Mathematics, the media, and the public

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Abstract. It is becoming increasingly necessary, and important, for mathematicians to engage with the general public. Our subject is widely misunderstood, and its vital role in today's society goes mostly unobserved. Most people are unaware that any mathematics exists beyond what they did at school. So our prime objective must be to make people aware that new mathematics is constantly being invented, and that the applications of mathematics are essential in a technological world. The mass media can play a significant role in encouraging such understanding, but the world of the media is very different from the academic world. I describe what it is like to engage with the media, concentrating on my own experiences of the past 40 years.

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1. Introduction

For most of the 20th Century, mathematicians were free to pursue their subject essentially independently of the rest of human society and culture. In his celebrated book *A Mathematician's Apology* (Hardy [3]) the analyst G. H. Hardy wrote: 'It is a melancholy experience for a professional mathematician to find himself writing about mathematics.' In Hardy's view, writing about existing mathematics paled into insignificance when compared to creating new mathematics. In many ways he was, and still is, right. But the two activities are not mutually exclusive. Moreover, as the 20th Century has given way to the 21st, it has become increasingly vital for mathematicians to take steps to increase public awareness of their motives, activities, concerns, and contributions. Such awareness has direct benefits for the mathematical enterprise, even if that is viewed entirely selfishly: ultimately, the public purse funds our private obsessions, and will cease to do so unless the guardians of that purse are assured that the money would not be better spent elsewhere. Public awareness of mathematics (within the broader context of the 'public understanding of science') also benefits the populace at large, because we live in an increasingly technological world that cannot function effectively without substantial input from mathematics and mathematicians.

However, the role of mathematics in maintaining society is seldom appreciated – mostly because it takes place behind the scenes. The computer industry has made sure that it takes the credit (and sometimes the blame) for anything even vaguely related to its machines, but we mathematicians have failed completely to make it known

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that without our contributions, such as algorithms (and of course much else that has nothing to do with us) those machines would be unable to add 1 and 1 and make 10. So we have a lot of work to do if we want to demonstrate that mathematics is not – as many imagine – a subject that has been rendered obsolete by the computer, but a vital part of what makes computers work. And almost everything else. To quote the preface of my recent book [9]:

> No longer do mathematicians believe that they owe the world an apology. And many are now convinced that writing about mathematics is at least as valuable as writing mathematics – by which Hardy meant new mathematics, new research, new theorems. In fact, many of us feel that it is pointless for mathematicians to invent new theorems unless the public gets to hear of them. Not the details, of course, but the general nature of the enterprise. In particular, that new mathematics is constantly being created, and what it is used for.

At the end of the 19th Century, it was not unusual for the leading mathematicians of the day to engage with the public. Felix Klein and Henri Poincaré both wrote popular books. David Hilbert gave a radio broadcast on the future of mathematics. But within a few decades, the attitude typified by Hardy seems to have taken over. Fortunately, we are now reverting to the attitudes of the late 19th Century. Distaste for mere vulgarisation gave way to grudging acceptance of its occasional necessity, and this in turn has given way to active encouragement and approval. Even today, the role of populariser is not all sweetness and light, but the days when (as happened to a colleague at another institution) a senior member of the administration would castigate a member of his academic staff for daring to write a column in a major daily newspaper are long gone. If anything, we are now more likely to be castigated for *not* not writing a column in a major daily newspaper.

Since my first appointment at the University of Warwick in 1969, indeed even before that, I have been involved in many different forms of mathematical popularisation – mainly books, magazines, newspapers, radio, and television. I generally feel much more comfortable *doing* popularisation than talking about it – in fact the main advice I give to people who are interested in becoming a populariser is to get on with it – so my intention here is to describe what it is like to be engaged in such activities, with specific reference to my own experiences. I hope that this may prove useful for others who may wish to play the role of media mathematician, and informative for those who prefer to watch from the sidelines but would like to understand the nature of the game better.

