28
Interpreting scientific evidence

by

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[28.10] Authors

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During their visit to Oxford in 1994 Bernard Robertson and Professor Vignaux completed their book *Interpreting Evidence: Evaluating Forensic Science in the Courtroom* published in 1995 by John Wiley & Sons (UK), soon to have a second edition. They have written numerous journal articles on forensic science and the interpretation of probabilistic evidence and their implications for legal procedures.

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INTRODUCTION

[28.100] Introduction

Expert scientific evidence usually involves the forensic scientist making an observation on some aspect of the case and, based on past experience, reporting inferences to the court. For example, the scientist may compare a DNA profile from blood found at the scene with that of the accused and find them to be the same. Our task is to see what inferences can and cannot legitimately be drawn from such an observation. There is a simple and logical solution to these questions that deals with many of the difficulties courts have perceived with expert evidence.[1]

1 This chapter necessarily deals only with the central matters relating to the interpretation of forensic scientific evidence. For a full discussion and for a discussion of surrounding issues, see Robertson BWN, Vignaux GA, Berger CEH, *Interpreting Evidence*, 2nd ed, John Wiley & Sons, Chichester (2016).

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RELEVANCE AND PROBATIVE VALUE

Introduction .... [28.200]
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[28.200] Introduction

Evidence tendered in court must be relevant. A typical definition of relevance that reflects that used in all common law systems is found in Rule 401 US *Federal Rules of Evidence*:

> "Relevant evidence" means evidence having any tendency to make the existence of any fact that is of consequence to the determination of the action more probable or less probable than it would be without the evidence.[1]

Rather than the term "fact" we will use the words "proposition" or "hypothesis" for what must be proved in either a civil or criminal case. If an item of evidence does not cause us to change our probability assessment for the hypothesis then we would not normally describe it as evidence either for or against it. Thus if an item of evidence is worth considering it is one that might cause us to increase or decrease our assessment of the probability of some fact which is of consequence in determining the case.[2]"Good evidence" will have a substantial effect on our probability assessment. What is it about a piece of evidence which enables us to change our probability assessment? Consider some extreme cases.

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1 Alternative definitions include "Evidence is relevant in a proceeding if it has a tendency to prove or disprove anything that is of consequence to the determination of the proceeding" ((New Zealand) *Evidence Act 2006*, s 7(3)); and "relevant (i.e. logically probative or disprobative) evidence is evidence which makes the matter which requires proof more or less probable"*Director of Public Prosecutions v Kilbourne* [1973] 1 All ER 440, 461, per Lord Simon of Glaisdale.

2 Montrose uses the term "material" rather than significant. See Montrose J.L., "Basic Concepts in the Law of Evidence" (1954) 79 *LQR* 527.

[28.210] Ideal and useless evidence

An *ideal* piece of evidence would be something that always occurs when what we are trying to prove is true and never occurs otherwise. If we are trying to demonstrate the truth of an hypothesis or proposition we would like to find as evidence something which is always observed when the hypothesis is true and is never observed when the hypothesis is not true. An example is the old proverb "where there is smoke there is fire". In real life, evidence this good is almost impossible to find. Suppose a blind person needed to determine whether it was cloudy. Rain is not ideal evidence because absence of rain does not imply absence of clouds. If it is raining we can be sure there are clouds about but there may also be clouds if it is not raining.

At the other end of the scale, some true information is certainly useless as evidence. Imagine a child being interviewed because of suspected sexual abuse. We seek factors which indicate abuse (or otherwise). If we looked at "all data" without discrimination we might note that she is breathing at the time of the interview. After many such interviews we conclude that all children who allege abuse are breathing at the time of the interview. But of course this is useless as evidence of abuse because all other children breathe as well. In other words the child is equally likely to be breathing whether it has been abused or not. Despite being a characteristic shared by all abused children, breathing is not any sort of evidence for abuse. It does not *discriminate* between abuse and non-abuse.

Likewise, a large proportion of the DNA in our cells is indistinguishable in all human beings. This is why we nearly all have two eyes, two legs etc. The presence of this common material in DNA samples taken from the scene of a crime and from a suspect is useless as evidence of identification. Since everyone shares such characteristics the finding is equally likely whether or not it was the accused who left the mark.[1] DNA gets its immense discriminating power from those areas which differ from person to person.

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1 Lempert R, "Some caveats concerning DNA as criminal identification evidence; with thanks to the Reverend Bayes" (1991) 132 *Cardozo LR* 303–342.

[28.220] Typical evidence

In practice, ideal evidence is seldom found. Even if the evidence always occurs when the hypothesis is true it may also occur when it is not. Alternatively, when the hypothesis is true the event may not invariably occur. Thus, in the real world, evidence is something that is more (or less) likely to occur when what we are trying to prove is true than when it is not. Good or strong evidence would be something that is much more (or less) likely to occur when what we are trying to prove is true than when it is not.

For example, during a career of interviewing, a doctor might observe that a high proportion of abused children display signs of stress such as nail-biting. This will be evidence of abuse *if and only if* abused children are more likely to bite their nails than other children. If abused and non-abused children are equally likely to bite their nails this observation is useless as evidence of abuse. On the other hand, if abused children are much more likely to bite their nails than non-abused then observing nail biting is strong evidence of abuse. Suppose 80% of abused children bite their nails but only 10% of other children do so. Nail-biting would then be eight times more likely in the case of an abused child than in another child. If, on the other hand, 90% of other children bite their nails then nail-biting would point the other way and reduce our level of belief that the child had been abused (but only weakly).

There are two points to notice. First, the strength (or probative value) of the evidence depends not only on how many abused children bite their nails but also on how many non-abused children do so. Second and most importantly, all we know at this stage is the probability of the *evidence* in each case. We still do not know how likely it is that the child has been abused.

The probative value of any piece of evidence can be assessed in the same way. A scientific test result is good evidence for a particular hypothesis if it is much more likely to occur if the hypothesis is true than when it is not. We will know this only if we have seen the result of the test not only on a number of occasions when the hypothesis is true but also when it is false. We cannot know the strength of the evidence if we only observe cases when the hypothesis is true. Again, what we will know at the end of this test is how likely the *test result* is if the hypothesis is true and *not* how likely it is that the hypothesis is true.

[28.230] A breath-testing device

Consider a simple breath-testing device designed to be used at the roadside for checking whether a driver is over or under the legal alcohol limit. It is supposed to show a red light if the driver is over the limit, a green light if he is under. It will have to be calibrated before being used to determine how accurate it is. We must guard against two types of error: a false positive and a false negative. A false positive – a red light shows when the person is actually under the limit – leads to someone being wrongly arrested and inconvenienced at least by having to be tested with a more accurate method at the police station. A false negative – a green light shows when the person is really over the limit – leads to a drunk driver remaining on the road.

Unfortunately, adjusting the settings of the device to reduce one of these rates will inevitably increase the other. It is impossible in practice to eliminate errors altogether and we simply have a choice of which errors to make. Which error is the more serious is a political question, but let us suppose some figures purely for sake of example.

Before using it, we calibrate the testing device with samples of air with a measured alcohol content. Many such samples are tested. Suppose, as a numerical example, we test 1,000 samples with an alcohol concentration marginally below the legal limit and 1,000 samples marginally above. We adjust the device so that of the samples over the limit, 950 read red and 50 read green, and of the samples below the limit, 995 read green and 5 read red.[1]

From the data from the calibration tests we can see that:

1. If the sample is over the limit there is a 95% probability (950/1000) the device will indicate red and a 5% probability (50/1000) it will indicate green – the odds are 19 to 1 that it will indicate red if the sample is over the limit.[2]
2. If the sample is under the limit there is a 0.5% probability the device will indicate red and a 99.5% probability it will indicate green – the odds are 199 to 1 that it will indicate green if the sample is under the limit.[3]

Thus a red light on the breath test is pretty good evidence for the assertion "the person is over the limit". If a person is over the limit there is a 95% probability of a red light; if a person is under the limit there is only a 0.5% probability of a red light. Thus a red light is 190 times more likely to occur if the subject is over the limit than if under (95/0.5 = 190). It strongly discriminates between the two cases.

In contrast, a green light is good evidence *against* the assertion "the person is over the limit". If a person is over the limit there is a 5% probability of a green light; if under the limit there is a 99.5% probability of a green light. A green light is about 19.9 times *less* likely to occur if the person is over the limit than if under (5/99.5 = 1/19.9). So, depending on the light shown the tester can provide good evidence either for or against the assertion "the person is over the limit". The information at this stage is the "wrong way round". We knew the contents of the samples and we have determined the probability of getting a red signal *given* that the sample is over the limit. But when the device is used we want to know something quite different: Given that the device gives a red light what is the probability that the person is over the limit?

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1 We must make two points about this exposition. First, the figures have been chosen simply for arithmetic simplicity and may well be wrong by orders of magnitude. Second, the problem has been simplified. In fact, the probability of a false reading will decline as one moves away from the limit so that the chances of a false positive from a sample substantially under the limit will be negligible.

2 It is much, much clearer and more precise to express this in symbols: Probability(red | over the limit) = 0.95 where the symbol "|" stands for "given the condition" or just "if". Similarly, Probability(green | over the limit) = 0.05. Readers who would like an explanation about probability and odds should go to the appendix.

3 Probability(red | under the limit) = 0.01 and Probability(green | under the limit) = 0.99.

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THE LIKELIHOOD RATIO AND BAYES' RULE

The likelihood ratio .... [28.300]
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[28.300] The likelihood ratio

We have already met the likelihood ratio (but without using that term) in considering the evidence of nail-biting and the evidence of the breath tester above. In the child-abuse case the likelihood ratio for nail-biting is the 80% chance of nail biting if the child *has* been abused divided by the 10% chance of nail biting if the child *has not* been abused, 80/10 or 8.

In the breath test example at [28.230], the likelihood ratio for a red light[1] is:

The likelihood ratio, then, is the probability of the evidence supposing our assertion is true divided by the probability of the evidence if the assertion is not true. The probability of the evidence supposing the assertion is true, is the *numerator*. The probability of the evidence if the assertion is not true, is the *denominator*. When we divide them we get a single figure, *a ratio which tells us the strength of the evidence in discriminating between the two*.

If the likelihood ratio is more than 1 the evidence tells in favour of the hypothesis. If the likelihood ratio is less than 1 (usually expressed as a decimal fraction) then it tells against the hypothesis. If the ratio is exactly 1 then the evidence is neutral and hence is irrelevant. The strength of the evidence is measured by how much the likelihood ratio differs from 1, in either direction.

1 For a green light the likelihood ratio is (5)/(99.5) = 1/(19.9).

[28.310] Bayes' rule

Bayes' Rule is a logical theorem – there can be no doubt about its truth. It tells us how to update our knowledge by incorporating new evidence. We start with some knowledge about the hypothesis and its alternative, expressed as odds in favour of it. These are known as the *prior odds*. The prior odds (our assessment without the evidence) must be multiplied by the likelihood ratio of the new piece of evidence to give the *posterior odds*.[1] The posterior odds are what we want to know – the odds in favour of the hypothesis after taking into account the new piece of evidence.

$$\text{Prior Odds x Likelihood Ratio} \rightarrow \text{Posterior Odds}$$

For the breath tester, a red light makes the odds that the person was over the limit 190 times greater than we would have assessed them to be without it.

