WINNERS AND LOSERS

Insect diversity is not equally distributed across all the insect orders. While we know of close on half a million different kinds of beetle,[38] we've only ever found a few dozen kinds of the little-known heelwalkers (Mantophasmatodea) from Africa. Heelwalkers were not discovered until 2001,[39] and the fact that a whole new order of insects was happily going about its business unknown to us until the start of the twenty-first century again illustrates how many surprises still await us as we try to come to terms with the diversity of insects. The heelwalkers were the first new insect order to be discovered for nearly a hundred years, since ice crawlers (Grylloblattodea) crept into our awareness in 1914. As their name suggests, ice crawlers are yet more insects at home in extreme conditions, in this case around glaciers in the mountains of North America, China, Siberia, Korea and Japan, although more than likely these inconspicuous insects will turn up in other high mountain areas if anyone bothers to look. Currently, only a few dozen species have been described.

These two orders are clearly related to each other, and they are now lumped together in a newly created order called Notoptera. Together, they number just over fifty species, but even notopterans are not bottom of the league. Zorapterans seem somewhat overglorified by their common name of angel insects. About 3 millimetres long, they hide away beneath bark and number only about forty species. In fact, the whole order Zoraptera consists of just one family and one genus, the antithesis of the hyper-diverse insect orders.

The vast bulk of the exceptional diversity of insects resides in just a few orders. The big four are the flies (Diptera), the butterflies and moths (Lepidoptera), the ants, bees and wasps (Hymenoptera) and the beetles (Coleoptera). All four of these orders comprise insects that exhibit larval, pupal and adult stages. We'll see in the next chapter that this kind of life cycle – complete metamorphosis – was one of the evolutionary innovations that gave insects a real edge. However, there is one other mega-diverse order, the true bugs (Hemiptera), which is the fifth largest order of insects. Although exhibiting only incomplete metamorphosis, with no pupal stage, the true bugs have clearly come up with their own strategies for success.

There is a tale, probably apocryphal, that the eminent evolutionary biologist John (J. B. S.) Haldane, seated next to the Archbishop of Canterbury at a Cambridge college dinner, was asked by the eminent theologian what his studies of the natural world had taught him about

A small selection of moths from my moth-trap in an urban garden in the UK. *Top row, l–r*: the herald, *Scoliopteryx libatrix*, dusky thorn, *Ennomos fuscantaria*. *2nd row*: orange swift, *Hepialus sylvina*, lunar spotted pinion, *Cosmia pyralina*. *3rd row*: the gothic, *Naenia typica*, buff ermine, *Spilarctia luteum*. *Bottom*: elephant hawkmoth, *Deilephila elpeno*.

the Creator. Haldane's reply was that He had 'an inordinate fondness for beetles'. This sentiment was later shared by the Coleopterists Society. This august society, which may of course have a slightly biased view, tells us that 'we live in an age of beetles'.[40]

To be fair, it has long been a central tenet of entomology that beetles are the most diverse order of insects, indeed the most diverse group of organisms on Earth.[41] This was one of the assumptions made by Terry Erwin as he extrapolated from the beetles he collected in Panama a total number of arthropods in the tropics. However, when scientists fogged the forest canopy in Brunei, on the island of Borneo, as Erwin had done in Central America, they found more hymenopterans than beetles. Likewise, in Britain there are more species of both Hymenoptera and Diptera than of beetles. One study has suggested that for every beetle, there may be two or three associated parasitic wasps, which would push the Hymenoptera right to the top of the league.[42]

Flies are not far behind, however. Gall flies (Cecidomyiidae) are tiny flies that induce plants to make often elaborate structures (galls[★]) to house and feed their larvae. Genetic studies in Canada suggest that there may be 16,000 species living there and possibly 2 million species worldwide – in just one family among the 188 described fly families.[43] In 2015, thirty new species of fly belonging to a different family (Phoridae) were discovered living within the city boundary of Los Angeles. There are obviously a lot of flies left for us to find, even in the heart of our biggest cities.[44]

The jury is still out on which order of insects holds the most species – we still don't know whether God's inordinate fondness was for beetles or for flies, wasps or moths (or even for mites or nematodes). If we still can't give a definitive answer to the question of how many kinds of insect there are, we do know that the number is still rising, and it wouldn't be at all surprising to see future estimates rise even higher than the largest current assumptions.

This richness has arisen not, as might be expected, by insects evolving species more quickly than other groups. Indeed, their rates of speciation are generally equivalent to those of many other animal groups. Rather, insects seem less prone to extinction than other groups of animals, which means that, over time, their diversity has just grown and grown. For ex-

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[★] A gall is an abnormal growth of plant tissue, often creating a large structure, caused by an insect, fungus, bacteria or even a mechanical injury. A gall often takes on a distinctive shape and texture depending on what caused it, and the gall tissue often serves as food for the creature that caused it.

ample, for reasons not fully understood, a remarkable number of insects survived the famous extinction event at the end of the Cretaceous period (the K-Pg extinction),* which brought about the end of the dinosaurs.[45] That's not to say that some insect groups in some cases haven't experienced increased rates of speciation, but in searching for factors that explain the diversity of insects, we need to assess them on the basis of how they confer resistance to extinction rather than how they promote speciation,[46] and one such factor is size.

BIGGEST AND SMALLEST

Insects are small, which means that large numbers of both species and individuals can be crammed into a limited space. A single acacia tree in Africa can't feed even a single giraffe, but it's more than enough for a whole community of insects. On one such tree in Uganda, thirty-seven different sorts of insects were making a good living. Large local populations make it far less likely that an insect species will become extinct.

Small size also opens more opportunities for insects. I recently filmed a colony of acorn ants, *Temnothorax* sp., which – as their name suggests – house their whole colony inside a single acorn. On a broader scale, a single acre of soil might contain 3–25 million individual wireworms (the larvae of click beetles). As we'll see in later chapters, locusts swarm in their billions, while lake flies (Chironomidae) rising over Lake Victoria in Africa form dense, towering clouds that look like smoke and are visible from miles away.

Melbourne Museum's splendid 'Bugs Alive' exhibit tells its visitors that across the planet there could be 1 quintillion (that's one with *eighteen zeros* – or 10^{18}) insects alive at any one moment. Others have suggested 10 quintillion, but both figures can only be wild guesses, and both are figures that are so large as to be impossible to imagine. Trying to give this some context, this works out to be 150 million insects for every one of us lucky human beings. According to the *New York Times*, that translates to 300 pounds of insects for each and every one of us. These

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* The K-Pg extinction marks the boundary between the Cretaceous period (the 'K' comes from the German word *Kreide*, meaning chalk, used to avoid confusion with 'C' for Cambrian) and the Palaeogene period. It is often referred to as the K-T (Cretaceous-Tertiary) extinction, but many geologists favour phasing out the term Tertiary. The extinction event was caused by a massive asteroid impact and wiped out three-quarters of all animals and plants. It spelt the end of all the non-avian dinosaurs, although avian dinosaurs (birds), like many insects, survived.

figures are even more speculative than those for numbers of species, but at least they serve to hammer home how successful insects are – as well as why they should become an integral part of our diet.

If size has been a key part of insects' success, how small can they get? For once we do have an answer to that question – 139 microns, or just over one-tenth of a millimetre. This is the adult size of the world's smallest insect, the males of a mymarid wasp, *Dicopomorpha echmepterygis*, whose name printed here is about two hundred times longer than the insect it describes. These male wasps are smaller than some species of *Paramecium*, which are single-celled protozoans. It's possible that an even smaller species exists among the vast number of undescribed species of parasitic wasps, but it probably won't break the record by much. Studies on these micro-insects show that they are approaching the lower size limits of the insect body plan, and they have already had to come up with some innovative workarounds to cope with being so tiny.[47]

The basic insect body plan, with its regional specialization, has to be abandoned in the very smallest insects. *D. echmepterygis* has only two visible abdominal segments, reduced from the eleven of most insects. A tiny feather-winged beetle, *Mikado* sp. (Ptiliidae), has such a small head that it has had to shift its brain into its thorax.[48] Additionally, due to their tiny size micro-insects can fit far fewer neurons into their brains, perhaps just a few thousand in the smallest examples, which creates problems for controlling complex behaviour. Many feather-wing beetles are so small that they've had to make other significant sacrifices. A male has room for only one testis and a female just one ovary, and in some cases female ptiliids can lay only one egg in each cycle. There is also a size limit below which conventional insect eyes won't work. The tiny males of *D. echmepterygis*, for example, are blind. However, the hallmark of the success of insects is their adaptability, and several insect groups have come up with a new eye design to solve that problem.[49]

A major limit to miniaturization is that an insect needs to be large enough to lay an egg containing sufficient yolk to nourish the growing embryo. However, even with such a seemingly unbreakable barrier, insects have found a way to circumvent the problem – just use someone else's yolk. This is exactly what the tiniest parasitic wasps do. They can afford to lay microscopic eggs with no yolk at all because their eggs are laid directly into the eggs of much larger insects. We've already seen how successful a strategy that is.

