonator will spontaneously resonate, or “light up,” whenever its particular pattern is present on the plate. There is a *dimensional reduction* that occurs between the two-dimensional spatial pattern that appears on the plate, and the one-dimensional activation of the resonator that reacts to that pattern, like the reduction between a two-dimensional stimulus pattern and its corresponding “grandmother cell” feature response. But the resonator does more than merely register the presence of its pattern on the plate. What makes the resonator a *meaningful* representation of that pattern is its ability to regenerate its characteristic pattern on the plate, which it does spontaneously and automatically simply by vibrating at its characteristic frequency. The mere activation of a resonator, an essentially one-dimensional event, expands into a two-dimensional standing wave, due to the automatic reification of the spatial standing wave from the simple resonant tone. It is this *constructive*, or *generative* function of visual perception that is prominently absent from so many theories of visual recognition.

Aesthetic Resonance

There is another factor that would be immediately apparent to the alien visitor to Earth, to which we humans seem to have a peculiar blindness, and that is a basic symmetry and periodicity across a vast range of human aesthetic creations, from music, to dance, to ornamental patterns, Gothic cathedrals, Islamic mosques, churches and palaces everywhere. Some of this symmetry can be accounted for by engineering considerations that favor the regularities of a an arch, dome, or vault, as well as of straight planar walls with right-angled corners, and flat floors laid with arrays of identical tiles. But great places of worship take symmetry and periodicity far beyond mere functional necessity and turn it into a joyous celebration of symmetry and periodicity for its own sake, in both simple, and compound hierarchical form. So many of the articles that we make or use are decorated with periodic and symmetrical patterns in both simple and compound hierarchical forms. We decorate our clothing, our wallpaper, pots, and vases, with all kinds of periodic and symmetrical patterns, especially objects of particular religious or ceremonial significance, such as crowns and scepters, crosses and

chalices, cutlasses and candelabras. And even those patterns that we enjoy for their simplicity, such as the circle, the ellipse, the heart shape, the equilateral triangle, the regular hexagon, it is their regularity that we enjoy, because the lawful elegance of a regular curve reflects a more general concept of symmetry as a continuation of the same pattern by the same rules. And the periodicity of a polygon is seen in the rotational periodicity of its vertices, the most primal polygons being those with the smallest number of vertices, such as squares and triangles, or no vertices at all, like the circle. And there is periodicity evident at the core of our number system, the periodicity of the concept of number itself, an item that cycles endlessly in identical units that are counted in groups of tens, and then tens of tens, and tens of tens of tens, in a hierarchical pattern that is directly borrowed from the principles of harmonic resonance itself. The concept of the rational fraction, like the subdivision of the unitary interval into the equal intervals of halves, quarters, eights, and sixteenths, or into tenths, hundredths, and thousandths, corresponds directly to the higher harmonics of a fundamental resonance, as seen for example in the standing waves in the body of a bugle as different notes are blown. Only an alien to human culture is likely to notice this pervasive appearance of symmetry and periodicity in human affairs, exactly because it is so pervasive and ubiquitous that we don't even notice it as anything special at all.

Figure 15 shows a variety of ornamental patterns from a variety of different cultures and historical periods, showing the common principles of symmetry and periodicity in simple and compound hierarchical forms. The alien visitor, on seeing these kinds of patterns throughout human art and architecture, would immediately conclude that humans have *harmonic resonance* brains, that is, our brains operate by generating periodic and symmetric patterns of standing waves across the neural tissue, and those standing waves are the principle by which spatial structure is represented and experienced in the brain.

Another manifestation of harmonic resonance in human affairs is seen in human music, with its harmonies and melodies and rhythms, patterns of symmetry and periodicity across tone and time, in both simple and compound hierarchical forms. Music is nothing other than an elaborate system of resonances of resonances of resonances in fantastically complex hierarchical arrangements. Even the basic tones of which music is composed, a sustained note on a bugle, or a violin, or didgeridoo, sounds beautiful to our ears, and that beauty is the beauty of raw resonance itself. Pairs or triplets of tones that are *consonant*, that is, they sound

