equally well. And the two years have something else in common: political investment in science sits at a crossroads.

On 9 July, a group of scientists set up to advise the United Nations secretary-general Ban Ki-moon startled many researchers with a bold assertion: nations should invest up to 3.5% of their gross domestic product (GDP) in science.

Cue snorts of derision. Although a tiny group of nations invests around this much — Sweden and Israel among them — most fall well below this threshold. According to the latest figures from the Organisation for Economic Co-operation and Development, the United States invests 2.7%, and China 2%. The European Union average comes in at just under 2%.

Even the UN science advisory board admits that a target of 1% is perceived as high by many governments. It does, however, say that 3.5% of GDP is necessary to put the world on a sustainable development course. If this target seems rather arbitrary, it is because it probably is. But this crude measure of support for science can still be a useful metric.

Take the case of the United Kingdom. Combined private and public spending on UK science is around 1.6% of GDP. Earlier this year, the heads of various learned societies called for politicians to increase this figure to 3%, but the plea raised little more than eyebrows.

An ambition to boost government spending on science might have received a more welcome response in 2009 — but since then austerity has dominated in the United Kingdom. The Conservative–Liberal Democrat coalition government that came to power in 2010 did fulfil its promise to protect the core UK science budget from cuts, but inflation has whittled away the amount that is available for research.

Following last week's UK budget statement, there are signs that austerity measures are being relaxed — for some at least. In the first fiscal plan produced by a majority Conservative government for nearly two decades, Chancellor of the Exchequer George Osborne announced some cuts — to welfare benefits and national broadcaster the BBC, for example — but he also unveiled significant belt-loosening measures, including tax cuts for the middle classes.

Exactly what this means for science is not yet clear. The Conservatives say that they will cut about £17 billion (US$26 billion) from government departments. Some of these axe blows may fall on research spending.

But the party has been vocal in its support for some scientific projects. They have championed the (nebulous) term 'innovation' as key to improve the Britain's woeful workplace productivity. And cash has flowed, up to a point, to huge projects such as the Francis Crick Institute for biomedical research in London and the National Graphene Institute in Manchester.

"If there is money to cut taxes, there should be money to support the work that can drive economies."

Still, of Britain's 1.6% of GDP spent on science, the public spend makes up just 0.44%. Compare that with Germany, where the government contributes 0.85% of GDP out of an overall spend on science of 2.9% of GDP. And the US government spends 0.76% of GDP out of an overall investment in science of 2.7% of GDP.

If Osborne is serious about science, now is the time to prove it. At a parliamentary gathering last month, at which politicians rubbed shoulders with researchers, the subject of science funding was on the lips of many. A reference to the percentage of GDP spent on science has become de rigueur in such conversations, often with an addendum that the United Kingdom 'punches above its weight' in achieving what it does with its limited means. This attitude has almost become part of the political identity of UK science: 'we do so well with so little — why not give us more money and let us show you what we can really do'.

It has a point — if there is money to cut taxes, there should be money to support the work that can drive economies.

There are, of course, many claims on public financing, and scientists must be prepared to fight for their share alongside hospital administrators, road builders and arts funders. But if the UK government wishes to continue to wear the mantle of a science supporter, pushing towards 3.5% would be a step in the right direction. ■

An education

A special issue looks at how science is taught — and why a change in methods is essential.

One of the subjects that people love to argue about, following closely behind the 'correct' way to raise children, is the best way to teach them. For many, personal experience and centuries of tradition make the answer self-evident: teachers and textbooks should lay out the content to be learned, students should study and drill until they have mastered that content, and tests should be given at strategic intervals to discover how well the students have done.

And yet, decades of research into the science of learning has shown that none of these techniques is particularly effective. In university-level science courses, for example, students can indeed get good marks by passively listening to their professor's lectures and then cramming for the exams. But the resulting knowledge tends to fade very quickly, and may do nothing to displace misconceptions that students brought with them.

Consider the common (and wrong) idea that Earth is cold in the winter because it is further from the Sun. The standard, lecture-based approach amounts to hoping that this idea can be displaced simply by getting students to memorize the correct answer, which is that seasons result from the tilt of Earth's axis of rotation. Yet hundreds of empirical studies have shown that students will understand and retain such facts much better when they actively grapple with challenges to their ideas — say, by asking them to explain why the northern and southern hemispheres experience opposing seasons at the same time. Even if they initially come up with a wrong answer, to get there they will have had to think through what factors are important. So when they finally do hear the correct explanation, they have already built a mental scaffold that will give the answer meaning.

THE 21ST CENTURY SCIENTIST
A *Nature* and *Scientific American* special issue nature.com/stem

In this issue, prepared in collaboration with *Scientific American*, *Nature* is taking a close look at the many ways in which educators around the world are trying to implement such 'active learning' methods (see page 271). The potential pay-off is large — whether it is measured by the increased number of promising students who finish their degrees in science, technology, engineering and mathematics (STEM) disciplines instead of being driven out by the sheer boredom of rote memorization, or by the non-STEM students who get first-hand experience in enquiry, experimentation and reasoning on the basis of evidence.

Implementing such changes will not be easy — and many academics may question whether they are even necessary. Lecture-based education has been successful for hundreds of years, after all, and — almost by definition — today's university instructors are the people who thrived on it.

But change is essential. The standard system also threw away far too many students who did not thrive. In an era when more of us now work with our heads, rather than our hands, the world can no longer afford to support poor learning systems that allow too few people to achieve their goals. ■

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SPECIAL ISSUE

THE SCIENTIST OF THE FUTURE

A special issue of Nature *examines what is needed to grow the next generation of scientists.*

THE 21ST CENTURY SCIENTIST
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What does it take to be a successful scientist in the modern world? The obvious answers are deep knowledge of a discipline and mastery of the scientific method. But there are other key requirements, such as the ability to think critically and solve problems creatively and collaboratively. Communication skills are a must, and mastery of modern technology helps.

