SENSE ABOUT SCIENCE

MAKING SENSE OF UNCERTAINTY

Why uncertainty is part of science

CONTRIBUTORS

The contributors met over 2012 to review what is being said about scientific uncertainty in the media, policy and public life; to identify the misconceptions in these discussions and share insights that help to dispel these; and to draft and edit the guide.

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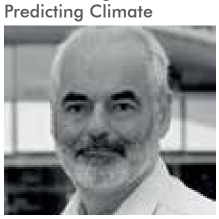

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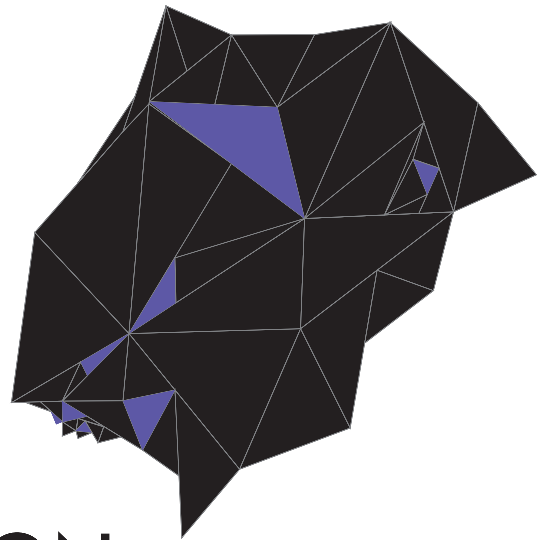

INTRODUCTION

why make sense of uncertainty?

Scientific uncertainty is prominent in research that has big implications for our society: could the Arctic be ice-free in summer by 2080? Will a new cancer drug be worth its side effects? Is this strain of 'flu going to be a dangerous epidemic?

Uncertainty is normal currency in scientific research. Research goes on because we don't know everything. Researchers then have to estimate how much of the picture is known and how confident we can all be that their findings tell us what's happening or what's going to happen. This is uncertainty.

But in public discussion scientific uncertainty is presented as a deficiency of research. We want (even expect) certainty – safety, effective public policies, useful public expenditure. Uncertainty is seen as worrying, and even a reason to be cynical about scientific research – particularly on subjects such as climate science, the threat of disease or the prediction of natural disasters. In some discussions, uncertainty is taken by commentators to mean that anything could be true, including things that are highly unlikely or discredited, or that nothing is known.

This conflict frustrates us at Sense About Science, and we know that it frustrates researchers we work with and the public we hear from. Some clearer ideas about what researchers mean by scientific uncertainty – and where uncertainty can be measured and where it can't – would help everyone with how to respond to the uncertainty in evidence.

This guide has brought together specialists in many areas – climate science, clinical research, natural hazard prediction, public health, biostatistics and epidemiology. We asked them for the reasons why they are not automatically so troubled by the presence of uncertainty in the most heated debates.

We have looked at what uncertainty means and doesn't mean in science, how it is measured, when it can't be measured and how that might change through research into the big questions. Above all we asked how other people can grapple constructively with advances in knowledge and changes in thinking, instead of despairing at 'those uncertain scientists'.

TRACEY BROWN
TABITHA INNOCENT

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"...IT BECOMES EVER MORE OBVIOUS THAT NONE OF THEM REALLY HAS A CLUE"

"WHEN DISTINGUISHED SCIENTISTS SAY IT ISN'T ACTUALLY PROVEN..."

"YOU CAN'T ABSOLUTELY PROVE, CAN YOU, THAT CO_2 IS RESPONSIBLE FOR GLOBAL WARMING?"

"LIKE WITH MANY NEURAL DISORDERS AND CONDITIONS ..THERE IS ALWAYS UNCERTAINTY IN THEIR ANSWERS"

In the areas of research that are most often in the public eye, uncertainty has become a big point of misunderstanding (even conflict) between scientists and commentators. A researcher presents his or her findings, the radio interviewer (or the politician, journalist or official) asks: 'can you be certain?'. The researcher has to answer truthfully 'no' and then defend their findings, for fear they will be interpreted as meaningless. In fact, they have provided important limits to the uncertainty.

Researchers use uncertainty to express how confident they are about results, to indicate what scientists don't yet know, or to characterise information that is by nature never black and white. But saying that something is 'uncertain' in everyday language has a negative connotation. When a researcher says 'the predictions we made on the basis of our research have a margin of uncertainty', they mean they are very confident that the outcome will fall within the predicted range. But a commentator is likely to understand from this 'the piece of research is unreliable'.

This is the type of disconnection we see in media reports of global warming, public health risks and earthquake prediction.

BUT WHY IS UNCERTAINTY SEEN TO UNDERMINE RESEARCH?

Put crudely, scientists tend to think science is about things we don't know fully. Journalists and politicians (and to a large extent, many people) think it is about things we do know, and they're impatient with 'maybe's.

The problem here is that not all scientific knowledge is the same, so treating it as though it were is misleading.

In the first place, there is rarely such thing as 100% certainty – and everything less than this is uncertain. Scientific inquiry makes some (potentially imperfect) observations, then makes predictions to test how widely the observed pattern holds true – from looking at how a molecule will behave in combating a disease to understanding the metabolisms of dinosaurs. Most people know this to some extent. They know that there are varying risks in the things they do every day, and that perfect knowledge is rarely possible (most knowledge is not like a mathematical proof). But reports and commentaries like those heading this section show that complete certainty is still seen in society as the test of new knowledge.

