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Solving the Tacking Problem with Contrast Classes

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ABSTRACT

The traditional Bayesian qualitative account of evidential support (TB) takes assertions of the form 'E evidentially supports H' to affirm the existence of a two-place relation of evidential support between E and H. The analysans given for this relation is $C(H,E) =_{def} Pr(H|E) > Pr(H)$. Now it is well known that when a hypothesis H entails evidence E, not only is it the case that C(H,E), but it is also the case that C(H&X,E) for any arbitrary X. There is a widespread feeling that this is a problematic result for TB. Indeed, there are a number of cases in which many feel it is false to assert 'E evidentially supports H&X', despite H entailing E. This is known, by those who share that feeling, as the 'tacking problem' for Bayesian confirmation theory. After outlining a generalization of the problem, I argue that the Bayesian response has so far been unsatisfactory. I then argue the following: (i) There exists, either instead of, or in addition to, a two-place relation of confirmation, a three-place, 'contrastive' relation of confirmation, holding between an item of evidence E and two competing hypotheses H_1 and H_2. (ii) The correct analysans of the relation is a particular probabilistic inequality, abbreviated $C(H_1, H_2, E)$. (iii) Those who take the putative counterexamples to TB discussed to indeed be counterexamples are interpreting the relevant utterances as implicitly contrastive, contrasting the relevant hypothesis H_1 with a particular competitor H_2. (iv) The probabilistic structure of these cases is such that $\sim C(H_1, H_2, E)$. This solves my generalization of the tacking problem. I then conclude with some thoughts about the relationship between the traditional Bayesian account of evidential support and my proposed account of the three-place relation of confirmation.

1 The 'tacking problem' and the traditional Bayesian response

The traditional Bayesian qualitative account of evidential support (TB) takes assertions of the form 'E evidentially supports H' to affirm the existence of

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a two-place relation of evidential support between E and H. This relation is analysed as follows:

TB: assertions of the form 'E evidentially supports H' are true iff C(H, E) $=_{def}$ Pr(H|E) > Pr(H)[1,2]

Now C(H, E) has a well-known property. The following theorem can be easily demonstrated:

Theorem 1: for any E, H and X, if [1] Pr(E|H) = 1, [2] 0 < Pr(E) < 1, [3] Pr(H) > 0, and [4] Pr(H&X) > 0 then C(H, E) and C(H&X, E).[3,4]

In other words, it can be demonstrated that, given minimal and plausible assumptions about the values of certain probabilities, according to TB, in cases in which a hypothesis H entails evidence E, not only is the assertion 'E evidentially supports H' true, but so is the assertion 'E evidentially supports H&X', for any X. According to many, however, this result is counter-intuitive. Say, for instance, that we are playing cards. I manage to take a peek at what you have in your hand and see that you have at least three red cards (E). Now everyone agrees that the following assertion is true:

A1: 'My observation that you have at least three red cards (E) is evidence that you have a handful of red cards (H)'

There is, however, a widespread intuition that the following assertion is *false*:

A2: 'My observation that you have at least three red cards (E) is evidence that you have a handful of red cards and a pocketful of pennies (H&X).'[5]

According to TB however, A2 would appear to be true. This is often known as the 'tacking problem' amongst those who feel that A2 is false, because,

[1] Strictly speaking, a relativization to background knowledge K should be made here. TB should really read: C(H, E|K) iff Pr(H|E & K) > Pr(H|~E & K). Omitting reference to K however, yields a considerable gain in expository simplicity without impacting in any way on the arguments that follow.

[2] And of course one must add that the evidence have a prior probability strictly superior to 0 (0 < Pr(E)), or else the left-hand side of the inequality would come out as undefined.

[3] See Appendix A.

[4] This is noted, for instance, by Earman ([1992]) and Fitelson ([2002]).