For generations, classes in science, technology, engineering and maths (STEM) have been focused almost exclusively on building knowledge alone. A steady diet of lecture-based learning was designed to fill students up with facts and test their ability to memorize them. Teaching the other skills was too often given short shrift.

Now educators and education researchers are calling for change. They argue that creative thinking, problem solving, motivation, persistence and other 'twenty-first-century skills' can, and should, be taught and fostered through well-designed courses. Developing these skills enhances students' abilities to master and retain knowledge; many hope that focusing on them will help to curb the alarming rate at which students interested in STEM abandon the subjects. The Organisation for Economic Co-operation and Development deems STEM education as crucial to powering innovation and economic growth, and has strongly encouraged investment in education strategies that focus on twenty-first-century skills.

Now *Nature*, in collaboration with *Scientific American*, is taking a look at the challenges in STEM education (a full listing of content is available at nature.com/stem). A News Feature on page 272 discusses the move towards 'active learning' rather than passive lecturing in the undergraduate classroom, but finds that encouraging innovative methods requires a change in incentives. A Comment article by representatives of the Association of American Universities and the Research Corporation for Science Advancement Cottrell Scholars on page 282 offers a road map for the institutional changes that will be required to shift the status quo.

Those teaching science in primary and secondary schools face different constraints, but have no shortage of innovative practices. A News Feature on page 276 looks at some of the most creative STEM education programmes around the world, for preschoolers up to teens. On page 286, leading design practitioners explain how nature itself aids early child development, and how architecture and play spaces are best engineered for learning. At the other end of the spectrum, senior researchers should brush up their leadership skills, says a Comment piece on page 279.

Finally, *Nature* polled some of the leading thinkers in science and education for what it takes to make an effective scientist in the twenty-first century. With answers on page 371 that range from the practical to the philosophical, it is clear that the science classroom is in for a radical change. ■

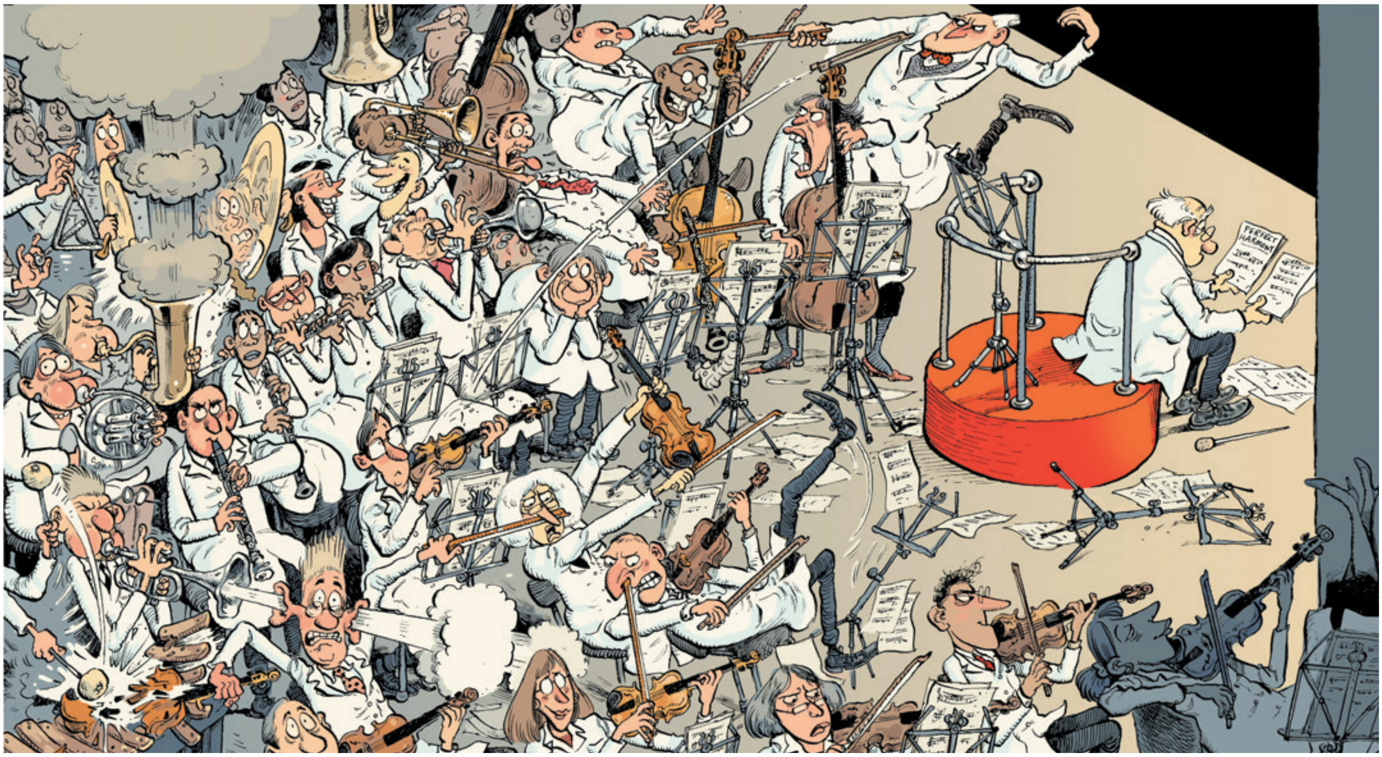
EDUCATION Improve university teaching with funds, support and data **p.282**

LEARNING Enable young scientists to get to grips with the wild **p.286**

CONSERVATION Clamp down on illegal trade in tiger parts could be harming lions **p.290**

HEALTH Call for a crack down on unaffordable essential medicines **p.290**

ILLUSTRATION BY DAVID PARKINS



Science professors need leadership training

To drive discovery, scientists heading up research teams large and small need to learn how people operate, argue **Charles E. Leiserson** and **Chuck McVinney**.

