electric currents that typically flow through electronic circuits, sensors and logic components could be seamlessly integrated with the actuators.

Similar integration is probably possible for certain other micromotor propulsion mechanisms, but the pathway is not as clear. Self-electrophoretic micromotors[5–7], for example, are also powered by electric currents that could potentially be connected to onboard circuitry. But those mechanisms require specific chemical environments to function, and convert energy sources into motion up to one million times less efficiently[8] than do Miskin and co-workers' machines.

More generally, researchers have pursued two strategies to overcome the technological challenges of making microrobots. Some prototype machines have a power source and computational or decision-making components that are separate from the machine itself. We can call these devices marionettes, to reflect the use of a remote energy supply and cognitive functions. Miskin and colleagues' devices fall into this category, because an operator provides instructions by shining a laser on photovoltaic patches on the robot's chassis.

The advantage of the marionette approach is that it allows functional components to be tested without having to integrate an on-board power supply and computational circuits — such integration presents technological problems that have not yet been completely solved. Marionettes might, in fact, be useful technologies in their own right, as has been demonstrated by microscale tools that can be manipulated by magnetic fields to perform eye surgery[9]. The main drawback of the marionette approach is that the robots must always be 'tethered' to their energy and information sources.

The second strategy is to try to build fully autonomous devices free of any tethers. Microrobots have been made that combine energy-storage technology, or methods for scavenging energy from the environment, with on-board logic circuits and sensors to produce controlled outputs, without tethers[10–12]. Such autonomy will probably be needed for many practical applications of microrobots.

It remains to be seen how much miniaturization might be achieved for autonomous devices without losing the capacity to program them to carry out 'smart' functions, taking into account the limits of energy storage, computational ability and fabrication methods at small scales. The limits will change as technology advances, but what is possible in a microrobot 500 micrometres in size will probably be extraordinarily difficult at 50 µm, and might be impossible at 5 µm. Marionettes will always seem more impressive than autonomous machines, because they can be used as models to showcase capabilities long before such technologies can be integrated into an autonomous device that has limited energetic and computational resources.

The resource limitations of autonomous micro-machines currently lead to design trade-offs: researchers have made great progress in designing microparticles that convert either stored or scavenged energy into mechanical motion (such as 'active colloids'[13]), but programmability remains a challenge. Miskin *et al.* provide a clear vision for solving this issue. The authors' robots, although not autonomous in their current form, can be seen as a platform to which 'brains' and a battery can be attached. Untethered, submillimetre-sized chips with sensors and integrated circuits are an active area of research[10–12], and so the hurdle of developing autonomous programmability for microrobots will soon be overcome. The integration of microscale actuators with submillimetre circuit boards and sensors will undoubtedly bring us closer to Feynman's vision.

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Ecology

An inventory of plants for the land of the unexpected

Vojtech Novotny & Kenneth Molem

New Guinea has the world's richest island flora, according to the area's first plant list catalogued by experts. Completing this list poses a formidable challenge that New Guineans are best placed to take up. **See p.579**

"I left my revolver at home, but I certainly did not forget my notebook and pencil," wrote the anthropologist Nicholas Miklouho-Maclay in 1871 when first visiting a New Guinean village[1]. His was one of the earliest long-term research residences on the island, not far from the village where one of us (K.M.) was born. The difficulty of exploring and understanding New Guinea has rarely been underestimated — it has rightly earned its name as 'the land of the unexpected'. On page 579, Cámara-Leret *et al.*[2] have shed botanical light on the richness of species there by generating a checklist that provides an inventory of the island's vascular plants (those with water-transporting tissues).

The authors' efforts have produced a list of 13,634 scientifically described plant species for the flora of New Guinea (which comprises Papua New Guinea and Indonesian Papua), of which 68% are known to occur only on the island. This tally captures the knowledge gained during nearly 300 years of scientific exploration, preceded by the 50,000 years of practical engagement with the flora that has occurred since human colonization of the island[3]. The botanical activities of these early New Guineans included the collection of wild yams and *Pandanus* nuts for food[4], followed by the independent invention of agriculture[5] and then of agroforestry. This approach of growing both trees and crops in the same place used nitrogen-fixing *Casuarina* trees 1,000 years ago, and has proved to be sustainable to the present day[6].

Cámara-Leret *et al.* enlisted 99 taxonomy experts for the task of species curation. They began by assessing the available data, which indicated the presence of 23,381 named species. However, 42% of these names had to be excluded on the grounds of being taxonomically invalid (when a species has been given more than one name), or because the plants were erroneously reported as being found in New Guinea. This demonstrates the key role of expert taxonomists' work in accurately curating messy biodiversity data. The discovery of new plant species in New Guinea continues unabated.