So we must first consider how likely the person was over the limit *before* we consider the evidence of breath test. In other words, what were the prior odds that the person was over the limit? If the driver was stopped for no particular reason (for so-called "random testing") these odds may just reflect the proportion of drivers at that time of day who are over the limit. There might be only 1 out of 100 drivers who are over the limit. The prior odds of being over the limit would then be 1 to 99. The posterior odds would be (1/99)190 or 190/99, about 2:1 in favour of the hypothesis that the drive was over the limit. (This corresponds to a probability of about 66%.)

Usually, though, there will be evidence such as erratic driving which alerted police and caused the driver to be stopped. The prior probability will then be higher.

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1 This is more formally presented in the appendix where there is also a discussion of probability and odds.

[28.320] The effect of prior odds

With a different prior probability, one will get a different posterior probability. Very large or very small prior odds can give some startling effects. For example in testing for HIV among potential blood donors, it is important to avoid false negatives: that is to say failing to detect infection with a dangerous virus, and keeping the carrier unaware. In tests used in 2005, in order to minimise false negatives to 0.3% a false positive rate of 1.5% had to be accepted.[1] This meant that on average out of every 1000 tests administered to those who were virus-free, 15 tests wrongly said that HIV was present. A positive result was 99.7% likely to occur if the subject carried HIV and had a 1.5% chance of occurring if the subject did not. In other words a positive result had a likelihood ratio of 99.7/1.5 = 66.5. To obtain posterior odds for any tested person we need to combine the evidence with the person's prior odds.

At that time, in South Africa, the estimated rate of infection was 20% or 1 in 5, giving prior odds of 1 to 4 in favour of infection (4 to 1 against infection). Using the test, a positive result gives posterior odds of infection of 66.5 to 4 = 16.6, i.e. odds of 16.6 to 1 in favour of infection.

At the same time, in the Netherlands, the estimated HIV rate in the population was 0.2% or 1 in 500 (i.e. odds of 1 to 499). The likelihood ratio of the positive result again is 66.5. Multiplying the prior odds in favour of infection by the likelihood ratio gives posterior odds of infection of 66.5/499 = 0.133; nearly 1 to 8. In other words *even given a positive test* (in the absence of other information), the odds were still nearly 8 to 1 *against* the person having the virus.

This at first surprising result demonstrates that when prior odds are very low, posterior odds might still be lower than 1, in spite of some good evidence. We can also understand this result without explicitly applying Bayes' Rule. Suppose we test 1000 Dutch persons and we now assume for simplicity that the test gives no false negatives but still gives 1.5% false positives. We expect to record two real infections, based on the 0.2% HIV rate and the absence of false negatives. But we would also expect to record about 15 false positives from those without the infection. Thus we would expect 17 positive results, only two of whom actually carry HIV. So the posterior odds, of carrying HIV after considering a positive result, are 2 to 15 (or 15 to 2 *against* the subject being infected – close to the nearly 8 to 1 odds demonstrated above). This is why a second, independent test must be administered when a positive result occurs.

Still using imaginary figures, if the result of a second, more expensive, test had a likelihood ratio of 1500, the posterior odds after both tests would be (2/15)(1500) = 200 to 1 in favour of the assertion of the presence of HIV.

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1 Chou et al, "Screening for HIV: a Review of the Evidence for the U.S. Preventive Services" (2005) 143 *Ann Intern Med* 55–73

[28.330] Transposing the conditional

The single most important mistake made in discussing scientific evidence is transposing the conditional. Non-scientists including eminent lawyers easily fall into this error and scientific witnesses can do so, especially under cross-examination. This error is particularly common when a probability is described in words.

Using the figures from the Netherlands test above, the error is to slip from the knowledge that if you have the virus there is a 99.7% probability of obtaining a positive result to wrongly thinking that if the result is positive there is a 99.7% probability that you have the virus.

The error can be recognised clearly in a case where nobody would make a mistake. The probability that a cow has four legs is clearly much higher than the probability that an animal with four legs is a cow.

As another example, consider the probability that a person, known to be over six feet tall, is a man. This is obviously high – most six-footers are men. Now, in contrast, consider the probability that a person known to be a man, is over six feet tall. This is obviously not the same since only a small proportion of men are over six feet tall. In the one case we are considering the probability that "the person is over six feet" and in the other the probability that "the person is a man". The two cases also have different conditions. The confusion arises because the assertion in one statement is the evidence in the other (and vice versa).

To look at this numerically, suppose that 5% of men but only 0.5% of women are at least six feet tall. Knowing that a perpetrator is six feet tall should multiply our assessment of the odds in favour of their being a man by the likelihood ratio of 5/0.5 = 10. Assuming that the number of men and women in the population are roughly equal, the prior odds that a person is a man is 1 to 1. If we are told that the perpetrator is over six feet tall then the posterior odds that they are a man are (1/1)(10) = 10 to 1.

Suppose we had originally been given the information that the six-foot person, whose sex we are considering, was a nurse. We know from the information above that the fact that someone is over six foot multiplies the odds that they are a man by 10. However the fact that someone is a nurse give us *prior* odds that they are a man equal to the small proportion of nurses who are men. If only 2% of nurses are men this gives prior odds of 1 to 49. The evidence that the person is over six feet tall multiplies these odds by 10. This gives posterior odds in favour of being a man of 10 to 49 (odds of about 5 to 1 against being a man). It is important to realise that the value of the evidence of height has not itself changed, but a six-foot nurse is still much more likely to be a woman than a man because of the huge imbalance of the sexes in that profession.

[28.340] Giving evidence

If a case involving the breath test device were contested in court forensic scientists might give evidence about the result of the test. What evidence could they give? They could not tell us the probability that person was over the limit since to do so they would have to hear and consider all the other evidence to assess the prior probability, which is really the job of the court.[1] What they *could* tell us, in this simplified example, is that a positive test should multiply the prior odds that the person was over the limit by 190. That is, they should state the likelihood ratio *and that is all they could say*.

We have already seen how easy and how misleading it is to transpose the conditional. It is vital, therefore, that expert witnesses ensure that their language is absolutely precise. In particular, when being examined or cross-examined by counsel expert witnesses should reply in whole precisely framed sentences and not agree with the wording of questions which, on reflection, can be seen to be ambiguous or wrong.

The court cannot determine the probability of guilt (or presence at the scene, or paternity, or whatever else is to be proved) simply on the basis of the expert evidence. It must assess prior odds as well; that is a task for the judge or jury and not for the expert, who is not privy to the rest of the evidence in the case.

So, expert evidence should be restricted to the likelihood ratio given by the test or observation perhaps accompanied by a statement that the evidence therefore supports, strongly supports, or very strongly supports a particular hypothesis.

If experts purport to give a probability for the hypothesis they must be assuming some prior probability. This is wrong in both law and logic.

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1 We use the term "court" informally to mean "tribunal of fact" as opposed to the forensic scientist. In the small percentage of cases tried on indictment this will be the jury rather than the judge.

[The next text page is 28-1501]

ADMISSIBILITY AND RELEVANCE

Introduction .... [28.400]
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[28.400] Introduction

As we have seen, an item of evidence will change the odds if it has a likelihood ratio different from 1. If the likelihood ratio is greater than 1 then the evidence will cause the assessment of probability for the assertion to increase. If it is less than 1 then our assessment of the probability should decrease. Hence any piece of evidence giving a likelihood ratio other than 1 is relevant and, in principle, all relevant information should be used in coming to a rational assessment of the probability.[1]

To assess a likelihood ratio it is not essential to have precise numbers for each of the probabilities. The value of the evidence depends upon the ratio of these numbers. Therefore, if one believes that the evidence is 10 times more probable under one hypothesis than the other, the likelihood ratio is 10, whatever the precise values of the numerator and denominator may be. Often one will be able to assess this ratio roughly on the basis of general knowledge and experience. *Saying that evidence is relevant is just another way of saying that it is more probable under one hypothesis than another and, therefore, has a likelihood ratio different from 1.*

"Probative value" is clearly directly related to the likelihood ratio. Evidence with a likelihood ratio not far from 1 (say only 0.8 or 4), will have low probative value and might not be worth admitting if the cost (in the wider sense described) is too high. In the case of newly developed forms of scientific evidence, it is up to the proponents to demonstrate on the basis of independent tests that useful likelihood ratios can be produced.

On the other hand, when examining forensic scientific evidence, there is a tendency to demand very high likelihood ratios. DNA evidence, for example, can have likelihood ratios in the billions. It seems that courts then might regard the evidence as almost useless if the likelihood ratio is less than 100. In the Australian case *R v Van Hung Tran* (1990) 50 A Crim R 233 aspersions were cast on the DNA evidence because the likelihood ratio may have been as low as 87.

Values as low as these may actually compare favourably with much evidence that is traditionally admitted such as eye-witness descriptions and identifications, although it will be difficult to obtain data to establish their likelihood ratios without formal scientific experiments. There seems no special reason why forensic scientific evidence should be subject to any more rigorous conditions, always assuming that the evidence does not fall foul of some other exclusionary rule. A (morphological) hair comparison,[2] for example, might give a likelihood ratio of only 4 or 5 but should not be rejected on that ground alone. The question for the court is whether there is sufficient other evidence to combine with it to attain the required standard of proof.

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1 "…unless excluded by some rule or principle of law, all that is logically probative is admissible." (Thayer J.P., *A Preliminary Treatise on Evidence at the Common Law* (Little, Brown & Co, Boston, 1898) p 264).

2 i.e. (microscopic) visual comparison.

[28.410] Prejudging the case?

To calculate the numerator of the likelihood ratio one has to assess the probability of the evidence supposing that the prosecution case were true. This has led some to believe that calculating a likelihood ratio involves *assuming* that the prosecution case is true. This is misconceived. One is only considering how probable the evidence would be supposing (for the sake of argument) the prosecution case were true and then comparing that with the probability of the evidence supposing (for the sake of argument) that the defence case were true. This process requires no level of belief in either of these hypotheses. Furthermore it merely makes explicit the logical reasoning process naturally applied to any piece of evidence. If a juror thinks that a particular piece of evidence is incriminating this can only be because the juror thinks that the evidence is more probable if the prosecution case is true than if the defence case is.

[The next text page is 28-2001]

THE ALTERNATIVE HYPOTHESIS

Introduction .... [28.500]
Some symbols .... [28.510]

[28.500] Introduction

It is logically meaningless to suggest that any item of evidence has any value in itself as support for any particular hypothesis. Its value depends entirely upon its ability to discriminate between one hypothesis and another. The first hypothesis will be the case the prosecution has to prove. What is the second?

So far we assumed that the second hypothesis was just the negation of the first: "the person was over the limit", "the person was not over the limit"; "the person is guilty", "the person is not guilty". It is often difficult if not impossible to determine the probability of the evidence with a vague and ill-defined hypothesis such as "the person is not guilty". The value of the evidence will best be realised if the two hypotheses are well-formed, positive and specific.

[28.510] Some symbols

Despite the risk of intimidating readers by including symbols we believe that, as they are such an important aid to clear thinking, they ought to be used. It is almost impossible to discuss abstract notions with precision in the absence of such aids. We do not intend to go into the higher reaches of mathematics. We are only using the symbols as an efficient notation in our analysis of the legal problems. Here we introduce the symbols for hypotheses, evidence, and probability. They are described at greater length in the appendix.