Education does not stop. Professors must update and develop their technical skills throughout their careers. But as they progress, few take the time — or are offered the opportunity — to become educated in how to be an effective leader.

As a consequence, academic teams waste time dealing with unproductive interpersonal issues, lack of motivation and unnecessary conflict. When things do not run smoothly, the costs in terms of money, productivity and retention of talent are high[1].

Leaders should inspire others to achieve clearly articulated, shared goals. Professors head research teams and manage teaching staff. They lead intellectually, charting directions for advances in engineering and science that benefit society.

And the importance of these leadership skills grows as scientists gain in seniority. Even well-meaning senior professors can wreak havoc by throwing their power around and failing to take into account the emotions of others or their own. Equally, principal investigators taking too much of a back seat can result in teams being less than the sum of their parts.

Take this true (sanitized) scenario. A major university laboratory wanted to replace their retiring director. There was no doubt as to the successor — the energetic and popular assistant director was a shoo-in. At the first meeting of the search committee, made up of a few senior lab members, the chair reviewed the procedures, which included soliciting opinions from the rest of the faculty. A consensus quickly emerged ▸

that this 'bureaucratic process' would be a waste of time. "We know what the answer will be," they said. "Everybody likes him. Let's just appoint him now."

See the committee's blind spot? They were threatening to marginalize the rest of the lab, particularly junior faculty members, by failing to get their buy-in for the appointment. Instead of saving time, this high-handed behaviour could have degraded the collegiality of the lab and required needless effort to deal with the fallout. A professor who feels disenfranchised is less motivated to help solve lab issues, leaving more work for others. If they depart for greener pastures, the rest of the faculty must hire a replacement, cover the lost professor's classes and take responsibility for abandoned graduate students. When emotions are involved, what seems like expediency can turn out to be the opposite.

In this case, one member of the committee did show true leadership, even though she had no official leadership position. She explained the risks of the rash action and persuaded a majority of the committee that the 'bureaucratic process' was a necessary step. The faculty interviews identified major issues for the next lab director to face, and when the popular assistant director was promoted as expected, he had a mandate for instituting important changes.

LEADERSHIP LESSONS

Over the past dozen years, we have taught leadership workshops for hundreds of engineering and science faculty members. Hardly any of the professors had ever taken a class in leadership skills or knew of any other programme similar to ours. Those who had had leadership education learned it in industry. US corporations spend about US$14 billion each year on educating their employees in leadership and management (see go.nature.com/2kgaya). But whereas universities welcome business people taking management training courses, leadership — a word synonymous with administration and manipulation — seems to be a dirty word when it comes to their own faculty members.

Being a professor is a human-centred activity. We work with people. We teach students in classrooms, mentor our PhD students, collaborate with peers and try to persuade people in funding agencies to give us money. But leading people can be difficult, because people are not entirely rational[2]. At most universities, junior faculty members must learn leadership skills on the job by trial and error, to the detriment of their students and careers. Senior faculty members may not understand that a failure to provide a supportive and collegial culture harms the reputation of their department or laboratory, and that they may be ill-equipped to engage effectively in large collaborative projects, such as those that dominate genomics and particle physics.

We call on academic institutions to invest in developing their professors' human-centred leadership skills.

BACK TO SCHOOL

We met in 1999. One of us (C.E.L.) had taken a two-year leave from Massachusetts Institute of Technology (MIT) in Cambridge during the Internet boom to serve as director of system architecture at the MIT start-up Akamai Technologies. Most of the firm's original 100 engineering staff were recruited directly from MIT and other top universities.

At the start, these brilliant academics were totally dysfunctional as a team. Every interpersonal issue you can imagine arose: alienation, anger, apathy, arrogance, belligerence, contempt, despair, disgust, disrespect, envy, exasperation, fear, hate, impatience, indifference, jealousy, outrage, resentment, self-righteousness, spite, suspicion, vindictiveness — the whole gamut. Despite their intellectual prowess, these erstwhile academic colleagues could find no way out of this emotional morass. Many worried that they had made the wrong move in leaving academia. Morale was low.

"Research teams are best formed from a mix of diverse thinkers."

Fortunately, Akamai's vice-president of human resources, Steve Heinrich, supplied the right medicine. He brought in the other of us (C.M.), an experienced management consultant, to run an intensive leadership workshop for the technical leaders. Topics included dealing with emotions in the workplace; working effectively with people who think differently from you; fostering creativity; resolving conflicts; giving effective feedback; learning to recognize when different situations call for different leadership strategies; and understanding how learning curves relate to motivation. The results were immediate: harsh feelings dissipated, the engineering staff began to cooperate and technical successes started to pile up.

Back at MIT, we wondered why these 'soft' leadership skills were not being taught to engineering and science professors. The same kinds of emotional issues arise in university labs as in corporate workplaces. Although professors pride themselves on their rationality, they have feelings, too.

So, the two of us teamed up to adapt materials normally used for corporate training to the academic context. We also developed university-specific content from scratch, including role-playing activities involving professors and funding agencies, professors and peers, and professors and students.

We offered the workshop for the first time in 2002 to a computer-science lab (C.E.L.'s) at MIT. The response was so positive that we expanded participation to include the Electrical Engineering and Computer Science department, and eventually, the School of Engineering and the School of Science. In 2007, we offered our two-day workshop to professors outside MIT (see shortprograms.mit.edu/lsf).

Hundreds of professors in the United States and several other countries have now taken our workshop at MIT and through custom offerings at the University of California, Berkeley; Purdue University in West Lafayette, Indiana; Harvard University in Cambridge, Massachusetts; and the National University of Singapore. Participants often express amazement at what a little leadership education can do, from reducing the number of hours spent on interpersonal issues to supplying tools for motivating students.

Our workshop focuses on how people can work together effectively. It promotes self-awareness of personal styles of leadership and offers participants new approaches to explore. Through interactive activities, self-assessment exercises and group discussions, attendees develop a repertoire of strategies for addressing common situations such as how to pitch your research programme to people outside your discipline.

