INTRODUCTION

Small in size but high among the wonders of nature, insects delight and amaze us with their skill in flight and their obvious ability to see. A pursued dragonfly will turn and twist but will not escape the one chasing behind, yet it can stop in an instant or catch a mosquito in midair. Unerringly, a bee will take the direct path to the hive and a hoverfly will stand still in the air with invisible vibrating wings. These actions are all controlled by vision.

We know, however, that when an engineer constructs a visual system it requires a huge computer behind the digital camera, and when we see things ourselves and make sense of them, we are using billions of nerve cells in our visual system, which occupies a large portion of our brain. So, it is a serious task to understand what insects see and how they do it, because anything that insects tell us about vision could be useful in constructing simple brains that see.

Medicine, psychology, law and religion are all subjects with a long written history loaded with confusions, contradictions and unjustified conclusions. One hopes it might be different in science, where there is supposed to be impersonal validation. Experience shows, however, that the original scientific literature is scarcely read, the all-important authors' summaries can hide the weakness of the data, the conclusions often turn out to be invalid, the titles of the papers are often misleading and textbook writers cannot know it all. Few go back and study the original design of the experiments and the data. In fact, experts are so few in the world that often there is only one research group at the cutting edge—and they have baggage and axes to grind.

The quest for scientific literacy and deep understanding is hampered by vast arrays of facts, huge reference lists and gigantic projects. The good life in science is achieved by a new technique, a chance discovery and having time to think. A student with nothing to offer but enthusiasm has two options: to join an established group or to find a little local topic that can be expanded later.

What the bee sees is an accessible topic large enough to show how we observe natural events, use experiments to discover how things work and validate the conclusions, and bee vision is a small enough topic to grasp as a whole. Bees are available worldwide and they are easily trained to select objects, patterns or any easily manipulated stimulus to receive the reward of sugar. The research is very cheap and anyone can set up shop in the hope of making discoveries.

Discovery of visual mechanisms has been sufficiently slow and controversial to make a good story. The subject is not threatening or overdone, such as climate change, nuclear power, oil or food supply. There are no high voltages, nasty chemicals, radioactivity, risks of infection or heavy lifting. The experiments are not dangerous, except to those few people who are allergic to bee stings. Moreover, the experiments are a pleasure to watch as the bees make their choices, show their abilities and reveal the errors in existing theories before your very eyes.

During the nineteenth century, 'what bees could see' was an unfathomable topic. In the twentieth century, there was haphazard progress with lots of good data, many erroneous conclusions, internal contradictions and controversies. It was a topic in crisis looking to harmonise two paradigms that seemed true but incompatible. Then suddenly, about 1990, the way forward became clear.

Examination of the process of discovery leads me to the conclusion that there is no philosophy for scientific advance. Many practical strategies are essential. We do not need full understanding to be able to make discoveries, but it is a good idea to read the literature to know what has been done. Observe nature with an informed mind. Repeat old experiments that look interesting. Look for unresolved controversies and inconclusive experiments. Design original new apparatus and techniques. Plan for the next decade of discovery. Think about the problems all the time. Go for mechanistic analysis and make an observation every day. Never accept a conclusion that is merely compatible with the data; always devise a test to check it in a different way. Avoid noology—that is, science based on thought, not observation—and avoid computer models until the very end. In fact, all models are dangerous. Learn the lesson that Darwin demonstrated by collecting lots of data before venturing to conclusions. Keep making theories but put no trust in them. Look for real mechanisms but look out for anthropomorphism.

The factor that most governs the advance of understanding is undoubtedly the ability to produce the correct thought. At any time, there is a network of mutually consistent concepts that explains most of a topic. To break out of this paradigm requires a lucky observation, a stroke of imagination or a new technique that leaps ahead. When bees were first trained to come to a pattern, it was believed that they saw and remembered the pattern. When trained bees accepted unfamiliar patterns, it was believed that they generalised certain patterns that had a parameter in common. The technique of shuffling the patterns was thought to make the bees look at them, but it also taught the bees to ignore looking anywhere else, so they were left with only one landmark to identify the place of the reward. For about 100 years, bees were trained to look at patterns before it was realised that they were not interested in the pattern, only the cues, and that they did not have foveal vision to look at things, only 300-degree vision to triangulate on a few cues at wide angles to each other to locate a place.

The factor of next importance is the ability to spot the unjustified conclusion, find its source and change it. Unfortunately, most experts are committed to their own variety of the truth as they see it, and most scientists cannot understand most scientific papers. A researcher has an idea, tests it with an experiment, finds the results are compatible with the idea, writes it up as proven and turns to another topic. A textbook writer takes the result from the title of the paper, incorporates it in a wider theme and consolidates the error in a broader theme to a larger audience. Sadly, peculiar results are not rejected, just not mentioned, like family black sheep. It is impossible to change ideas, though ideas are changed. Researchers should publish a list of known errors to guide future textbook writers. At all times, progress has been achieved by hard slog, training and testing bees in hundreds of experiments—not by insights of genius.

In scientific research, almost everything that you need to know must be learned on the job: doing research, observing nature, building experimental equipment, and so on. Existing theories can help in planning only when you notice that they are out of line with your observations.

I have tried to push back anthropomorphic concepts—such as shape, topology, fitness, generalisation and cognition—and replace them with mechanistic principles derived directly from experimental tests of theories in turn derived from earlier experimental results on bees. In a topic such as vision, an analytical mathematical theory is not appropriate, but synthetic computer models are quite valid and might lead to useful applications in computer vision. They are single channel and iterative, however, and so are not models of the visual system, which is heavily parallel with successive arrays of adaptive filters.