2. What is popularisation?

I have given many talks that popularised mathematics, but I once gave a talk *about* popularising mathematics, which is not the same thing. One example I mentioned was a description of the Galois group of the quintic equation in comic book form [8]. Here a character in the story juggled five turnips (the 'roots' of the equation) in a blur, showing that they were indistinguishable – in short, the Galois group of the general quintic equation is the symmetric group $\mathbf{S}_5$.

A mathematics teacher in the audience objected that this was not popularisation. Just as Monsieur Jourdain, in Moliere's *The Bourgeois Gentleman*, was astonished to discover that he had been speaking prose all his life, I was astonished to discover that I had *not* been speaking popularisation. The teacher then explained that popularising mathematics meant making it accessible to children and getting them excited about it.

No: that's education. Not, perhaps, education in the sense currently envisaged in the UK (and increasingly everywhere else), which is a sterile process in which boxes are ticked to indicate that the child has temporarily mastered some small item of knowledge or technique, regardless of context, but education in the sense it used to mean, which was teaching things to children. Explaining things in a comprehensible manner, and enthusing children about the topic, are essential features of education at school level – and, indeed, in adult education too.

It was particularly clear that the teacher's view of what constituted 'mathematics' differed from mine. She was referring to the nuts and bolts of the school syllabus; my main concern was, and always will be, the frontiers of past of present mathematical research. The two are about as similar as do-re-mi and Wagner's Ring Cycle.

There is, of course, common ground. It is possible to popularise school mathematics among children without trying to teach it to them. But one of the biggest misconceptions among otherwise intelligent adults is that the 'mathematics' they did at school is *all there is*. One of the most important aspects of popularisation is to make it clear to both children and adults that this presumption is wrong.

By 'popularisation' I mean attempts to convey significant ideas from or about mathematics to intelligent, mostly sympathetic non-specialists, in a manner that avoids scaring them silly and exploits whatever interests them. I say 'attempts' because success can be elusive. The level of exposition can range from humorous short puzzles to books on hot research topics.

3. The public

The phrase 'public understanding of science' is widely used but seldom clarified. *Which* public? What are they supposed to understand? Why don't they understand it already?

The schoolteacher mentioned above had a very different idea of what the words 'public' and 'understand' meant, compared to what I meant. Many scientists consider the public to be anyone who is not a scientist, and view their alleged lack of understanding as a deficiency to be remedied by supplying the required information. Thus members of the public who are concerned about possible effects of genetically modified organisms are directed, by such scientists, towards research that demonstrates the (alleged) safety of GMOs as food; people concerned about the safety of nuclear power are directed to statistical analyses of the probability of accidents, and so on. In this view, the public – whoever they may be – are considered ignorant, and the objective of the ‘public understanding of science’ is to remedy this deplorable deficiency.

I don’t find this view helpful. Even when correct, it is patronising and self-defeating. But mostly it is not correct. Often the public, for all their ignorance of technical details, have a much clearer grasp of overall issues than specialist scientists. A major problem with GMOs, for instance, is not their safety as food, but potential damage done to the ecosystem by introducing alien species. You don’t need to know any genetics to observe that numerous confident pronouncements about GMOs made by scientific experts have turned out to be wrong, and badly so. Not long ago people in the UK were assured that genetically modified DNA could not be transferred more than a few metres by pollen. It quickly transpired that such transfer routinely occurred over distances of several kilometres. It is not necessary to prove that such transfer is harmful to notice that the experts did not have a clue what they were talking about, or that their alleged expertise had led them to wildly inaccurate conclusions. On many issues of public concern, reassurance by scientists serves only to educate the public in the limitations of reductionism and the narrow-mindedness of many scientific experts.