Hypotheses

H	stands for an hypothesis. An hypothesis (or premise or assertion) is a statement that is either true or false, such as "It rained today". Since we may have more than one hypothesis we will number them:
H1	is usually what the prosecution is trying to prove, such as "The accused was present at the scene".
H2, H3 etc	stand for different alternative hypotheses.

Evidence

E	stands for some item of evidence. Again, this is in the form of a statement that is true or false, such as "The blood type of the accused matches that found on the scene." Again there will be many items of evidence so they will be numbered:
E1, E2, E3 etc	stand for different items of evidence.

Probability

P(A)	stands for the probability of A, e.g., P(H1) means the probability that hypothesis H1 is true. It will have a numerical value between 0 and 1. Thus, if H1 = "The murderer is the accused", at some point in the trial we might say that P(H1) is 0.5. Since all these probabilities will require us to describe their conditions we add to the notation the symbol
|	meaning "supposing" or "given" so that
P(A|B)	means the probability of A given B. Thus, we might use P(H1|E1) to mean the probability of H1 given evidence E1; or P(E1|H1) to mean the probability of the evidence E1 if hypothesis H1 is true.

We do not use symbols more complicated than these.

The likelihood ratio for a particular item of evidence, E, in distinguishing between two hypotheses can then be written

$$\frac{P(E|H1)}{P(E|H2)}$$

where H1 and H2 are the two hypotheses to be compared.

[The next text page is 28-2501]

WHICH ALTERNATIVE HYPOTHESIS?

Introduction .... [28.600]
Probative value and the alternative hypothesis .... [28.610]
Selecting the appropriate alternate hypotheses .... [28.620]
Example .... [28.630]

[28.600] Introduction

Theoretically there can be an infinite number of different explanations for an event; it would be impossible to compare the prosecution's hypothesis with all of them. In practice, we can usually identify a small number worth considering. For example a robbery charge might be defended by denying that the incident took place or by denying that the accused was the person involved and each of these has many variations.

During the course of the trial (and before the trial in civil cases) it will become clear what the grounds of the defence are. In the vast majority of cases the two most likely explanations will be those put forward by the prosecution and by the defence respectively. So although it is the task of the prosecution to prove its case (that is, its assertion or hypothesis) beyond reasonable doubt we can judge whether it has done so by comparing its case with a small number of alternatives and frequently just with the one offered by the defence (which we will often designate H2).

[28.610] Probative value and the alternative hypothesis

It follows that to determine the value of any particular piece of evidence for the prosecution case one has to identify the particular defence argument, the hypothesis that we are comparing it against.

This can be illustrated by considering an extreme example. A person dies after being stabbed and a suspect is arrested nearby wearing bloodstained clothing. DNA testing is carried out and the scientist reports a likelihood ratio for this evidence (E) – that the evidence is at least one million times more likely if the blood on the suspect came from the victim (H1) rather than from a randomly selected person (H2): powerful evidence that the blood came from the victim.[1]

At trial, the accused states that he did not stab the victim but found him bleeding and rendered first aid, getting the victim's blood on his clothes. If this explanation (H3) is the defence the DNA evidence immediately becomes valueless. Why? Because though the probability of the evidence given that the accused was the perpetrator[2] may be 1, so is the probability of the evidence given the defence story.[3] The ratio of these probabilities, the likelihood ratio, $P(E|H1)/P(E|H3)$, is 1 and so the evidence does not help us to choose between the prosecution and defence hypotheses. The DNA analysis is no longer relevant to the assessment that the court has to make.

In a less extreme case one just gets a less extreme result. Thus the accused might instead confess to having had a fight with the murder victim's brother, getting his blood on him (H4). To determine the likelihood ratio of the DNA evidence we find the probability of the DNA evidence if the blood on the accused came from the brother.[4] The likelihood ratio, P(E|H1)/P(E|H4), will be greater than 1 but almost certainly much less than the one million figure. This is because two brother's DNA analyses are much more likely to resemble each other than either is to resemble that of another person randomly selected from the general population (see below).

Alternatively the accused's blood might resemble that of the victim and so the hypotheses to be compared are that the blood found came from the accused (H1) and that the blood is from the victim (H5), as in *Preece v H M Advocate* [1981] Crim L.R. 783.

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1 The likelihood ratio is P(E|H1)/P(E|H2) = 1,000,000

2 P(E|H1) = 1

3 P(E|H3) = 1

4 P(E|H4)

[28.620] Selecting the appropriate alternate hypotheses

One must think carefully to identify the appropriate alternative hypotheses and determine the correct likelihood ratios to use. Frequently the defence will be that the perpetrator was not the accused but someone else, not otherwise specified. We must then consider how probable the evidence is if the perpetrator were someone other than the accused.[1] There will usually be other evidence about the perpetrator, which will tend to narrow down the alternative hypothesis. For example, if the perpetrator was of Vietnamese appearance we have to consider how probable the DNA test result is if the perpetrator were a Vietnamese other than the accused. There is not much point in considering how probable the evidence is if the perpetrator were Caucasian.

How should the investigator determine what is the appropriate alternative hypothesis? Forensic scientists have often assumed in the past the alternative hypothesis that the perpetrator could have been any other member of the population.[2] The probability of the evidence will then be derived from the frequency of the characteristic in the population. It appears that only as an afterthought is the comment sometimes made that one may need to alter the alternative hypothesis in the light of the facts of the particular case. This may be because the forensic scientist is not aware of all the evidence at the time. But determining the appropriate alternative hypothesis is no mechanical task. The starting point should be the facts of the particular case and the argument put forward by the defence. The decision to compare with a randomly selected person from the population (or a randomly selected member of a sub-group) should be regarded as a conclusion to be justified, rather than as a starting point.

It would be legitimate to compare the profile found with that from a randomly selected person only if there is no evidence to separate the perpetrator from the general population, or there is no explanation forthcoming for a mark on the accused.

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1 P(evidence | perpetrator is someone else).

2 "Typically, forensic scientists use the concept here of a random man" Buckleton J.S. and Walsh K.A.J., "Knowledge-Based systems" in Aitken C.G.G. and Stoney D.A. (eds) *The Use Of Statistics in Forensic Science* (Ellis Horwood, Chichester, 1991).

[28.630] Example

As an example of the complexity of identifying appropriate alternative hypotheses consider the facts surrounding the murder of the English tourist Marjory Hopegood in Hamilton, New Zealand in January 1992. A man of Maori appearance was seen running away from the scene and subsequently washing himself in the Waikato river.[1] Blood was found at the scene which did not belong to the victim and was analysed using a DNA test which produces results which vary in frequency from race to race. Suppose that subsequently a Maori is arrested and is identified by an eyewitness as the man seen. The prosecution hypothesis is that this man was the perpetrator (H1).

Two possible lines of defence might be imagined:

1. that the accused was the person seen running away but was not the murderer (H2); or
2. that the accused was not the person seen running away and the eyewitness identification was wrong (H3).

In the first case if the defence story were true, the murderer is not the man seen running away and so we have no information about the murderer. The relevant questions are then: (1) what is the probability of the DNA evidence if the murderer was the accused, P(E|H1)? and (2) what is the probability of the evidence if the murderer was a randomly selected person in New Zealand, P(E|H2)? This will depend on the frequency of the DNA test result in the population as a whole.

In the second case, if the eyewitness identification of the accused is wrong, there would be some reason to believe that the murderer was of Maori appearance even if it were not the accused. The appropriate questions therefore are: (1) what is the probability of the DNA evidence if the murderer was the accused, P(E|H1)? and (2) what is the probability of the evidence if the murderer was a randomly selected man of Maori appearance, P(E|H3)? This will depend upon the frequency of the DNA test result in the Maori population.

Suppose, to everyone's surprise, a European rather than a Maori is arrested and his defence is that the murderer was the Maori seen running away. In this case the relevant questions would be:

1. what is the probability of the DNA evidence if the murderer was the accused, P(E|H1)?; and
2. what is the probability of the evidence if the murderer was a randomly selected man of Maori appearance, P(E|H3)? – despite the fact that the accused is a European!

We saw earlier that an expert cannot, on the basis of one item of scientific evidence, state a probability of paternity, presence, occurrence, or any other hypothesis. The evidence should be given in the form of a likelihood ratio. We now see that not only can a single piece of evidence not justify a "probability of occurrence" but also that items of evidence do not have their own intrinsic likelihood ratios. *The likelihood ratio depends crucially upon the alternative hypothesis, which in turn, will usually depend upon the nature of the defence*.

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1 *The Evening Post*, Wellington, Monday January 13 1992, p 3.

[The next text page is 28-3001]

EXCLUSIVE, EXHAUSTIVE AND MULTIPLE HYPOTHESES

Introduction .... [28.700]
Exclusiveness .... [28.710]
Exhaustiveness .... [28.720]
Multiple hypotheses .... [28.730]

[28.700] Introduction

In order to be compared rationally, hypotheses have to comply with certain conditions.

[28.710] Exclusiveness

The two hypotheses used in the likelihood ratio, say H1 and H2, must be mutually exclusive. That is to say, they cannot both be true. For example, the propositions that the accused was the perpetrator and that someone else was the perpetrator are exclusive. The propositions that the perpetrator was an American and that the perpetrator was an Afro-American are not exclusive because it is possible to be both. The likelihood ratio cannot sensibly be used with non-exclusive hypotheses. It makes no sense, for example, to compare the frequency of a DNA profile in Britons of West Indian origin with the frequency of the profile in the population as a whole including those of West Indian origin.

[28.720] Exhaustiveness

Although the hypotheses must be exclusive they need not be exhaustive. That is to say they need not account for all possibilities. It is true that *odds*, by definition, are found only by comparing two exclusive and exhaustive hypotheses. The hypotheses, H1 that the accused was present at the scene and H2 that the accused was not present are exhaustive and these are the hypotheses that are frequently used in presentations of forensic scientific evidence. P(H1)/P(H2) gives true odds. We might say that it was 100 to 1 that he was present.

It is impossible, however, to assess the probability that the accused would have, for example, blood on his clothing if he were not present at the scene. This hypothesis can be subdivided in so many ways that it has no graspable meaning. Any such probability is really just a sum of the probabilities of the evidence under each of these possible sub-hypotheses. Nearly all the probability in such an assessment will be accounted for by the one or two most likely hypotheses and the others can safely be put to one side. What is required in practice is some positive theory as to how this mark came to be on the accused. In the absence of any such theory we are forced to ask how likely it is that the ordinary person would have this blood on their clothing.[1]

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1 We propose that this is the answer to the question raised by Zuckerman A.A.S., "Law, fact or justice?" (1986) 66 *BULR* 487, of how the jury should react to a failure by the accused to provide an explanation for such evidence. The distribution of blood stained clothing in the general population was examined in the pioneering study by Briggs T.J., "The probative value of bloodstains on clothing" (1978) 18 *Med Sci & Law* 79.

[28.730] Multiple hypotheses

If the hypotheses being compared are not exhaustive then there must be more than two possible explanations. The prosecution hypothesis may have to be compared with several other hypotheses. But when the alternative hypothesis changes, the value of the evidence changes. Evidence which may be of enormous value in distinguishing between one pair of hypotheses may not distinguish between another pair at all.

