Chapter 1

Shell patterns - a natural picture book to study dynamic systems and biological pattern formation

1.1 Dynamic systems everywhere

Everyday we are confronted with systems that have an inherent tendency to change. The weather, the stock market, or the economic situation are examples. Dramatic changes can be initiated by relatively small perturbations. In the stock market, for instance, even a rumour may be sufficient to trigger sales, lowering quotations and causing panic reactions in other shareholders.

An essential element of dynamic systems is a positive feedback that self-enhances the initial deviation from the mean. The avalanche is proverbial. Cities grow since they attract more people, bacteria or viruses can replicate and the progeny start replicating too. In the universe a local accumulation of matter may attract more dust, eventually leading to the birth of a star.

Earlier or later self-enhancing processes evoke antagonistic reactions. A proliferating virus may trigger an immune response that neutralizes the virus. A collapsing stock market stimulates the purchase of shares at a low price, thereby stabilizing the market. The increasing noise, dirt, crime and traffic jams may discourage people from moving into a big city.

In addition to the balance between self-reinforcing and antagonistic tendencies, several other elements play a decisive role in the fate of dynamic systems. For instance, if the antagonistic reaction follows with some delay, the self-enhancing reaction can cause an overshoot or even an explosion. The explosion of dynamite is a good example. After ignition of a small portion the resulting heat and the shock wave ignite more of the explosives in the neighborhood. The reaction is so vehement because the oxygen required for burning is part of the chemical and is available immediately. Thus, no antagonistic effect slows down the reaction until the explosive is used up. Of course, afterwards a further ignition is impossible.

But let us consider a fire. Fire is also a self-enhancing process since more heat releases more burnable gases from the fuel. But the depletion of oxygen may represent an antagonistic reaction that keeps the fire down to the point that only smouldering is possible. In such a case, the rapid antagonistic reaction, the oxygen

H. Meinhardt, *The Algorithmic Beauty of Sea Shells*, 4th ed. The Virtual Laboratory,
DOI 10.1007/978-3-540-92142-4_1,

depletion, hinders the development of a big fire. The burning process can go on for a much longer period although at a lower level. Thus the ratio of reaction times between the self-enhancing and the antagonistic processes plays a decisive role.

Another example should illustrate the same fact. As a rule, it takes about two days to fully develop an influenza but it takes about a week to get rid of it. Thus, it appears that our immune system responds too slowly when compared with the growth rate of the virus. Initially the virus proliferates in an avalanche-like manner and we become sick. But what appears at first as a misconstruction turns out to be an advantageous strategy. The slower responding immune system accumulates more and more specific antibodies until the entire virus can be trapped. The body can completely rid itself of the virus. If the immune system responded much faster, a balance between the proliferating virus and the immune system would be established at a lower level. The body would have to fight for the rest of its life against the ever proliferating virus since partial removal of the virus would lead to a corresponding down-regulation of the immune response, providing a new chance for the virus. With the system as it is, we are sick for a week, but after this week we are healthy again and free of the virus.

1.2 Pattern formation

Another decisive parameter in a dynamic system is the spread of its components. In the example mentioned above, the virus may be transmitted to another person who will also become sick after some delay. The infection spreads like a traveling wave. This spread is possible only since the self-enhancing agent, the virus, but not the antagonistic reaction, the immune response, can be transmitted to another individual.

In other systems, it is the antagonistic reaction that spreads more rapidly, and this can lead to stable patterns. Let us regard the formation of sand dunes in the desert (Figure 1.1). Dunes are formed despite the fact that the wind very quickly redistributes the sand. Dune formation may be initiated by a stone in the desert that provides a wind shelter. Sand accumulates behind the wind shelter, and a dune begins to grow. But the sand, once settled in the dune, cannot participate in dune formation somewhere else. The growth of a dune lowers the sand content in the air. The antagonistic reaction results from this removal of sand particles being moved by the wind, and has a long range effect. In this way, the probability of initiating new dunes and the growth of existing dunes in the surrounding area is reduced. In contrast, the increased accumulation of sand behind the wind shelter has a range comparable with the size of the dune. Thus, the basic elements for the formation of stable patterns are a short range self-enhancing reaction and a long range antagonistic reaction.

A similar argument can be made for the formation of valleys and rivers by erosion. The pattern of a ramified river system is certainly not preceded by a