A few insects grow to much larger sizes, dwarfing these tiny species. Such a large variation in size is another factor promoting insect diversity,

The giant scarab beetles such as this *Eupatorus birmanicus* from Asia are among the biggest of all insects.

by opening up a wider variety of different habitats and lifestyles. However, it's unlikely that size range is one of the main reasons for the richness of insects. The size range of insects covers only three orders of magnitude, small compared to fish, for example, whose size range covers eight orders of magnitude.

Just as the insect body plan imposes limits on miniaturization, so it also prevents insects from growing to the monster sizes depicted in some sci-fi films. The problem lies in the way they are built and in the way they breathe. Insects inherited an exoskeleton from their arthropod ancestors – a tough suit of armour protecting all their soft tissues on the inside. But to grow, an insect must shed its exoskeleton; then, while the new one is still soft, it must pump up its body with air or water, so that when this new cuticle hardens, it's a size bigger, creating space for the insect to grow into.

If an insect was too big, it would be hard for it to support itself after discarding its old exoskeleton before its new one hardened. It could end up as a shapeless blob. However, this constraint only applies in air. Water is denser than air and therefore provides more support; so crustaceans, which also must moult to grow, can reach enormous sizes. The Japanese spider crab, *Macrocheira kaempferi*, has a leg span approaching 4 metres, making it the world's largest crab, forty times the size of the largest insects (giant wētās from New Zealand, about which more in a moment).

However, the limitations of moulting on dry land can't be the whole story.

Christmas Island in the Indian Ocean is a crab-lover's paradise. Once a year the forest floor comes alive with land crabs, *Gecarcoidea natalis*, tens of millions of them, a great red army all marching downslope to the ocean where they will spawn. Their migration is one of the great natural spectacles – it has appeared in so many natural history films that I've lost count. It's so famous that you can buy soft-toy versions of the Christmas Island red crab bearing greetings from the island, one of which is perched on the corner of my desk as I write this. There is, however, another kind of land crab on Christmas Island that to me is even more impressive. It lurks under cover in the forests but ventures into town at night to raid dustbins. And it is huge. At 4 kilograms in weight and with a leg span of 1 metre, robber crabs, or coconut crabs, *Birgus latro*, are the biggest terrestrial invertebrates in the world. They are more than fifty times heavier than the heaviest recorded insect, and with their massively powerful claws, they demand some serious respect. However, like their insect relatives, these crabs must moult to grow. So simply having an exoskeleton can't be the sole reason for a limit on the size of insects.

One big difference between crustaceans and insects is in the way they supply their tissues with oxygen. Aquatic crabs breathe using gills and land crabs have adapted this system to work on dry land by enclosing the gills in a damp chamber that works a little like our lungs. In addition, crabs have an internal circulatory system to carry oxygen to their tissues. Insects, as we've seen, have adopted an entirely different approach. They breathe through a series of holes or spiracles, no more than two on each segment, which connect to an elaborate network of tubes. These tubes (tracheae) branch throughout the insect's body, getting finer and finer until they end as microscopic tracheoles close to the cells they serve. In tissues such as flight muscles, which have a huge demand for oxygen, the tracheoles actually penetrate individual cells, but in both these cases the insect depends on oxygen simply diffusing along the tubes to reach the cells – and herein lies the problem.

If an insect doubles in size, the rate of diffusion along its larger tracheae also doubles, but the oxygen demand of the insect's tissues increases by four times. This means that, as insects get larger, their tracheal system can't keep up – and the insect body plan based on an exoskeleton doesn't help. As insects get larger, the exoskeleton of their legs must get thicker to support their increased weight. However, this narrows the space through which the tracheae need to pass to supply the leg muscles with oxygen, so making it even harder for insects to evolve into larger sizes.[50]

Today, the heaviest insect is a flightless cricket from New Zealand, a giant wētā, *Deinacrida heteracantha*, weighing 71 grams. But even this mega-bug is an exception. The record is held by a female heavy with an exceptionally large number of eggs, and most giant wētās are a lot smaller. There are five kinds of giant beetle that are generally accepted as the biggest insects, at least by bulk: the long-horned beetle, *Titanus giganteus* (167 mm), the elephant beetles *Megasoma elephas* (137 mm) and *M. actaeon* (135 mm), and the goliath beetles *Goliathus goliatus* and *G. regius* (110 mm). But there are other ways of measuring size.

The longest insect is, unsurprisingly, a stick insect – Chan's mega-stick, *Phobaeticus chani*, from Borneo. The body of a big female (not including its long legs) can reach nearly 40 centimetres.[51] This just beats a related stick insect from Borneo, the previous record holder, *P. kirbyi*. In 2006 another giant stick insect was discovered, this time in the rainforests of Queensland in Australia. Only a few female gargantuan stick insects, *Ctenomorpha gargantua*, have ever been found in the wild. They are much bigger than the males and the first one found, named Lady Gaga, was sent to Melbourne to start a captive breeding colony. The gargantuan stick insect is currently the third largest stick insect, although there are rumours that someone came across a really huge individual, photographed it and re-released it; admirable behaviour but precluding this species from perhaps claiming the world record. However, these mega-insects are dwarfed by some of the giants from the past.

Around 300 million years ago, a monstrous beast called *Meganeura monyi* roamed the skies. It probably resembled a modern dragonfly, although only distantly related, but had a wingspan of about 70 centimetres and body length of 30 centimetres. Assuming similar proportions to a modern dragonfly, it must have weighed more than 200 grams, nearly three times more than the heaviest insect known today.[52] This makes it the heaviest insect ever, at least as far as we know, and it flew rather than crawled like today's giant wētās, which demands a lot more oxygen. Nor was it the only ancient giant.

From the late Carboniferous period and on through the following Permian period, insect evolution produced some real monsters. Most impressive were the Meganisoptera, the group to which *M. monyi* belonged. Most fossils of these creatures, now commonly called griffinflies, are fragmentary wings, but more complete fossils of one species, *Meganeurites gracilipes*, have been found and show it to have had large eyes with acute vision and spiny front legs. These are features also found in modern hawker dragonflies, making it likely that griffinflies were active hunters, grabbing prey in flight much like modern dragonflies.[53] Another extinct order of flying insects, the Palaeodictyoptera, reached wingspans of more than 40 centimetres, as did the mayflies of the time. An entomologist exploring the swamp forests of the Carboniferous period would have needed a very large collecting net.

During this time, other arthropods produced even more impressive giants. Without the constraints imposed by aerodynamics, a millipede called *Arthropleura armata* reached more than 2 metres in length. In 2021, a chance rockfall along the coast of Northumberland in north-eastern England revealed the largest specimen of *Athropleura* yet discovered. This monster was half a metre wide and more than two and a half metres long, making it the largest arthropod in Earth's history – at least that we know of.[54] Giant arachnids also stalked the great forests of the coal swamps. The likes of these giant terrestrial arthropods have never been seen on Earth since – and many might be very grateful for that. The reason is that the late Carboniferous period presented them with a unique opportunity. Extreme gigantism during this period was possible because atmospheric concentrations of oxygen reached 35 per cent, compared to just 20 per cent today. Such high levels of oxygen loosen the constraints on insect body size by making insect tracheal systems much more efficient. Oxygen could diffuse further and faster down longer tubes, allowing much larger species to evolve.[55]

There's evidence from living insects that oxygen concentration really can affect the size of arthropods. The life cycle of fruit flies is so quick that they can squeeze many generations into a short time, making them a favourite laboratory animal for studying evolutionary processes. Colonies reared in high oxygen levels do produce larger individuals over time, as long as the temperature is also high. In the wild, too, there is a correlation between the maximum size reached by aquatic amphipod crustaceans and the oxygen content of the water in which they are living. Such studies suggest that higher oxygen concentrations really do allow arthropods to get bigger.[56]

