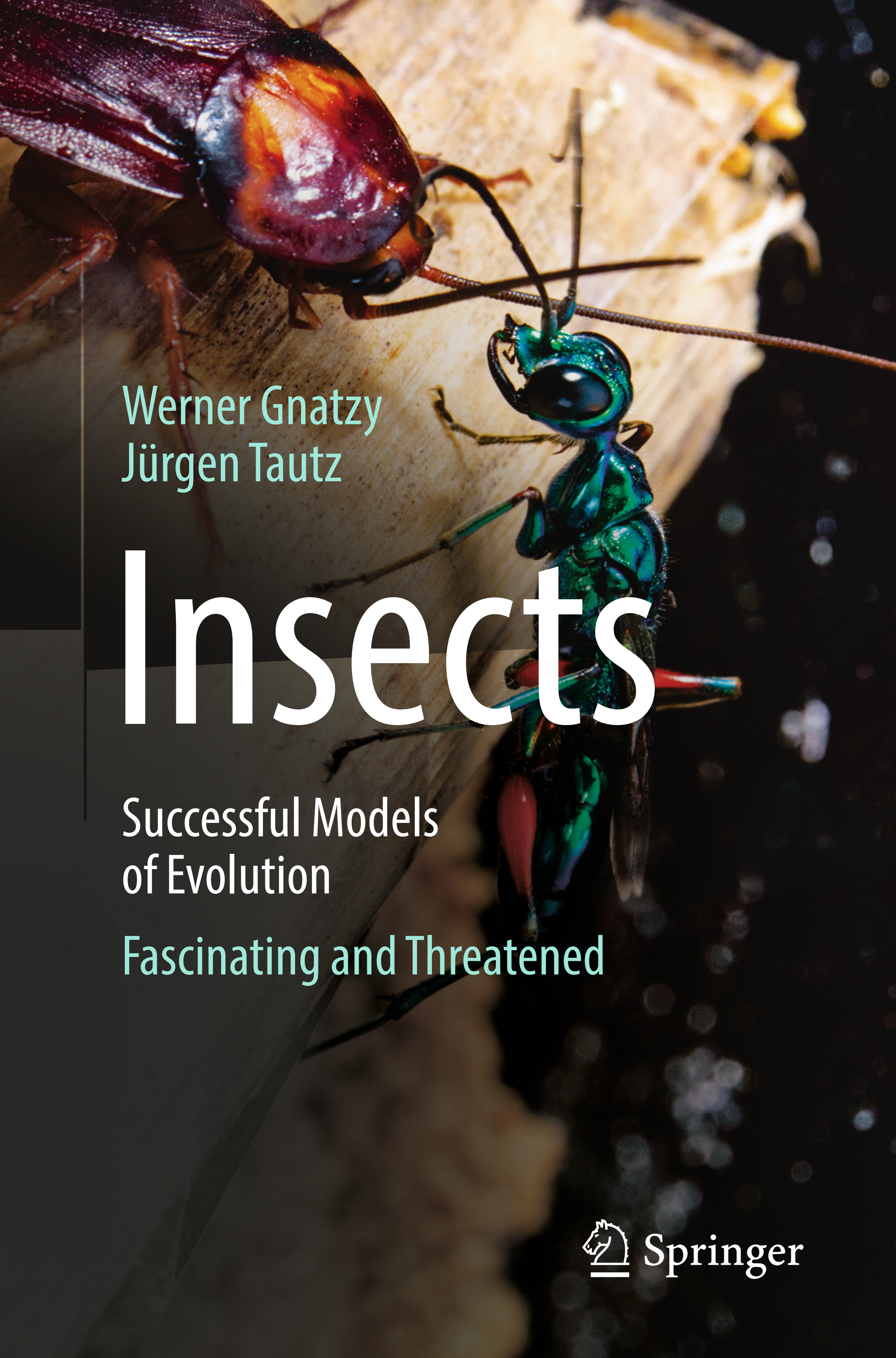

Werner Gnatzy
Jürgen Tautz

Insects

Successful Models of Evolution

Fascinating and Threatened

Springer

Insects - Successful Models of Evolution

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Foreword

Insects. The term was introduced in the eighteenth century for the class of animals with the most species. Derived from the Latin word insectum (cut into, notched), this designation referred to a special characteristic in the body structure of these animals. Beetles, butterflies, bugs, and their ilk all have bodies that are composed of three segments. They are also commonly dubbed vermin, which carries a deliberately negative connotation.

However, early biologists did not manage to coin a compelling term with the generic name "insects" as other small insect-like animals are also notched, segmented, and disliked. As a result, today the vast world of insects is split up into more familiar, albeit not always clearly understood, groups such as butterflies and beetles as the most common groups, in addition to dragonflies, grasshoppers, and others. This includes true bugs, which have few friends in terms of biodiversity, beauty, and unique lifestyles, even among insect specialists. The generic name "bug" can even refer to vermin per se and often to insects in general.