In theory, the probability of the evidence given innocence (or, for that matter, given guilt) is the combination of the probabilities of the evidence given every possible hypothesis consistent with innocence and the prior probabilities of those hypotheses. In practice two factors make this much easier than it might sound. First, large numbers of these component hypotheses can be lumped together, e.g. in the breath-test case example, for a finding of guilt we are only concerned with whether the accused was over the limit, not in the precise blood alcohol content. Even when it comes to sentencing, we will probably be concerned with ranges of blood alcohol level. The second factor is that, for vast numbers of the theoretically possible hypotheses, the prior probabilities will be so low that they can be ignored. We will then be left with a manageable small number of component hypotheses.

In summary, the hypotheses being compared must be exclusive but need not be exhaustive.

[The next text page is 28-3501]

PATERNITY CASES

Introduction .... [28.800]
No alternative father is named .... [28.810]
A named alternative father .... [28.820]
Example .... [28.830]
"It was my brother" .... [28.900]

[28.800] Introduction

Paternity cases provide good illustrations of the effect of changing the alternative hypothesis.[1] The simplest example is where one man (called Man-1) is alleged to be the father of a child but he denies paternity.

To be more specific assume that we all have a pair of a particular genetic characteristic which can take the values (called alleles) A, B, C, or D. Each of us has received one of the pair from our mother and one from our father. It is possible to have an identical pair (such as CC). The person is then termed homozygotic in relation to that characteristic.

For example where the Mother has AB, the Child has BC and Man-1 has CD, then we have:

H1 = "The Mother and Man-1 are the parents of the child"

E = "The Child has the characteristics, BC"

If H1 is true there are four possible combinations of characteristics that the child might have had: (AC, AD, BC, BD). The probability that the Child is BC is therefore 1/4 and we write $P(E|H1) = 0.25$.

That is relatively easy but we must consider the alternative hypothesis. There are two obvious possibilities, one where no alternative father is named and the other where one particular alternative father is named.

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1 The purpose of this section is to demonstrate the effect of changing hypotheses and not to examine paternity cases in detail. The case given here is therefore the simplest case and other, more complex, cases, for example when one parent is homozygotic (e.g. the Mother is AA) or where both parents have the same characteristics are discussed (Please see ch 82 on Parentage analysis and other applications of human identity testing). A particularly authoritative reference for problems in the area of paternity testing is Evett I.W. and Weir B.S., *Interpreting DNA evidence* (Sinauer Associates, Inc, Sunderland, Mass, 1998)

[28.810] No alternative father is named

If no alternative father is named there are two exclusive and exhaustive hypotheses to be compared:

H1 = "The Mother and Man-1 are the parents of the Child", as before

H2 = "The Mother and some (other) 'Random Man' are the parents of the Child"

Assuming H2, the B characteristic in the Child must have come from the mother and there is a probability of 1/2 that she would have passed it on (rather than the A). The C characteristic must have been inherited from the father, whoever he is. The probability of that is the frequency of C in the population (call this f_C). The probability of the evidence, E, is therefore 1/2 times the frequency of C:

$$P(E|H2) = 0.5\, f_C$$

Suppose f_C is 1 in 100 (0.01) then P(E|H2) = 0.005. The likelihood ratio is then

$$P(E|H1) \;/\; P(E|H2) = 0.25 \;/\; 0.005 = 50$$

So the evidence is 50 times more probable if Man-1 is the father than if a "Random Man" from the population is the father.

[28.820] A named alternative father

In the other case we might have a named alternative candidate, Man-2, and have good evidence that the mother only had intercourse with these two men during the relevant period. Although the assertions that Man-1 was the father, H1, and that Man-2 was the father, H3, are not theoretically exhaustive, on the evidence, no other hypothesis is worth considering.

We then have to consider what we know about Man-2. If we know his characteristics then he may have the "wrong" pair of alleles. This would not contain the C of the child's BC group, for example, AD. In that case Man-2 can be excluded as the father. Alternatively he has the "right" alleles, including C (such as BC, CC, or CD) in which case he cannot be excluded.

To illustrate, suppose in our example Man-2 has the blood group CC. The characteristics of all the parties are, in summary:

Mother	Child	Man-1	Man-2
AB	BC	CD	CC

The child has a C allele and the mother does not have one. Thus the father must be the source of the C allele and therefore must have at least one C allele himself. Man-1 might have passed on either the C or the D while Man-2 would certainly have passed on a C. The evidence is twice as likely if Man-2 is the father than if Man-1 is. This gives us a likelihood ratio of 2 in comparing the two hypotheses. This does not sound very powerful but in paternity testing a number of such characteristics can be examined and the results multiplied together.

The court also has to consider the other evidence in the case, the frequency and timing of alleged intercourse, the credibility of the witnesses and so forth. On the basis of this evidence it has to come to some assessment of the odds in favour of the proposition that the defendant was the father. In a particular case it may be a matter of comparing the probabilities in favour of one candidate and another.

There are cases when we do not know the characteristics of the alternative, Man-2. He may not be accessible or he may refuse to take a blood test. The best we can do then is to fall back on the "random man" calculation and accept that there is only a 1% chance that he would have characteristic C and therefore that the evidence is 50 times more likely if Man-1 is the father than if Man-2 is. Of course, evidence of the characteristics of Man-2 would cause us to change the assessment radically one way or the other if only we had it. Judges appear to be intuitively reluctant to use the population frequency of occurrence when a blood-test of the alternative father is not available, *Loveridge v Adlam* [1991] NZFLR 267. On the other hand, once DNA analysis has been completed, it appears that courts will not order further testing even when there is a quantifiable, although a very small, chance that a further test might lead to an exclusion, *G v T* [1994] NZFLR 145.

The important point is that the identical item of evidence, namely the child's characteristic, gives us a LR of 50 when H1 is compared with H2 and of only 2 when H1 is compared with H3.

[28.830] Example

The English case *Re J S (a minor)* [1981] Fam 22 (CA); [1980] All ER 1061 was such an example. This case is also famous because in considering the evidence Ormrod LJ made the unfortunate statement:

> The concept of "probability" in the legal sense is certainly different from the mathematical concept; indeed, it is rare to find a situation in which these two usages co-exist, although when they do, the mathematical probability has to be taken into the assessment of probability in the legal sense and given its appropriate weight.
>
> *Re JS (A Minor)* [1981] Fam 22, 29; [1980] 1 All ER 1061.

R accepted his girlfriend's baby (baby JS) as his own but J alleged that it was his. J underwent a blood test which showed that he was one of 1% of the European population who could not be excluded from being the father of baby JS. A key point is that R refused to take a blood test.

The hypotheses and evidence are:

H1 = "J is the father of Baby JS"

H2 = "R is the father"

E = "Baby JS has a particular characteristic"

Assuming that the characteristic is shared only by 1% of the population ($f_C = 0.01$) and that the mother did not share it then the father must have had that characteristic. The probability of obtaining the evidence if J is the father is P(E|H1) = 0.25. The probability if R is the father is P(E|H2) = $f_C/2$ = 0.005 (assuming R is a heterozygote for this characteristic). The likelihood ratio for the evidence is therefore 0.25 / 0.005 = 50.

This must be combined with other items of evidence including that:

- R refused the test.
- The Mother had had intercourse much more often with R than with J over the relevant period. This must give a likelihood ratio in favour of R of perhaps the ratio of the numbers of instances of intercourse. This makes a crude assumption that there was an equal probability of conception on each occasion, but we have no information justifying any other distribution.
- After having lived with R for some time without conceiving, the mother had an affair with J and then conceived. This will weigh in favour of J being the father.

If R had allowed a blood test the picture would have been very different. Either he would be excluded (that is, he did not have the important characteristic) in which case the likelihood ratio would be infinitely large in favour of J (since P(E|H2) = 0), or he would have had the characteristic just like J and P(E|H2) = 0.25. The likelihood ratio would be 0.25 / 0.25 = 1 and the evidence would be of no value in distinguishing between H1 and H2 and, hence, irrelevant in the sense of Federal Rule 401.

Alternatively, as in the second example above, he could have been homozygotic (with 2 chances of getting the characteristic) and the LR in favour of his paternity would have been 2. As it turned out the court decided on other grounds that J was quite unsuitable to have access to the child.

Far from revealing any difference between probability theory and legal probability, this case shows that careful attention to the principles of logical inference would have identified the relevant questions and shown how to use the evidence.

Correct presentation also solves the question Ormrod LJ raised about the weight to give the evidence.[1] The answer is that the evidence should be given *precisely* the weight it rationally merits and that is its likelihood ratio.[2]

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1 For an extended discussion of this quotation, see, Robertson B.W.N. and Vignaux G.A., "Probability - the Logic of the Law" (1993) 13 *OJLS* 457.

2 The analogy of weight can be pursued by substituting the logarithm of the likelihood ratio which can then be added to or subtracted from the logarithm of the prior odds (see: https://en.wikipedia.org/wiki/Algorithm). I.J. Good even coined the term "the weight of evidence" to describe this measure. See Good I.J., *Probability and the Weighing of Evidence* (Charles Griffin & Co, London, 1950) ch 6.

[28.900] "It was my brother"

In criminal cases where the evidence is of DNA tests, the lowest likelihood ratios will occur where the hypotheses being compared are that the accused or one of the members of his family, perhaps a brother, is the perpetrator.[1] Of course, there are fewer suspects in such a case but they are harder to distinguish. Ideally one would like samples from all the suspects and it is worth considering whether a power should exist in such circumstances to take samples from people other than the person arrested.

One should never lose sight of the other evidence in the case. The "worst case" is that the DNA evidence fails to distinguish between the two brothers. If the non-defendant brother has not provided a sample then one can only assess the probability that the samples would fail to distinguish. The case will then rest on the remainder of the evidence which, one hopes, will enable us to make the distinction. If the prior odds based on the rest of the evidence in the case is high enough then it will not matter what the result of the DNA analysis might have been.

It is important to note that although the value of the evidence is decreased if the alternative perpetrator is a brother, so is the pool of possible suspects. In fact, specifying a brother as the alternative may reduce the prior odds from one in several million to one in three or four. The combined effect of this and the DNA evidence may even be to strengthen the case against the accused.

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1 With acknowledgement to Evett I.W., "Evaluating DNA Profiles in a Case Where the Defence is "It was my Brother"" (1992) 32 *J Forensic Sci Soc* 5, where the problem is fully worked through. For full discussion of a recent case in which the question arose see Kaye D.H., ""False, But Highly Persuasive": How Wrong Were the Probability Estimates in McDaniel v. Brown?" (2009) 108 *Mich L Rev. First Impressions* 1 http://repository.law.umich.edu/cgi/viewcontent.cgi?article=1059&context=mlr_fi.

[The next text page is 28-4001]

MARKS AT THE SCENE AND MARKS ON THE SUSPECT

Introduction .... [28.1000]
Marks at the scene .... [28.1010]
Mark on the accused .... [28.1020]
The accused's race .... [28.1030]
Hypothetical questions .... [28.1040]
Pre-trial conferences and defence notice .... [28.1060]

[28.1000] Introduction

Evidence may be left at the scene by the perpetrator or picked up by the perpetrator from the scene or the victim. The logical analysis is the same.