Because leadership styles are individual and situational, we are careful not to judge styles as good or bad, focusing instead on helping participants to see that there may be more options available than they realized. For example, although graduate students sometimes respond well to in-depth coaching from their adviser, there are times when over-involvement can be suffocating, such as when students are starting out and need some space to get their bearings.

Participants practice their skills. For example, the module on conflict resolution concerns a dispute between two students on first authorship. One participant plays the part of the professor trying to resolve the dispute. Method-acting techniques encourage the participants playing the students to empathize with their characters, making the activity as close to a model of a real-world situation as it can be in the classroom, emotions included.

THINKING DIFFERENTLY

We use the Herrmann Brain Dominance Instrument (HBDI)[3], a self-assessment survey, to explore participants' mental diversity. Most people think of diversity in terms of the first three things that psychologists say people notice when meeting someone new: race, gender and age. But there is probably more diversity in how people think than in any physical aspect of their being.

Creativity researcher Ned Herrmann originally developed the HBDI in 1979 when he was leading management education at the General Electric conglomerate.

Herrmann was inspired by neuropsychologist Roger Sperry's work on 'split-brain' patients[4], which showed that different areas of the brain perform specific functions (Sperry shared the 1981 Nobel Prize in Physiology and Medicine for the work). In most people, the left hemisphere is associated with speech and symbol manipulation, whereas the right hemisphere processes images and responds to sensory experiences and non-verbal clues.

Herrmann augmented Sperry's left- and right-brain metaphor to incorporate the part that emotions play in thinking. Emotions sway intellect, and intellect tempers emotions[5]. The resulting 'whole brain' model categorizes thinking styles in four quadrants (see go.nature.com/jfbqky). Left-brain thinking includes rational and safekeeping processes; right-brain thinking includes feeling and creative processes. Of course, human thought is much messier, but this approximation is helpful for understanding communication and conflicts among people.

For example, a professor can use such knowledge to 'up the game' of her research group. She realizes the advantages of matching a student's role in a project to his thinking preferences rather than to her own. Suppose that a laboratory experiment requires detailed accounting and focused individual work. A student with strong safekeeping preferences is likely to be happier and more productive in this role than a student whose preferences incline them towards interpersonal relationships. When matched to their thinking preferences, students are more likely to be motivated, to work happily and efficiently, and to self-manage, leaving more time for the professor to focus on her other priorities.

TEAM SCIENCE

Research teams are best formed from a mix of diverse thinkers. Most real-world tasks require contributions from all four quadrants. When too many people on a team exhibit the same preference patterns, they tend to compete for the same 'desirable' roles, and it can be hard to find someone to do the 'undesirable' chores. A diverse team gives everyone a chance to contribute in a complementary fashion. And research shows[6] that gender-balanced teams of diverse thinkers tend to outperform same-thinking teams.

Professors tend to be sceptical about many things, and leadership is no exception. Over the years, we have heard many academic colleagues in engineering and science, especially senior ones, express opinions as to why soft skills are pseudoscience and should not be taken seriously: "people skills cannot be measured and understood the way that a subatomic particle, a strand of DNA or a computer algorithm can be"; "humans are unpredictable and emotional and cannot be understood systematically"; and "people skills are unimportant in the academic world because everyone tends to act rationally". It is no wonder that so few universities have bothered to teach leadership skills to their faculty.

Although persuading professors to change is notoriously hard[7], there are indications that things are improving. Team science[8] is a rapidly growing cross-disciplinary field of study that aims to maximize the efficiency and effectiveness of team-based research in the sciences. The growing interest in entrepreneurship among technical academics has led to a greater understanding in universities of the importance of leadership skills. And 'big science' endeavours highlight the importance of getting many people to work together effectively. Examples include CERN (Europe's particle-physics lab near Geneva, Switzerland), ENCODE and the many '-ome' projects (such as the Human Genome Project).

But leadership training alone is not enough. Academia must support and reward leadership, embracing the modern understanding that thinking — the cornerstone of academic accomplishment — involves emotion. Engineering and science must adapt to value the quality of interpersonal relationships, which are essential to teamwork. They must respect diversity of thought, especially non-technical modes, if they wish to inspire creativity.

Smooth-functioning and innovative research teams are essential for producing the inventions and discoveries needed to address the many challenging problems that our society faces. ■

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VASAVA

STEM EDUCATION

To build a scientist

Thought leaders across the globe answer one question: what is the biggest missing piece in how we educate scientists? Responses ranged from the practical to the philosophical.

PAUL NURSE
Expand across specialities

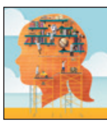
Director of the Francis Crick Institute, London

PhD programmes often lead to an increasing narrowness and specialization, which results in graduate students who are not sufficiently exposed to wider aspects of their subject and of related subjects. Looking outside the immediate interests of a thesis project can lead to real creative advances.

One way to expand thinking is to ensure that students have access to a series of inspirational speakers who will cover a wide range of scientific topics, with at least some who are more removed from their PhD focus. At the Francis Crick Institute, we will cover a wide range of biomedicine with truly inspirational speakers, but also look at other areas of science, such as high-energy physics, dark matter and aspects of biology, such as evolution and ecology, that are more distant from biomedicine.

Another suggestion is for what I call 'master classes', after the model of players of musical instruments. In science master classes, a group of graduate students would be exposed to a true expert, an excellent practitioner who would talk about doing science. I don't mean discussing the details of experiments, but discussing the broader questions: how do you do a satisfactory experiment, how do you do rigorous work, what is the nature of knowledge and so on.