[5] A sizeable majority of theorists agree that A2 seems false. Amongst these, one finds, for example, Merrill ([1979]), Glymour ([1980]), Earman ([1992]), Gemes ([1993]), Fitelson ([2002]), Fitelson and Hawthorne ([2004]) and Waters ([1987]), who all think that this poses a problem for those theories of confirmation which fail to account for this intuition. Maher ([2004]) also holds that it is a common intuition that A2 is false, although he subsequently argues that this does not pose a problem for traditional Bayesianism (insofar as traditional Bayesianism does not attempt an explication of the folk notion of confirmation).

according to TB, for any H such that H entails E, any arbitrary proposition X can just be 'tacked on' to H to yield a conjunction H&X such that the assertion 'E evidentially supports H&X' comes out true.

In fact, it also turns out that one can easily prove a more general result than Theorem 1. It can be demonstrated that:

> **Theorem 2**: for any E, H and H^+, if [1] C(H, E), [2] $Pr(H|H^+) = 1$, [3] $Pr(E|H \& H^+) = Pr(E|H)$, [4] $Pr(H^+) > 0$, [5] $Pr(H) > 0$, [6] $Pr(E) > 0$, [7] $Pr(H^+ \& H) > 0$, and [8] $Pr(H^+|E) > 0$, then $C(H^+, E)$.[6,7]

In other words, given minimal and plausible assumptions about the values of certain probabilities, according to TB, if the assertion 'E evidentially supports H' is true, so too is the assertion 'E evidentially supports H^+', where H^+ is any state of affairs stronger than H that is 'screened off' from (i.e. made probabilistically irrelevant with respect to) E by H. Theorem 2 generalizes Theorem 1 in two ways. First of all, it demonstrates that, for TB, the transmission of evidential support extends to any proposition that satisfies the screening-off condition and is stronger than H, rather than simply those screened-off propositions that are *conjunctions* of H with some further proposition X. Secondly, it shows that this kind of transmission of evidential support extends beyond the deductive case to *any* situation in which (a) E supports H and (b) H screens off, from E, some H^+ which entails H.

Now Theorem 2 generates a number of further prima facie awkward results for TB, in addition to TB's positive verdict on the truth of A2. For instance, returning to the card example above, it was pointed that many share an intuition that A2 is false. But, in addition to this, it *also* seems wrong to make the following assertion:

> **A3:** 'My observation that you have at least three red cards (E) is evidence that you have a handful of hearts (H_1^+).'

However, according to TB, A3 should come out true (indeed $Pr(H|H_1^+) = 1$ and $Pr(E|H\&H_1^+) = Pr(E|H)$).

The traditional Bayesian response to this kind of worry has been to argue that, in the problem cases, various plausible Bayesian quantitative accounts of evidential support yield the result that H is 'more' confirmed by E than H^+ is. Fitelson and Hawthorne ([2004]), for instance, prove that, if, and only if, $Pr(H|E) > Pr(H|{\sim}E)$, $Pr(E|H\&X) = Pr(E|H)$, and $Pr(X|H) < 1$, then E incrementally confirms H more than it does H&X on the first two of the

6 See Appendix B.

7 Note that this is not the claim that TB satisfies the so-called 'Converse Consequence Condition' (CCC), i.e. the condition that if C(H, E) and $H^+ \rightarrow H$, then $C(H^+, E)$. Indeed it is well-know that TB *does not* satisfy this condition (Salmon [1975]).

following popular quantitative accounts of incremental confirmation (but not on the third):

d: C(H,E) = Pr(H|E) − Pr(H),

l: C(H,E) = Pr(E|H)/Pr(E|∼H),

r: C(H,E) = Pr(H|E)/Pr(H).[8]

Now of course, there may be a problem to do with the fact that these 'quantitative' responses depend on the adequacy of one of the particular accounts for which the result holds (in Fitelson and Hawthorne's case: d or l). And the ratio account r, which the respondents are banking on being false, has a number of enthusiastic supporters (e.g. (Horwich [1982]; Milne [1996]; Schlesinger [1995]; Pollard [1999]); though see notably (Fitelson [2001]; Eells and Fitelson [2002]) for some considerations against r. But 'measure-sensitivity' is not half of the trouble. The fact of the matter is that, as Maher ([2004]) has recently reminded us, the response quite simply *does not address the issue at hand*. The critic points out that TB tells us that certain conjunctions are confirmed by various observations when there is a widespread intuition that they are not. The defender of TB then turns round and argues that that's not a problem, or at least not much of a problem, because TB's quantitative counterpart judges those conjunctions to be—possibly infinitesimally—less confirmed than some other propositions that we do take the observations to confirm. Now unless someone manages to show how the fact that E confirms H more than it does H&X accounts for why many judge that E confirms H but does not confirm H&X at all, it's hard to see what the response has to do with the original problem. The Bayesian's move here seems comparable to (i) providing an account of indebtedness from which it follows that, for any x indebted to y, x's next-door neighbour is also indebted to y and then (ii) following that up by pointing out that, in fact, all is not as bad as it seems because the account's quantitative theoretical counterpart yields the result that x's neighbour is however less indebted to y than x herself is.