We associate a great deal with this name. We do not have to like gnats, and especially not mosquitoes, even if they can be considered fascinating from a scientific point of view and extremely important from a medical perspective. Jewel beetles enjoy great admiration, even by those who show little interest in beetles or the world of insects, simply because many of them are beautiful. Opinions diverge when it comes to dragonflies, which are also called devil's arrows despite their shimmering and dazzling beauty. The resounding success of the "save the bees" referendum, which was passed several years ago in Bavaria, Germany, as a result of great political pressure, cannot be attributed to beekeepers and honey alone but rather can also be ascribed to Maya the Bee. Despite the fact that biology has received less and less attention at school of late, biology lessons may have managed to spread the word that bees (and other insects) are important for pollinating flowers and thus for fruit production. During the referendum, the bees pulled along the large mass of other insects almost unnoticed. Those who signed likely did not even know that bugs are also insects. And what great bugs we have. A long-term study by entomologists in Krefeld, Germany, documenting the disappearance of insects over the last several years and decades attracted a sudden surge in media interest, which is now threatening to subside without any appreciable effect. Their findings, which showed declines of roughly three-fourths the earlier abundance at the beginning of the 1990s, were picked up by the media and disseminated around the world. And for good reason as it is important to emphasize that this disappearance was noted in protected areas and not in open, intensively farmed fields treated with insecticides and overflowing with manure where nobody would have expected to see a swallowtail or a rare wild bee in the first place. The fact that many amateur entomologists had noticed similar or even heavier declines in insects in "good" areas completed the picture. Ecologists such as Wolfgang Tischler and Bernd Heydemann had studied what was happening on agricultural corridors as early as the 1950s and 1960s, without producing an effect. They failed, as did many other researchers who had focused on the corridors, because the millions spent on supporting farms bulldozed everything else out of the way in politics, even when human health and safety were at stake. Even Rachel Carson's book *Silent Spring*, which shook the globe, vanished with virtually no effect because the prohibitions on DDT and other harmful insecticides were followed by even more toxic substances. By the time these new substances were prohibited, they had already generated high profits for the manufacturers and the farming industry. The move to ban glyphosate in Germany has dragged on for some time due to a lack of pressure from sufficiently large groups of the population. The general public is being sedated with prices for agricultural products well below the true costs, which should include subsequent damages and negative impacts on the environment. However, the energy crisis is now demonstrating how much cheap production depends on external energy markets and on large volumes of fertilizers and agrochemicals. Now even more is to be produced, after half a century of sustained overproduction pouring onto the global market, ruining prices in developing countries, and destroying agricultural reforms. The farming lobby is now demanding the last remaining land that has not (yet) been used with its residual nature in order to share the spoils in the aftermath of the war in Ukraine.

So things are not looking good for the insects. The situation is deteriorating tremendously at the moment. If the public were to put up more opposition to the destruction of key habitats and breeding grounds for birds, then insect advocates would have little more than the hope that private gardens and urban installations will remain intact as life rafts for butterflies, beetles, and their like since insects still do not inspire the enthusiasm that would be required as a basis to protect them effectively. Difficulties with regard species conservation regulations exacerbate the dire situation still further. They impede or prevent spontaneous interaction with insects because many species or entire groups, such as wild bees, are under protection. Closer observation beyond merely watching from a distance—and especially accurate identification, which involves capturing a specimen—requires a special permit. Mass destruction with poison, however, does not require such a permit. Apparently the cheap over-the-counter insect killers sold at supermarkets during the summer are also exempt from the conservation provisions. Strange circumstances, to put it mildly, and miserable parameters for improving our understanding of insects and arousing interest.

This book should be considered against this broadly outlined backdrop. I truly believe that this is a unique and magnificent work as it introduces us to the unseen universe of insects, which is only acknowledged sporadically at best even in biological research. The images shown here and the texts describing them could almost be from a different world—the insights are marvelous, the small-scale structures and microstructures are magnificent, and the feats of the insects are downright incredible. These images and texts make it abundantly clear that protecting insects is not limited solely to the ecological roles of several species and groups, such as the pollination of flowers. Although the usefulness of such species is readily emphasized as the main reason for the protection and conservation of insects, especially in light of our extreme focus on yield and profit, this book delves deeper to reveal that there is much more to insects than first meets the eye; ultimately, this concerns preserving the magnificence and diversity of living creatures. With this in mind, it includes all the figures and statistics regarding the decline in insect populations and embeds them within a much wider context. That is science at its best: accessible to everyone!

Munich, Germany Josef H. Reichholf
June 2022

Preface

This book arose out of a passion for the fascinating world of insects.

Their wide variety of shapes, which can only really be illustrated generically within the scope of a book, and their ingenious engineering solutions, which they have developed in the course of their evolution, are the secret to their success. Insects have managed to occupy virtually every habitat on our planet, and today they play a key role in the environment. This book also arose out of the concern about the increasing disappearance of insects due to environmental degradation caused by humans.