The final suggestion is to broaden expectations. When students are three-quarters of the way through their graduate degree, they should be intensively mentored and urged to discuss their future careers. If they want to consider other careers, we need to build in a period of time — a few weeks — which they can use for short internships. We need to be honest, and acknowledge that not all of our students and postdocs will have a long-term career in basic research, but their education is still meaningful because they attain skill sets that they can take elsewhere — to enterprises that will profit from having scientists. We need to establish ▶



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a culture among advisers and investigators in which students who leave the academic pipeline are not considered 'failures'. They are making sensible choices and are to be cherished because they are taking science to other areas that will benefit from having them.

ATSUSHI SUNAMI

Broaden expertise across institutions

Professor at the National Graduate Institute for Policy Studies, Tokyo

As a nation, Japan needs more expertise in emerging fields such as brain science, cell engineering, data science and cybersecurity, but universities are still stuck in conventional scientific disciplines. We are asking universities to create programmes to represent these growing fields. Educational institutions need to cooperate to form a network of such programmes as they face the decline of Japan's university-age population and severe limitations on their resources.

Another urgent problem is how to encourage young scientists and engineers to go out and work with the best in the field and to gain the global connections that have become an essential aspect of science. Under changes to Japan's university system that have taken place over the past decade, many new positions are supported by competitive outside funding. This means that young scientists are hired on a fixed-term contract, which creates an insecure employment situation. Every 3–5 years, they look for another 3–5-year job. If we ask them why they do not go abroad to gain international experience, they say that they cannot risk losing the opportunity to secure another project in Japan. To resolve this, we are working to create international connections within our universities that will allow researchers to move to another country and back home again.

We also have to force change and diversity in the career track. In Japan's private sector, it is still rare for companies to hire PhD students and postdocs after they complete their training. In the past, it was almost customary to hire people directly from their undergraduate institution and route workers through their own training programmes, bypassing graduate education in exchange for lifetime employment. Universities can help to change the system: they can provide training and experience working in industry to mentor their PhD students and postdocs. To help to make this happen, we are introducing a scheme of cross-appointments of faculty-level experts in universities and companies. It will give trainees valuable skills and encourage companies to hire more PhD graduates and postdocs from universities.

JESSICA POLKA

Define purpose; demand decisions

Postdoctoral research fellow at Harvard Medical School, Boston, Massachusetts

What is missing from graduate education is a clear definition of its purpose. If graduate students are considered to be trainees, it behooves the funding agencies and everyone involved to make sure that their training is valuable to both society and the students. Graduate school is currently a research experience that is intellectually stimulating but not a clear stepping stone towards any career path. I question whether the graduate student–postdoc sequence is really necessary for training or whether it is a method of accruing credentials — and for getting science done at low cost. We should consider what benefit students gain from years four, five and even six versus their first three years. There needs to be a way to balance the needs of graduate students as students and not just as a research workforce.

To decide whether they will benefit from graduate school, people need to know where it may lead, and they need to stop thinking about faculty jobs as the probable end of the pipeline. The careers that people go into are diverse — many feel that they make use of their research training, but others do not. Mandates to create individual development plans for graduate students and to track their career outcomes would help to reveal what the job market actually looks like.

There should be more opportunities for people to make conscious career decisions. For example, I think master's degrees should be more prevalent. People who take a master's after passing a qualifying exam should be viewed as making a reasonable decision about whether to pursue a PhD, and not for failing to continue as expected.

MICHAEL TEITELBAUM

Track PhDs after their degrees

Senior Research Associate at the Labor and Worklife Program, Harvard Law School, Cambridge, Massachusetts

For decades, aspiring young scientists in PhD programmes have been unable to get a good picture of what their career opportunities might be — not even of what recent graduates have experienced. That is a recipe for them to become disappointed, disheartened and potentially forced out of science. It is the responsibility of doctoral programmes to do their best to improve this situation.

Most graduate schools seem not to try very hard to keep track of their former PhD students and postdocs. They might know where their PhD graduates go for a postdoc, but not what they are doing 5–10 years on. Faculty members may know what their lab alumni are doing, but these data typically are not centrally assembled. That information, if universities compiled it as systematically as they do for those who earn their undergraduate degrees, would be useful to prospective PhDs and postdocs who are thinking about their careers.

Universities should also consider limiting the length of the postdoc term. Many institutions have embraced formal limits — most commonly of five years — but these constraints can sometimes be sidestepped by a change in job title without a real change in role or prospects. Neither time constraints nor new job titles fixes the underlying problem of a lack of job options: the labour market for PhD scientists in most fields has not been robust. Understandably, they may want to continue for a sixth year in hopes that something will turn up, or stay for a seventh year and hope that they get that paper published in a top-tier journal.

If a postdoc wants to stay, if the principal investigator (PI) welcomes this and if there is research-grant money available, some ask why an arbitrary time limit should get in the way. But the dynamic is not working long term. Trainees need to understand that there could be diminishing career returns to opting for an extra year or two as a postdoc. Before they get to that point, PIs should be advising their PhD students and postdocs to broaden their skills beyond those typically taught in a PhD programme. Given the difficult current and prospective labour markets, well-advised PhD students and postdocs will probably realize that they need non-science professional and managerial skills if they wish to find attractive long-term careers that build on their scientific talents.

ROBERT TJIAN
Teach people management

President of the Howard Hughes Medical Institute, Chevy Chase, Maryland

My students and postdocs spend all their time focused on experiments, which is, of course, the top priority for young scientists who are building their careers. But something that we in the scientific community have not confronted very well is how to get them to focus on interacting productively with other people. Learning to manage teams and to work with others is going to become more important as science becomes more collaborative.

We are getting a little better at teaching students to write grant applications, but that is just a small part of running your own laboratory. The biggest part of leading a lab is getting the best work out of technicians, trainees and even colleagues. Typical graduate and postdoc programmes include little or no training in people management. I had to learn it by watching how my mentors ran their labs; there was no formal management training of any sort. It took a while before I learned how to guide students without tearing down their self-confidence or how to motivate students in different ways depending on their personalities.