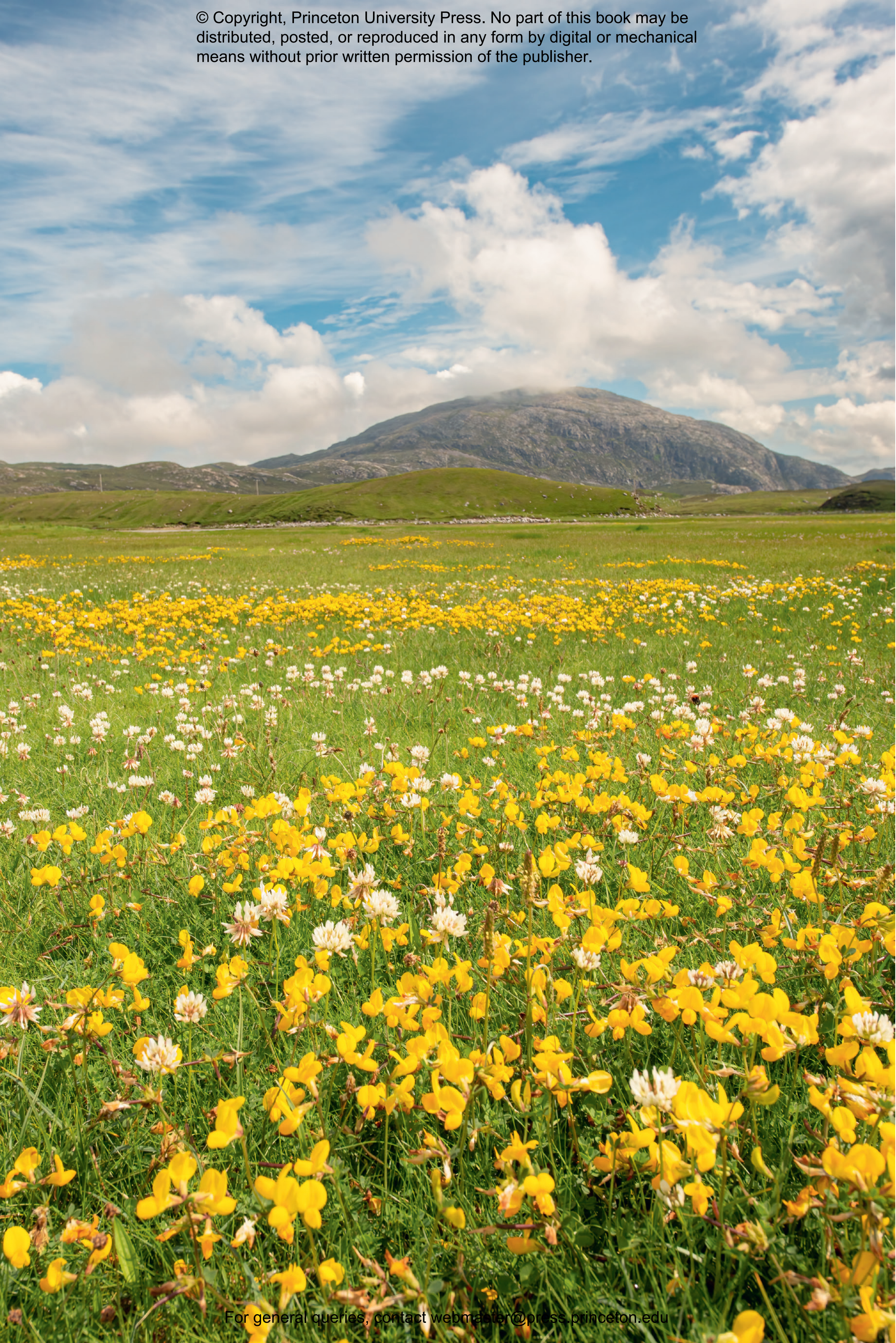
The giant meganeurids probably averaged around 150 grams in weight and, even in their high oxygen world, insects of this size faced problems. In the late Carboniferous and Permian periods, the climate was much warmer than it is today. In such a hothouse world, the energy needed to power these heavy hunters in pursuit of prey would soon cause them to overheat. None of the ways in which flying insects cool themselves today would have been sufficient to prevent burnout, although calculations show that if the atmosphere was also denser than today's, meganeurids could balance their heat budgets. The existence of these giant flying insects suggests that at the time they flew, the atmospheric pressure must have been about one and half times that of today.[57]

Times have changed. Today's thinner atmosphere with its lower oxygen concentration can't support these real giants. Given time, the ever-adaptable insects may have come up with a way around this, but something else happened that doomed giant flying insects. Vertebrates conquered the air. Vertebrates evolved flight on at least four separate occasions, beginning with the pterosaurs in the late Triassic period, around 220 million years ago. They were followed by birds, then by bats. Recently, some curious little dinosaurs have turned up in China that had winged hands, not unlike bats. There is still much debate about these creatures but it seems that dinosaurs may have evolved the ability to fly twice, one line using feathers to create a wing surface (birds) and another using bat-like membranous wings.[58] All of these creatures no doubt relished large flying insects.

The vertebrate endoskeleton, an internal scaffolding of bone, is more suited to large body sizes, as is the vertebrate lung system, so flying vertebrates easily reached sizes greatly exceeding those of flying insects. One pterosaur, with a wingspan of more than 10 metres, grew to the size of a light aircraft. Birds later achieved similar scales. *Pelagornis sandersi*, described as a seagull on steroids, had a wingspan of more than 7 metres. Even today, birds reach sizes far greater than any of the giant insects of the past, and all the flying vertebrates had no trouble evolving to sizes that made giant flying insects nothing more than bite-sized snacks. The mega-insects didn't stand a chance.

RARE – AND GETTING RARER

Predation still plays a role in cutting insects down to size. Wētās, of which there are a whole variety in New Zealand, can only grow so big because, until humans arrived, their home was free of predatory mammals.[59] Many of the largest insects today are confined to similar isolated and predator-free islands. *Polposipus herculeanus*, a giant darkling beetle (Tenebrionidae), is only found on Frégate Island in the Seychelles. The Lord Howe Island stick insect, *Dryococelus australis*, at 20 centimetres in length, is large enough to have earned the name *tree lobster*. It thrived



in its only home, a tiny volcanic speck 600 kilometres due east of Port Macquarie in New South Wales.

Until 1918, Lord Howe Island was also free from mammalian predators. Unfortunately, in this year a British ship ran aground on the island. Inevitably, it had plenty of stowaways in the shape of black rats, which soon escaped to shore. Two years later, they had eaten their way through the entire world population of Lord Howe Island Stick Insects – and, in 1920, the tree lobster was declared extinct. Then, in 2001, two intrepid scientists made an exciting discovery. Intrigued by tales from climbers of hand-sized dead insects littering the rocks at the base of Ball's Pyramid, a 600-metre remnant volcano close to Lord Howe Island, they explored the place at night and found a small population of living Lord Howe Island stick insects.

We saw earlier that the potentially enormous populations of small insects give them some degree of protection from extinction, but giant insects on tiny islands are the exact opposite. They are much more vulnerable to extinction. The Lord Howe Island stick insect is sometimes cited as the world's rarest insect and if black rats ever make it to Ball's Pyramid it will probably be gone for good this time. Other modern giants, though, have already gone the way of the ancient griffinflies.

The giant earwig, *Labidura herculeana*, a creature that reached 8 centimetres in length, was last seen in 1967. It lived only on St Helena, one of the British Overseas Territories and an island so remote that the British chose it as a place to keep Napoleon Bonaparte out of harm's way after his defeat at Waterloo. It sits in the Atlantic Ocean, a tiny pinprick on the map nearly 2,000 kilometres off the coast of southern Africa and it's not an easy place to get to, or at least it wasn't until recently. In 2016, a somewhat precarious-looking airport was opened to receive flights from Africa, but when I travelled there in the early 1990s, it required a flight with the RAF to Ascension Island some distance to the north-west, followed by a sea journey of 1,300 kilometres on a Royal Mail Ship, the RMS *St Helena*.

The strangest thing about finally arriving on this remote island is how little out of place the main town, Jamestown, would seem if it were relocated to the coast of Dorset or Devon. But beyond this home from home, the island, surrounded by dramatic cliffs, rises to spectacular heights cut by deep valleys. When it was discovered by the Portuguese in 1502, it was a verdant place, covered in trees, many of which were found nowhere else on Earth. Giant earwigs were thought to have lived in forests of endemic gumwood trees. In 1995, some dried remains of

Despite their evolutionary success, many insects are currently suffering catastrophic declines, caused by pesticides and habitat loss among other reasons. Few flower-rich meadows, like this one on the machair of the Isle of Lewis, in the Outer Hebrides, still remain.

this earwig were found in an area that suggested that the species also frequented the vast seabird colonies that once covered large areas of the island before they too were wiped out.

Much of the native vegetation has also now been cleared, either by human hands or by the mouths of introduced grazing mammals, so there weren't many places left for the earwig to live. Living specimens were found under boulders at Horse Point Plain in 1965 and there were other reports from 1967. I had been asked by concerned entomologists to spend some time looking for this charismatic earwig in the places where it was last seen alive, and I was happy to create some space in my filming schedule to go on a giant earwig hunt. An expedition mounted by London Zoo in 1988 had failed to find living earwigs and, sadly, I too failed. Subsequent searches in 2005 also proved fruitless, and in 2014 the giant earwig was officially declared extinct.

Since they evolved around 480 million years ago, insects have gradually increased in diversity to the astounding levels that we have encountered in this chapter. Many aspects of insect life have contributed to this success (and we'll discover more of them in the coming chapters). Many of these factors enhanced insect diversity by making them less prone to extinction. Extinction, however, is as much a part of evolution as speciation and happens all the time, although the history of life on Earth has been punctuated by five mass extinctions, in which extinction rates reached much higher levels. The worst of these, at the end of the Permian period, saw 96 per cent of marine life disappear along with 70 per cent of terrestrial vertebrates. This 'Great Dying', as it has been called, also had a huge impact on insects. More than half of all insect families disappeared, the worst extinction suffered by insects in their long history. Yet in the long run, insects continued to thrive and increase in diversity.

Unfortunately, the fate that befell the giant earwig on St Helena – and that might yet befall the Lord Howe giant stick insect – is now being repeated around the whole planet. The scale of this became headline news in 2017, when a report re-analysed data from an entomological society in the small German town of Krefeld near Düsseldorf. The society's headquarters were stacked with alcohol-filled specimen jars crammed with insects collected locally since the society's formation in 1905. In the past they needed so much alcohol to preserve their specimens that the local narcotics bureau took a serious interest in their activities. But society member Martin Sorg noticed that recently their alcohol bill had dropped dramatically.