2 Contrastive support

It has long been noted that claims concerning relations of evidential support come in two different kinds of surface forms. There is the familiar 'E confirms H'. But there is also the explicitly contrastive construction 'E confirms H_1 rather than H_2'. However well proponents of TB may claim to handle the

8 Previous Bayesian responses appealing to a quantitative distinction include notably (Earman [1992]; Rosenkrantz [1994]; Fitelson [2002]).

former, TB obviously has little to say about the latter. In what follows, I would like to outline a probabilistic account of contrastive confirmation based on a probabilistic account of contrastive *explanatory support* due to Chris Hitchcock ([1996], [1999]). This account is, I believe, not only intuitively compelling but, as we shall see towards the end of this section, has a formal property that helps illuminate our intuitions concerning the falsity of A2 and A3 above.

According to Hitchcock, a factor A counts as a partial explanation of why P rather than Q if and only if (1) P and Q are incompatible[9] and (2) A raises the probability of that P whilst holding the exclusive disjunction of P and Q fixed. In other words:

> EXPL(P, Q, A) iff (1) $\Pr(Q|P) = 0$ and (2) $\Pr(P|A \,\&\, (P \vee Q)) > \Pr(P|{\sim}A \,\&\, (P \vee Q))$[10]

Consider how this account handles a sample scenario. It is late in the afternoon on Christmas day, the Christmas meal has not started yet and I start to feel peckish. I wander over to the kitchen cupboard, take a look inside

[9] This requirement is a common way to understand the inappropriateness of asking why, for instance, Kodaly is a Hungarian rather than a vegetarian (the example is due to Sober [1994]). It is endorsed notably by Garfinkel ([1981]), Ruben ([1987]) and Temple ([1988]). Note however, that Lipton ([1990]) argues that this requirement is too strong. He points out that the following question seems legitimate: 'Why did Jones rather than Smith develop paresis?' Here it appears that we have here a case in which 'why *P* rather than *Q*?' is appropriate but $\Pr(Q|P) \neq 0$. Both Jones and Smith can develop paresis but the relevant contrastive question can nevertheless be posed. Note furthermore that, while it is possible to cook up bizarre scenarios in which it is impossible in the circumstances for both Jones and Smith to develop paresis, the apparent legitimacy of Lipton's question does not hinge on our presupposing such kinds of baroque circumstances to hold.

In response to Lipton, one might want to question whether one *can* indeed ask why Jones rather than Smith got paresis, or at least ask so *literally*. If I were to ask you: 'Why did Jones rather than Smith develop paresis?', and you were to reply: 'I really do not see what you mean, *both* Jones and Smith could have developed paresis. What are you talking about?', it seems plausible to say that I could accuse you of being uncooperative but not of being semantically incompetent. Your comment would have merely been pragmatically inappropriate, in much the same way that your meeting my asking you 'Can you pass the salt?' with a simple 'Yes I can' would be uncooperative: I would certainly be frustrated by your response but I only to the extent that I expect you not to take me literally. So it might be suggested that to the extent that: 'Why did Jones rather than Smith contract paresis?' is appropriate, it is really shorthand for: 'Why did Jones develop paresis and Smith not rather than both of them develop paresis, neither of them develop paresis, or again Smith develop paresis and Jones not?', in which case we do have opposition after all.