Outside master's programmes in business administration (MBAs), there is little training in leadership, how to form the right team and how to run it effectively. But how teams work together can really influence the way you do science. Regardless of whether things are going really well or everything is messed up, you, as the lab head, must keep cool and positive. You are the proverbial cheerleader, and getting depressed — and showing it — is rarely helpful.

Better training in lab and people management will also help lab heads to guide students to choose good problems and avoid getting overly enamoured with a specific model or system, and teach them to do experiments with rigour. Universities have to recognize that leadership training is a valuable lab skill, and they need to learn how to address it.

JARI KINARET
Practise the art of incisive questions

Director of the Graphene Flagship, Chalmers University of Technology, Gothenburg, Sweden

One of the issues that is not systematically covered in most graduate programmes is how to identify good research topics. Of course, there is no single way to do this — for one thing, it depends on what you regard as a good research topic, and opinions clearly differ. For every individual, the answer evolves as one acquires skills and experience, makes new contacts and so on, but some questions remain constant. Is this worth doing? Who cares if I or we succeed? Can I do it, either alone or with colleagues? What is the competition? Is this a one-off problem or is there a future in the area?

It is not clear whether the skill of choosing good topics can be taught, but it can clearly be learned: some researchers make the right choice more often than others, and it is hardly a talent that they have from birth. The first step is for supervisors and graduate students to discuss the choice — frequently, openly and critically. I think that this aspect of graduate studies is on the decline because many researchers are bound by their grants, which are usually written and decided before the student is hired, and many graduate students must execute a pre-defined plan within strict time constraints. Planning in advance is essential, of course, but training to set — and alter — topics for study is, or should be, an integral part of graduate studies.

JO HANDELSMAN
Match training to job trends

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Because academic jobs are scarce, some analysts have proposed reducing the number of trainee positions in science, technology, engineering and mathematics (STEM). But this argument errs in its assumption that STEM students are — and should be — trained exclusively for faculty positions at research universities.

It is true that only a small proportion of those who start STEM doctoral degrees from US institutions today will go on to attain faculty positions. In biology, for example, fewer than 8% of new PhD students do so. Although that statistic might look alarming, it does not reflect the growing employment needs and opportunities that exist outside of traditional academia.

Today, the United States actually needs more, not fewer, PhD graduates in STEM fields. We must abolish the idea that these people will aim solely for academic research posts. More than 98% of STEM PhD graduates are employed, and in diverse careers. Furthermore, faculty positions are no longer the top career goal of many graduate students. A 2011 survey at the University of California, San Francisco, for instance, found that its graduate students are increasingly eager to manage research labs, direct education programmes, write, make public policy, start companies and teach at small universities. Few of these keen students, however, receive training in the skills necessary for non-conventional careers.

Graduate education in STEM should evolve to meet these needs. Courses in pedagogy, science writing, entrepreneurship or administration offered either on campuses or by professional societies would equip PhD students to confront the broad scientific job market.

The incorporation of more diverse educational experiences into US graduate training need not lengthen the time commitment. At the University of Wisconsin–Madison, for instance, some STEM graduate students have been required to do a three-month internship in industry or government. The internship did not affect time to degree, perhaps because the experience strengthened students' focus and motivation.

If graduate training were redesigned to better prepare graduate students for non-academic research careers, would they pursue more-varied career opportunities, and more confidently? Would they be more satisfied with graduate school? It's worth finding out. ■

CHRISTOPH WEHRER/STIFTUNG HAUS DER KLEINEN FORSCHER

INNER SCIENTISTS UNLEASHED

Educators worldwide are experimenting with new ways to teach future researchers — from preschool onwards.

BY MONYA BAKER

The five-year-olds are confident: trees, they agree, make the wind by shaking their branches. Their teacher does not correct them, but instead asks whether anyone has seen the wind in a place where there are no trees. One boy recalls a visit to the seashore, where the wind was whipping up water and sand with no trees in sight. Another child says that moving cars make fallen leaves twirl. Perhaps, they decide, trees are not the source of a breeze.

So goes a typical day for participants of Germany's *Haus der kleinen Forscher* (Little Scientists' House), a programme that in less than a decade has grown to reach about half of that country's children between ages three and six. Launched in 2006 by a group of German business leaders who were dismayed by their country's lacklustre performance on international student exams, Little Scientists' House got support and funding from the federal government in 2008. Today, versions of the programme are also operating in Australia, Austria, the Netherlands, Brazil and Thailand — including more than 14,000 centres in Thailand alone.

Little Scientists' House is just one of many programmes around the world that try to inspire young people's inner scientists through active engagement with the world around them. The effectiveness of this approach has been verified by hundreds of empirical studies. "It means learning content not as something you memorize and regurgitate, but as raw material for making connections, drawing inferences, creating new information — learning how to learn," says Jay Labov, a senior education adviser at the US National Academy of Sciences, one of many organizations to endorse this mode of learning. Here, *Nature* profiles innovative exemplars of such engagement, from preschool to university. If someone wanted to turn a toddler into a scientist for the twenty-first century, this is what the curriculum might look like.

Children at a German kindergarten have just found out how to make their 'bottled tornado' work.

PRESCHOOL EXPERIMENTERS

Little Scientists' House marks a departure from educators' traditional role, says Christina Jeuthe, a kindergarten teacher who participates in the programme. "You have to be willing to do something with the kids that might not lead to a result," she says. "They will not take something home that they can show their parents." Instead, teachers trained in the method try to get children to ask questions about natural phenomena and everyday objects. And when the children give naive answers (for example, that shaking leaves produce wind), the teachers help them to come up with activities to test those answers — in effect, emulating how grown-up researchers do science. But just as with scientific discovery, the end points are uncertain, says Jeuthe. "I myself had to be strong enough to not put my expectations on a specific scientific question for the kids — but let them decide, ask and discover."