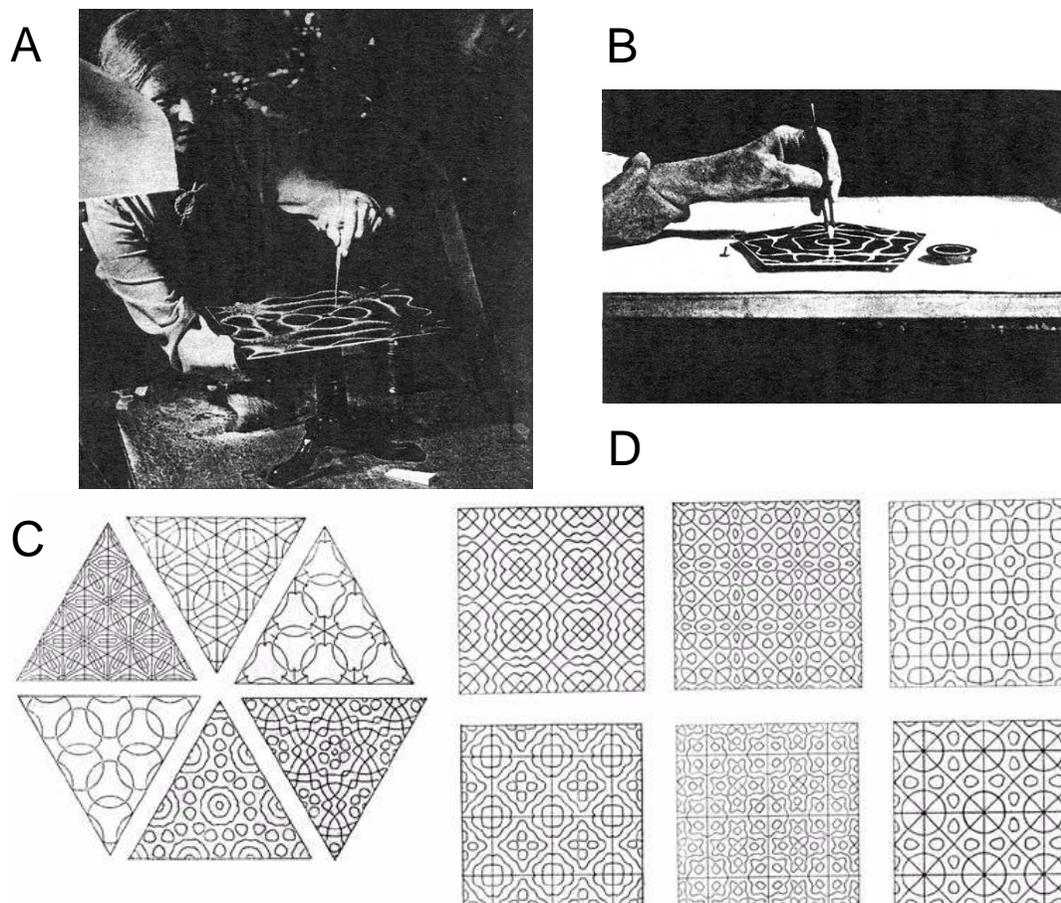


Fig. 16. A: Mary Waller creating an ornamental Chladni figure by pressing a piece of dry ice held in tweezers against the plate. B: A Chladni figure on a pentagonal plate. C and D: Ornamental standing wave patterns on triangular and square plates respectively. Photographs and Chladni figures from Waller (1960).

The existence of human music is perhaps the most convincing evidence for a harmonic resonance theory of brain function. The same ratios that we find pleasing aesthetically, are the very ratios on which our number system is based, and the same kinds of ratios extended into three dimensions correspond to the architectural and sculptural proportions that we consider aesthetically to be pleasing and balanced and harmonious. The connection between music and human behavior can be seen by the effect that human music has on human behavior. Music tends to make us gyrate and oscillate in periodic and symmetrical motions in both simple and compound hierarchical patterns. It would take an alien visitor to notice those aspects of our nature that are so common and pervasive throughout every culture and throughout history, because we humans have become so habituated to these prominent characteristics of human aesthetic preference that they are almost completely invisible to us. We simply take it for granted that periodic and symmetrical patterns are intrinsically beautiful. It needs

