Guidelines for healthy scientific writing

Introduction

In 'Uncertainty and Efficient Science' I argued that thinking about efficiency was a good way to approach the philosophy and practice of science. By that I meant that we should focus on the efficiency with which scientific research provides knowledge that is reliable and useful.

One way that science can become very *inefficient* is through poor writing. That is, writing that is unclear, confused, rambling, misleading, or openly discourages scepticism.

This can happen in even the most impressively technical areas of mathematics and science when people confuse complexity with sophistication, confuse theory with fact, and lose track of why they believe what they believe. If they then start to teach the next generation of 'scientists' to think in the same way, and even exhort them to suspend disbelief when they do not agree with what they are being told, then the science has become unhealthy.

In this article I present some simple guidelines for scientific writing.

Guidelines for research and dissemination

Write a clear, concise statement of each theory

Writing about a theory should include a concise but complete statement of that theory. This applies whether the theory is regarded as a model, hypothesis, law, or some other type of theory.

Without a clear, concise statement of what is proposed it is hard to focus critical effort on checking it logically and empirically.

Written illustrations of that theory applied to different situations can be much longer, as can explanations of empirical and theoretical tests.

Write to be understood and checked

Write so that readers can understand clearly and exactly what is being said, easily, and so can mentally check what is being said.

This is important when proposing theories, describing research, and explaining theories that have been proposed by someone else.

Obviously, it is important to avoid internally contradictory statements, mis-uses of words, and words that change meaning from one use to another without very clear explanation.

It is also wrong to use words that need to be defined but are not defined at all, are not defined until much later, or are defined only abstractly in situations where one or more examples is needed for the reader to connect the words with their existing knowledge effectively.

Hyperlinks can help tackle the problem of terminology but if there are many new terms and they are linked in complex ways then even this is not a solution. Readers become confused and lost in the web of links. Wikipedia's pages on quantum mechanics occasionally illustrate this problem.

Creating an unnecessarily large body of new terminology and abstract symbols can also be a barrier to understanding and validation by readers.

Write mathematics to be understood and checked

Crystal clear writing is particularly important for any mathematics used. This is a big subject and the article 'How to write mathematics clearly and keep more readers' gives 78 technical suggestions.

Poor mathematical writing is common and greatly reduces the number of people who can check and use it.

Avoid Analogies

Analogies are not theories, descriptions, or facts. It is a mistake to present an analogy as if it is any of those because it can lead to confusion.

> *Example:* Kurt Lewin's theorising about fields and forces uses the language of physics to talk about human minds. Taken literally this is nonsense. There is no life space in the literal sense. There are no force fields. This is a fancy way of talking about motives that tries to borrow some credibility from physics.

> *Example:* In chapter 3 of *The Quantum Universe*, Brian Cox and Jeff Forshaw introduce the idea of representing information about waves using imaginary clocks. Within a few pages they are describing the universe as teeming with clocks. Of course, there are no actual clocks. The clocks are just an analogy. The authors point this out, but that does not remove the danger of confusion. This is not an example of scientists creating or justifying a theory using analogies, but it is an example of communicating theories using analogies.

Avoid leading language

Sometimes language makes it hard to avoid confusing facts with models of those facts. This kind of language (and sometimes notation) should be avoided so that it is easier to avoid mistaken reasoning.

> *Example:* It is common in quantum mechanics to say 'the wave function collapses' when an observation is made of the state of a particle or other miniscule object. The wave function in question is a mathematical function, not some kind of physical phenomenon, but this turn of phrase creates the image of something physical. It would be better to say that the scientist can replace a probabilistic prediction of a future state by a much more precise probabilistic estimate of a past state.

> *Example:* A misleading turn of phrase often used when talking about the evolution of living things is 'in order to'. For example, 'The giraffe has a long neck *in order to* reach the edible leaves at the top of trees.' This phrasing suggests that long necks are an intentional adaptation. It is better to say that 'The giraffe's long neck allows it to reach the edible leaves at the top of trees.'

Avoid nonsense

It is also wrong to build a model that incorporates an idea you know to be nonsensical, even if the model is able to give some predictions that agree with facts. It is better to eliminate the nonsensical element and find some other way to make the same predictions.