In a unit about water, for example, one five-year-old argued that more water drops could collect on a euro coin than on a slightly larger 50-cent piece because the former buys more. He and his classmates counted how many drops they could dribble onto the coins' surfaces. In the end, the children could not come to a definitive answer, but that is OK, says Jeuthe. The point is to spark questions, and a conviction that they can be explored rationally.

Activities start with objects and experiences that children are familiar with — which can call for considerable creativity when adapting the programme to different places and cultures. The Australian version cannot draw on children's experience of wintry weather; instead, they focus on ice cubes. In Thailand, one activity relies on sky lanterns — miniature hot-air balloons that are common in holiday festivities. However it is done, the children say that they have fun carrying out their impromptu experiments — and in the process, say advocates of the programme, the children are learning invaluable lessons on how to plan and solve problems, not to mention gaining self-confidence.

Unfortunately, pinning down the programme's effects on students will be hard, warns Mirjam Steffensky, a chemistry educator at the Leibniz Institute for Science and Mathematics Education in Kiel, Germany. If nothing else, she says, comparisons are difficult because educators in each location are free to implement the Little Scientists' House curriculum in different ways. Still, the German Academy of Science and Engineering and other education foundations have commissioned Steffensky and several other researchers to carry out independent assessments of the programme. The three-year studies, which include control groups, will cover hundreds of students from dozens of centres to see whether the programme boosts children's language and science skills.

These assessments will not be completed until next year, but a 2013 questionnaire of more than 3,000 participating educators found that they felt more confidence and interest teaching science. "Just give the children the room, the time and the possibility," says Jeuthe. "Believe that they will work it out, and they will."

HIGH-SCHOOL COLLABORATORS

The Hwa Chong Institute (HCI) is an elite high school in Singapore that enrols only the best-performing students and then gives them access to advanced equipment, including an atomic force microscope and cell-culture incubators. The tools would be the envy of many a university, but to director of studies Har Hui Peng, that is not enough. She has always wanted to give her students an extra challenge, and a flavour of doing science in an interconnected world. She got her chance a decade ago thanks to a lucky encounter with George Wolfe, a US educator who told her that he was setting up the Academy of Sciences (AoS): a selective, publicly funded high school in Sterling, Virginia, where students could design and conduct research. Both recognized a unique opportunity to teach their students a skill essential for twenty-first-century science: collaboration.

Every October or November since 2006, a dozen or so 14- and 15-year-old HCI students have travelled to the AoS to start research projects that will last the academic year. They work in teams of four — two students from each country — on projects such as screening maggots for antimicrobial compounds. Nine months later, the AoS students join their HCI teammates back in Singapore to complete the final analysis and prepare presentations of the results.

Particularly at the beginning, some of the cultural stereotypes applied, says Ashley Ferguson, who took part in the programme as an AoS student. The US students were "more creative and free-flowing", she says, whereas their HCI teammates were more focused and directed: they considered what instruments were available and what experiments could be designed around them. "Some of that more-structured thinking was good for us to learn," says Ferguson, now a senior student at the University of Virginia in Charlottesville.

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Ernest Chen, an HCI graduate now studying at the University of Cambridge, UK, says that the project taught him the importance of communication. When he hit a snag with his project — chemically modifying a polymer to sop up dissolved metal ions — he and the other HCI student in his team wanted to change the methods. This annoyed their AoS teammates, who wanted to stick with the agreed protocol. The resulting e-mail exchanges taught everyone the skills of persistence and persuasion. "Instead of just sending a first e-mail saying, 'I'm going to change this', I would say, 'we tried this, and it doesn't work, therefore we want to change it'." Several years later, the team still stays in touch over social media.

Most important is learning to work effectively as a team, Har and Wolfe agree. The best part is when the students "start to care for each other", says Har. For example, students at one school will make sure their part of a project is completed well before another schools' exams to give their colleagues time to study, she says.

Such consideration is exactly the point, says Wolfe, now director of the AoS. "Our mission is to teach kids to do science. If you look at what scientists really do in the real world, people don't work in a vacuum."

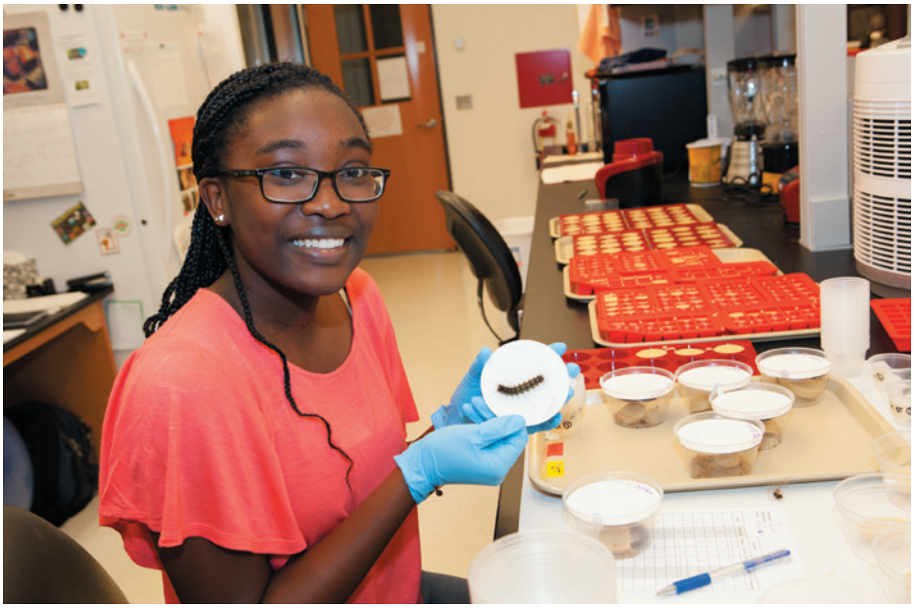
TEENAGE RESEARCHERS

Cal Hewitt does his physics calculations by accessing a grid of distributed computers set up in the United Kingdom by CERN, the European particle-physics lab near Geneva, Switzerland. Tapping into the equivalent of nearly 40,000 personal computers, Hewitt and his colleagues are calculating the types, energies and trajectories of particles detected by an experiment developed at his institution and launched into space last year. The group's findings could suggest ways to prevent damage to satellites, and perhaps firm up theories about the source of extragalactic cosmic rays. And with any luck, this will happen before Hewitt turns 18.