Some scientists even seem to think that it is possible to draw up some list of basic scientific ‘facts’ that members of the public should know, and then teach them. So they should know that the Earth goes round the Sun, that genetic information is encoded in DNA, that the Earth is 4.5 billion years old, and so on. It would certainly help if most people were aware of such things, but this attitude encourages the view that the task of science is to establish ‘the facts’, and that once these are known, that’s all there is to be said. Or, as a friend of mine’s Head of Department put it many years ago: ‘Our task as educators is to give the students the facts, and their job is to give them back to us in the exams.’ Whatever that process might be, it’s not education, and it’s not public understanding either. Though it does help to train a lot of ‘experts’ who think that their limited understanding of laboratory genetics qualifies them to pronounce on the effects of GMOs on the ecology.

My view, for what it’s worth, goes something like this. Let me phrase it in the context of mathematics, for definiteness: much the same goes for other areas of science.

All over the globe, every day of the week, mathematicians are carrying out research, proving new theorems, inventing new definitions, solving problems, posing new ones. The vast majority of the public have no idea that any of this is happening. They got excited by the TV programme on Andrew Wiles and Fermat’s Last Theorem, but that wasn’t because they thought it was the most interesting new idea in mathematics. They thought it was the *only* new idea in mathematics. What excited them was not a new breakthrough on an old problem, but the belief that for the first time in several centuries a new piece of mathematics had been brought into existence.

So the primary objective, for the public understanding of mathematics, has to be to make people aware that new mathematics is constantly being created.

This objective is more important than explaining what that new mathematics consists of, and it is more important than explaining what mathematics actually is. Only when people recognise that mathematicians are doing *something* do they start to get interested in *what* they are doing. Only when they've seen examples of what mathematicians are doing do they start to wonder what mathematics is.

If by 'the public' we really do mean the typical, randomly chosen person on the street, then we have succeeded in improving their understanding of our subject as soon as they realise that there is more to it than they met at school.

There is a more restricted subset of the public that requires, and should be given, more. These are the people who are actually interested in mathematics. They are the core audience for popularisation. For them, it is worth trying to convey more than the existence of new mathematics. It is possible to try to give a feeling for what it is.

When you watch a football match on television, it is assumed that you enjoy football and have some general idea of the rules. The commentators do not explain that the round object is a 'ball' and that the aim is to get it into the net; nor do they point out that you have to choose the right net, and that the total number of 'goals' determines who wins. You are expected to know this. On the other hand, you are not expected to know the latest version of the offside rules. The commentators assume you are aware of the issue, but have temporarily forgotten the details. By reminding you of those, they can then engage your attention in a discussion of the issues.

Too often, the media treat science very differently. You want to tell people about Fermat's Last Theorem, but first you are obliged (so the producer or editor insists) to explain what a square and a cube is and who Pythagoras was. If you want to describe the latest work on polynomial-time algorithms for primality testing, you have to explain what a prime number is and what a polynomial is. In that case, the missing information can be sketched quite quickly, but it's all too easy to find yourself in a situation where the main point you are trying to address is Galois theory, but all the programme manages to tackle is the concept of a square root. Better than nothing... but not what you intended, and not what is needed to break the mental link 'mathematics = school'.

4. Be warned

If you want to promote mathematical awareness among the public by making use of the mass media, you should be aware that it is not quite like standing in front of a blackboard or data projection screen and delivering a lecture to undergraduates. Rather different talents are needed, and in particular you have to be prepared to risk making a fool of yourself. I have dressed up in a white lab coat to talk about the probability theory of Friday 13th, presumably because the TV company concerned thought that was what mathematicians wear – or more likely thought that viewers thought that was what mathematicians wear. I have had my name up in lights on the scoreboard at Wembley football stadium, for a programme about crowd modelling that should have taken an hour to film and actually took five because the stadium – which was supposed to be empty – was full of schoolkids on their Easter break, and was being dismantled around our ears as well.