[28.1010] Marks at the scene

In the Marjory Hopegood case we considered earlier, a mark (the bloodstain, E) was left at the scene. The race of the *accused* was not relevant in establishing the alternative hypothesis. This is because, no matter what the defence offered, the second question assumed that it was someone other than the accused who left the trace. The alternative hypothesis (H2) is that the perpetrator was someone else. Thus it does not matter whether the accused is a member of the most tightly knit genetic sub-population. Of course what may matter is any evidence relating to the *perpetrator*.

If there is no evidence about a perpetrator other than the analysis of a sample from the scene, an appropriate alternative is a randomly selected person from the population of possible perpetrators, regardless of the race of the accused. If we have eyewitness evidence that the perpetrator was of Hispanic appearance and a suspect is arrested on the basis of evidence other than sample analysis then the appropriate population is all those of Hispanic appearance and not the population of the suspect's particular sub-population.[1]

Thus, where a mark is left at the scene and alleged to have come from the accused, the two questions to be asked are:

- What is the probability of obtaining this evidence if it was the accused who left the mark, $P(E|H1)$?
- What is the probability of obtaining it if someone else left the mark, $P(E|H2)$?

1 Note that while, ideally, the alternative hypothesis should be that another person of such appearance committed the offence, the data available will be from surveys in which the people surveyed are usually asked to nominate their own race. There may be a difference between the self-identified race and the race that an observer would ascribe to an individual.

[28.1020] Mark on the accused

When we consider a mark (such as a bloodstain) found on the *accused* and alleged to have come from the scene, the alternative hypothesis (H3) is that the accused, though having no contact with the scene, would have this mark for some other reason. Of course, there may be yet another defence which involved the accused being at the scene. The mark evidence would probably not distinguish between these two hypotheses.

In order to determine the probability of E supposing the accused had not been at the scene we need information about the accused's characteristics, lifestyle and movements. A demolition worker is more likely than others to have glass on his shoes, an habitual violent offender might be more likely to have glass or blood on his clothing, and the blood most likely to be on anyone's clothing is their own. If we have such information about the accused, whether provided by the accused or anyone else, it should be used.[1] If we have no such information about the accused then we may have to resort to regarding him as similar to a randomly selected member of the population.

The two questions to be asked in such a case are:

- What is the probability that the accused would have this mark on him if he had contact with the scene, P(E|H1)?
- What is the probability that, taking account of his lifestyle and occupation, the accused would have this mark on him although he had no contact with the scene, P(E|H2)?

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1 See Buckleton J.S., Walsh K.A.J. and Evett I.W., "Who is random man?" (1991) 31 *J Forensic Sci* 463 for discussion of these problems.

[28.1030] The accused's race

It is often assumed by lawyers that the value of scene DNA evidence may be affected by the characteristics of the accused's race.[1] The alternative hypothesis, however, is that someone else committed the offence so the relevant race is the race of the *perpetrator*.

There may, of course, be some evidence that the perpetrator belonged to the same race or the same racial sub-population as the accused. The characteristics of this race may then be relevant when we are considering a mark left at the scene but that is because the perpetrator belongs to it, not because the accused belongs to it. These conclusions stem, not from biology, technology, or the intricacies of statistics, but from a simple logical analysis of the structure of the case.

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1 e.g. McLeod N., "English DNA Evidence Held Inadmissible" (1991) *Crim LR* 583, and Young S.J., "DNA Evidence - Beyond Reasonable Doubt?" (1991) *Crim LR* 264.

[28.1040] Hypothetical questions

It is settled law that an expert may be asked hypothetical questions. In particular, forensic scientists are often asked whether the observations they have made are consistent with circumstances other than those forming the prosecution case.[1] These questions are obviously aimed at raising alternative hypotheses H2, H3, H4 … which might yield a lower likelihood ratio. They recognise that the value of such evidence varies according to the hypotheses being considered. Evidence does not, of course, become valueless because it is consistent with more than one hypothesis. The important point is that the relative probability of the evidence under each hypothesis should be compared.

How hypothetical can a hypothetical question be? Hodgkinson cites American and Australian cases to support the argument that such questions do not have to be tied rigidly to facts proved at the trial but must bear some relationship to the evidence given.[2] He summarises by making three points:

> First, no party should, without more [evidence], diverge in its hypothetical questions to an expert from the evidence of fact. Such a course should always be justified by elements in the evidence of fact …
>
> Secondly, whether such a course is proper will also always depend upon whether the expert opinion which relies upon it is undermined by any such discrepancy …
>
> Thirdly, expert opinion is only admissible if it is relevant to matters in issue. If it is founded upon facts which have not been or will not be even approximately proved it should not be given.

This summary seems to be conditioned by thinking about civil cases in which both parties are obliged to commit themselves to statements of claim and defence. It is not so clear that these requirements apply strictly to the defence in a criminal trial, who, for the most part, are not required to produce evidence of anything. The governing proposition is obviously "expert opinion is only admissible if it is relevant to matters in issue". Hodgkinson's final sentence can only fully apply to civil cases. When a criminal defence lawyer is cross-examining a prosecution witness no notice need necessarily have been given of the defence case and, indeed, defending attorneys might actually alter tactics depending upon the replies.

This is especially true where DNA evidence is being considered. An expert might give a extremely high likelihood ratio strongly supporting the proposition that the mark came from the accused, H1, rather than from a "randomly selected person", H2, but the likelihood ratio for the evidence if the alternative hypothesis were that the perpetrator were the accused's brother, H3, will be very much smaller.[3] There is no burden on the defence however to produce any evidence to support the contention that the perpetrator might have been the accused's brother, rather the prosecution will need to demonstrate the very low probability of the defence's alternative hypotheses. This also means that the scientist must prepare to meet several defence hypotheses as it is extremely difficult, often impossible, to make these calculations while in the witness box, under pressure, and without access to data.

As we saw, each of the implied alternative hypotheses will have corresponding prior odds relative to the prosecution hypothesis, H1, and these must be considered as well as the likelihood ratio.

This suggests three conclusions:

- there should be some reasonable prior probability in favour of the hypothesis advanced;
- the prior odds suggested by the new hypothesis must be taken into account as well as its effect on the value of the evidence;
- the defence should not be allowed to ask a series of hypothetical questions just to produce a barrage of different numbers to confuse the jury and cause them to believe that the evidence is in some sense "unreliable". The point that the value of the evidence will vary according to the hypotheses being compared should be made but subsequent discussion should comply with the first two points above.

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1 What "consistent" means and what lawyers sometimes think it means are discussed in Ch 4 of Robertson BWN, Vignaux GA, Berger CEH, *Interpreting Evidence* (John Wiley & Sons, Chichester, 2016).

2 Hodgkinson T. and James M., *Expert Evidence: Law and Practice* (Sweet & Maxwell, London, 2007) p 207.

3 Evett I.W., "Evaluating DNA Profiles in a Case Where the Defence is "It was my Brother"" (1992) 32 *J Forensic Sci Soc* 5.

[28.1060] Pre-trial conferences and defence notice

We have seen that the value of forensic scientific evidence may depend crucially on the circumstances of the case. Likewise, its value may be altered not only by the defence's expert evidence but also by its general line of argument. Often the scientific witness will be deliberately kept unaware of these factors. Indeed, the popular perception amongst police and lawyers is that scientific witnesses should not be told the facts of the case so that they will be "unbiased". This supposes, wrongly, that scientific evidence can be viewed "objectively" and in isolation. Furthermore, the defence in a criminal case seldom have to reveal their line of defence in advance and, in some jurisdictions, do not even have to give notice of their expert evidence.

This provides a dilemma for reformers of legal, and especially criminal, procedure. It is already enacted in some jurisdictions (and proposed in several more) that there must be a pre-trial exchange of expert evidence even in criminal cases. Much more controversial are proposals to require the defence to reveal their general line of argument in advance.[1] In a criminal case the defence is, traditionally, entitled not to put forward any explanation for the evidence, even at trial. In that case, the jury can only consider the alternative hypothesis that the perpetrator was some other member of the general population.

Particular problems are caused when the defence produce at trial, as they are traditionally entitled to do, an explanation which has not previously been mentioned. Part of the stock-in-trade of the prosecutor is the ability to predict lines of defence but when the unexpected occurs, the scientific witness may be left in a difficult position.

There have been proposals for pre-trial conferences in criminal cases. These are intended to "narrow the issues" and to save time and money at trial. Such conferences would have the side effect of revealing lines of defence so that scientific witnesses for both sides can assess their evidence in the light of the appropriate alternative hypotheses.

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1 As the UK Royal Commission on Criminal Justice recommended in 1994. For reaction to these proposals see the index to (1994) 144 *New Law Journal*. In England and Wales, see Criminal Procedure Rules, r 33.6.

[The next text page is 28-4501]

CASE STUDIES

A case involving DNA evidence .... [28.1100]
The probability of paternity .... [28.1110]
Child sexual abuse .... [28.1120]
Alternative hypotheses in cases of child sexual abuse .... [28.1130]

[28.1100] A case involving DNA evidence

The New Zealand case *R v Pengelly* [1992] 1 NZLR 545[1] provides an example which helps us to see what should be done with the evidence. The case concerned a murder in Auckland, in the course of which the assailant cut himself and left bloodstains at the scene. These were analysed using a DNA profile. In court, the forensic scientist, Dr Margaret Lawton, described her results by saying:

> In the analysis of the results I carried out I considered two alternatives: either that the blood samples originated from Pengelly or that the … blood was from another individual. I find that the results I obtained were at least 12,450 times more likely to have occurred if the blood had originated from Pengelly than if it had originated from someone else.[2]
>
> Question: Can you express that in another way?
>
> Answer: It could also be said that 1 in 12,450 people would have the same profile … and that Pengelly was included in that number.

Although she did not use the term, the witness had stated the likelihood ratio for the evidence on the two hypotheses that the blood came from Pengelly and that it instead came from a randomly selected person. This likelihood ratio had then to be multiplied by the prior odds.

There are two ways to do this. One is to consider the DNA evidence as the first item of evidence and determine the prior odds by asking what is the population from which the perpetrator could have come? As the population of Auckland is approximately one million we would assign prior odds (that is prior to any evidence) of about 1 to 1,000,000 that Pengelly was the killer.[3] When we multiply those (conservative) odds by the likelihood ratio of 12450 we get for the posterior odds

$$\frac{1}{1,000,000}12450 = \frac{1245}{100,000}$$

These are odds of 1 to 80 that Pengelly is guilty (or 80 to 1 *against* his guilt). In other words, instead of being 1 out of a million people who might have committed the murder, Pengelly was 1 out of only about 80 who could have been guilty. The effect of the evidence is to change the odds that Pengelly is guilty from 1 to 1,000,000 down to 1 to 80. The jury needs to hear more evidence before Pengelly can be convicted.

Equally, one could consider the other evidence first and come to a judgment of prior odds based upon that. The other evidence in the case pointed to quite a small group, including Pengelly, which probably contained the perpetrator such that the prior odds were down to about 1 in 4. When these prior odds are multiplied by the likelihood ratio of 12,450 we get for the posterior odds

$$\frac{1}{4}12450 = 3112$$

Thus the posterior odds are over 3000 to 1 in favour of the assertion that Pengelly is guilty. This is equivalent to a probability of over 99.9%[4]. Dr. Lawton did not attempt to give the jury direct guidance on how to handle the likelihood ratio. However, the important point to note is that, correctly and consistently with the argument in this chapter, at no stage did she express an opinion as to the probability that the blood came from Pengelly. She summed up her evidence by saying that the likelihood ratio of 12,450 "very strongly supports the premise that the two blood stains examined … came from Pengelly."