Hewitt is a student at the Simon Langton school in Canterbury, UK, where students routinely design and perform real, ambitious experiments. Some of the students — Hewitt included — have presented their work at scientific conferences; a few have even published original research in the peer-reviewed literature.

The school's philosophy is simple, says Becky Parker, who directs the Langton Star Centre, which hosts the school's research programmes: "Let's give students a chance to do real science and get the thrill of discovery."

Simon Langton is a state-funded, elite institution: students are accepted on the basis of an aptitude test at the age of 11. But the school's path to teen research began just over a decade ago, when Parker decided to sign up for a programme that gave secondary students remote access to telescopes in Australia and Hawaii. Rather than opting for the standard teacher-led


UNIV. RICHMOND

Summer lab research for a student on the University of Richmond integrated science course.

demonstration, Parker handed the reins to her students — who used their freedom to confirm the presence of half-a-dozen known asteroids with orbits that bring them near Earth, and went on to discover two new ones.

Around the same time, Langton students entered a competition run by the UK National Space Centre to design an experiment that would be conducted in space, basing their proposal on cosmic-ray-detection technology that they had encountered on a field trip to CERN. Contest organizers offered to launch the programme if students found the funding for it. They did. And high-calibre research projects have topped students' extracurricular activities ever since.

Now the students are running calculations on data from CERN's MoEDAL (Monopole and Exotics Detector at the Large Hadron Collider) to look for some of physics' most exotic phenomena, such as microscopic black holes. Langton is the only secondary school participating as a full member in any major particle-physics collaboration, says James Pinfold, a particle physicist at the University of Alberta in Edmonton, Canada, and spokesperson for the MoEDAL collaboration. "This work in space convinced us they could handle the job," he says.

Elsewhere in the school, one student team is using genetic analysis to breed and evaluate drought-resistant strains of wheat. Another is unravelling molecular mechanisms for multiple sclerosis — a project that required a licence for genetic modification of yeast so that the students could investigate the human gene for myelin basic protein. Langton is the first secondary school to get such a licence.

Parker estimates that Langton supplies almost 1% of all students, and at least 2% of female students, who enter undergraduate physics programmes in the United Kingdom.

Other secondary schools also promote student-led research. But the scale, scope and quality of the work at the Langton centre make it stand out. To support the work, Parker and her students have raised funds from bodies such as local government and national science organizations. Such awards even supported a particle physicist to work on Langton's campus full time to advise students and build research capacity at other secondary schools.

Most credit Parker for the school's scientific success. (At one point, project teams were limited to the number of students she could fit in her car.) But Parker says that teachers are eager to put in the time for extracurricular research once they see what is possible.

To help the Langton idea spread, Parker's next project will be the Institute for Research in Schools, which will support school science teachers who want to launch genuine research projects.

And that is what education should be, says Caitlin Cooke, a Langton student who works on the MoEDAL team. "Because we've already experienced so much work at the frontier, it demonstrates to us the reality of what it is to do physics." Her colleague, Fleur Pomeroy, agrees. "Why do people question why we can be doing real science?"

INTERDISCIPLINARY UNDERGRADUATES

When Tyler Heist was considering his first year at university, he decided to throw himself into science with abandon. Most university science courses are run by individual departments and focus on a single discipline. But the Integrated Quantitative Science class at the University of Richmond in Virginia offered simultaneous introductions to five: biology, chemistry, physics, mathematics and computer science. Better still, the course would organize the lessons around interdisciplinary problems such as antibiotic resistance and cells' responses to heat. In 2010, Heist applied for one of the course's 20 available spots and was accepted. Inspired by that experience, he will head off later this year to do doctoral work in computational biology at Princeton University in New Jersey.

The origins of the integrated course stem from a report issued more than a decade ago. The US National Research Council concluded that biological research had changed dramatically to incorporate physical and computational sciences, but biological education had not. April Hill, a biology professor at the University of Richmond, thought that the best way to fix that problem was to retool the introductory courses to view core concepts from many disciplines through the lens of real science questions, rather than taking students on the traditional march through the disciplines one by one. Hill and her colleagues ran their course for the first time in 2009.

Although interdisciplinary courses are hardly new, Hill's approach stands out for combining five distinct disciplines, for targeting introductory classes, and for including a stint of paid laboratory research in the summer following the course. Ellen Goldey, who chairs the biology department at Wofford College in Spartanburg, South Carolina, says that the University of Richmond effort has inspired other undergraduate institutions to set up similar programmes. "There is an existing model now so they will not need to reinvent the whole wheel," she says.

Hill says that the extra effort required to integrate multiple disciplines more than pays for itself; the course has prompted cross-disciplinary collaborations in her own work, on gene networks that govern the development of the most basic multicellular creatures. "Now that I have six years of interdisciplinary teaching I can't imagine not doing it," says Hill.

In 2012, the number of students taking interdisciplinary courses doubled at the university, as did efforts to recruit students from a minority background. A companion programme called SMART, now in its second year, serves students with less rigorous high-school preparation. A precollege summer programme full of mentoring and maths helps to prepare students for the interdisciplinary courses. More than 30% of the students who took the integrated class in 2009 and 2010 went on to PhD programmes. Those who take the integrated course are more likely to graduate with a STEM major — 92% versus 60% or less of other undergraduates who start out in STEM. And they also take a greater variety of classes.

Heist, for example, says that the programme helped him to get through upper-level classes that required him to read primary biology literature that incorporated concepts from physics or computer science, and credits the course with broadening his approach to scientific investigation. "It makes you rethink the boundaries you put on things," he says. ■

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