Our goal of writing a book that would be accessible to a general audience despite the extensive specialized knowledge proved especially challenging. The individual chapters are intended to be short, understandable, and entertaining, while not going into too much detail. Therefore, the book is not addressed to specialists, but rather it aspires to appeal to nature lovers and environmentalists.

The authors would like to thank the many colleagues who contributed greatly to the success of this project with their support and expertise, as well as those who provided materials and/or the opportunity to use their optical devices: Dieter Schulten (Aquazoo Löbbecke Museum Düsseldorf), Thomas Eltz (Ruhr-Universität Bochum), Damir Kovac and Wolfgang Nässig (Senckenberg Research Institute and Natural History Museum Frankfurt), Michael Boppré and Anita Kiesel (Institute of Forest Zoology, University of Freiburg), Konrad Fiedler (University of Vienna), Helmut Schmitz (Institute of Zoology, University of Bonn), Flavio Roces (Biocenter of the University of Würzburg), Reinhold Hustert (University of Göttingen), Günter Gerlach (Botanical Garden of Munich), Stefan Schulz (TU Braunschweig), Ulrich Maschwitz (†) (Goethe University Frankfurt), who encouraged W. Gnatzy to take on this project, Klaus Schurian and Alfred Westenberger (Frankfurt am Main), Stanislav Gorb and Esther Appel (Kiel University), Christian Trömel (Goethe University Frankfurt), and, last but not least, Juliane and Erich Diller (Bavarian State Collection of Zoology). Thank you to Rudolf Alexander Steinbrecht (Max Planck Institute for Ornithology, Seewiesen campus) for taking the trouble to read a first draft of the manuscript.

The images captured by means of a scanning electron microscope were created in close collaboration with Manfred Ruppel (Center for Electron Microscopy of Goethe University in Frankfurt). Thanks to his patience and expertise, he

contributed greatly to obtaining high-quality images with the scanning electron microscope (Hitachi S-4500), even in the case of challenging objects.

We would like to extend a special thanks to Martin Jatho as well (former employee of W. Gnatzy, Goethe University in Frankfurt), who was involved in the project for some time. We greatly appreciate his competent advice and constructive recommendations. In collaboration with him and with the help of his first-rate photography equipment, we managed to capture several extraordinary images.

Frankfurt, Germany Werner Gnatzy
Würzburg, Germany Jürgen Tautz
May 2022

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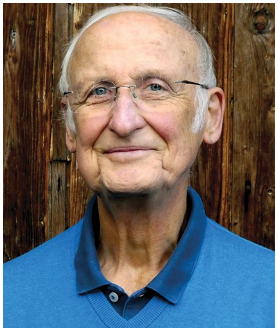
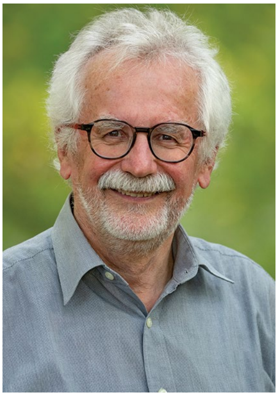


Werner Gnatzy studied biology, chemistry, and physical education for high school at Johannes Gutenberg University Mainz. First state examination in 1966. Doctorate (Dr. rer. nat.) in 1970. Habilitation in 1975, also in Mainz. From 1975 to 2006, he was a professor at the Zoological Institute of the Goethe University in Frankfurt. Since 2006, he has been giving lectures at Goethe University as part of the University of the Third Age (U3L).



Jürgen Tautz is one of Germany's leading bee researchers, a retired professor at the Biocenter of the Julius-Maximilian University in Würzburg, and author of numerous non-fiction books, including the bestseller *The Buzz about Bees*. He has received numerous awards for his exemplary communication of knowledge to the general public.

1 Introduction

Anyone who takes a closer look at the world of insects will recognize the unimagined wealth of inventions that nature has produced in this group. We can only marvel at nature's limitless possibilities for development. This book is intended to open the door to this world.

Insects form a universe that could not possibly be more alien to us humans. Unless you are an entomologist, there are basically only two major areas in which the world of insects and the world of mankind come into contact, and unfortunately not in a very pleasant way: We either perceive insects as carriers of diseases (e.g., mosquitoes, fleas, and tropical assassin bugs) or as pests that lead to crop losses (e.g., migratory locusts, aphids, potato bugs). It is therefore not surprising that most people find insects repulsive or even frightening. But there is also one area in which insects are indispensable helpers to us humans: in their role as pollinators of flowering plants.

The world of insects is alien to us. Although they have the same tasks to fulfill and problems to solve as all other animals, including us humans, the solutions they have found in the course of their evolution are so fundamentally different from the solutions of vertebrates that we cannot imagine ourselves in their world at all, or only with considerable imagination. Evolution is based on structures that, once invented, are tested and further developed. In insects, this means the more than 400-million-year-old invention of a skeleton that completely envelops the body as an external skeleton and not inside the body as in humans. The exoskeleton protects all internal organs. However, it is not a uniform envelope, but rather it forms the basis for the development of structures that are adapted to the insects' unique way of life: Legs and wings allow for locomotion, sensory organs convey information about the environment, and special structures facilitate visual or acoustic communication. Other structures are used for foraging and reproduction or to avoid enemies.