Whatever the correct view on the incompatibility of members of contrast classes, note that Hitchcock's account can easily be modified so as to allow for P and Q to be compatible. All that is needed is to conditionalize, not on the mere disjunction of P and Q, but on the negation of their conjunction as well:

$$\text{EXPL}(P, Q, A) \text{ iff } \Pr(P|A \,\&\, (P \vee Q) \,\&\, {\sim}(P \,\&\, Q)) > \Pr(P|{\sim}A \,\&\, (P \vee Q) \,\&\, {\sim}(P \,\&\, Q))$$

[10] Again, as in note 1 above, strictly speaking a relativization to background conditions K should be made here (A explains why P rather than Q relative to background conditions K).

and come across the Christmas cake and, right next to it, a box of baqlawa. It occurs to me that cutting a slice out of the cake would not really be all that appropriate so I decide to opt for the baqlawa instead. Hunger explains why I ate the baqlawa rather than went hungry. It does not explain why I ate the baqlawa rather than the cake. On the other hand my worrying about spoiling the whole Christmas dinner experience for everyone *did* cause me to eat the baqlawa rather than a slice of the cake, but did not impact on my decision to break fast. According to Hitchcock, 'I ate the baqlawa rather than left it in the cupboard because I was hungry' means 'conditional on my either eating the baqlawa or starving, my being hungry raised the probability of my eating the baqlawa', whereas 'It was not because I was hungry that I ate the baqlawa rather than the cake' is to be translated as 'conditional on my either eating the baqlawa or my eating the cake, my being hungry failed to raise the probability of my eating the baqlawa'.

Now if the account does, on the face of it, appear to accord with our intuitions about particular cases, handling the data is not the only motivation for the account. According to Hitchcock, $P \vee Q$ is conditionalized upon because it is *presupposed*, the most natural way to formalize the notion of presupposition being, again according to Hitchcock, to conditionalize on whatever is presupposed. We need to be careful here however, as there are two kinds of 'presuppositions' at play. There are first of all presuppositions which must be true for the question to be intelligible. In this sense 'why P rather than Q' presupposes notably that P and that $\sim$Q. Presumably we *do not* want to conditionalize on $P \& \sim Q$ as nothing would have any kind of explanatory relevance at all. Then there are presuppositions whose falsity does not entail the unintelligibility of the question but which constrain the range of pragmatically acceptable answers. They correspond to a background of assumptions shared between the participants of the conversation prior to the discovery that the fact to be explained obtained. When asking why P one is expecting a new reason to believe that P, not a reason which is mutually taken for granted. Hitchcock ([1999], p. 598) gives us the following example. Say John catches syphilis. He is diagnosed relatively early on and is prescribed medication which he never ends up taking. As a consequence of this, his syphilis gets worse and he ends up developing paresis. Say that his family know that he contracted syphilis and John knows that they know (and knows that they know that he knows that they know, etc.). They ask John for an explanation of why he got paresis. It is clear that they are not expecting a story about how he ended up with syphilis. They will be satisfied however with an admission that he did not take the medicine he was prescribed after contracting syphilis. Even though his getting syphilis is a part of the cause of his getting paresis, it is a conversationally inadequate response. Conditional on background knowledge, his getting syphilis is explanatorily irrelevant

(Pr(Paresis & Syphilis & K) = Pr(Paresis & K), as K includes the knowledge that he had syphilis). *This* is the sense in which Hitchcock thinks that 'why P rather than Q' presupposes (inter alia) $P \vee Q$. Asking why P rather than Q signals that one took for granted, prior to finding out that P, that either P or Q.

But does this mean that one should not be asking 'why P rather than Q?' unless one already knew that $P \vee Q$ prior to finding out that P? Surely that would not be right. Say I know that a whole load of people are going for a particular job in the company. I find out that Susan ends up with the job. It still seems like it should be legitimate to ask why Susan got the job rather than Harry, although I did not know that the job was going to go to either Susan or Harry. Fortunately Hitchcock is not implying this:

> One who asks [why Adam ate the apple rather than the pear] need not have known that Adam ate something prior to learning that he ate the apple, but she may affect having been in this state of knowledge for a variety of reasons. Perhaps while the seeker did not actually know that Adam ate something, she does not find this particularly puzzling; had she first learned that he ate something and then learned that it was the apple, she would not have requested an explanation in the first of these knowledge states. Although the proposition that Adam ate something was not actually in the speaker's initial knowledge state, she may use contrastive stress to indicate that this proposition is to be treated as if it were in the initial knowledge state, and thus direct the speaker away from an explanation that the seeker has no interest in. (Hitchcock [1996], p. 416)