Secondly, new research needs to be looked at differently from settled science. Settled science is concerned with fundamental scientific principles, well-established and supported by large bodies of evidence (generally, the science we all learned in school). Everyone can be confident about a great deal of knowledge: that the earth goes round the sun, the germ theory of infectious disease, Pythagoras's theorem. Some science is widely accepted as explaining the world around us: it underpins commonplace inventions such as TV or pasteurisation, and can get us to the moon, predict an eclipse and explain why our feet stay on the ground. And while exceptions are found that show settled science can be revised ('game-changers', see section 5), research discoveries rarely change our overall understanding of the underlying scientific principles.

For the most part, settled science is not what scientists spend time thinking about, questioning or researching. Researchers aspire to add something new to what we know. Uncertainty is what they are interested in. Scientists design experiments or data-gather to get new evidence which tests models and theories in as minimally biased a way as possible – but there are limits on what can be done, and simplifying assumptions that have to be made. Research science is moved forwards by knowledge that is modified with new evidence – and most areas of research include some knowledge that is settled, and some that is more uncertain.

Across society, we don't talk much about the settled things we are confident of – the fact that an antibiotic works, say. We talk about the interesting, newer issues – such as assessing when antibiotic resistance might occur.

The essential point is that new scientific knowledge usually includes greater uncertainty and researchers often don't know how much of the picture it shows. It doesn't mean scientists know nothing, and we should not be exasperated that it is less settled than the explanation for why the sky is blue.

MICHAEL RAWLINS

"The term 'uncertainty' is unquestionably fraught with misinterpretation – especially for non-scientists. I'd prefer the phrase 'how confident am I?', the reciprocal of uncertainty."

ELIZABETH MORRIS

"The word 'certain' is like 'perfect' in the sense that it describes an end state, so it is understood that there cannot be degrees of certainty or perfection, only degrees of uncertainty or imperfection. We can say how far we are from the end state, 'almost certain' for instance."

02

WHAT DOES UNCERTAINTY MEAN FOR SCIENTISTS?

"SATELLITE DATA SOLVES ANTARCTIC SEA ICE MYSTERY"

"...ASTRONOMERS ARE CERTAIN THE ASTEROID WILL MISS"

"THE EMERGING CONSENSUS WAS THAT THE BENEFITS OF HRT OUTWEIGH THE RISKS..."

Scientific researchers have to work out whether uncertainty can be calculated and how to do so, and then whether it matters and what can be done about it.

THERE ARE SEVERAL DIFFERENT CONCEPTS OF UNCERTAINTY

Uncertainty is a hard thing to discuss because it is inherently intangible. The difficulty expressing it is not exclusive to science: it became familiar after a rather baffling speech by US politician Donald Rumsfeld in 2002:

"Reports that say that something hasn't happened are always interesting to me, because as we know, there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns – the ones we don't know we don't know."

Rumsfeld had a point. Some scientific uncertainty can be 'known': in a sense, signposted. There is uncertainty about how much global temperatures will change if carbon dioxide emissions continue at current levels for the next 50 years. But researchers know what information they would need to work this out – it is a ‘known unknown’. Knowing just what it is that we don’t yet know is very useful because it guides further research to find an answer.

But we also face ‘unknown unknowns’ – questions not yet thought of, and information we do not realise is missing at all.

These concepts of uncertainty are like the difference between a Victorian map with central Africa marked ‘unexplored’, which indicates known unknown data, and medieval maps made before Europeans knew that the New World existed, which show sea where the land should be.

DAVID STAINFORTH

UNCERTAINTIES WE CAN WORK OUT AND UNCERTAINTIES WE CAN’T

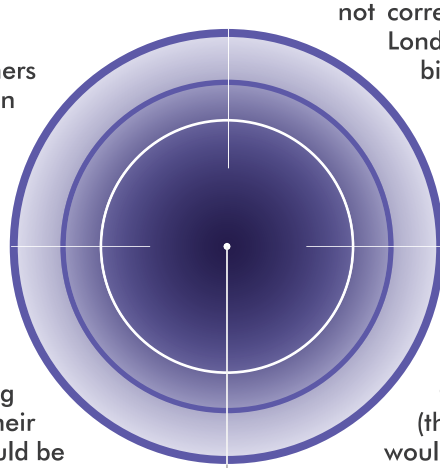
“If I drop a tennis ball, what will happen? There is some uncertainty: I don’t know details about this particular ball. I haven’t done experiments to see whether the ball falls every time. But I still know, almost certainly, that the ball will fall. I know that this would be true if I was standing in Australia, and that the way it falls would be different if I was standing on the moon. There isn’t 100% certainty because the situation might be different from what we expect – if I were working with a magician I might be suspicious about the possibility of tricks; maybe magnets in the ball and the ceiling. This could be the case. But without evidence for it I would be foolish to bet against the ball falling. Indeed I’d bet a lot that the ball would fall. Now think of a different question. When I drop the tennis ball, where will it stop? This is difficult to tell. It might bounce off a chair, a table or someone’s foot. I can calculate some limits to give me a rough idea of where the ball might end up but there will remain substantial uncertainty.

When we’re thinking about how the climate might change, the system is more complicated but the same thinking applies. There are many details about which we are extremely uncertain but there is very little uncertainty over the big picture of serious warming and significant disruption for human societies. The ball will fall we just don’t know where it will stop.”

HOW DO SCIENTISTS WORK OUT UNCERTAINTY?

The best approach to uncertainty is pragmatism. While it is important to be alert to the possibility of 'unknown unknowns' – of discovering that ideas about how the world works are stronger or weaker than we realised – that possibility alone doesn't point us towards better explanations.