I have spent a day lugging a stuffed duck-billed platypus round an ancient castle… a colleague, who often does TV biology, remarked ‘I've never done that.’ Pause. ‘Mine was a stuffed echidna.’ (We contemplated forming the Monotreme-Luggers' Society.) I have sat in the hot sun, visibly becoming more and more sunburned as the filming progressed, because the topic was Maxwell's equations and the backdrop of an array of radio telescopes was deemed essential to the atmosphere. I have stood in a huge supermarket at peak period to deliver five seconds of wisdom about the National Lottery to BBC news, live…terrified that the woman who was noisily changing thousands of coins at a nearby machine would still be doing so when we went on air. I have spent 16 hours in a muddy quarry filming the end of the world, and driving a battered VW beetle painted to *resemble* the world. Appropriately, its clutch-cable broke ten minutes into the filming, and I had to drive it all over the quarry, and a local farm, by crashing the gears.

One attempt at a live broadcast for Irish local radio, about alien life forms, failed because they lost the connection. We did it again the next week. In another attempt at a live broadcast – I forget what about – I sat in a cramped studio for an hour, and my slot was then pre-empted by a news flash, so nothing went out at all.

On the other hand, working with the media is occasionally wonderful. My most memorable moment ever was when we started a televised lecture by bringing a live tiger into the lecture room. (Warning: do not attempt this at home.) It's a long story, but here are the bare bones.

In 1826 Michael Faraday inaugurated a series of lectures on science for young people at the Royal Institution in London, where he was resident scientist. They have continued annually ever since, except for four years during World War II, and for almost 40 years they have been televised. Until recently they were recorded ‘as live’, meaning that most mistakes were left in, in front of an audience consisting mainly of schoolchildren. (Three things you should never do in show business: work with children, work with animals, work without a script. Christmas lecturers have to do all three simultaneously.) There are a few parents too, but they are placed out of sight of the cameras.

Twice in the ensuing 180 years the topic has been mathematics. Christopher Zeeman delivered the first such series in 1978, and I gave the second in 1997. One of my lectures was on symmetry and pattern-formation. We decided to open the lecture with Blake's ‘Tyger’ poem (‘dare frame they fearful symmetry’), which, although being a cliché, seemed unavoidable.

Which meant, by the very direct logic of television, that we had to have a tiger.

A month-long search yielded a baby puma, but no tiger. We had just about decided to go with the puma when my colleague Jack Cohen found us a tiger. More accurately, a six-month old tigress called Nikka. She was wonderful, a real pro – used to the lights and an audience. She had the requisite stripes (pattern-formation, remember?). For

Health and Safety reasons she was separated from the audience by a row of upturned seats, while two burly young men held her on a chain. Apparently Health and Safety did not extend to presenters (me) so I delivered the relevant material squatting next to her. It was one of the most amazing experiences of my life, and I've never really been able to match it as a way of starting a lecture.

5. What the media want

When we write research papers on mathematics, the main criteria for publication are that the paper should be competently written, new, true, and interesting.

The criteria for acceptance of a newspaper article, a magazine article, a radio interview, or a TV broadcast are somewhat different. The most important difference is that you have to tell a story. A story has a beginning, an end, and a middle that joins them. Moreover, it should be clear at all times where the story is and where it is heading. This does not mean that you have to give away the punch line before you get to it: it means that the reader or listener must be made aware that a punch line is on its way. One way to describe the process is to say that the reader or listener needs to be given a 'road map', or at least a few signposts.

My feeling is that in principle even a research paper ought to tell a story, but mathematicians are not trained in narrative thinking, and readers are generally able and willing to go over a research paper several times seeking understanding. This is not the case for a newspaper article or a radio broadcast. Readers or listeners are busy people, often on their way to or from work, and they expect to be able to follow the story as it unfolds. A few may read an article twice, or record a radio programme and listen to it again, but on the whole they will do this because they *did* understand it first time, not because they did not.