The great yellow bumblebee, *Bombus distinguendus*, was once widespread across Britain but is now confined to flower-rich meadows along Scotland's west and north coasts.

The data held by the society is so complete that they allowed Sorg to look at how the abundance of insects on local nature reserves had changed over the last hundred years or so. The results shocked not only members of the society, but scientists and naturalists around the world. On one reserve, insect abundance today was 80 per cent lower than in 1989. That pattern repeated itself across the sixty-three reserves they looked at. Overall, in just the last few decades, insect abundance in this corner of Germany had fallen by three-quarters.[60] The speed and scale of the drop was so startling that the paper rapidly became one of the most widely discussed that year among scientists and naturalists around the world. It received a lot of global press coverage too; though, as is often the case, it was soon replaced by other news.

At the same time, a Danish naturalist had noticed that on a drive through the countryside, his windscreen remained free of bugs. He remembered that the same journey in his youth had resulted in a windscreen so spattered with dead bugs that it necessitated frequent stops to clean it. So, with the support of colleagues, he began to gather quantitative data – by equipping cars with large nets on their roofs. These drew plenty of attention from passing motorists, but also from scientists around the world. As in Germany, insect populations had crashed in the last few decades, and following this study the phenomenon

of insect decline is often called the windscreen effect.

To cut an increasingly long and depressing story short, this catastrophic collapse of insect populations seems to be global in scale and is attracting epithets such as ‘Insect Apocalypse’ and ‘Insect Armageddon’. Data from many places is still sparse and it’s already clear that not all insect groups are declining. Some are stable and some have even shown recent increases.[61] For example, a wide-ranging analysis shows that terrestrial insects are declining at a rate of 1 per cent a year, while aquatic insects are increasing at the same rate.[62] Some studies are also contradictory. One study claimed that insects have suffered a catastrophic collapse in Puerto Rico’s Luquillo Experimental Forest,[63] while another suggests that insect numbers have been more or less stable.[64]

In 2019, the Entomological Society of America hosted a symposium in St Louis, Missouri, to pull together data from around the world to clarify patterns of decline. The participants outlined the wide range of threats faced by insects, describing it as ‘death by a thousand cuts’. Although the picture is far more complicated than some of the earlier reports suggested, the scale of the decline is nevertheless alarming, since insects underpin virtually all terrestrial ecosystems.[65] Many scientists now regard our current impacts on the natural world as a sixth mass extinction. Insects survived all five of the others, but human activity seems to be having a far greater impact on insects than any of the previous five. To continue on the same path and further erode insect numbers and diversity is the height of folly. Three-quarters of all the different crop types that we rely on require insect pollination, and many other large animals are equally dependent on insects for their survival.[66]

Insects are also food for people. Around the world, some 2,000 species of insects are eaten by humans. Some are curious luxury items, such as chocolate-covered ants or mealworms embedded in candy. The late Emperor Hirohito of Japan was apparently very partial to boiled wasps with rice, and tinned grasshoppers (*inago*) are still sold in Japan as a luxury food. However, many more people rely on harvesting insects for at least part of their livelihood.

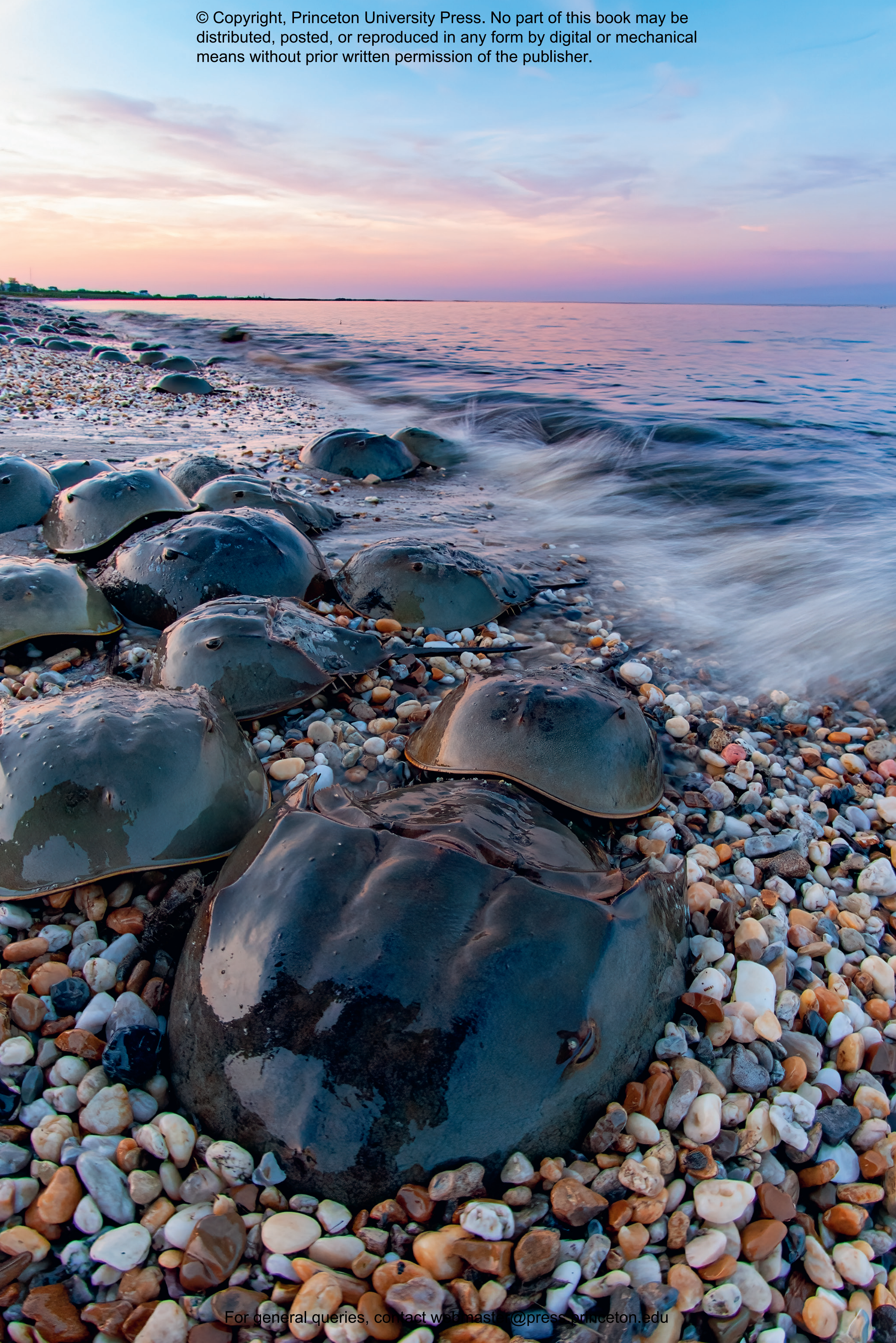
From our biased Western perspective, we might view such people as struggling to survive, forced into eating insects as a last alternative. In fact, they have the moral high ground. Insects are by far the most ecologically sound way of producing animal protein. Crickets, for example, convert their food into edible protein with more than ten times the efficiency of cows – and in doing so, they need over fifty times less water. Eating insects could, quite literally, save our planet.

For the economically minded, there's already big money in insects as food. Tinned silkworms, to pick just one example, are worth $50 million in exports to Thailand. Because economics rather than ecology makes most world leaders sit up and take notice, scientists have also tried to put a monetary value on the pollination services that insects carry out for us. It's based mostly on inspired guesswork, but the global figure is somewhere between $235 and $577 billion dollars annually. In one sense, though, these are meaningless figures. If we lose these pollination services, no amount of money will buy us out of a diet based solely on wheat, rice and maize, our main wind-pollinated plants. Forget your 'five-a-day'.

Already, in south-west China, pollinators are so scarce that farmers have to pollinate apples and pears by hand, an unbelievably tedious and time-consuming process. Even in Britain, apple crops today are smaller than they could be. It's estimated that the recent drop in pollinator abundance is costing growers here around £6 million each year. In response, engineers are trying to design robotic bees that can take on the duties that insects already provide for free. Is it just me – or is this utterly crazy?

The decline of insects is having a huge impact on economy and ecology alike, enough that you might think that by now this problem should have risen up the political agenda. Sadly not. Part of the reason lies in the fact that most people don't really care about insects. At a 1968 meeting of the International Union for the Conservation of Nature, a Senegalese forester, Baba Dioum, remarked: 'In the end we will conserve only what we love, we will love only what we understand.'

He was absolutely right. We need to learn to understand and love insects if we want a future on this planet. In the following pages, I hope to bring a greater understanding of why insects are so vitally important, by exploring their long history and their diverse and often surprising behaviour and ecology. Perhaps then we'll realize why our future depends on these little creatures. Because they've been so successful over their evolutionary history, these teeming hordes have become the lynchpins of terrestrial ecosystems. The simple fact is that we need insects far more than they need us.



2

Origins
The long history of insects

…what can be more different than the immensely long spiral proboscis of a sphinx-moth, the curious folded one of a bee or bug, and the great jaws of a beetle? Yet all these organs, serving for such widely different purposes, are formed by infinitely numerous modifications of an upper lip, mandibles, and two pairs of maxillæ.