On the other hand, if researchers are describing the uncertainty in how they understand a particular problem, it actually means quite a lot is known in this case about the strengths and weaknesses of the science. They may know enough about the uncertainty to be able to quantify it, e.g. 'there is a 20% chance of rain'. So if we hear scientists talking about the uncertainty in their findings in some detail we should be more reassured rather than more worried!



There are some well-established principles in statistics for calculating and expressing uncertainty (these have been explained in detail elsewhere, see Resources). They ask whether an observation or result is in the right ball-park, or how likely it is that an observation made in a piece of research is not simply a random event.

Confidence intervals tell us how reliable researchers think their observations are.

Researchers gather data; if, for example, they want to find the average height of people in London, they measure the heights of a sample of Londoners and calculate the mean average. There is some chance that the mean average (the value) the researchers have calculated is not correct. The real average height of Londoners could be a bit higher or a bit lower.

The researchers need to express that uncertainty about the value as precisely as possible, so that their result is useful to other researchers and everyone understands how likely it is to be right. Using the range of observed individual heights they can calculate the range (the confidence limits) that they would expect the mean average to fall within for at least 95 out of 100 repeats of the measurement exercise. This is a 95% confidence interval. If they wanted to know the limits of that range for a 99% confidence interval, i.e. where the mean average is likely to fall in 99 out of 100 repeats of the experiment, they would expect to give a bigger range.

> This trade off between precision and certainty is a fairly intuitive point. If you throw a ball at a target on the floor and are asked to draw a circle within which you are confident it will land, you would draw a bigger circle around the target if it had to land in the circle 99 times out of 100 than if it had to land in the circle 90 times out of 100.)

PRECISE NUMBERS SHOULD ONLY BE USED WHERE THEY ARE JUSTIFIED

DAVID SPIEGELHALTER

"In clinical medicine, doctors cannot predict exactly what will happen to anyone, and so may use a phrase such as 'of 100 people like you, 96 will survive the operation'. Sometimes there is such limited evidence, say because a patient's condition is completely novel, that no number can be attached with any confidence."

MICHAEL HANLON

"When the uncertainty makes the range of possibilities very broad, we should avoid trying to come up with a single, precise number because it creates a false impression of certainty – spurious precision."

When researchers are looking at cause and effect relationships, they usually calculate uncertainty by asking how likely it is that their observations represent a real effect, rather than simply happening by chance. This question is incorporated into the design of the study. Researchers start with a description of what they would expect to see if there was no effect (a 'null hypothesis'); they then look at how close the match is between this pattern and their observations. Researchers can put a number on the extent to which the results and the hypothesis match (a 'p-value'). This is essentially asking, 'Is our result different enough from a pattern of 'no effect' that there really looks to be something going on?'.

Where uncertainty is known, it can be incorporated into the way that effects are predicted. For example, there is some uncertainty in the initial conditions that form the basis of a hurricane forecast. In the past, forecasters showed one predicted path of a hurricane, with caveats about the uncertainty of the initial conditions. Now they tend to use the uncertainty to vary the initial conditions they put into the forecast and show the resulting range of what the hurricane will do – an ensemble forecast – so we can see how many of the forecasts come up with a similar path.

USE SEPARATE MEASURES FOR HOW GOOD THE EVIDENCE IS, AND HOW CONFIDENT THE CONCLUSION

Organisations have come up with new ways of expressing their confidence in the data. In medicine, the GRADE scale (a grading system for evidence and recommendations) is widely used, which takes into account the quality of the underlying evidence. And, in climate science, the most recent Intergovernmental Panel on Climate Change (IPCC) assessment used one verbal scale to express their confidence in the scientific understanding, and another to give the likelihood of something occurring (where 'virtually certain' corresponds to a level of more than a 99% likelihood of happening, for example).

ELIZABETH MORRIS

SEPARATE LONG TERM EFFECTS FROM SHORT TERM EFFECTS

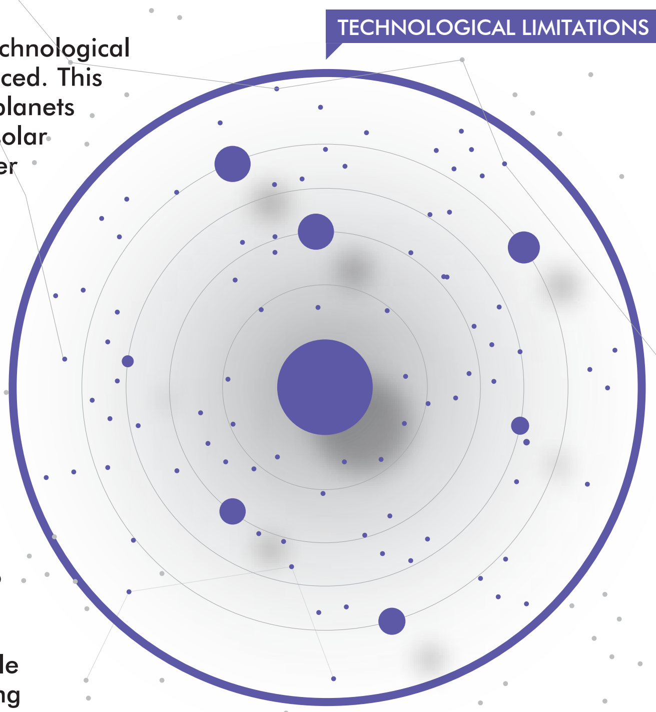
"Glaciologists use satellite data to assess changes in ice-sheet elevation and estimate their impact on sea level. We need to know whether these are long-term changes (for example produced by climate change) or just short-term fluctuations (for example produced by a particularly heavy snowfall, or if a particularly warm summer makes the surface snow denser). We can understand the uncertainty in the satellite observations of long-term change better by defining the size of the effect that short-term fluctuations could have on the satellite observations. If we observe changes which are significantly bigger than this, and we can characterise the uncertainty with the satellite observations themselves, then we can more clearly attribute these changes to long-term processes such as climate change."