As an example, suppose you want to write about Andrew Wiles's proof of Fermat's Last Theorem, for the *Ghastliegh Grange Gazette*. It does not work if you start with something like 'Let E be an elliptic curve...' or even something more civilised like 'The key to proving Fermat's Last Theorem is Galois cohomology...' Instead, you need to structure the story around things the reader can readily identify with. The bare bones of the story might be something along the following lines: 'Notorious puzzle that mathematicians have failed to solve for 350 years... Very simple to state but impossible to prove until now... After seven years of solitary research, major breakthrough by Wiles... Unexpectedly linked puzzle to a different area of mathematics, making breakthrough possible... Proof temporarily collapsed after being announced... After desperate last-ditch battle, proof repaired... Triumph!'

Notice that this summary of the narrative line does not include a statement of the theorem (though you would normally work this into the article somewhere) and in fact it does not even include Fermat (though again some historical background would be a good idea). It does not mention elliptic curves or Galois cohomology, and it absolutely does not define them. Your typical reader may well be a lawyer or a greengrocer, and these terms will be meaningless to them. If some technical idea is absolutely essential to your story, then you will have to find some way to make it comprehensible – but be aware that your readers have no idea what a function is, or a group, or even a rational number. This does not mean they are ignorant or unintelligent – after all, how much do you know about conveyancing or vegetables? It means that you are enticing them to venture into territory that is, for them, very new. They will need a lot of help. 'Infinite intelligence but zero knowledge' is a useful, though perhaps flattering, description.

Another extraordinarily important aspect of a story, for the media, is timeliness. The editor or producer will not only ask 'Why should I publish/broadcast this story?' They will ask 'Why should I publish/broadcast this story *today*?' (Or 'this week' or 'in the next available issue' or whatever.) It is not enough for the material to be important or worthy. There has to be a 'hook' upon which the story can be hung.

Typical hooks include:

- Recent announcement of the relevant research.
- Recent publication of the relevant research.
- A significiant anniversary – 100 years since a major historical figure associated with the work was born, died, or made a key discovery. A genuine professional science writer will keep a diary of such occasions, and be ready for them as they come along.
- A timely application (preferably related to stories currently considered newsworthy – such as cloning, nanotechnology, anything with a gene in it, mobile phones, computer games, the latest blockbuster movie. . .).
- A current controversy – the media always go for a dust-up, and it seldom matters if the source of the dispute is totally obscure. Everyone understands a fight.

There are other kinds of hook. With Christmas coming up, the TV programme *Esther* once decided to feature the science of Christmas, but much of it was deliberately spoof science – for example, my contribution was to point out that the aerodynamics of supersonic flight is very different from subsonic, so that at the hypersonic speeds employed by Santa Claus, reindeer antlers might be much more aerodynamic than they look.

They aren't, of course, but viewers knew it was a joke and subliminally took on board the message about supersonic flight changing the geometry. And they also got to see the back-of-the-envelope calculation that estimated Santa's speed.

One of the more bizarre hooks arose in 2003, when I received a phone call from the *Daily Telegraph*, one of the UK's major newspapers. A reader had written a letter, recalling a puzzle with 12 balls that he had heard about as a boy. All balls have the same weight, except for one. He had been told that it was possible to work out which ball, and whether it was light or heavy, in 3 weighings with a balance but no weights. Could anyone tell him how?

The response was remarkable. The newspaper reported [10] that 'By teatime yesterday [7 February 2003], *The Daily Telegraph* had received its biggest mailbag in living memory and our telephones were still ringing off the hook'. But the editors had a serious problem: it was unclear to them whether any of the proposed solutions was correct. Could I supply a definitive answer?

As it happened, Martin Golubitsky was visiting, and he remembered being inspired by this puzzle as a teenager. In fact, his success in solving it was one of the things that had made him decide to become a mathematician. We put our heads together and reconstructed one method for solving the puzzle. The newspaper duly published it, mainly as a way of ending the flow of letters and phone calls.