1 The material quoted is from the trial at first instance and taken from the transcript in the Case on Appeal.

2 It became clear in cross-examination that "someone else" meant "a randomly selected member of the population".

3 We have not even yet taken into account that violent burglaries are carried out by able-bodied people (usually male) over about 12 and under 60, which would cut the odds down further.

4 From the odds, 3112/(3112+1) = 0.9997.

[28.1110] The probability of paternity

Experts commonly testify to the probability of assertions. They should *not* do so. The error is particularly common in paternity cases where courts are used to hearing witnesses give a probability that X is the father of Y.

Thus in the New Zealand case *Byers v Nicholls* (1988) 4 NZFLR 545 we find testimony that "evidence of the [tests] indicates that there is a 99% probability for [Byers] being the father of [the girl]." This typical statement follows a formula advocated as long ago as 1938.[1] It is still in common use in several jurisdictions despite having been exposed as fallacious by eminent US scholars.[2]

Experts who adopt this method of giving evidence commit three major errors. The first error is that they have assumed prior odds which have no connection with the facts of the particular case. Before we can state a probability or odds for any assertion, we must assess prior odds. These odds will depend upon the other evidence in the case. But experts in paternity cases have developed the habit of routinely assuming prior odds of 1 to 1 (evens) on the grounds that they know nothing about the case.[3] But the experts certainly know something and the court probably knows more. They know that this is a case in which someone has fathered a child but it is not known who. Why take prior odds of 1 to 1? Why not take prior odds of 1 to the male population of the world (say, 3 billion) or 1 to the male population of the country?

Secondly the witness is assuming an alternative hypothesis, that if the father were not the defendant it was some randomly selected male from the population, again without reference to the facts of the individual case.

Thirdly, and worst of all, the witness may conceal these assumptions by wrapping them up in a single probability. It is quite impossible to take evidence given in this form and combine it with the other evidence in the case.

Sometimes the expert openly states what the assumed prior is and says (for example) "assuming a prior of evens, and considering the odds against a match by chance, on the basis of this evidence alone, I believe the odds in favour of X being the father of Y are 10,000 to 1 – that is a probability of 99.99%", e.g. *Loveridge v Adlam* [1991] NZFLR 267, *Brimicombe v Maughan* [1992] NZFLR 476. As it stands this is not incorrect but it introduces an arbitrary assumption and confuses the issues.

In some jurisdictions in criminal cases witnesses state in a similar way the probability that the accused left a mark found at the scene of the crime. Such evidence is sometimes called the "probability of contact". In a German case the witness gave a "probability of contact" but made clear that it was based on a prior of evens (in other words: without the evidence the accused was as likely as not to be the person who left the mark). The court said *(in translation)*:

> The conversion of the probability of the characteristics of 0.014% into a probability of incrimination … of 99.986% requires, as the expert witness Dr H has set out to the Supreme Court, the establishment of a prior probability. One can only reach a result of 99.986% if the prior probability of 50% is assumed. That means … that before the DNA analysis the probability that the seminal fluid is from the accused is as high as the probability that it is not. The expert witness, who should only report about the result of this DNA analysis, could start from this (neutral) prior probability. The Court had to be aware that the result of the expert witness's opinion only makes an abstract statement about the statistical probability of incrimination. This result is not allowed to be treated as the equivalent of the concrete incrimination of the accused.
>
> BGH, Urteil vom Urt v. 12.8.1992-5 StR 239/92 (L.G. Hannover), BRD 10 MDR (Germany) 1992 vol 10 988-989.

The court had not been given guidance about how to use this "abstract probability" as evidence. If it had been, it would have been to combine the likelihood ratio for the evidence with the prior the *court* (not the expert) had assessed on the basis of the other evidence. This would have made the expert's prior assessment redundant. The expert should simply have stated the likelihood ratio for the evidence.

Whenever expert witnesses purport to assess the probability of an hypothesis they should be questioned to establish the assumptions which have been built into their prior odds and to establish the true value of their evidence in the context of the particular case.

Although the courts have become accustomed to receiving such evidence (especially the "probability of paternity") they have such difficulty in dealing with it that, as we saw in *Re JS (A Minor)* [1981] Fam 22; [1980] 1 All ER 1061, it is in precisely these cases that we find the courts agonising over the relationship between "statistical" and "legal" probability. The idea that there is such a thing as a "mathematical probability" or an "abstract statistical probability" which plays no part in common sense or legal reasoning stems from the way this sort of evidence has been given. The solution is that experts should not give evidence in this fashion.

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1 Essen-Möller E., *Die Beweiskraft der Ähnlichkeit im Vaterschaftsnachweis; Theoretische Grundlagen* (Anthropol. Gesellschaft, 1938).

2 For example see Kaye D.H., "The probability of an ultimate issue; the strange cases of paternity testing" (1989) 1 *Iowa LR* 75–109.

3 The search for methods of determining uninformative priors has been a constant theme in the Bayesian literature

since the time of Laplace. See, for example, Box G.E.P. and Tiao G.C., *Bayesian inference in statistical analysis* (Addison-Wesley, Reading, Mass, 1973) and Jaynes E.T. "Where do we stand on Maximum Entropy?" in Rosenkranz (ed), *E.T. Jaynes: Papers on Probability, Statistics and Statistical Physics* (Dordrecht: Reidel, 1983).

[28.1120] Child sexual abuse

The logic explained in this chapter can also help to untangle cases where evidence is not given in the form of numbers. The likelihood ratios we have seen above happen to have been derived from statistical surveys or series of scientific measurements but our aim is to make the best possible use of all the information we have, in order to decide a particular case, including evidence which is not statistical in form. The likelihood ratio provides the appropriate logical tool for doing this, even when we cannot state precise numbers.

In the New Zealand case *R v B* [1987] 1 NZLR 362 (see also *R v S* [1989] 1 NZLR 714) a man was accused of sexually assaulting his adopted daughter. A psychologist gave evidence of a number of tests and observations which she had carried out while interviewing the girl. Some of these were formalised tests such as the Family Relations Test and the Rotter Incomplete Sentences Test. Others were simply observations of the matters that the child talked about, for example her dreams and her self-image. In discussing each observation the psychologist made some comment such as:

> "[this] is typical of sexually abused girls/children/young persons"

except for the dreams about which she said:

> "dreams of this kind are frequently experienced by sexually abused young people."

The Court regarded the psychologist's evidence as inadmissible for a number of reasons, one of which was:

> its admission must inevitably lead to the jury learning the expert's opinion on the very issue it is required to answer … large parts of the … evidence clearly reflect the psychologist's view that she was examining a child who had been sexually abused by her father
>
> per Casey J at p 372.

In another New Zealand case just two years later, *R v S* [1989] 1 NZLR 714 a psychologist gave evidence of a number of characteristics presented by a child alleging sexual abuse such as self-mutilation, lack of eye contact and unwillingness to talk about home life. Before detailing these she had been asked the question:

> Did [the complainant] exhibit any characteristics which were consistent with what you had come to know as the characteristics of sexually abused children?

to which she replied

> very definitely.

In the first case the expert is saying that she has examined a number of abused children and a high proportion of them exhibit these signs. In other words she was giving the probability of finding the behaviour supposing that the child has been abused.[1] Most explicitly "dreams of this kind are frequently experienced by sexually abused young people". In *R v S* [1989] 1 NZLR 714 the expert was asked whether the child exhibited characteristics she had come to know as the characteristics of sexually abused children. Again this clearly means characteristics frequently observed in abused children. The probability of these characteristics is high supposing the child has been abused.

Of course, what the jury had to decide in each case was the probability that the child had been abused, given the psychologist's evidence and all the other evidence in the case. We can now see that the psychologist has not provided all the information the jury needs. First there must be prior odds, though that is not the responsibility of the expert. The prior odds may be provided by other evidence or, when none is available, might simply be the result of a survey as to the occurrence of the relevant type of abuse. Then the court also needs to know how probable the evidence is if that child had not been abused. The Court of Appeal rejected the evidence for a number of reasons which missed the real issues but it approached this point when it pointed out "some at least of those characteristics … may very well occur in children who have problems other than sexual abuse". In other words there may have been alternative explanations for the evidence. This reinforces the need for alternative hypotheses to be positive and specific.

1 P(this behaviour | abuse)

[28.1130] Alternative hypotheses in cases of child sexual abuse

In *R v B* [1987] 1 NZLR 362, the Court of Appeal mentioned that there might be alternative explanations for the behaviour (E) observed. In other words the Court was asking what was the appropriate alternative hypothesis (H2). Mere "non-abuse" is not a positive and specific hypothesis. Should it be that the child is a typical child of the same age group? Should it be that the child comes from a stressful and dysfunctional family? If so, we might expect the value of the evidence to be sharply reduced because many of the signs reported, though perhaps not all, are likely to be produced by a home life that was generally stressful.[1]

One could go further and ask whether step-children should be compared with step-children, orphans with orphans, children in day care with other children in day care and so forth. Any of these groups might display the behaviour to a greater extent than a typical child so that it would be a less valuable indicator of abuse for such children.

The second question is how the probability of the evidence assuming the alternative hypothesis, P(E|H2), is to be assessed. Survey evidence of the incidence of various characteristics may be limited. If the appropriate alternative hypothesis is that the child was randomly drawn from the population perhaps the best we can do is leave the jury to make the assessment.

1 Levy R.J., "Using "scientific" testimony to prove child sexual abuse" (1989) 23 *FLQ* 383.

[The next text page is 28-5001]

WHAT QUESTIONS CAN THE EXPERT DEAL WITH?

Introduction .... [28.1200]
Explanations .... [28.1210]
International developments .... [28.1220]

[28.1200] Introduction

So far we have discussed how a scientist should assess the value of the evidence provided by an observation in distinguishing between two hypotheses. The next question is, on what kind of propositions can the scientist shed light? The traditional picture is of a scientist receiving samples in a laboratory and comparing them without having any information about the case. This reinforces the picture of an independent scientist working with purely objective evidence. But as we have seen, the value of any item of evidence depends on the hypotheses being compared. In recent decades, forensic scientists have come to see that they can help the court answer questions closer to the final decision it has to make, if they expand their knowledge and expertise. There has also been a trend in recent years for the defence to produce alternative explanations for how trace evidence came to be on the defendant, for example, rather than contesting that the trace evidence came from the relevant source.

Consider a simple case in which a window is broken and a person is arrested and found to have glass fragments in his clothing. Traditionally the scientist would have compared the refractive indices of the glass from the clothing and that from the broken window and if they "matched" would have said that "the glass in the clothing *could have* come from the window". But this evidence is not terribly helpful to the court.

The next step was to try to assess the strength of the evidence. To assess the value of the evidence for the hypothesis that the glass came from the window in question, scientists had to know how common the particular refractive index is in window glass. To answer this question, forensic scientists approached manufacturers to build up a database of types of glass and the quantities manufactured. If we are to go further and consider the hypothesis that the suspect was present when the window was broken, scientists have to know the answers to questions like: "How common is it for people to have this quantity of fragments of glass in their clothing?". To answer that question forensic scientists in Britain conducted a survey of clothes handed in to dry-cleaners.[1] Naturally if the defence is that the accused is a demolition worker the value of the evidence would have to be reconsidered.