Disappointingly, it is unclear how many plants from New Guinea are still missing from

the scientific record and are thus absent from the list assembled by Cámara-Leret and colleagues. The authors' list includes 3,962 tree species, compared with 10,071 listed in an inventory for Amazonia[7]. The overall number of tree species in Amazonia is estimated[8] to be around 15,000. This estimate is based on extrapolations from an inventory of all of the trees surveyed in 1,946 study plots, comprising a total area of 20 square kilometres – this surveyed total represents 0.00035% of the area of the Amazonian forest[8]. It has been suggested[8] that most of the missing diversity will be captured only by intense and geographically widespread surveys, leaving us to speculate on the ecology and conservation status of Amazonia's 5,000 'ghost' tree species.

The situation in New Guinea is even worse, because the tree list generated by Cámara-Leret and colleagues cannot be assessed against a meaningful estimate of all the tree species present, owing to the lack of island-wide data from plant plots. A set of 300 plots covering a total of 3 square kilometres would match the sampling intensity achieved in Amazonia (which has forested land that is more than six times larger in area than such habitat in New Guinea)[8]. A National Forest Inventory[9] currently being carried out for Papua New Guinea could provide such data, together with data from the 50-hectare plot being investigated by the international ForestGEO forest-research network; this plot represents a key facility for biodiversity research in the country[10].

The 3,962 New Guinean tree species catalogued by Cámara-Leret and colleagues provide a resource base that supports a complex food web, including herbivores, predators, parasites and disease-causing agents (pathogens). Fifteen years of research in an area of the lowland rainforests (owned by K.M.) found that an average tree species supports around 250 species of herbivorous insect, and that the total number of herbivorous insect species increases by 50 for each additional tree species present[11]. A back-of-the-envelope calculation (ignoring differences in insect species between different geographic areas and habitats) suggests that, with 3,962 tree species, there might be up to one million different types of plant–herbivore interaction and around 200,000 tree-eating insect species in New Guinea.

One in five plant species on the list is an orchid, and, with 2,856 species, the Orchidaceae family is more diverse than the next seven-largest plant families combined. The evolutionary innovations that probably accelerated orchid speciation worldwide include pollinia (pollen parcels transferred onto a pollinator), an epiphytic lifestyle (an orchid plant grows on another plant) and a type of carbon-fixing photosynthetic process called crassulacean acid metabolism that is adapted to the arid conditions faced by epiphytes not rooted in the soil[12].

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Figure 1 | Sampling botanical specimens from rainforest canopies in Papua New Guinea. Local paraecologists (research assistants with specialized knowledge of local ecosystems and taxonomy but lacking formal academic training[17]) shoot lines to the treetops for sample collection for the Wanang Conservation Area, a conservation project being conducted on land owned by the community.

If, in a thought experiment, we imagine that all the orchids in New Guinea, with their low biomass, low number of associated herbivores, and specialized pollinators, were suddenly to disappear, the effect on most ecosystem functions would probably be rather limited, despite the loss of 21% of the island's floral diversity. This is a cautionary tale against justifying biodiversity conservation in utilitarian terms,

"There is arguably no other country whose citizens are more knowledgeable about, and comfortable living in, rainforests."

by ecosystem services, including carbon capture[13]. The most common orchid in New Guinea might be *Vanilla planifolia* (native to Mexico and Central America), which benefits from the human fondness for vanillin (one of the molecules that gives vanilla its flavour) that induces people to spread the plant to new locations and help to eliminate its plant competitors by clearing the forest, planting it and even hand pollinating it. Indonesia and Papua New Guinea rank among the world's top vanilla producers.

Scientists based in Papua New Guinea have co-authored only 15% of the papers published on the country's plants in the past 10 years, by our estimation from an online search of published papers (see go.nature.com/2eimuf2; search terms 'All databases', 'Plant sciences', Topic 'Papua New Guinea', '2010–2019'). At the same time, there is arguably no other country whose citizens are more knowledgeable about, and comfortable living in, rainforests (Fig. 1). New Guinea is the land of a thousand plant taxonomies. Insight into these plants has been developed by rainforest-dwelling societies speaking 1,053 indigenous languages, and orally transferred between generations[14]. For example, there are at least 578 ways to say 'banana', a native crop of New Guinea (see go.nature.com/2x2kcpt). One of us (K.M.) has based his botanical training on local plant knowledge, rather than university instruction, using his native Amele, a language spoken by 9,500 people over an area of 100 square kilometres.

Efforts should be made to develop a critical mass of biological expertise in Papua New Guinea (and Indonesian Papua, too), to boost the region's profile as a globally attractive option for biological research. To build on the widespread interest in the island's biology, research reform is needed, including an expansion of postgraduate education on the island, merit-based competition for research funds and closer integration of teaching universities with research institutes.

Industrialized countries have been better at transferring manufacturing expertise to tropical countries than at boosting research there.