There is, by the way, a more elegant solution than the one we devised. The puzzle has been discussed by O'Beirne [4], who gives a solution originating with 'Blanche Descartes' (a pseudonym for Cedric A. B. Smith), see Descartes [2]. Here the hero of the narrative, known as 'F', is inspired to write the letters

F AM NOT LICKED

on the 12 balls: '... And now his mother he'll enjoin:

MA DO LIKE
ME TO FIND
FAKE COIN'

The poetic solution lists a set of weighings (four balls in each pan) whose outcome is different for all 24 possible choices of the odd ball out and its weight. The problem with this answer, clever though it may be, is to motivate it. This is why we settled for the more prosaic 'decision tree' of weighings that you will find in the published article. We felt that readers would be more likely to follow the logic, even if our method was less elegant.

6. The media

Let's take quick trip through the main types of media outlet. There are others – webpages, CD-ROMs, DVDs, blogs, podcasting, whatever.

6.1. Magazines. Popular science magazines have the advantage that their readership is self-selected for an interest in science. Surveys have shown that mathematics is very popular among such readers. Each magazine has its own level, and its own criteria for what will appeal. *Scientific American* is justly famous for the 'mathematical games' columns originated by the peerless Martin Gardner, which unfortunately no longer run.

In the UK there are *New Scientist* and *Focus*, which regularly feature mathematical items ranging from primality testing to su doku.

If you are thinking of writing an article for such a magazine, it is always better to consult the editors as soon as you have a reasonably well formulated plan. They will be able to advise you on the best approach, and will know whether your topic has already been covered by the magazine – a problem that can sink an otherwise marvellous idea.

Expect the editors and subeditors to rewrite your material, sometimes heavily. They will generally consult you about the changes, and you can argue your case if you disagree, but you must be prepared to compromise. Despite this editorial input, the article will usually go out under your name alone. There is no way round this: that's how things are in journalism.

6.2. Newspapers. Few newspapers run regular features on mathematics, bar the odd puzzle column, but most 'quality' newspapers will run articles on something topical if it appeals to them. Be prepared to write 400 words on the Fields medallists with a four-hour deadline, though, if you aspire to appearing in the national news.

6.3. Books. Books, of course, occupy the other end of the deadline spectrum, typically taking a year or so to write and another year to appear in print. They really deserve an article in their own right, and I won't say a lot about them here, except in Section 7 below. Sometimes expediency demands a quicker production schedule. I once wrote a book in 10 weeks. It was short, mind you: 40,000 words. The quality presumably did not suffer because it was short-listed for the science book prize.

If you want to write semi-professionally, you will need an agent to negotiate contracts. At that level, book writing is much like getting a research grant. Instead of ploughing ahead with the book, you write a proposal and go for a contract with a specified advance on royalties.

6.4. Radio. Radio is my favourite medium for popularising mathematics. This is paradoxical, because radio seems to have all of the disadvantages (such as no pictures) and none of the advantages (such as being able to write things down and leave them in full view while you discuss them) of other media. However, it has two huge advantages: attention-span and imagination. Radio listeners (to some types of programme) are used to following a discussion for 30 minutes or longer, and they are used to encountering unfamiliar terminology. And radio has the best pictures, because each viewer constructs a mental image that suits *them*.

On radio you can say 'imagine a seven-dimensional analogue of a sphere', and they will. It may not be a good image, but they'll be happy anyway. Say the same on TV and the producer will insist that you build one in the studio for the viewers to see. TV removes choice: what you get is what they choose to show you. On radio, what you see is what you choose to imagine.

6.5. Television. Television is far from ideal as a medium for disseminating science, and seems to be becoming worse. As evidence: every year the Association of British Science Writers presents awards for science journalism in seven categories. In 2005 no award was made in the television category, and (Acker [1]) the judges stated:

> To say the quality of entrants was disappointing is an understatement. We were presented with 'science' programmes with virtually no science in them. Some were appalling in their failure to get across any facts or understanding. Whenever there was the possibility of unpicking a little, highly relevant, science, or research methodology, the programmes ran away to non-science territory as fast as possible, missing the whole point of the story as far as we were concerned.