> *Example:* There is no number that, when multiplied by itself, gives the value -1. No number, that is, that can be used to measure quantities, or position, or value. Nevertheless, in some theories it has become traditional to use the imaginary value i, with the property that $i^2 = -1$,

and the model resulting agrees well with reality. The bizarre imaginary element could be eliminated and ordinary vectors could be used throughout, with some suitable definitions and abbreviations to make it all convenient. Specifically, the convenient property of i that largely justifies its continued use is that multiplying two complex numbers together has an effect rather like adding two angles. The same effect is achieved by defining an operation for ordinary vectors of the same size. So

$$(\mathrm{a}+\mathrm{bi})(\mathrm{c}+\mathrm{di}) = (\mathrm{ac}-\mathrm{bd}) + (\mathrm{ad}+\mathrm{bc})\mathrm{i}$$

gets rewritten as something like

$$(\mathrm{a},\mathrm{b}) \otimes (\mathrm{c},\mathrm{d}) = ((\mathrm{ac}-\mathrm{bd}),(\mathrm{ad}+\mathrm{bc})).$$

Value ‘engineering’ research too

Scientific writing should acknowledge the value of all types of efficient, scientific research – not just work on supposedly fundamental theories.

How do you make a racing car go faster? The approach taken by modern Formula 1 teams gives us a sense of the contributions of various types of research to overall achievement.

There are theories about the behaviour of molecules in a gas and about the flow of liquids. However, you can’t just use their mathematical formulae to calculate the best shape for a car. The formulae might give you interesting ideas, they certainly allow you to simulate imagined shapes on a computer, and just occasionally they will allow you to estimate ideal sizes for elements of a design.

But teams don’t just do those things alone. They also use physical models in wind-tunnels to check and improve their designs – dealing with complexities that their theoretically-based simulations might have got wrong.

They also test components on the cars on a race track to find out how they perform in real conditions that even the wind-tunnel cannot replicate.

And on race weekends they continue that testing to work out what components to use and how to set up the car for the unique conditions of that track in that weather with that driver.

At each stage they try to do their tests as scientifically as possible. That is, they try to make their tests accurate and reliable, removing possible sources of bias where they can.

From this example we can see that, at least in some situations, those fair tests of what works best are a vital part of the overall approach and the theoretical models are only one small element.

This is very different from the impression ones gets from histories of science that glorify one particular discovery or theory, crediting it with all the benefits to humanity it might conceivably have contributed to, whether or not it actually did.

Early materials science was mostly done by people mixing ingredients and trying different recipes and processes to make new materials and then testing their properties. Initially, very little was known about why materials have the properties they have, and yet this process of experimentation worked.

More recently, scientists have understood more about what goes on at the microscopic and even inter-atomic level to give materials their properties. This has helped, but even today a lot of progress is still made by just trying things to see what will happen. These experiments might or might not be inspired by theories, and that inspiration might be only in general terms, not with exactly calculated predictions of properties.

In the currently popular[1] sit-com ‘The Big Bang Theory’ the three main male characters are a theoretical physicist, an experimental physicist, and an engineer. The theoretical physicist looks down on the other two, especially the engineer. The others go along with his assessment, but resentfully.

This is not a healthy situation. All those types of research have an important role.

Separate facts from models

Models (i.e. theories, hypotheses, and descriptions) are not facts. Facts are observations made. In most of life the difference between what we think will happen and what actually does happen is great, and yet we still confuse the two from

[1] As at 2016 in the UK.

time to time. In some branches of science, predictions are so accurate so often that it is easier still to get confused.

> *Example:* According to many descriptions, psychologists have 'discovered' a large number of 'cognitive biases'. In reality they have performed a large number of experiments and tried to account for them using theories that incorporate cognitive biases. Often the same results can be explained by more than one such theory and the psychologists are battling with each other to establish who has the best model. To give a specific example, the phrase Cognitive Dissonance is often used as short hand for the phenomenon observed in a particular set of experiments, but also as a reference to a theory. The results of the experiments are not controversial, but their explanation in terms of Cognitive Dissonance is, so this dual use of the term is dangerous.

Some simple habits help to keep the distinction clear.

> *Example:* In psychology, models are usually credited to particular researchers by name or with a name invented to label the theory. (Cognitive biases are an exception.) This is a habit that helps to keep in mind that some statement is a model, not a fact.

Accept that not all descriptions are explanations

Imagine that a scientist measures two variables in an experiment and finds that one is always almost exactly the square root of the other. The scientist writes down an equation that relates the two variables. That equation describes fairly accurately the relationship between the two variables but it does not explain it. There's a difference.