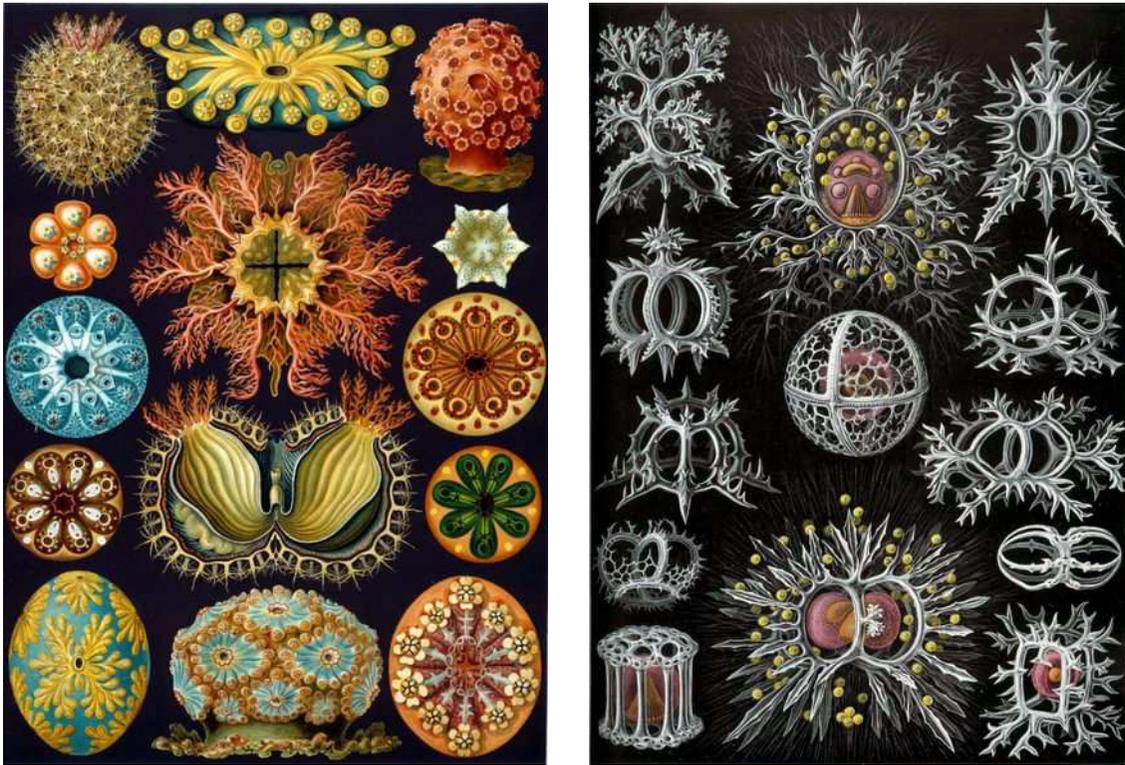


Fig. 17. Two of many pages from Ernst Haeckel's breathtaking book *Kunstformen der Natur*, revealing a profoundly ornamental, and aesthetically pleasing aspect of simple life forms. We now know that the periodicity and symmetry of these body forms is itself a consequence of a chemical harmonic resonance.v

neither to be proven nor justified, it is just how things are. And we think nothing is strange when a person in our company suddenly gets up and starts gyrating wildly in compound oscillatory motions, with their face screwed into expressions of extreme agony or ecstasy, just because they hear patterned vibrations in the air. We just turn aside and sip our drink, or jump up and join them, as if this were the most normal behavior in the world. But in fact this wild profusion of symmetry and periodicity throughout human affairs is very telling of the foundational principles behind how our brains operate, just as the symmetries and periodicities in our bodies are telling of the mechanism of embryological morphogenesis.

The reason why beautiful music sets our body into motion is because music is the language of the brain. It is what integrates the millions of individual brain cells into a single unified resonance, resulting in a unified global experience in the form of spatial patterns in our brains. The individual neurons are doing very much what human dancers do when they all dance to the same tune. The cells all begin to oscillate electrically in a synchronous global wave that unites the individual activations into a larger global wavelike entity that emerges, as if out of nowhere, across neural tissue in beautiful periodic spatial patterns, paying only the scantest

heed to the barrier of the cell wall. The lawful geometry of the standing wave patterns in the brain is very much like the patterns seen in visual ornament, with basic elements repeated in periodic and/or symmetric patterns of infinite variety, whose elements are defined by the more general symmetry of the line, the circular arc, the right angle, sinusoids, zig-zags, crenellations, and other lawful patterns of lines and curves. And the patterns in the brain are also similar to the patterns in mathematics and in music. It is a pattern that requires energy for its construction, and releases energy in its destruction. But it is a spatial structure that is composed of nothing but energy, magically superimposed on the physical tissue of the brain. This is the "ghost in the machine", the substance of *mind*, that peculiar, immaterial substance that pops spontaneously into existence in a waking brain, like a note from a horn when it is blown, and disappears again without a trace when we fall asleep, like a horn resting silently in a corner.

Universal Resonance

One of the most profound discoveries of modern science has been the fundamentally wave-like nature of matter, and the fact that matter and energy are mutually inter-convertible. The fundamental particles of matter, protons, neutrons, electrons, are now conceived of as standing waves, whose discrete nature is a manifestation of the discrete nature of resonance itself. Electrons are not point-like particles in orbit around the nucleus, but waves that occur only at those radii or in those configurations in which they interfere with themselves constructively. A particle is like light that is trapped in a feedback loop, going round and round, or back and forth, indefinitely about the same point. It is harmonic resonance that provides the structural patterns of matter. For example electron orbitals come in different modes, based on different standing wave functions, as shown in Figure 18. The spherical-symmetrical *S-mode* atomic orbitals define a series of concentric spherical shells, a radial in-and-out resonance that is isotropic, the same in all directions, as shown (in cross-section) in Figure 18 A. The sun and other stars breathe in and out radially in this manner, oscillating about an equilibrium level determined by the dynamic balance between the outward blast from the nuclear furnace at the core, and the weight of gas pressing inward. The *P-mode* orbitals define standing waves going back and forth across the center in one dimension, as shown in Figure 18 B, with compression in one direction balanced by expansion in the other. A baseball experiences this kind of oscillation immediately after contact with a bat, as the compression wave from the struck side propagates to the opposite pole and back, alternately compressing and expanding the two hemispheres in counterphase to each other. The higher