The attitude to international research also varies among tropical countries, being determined by the opposing forces of cosmopolitanism and parochialism. An index of the ease of doing biodiversity research, analogous to the World Bank's index of the ease of doing business[15], should be developed to rank the competitiveness of tropical countries vying for the limited pool of international expertise and research funds. The 2014 Nagoya Protocol for the Convention on Biological Diversity was meant to enhance international scientific collaboration by ensuring benefit sharing. Unfortunately, over-regulation has produced the opposite effect, stifling much-needed biodiversity research in the tropics[16]. Paradoxically, this might open up an opportunity for Papua New Guinea. Unlike Indonesia, Papua New Guinea is not a signatory to the Nagoya Protocol, and this might aid its efforts to become one of the most biodiversity-research-friendly countries in the tropics.

The authors' plant list for New Guinea is an excellent start on a long journey towards obtaining a full inventory of New Guinean biodiversity — a necessary tool for ensuring plant conservation and sustainable use. It is crucial that New Guineans themselves, as the custodians of this biodiversity, should forge the path towards achieving this goal.

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Immunology

A dendritic cell multitasks to tackle cancer

Marianne Burbage & Sebastian Amigorena

Learning how immune cells target tumours is crucial for cancer immunotherapy. The finding that a type of dendritic cell activates two sorts of T cell and coordinates their crosstalk sheds light on immune responses to tumours. **See p.624**

The generation of an efficient immune response against cancer is a multifaceted, multistep process. Ferris *et al.*[1] reveal on page 624 that a type of immune cell called a dendritic cell is more versatile than was previously thought in its ability to orchestrate tumour targeting.

A key feature of the process in which immune cells target cancer is the activation of CD8 T cells. These immune cells can recognize antigens, short peptide fragments that derive from tumour cells. The initiation of antitumour responses also requires the action of dendritic cells (Fig. 1), which ingest and capture tumour-derived proteins, and process them into antigens. Dendritic cells display these antigens on their surface, bound to major histocompatibility complex (MHC) molecules, and present them to the T-cell receptor (TCR) on T cells.

Another type of T cell, called a CD4 (or helper) T cell, recognizes antigens displayed on a category of molecule termed class II MHC molecules. CD4 T cells provide accessory signals that allow CD8 T cells, which are primed by antigens presented on class I MHC molecules, to kill tumour cells (CD8 T cells that have developed this capacity are also called cytotoxic T cells). CD8 T cells can then establish long-lasting protection against tumour recurrence. Knowing how CD4 and CD8 T cells are stimulated, and by which type of dendritic cell, is central to understanding and manipulating antitumour immune responses in the clinic[2].

Most of what we know about immune responses, including antitumour responses, comes from studies of infection rather than of cancer. During viral infections, two types of dendritic cell, called DC1s (also known as conventional type I dendritic cells) and DC2s, initially activate CD8 and CD4 T cells, respectively. The two types of activated T cell then sequentially or simultaneously recognize antigens on DC1s, and CD4 T cells provide effective 'help' to CD8 T cells[3,4]. For example, CD4 T cells secrete molecules that directly support CD8 T cells. CD4 T cells also induce DC1s to express molecules that further boost the activation of CD8 T cells, a process referred to as licensing.

Whether the interactions of CD4 and CD8 T cells with DC1s are simultaneous or sequential is debated. Either way, previous results[3,4] are consistent with the model that DC1s must present antigens on both class I and class II MHC molecules to generate an immune response against an infectious agent. A microscopy method for studying cells in living animals, called intravital imaging, has already provided spectacular evidence that DC1s act as platforms that support simultaneous interactions with CD4 and CD8 T cells[3,4]. However, many studies have shown that DC1s present antigens on class I MHC molecules to CD8 T cells, whereas DC2s present antigens on class II MHC molecules to CD4 T cells[5]. Even though the selective presentation of antigens on class I and class II MHC molecules by distinct types of dendritic cell is widely accepted, it is not easy to reconcile this view with the platform model for how help from CD4 T cells occurs, because in this model the same dendritic cell needs to present antigens to both CD4 and CD8 T cells.

The platform model of DC1s enabling CD8 T cells to get help from CD4 T cells has not received definitive genetic support from *in vivo* experiments. Ferris and colleagues now report such evidence. First, the authors assessed the role of the help provided by CD4 T cells at different stages of antitumour immune responses in mice, using a type of mouse cancer, called fibrosarcoma, that is known to induce strong immune responses. One month after surgical removal of primary fibrosarcoma tumours, the authors injected cancer cells of the same type and monitored tumour growth. In control animals, these secondary tumours were rejected — destroyed by immune cells with 100% efficiency. However, antibody-mediated removal of either CD4 or CD8 T cells during the immune response against the primary tumour, or the memory immune response against the secondary tumours, abolished immune-system control of the secondary tumour. This indicates that CD4