The group of insects seems to have almost unlimited development possibilities. Our imagination is not creative enough to picture everything there really is to

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discover about insects. On the contrary, insects serve as models for countless characters and stories in the field of science fiction.

The basic model has six legs, the ideal number for moving safely over any surface. Most insects have two pairs of wings. They conquered the skies almost 100 million years before other airborne animals. Giant dragonflies from the Carboniferous period achieved wingspans of 70 cm. In contrast, today's dwarf wasps are tiny creatures measuring just 0.15 mm. Miniaturization is generally seen in insects when it comes to their sensory organs, which are used to detect, categorize, and measure every conceivable environmental variable. Physical phenomena are used by insects in a highly sophisticated way when it comes to becoming conspicuous or, conversely, unrecognizable to other creatures.

Natural and sexual selection are the two driving forces that allow organisms to develop and change their characteristics and abilities in the course of evolution. The results of natural selection ensure life and survival. Upon closer inspection, the structures, properties, and capabilities that have emerged make a lot of sense in terms of their functions and use. Sexual selection is different. It is not uncommon for structures to emerge here that not only appear bizarre but can even be a hindrance to their owners in their everyday lives. By selecting the males they allow to mate with them, the females drive the development of such traits.

There are criteria based on which insects are clearly the most successful group of organisms in the course of the development of life on our planet to date, and this will certainly also hold true in the future.

Insects are our constant companions. They have opened up habitats like no other group of animals, proving to be true cosmopolitans. They can be found almost everywhere: in the hot and humid rainforests of the tropics, in the driest deserts, in the boiling hot springs of Yellowstone National Park, in petroleum puddles in oil fields, in acidic horse stomachs, and even in carefully sealed jars of oatmeal in the kitchen cupboard. Thanks to specially produced antifreeze, they can survive extreme cold and have successfully established themselves in the crevasses of Antarctic glaciers and in the eternal ice of the Himalayas. Even years of drought do not harm the larvae of an African mosquito that lives in water: As soon as it rains, they wake from their dry sleep. There is only one habitat that insects have hardly conquered at all: the oceans. Why is this?

The reason for this could be their tracheal system, which does not allow them to escape predators in the sea. The relatives of insects in the sea, small crustaceans, for example, breathe with gills and can evade voracious fish by diving into the dark. In the case of insects, the high water pressure at a depth of a few dozen meters would compress the gas in the tracheoles and cause the system to collapse. However, even if insects could make themselves invisible on the surface of the water through transparent bodies, as some small crustaceans do, then the air inside the tracheal system would reflect light and make them visible to fish from afar. They would not survive in any depth.

Nevertheless, a few insect species have colonized the sea. The wingless sea skaters (genus *Halobates*) glide over the sea surface in the tropical regions of the Atlantic, Indian, and Pacific Oceans. Lice of the genus *Echinophthirius* reach depths of several hundred meters as stowaways on harbor seals and sea lions. They use the air trapped under the fur of the host animals to breathe and thus elude the direct water pressure.

The number of insect species is huge, and we can only guess at how many really exist. Around 1 million insect species, corresponding to about three quarters of all known animal species, have been described to date. They range from tiny wasps and mini beetles, which are just 0.21 mm long and therefore smaller than the single-celled paramecium, to the largest, the stick insects, measuring over 30 cm in length, from morpho butterflies, ladybugs, and bees to praying mantises and flies. Most species have probably not even been discovered and described yet; some researchers estimate their number at 15 or even 30 million.

The number of individuals populating the planet is almost incomprehensible. According to calculations by Canadian entomologist Brian Hocking, around one trillion—a number with 18 zeros after the one—live on Earth. Together they weigh around 2.7 billion tons, five times as much as all the people alive today. There are 166 million insects for every single *Homo sapiens* living today—an impressive success story.

The success story of insects began over 400 million years ago in what is now Scotland. Even back then, in the Devonian period, an inconspicuous animal about 1.5 mm in size, *Rhyniella praecursor,* hopped through the horsetail forests. It is the oldest insect preserved in fossil form. *Rhyniella* was already protected by an exoskeleton and, together with various arachnids, was probably one of the first creatures to switch completely to life on land. This prehistoric insect looked similar to today's springtails, which populate forest floors in huge numbers or live in flower pots.

Whether insects evolved together with millipedes from a common arthropod ancestor before their paths diverged on land, as was long believed, now seems uncertain as recent genetic analyses have shown increasing evidence that insects may be more closely related to crustaceans. One of the things they have in common with crabs is the architecture of their brains; some scientists even refer to insects as "crabs adapted to life on land." Insects, on the other hand, share the structure of their respiratory and excretory systems with millipedes. However, the primitive wingless insect *Rhyniella* already possessed the typical characteristics of insects: a body composed of three segments and six legs.