WHAT CAN BE DONE ABOUT UNCERTAINTY?

Sometimes it is a question of making more observations or designing experiments or computational models to improve the available information. This is not always as straightforward as it might seem, and it can take a while to identify the information that is missing:

The early climate model simulations only included the effect of greenhouse gases. When run over the last 100 years or so for which we have instrumental measurements of surface temperature, these simulations were warm compared to observations. In time, the effect of other factors (industrial aerosols produced by burning fossil fuels, the effect of volcanic eruptions, possible variations in solar irradiance) were added. The agreement of scientists models with our observations improved, particularly due to the inclusion of the effect of industrial aerosols.
JOHN MITCHELL

Sometimes it is only through technological developments that uncertainty can be reduced. This has happened in the search for exoplanets (planets that go round stars outside our solar system) – a step towards detecting whether there is life on other planets. These planets were only detected very recently when instruments and techniques became sufficiently accurate, but progress has been rapid. The first exoplanets were discovered in the 1990s, and thousands have now been identified. Their discovery is progressively reducing the degree of uncertainty we have about things like the existence of life on other planets, by improving our estimates of the number of planets outside the solar system, and of the fraction of these that may be able to support life.



But reducing uncertainty is often not possible or necessary and this is not a barrier to using scientific knowledge.

The question is not ‘do we know everything?’

it is ‘do we know enough?’

or ‘how can we best make a decision using what we do know?’.

For example, Newton’s law of gravity is still sufficient to get us to the moon and back in spite of not being a complete model of the way gravity works. Or if, say, all values within a confidence interval point to the same clinical decision, further narrowing the uncertainty may be a waste of public funds. Researchers can incorporate uncertainty into calculations or work round it.

Quantify 'routine' uncertainty and incorporate it into calculations

Uncertainty is considered routine in a lot of cases – it can't be eliminated but it's not necessarily problematic (and a decision can be made 'beyond reasonable doubt'). For example, there is a degree of imprecision in assessing the fetal age from ultrasound scans during pregnancy (which are used to estimate the due date). This arises from the natural variation of size-for-age and from differences in the skill, experience and equipment of the ultrasonographer. However, we can quantify this uncertainty and use it to explain to women that the calculated due date should be used as a guide, rather than an exact prediction of the actual due date.

Calculate risk, a more usable measure of uncertainty

When uncertainty relates to a real-life situation with important and perhaps detrimental consequences we can work out how the uncertainty affects the risk, which is more tangible.

There is some confusion between scientific and everyday uses of the words 'uncertainty' and 'risk'. In everyday language, we might say that something that is uncertain is risky. But in scientific terms, risk broadly means uncertainty that can be quantified in relation to a particular hazard – and so for a given hazard, the risk is the chance of its happening. For example, research shows that oestrogen therapy (a form of HRT, to relieve the symptoms of menopause) appears to increase the risk of women suffering from heart disease (an associated hazard). Current evidence suggests the risk is small, but there is a lot of uncertainty around the estimate and so the real effect could be larger or smaller than estimated.

Risk is also a way of thinking about which uncertainties to worry about. For example, there is a greater risk of agricultural chemicals running off into waterways and damaging aquatic life when land is bare. We should therefore be more interested in reducing uncertainty about the hazard to aquatic life of those chemicals used on bare land. Risk is especially important when we want information that is useful for decision-making. (But risk itself is a whole other story, told in some of the resources at the end.)

Mitigate the effects of uncertain events

Another response to uncertainty is mitigation. There is currently irresolvable uncertainty about earthquakes: researchers know where they are going to occur, but cannot predict when they will happen.

"In a scientific sense, earthquakes are unpredictable. But that does not mean that you can't predict things about them."
PETER SAMMONDS

Using historical data and geology, researchers can calculate how frequently a particular scale of earthquake is likely to occur in a specific location. A one-in-ten year calculation doesn't say anything about which ten years in 100 will see an earthquake. But it means researchers can calculate what kind of reinforcement to buildings would be needed to make sure they could withstand this frequency of quakes. If a serious earthquake is a one-in-200 year event, a community might only put resources into reinforcing a building that is designed to last ten years if its function was sufficiently important – a school or hospital, for example.

03

PREDICTIONS AND MODELS

"FORECASTS FOR GLOBAL WARMING TOO HIGH"

"NEW COMPUTER MODEL PREDICTS WHEN AVIAN INFLUENZA STRAIN BECOMES INFECTIOUS"

"ECONOMY WILL SHRINK THIS YEAR, TREASURY FORECASTS SHOW"

"WHICH WEATHER FORECAST SHOULD YOU BELIEVE?"

Modelling is an area that regularly causes misunderstanding about uncertainty; recriminations quickly follow events that don't match predictions.

Many of us look at models as a 'black box' where data go in and answers come out. Some scientists find that image annoying because of the scientific insight that goes into how models are constructed. Scientific models differ greatly across fields of research, and specialists in one field might have no idea about what is involved in modelling in another. Suggesting all models are the same is like saying that all experiments are the same or all tools are the same.

SCIENTIFIC MODELS

The scientific models we are concerned with here are numerical representations of a process or system to simulate some aspect of the world: how will a disease epidemic progress? Will a new bridge hold sufficient weight? How have genetic traits spread among human populations? These models usually involve joining up different ideas or information about how different parts of a process work.