I still vividly recall a TV science programme which informed viewers that Doppler radar uses sound waves to observe the speed of air in a tornado. No, it uses electromagnetic waves – the word 'radar' provides a subtle clue here. Sound waves come into the tale because that's where Doppler noticed them.

The reasons *why* television is far from ideal as a medium for disseminating science are equally disappointing. It is not the medium as such that is responsible – although it does discourage attention-spans longer than microseconds. The responsibility largely rests with the officials who commission television programmes, and the companies who make them.

Television changed dramatically in the 1980s, especially in the UK. Previously, most programmes were made 'in-house' by producers and technicians with established track records and experience. Within a very short period, nearly all programming was subcontracted out to small companies (many of them set up by those same producers and technicians) on a contract-by-contract basis. This saved television companies the expense of pensions schemes for their employees (since they now had none) and protected them against their legal responsibilities as employers (ditto). But as time passed, contracts were increasingly awarded solely on the basis of cost. A new company would get the commission to make a programme, even if they had no experience in the area, merely because they were cheaper.

Very quickly, most of the companies that knew how to make good science programmes were ousted by new kids on the block whose main qualifications were degrees in media studies and, the decisive factor, cheapness. Any lessons previously learned about how to present science on television were lost, and had to be re-learned, over and over again, by a system dedicated to the perpetual reinvention of the wheel. There is still some good TV science, but nowhere near as much as there ought to be given the proliferation of satellite and cable channels.

The good news here is that TV is once again wide open as a medium for popular science, especially now that there are hundreds of channels desperate for content. But we will have to fight all the old battles again.

7. Narrative imperative

Sometimes an unexpected opportunity presents itself.

The Science of Discworld and its sequels *The Science of Discworld 2: The Globe* and *The Science of Discworld 3: Darwin's Watch* (see [5, 6, 7]) were written jointly with Jack Cohen, a biologist, and Terry Pratchett, one of the UK's bestselling fantasy authors. They are superficially in the tradition established in *The Physics of Star Trek*, *The Science of Jurassic Park*, and *The Science of Harry Potter*, but on closer analysis they are distinctly different, and the difference is important. The latter three books all start from a popular television, film, or book series, and use that as a vehicle for *explaining* the alleged science that could actually make such things as space warps, resurrected dinosaurs, or flying broomsticks work. This approach may be an excellent way to interest non-scientists in Relativity, DNA, or anti-gravity, but it rests on a fundamental untruth: that today's science tells us that such fiction could one day become fact. But typically the true link is rather more tenuous than that between a hang-glider and an interstellar spaceship.

The Science of Discworld series takes the opposite stance. Instead of exploiting an existing body of fantasy as a basis for dubious science, it uses genuine science as a basis for new works of fantasy. In the three Science of Discworld books, we interwove entirely new fantasy stories with voyages through significant areas of modern science. We designed both aspects of the books to complement each other. The three authors worked together to plan the combined structure, choosing scientific topics that would lend themselves to a fantasy setting, tailoring the fiction to fit the facts, and selecting the facts for suitability as components of a work of fiction.

If you've not encountered Discworld before, here's a quick introduction. Pratchett's Discworld series of humorous fantasy novels now comprises 31 novels, three graphic novels, four maps, 12 plays, two television animations, a cookery book, and countless spin-offs ranging from ceramics to computer-games. Its fans are numbered in the millions. Discworld is, as its name suggests, circular in form, and flat (though decorated with forests and oceans and deserts, hills and mountains dominated by the vast heights of the central Ramtops, where the gods live in an analogue of Valhalla). The disc is about 10,000 miles across, supported by four elephants standing on the back of the great turtle A'Tuin, who swims through space.

Discworld is inhabited by people just like us, and by an assortment of wizards, witches, elves, trolls, zombies, ghosts, golems and vampires. Much of the action takes place in the city of Ankh-Morpork, where the wizards reside within the hallowed walls of Unseen University. It is a city of medieval proportions and Elizabethan filth.