What soon made insects the prevailing animal group on Earth was the development of wings. They were the first animals ever to conquer the skies. The oldest known fossil of a flying insect, *Delitzschala bitterfeldensis, which was* already a perfect flier, is around 320 million years old. According to one of the many theories, the wings developed from paddle-like projections on the thorax, which could have been used by primitive aquatic insects to row around. However, this assumption has yet to be proven as there is a gap of around 40 million years in the fossil evidence for this important epoch of insect evolution.

In the beginning, the wings were probably simple cuticle projections that enabled sailing like airfoils. Later, after the formation of joints, insects were able to rise into the air under their own power and thus flee from enemies more easily, hunt prey, and quickly colonize new habitats. A large number of mayfly-like insects and prehistoric dragonflies already dominated the skies in the Carboniferous period. Soon after, insects developed additional wing joints, which made the wings more flexible and allowed them to fold back against their bodies. About 97% of all insect species known today belong to these Neoptera.

The giant dragonfly *Meganeura* probably fluttered more than it flew. With a wingspan of up to 75 cm, it was the largest insect ever to have lived on Earth, a creature for which the construction plan of insects had probably reached the limits of growth.

1.1 The Insect's Respiratory System Draws the Line

Unlike fish or mammals, for example, insects do not breathe with the help of gills or lungs, from which the vital oxygen, bound to blood pigment, is transported in an aqueous medium to wherever the body needs it. In insects, a fine-meshed network of tubes, the tracheal system, delivers the gas directly to the individual cells. Through small openings, the stigmas, which are located on the sides of the thorax and abdomen, insects pump oxygen into themselves with rhythmic movements and expel carbon dioxide to the outside.

The advantage of tracheal breathing: The oxygen reaches its destination faster than in vertebrates. After all, flying requires a lot of energy. Insects therefore need large amounts of oxygen to burn as "fuel." From a certain body size, however, the tracheal network is no longer efficient enough, and the pumping movements are no longer sufficient for rapid gas exchange. The limit was probably reached with the giant dragonfly, which became extinct around 250 million years ago.

1.2 The Composite Material Cuticle: The Basis for the Diverse Variety of Insect Shapes

Cuticle is the basis of an incredible wealth of forms and functions. It is a special material, light yet strong, durable, and extremely malleable. The ancestors of insects had already developed this substance and formed an outer skeleton, the exoskeleton, from chitin together with proteins. This forms a stable shell and protects insect bodies on the outside, as well as the organs on the inside. It also offers muscle attachment points. For the first time in the animal kingdom, the exoskeleton enabled the formation of articulated legs with joints. Arthropods, which include crustaceans, spiders, millipedes, and insects, therefore do not slide and crawl like snails and worms but rather can move with extreme precision, even running and jumping.

The cuticle is almost omnipresent. It is not only the main component of the exoskeleton; it also lines parts of the intestinal tract and is part of the tubular trachea that penetrate far into the body.

Insects have developed suitably shaped mouthparts for any type of diet. From standard "biting and chewing" jaws, they have developed sharp knives and fine stylets. The toolkit of mouthparts is highly variable: Dragonflies hold their prey with hard jaws, ants defend themselves against attackers, grasshoppers bite through plant leaves, and beetles drill holes into wood to lay their eggs. Bedbugs, fleas, and mosquitoes use a needle-shaped proboscis to penetrate the skin of plants or other living organisms in order to suck out the juices, blood, or other bodily fluids like a drinking straw. Butterflies sip nectar with a tubular proboscis; when this “fuel nozzle” is not in use, it is simply rolled up under the head. These efficient tools evolved from structures that were still legs in the ancestors of insects.

Flexible and foldable wings allow them to move from place to place. The bushy or feather-like antennae with which moths filter sex pheromones from the air and the fine hairs on the cerci that crickets use to “hear” hunting female digger wasps are also made of cuticle.

The diverse color variations that characterize insect bodies can be traced back to properties of the cuticle: Embedded pigments and microscopic geometric structures on or in the cuticle bend, scatter, or refract incident rays of light.

Six legs are the feature by which insects can be most easily recognized, which is why they are called hexapods. They include high-speed runners, such as the 2-cm-long Australian tiger beetle *Rivacindela hudsoni*. It can reach a top speed of 2.5 m/s (9 km/h), easily overtaking the previous record holder, the American cockroach, which can reach 1.5 m/s (5.5 km/h). The long legs of the desert ant *Cataglyphis bicolor*, which is found in the Sahara, give it an advantage for surviving in a hostile environment. It emerges from its burrow when the surface temperature reaches 56 °C when no food competitors or predators are active. Even at a surface temperature of 60 °C, the ant’s body temperature does not rise to this dangerous level. With the help of its long legs, it can lift its body 4 mm off the ground. As a result, it moves in a layer of air that is six to seven degrees cooler than the surface of the sand. The ant runs around at a speed of 1 m/s, with the “airstream” helping to cool it down further. Nevertheless, it has to disappear back into its den after a few minutes because of the deadly heat. This is enough time for the ant to find food: dead insects.