Can the scientist go further? Experiments were conducted to find out how much glass one would expect to find on a person who broke a window as opposed to somebody standing nearby.[2] The passage of time and what forensic scientists call "persistence" must also be considered. Would we still expect to find glass in someones' clothing six hours, 24 hours, a week after the offence? Given the results of these experiments the scientist is in a position to help with questions like "What is the probability that this amount of glass would be found on someone's clothing three days after they broke a window?". In other words the scientist is starting to move up what has been called *The Hierarchy of Propositions*. Rather than merely consider propositions related to the *source* of the material, they can contribute to discussion of how it got there (called *activity* propositions by Cook et al).[3] What the scientist cannot do is express an opinion on legal ingredients of an offence, for example even where an action appears to have been deliberate in the normal sense of the word, the defendant could still plead insanity which the scientist could make no comment on. This leads Evett et al to talk about *source*, *activity*, and *offence* propositions as three non-watertight, but useful, categories in the hierarchy of propositions.[4] Thus experts can strive to increase their ability to help investigators and courts, provided that they speak in terms of likelihood ratios and do not express views on guilt or innocence.

The offence propositions will be determined by the legal ingredients of an offence and in turn determine what needs to be proved. For example, to convict someone as a party to the offence it may be sufficient to produce evidence that they were very close to the window when it was broken, even though the evidence cannot distinguish between that proposition and the proposition that they physically broke the window.

This expanded role for forensic scientists requires wider expertise. Scientists have to be able to think through the issues in the case and work out how the evidence can contribute to resolving them rather than merely comparing samples.

1 Curran J.M., Hicks T.N., and Buckleton J.S., *Forensic Interpretation of Glass Evidence* (CRC Press, 2000), p 105–106 and references cited there.

2 Curran J.M., Hicks T.N., and Buckleton J.S., *Forensic Interpretation of Glass Evidence* (CRC Press, 2000), p 124.

3 Cook R., Evett I.W., Jackson G., Jones P.J. and Lambert J.A., "A hierarchy of Propositions: deciding which level to address in casework" (1998) 38 *Science & Justice* 231–239; Evett I.W., Gill P.D., Jackson G., Whitaker J. and Champod C., "Interpreting small quantities of DNA: the hierarchy of propositions and the use of Bayesian networks" (2002) 47 *J For Sci* 520–530.

4 See Robertson B.W.N. and Vignaux G.A., "Taking Fact Analysis Seriously" (1993) 91 *Mich LR* 1442 and references therein.

[28.1210] Explanations

At the earliest stages of a case investigators are not presented with well-formed hypotheses and asked to evaluate the strength of the evidence in discriminating between them. They are presented with a mass of disorganised data and part of their job is to frame hypotheses.

These may include explanations for the evidence.[1] Explanations, as the word implies, explain the evidence. It follows that the evidence itself cannot distinguish between them. For example, explanations for a DNA sample at the scene which matches that of the accused might include:

- the accused was present at the offence and left the material;
- someone with the same DNA profile left the material;
- the accused was present at some other time and left the material;
- someone obtained material from the accused and planted it at the scene.

The focus must then switch to all the other evidence for or against these propositions. In the case that someone with the same DNA profile left the material, two lines of inquiry suggest themselves. The first is whether the accused has an identical twin or very close relative. The second is to consider the probability that a randomly selected person would have this DNA profile. These then become the hypotheses to be considered. In the case of the other two explanations, ordinary police work is required to establish whether the accused had previously been to the premises or whether anyone had the motive and opportunity to plant evidence against him.

In this way, forensic scientists can become more helpful in structuring the argument in cases and as research progresses will continue to increase their ability to help investigators and courts.

1 Evett et al, "More on the hierarchy of propositions: exploring the distinction between explanations and propositions" (2000) 40 *Science & Justice* 3–10.

[28.1220] International developments

In 2009 the Association of Forensic Science Providers (AFSP) published standards for giving evidence which adopt this approach:

> The strength of evidence will be expressed either by a value of the likelihood ratio or using a verbal scale related to the value of the likelihood ratio. This verbal scale will be adopted by all AFSP organisations.[1]

The AFSP gave a number of specific examples including:

- My findings are far more likely if the amphetamine came from the suspect's stock than if they had come from some other stock.
- My glass findings provide support for the view that the suspect broke the window rather than he poked his head through the broken pane afterwards.
- My observations are equally as likely if Ms. X's or Mr. Y's versions of events were true.
- The pattern and distribution of the blood spots are far more likely if Mr. X had assaulted Mr. Y than if he had been standing close to the assault when someone else did.

The Board of European Network of Forensic Science Institutes (ENFSI), an organisation with 66 member laboratories in 36 countries, has undertaken to implement these principles in its member laboratories.[2] In 2015 ENFSI published a guideline for evaluative reporting in forensic science that follows the principles outlined in this chapter.[3]

1 Association of Forensic Science Providers, "Standards for the formulation of evaluative forensic science expert opinion" (2009) 49 *Science & Justice* 161–164.

2 "Expressing Evaluative Opinions: a position statement" *Science & Justice* 51 (2011) 1–2.

3 Aitken, C.C.G.; Barrett, A.; Berger, C.E.H.; Biedermann, A.; Champod, C.; Hicks, T.N.; Lucena-Molina, J.; Lunt, L.; McDermott, S.; McKenna, L.; Nordgaard, A.; O'Donnell, G.; Rasmusson, B.; Sjerps, M.J.; Taroni, F.; Willis, S.M.; Zadora, G., ENFSI guideline for evaluative reporting in forensic science, 2015, European Network of Forensic Science Institutes (ENFSI).

[The next text page is 28-5501]

SUMMARY

[28.1300] Summary

- An item of evidence cannot, by itself, prove a hypothesis considered in isolation but can only help to distinguish between hypotheses.
- The value of a piece of evidence, E, is not intrinsic but varies depending upon the hypotheses being considered.
- The question must be asked: *What are the appropriate alternative hypotheses?*
- Two hypotheses being compared must be positive, specific and exclusive of each other.
- It may be necessary to compare the prosecution hypothesis with more than one defence hypothesis.
- A forensic scientist cannot tell us how probable the prosecution case is but only how much more probable the *evidence* is if the prosecution case is true than if an alternative hypothesis is true.
- The likelihood ratio compares the probability of the evidence given each hypothesis and expresses the strength of the evidence in distinguishing between them.
- In principle, evidence will be relevant when the likelihood ratio is less than or greater than 1. A likelihood ratio of 1 means that the evidence is unhelpful and therefore is irrelevant.
- Although relevant, evidence may be excluded by an exclusionary rule or because its probative value (measured by the likelihood ratio) is not sufficient to overcome the cost of admitting it in terms of time, money, confusion, or prejudice.
- Where a mark is left at the scene of a crime and it is disputed whether it came from the accused, the likelihood ratio is the probability of the evidence supposing the accused left the mark divided by the probability of the evidence if "someone else" left the mark. Who the "someone else" might be will depend upon what is known about the *perpetrator* and what line of defence is chosen.
- Where a mark is found on the accused and it is disputed whether it came from the scene, the likelihood ratio is the probability of the evidence supposing the accused received the mark at the scene divided by the probability that the accused would have received this mark although not present. The latter will depend upon what is known about the *accused* and the line of defence chosen.
- In paternity cases the value of the evidence will vary according to what is known about alternative possible fathers.

- Hypothetical alternatives may reasonably be put to expert witnesses provided they have some reasonable prior probability.
- Experts may be able to consider questions other than whether two samples had the same source or not. They may be able to consider hypotheses as to how the trace came to be where it was found, or what activity was taking place.
- In a rational procedural system all the hypotheses to be considered at trial would be known to the expert witnesses beforehand so that they could assess the value of their evidence in the light of these and make appropriate calculations.

[The next text page is 28-6001]

APPENDIX

Probability, odds and Bayes' rule .... [28.1400]
Laws of probability .... [28.1430]

[28.1400] Probability, odds and Bayes' rule

Probability

Probability is a rational measure of the degree of belief in the truth of an assertion based on information or evidence. The assertion, hypothesis, or premise is itself a statement that is either true or false. For example, the assertion "The driver is over the blood/alcohol limit" is either true or false but we may not be sure of whether it is true or not. Our degree of belief about the truth of the assertion is measured by our assessment of its probability.

The value of all probabilities depend on the assumptions and information used in assessing them. Thus, we would assess a different probability for the assertion "the driver is over the blood/alcohol limit" if we had evidence of the result of the breath test than without that evidence. All the evidence that is used to assess a probability is known as the *condition* for the probability. All probabilities are conditional on the evidence used.

Evidence is also described in the form of statements. Thus "the light showed red", if true, is evidence for the hypothesis that "the person is over the limit" and would lead to a different probability of the hypothesis than would be assessed if the evidence "the light showed green" were true. That, again, would generally be different if we either had no evidence of the colour of the light or had additional evidence of erratic driving. Mathematically there is no difference between evidence and hypotheses, they are both statements which are either true or false. But evidence concerns (direct) observations, while hypotheses are about things we cannot directly observe. We will therefore usually write E for evidence and H for hypotheses.

An assessment of probability is usually expressed as a value between 0 and 1 but can equally be represented as a corresponding percentage between 0 and 100%. We switch between these forms at will.

A probability of 0 indicates complete disbelief in an assertion or hypothesis given the information one has. Thus my probability for the assertion "I will live for ever", given what I know about the world, is 0.

A probability of 1 (or 100%) indicates absolute belief. My probability for the proposition that "the sun will rise tomorrow", given my experience and what I know about the working of the solar system, is 1.

A probability between 0 and 1 indicates less than certainty. An assessment of probability of 0.5 or 50% means that we consider the event to be as likely as not to happen. An assessment of more than 0.5 means that we consider the event more likely to happen than not. Thus, my probability that there will be rain today may be about 0.25 (25%) given the weather forecast I heard this morning and looking out of the window at the clouds. In ordinary language I think there is quite a possibility of it raining but it "probably won't".

One must bear in mind always that the probability one has for an assertion depends on the information one has. My probability that it will rain may be different if I have heard a weather forecast that says it will be dry than if I have not. The information is called the condition.

An assertion will have a negation. Thus the assertion “It will rain today” has a corresponding negative assertion “It will not rain today”. In this instance one can calculate the probability of the negative form of the assertion since it will either rain or not. It is done quite simply. The probability that there will *not* be rain (given the information we have) is 0.75, which is 1 minus the probability that there will be.

Odds

We are also going to need to describe probabilities in the form of *odds*. Many people are familiar with odds, if only from betting. They also recognise that they are a description of uncertainty, like probability. But not everyone realises that they are only another way of representing probability and one can go from one form to another quite easily.

To get the odds from the probability of an assertion you calculate the ratio of the probability to (1- the probability). Thus a probability of 0.3 has equivalent odds of

$$\text{Odds} = \frac{\text{Probability}}{(1 - \text{Probability})} = \frac{0.3}{(1-0.3)} = \frac{0.3}{0.7} = \frac{3}{7}$$

This could also be written as odds of 3 to 7 (in favour of the assertion).

Odds corresponding to a probability of 0.5 are

$$\text{Odds} = \frac{0.5}{(1-0.5)} = \frac{0.5}{0.5} = \frac{1}{1}$$

These odds would be described as 1 to 1 or *evens*.