These models are a necessary simplification of the real world and use experimental data or observations, or physical understanding of nature, or some combination of these. Sometimes the components are empirical, sometimes statistical, and sometimes direct applications of physical laws. Different problems require different modelling approaches and, because not all models are the same, the uncertainty around models can be very different.

WHAT MODELS CAN DO

The vast majority of models that researchers make have a fairly routine use in research and in everyday clinical applications, and are often a simple descriptor of a process.

Models are usually used for two reasons, to:

1 ...understand patterns or the interplay of different factors

If researchers already know an outcome they can use a model to work out the possible ways this could have come about or which factors have an important influence. Models can fill in the gaps between observations – for example, in the process of reconstructing evolutionary trees.

2 ...make predictions

Researchers start with observations about how things are now, and use models to predict the future evolution or to create different future scenarios that could result from this starting point. This gives an idea of the range of things that could happen.

Modelling can be one of the most useful tools for reducing uncertainty in a crisis. Researchers turn to models when there is already a lot of uncertainty about a question, and they need more information to support decisions on what to do next. Modelling can generate a 'shopping list' of things researchers would like to know more about.

"In epidemiology, one difficulty is that people's behaviour directly affects the course of an epidemic (unlike, say, the weather, which will be the same regardless of how people respond to it). How people mix – how many people, and from which age groups – tells us a lot in predicting how a virus will spread. Past estimates of how much mixing occurs were very uncertain and epidemiologists knew this was an important 'unknown' in their models. Then a recent study recorded and quantified how often different age groups interact with each other over an individual's lifetime, for the first time. We can now use this to inform models of disease epidemics. By identifying the important uncertainties, we can try to reduce them."
ANGELA MCLEAN

Do models reinforce assumptions?

Because models simplify the world they have to make assumptions, some of which may not be correct. Are models verified independently or do they reinforce the same assumptions? That depends. Some models can be verified – for example the accuracy of weather forecasts can be tested against what actually happens with the weather. But some models cannot be verified in this way. If two models are based on the same assumptions they are likely to produce more similar results – so an answer from one is not entirely independent of the other. Where models based on different assumptions give a similar answer, these are more independent and can therefore provide an indirect way of verifying the original model. (This question about independence is currently the subject of a lot of debate among researchers.)

MODELS ARE NOT…

…intrinsically uncertain

There are many models in routine, everyday use and often these are already settled science and have low uncertainty.

"Early signs of a measles outbreak were detected in New Zealand in 2011, alongside a very low level of immunity among young people. Because the government was slow to respond, an outbreak started. Fortunately, as we know a lot about this virus, they already had models of how a measles outbreak escalates and had plans in place to control its spread. They were well able to stop the outbreak escalating. Because the uncertainty in the models was relatively low, they generated confident predictions that informed a useful intervention." ANGELA MCLEAN

… static

Models change as the information researchers have changes.

"We used to think that everyone who caught flu became ill, but the 2009 H1N1 (swine flu) pandemic taught us that this clearly isn't true. The biggest uncertainty throughout the pandemic was the proportion of people who would become ill after getting the virus. Models of the worst-case scenarios predicted this could be high, which was picked up in alarming headlines saying that lots of people would die from swine flu. In the end, roughly one third of the UK population were infected, which was as expected. But it was something of a surprise that only a tiny fraction became ill; it turns out that for H1N1 pandemic flu it is about 1 in 20. This makes the distinction between infection and disease very clear: lots of people were infected, far fewer were ill.

There had to be a real-life pandemic event for us to find this out because it is impossible to discriminate clearly between strains of seasonal flu virus. Now that we know this, models can change to make more accurate predictions. This will improve our ability to manage pandemic threats. It will also inform the type of statements scientists and others make about the public health risk." ANGELA MCLEAN

…an answer waiting to be discovered

There is often more than one way to model any problem. Most processes and scenarios are not straightforward to model, and experts do not all agree on the best approach. This disagreement is sometimes taken to mean that everything is contested and unreliable. In fact, using diverse approaches is a good thing in any area of scientific research, and is encouraged. Researchers can then see whether different models produce a similar answer independently of each other; if they do, this helps to quantify the uncertainty.

…always very interesting (to most people)

Small changes to models never make the news. They rarely capture much attention among scientists either. These tweaks are often not even well documented – but should be, by the modellers at least – because most of them are not viewed to be scientifically important enough. But this means that the effects on data over time can be hard to track – similar to the problem of negative trial results going unreported – and introduce unknown bias. Some modellers have suggested there should be a Journal of Tweaking!

…able to answer everything

The capacity of models to answer increasingly sophisticated questions is sometimes limited by technology. For example, current limits with computing power put some constraints on the progress climate modellers and others can make – there are not yet powerful enough computers to consider all possible future climate scenarios to the same level of detail as it is possible to forecast the weather. This means that researchers have to make choices that restrict models to answering specific parts of a problem. In the case of climate modelling this might mean researchers can use a model to look at climate for a large geographic area, or for a much smaller area in greater detail, but not both at the same time.

04

DO WE EVEN NEED MORE CERTAINTY?

"WE WERE TOLD 'NO RISK', CLAIM FLOOD FAMILIES"

"MORE BSE CASES BUT MINISTER INSISTS BEEF IS SAFE"

"SCIENTISTS BLAMED FOR QUAKE DEATHS"

"DECLARING A SWINE FLU PANDEMIC WAS A 'MONUMENTAL ERROR' "

The UK government used its stockpile of antiviral medication in 2009 when a swine flu pandemic was predicted, at great expense; did they over-react to the uncertainty inherent in the swine flu model?