Muscle-packed thighs turn grasshoppers and some cicadas into vaulters that can flee from enemies unexpectedly at a moment’s notice. However, the long distances cannot be attributed directly to muscle strength: Grasshoppers, for example, twist their hind legs to store kinetic energy, which, when released at the right moment, catapults the animals explosively into the air. Meadow spittlebugs *(Philaenus spumarius)*, a type of cicada that reaches only 6 mm in size, use a sophisticated technique to jump away at an angle of around 45° with record-breaking power. Researchers have discovered that the cicadas drill tiny, thorn-like projections (spikes) on their jumping extremities into the surface on which they are sitting before jumping. In doing so, they create enough grip and friction to convert the force from their jumping muscles into kinetic energy. The spikes are extra hard, thanks to zinc deposits, and are apparently reinforced specifically for this purpose.

Water boatmen and water beetles have converted their legs into oars. The sturdy mole cricket uses its flattened front legs, which have been transformed into shovels, to tunnel through dry soil in search of edible roots.

However, insect legs are not just used for locomotion. The front extremities of the praying mantis, for example, have been converted into a highly effective catching apparatus that picks off prey at lightning speed. Bees use the special bristles on their legs as a "basket" to collect pollen and transport it to their home hive, while some male water beetles attach themselves to their partner when mating using suction cups on their front extremities. Some crickets and katydids can even hear with their front legs, where they have developed "ears." An eardrum-like membrane, the tympanum, picks up vibrations, and nerve cells then transmit the vibrations to the auditory nerve, which in turn transmits impulses to the brain. Many female butterflies and flies choose where to lay their eggs on plants or animal carcasses based on the flavor they "taste" with contact chemoreceptors on their feet. And the native red admiral butterfly with its black and white spots has extremely sensitive gustatory sensilla on its feet, which are around 200 times more sensitive to sugar than the human tongue. Webspinners, on the other hand, are insects barely 2 cm in size that use glands on their forefeet to weave webs as their home.

More than a third of all insect species, around a quarter of all known animal species, are beetles; of these, around 370,000 have been described to date. Their unique wing structure was likely decisive in ensuring their viability: They use only the two rear, membranous wings to fly. After landing, these wings are folded together and packed up under the hard forewings, the elytra. This allows beetles to live on the ground, move under dense undergrowth or through fallen leaves, and even crawl into narrow crevices in bark without damaging their sensitive membranous wings.

Beetles have existed for around 250 million years, but their numbers exploded when the first angiospermous flowering plants, which today include fruit trees and flowers, evolved around 140 million years ago. It was a classic evolutionary scenario with a new, untapped food source, the flowering plants, and a group of animals, the beetles, which were able to switch their diet to greens and fruits. In an evolutionary arms race, plants and beetles constantly spurred each other on to create ever new forms, a particularly beautiful example of coevolution.

To ward off voracious caterpillars, for example, the plants had to defend themselves. They formed thick fruit casings or shells around their seeds, hid their pollen, covered their leaves with sticky hairs, or produced poisonous ingredients, organic insecticides. The beetles, in turn, developed tricky counterstrategies. They acquired boring mouthparts, such as the nut weevil, which can even bore through hard nutshells to lay its eggs. Monarch butterfly caterpillars switch off the chemical weapons of their host plants in the last larval stage. To do this, they gnaw on a small notch in the leaf stalks of milkweed plants *(Asclepias tuberosa)* and then crawl to the tip of the leaf to snap it off. This interrupts the supply of poisonous cardiac glycosides (pyrrolizidines) and milky sap to the leaf, allowing them to eat the leaves safely. Beetles were probably also the first animals to regularly pollinate the flowers of this new group of plants, the angiosperms. Until then, most plants had dispersed the pollen of the male reproductive organs with the wind and therefore had to produce huge quantities in order to guarantee fertilization, a lottery that wasted a lot of energy. Some insects have specialized in using the energy-rich pollen as food. They move from plant to plant and spread the pollen far more reliably than the wind.

Pollen-producing plants, which were more attractive to insects than others, therefore soon had a reproductive advantage. Other insects, especially bees, wasps, and butterflies, were increasingly involved in the sex life of flowering plants. The plants made themselves more attractive to visitors, luring them in with bright colors and sweet scents. As a reward for transporting the pollen, they paid with energy-rich currency: nectar.

In the liaisons between plants and insects, a variety of specializations and dependencies have developed, and some plants could no longer survive without their own pollinators and vice versa (e.g., orchids and orchid bees). The Madagascan orchid, for example, relies on the sphinx moth *Xanthopan morganii praedicta* for pollination: With a proboscis reaching lengths of up to 28 cm, only this moth can reach the nectar at the base of the calyx, which is almost as many centimeters deep.