Charles Darwin, *On the Origin of Species*, 1859[1]

Cape May, protecting the entrance to Delaware Bay on America's East Coast, is less than a couple of hours' drive from Philadelphia. Historically, this 'city of brotherly love' served briefly as the nation's capital and today lies at the centre of the Northeast Corridor, a relentlessly bustling and claustrophobic strip of concrete, glass and asphalt anchored at one end by the modern capital of Washington DC, and at the other by the financial capital of New York City. But as dawn broke and the bay slowly revealed itself, I could have been half a planet away from the modern world with all its incessant noise and bustle. A long beach curved away into the pre-dawn glow, backed by low dunes of rustling grasses. From where I stood, a few deserted beach shacks poked above the dune line, loosened shutters clattering in gusts of wind. The braying of laughing gulls as they greeted the new day echoed out of the receding darkness. As more of the landscape was illuminated, my sense of remoteness only grew. Soon I would feel distant from the civilized world not just in space, but in time as well. The event that I had come here to film would transport me back beyond the time the first Europeans stood on these shores, further back even than the first American Indians to see this bay, all the way past the last and first dinosaurs, to a point nearly 450 million years ago.

It began with a few shapes exposed by the backwash of the waves, to be covered again as the next wave rolled in, more and more over the next ten minutes until the shapes started to haul themselves clear of the water. Now, they revealed themselves as strange alien creatures, some up to half a metre in length, including a long spike of a tail that projected from a domed body topped by two frowning eyes. They could have stepped straight from a *Star Wars* film. This was the first time I'd ever seen a horseshoe crab, although in just an hour's time I would have seen tens of thousands of them. On the spring tides in May and June, they emerge from the murky depths of the bay in vast numbers to lay their eggs at the high-water mark. There the eggs will develop, safely buried in the sand, until the next spring tide in a couple of weeks' time washes newly hatched larvae out into the bay.

Horseshoe crabs have been around for a very, very long time. The oldest known fossils, at 445 million years old, date back to the Ordovician period.[2] Although we can't know whether these ancient horseshoe crabs spawned in the same way as their modern descendants, it would make a lot of sense. The Ordovician seas teemed with predators, whereas no animal had yet set foot permanently on dry land. It was by far the safest place to lay their eggs.

(*previous page*) Every spring and early summer, on spring tides, thousands of Atlantic horseshoe crabs, *Limulus polyphemus*, crawl on to the beaches of Delaware Bay on America's east coast to lay their eggs at the high-tide mark.

Horseshoe crabs are not insects – they're not even crabs. They're more closely related to spiders, but like crabs, spiders and insects they *are* arthropods; by crawling ashore, they are reliving a turning point in arthropod history. I've revisited this spectacle on many occasions since, and every time, as I watch the drama of their mass spawning unfold, I can't help but imagine that at some time in the past, the far distant marine ancestors of insects must have done something similar, their first faltering steps on land driven by the need to keep their eggs safe or perhaps to graze on bacterial mats just above the tide line. Over time, generations of these unknown creatures could have ventured ever further from the water until finally they became true land dwellers – ready to spawn the most successful group of animals ever to have evolved, above or below the waves.

THE ARTHROPOD DIASPORA

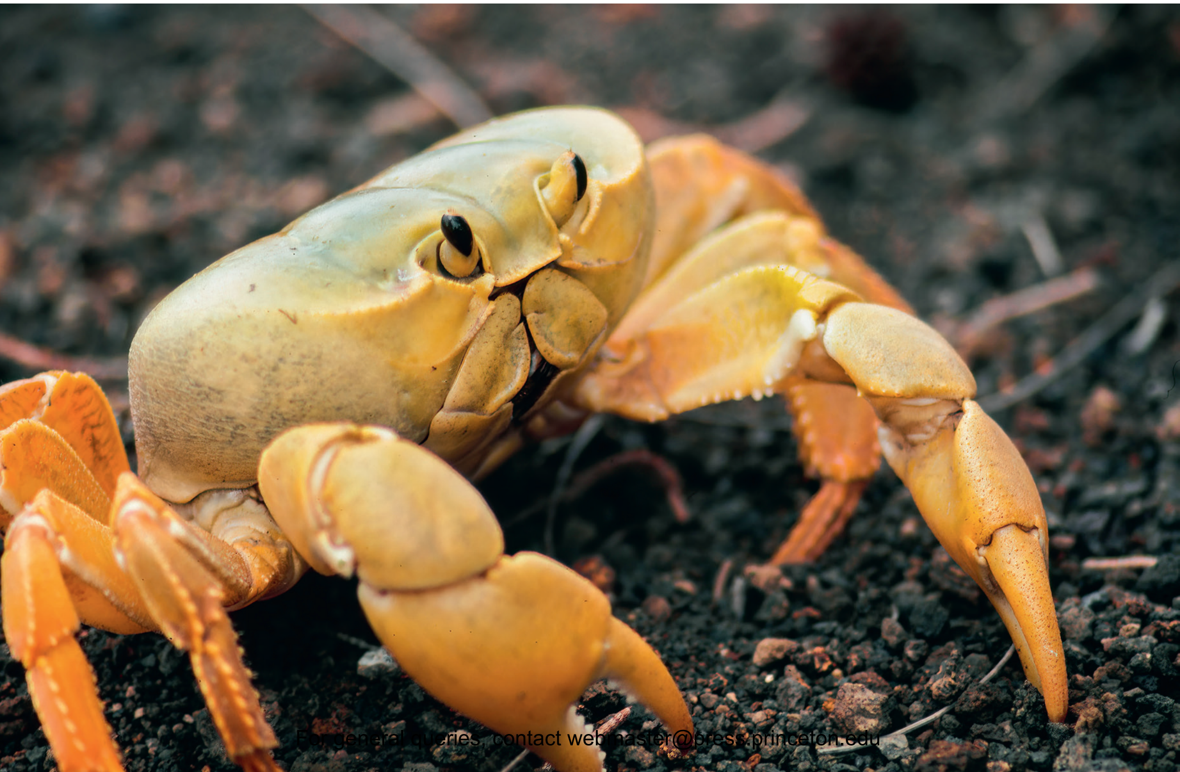
We have absolutely no idea what the ancient ancestors of the insect dynasty looked like and much of their early story remains a mystery, lost in deep time. Even so, we can now lay out a generally accepted broad timeline for their conquest of the planet, informed both by good old-fashioned fossil digging and by ingenious new molecular and imaging techniques. We know for certain that the ancestors of insects, like those of all other arthropods, began life in the ocean and at some point crawled ashore to colonize dry land, although they weren't the only arthropods to take this bold step.

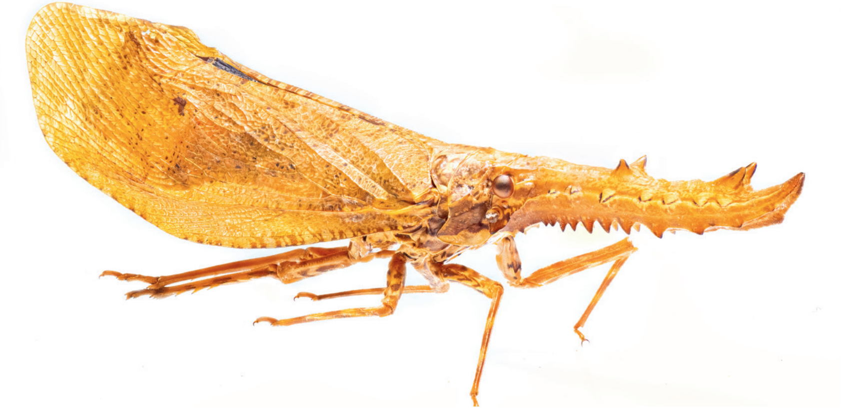
Arthropods have invaded land on several separate occasions, at least three times in the ancient past, to give rise to three different terrestrial dynasties – the arachnids (spiders and scorpions), the myriapods (centipedes and millipedes) and the insects.[3] In more recent times, some crustaceans have also successfully emerged from the waves. The woodlice in your garden are crustaceans, as are the strange little amphipods called lawn shrimps, originally from Australia although now successfully invading many parts of the world thanks to human assistance. True crabs have also made it a surprisingly long way from the ocean. I've followed hordes of large yellow land crabs, *Johngarthia lagostoma*, as they descended more than 300 metres from the high central mountain on Ascension Island to the jagged lava coast where they spawn, an arduous trek that takes them several days.

However, the most impressive example that I've ever come across is the desert crab, *Austrothelphusa transversa*, which lives in Australia's dry interior, admittedly buried in a small, damp hole deep below ground for most of the year, only emerging when occasional rains form temporary pools into which females can release their young. Vertebrates, including our far-distant ancestors, also successfully invaded land, but only once and much later than the three oldest terrestrial arthropod groups. Clearly, there is something special about arthropods.

Arthropod means ‘jointed foot’, and such jointed limbs are shared by all these varied creatures, along with their extinct relatives such as the trilobites. Articulated legs allowed for efficient crawling on the seabed or swimming through open water, but would eventually prove equally useful for crawling out onto land. The earliest arthropods had lots of these legs, whereas our own forebears had to make do with just four, derived from the cumbersome, fleshy, lobed fins of a fish-like creature, perhaps resembling a modern lungfish or coelacanth. ‘Creepy crawly’ might be a term of disparagement that we heap on ‘bugs’ of all sorts, but those creeping, crawling jointed limbs allowed arthropods to run before we could even walk.