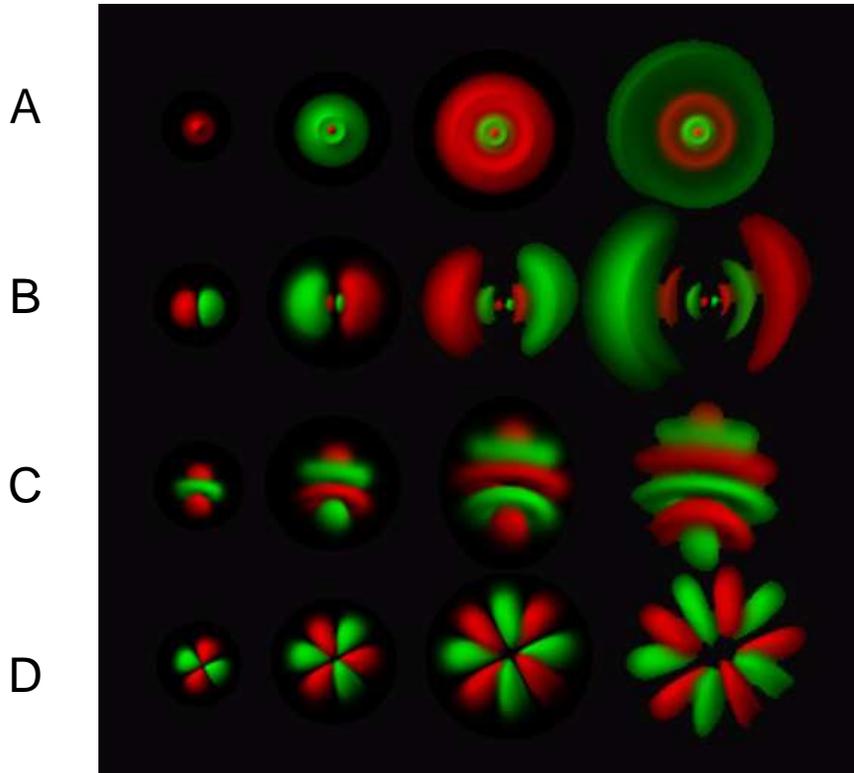


Fig. 18. Various modes of atomic orbitals. A: The s-mode is a concentric in-and-out vibration (cross section). B: The p-mode is a lateral vibration across one dimension. C: The d-mode orbital is equatorial/polar, like the lines of latitude on a globe, and D: the f-mode is a circumferential or equatorial resonance, like the lines of longitude on a globe.

harmonics of this resonance add additional layers in periodic alternation. The *d-mode* orbitals shown in Figure 18 C represent an equatorial/polar oscillation, with motion from the equator towards the poles, alternating with motion from the poles back toward the equator. The higher harmonics of this oscillation create more alternating layers of reciprocating motions like the lines of latitude on a globe. And the *f-mode* orbitals shown in Figure 18 D define a circumferential resonance running around the equator, creating an alternating pattern like the lines of longitude on a globe. Atomic orbitals are wave functions that are characterized by a perfect symmetry of positive and negative regions, periodically distributed across some dimension. These are the patterns taken on by electrons in orbit about a charged atomic nucleus, but they are also the patterns observed in falling droplets, or flying baseballs, or stars and planets, when they rebound and recoil after energetic collisions. They all exhibit a remarkable self-organizing tendency to spontaneously sub-divide the space of their possible motions into periodically and symmetrically arranged alternating volumes, with exactly balanced reciprocating motions.

Harmonic resonance is *the* preeminent organizational principle of matter and energy in the universe. Like life itself, harmonic resonance represents a rare example where the *entropy* or disorder of a system is not increased, but is actually reduced with the onset of resonance, a spontaneous emergence of ordered spatial pattern out of a high entropy homogeneous medium. Harmonic resonance is the force that binds waves into particles of matter, and it is the harmonic resonance of chemical bonds that lock particles into bulk material substance. The octet rule that makes atoms swap or share electrons in an attempt to form complete outer shells, is itself a resonance phenomenon. A planet spinning on its axis is a kind of round-and-round pendulum, a rotational resonance with the surrounding universe, as is the orbit of a satellite around its planet, which can range from a near circular orbit to an extreme back-and-forth pendulum motion. Harmonic resonance is the force that organizes planets in their orbits, and stars in their galaxies. And it is harmonic resonance that binds the individual activations of countless billions of individual neurons into the coherent integrated framework of experience and willful action that we call Mind.