However deep our understanding, we will never know every detail of the bee's visual system or any other simple brain, because even if we describe every detail of the nerve cells and synapses, and record the activity of all simultaneously, we still omit the essential settings of the gain, noise, time constants, feedback loops, ionic changes and hormonal effects, as well as the processes of growth and decay that all contribute to neural activity. Anyway, vision is active; the motion of the bee activates the visual system.

Contemporary culture often appears to be in the grip of numerous contradictory beliefs, conclusions, theories or truths—call them what you will. One doomed belief was the idea that the more science became testable by being experimental, the fewer ridiculous beliefs would persist, but science is now so extensive it has become a race between the speed of education and the mortality of the experts. One sensible view was that science was what was in the textbooks, but the more that science became testable, the faster the textbooks went out of date. *Wikipedia* might keep some topics up to date, but it will struggle to provide a consensus view because experts always disagree at some level of detail.

Meanwhile, keen, hardworking undergraduates believed that science was a process of steady discovery. Their older brothers doing research knew it to be a trail marked with the corpses of previous theories and conclusions, but they still persisted in doing some experiments. Then, out of the air, they would guess a new conclusion that was consistent with their new observations. At this point, problems multiplied. First, the conclusion might have been incorrect. Second, conclusive experiments can be impossible to do. Third, secular fundamentalist professors—all German in the case of insect vision—continued to teach their erroneous beliefs, as long as they lived, as Kuhn (1970:151) quoted from the autobiography of Max Planck: 'a new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it.' My job is to inform that new generation.

In the mid-twentieth century, when scientists and social scientists alike believed that (apart from minor impediments such as communism, the Pope or a belief in Father Christmas) science and society had to build success on success to strive to arrive at truth or utopia, we thought of Reason versus Faith. Some said that the rise of nuclear power destroyed our innocence; some blamed the post-modernists; some blamed the break down of consensus societies when travel revealed their shallowness; some blamed the pluralist society with its mutually incompatible beliefs living in peace together. It is hard to accept, however, that an agreement to differ in our beliefs is a way of conducting our sciences.

Therefore, something must be decided, otherwise we dissolve in a soup of ideas. Modernisation has been a shift from a state of belief to one of choice. The way to restore much needed certainty is signposted by observations of the real world and turns out to be a perpetual seesaw between new theory and experimental demonstration.

At a dinner in the College Hall, I found myself asking the distinguished-looking woman next to me what was her attitude to the interaction of science and the arts. 'As for myself,' she offered, giving me a stern warning look, 'I am post-permissive—that is, I used to be permissive but am no longer' (I wish all women were as honest). She was referring, however, to a debate of the time called the 'science wars'. One side said that scientific theories were reliable conclusions from experiments based on earlier validated theories, and nothing else was to be believed. The other side said that theories were unreliable personal whims based on experiments that someone thought might be helpful or possible. Each accused the other side of being chicken-brained and pig-headed. On one side we have the idea that scientific objectivity is impossible because opinions and conditions in different societies differ and are volatile. This position is as impossible to sustain as the view that absolute truth exists. In all subjects, claims about truth come in all sizes and shades of grey, and fill the time of the chattering classes.

No doubt there is a difference between those who passed their science exams and those who didn't. Nonetheless, a compromise can emerge from the study of the development of ideas as we pass from one practitioner to another in the history of a topic. The realists had in mind the hard sciences of metallurgy, geology, thermodynamics, physiology, molecular biology, all three branches of chemistry, and so on, which were closed books to the radical philosophers. Their critics had in mind the so-called soft sciences such as anthropology, psychology, psychiatry and lesser superstitions such as media studies, business ethics and aromatherapy. They presented as being mutually exclusive, but they were both right. Bee vision has both hard and soft material and my effort has been to harden some of the softest parts.

This account of what honeybees see could be cannon fodder for this battle. There is an abundance of explosive material and generations of potential victims. The ideas, even in the hard sciences, are always personal but might not show it. In the hard sciences, however, they are mostly reasonably testable ideas, and some concerning bee vision have now been tested. There are interesting themes along the roads of discovery, and the foundations are strengthened by knowing their historical development.

The history of science teaches us that new ideas are thinly scattered and winners are not easy to spot. Also, we are notoriously lazy in consolidating the new into the old and especially in working out the logical consequences of new findings and deleting sections of old teaching. So, progress is slow. To pass even the most elementary examination on inshore navigation in several advanced countries, it is still essential to learn Newton's seventeenth-century theory of the tides, although the data to change it lie in every book of tide tables.

Like all science, the topic of insect vision is dotted with forgotten unsolved problems and theories that have turned out to be inadequate. The original observations were usually valid, but on the evidence available at the time the authors drew erroneous conclusions that were later overgrown with new ideas. Ageing experts become unwilling to revise their basic beliefs and nowadays it is almost impossible for anyone to finance a promising heresy. Knowledge staggers along in search of simple statements until a theory fails in too many ways and is replaced. 'Accepted, if not disproved' is not, however, sufficient. There must be no sensible alternative to the accepted story. Testing a theory means testing it with the facts against all other theories that can be imagined—an impossible task. The non-stop nature of all science soon puts books out of date and the patchy nature of publication in journals never forms a complete account. Generations of students are puzzled by inconsistencies in old accounts or they search for help in recent journals. They continually need a new synthesis. I hope that I can provide one, for a very small part of science.