Hitchcock's account of contrastive explanatory support can be used as an inspiration for a convincing contrastivist Bayesian account of evidential support (CB):

> **CB**: assertions of the form 'E evidentially supports H_1 rather than H_2' are true iff $C(H_1, H_2, E) =_{def}$ [1] $Pr(H_1|H_2) = 0$ and [2] $Pr(H_1|E \& (H_1 \vee H_2)) > Pr(H_1| \sim E \& (H_1 \vee H_2))$

This makes good intuitive sense: intuitively, if we know that either H_1 or H_2, gaining evidence that H_1 rather than H_2 should increase our degree of confidence in H_1 (i.e. if K entails $H_1 \vee H_2$, E should increase the probability of H_1 conditional upon K). Furthermore, CB does a good job of yielding verdicts that accord with our pre-theoretic intuitions concerning various cases of contrastive evidential support, much as Hitchcock's account did with respect to contrastive explanation. The fact that Jon cannot drive is evidence for his having stolen a motorbike rather than a car but is not evidence for his having stolen a motorbike rather than a bicycle. This is plausibly the case because

Jon's not being able to drive raises the probability of his having stolen a motorbike conditional on his having stolen a motorbike or a car but not on his having stolen a motorbike or a bicycle.

Now what does any of this have to do with the tacking problem? Let us now return to our first example, in Section 1. I noted that there is a common intuition that statement A2 is false. Now, as someone who shares this intuition, I can report that my immediate reaction to A2 would be something like the following: 'but it is not the case that your observation that your opponent has at least three red cards is evidence that he has a handful of red cards *and a pocketful of pennies*'. A number of fellow 'objectors' report the same reaction. Now note the emphasis. It turns out that prosodic stress of this kind is in fact a common linguistic device which serves to delimit a contrast class, indicating that the non-emphasized part is to be held fixed across that contrast class (Dretske [1972], p. 412). So this is my proposal: the intuition that A2 is false can be more perspicuously put as an intuition that the following utterance, A4, is false.

> **A4**: 'My observation that you have at least three red cards (E) is evidence that you have a handful of red cards and a pocketful of pennies (H&X) rather than a handful of red cards and not a pocketful of pennies (H&∼X).'

Similarly, our intuition that statement A3 is false can be more perspicuously put as an intuition that the following utterance is false:

> **A5**: 'My observation that you have at least three red cards (E) is evidence you have a handful of hearts (H_1^+) rather than a handful of diamonds (H_2^+).'

In other words, my suggestion is that those who judge A2 and A3 to be false, interpret them as having the implicit contrastive logical forms C(H&X, H&∼X, E) and C(H_1^+, H_2^+, E), respectively.

A2 and A3 have a commonality: in both case the relevant contrast class is such that the members of that contrast class are probabilistically screened off from the evidence by a proposition that they both entail. With respect to the first example, our contrast class is <H&X, H&∼X>. Both H&X and H&∼X entail H and both are screened off from E by H. With respect to the second example, the contrast class is <H_1^+, H_2^+>. Again, both H_1^+ and H_2^+ entail H and both are screened off from E by H. Now CB, it turns out, has a very interesting property indeed. It can be demonstrated that,

> **Theorem 3**: for any E, H, H_1^+ and H_2^+, if [1] $Pr(E|H\&H_1^+) = Pr(E|H)$ and $Pr(E|H\&H_2^+) = Pr(E|H)$ (i.e. both H_1^+ and H_2^+ are screened off from E by

H) and [2] $Pr(H|H_1^+) = 1$ and $Pr(H|H_2^+) = 1$, then
$\sim C(H_1^+, H_2^+, E)$.[11]

And this is precisely what we were after. This solves our generalization of the tacking problem.