Multiple multi-jointed legs make arthropods seem very alien to us, so much so that these creatures are a frequent inspiration to designers of sci-fi monsters for film and television. However, there’s an even bigger reason why extraterrestrials often bear an uncanny resemblance to terrestrial arthropods. They have a hard external skeleton that can be sculpted into a profusion of bizarre spikes or horns, or textured to look like stone, bark, leaves or lichens. In the previous chapter I pointed





out that an exoskeleton limits the size that insects can reach, but any such disadvantages are more than offset by the advantages it gives an arthropod setting off to conquer dry land. Along with their jointed legs, their exoskeleton was a pivotal feature that gave arthropods the edge over our own ancestors in the invasion of dry land. Out of water, the exoskeleton provides support in the drastically less dense world of air, and it can easily be rendered waterproof, simply by a coating of wax, to avoid drying out.

However, these crucial attributes of terrestrial arthropods, their jointed legs and hard exoskeleton, didn't evolve as a solution to life on land. They are *exaptations* – features that became co-opted for uses different from those that drove their original evolution. They are fortuitous 'pre-adaptations' that gave arthropods a distinct advantage when it came to leaving the ocean world behind. So, in our quest for the reasons behind the ultimate success of insects, we must first ask where these key arthropod features came from. How and when did the first arthropods appear on the scene, and what originally drove the evolution of the features that made them arthropods? That search takes me back in time, further even than ancient horseshoe crabs – and, unfortunately, back into the busy Northeast Corridor, where I crawled slowly south through nose-to-tail traffic on Interstate 95 until I hit the Capital Beltway, a 64-mile-long car park encircling Washington DC.

The great cities of America's north-east are not my natural habitat, although I visit Washington frequently because it's the home of the Discovery Channel, the Smithsonian Channel and National Geographic, for whom I've made many documentaries over the years. Washington does have one other major draw for me – the National Mall, running from the US Capitol to the Lincoln Memorial and lined in part by the museums of

(left) Yellow land crabs, *Johngarthia lagostoma*, from Ascension Island are just one of a surprising range of crustaceans that have conquered dry land.

(top) A lantern bug, *Cathedra serrata*, from South America, illustrates just how versatile the insect exoskeleton is. It can be moulded to almost any shape.

the Smithsonian Institution. Halfway along the museum strip stands the National Museum of Natural History (NMNH), a monumental edifice to the natural world within which I'll find a major clue in our pursuit of arthropod origins.

The fossil hall of the NMNH is, inevitably, dominated by dinosaurs, a group of only middling success at best when compared to arthropods, but for some reason universally more popular. Tucked away in one corner, largely ignored, is a display of rocks covered in faint impressions, some like delicate etchings, others like photographic negatives, of creatures far more alien than even horseshoe crabs. These rocks originated in a remote corner of the Canadian Rockies, and they revolutionized our view of early life on Planet Earth.

WHERE DID ARTHROPODS COME FROM?

The fossils of the Burgess Shales date from around 505 million years ago, in the Cambrian period. They are housed here at the Smithsonian because they were originally discovered by Charles Walcott, who was at the time the fourth Secretary of the Smithsonian Institution and an expert on trilobites, a group of arthropods common in the Cambrian period. Towards the end of a busy field season in 1909, studying the Cambrian strata of the Rockies in British Columbia, he stumbled across a previously unknown treasure trove of ancient fossils. The often repeated, although probably apocryphal, story is that his wife's horse (his wife often accompanied him on these long field seasons) stumbled on a rock, which cleaved to reveal a fossil preserved in incredible detail. Whatever the true circumstances were, Walcott immediately recognized the very high quality of preservation, if not the true value of his find. In what later turned out to be a classic understatement, he wrote to a colleague that he had 'found some very interesting things', which – at the time – he identified as phyllopod crustaceans.

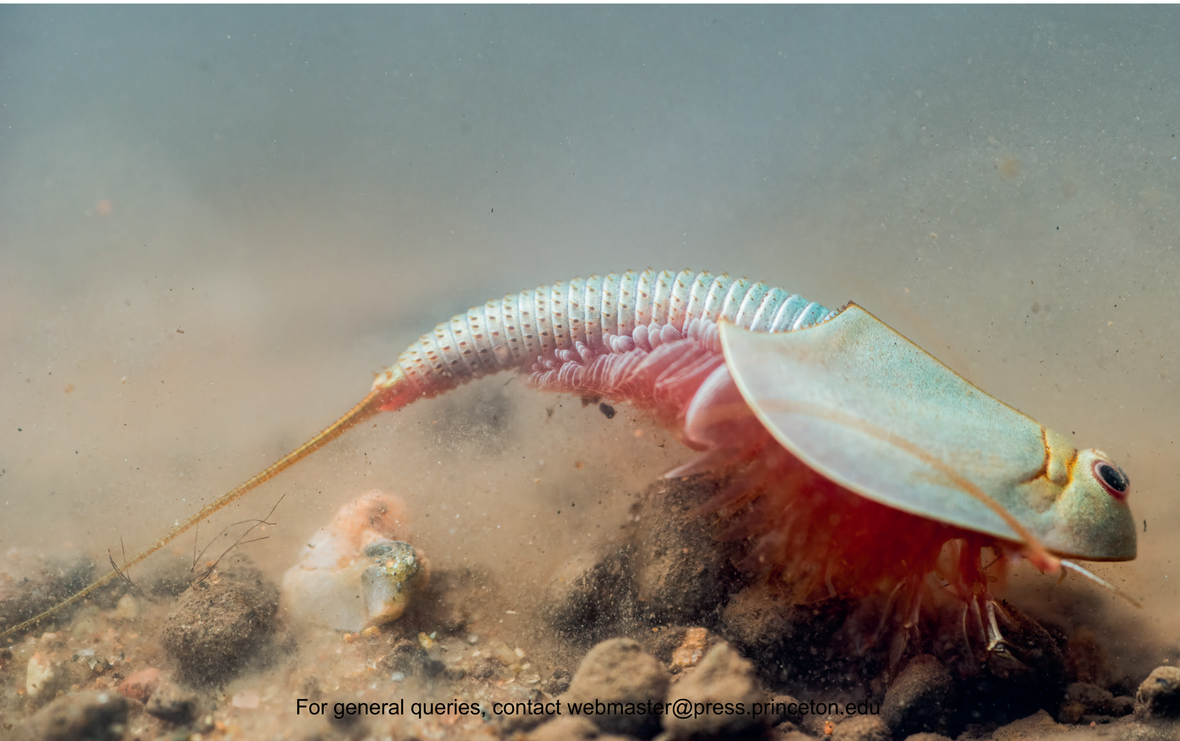
It was too late in the season to explore the site further, but when Walcott returned the following year the true importance of his find became apparent. The marine world of the early Cambrian period was laid out in unprecedented detail – a fauna of strange creatures that seemed to defy imagination. After nine more seasons in the field, Walcott had recovered 65,000 specimens of some 120 species, ranging from *Hallucigenia*, a creature that, as its name suggests, would not be out of place in a drug-induced vision, to *Anomalocaris*, a half-metre-long killer 'shrimp'. Since Walcott's day other locations around the world, with similar exquisitely

A tadpole shrimp, *Triops* sp. Only a few species of these primitive crustaceans survive today but their fossil record stretches back nearly 400 million years – a glimpse into the early history of arthropods.

preserved fossils, have been discovered, at Chengjiang in China, Sirius Passet in Greenland and Emu Bay in Australia, all of which pre-date the Burgess Shales. More recently, palaeontologists came across a remarkable site not far from Walcott's original find that gave up even more of the Cambrian period's secrets. In just one season, in 2012, 3,000 specimens belonging to 50 different kinds of animal were extracted from Marble Canyon, in a remote part of Kootenay National Park in British Columbia. Ten of these were entirely new to science.[4]

Together these discoveries paint a picture of the early Cambrian period as a time of rapid proliferation of life, a time when all the modern body plans, including that of the arthropods, first came into existence. These creatures appeared so suddenly that this period of evolution is often referred to as the 'Cambrian Explosion'. Whether this really *was* an explosion or just an artefact of a woefully incomplete fossil record has long been the subject of debate, although most scientists now agree that something special really did happen at the start of the Cambrian.[5] So, were arthropods born in this explosion, and if so, what was the trigger?

One intriguing suggestion, made by Andrew Parker of Oxford University, is that eyes evolved. Predators with the power of sight would have been a devastating new force in the ocean, prompting the rapid evolution of protective measures, such as, for example, the tough exoskeleton developed by the earliest arthropods. An escalating arms race of measure and countermeasure, as predators evolved ever more ways of overcoming their prey's defences, could fuel many such evolutionary innovations and create an explosive increase in diversity.