Striving for certainty in scientific research, even research that affects public policy, can be a waste of effort and resources. What we need instead is to talk about just how much information is enough to make a sound decision, because if we ask whether we really need more certainty, sometimes the answer is a clear "no".

DO WE EVEN NEED TO KNOW?

"In policy-oriented research, there is a tendency to focus on trying to establish more complete predictions, for example of future temperature variations, to feed into decisions. This leads to too much emphasis on improving knowledge of all the uncertainty ranges. Instead, we should identify which details are most relevant to a decision and extract the relevant information from models about processes and trade-offs, working on the uncertainties that really matter for the particular problem we are trying to address." ANDY CHALLINOR

OPERATIONAL KNOWLEDGE

Decision-makers generally look for a higher level of certainty for an operational decision (such as introducing body scanners in airports) than for a decision based on broader ideology or politics (such as reducing crime rates).

'When are we certain enough?' is never going to be easy to answer. It depends on the desire to act, robust public discussion, leadership, willingness to address criticism and the risks involved in getting things wrong. Decisions are usually made by policy-makers and officials, not researchers – science doesn't tell us 'what to do' – and what they need is 'operational knowledge'.

Engineers work with operational knowledge all the time – this comes down to knowing enough to be confident about carrying out a particular task. Take aeroplanes: every component and every aeroplane is regularly tested. As a result they are very safe machines that operate within well-known limits. So even though it is impossible for an engineer to predict every variable that an aeroplane will be subjected to, they can still be flown with confidence. And engineers can manage any events that introduce greater uncertainty. For instance, when the volcanic ash cloud accumulated over Northern Europe in 2010, planes were initially grounded as this increased the uncertainty about when it was safe to fly. Researchers subsequently developed remote ash sensors for aeroplanes and ran experiments to understand the extent to which engines could tolerate ash, to say confidently when it was safe to fly.

"All the time, multi-million pound decisions are made using weather forecasts that contain uncertainty: in energy trading to predict future energy demands, or by local councils deciding when to grit roads, for example. If you know the potential cost or damage, and the parameters that matter, you can work out when it pays to take action." LEONARD SMITH

SCIENTIFIC UNCERTAINTY & PUBLIC POLICY

Decisions are not made on the basis of scientific evidence alone, though it may play an important role.

"Scientific uncertainty is only one of a whole raft of factors that influence decision making: the impact on constituents, party votes, ideological perspective, economic implications and so on. The impression is sometimes given that policy makers and politicians are uncomfortable with handling uncertainty, but every day they have to make decisions on the basis of largely uncertain information."
CHRIS TYLER

Sometimes researchers don't have all the evidence and need to be clear when that is the case. In areas of scientific uncertainty this is particularly important given the scope for the uncertainty itself to become politicised. We have seen this when uncertainties in the details of predictions about climate change and disease epidemics have been amplified to cast doubt on any and all research.

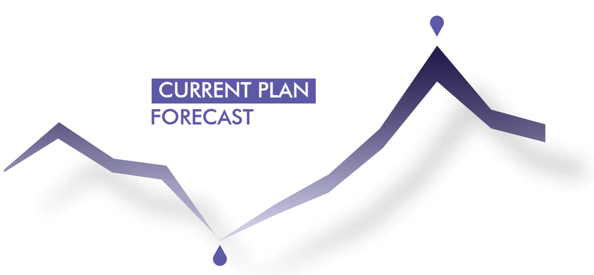
The reality is that scientists are not, for instance, debating the evidence for man-made global warming; they are debating uncertainty about the extent and timing of changes, and the most accurate methods for predicting these. We should recognise this misuse of uncertainty for what it is, essentially smoke and mirrors that distract from the decision-making process.

WE CAN'T ALWAYS IGNORE UNCERTAINTY SO WHAT ARE THE ALTERNATIVES?

Few people would argue that clear communication about uncertainty is unimportant, but there are different ideas on the most effective approach. Although there is still a long way to go, there are insights emerging from some areas of research – public health, climate science, economics – where understanding and communicating uncertainty is especially difficult.

As discussed in section 2, it is misleading to quantify uncertainty that cannot be quantified – in these cases there is an even greater need to talk equally clearly about what researchers do not know as what they do. 'Unknown unknowns' cannot be identified, much less quantified, and the best approach is to recognise this.

"The Bank of England produces forecasts with quantified uncertainties and contingent predictions – these completely leave aside some of the uncertainties deemed to be unquantifiable. They might say, for instance, 'this is what will happen unless the Euro collapses', acknowledging the deeper uncertainty – of whether or not the Euro will collapse, which they cannot know – without putting a spurious number on this. This has two direct effects. It makes clear the scale they are prepared to work on, and what they simply do not know and cannot say. And this encourages others using these forecasts – financial institutions, say – to adopt an approach for responding that focuses on resilience. There are dangers in thinking you can quantify something which cannot be quantified."
DAVID SPIEGELHALTER



RESEARCHERS CAN EXPLAIN THE EVENTS THAT WOULD CHANGE THEIR MIND

Sometimes changes in uncertainty can be predicted. In other words there may be uncertainty around future events but researchers can work out clear signs of a change in the level of uncertainty to look out for. This information helps people faced with similar, real-world scenarios to respond and make decisions.