Bees, of which there are probably up to 40,000 species worldwide, have become the most important pollinators of all; most live solitary lives, with only a few species forming colonies. The last major achievement in the evolution of insects to date, aside from the exoskeleton, wings, and complete metamorphosis, was the emergence of several independent communities in which the whole is worth everything and the individual counts for nothing. The rise of the termites and ants began around 130 million years ago, followed by wasps and bees 40 million years later.

These colonies are characterized by a strict division of labor and morphologically distinct castes (queen, workers, and soldiers). The vast majority of the members produce no offspring of their own and are prepared to sacrifice their lives for the whole: the superorganism. This has given rise to huge colonies, for example, African driver ants *(Anoma wilverthi),* with more than 22 million individuals. Today, social insects dominate many of the world's habitats. The total biomass of termites in the African savanna far exceeds the weight of the huge herds of wildebeest, zebra, and all the other grazers. And the worker bees in a single bee colony can visit and pollinate up to 6 million flowers a day.

Insects are therefore not just "essential animals of this Earth" because of their sheer mass and enormous diversity. Without them, the world would be a different place, less colorful and less fragrant, because around 80% of all colorful flowering plants are completely or partially dependent on being pollinated by insects. As a consequence, most plants would become extremely rare or even extinct without their pollinators. There would be no apples, pears, melons, figs, peaches, cherries, blueberries, kiwis, citrus fruits, and plums. The landscapes would be dominated by green, wind-pollinated plants, such as grasses, pines, or spruces.

In addition, the world would be drowning in waste, plant litter, and animal carcasses. More than 35,000 insects have been counted on one square meter of a North American deciduous forest, feeding mainly on dead organic matter. In addition to bacteria and fungi, insects contribute significantly to the decomposition of green plant matter. And as carnivores and scavengers, ants alone consume more meat than all carnivorous mammals put together.

Insects are the secret rulers of the world, and most of them are superspecialists that occupy tiny niches. The Asian owlet moth, *Lobocraspis griseifusca*, for example, does not drink flower nectar but sips the tears of buffalo and cattle. A ring of moths often gathers around a bovine eye and all dip their proboscis into (the salty) nutritious liquid on the eyelids. Another oriental moth has even modified its sucking mouthparts to pierce the skin of mammals in order to drink their blood; from an ecological standpoint, this moth has thus transformed into a mosquito.

On islands where many insect species are often absent, other species sometimes occupy vacant niches in surprising ways. The caterpillar of the moth *Eupithecia oricloris* in Hawaii, for example, is a master of the surprise attack: Camouflaged as a green twig, the caterpillar lurks motionless until its prey, usually a small insect, walks over it. Then it grabs the victim lickety-split with its front legs and eats it. Biologists Andreas Weißflog and Ulrich Maschwitz from the University of Frankfurt am Main have also discovered an extremely bizarre lifestyle in a 2-mm-long Malayan fly. Devoid of wings and legs, the insect lives practically unable to move among colonies of driver ants, which fed and transport it, probably because it resembles an ant larva.

Insects have already survived several mass extinctions in the history of Earth, including the Great Dying at the end of the Permian period around 245 million years ago and the extinction of the dinosaurs 65 million years ago.

Culex pipiens molestus, commonly known as the London Underground mosquito, is an impressive example of how evolution does not stop insects even in an environmentally damaging environment such as a modern megacity. When the Londoners built their underground over 100 years ago, a few specimens of the species ended up on the tube. While aboveground the pests mainly feed on the blood of birds, they have now had to switch to the blood of rats and mice in the subway in order to survive and occasionally also that of train workers and passengers. This new subway-dwelling species emerged within just a short period of time. It lives permanently underground and no longer interbreeds with mosquitoes of the original species that live aboveground. The mosquitoes between different subway lines already show considerable genetic differences. So the evolution of insects, the development of new diversity, continues to this day, even in the subway.

We are a long way from even beginning to understand the complexity of how the insect world interconnects with that of us humans. It is therefore only possible to name the very broad consequences associated with the disappearance of insects, regardless of the species involved. The epilogue provides more food for thought in this regard.

Whether the compound eyes of a moth, the calypters of a butterfly, or the suction feet of a great diving beetle, their abstract beauty is often only revealed under the scanning electron microscope. This book introduces the reader to an unknown world and reveals not only functional but also aesthetic aspects of nature's tremendous beauty. The macro images and the optical microscope simply serve as large magnifying glasses. The scanning electron microscope (SEM) opens up completely new points of view. The SEM can only be compared with a conventional optical microscope in terms of depicting the surface of an object. However, the image is not produced by means of optical imaging but by scanning a focused beam of electrons over the surface of a sample, interacting with the atoms on the sample. In this case, the image is the result of the various signals registered from these interactions. As the illustrations in the book show, the SEM is characterized by its high resolution (nanometer range) and depth of field (factor 100).

If this book manages to awaken awe and understanding among its readers through their amazement at a fascinating parallel universe, it would be considered a success.