Others have suggested that the key factor in igniting the Cambrian Explosion was oxygen. For much of Earth's four and a half billion-year history, our atmosphere was devoid of oxygen. It wasn't until a group of bacteria (cyanobacteria), sometime around 2 billion years ago, evolved the neat trick of photosynthesis – of using the power of sunlight to make carbohydrates from water and carbon dioxide – that things began to change. Life arose on Earth about three and a half billion years ago, and for several billion years existed as nothing more than microbes, including many and varied forms of bacteria. This period has been called the 'boring billions', which is a little harsh. Microbes are extraordinary – they are invisible chemical factories that even today still have a massive impact on the way our planet works.

Over their long history, bacteria came up with lots of ways of using the energy in light to make food. One of these, the type of photosynthesis that all modern plants now depend on, is called oxygenic photosynthesis, because its main waste product is oxygen. And it was a global catastrophe – at least at first. For all the organisms that existed at the time oxygen was deadly, so reactive that it could rip their molecules apart. However, in time, life would not only work out how to live with oxygen but turn it to a huge advantage.

It didn't take long for a different group of those little chemical engineers to evolve a way of harnessing oxygen, by allowing it to react in a controlled way with food molecules to release far more energy than was available to any of the other microbes around at the time. This evolutionary innovation changed the world forever, eventually paving the way for more complex cells, then for multi-cellular life – the first animals and plants.

After this *great oxygenation event*, oxygen levels in the atmosphere fluctuated over geological time, driven by biological and geological processes. We've already seen that such changes have had profound effects on insect evolution but, back in the Cambrian period, long before insects appeared on the scene, oxygen may have been the fuel that caused the Cambrian Explosion to burn so bright. Energized by raised oxygen levels, active hunters evolved, for example with jointed legs for crawling or swimming in fast pursuit of prey, or powerful, muscular claws for grabbing and crushing their victims. At the same time, their prey was not entirely helpless. These creatures also had energy to burn and could afford to build elaborate defences in the form of exoskeletons and mineralized shells or faster legs to escape. In this scenario, the controlled combustion of oxygen fuelled a diverse new array of lifestyles.[6]

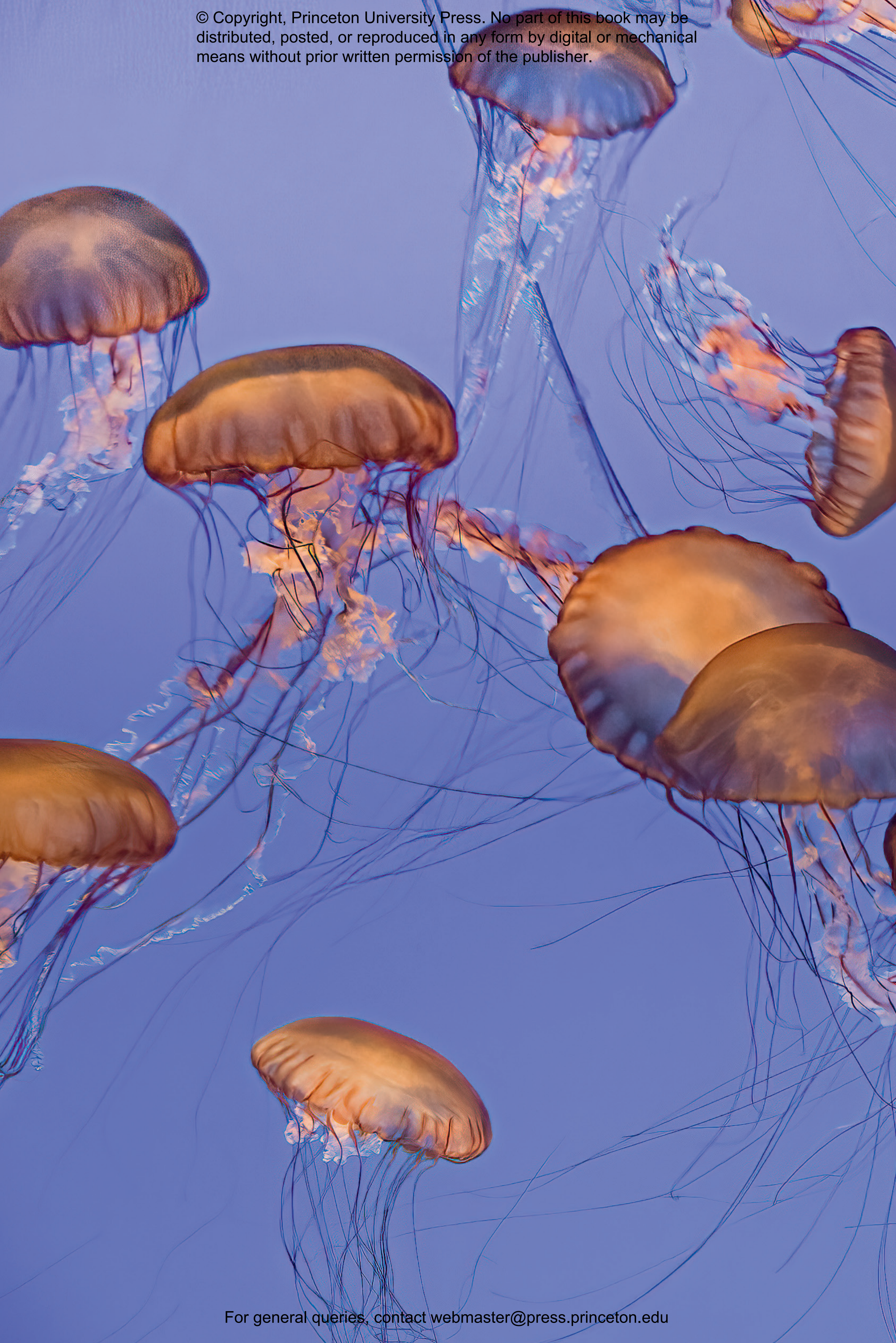
What does all this mean for our search for the origins of arthropods, and for those arthropod features that insects would later put to such good use? When Walcott began to examine the Burgess Shale fossils, he tried to fit them into existing animal groups. Later, some scientists were so bemused by the weirdness of creatures like *Hallucigenia* that they assigned many of the organisms of the Burgess fauna to entirely new groups of animals – strange experiments in evolution that blossomed and died in this first flowering of complex life. Later still, and with many more sites yielding fossils of a similar age or older, scientists have returned to Walcott's original interpretation. As weird as they are, these early Cambrian creatures show features that tie them to modern groups. And among these creatures are the first arthropods.

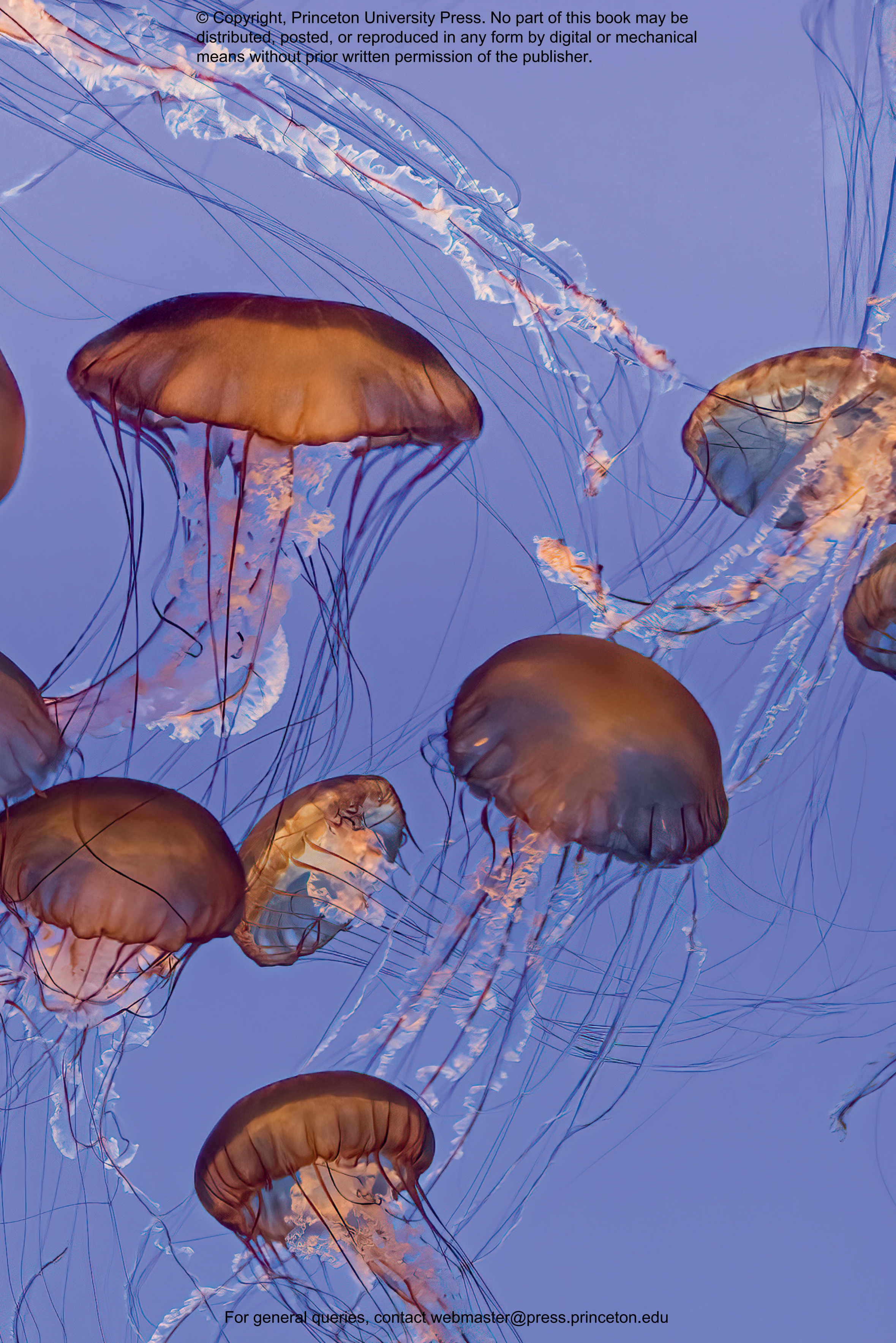
The earliest arthropod fossil that we know of dates to 537 million years ago, almost at the start of the Cambrian, which began 541 million years ago. It's a fossil called *Rusophycus*, but it's not an actual animal. It's a trace fossil, formed by an unknown, multi-legged beast as it rested in the mud, contemplating the strange new world in which it found itself.[7] Arthropods, it seems, arose very quickly as the Cambrian Explosion ignited – so quickly that some have their suspicions that they may have had their origins even deeper in time.