Discworld was originally conceived as a vehicle for poking fun at sword-and-sorcery books, such as Robert Howard's tales of Conan the Barbarian and Fritz Leiber's 'Fafhrd and Gray Mouser' series set in the environs of Lankhmar, the model for Ankh-Morpork. But Discworld rapidly transmogrified into a vehicle for poking fun at everything, from Hollywood to the Phantom of the Opera, from religion to engineering, from the press to the police – even mathematics.

Discworld has its own sideways logic, very appealing to mathematicians. It accepts the premises of fantasy (the Tooth Fairy really does come and take away teeth, leaving real cash) but asks hard questions (what's in it for her?). It has no qualms about world-girdling turtles swimming through hard vacuum, but wonders what happens when they mate. It acknowledges the Butterfly Effect of Chaos Theory, but wonders which butterfly has this awesome power, and how to get the blighter.

Discworld is our own planet, reified. Its driving forces are magic and Narrative Imperative. In magic, things happen because people want them to. In Narrative Imperative, things happen because the power of story makes them happen. The eighth son of an eighth son cannot avoid becoming a wizard – even if the midwife made a mistake and she was actually a girl. And so, in *Equal Rites*, the misogynist wizards of Unseen University have to come to terms with a female presence in the hallowed chambers.

Some time in 1998 Cohen and I became convinced that there ought to be a book called *The Science of Discworld*. We broached the possibility to Terry, who pointed out the fatal flaw in the plan. There is *no* science in Discworld.

In vain we argued that there is. When Greebo, the hyper-macho cat belonging to the witch Nanny Ogg is shut in a box, it rapidly emerges that there are three possible states for a cat in a box: alive, dead, and absolutely bloody furious. This is a profound comment on quantum superposition: what is the association between an object's quantum state (wavefunction) and its macroscopic state (what we observe)? If you knew the cat's wavefunction, could you tell whether it was alive or dead? My own view is that you couldn't even tell that it was a cat.

Terry gently explained why this approach would be misleading. On Discworld dragons do not breathe fire because of chemistry and genetics: they breathe fire because that's what dragons do.

What saved the idea was a concept breathtaking in its simplicity. 'Terry: if there's no science in Discworld, then you must put some there.'

Thus was born the Roundworld Project, in which the wizards of Unseen University set out to split the thaum (the fundamental unit of magic) and end up coming within a whisker of destroying the whole of the universe. As the magical reactor is about to go critical and explode, taking the universe with it, the computer Hex bleeds off the excess magic to create a small sphere, a magical containment field within which magic does not work. This is Roundworld, and it is our own universe. It runs not on magic, but on rules. It has helium and magnesium, but no narrativium. Things happen there because the rules say they must, not because someone wants them to.

Oddly, this makes everything in Roundworld harder to understand, not simpler. If a person wants something built – a house, say – then they get some builders and up it goes. But if the *rules* want something built, such as a human being, then the construction process is much more obscure, involving big molecules and bacterial blobs and billions of years of nothing much happening; then blink your eye and the humans have come and gone, leaving only the ruins of the Space Elevator, and you can't even be sure they were human.

The best way to envisage the structure of the Science of Discworld books is to think of a novelette by Pratchett, set on Discworld, with its usual cast of characters and its usual narrative constraints, but with Very Big Footnotes by Cohen and Stewart. The novelette, which comprises the odd-numbered chapters of the book, is fantasy; the footnotes, comprising the even-numbered chapters, are the scientific commentary, and are typically between two and three times as long.

This is a beautiful framework for writing about science, because the differences between magic and science are highly illuminating. Discworld is the perfect framework for a 'What if?' discussion of science – a well-established, self-consistent universe that can be used to 'compare and contrast'. We managed to work quite a lot of mathematics into the books, too: chaos, complexity, Langton's Ant, probability, phase spaces, combinatorics, information theory, infinity, and transfinite numbers. Not to mention scores of applications from astronomy to zoology.

It was fun, too.

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