"One example, from the UK BSE outbreak in the early 1990s, would be when the first cat became ill with mad cow disease. This is when lots of infectious disease experts stopped eating beef. However, the fact that a cat getting sick with a prion disease (TSE) for the first time was a big danger sign, and represented an increase in the certainty of health risk to humans, was not spread as widely as it might have been. I think being clear about what future events might change an expert opinion about the level of uncertainty would be helpful. This boils down to researchers saying 'we may be very uncertain now but are there warning signs that people should look out for?'"
ANGELA MCLEAN

LET'S FOCUS ON WHAT WE NEED TO KNOW, NOT ON THE MOST COMPLICATED ANSWER

A more complicated solution to a problem is not necessarily a better one. Keeping things simple is important when communicating what public policy decisions are made, and why.

"Take the debate about whether or not the UK's mandatory breast cancer screening programme of women above a certain age can be justified by a reduced incidence of breast cancer. There is considerable scientific dispute among experts who strongly disagree. And, any decisions have to be communicated to both policy makers and individuals. A recent review of evidence deliberately used a very simple model of the benefits and harms and was selective about what was included in the model. When they published their findings, the group acknowledged the considerable uncertainty in their estimates and explicitly said that, though they could not quantify how uncertain they were about the numbers, they were confident enough to make policy recommendations."
DAVID SPIEGELHALTER

05

PLAYING ON UNCERTAINTY

"ARE CELL PHONES SAFE? RESEARCHERS STILL UNCERTAIN"

"WHY EVERYTHING YOU'VE BEEN TOLD ABOUT EVOLUTION IS WRONG"

"UNCERTAINTY OVER MOBILE PHONE AND BRAIN CANCER LINKS"

"NEVER TRUST ANYONE WHO IS CERTAIN ABOUT ANYTHING..."

On emotive, economically important and political subjects, uncertainty in research findings has been played up and played down according to whether people favour or object to the implications. And many implausible products and theories are promoted by emphasising the uncertainty of mainstream knowledge, such as alternative medical therapies that remind customers, 'scientists don't really know what causes cancer...'.

'IT JUST SHOWS HOW WRONG SCIENTISTS CAN BE...'

In 2011, physicists were in the media talking about data that suggested a particle had broken the speed of light. Some commentators immediately took this to suggest that a fundamental law of physics had been undermined (it was, in fact, a fault in the recording equipment, not nearly so widely reported). A climate change contrarian argued that if we cannot have confidence in such fundamental scientific principles, we certainly cannot have any confidence in the evidence for global warming. In fact, researchers' willingness to find out whether this particle might exist is a good example of why we can be confident in scientific findings: if they're wrong, they'll be corrected - but only when evidence that stands up to scrutiny comes around.

The idea of 'epigenetics' in evolutionary biology suggests an individual's environment, as well as their genes, can affect the way traits are inherited. When researchers first suggested it, creationists asked whether this showed that the theory of evolution was wrong. In fact, epigenetics is a development of evolutionary thinking rather than an invalidation of the theory of evolution.

These presentations of uncertainty take discussions down a blind alley because they distort the working knowledge we do have. Findings are usually revisions and developments, not game changers. Uncertainty doesn't mean scientists know nothing.

DAVID STAINFORTH

GAME CHANGERS ARE EXCEPTIONAL

"The history of science is scattered with 'game changers', rare discoveries which substantially change our understanding of how the world works. These discoveries can change what we think is happening, beyond anything previously considered a possibility. Examples include the realisation that the earth isn't the centre of the universe, working out the structure of DNA (and that it encodes the information required to make living things), identifying that germs cause disease, or finding out that particles exist that are smaller than atoms.

Although such discoveries are important for science and can open up new opportunities for society, they needn't necessarily undermine conclusions based on our earlier understanding. Where earlier results are backed up by robust and relevant observations we can have confidence in them even if they are later shown to be based on an incomplete understanding. Scientists can often tell whether their conclusions have a significant risk of changing as our understanding improves, or are likely to stay the same regardless of any future discoveries. Sometimes observations can point to the limits of current theory long before a new theory is developed. For instance, measurements of the orbit of the planet Mercury suggested limitations in Newton's laws which were only explained many years later by Einstein.

As a result some uncertainty estimates are extremely robust, thanks to their foundation on widely demonstrated phenomena and methods, but others are much less so. The difficulty for non-specialists is that there is rarely an easy way of identifying the difference between the two. This point needs to be included in the questions put to the experts."

UNCERTAINTY DOES NOT MEAN THAT ANYTHING COULD BE TRUE

If there is uncertainty in new research that may become part of a wider public debate, that uncertainty should not be taken to cast doubt over the entire body of established knowledge. This type of thinking seems to play on the fear that the ground will disappear from under us if our current scientific thinking proves to be incomplete: quite the opposite is true.

'Game changers' in research are rare (see box). But even when these discoveries do happen, though they often open up new avenues of research, they are very unlikely to render all existing knowledge irrelevant. Game changers can go undetected for some time, even in active areas of research, precisely because the knowledge we do have works well enough that no-one has a strong reason to question it.

"They sap convictions by endlessly questioning data, dismissing experimental innovation, stressing uncertainties and clamouring for more research…. It takes something which is an essential part of science – healthy skepticism, curiosity – and turns it against itself and makes it corrosive." ORESKES & CONWAY, 2011

"Climate change controversy gets air-time. Although controversies are allegedly about science, often such disputes are used as a proxy for conflicts between alternative visions of what society should be like and about who has authority to promote such visions."
MIKE HULME

PLAYING UP AND PLAYING DOWN UNCERTAINTY

Exaggerated uncertainty is more often than not a vague appeal to things being uncertain. A good example of this is the ongoing public health controversy about the use of mobile phones and cancer.