Odds of less than evens are sometimes reversed and described as “odds against” the assertion. Odds of 3 to 7 in favour of an assertion might, instead, be described as odds of 7 to 3 *against*. To return from odds to probability you calculate the ratio of the odds to (1 + the odds). Thus odds of 3 to 7 would be the same as a probability of

$$\text{Probability} = \frac{3/7}{1+3/7} = \frac{3/7}{10/7} = 0.3$$

Even odds (1 to 1) correspond to a probability of 1/(1+1) = 1/2 = 0.5.

Odds have two key advantages:

- the odds form makes it easier to see the importance of the alternative hypothesis and to use the likelihood ratio for the evidence based on two specific hypotheses.
- odds are more comprehensible when we are dealing with extremely high or low

probabilities. There does not appear to be much difference between probabilities of 0.9990 and 0.9999, but we can immediately see that there is a great difference between the corresponding odds of roughly 1 to 1,000 and 1 to 10,000.

When odds are some whole number to 1 (such as “3 to 1”), the odds may be stated just as a number, i.e. 3. Sometimes odds are written as a fraction (such as 2/3) but this is easily confused with a probability. For both these reasons we will express odds for or against a proposition in the form “3 to 1” or “2 to 3”.

The symbols

It is often convenient, particularly when developing general methods of argument, to represent different assertions or hypotheses by different letters. Thus we would state:

H = “It will rain today”

and then refer to H in our discussions. The symbol not-H (often conventionally written, ˜H or H with a bar over it) is the negation of this, meaning that it is not true that “It will rain today” or, more directly, “It will not rain today”.

In symbolic form, a probability value and the conditions we are assuming are written as P(H|E). This reads “the Probability of assertion H if assertion E is true”.

- “P” stands for “Probability”
- H and E are assertions or statements; H is an assertion for which we are assessing a probability
- E is the *condition*
- “|” means “given” or “if”

Thus the construction “|E” means “given E is true” or “if E is true”. These statements can be further contracted to “if E”. It is important to note that *all* probabilities are conditional upon the information used to assess them. Thus we might say that

H = “It will rain today”

E = “the weather forecast said ‘fine weather’”

P(H|E) = 0.4 means that (my assessment of) the probability that “It will rain today” if “the weather forecast was ‘fine weather’” is 0.4 or 40%.

Our probability for rain might have been different if the weather forecast had been different and different again if we had failed to hear the weather forecast. The probability one assesses always depends on (is conditional on) the knowledge available. Often in this document, but only for clarity, we will leave the condition out of the formula.

[28.1430] Laws of probability

Complementarity

We have already noticed above that if P(H|E) = 0.4 then P(not-H|E) = 0.6. This is the consequence of the Axiom or *Law of Complementarity*. Since it is certain that a statement is either true or not, the probability assessments for all the possible ways it might be true plus the proposition that it is not true must add up to 1.

It follows that if we stipulate that a statement is true, the probabilities for all the ways it might be true must add up to one. For example, if we regard it as certain that a person was murdered then the probabilities for all the possible methods must add up to one.

It is important to be clear which probabilities must be complementary. We discussed earlier the example of a breath testing device. Let

E = "a red light shows" and

H = "the driver is over the limit" and

not-H = "the driver is not over the limit"

Then the sum of the probabilities that the driver is over and the driver is not over the limit (if the red light shows) must sum to 1.

$$P(H|E) + P(\text{not-}H|E) = 1$$

In contrast, probabilities which have different conditions do not have to add up to 1. Thus the probability that we got a red light if the subject was over the limit was 0.95 but the probability of getting a non-red (i.e. a green) light if the subject was not over the limit was 0.995 and these do not sum to 1. (Please see para [28.230] a breath testing device, above). The difference can be seen clearly if we use symbols:

$$P(E|H) = 0.95$$

$$P(\text{not-}E|\text{not-}H) = 0.995$$

So, if we change the conditions the probabilities do not have to add up to 1, but if we are discussing the probabilities of different hypotheses, one of which must be true, under the *same* condition then all the probability assessments must add to 1.

Product rule

We have discussed the Law of Complementarity above. There are two other Laws of Probability. These explain how to assess the probability that two statements are true, or that at least one of two statements is true.

The statement that A and B are both true is written (A and B). If we want to assess how probable it is that A and B are both true then the *multiplication rule*, or *product rule* tells us that we first assess how probable A is and then assess how probable B is if A is true. In symbols:

$$P(A \text{ and } B) = P(A) \cdot P(B|A)$$

Thus A might be "it will rain today"

and B might be "Phar Lap will win the Derby tomorrow".

Suppose I have already assessed the probability of rain today as 0.25, and I know the horse runs well when the going is soft. So, assuming it will rain, I assess the odds that it will win if it rains as 4 to 1, a probability of 4/(4+1) = 0.8.

If I want to assess the probability that it will rain today *and* that Phar Lap will win tomorrow

P(A and B) = P(A)·P(B|A) = (0.25)(0.8) = 0.2 (or odds of 1 to 4 or 4 to 1 against.)

Sometimes the product rule is written as

"P(A and B) = P(A)·P(B) provided that A and B are independent."

Note that odds *cannot* be multiplied in the same way as we have just multiplied the probabilities.

Sum rule

The statement that A or B (or both) are true is written (A or B). If we want to know how probable (A or B) is true given some condition, C, then we use the *addition rule* or *sum rule*. First we consider how probable it is that A is true, and how probable it is that B is true. We might then consider just adding those two probabilities together but inside our assessment of P(A) is the probability that A is true when B is also true and vice versa. We would therefore double count the probability that both would be true. To deal with this we subtract the probability that both are true. In symbols:

P(A or B) = P(A) + P(B) – P(A and B)

So, taking our horse-racing example, suppose we assess the probability that the horse will win P(B) as 0.5. The probability that it will either rain or the horse will win *or both* is

P(A or B) = 0.25 + 0.5 - 0.2 = 0.55

If A and B cannot both be true together, that is A and B are *exclusive* assertions, then the term to be subtracted, P(A and B), is 0 and the formula simplifies to

P(A or B) = P(A) + P(B)

This is a special case, though.

The longer form is the more general one. It takes all contingencies into consideration.

Note that we *cannot* combine odds in this simple way.

The likelihood ratio

The likelihood ratio is a number which is the ratio of two probabilities for the *same* assertion assuming *different* conditions. It is a number that can take any value above zero. It measures the weight of the assertion as evidence in distinguishing the conditions. To use the example given above for the breath tester, let

E = "a Red Light shows" and

H = "the driver is over the limit" and

not-H = "the driver is *not* over the limit"

$$\frac{P(E \mid H)}{P(E \mid \text{not-H})} = \frac{0.95}{0.005} = 190$$

Contrast this with odds which is a ratio for *alternative* assertions under the *same* conditions.

If the likelihood ratio is greater than 1 it indicates that the "Red Light" makes the proposition that the sample is over the limit *more* probable than it was before. If it is less than 1 it makes the proposition *less* probable.

Bayes' rule

Bayes' rule is a mathematical theorem that enables one to make new assessments of probability for assertions in the light of new evidence. It can be expressed in either a probability form or an odds form.

Probability form

The product rule is just as valid when we switch A and B in it, and since (A and B) is the same as (B and A) we obtain:

$$P(A \text{ and } B) = P(A) \cdot P(B|A) = P(B) \cdot P(A|B)$$

Dividing the latter two by P(B) we get Bayes' Theorem:

$$\frac{P(E \mid H)}{P(E \mid \text{not-H})} = \frac{0.95}{0.005} = 190$$

For our use of Bayes' rule it is useful to express it in terms of E and H.

Bayes' rule in this form gives the probability of H given evidence E and reads

$$P(H \mid E) = P(H)\frac{P(E \mid H)}{P(E)}$$

This gives the value of P(H|E) in terms of P(E|H) and two other probabilities. It can also be viewed as calculating the probability of H given evidence E from three components:

- the prior probability of H, P(H),
- the probability of the *evidence* assuming the truth of H, P(E|H), and
- the probability of getting the *evidence* in any possible way, P(E).

For clarity, we have left out an indication of the other conditions, C, which should properly appear in every term so that P(H|B) should, more accurately, read P(H|B,C).

Odds form

The probability form of Bayes' rule holds for any H:

$$P(H_1 | E) = P(H_1) \frac{P(E | H_1)}{P(E)} \quad \text{and} \quad P(H_2 | E) = P(H_2) \frac{P(E | H_2)}{P(E)}$$

Dividing these equations yields Bayes' rule in odds form. This shows us how to update the odds of H1 versus H2 in the light of evidence E:[1]

$$\frac{P(H_1 | E)}{P(H_2 | E)} = \frac{P(H_1)}{P(H_2)} \cdot \frac{P(E | H_1)}{P(E | H_2)}$$

The first ratio on the right-hand side is the odds of H1 versus H2 before we have the evidence E (the *prior* odds) and the second ratio is the likelihood ratio for evidence E given the two alternative assertions H1 and H2. On the left-hand side are the *posterior* odds. Thus if the likelihood ratio is greater than 1 the posterior odds are increased compared with the prior odds; if it is less than 1 the posterior odds are decreased.

Combining evidence

Bayes' rule in the odds form shows us how to update our odds when we have an item of evidence E. The odds are updated by multiplying them with the likelihood ratio. This update turns the prior odds into posterior odds. But what can we do if we have two items of evidence E1 and E2?

When E1 is independent of E2, we can simply update our odds twice by multiplying with their respective likelihood ratios. The posterior odds after considering E1 become the prior odds for considering E2:

$$\frac{P(H_1 | E_1 \text{ and } E_2)}{P(H_2 | E_1 \text{ and } E_2)} = \frac{P(H_1)}{P(H_2)} \cdot \frac{P(E_1 | H_1)}{P(E_1 | H_2)} \cdot \frac{P(E_2 | H_1)}{P(E_2 | H_2)}$$

The evidential value of combined independent evidence is therefore simply the multiplication of the separate evidential values.

If E1 and E2 are not independent it is more complicated. We can use the product rule:

$$P(E1 \text{ and } E2|H) = P(E1|H)\cdot P(E2|E1 \text{ and } H)$$

so the likelihood ratio for (E1 and E2) becomes:

$$\frac{P(E_1 \text{ and } E_2 \mid H_1)}{P(E_1 \text{ and } E_2 \mid H_2)} = \frac{P(E_1 \mid H_1)}{P(E_1 \mid H_2)} \cdot \frac{P(E_2 \mid E_1 \text{ and } H_1)}{P(E_2 \mid E_1 \text{ and } H_2)}$$

In theory, the formula becomes vastly complicated as more and more evidence is added. In practice, however, the complications are avoided as, during the course of an investigation or trial, the hypotheses being compared become narrowed down.[2]

1 Note that these are actually ratios of probabilities which are only truly odds when H2 happens to be the negation of H1. In evaluating evidence it is unhelpful to choose the alternative hypothesis H2 as the negation of H1. Still, the ratio of the probabilities of H1 and H2 is commonly referred to as odds.

2 Vignaux G.A. and Robertson B.W.N., "Hypothesis Refinement", pp 183–188, in Skilling J. and Sibisi S. (eds) *Maximum Entropy and Bayesian Methods 1994* (Kluwer, 1996).

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