The belief that the Cambrian period saw the birth of complex life was so entrenched up until the middle of the twentieth century that we consistently ignored evidence to the contrary. Then, in 1957, a schoolboy, Roger Mason, climbing in Charnwood Forest in Leicestershire, came across some strange markings in the rocks. He took a rubbing of the markings and showed it to scientists, who recognized it as a form of complex life, now called *Charnia*, in rocks that pre-dated the Cambrian period. *Charnia* became the first form of complex life to be described from Precambrian rocks.

The story of our discovery of these first glimmerings of complex life is one of misinterpretations and missed opportunities. Even *Charnia* should have been in the spotlight of geological fame earlier than it was. It turns out that the Charnwood fossil was originally seen by a fifteen-year-old schoolgirl called Tina Negus a year before Mason's climbing adventure. She had a deep interest in geology and knew she was exploring Precambrian strata, so was perplexed at seeing a clear, frond-like impression in the rocks. Of course, no one believed her, and her geography teacher informed her in no uncertain terms that there were no fossils in Precambrian rocks. When she insisted that she had definitely seen a fossil, the teacher's response was that therefore these were not Precambrian rocks.[8]

(*overleaf*) Black sea nettles, *Chrysaroa achlyos*, belong to a group (Cnidaria – the jellyfish and sea anemones) that probably evolved and thrived in the Ediacaran Period, before the Cambrian explosion, when much simpler body plans predominated.





That same logic had been applied to similar fossils, found long before in England, and to others from Newfoundland, Namibia and Australia. In 1946, the Australian geologist Reg Sprigg was working in the Flinders Ranges of South Australia when he came across faint impressions in the ancient rocks in the Ediacara Hills. These were clearly complex multicellular life forms, so by the reverse logic of the time, the rocks were therefore presumed to be of Cambrian age. After the description of *Charnia*, all these errors were corrected, and it became clear that we now needed a new geological period to encompass these discoveries. Eventually, this period, immediately preceding the Cambrian, became known as the Ediacaran, after the Ediacara Hills, which continued to reveal new fossils of this age.

The creatures that lived in this period are, to say the least, enigmatic. They are even harder to place on the tree of life than the Burgess Shale animals. They may represent an early explosion of multicellular life, unrelated to anything that followed. Some have even suggested that they are intermediate life forms between animals and plants. Others think that, among this strange fauna, they have glimpsed the earliest ancestors of the arthropods. This suggestion, based on existing fossil evidence, is hotly disputed, but there are other ways of looking at the problem of arthropod origins.

Evolution proceeds by the slow accumulation of mutations along the strands of DNA that make up chromosomes. These mutations occur at a more or less steady rate, so the greater the number of mutations that have accumulated, the more time must have passed. They act as a molecular clock, ticking away the time that has elapsed since any two groups of descendants diverged from their common ancestor. The bigger the differences in the genomes of species being compared, the further back in time they must have diverged. To get an absolute, rather than a relative, measure of time, the clock must be calibrated against fossils of known age, but then it can be used to estimate when groups of animals arose even if the fossil record is sparse or non-existent. In any case, the laws of probability – or at least the rarity of fossilization – make it highly unlikely that we'd ever find the earliest fossil of any group,[★] so these molecular analyses might be expected to give a more accurate picture of the timing of key evolutionary events. It's not an exact science since it depends on a series of assumptions about, among other things, the rates

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[★] This is known as the Signor-Lipps effect, after Philip Signor and Jere Lipps, which states that, since the fossil record is never complete, neither the first nor the last organism of any group will be recorded as a fossil.

that mutations happen. So, trying to marry the fossil record with what molecular studies tell us still engenders plenty of lively debate.

Molecular analyses of living arthropods do point to their origin in the Ediacaran period, although they can tell us nothing about what that earliest arthropod might have looked like or whether any of the many described Ediacaran fossils are actually arthropods.[9] There are no unequivocal arthropods from the Ediacaran, either body fossils or trace fossils, such as *Rusophycus* from the early Cambrian. In any case, the Ediacaran seemed like a gentle world, with simple animals going quietly about their business – until the Cambrian exploded.

Within a short time, arthropods began to diversify and dominate their ocean world. They were both fuel and catalyst for the Cambrian Explosion. As sophisticated predators like *Anomalocaris* evolved, arthropods helped to escalate the arms race that drove a rapid expansion of life in the early Cambrian. By the time the Burgess Shale creatures were crawling and swimming through the ocean around 30 million years later, arthropods had consolidated their hold on the world. About a third of all species in the Burgess Shales are arthropods. By the end of the Cambrian, almost all the major arthropod groups had evolved.[10] Today they are still the most diverse group of animals on the planet – a distinction they've held, unchallenged, since the early Cambrian.

Adaptations that evolved to cope with the new, tougher world of Cambrian oceans would later prove just as effective in conquering dry land. Insects inherited these features from their most distant arthropod ancestors, but it's what they went on to do with them that catapulted them to far greater success than any other arthropod group. To understand how they've done that, we need to know a bit more about how insects fit into this most ancient of dynasties.

ARTHROPOD EVOLUTION

The detailed relationships of all the varied arthropod groups to each other have long been the subject of much wrangling among biologists. It has, however, at least been agreed for some time that the living arthropods can be broken into two large-scale groups: the *Chelicerata* (sea spiders, horseshoe crabs, spiders, scorpions and their relatives) and the *Mandibulata* (myriapods, insects and crustaceans).

This fundamental division of the arthropods is based on the mouthparts of the two groups. The 'fangs' of spiders are more correctly called *chelicerae* (singular: chelicera) and all the Chelicerata, including the horseshoe crabs I watched spawn on Delaware Bay, share this feature, although spider fangs are a specialized form of chelicerate mouthparts, hinged like a jackknife for stabbing prey and injecting venom. In most other chelicerates, these mouthparts form pincer-like feeding structures, easily visible in those horseshoe crabs that get flipped onto their backs by the waves.

This may not now come as much of a surprise, but members of the second group, the Mandibulata, are defined by their possession of mandibles, which evolved as slicing and crushing appendages, although many insects have taken this basic design and modified it beyond all recognition. Being able to remodel their mouthparts to cope with radically different diets has helped insects exploit a huge range of ecological opportunities. These differences in mouthparts might seem like a tiny point of distinction, of interest only to biologists poring over jars of specimens in their ivory towers. However, in reality, understanding this very early step in the evolution of arthropods answers a big part of the question as to why they have been so successful for so long.

The first arthropods, as illustrated by those 537-million-year-old resting traces, were long-bodied creatures with many repeated segments, each carrying a pair of legs. We don't really know what the animal that made those impressions looked like, but we can make a good guess. In fact, I've found animals living today that are probably not all that different from the very earliest arthropods.

One of the joys of spending time in a rainforest is searching through the thick leaf litter or rolling over rotting logs to see what might be lurking beneath. If you are really lucky, your efforts might reveal a pencil-length 'worm' with little stumpy legs that quickly hides itself away again. Its skin, which may be a startling pink, red or blue depending on the species, has the appearance of soft velvet, so these elusive animals are often called velvet worms. They belong to a group known as *Onychophora*, which closely resembles fossils called *lobopodians* from very early in the Cambrian period. Several lobopodians are preserved in the Burgess Shales and this group of segmented, worm-like creatures shared a common ancestor with all the arthropods, an ancestor that probably looked a lot like those fossil lobopodians, or even modern velvet worms, at least as far as having a body composed of lots of similar segments. As arthropods evolved, some or all of those segments became specialized to perform specific functions, but the same segments were able to specialize in different ways in different types of arthropod.

The giant whip scorpion or vinegarroon (*Mastigoproctus giganteus*) is a relative of spiders, scorpions and horseshoe crabs. Like these creatures it's part of the chelicerate branch of the arthropods.

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