"An independent expert committee convened by the International Agency for Research on Cancer (World Health Organization) concluded that the scientific evidence of an increased risk of brain tumours in cell phone users was limited and that there was inadequate evidence to draw conclusions for other types of cancer.

Campaigners claiming that mobile phones do cause cancer say that because we cannot entirely rule out an increased risk, we should take immediate action. At the same time advocates of mobile technology argue that as there is no confirmed increase in risk and no established biological mechanism, no action is required. The significance of scientific uncertainty is interpreted differently by the parties in a debate; particularly when the conclusion has economic or public health consequences." FRANK DE VOCHT

UNCERTAINTY IS NOT A WEAKNESS OF SCIENCE!

1. Scientific research works on the basis that there are things we don't know.

Research is not done to 'prove' things by showing that there is no uncertainty, but to find the best explanation for our observations by testing each theory against alternatives. The most likely explanation, or theory, is the one that accounts for as much as possible of what we see. Scientists can also say in advance what evidence, if found, would refute their theory. And so to work out which of two competing alternatives is the better theory, we shouldn't focus on the amount of uncertainty but should ask how much of what we observe can each theory explain.

For example, sunspots (solar activity) have been suggested as an explanation for global warming. There is some evidence that solar activity affects the atmosphere in ways that cause the temperature to change. However, this theory cannot account for some important features of the observed warming patterns – most significantly, while temperature has increased steadily over the last 50 years, solar activity has not. As a theory, it doesn't account very well for our observations of changing climate.

You should ask anyone who promotes an alternative idea of what is going on to indicate the uncertainty levels in their own theory.

2. Scientists don't draw conclusions based on a single piece of evidence.

Scientists design experiments to gather data that answer specific questions; the aim is not to agree but to explore, test results and retest them. All measurements have an associated uncertainty – this uncertainty in data is different to uncertainty about a conclusion. Different interpretations of the same data are often possible, and different datasets on the same problem might reach different conclusions. This is precisely why uncertainty in any given piece of evidence does not necessarily undermine an overall conclusion.

3. Scientific research seeks evidence not consensus.

'Consensus' suggests that scientists aim to agree. This incorrectly implies that scientists try to minimise uncertainty for the sake of finding consensus. When researchers in a field assess the 'weight of evidence', they don't simply mean the number of studies on a particular question, or patients per study, but how compelling the evidence is and how thoroughly alternative explanations have been looked at – a result of the scientific process and peer review of new research.

4. Scientific research is not political, but the implications of research can be.

When research has a bearing on public policy it may seem that a consensus, if that is what emerges, tells people how to act or what decision to make. Similarly, if the policy implications of research findings are clear, questioning the uncertainty of the science becomes an easy way to dodge those implications. The conclusions of research can be, and often are, used as a proxy for political arguments. Researchers might well recommend or discourage a course of action but this is in the realm of policy making not research. Scientific evidence will seldom be the only factor in making a decision or creating policy.

WHY DOES ANY OF THIS MATTER?

Until we understand scientific uncertainty, we risk being seduced or confused by misrepresentation and misunderstanding. Without an understanding of uncertainty amongst the public and policymakers alike, scientists will struggle to talk about uncertainty in their research and we will all find it hard to separate evidence from opinion.

06

DELVING DEEPER

HANDLING UNCERTAINTY IN SCIENCE

was an interdisciplinary Royal Society meeting in 2010 to look at how uncertainty is used in different areas of research.
http://rsta.royalsocietypublishing.org/content/369/1956.toc

MERCHANTS OF DOUBT (2011)

is a book by Naomi Oreskes and Erik Conway on the tactical use of uncertainty by interest groups.

UNCERTAINTY AND STATISTICS:

UNDERSTANDING UNCERTAINTY

is David Spiegelhalter's website using everyday examples to help people 'make sense of chance, risk, luck, uncertainty and probability'.
www.understandinguncertainty.org

HOW TO READ A PAPER (2010)

is a book by Trisha Greenhalgh that explains the different statistical approaches in research papers; some key insights are summarised in this collection of BMJ articles.
www.bmj.com/about-bmj/resources-readers/publications/how-read-paper

MAKING SENSE OF STATISTICS…

is a guide, produced by Sense About Science with Straight Statistics, that gives some questions to ask and identifies some pitfalls to avoid to help people get behind news stories that use statistics.
www.senseaboutscience.org/resources.php/1/making-sense-of-statistics

ALL MODELS ARE WRONG

is a blog discussing uncertainty in relation to modelling and climate science.

www.allmodelsarewrong.com

UNCERTAINTY IN MEDIA AND POLICY-MAKING:

COMMUNICATING UNCERTAINTY

in a Soundbite is a guide from the Science Media Centre for researchers doing brief news interviews about research.

www.sciencemediacentre.org/wp-content/uploads/2012/09/Communicating-Uncertainty-in-a-Soundbite.pdf

CLIMATE SCIENCE, THE PUBLIC AND THE NEWS MEDIA

is a report looking at the communication of evidence, including uncertainty about evidence, in the context of discussions about climate science.

www.lwec.org.uk/publications/climate-science-public-and-news-media

REDUCING RISK OF FUTURE DISASTERS

is a report from the Government Office for Science's Foresight team that discusses policy making in relation to the risk of natural disasters.

www.bis.gov.uk/foresight/our-work/policy-futures/disasters

POST NOTES

are short briefings for Parliamentarians on scientific subjects and include many topical areas that deal with scientific uncertainty and the complexities of integrating uncertain science with actual policy decisions.

www.parliament.uk/mps-lords-and-offices/offices/bicameral/post/publications/postnotes/

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