When an equation does a good job of describing some data that does not mean that the equation is an explanation. It also does not mean that the mathematical elements of the equation all represent something meaningful in the real world. The mechanisms that really generate the behaviour that the model so nicely describes might be quite different from those that might be suggested by the form of the equation.

Guessing real-world mechanisms from the form of an equation that fits some of its behaviour is quite a good strategy, but not infallible. Sometimes more than one different mathematical model does about as well at describing some results, and if enough scientists try enough equations then some very well-fitting models can be generated by sheer guesswork.

Compare facts with models frequently and competitively

This is one of the essential disciplines of science and yet it is not always applied. Sometimes theories are developed in great mathematical detail, for chapters and chapters of a book, without any effort to check if they are accurate to reality.

It is true that there have been examples of now-famous and successful theories that at first did not agree with all the facts known at that time. However, the best way to deal with this kind of situation is not to suspend disbelief and plough on with a theory anyway, but to be sceptical. We must remember that most theories cannot be compared to reality without a host of supporting models/assumptions, and it could be one or more of these that is at fault. In addition, simple mistakes are often made; the data may be wrong.

Competitive comparison means comparing data not just with one model but with a set of models that are alternative explanations or characterizations. We don't just want to know if the data agree with a model; we want to know if they agree with the model better than the other models.

The comparisons can be with data already collected or with data newly collected to provide a more informative test.

Guidelines for education

Scientific writing is also important in educating the next generation of scientists. Here are some guidelines.

Apply the research guidelines to education

The experience of learning a science should be similar to that of conducting research, so that young scientists acquire healthy scientific writing habits. Facts and models should be clearly distinguished and frequently compared. Analogies, nonsense, and leading language should be avoided.

Example: Teaching of physics and chemistry in UK schools currently makes almost no attempt to distinguish between facts and models, though OCR's Advancing Physics course is a good move in the right direction. At GCSE level students are told what the inside of an atom looks like. At A level, a year or so later, they are told that it looks a bit different to that. At no stage is it explained that these are just simplifications of models proposed many decades ago and that even today alternative models are being devised and tested that are different from those presented in school.

Example: Young students of applied mathematics are taught to use the SUVAT equations (with constant acceleration) to model projectiles flying through the air. Except that, because air resistance is complicated to model, the object is assumed to be flying through an airless space that nevertheless features the usual gravitational pull of the earth. Leaving out air resistance is excusable, but providing no information at all about typical errors from using the simple models is not.

Encourage scepticism

This is surely an obvious guideline. We should encourage scepticism and never ever encourage students to stop trying to evaluate what they are told and just agree with it, ignoring any doubts they may have had.

Example: In *The Quantum Universe*, Brian Cox and Jeff Forshaw repeatedly encourage readers to suspend disbelief. For example, 'With this "a particle can be in more than one place at once" proposal, we are moving away from our everyday experience and into uncharted territory. One of the major obstacles to developing an understanding of quantum physics is the confusion this kind of thinking can engender. To avoid confusion, we should follow Heisenberg and learn to feel comfortable with views of the world that run counter to tangible experience. Feeling "uncomfortable" can be mistaken for "confusion", and very often students of quantum physics continue to attempt to understand what is happening in everyday terms. It is the resistance to new ideas that actually leads to confusion, not the inherent difficulty of the ideas themselves because the real world simply doesn't behave in an everyday way. We must therefore keep an open mind and not be distressed by all the weirdness.' A bit later they say 'If you are having trouble swallowing this anarchic proposal – that we have to fill the entire Universe with little clocks in order to describe the behaviour of a single subatomic particle from one moment to the next – then you are in good company. Lifting the veil on quantum theory and attempting to interpret its inner workings is baffling to everyone. Niels Bohr famously wrote that "Those who are not shocked when they first come across quantum mechanics cannot possibly have understood it", and Richard Feynman introduced volume III of *The Feynman Lectures on Physics* with the words: "I think I can safely say that nobody understands quantum mechanics." Fortunately, following the rules is far simpler than trying to visualize what they actually mean. The ability to follow through the consequences of a particular set of assumptions carefully, without getting too hung up on the philosophical implications is one of the most important skills a physicist learns.'

Finally

Are there any of these guidelines you would disagree with? Probably not, or not very strongly, or perhaps only on some nuance. So how well does today's scientific writing conform to these guidelines? You may have noticed that many of my examples come from physics, and I suspect that modern physics has some unhealthy aspects, but it is not alone. For example, business research is poorly written, though in different ways.

References

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