From an Egg to a Full-Grown Insect

2

2.1 No Two Eggs Are Alike: The Diversity of Insect Egg Shapes

Maria Sibylla Merian set off on a 2-year research trip to Suriname in South America in 1699. Among other things, she wanted to research the life cycles of exotic insects in tropical forests. Despite unspeakable hardships, partly due to the hot and humid climate, Maria Sibylla Merian pursued her scientific studies with perseverance and tenacity. She recorded her observations in lifelike images and watercolors. Her book *Metamorphosis insectorum Surinamensium*, published in 1705, also contained isolated depictions of insect eggs, a novelty at the time.

But you do not have to travel to the tropics. Insect eggs can also be found in your own backyard if you look closely enough. Depending on the insect species, the females lay their eggs, individually or in packets, in the soil, inside wood, on the upper and lower surfaces of leaves, on and in the stems of terrestrial and underwater plants, etc. Some even inject their eggs into other animals using their egg-laying apparatus. Female insects therefore lay their eggs in all kinds of ecological niches using a wide variety of strategies. This has contributed significantly to the insects' success in terms of numbers. Below are a few examples of the tricks and illusions they use.

The Throwaway Eggs of the Indian Stick Insect

The natural habitat of the Indian stick insect *(Carausius morosus)* is tropical forests in the East Indies and South India, China, Japan, and the Greater Sunda Islands. The females lay their hard-shelled eggs (length, approx. 2.6 mm; width, approx. 1.6 mm; height, approx. 1.9 mm) individually on the ground, usually at night (Fig. 2.1a, b). The eggs resemble plant seeds or droppings in shape and color. They feature striking button-shaped appendages (capitula) (Fig. 2.1b). These are fleshy structures

W. Gnatzy, J. Tautz, *Insects - Successful Models of Evolution*,
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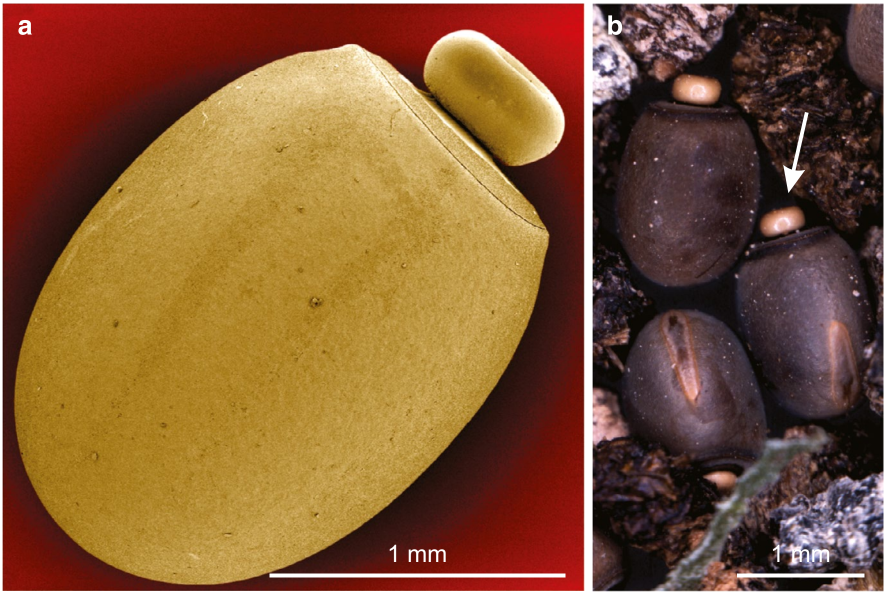

Fig. 2.1 (**a**) Female Indian stick insects (*Carausius morosus*) drop their hard-shelled eggs individually onto the ground; colored scanning electron micrograph. (**b**) The eggs of *C. morosus* resemble plant seeds in shape and color. Each egg features a nutrient-rich fleshy structure (elaiosome, *arrow*). After dragging these supposed plant seeds into their burrow, ants separate the elaiosomes there. As they are not interested in the eggs, they remove them from the nests again

(elaiosomes) that are rich in proteins and lipids. Ants therefore are prone to carry the supposed plant seeds into their burrows. There they separate the capitula and feed on them. As they are not interested in the eggs, they drag them out of the burrow, thereby contributing to the distribution of the Indian stick insect since it is unable to fly and is more or less tied to its location for the rest of its life. Stick insect species that bury their eggs or stick them to leaves lack these fleshy structures.

Female Indian stick insects lay up to three eggs a day, around 1200 throughout their lifetime. Of these eggs, only 100 animals usually survive in the wild. Depending on the temperature, the small stick insect larvae hatch from the eggs after 2.5–4 months (!).

Egg on a Stick: The Clutch of the Common Green Lacewing

Lacewings belong to the order of net-winged insects (Neuroptera). There are around 35 species of lacewing in Central Europe, of which the native common green lacewing (*Chrysoperla carnea*) is the most common. It is also known as the golden-eyed lacewing because of its remarkably beautiful eyes (Fig. 2.2b). The females, which visit flowers to feed on nectar and pollen, lay 100–900 eggs in the course of their lives. The oval, whitish eggs are laid at night individually or in groups on