3 Concluding comments

In the previous section, I argued that there exists a three-place[12] relation of confirmation, explicated by CB, suggesting that it is the fact that this relation fails to hold between the evidence and the would-be supported hypothesis that underlies our intuitions about the problem cases mentioned in the first section of the paper. It was not clear, however, whether we should claim that this three-place relation exists *instead of*, or rather *in addition to*, a two-place relation of confirmation.

Now the reason for holding that there exists a two-place relation *at all* presumably lies in the existence of a non-contrastive surface form of the type 'E evidentially supports H'. However, it would appear that the logical structure of at least *some* statements of non-contrastive surface form is properly explicated by appealing to a three-place relation of confirmation. But if this is true of *some* cases, why not hold that it is true of *all*? Why not hold that there is one single type of logical form underlying the two constructions, involving a relation between three propositions, with the verb in the 'non-contrastive' construction (or what has traditionally seen to be so) taking a covert argument? Surely the option should be preferred on grounds of parsimony.

If this is indeed an accurate picture of the situation, and CB does capture the logic of all statements of evidential support, note that $C(H, \sim H, E) =_{def} Pr(H|E \,\&\, (H \vee \sim H) \,\&\, \sim(H \& \sim H)) > Pr(H|\sim E \,\&\, (H \vee \sim H) \,\&\, \sim(H \& \sim H))$, which is itself obviously equivalent to $Pr(H|E) > Pr(H|\sim E)$. Now it is easy to prove that $Pr(H|E) > Pr(H|\sim E) \leftrightarrow Pr(H|E) > Pr(H)$, and $Pr(H|E) > Pr(H)$ of course, is the analysans given in TB for the concept of E's evidentially supporting H. In other words, if CB captures the logic of all statements of evidential support, TB can be seen as covering the special case in which an item of evidence E supports a hypothesis over its negation.

Before finishing this paper, I would like to point out one further felicitous aspect of CB, pointed out to me by an anonymous referee for this journal.

[11] See Appendix C.

[12] A referee from this journal reminds me to remind the reader of the fact that I have omitted reference to background knowledge (K) in this article. Strictly speaking, the relevant contrastive relation is in fact a *four*-place relation, involving E, H_1, H_2 and K. This may confuse a casual reader who may already be accustomed to talk of confirmation as a 'three-place' relation (involving E, H and K).

Whilst, as pointed out in note five, a sizeable majority hold that A2 seems false, it is important however to note that there is not a complete consensus on the matter. According to some, A2 seems *true* (and presumably, according to those same people, A3 seems true as well).[13] What is one to make of their views, and where does this leave the present proposal? Rather than dismiss their intuitions, there is a straightforward way to accommodate them within the present framework. I have suggested that those who judge A2 and A3 to be false interpret these assertions as shorthand for A4 and A5 respectively. Now it may very well be the case that those who judge A2 and A3 to be true simply have a different implicit contrast class in mind. They may indeed be interpreting A2 and A3 as, respectively, A6 and A7:

> **A6**: 'My observation that you have at least three red cards (E) is evidence that you have a handful of red cards and a pocketful of pennies (H&X) rather than not (~(H&X)).'

and

> **A7**: 'My observation that you have at least three red cards (E) is evidence you have a handful of hearts (H_1^+) rather than not ($\sim H_1^+$).'

If this is indeed the case, note that, according to CB, both A6 and A7 come out true.[14]

Appendix A: Proof Of Theorem 1

[1] $\Pr(E|H) = 1$ *(premise)*

[13] Indeed this is the opinion of Edidin ([1981]); Grimes ([1990]) and one of the referees from this journal.

[14] One might conceivably be tempted to offer an alternative explanation for the conflicting intuitions. Carnap ([1962]) famously claimed that there is an ambiguity in our layperson's notion of confirmation, distinguishing between incremental confirmation (C—confirmation as probability increase) and absolute confirmation (AC—confirmation as sufficiently high conditional probability). Now there is no analogue to Theorem 2 for absolute confirmation: it is not the case that, given conditions [2]–[8] of Theorem 2, if AC(H,E) then AC(H^+, E). This opens up the possibility of a case in which conditions [2]–[8] are met and we end up with the following: (i) C(H,E), (ii) C(H^+, E), (iii) AC(H,E), but (iv) ~AC(H^+, E). One could then perhaps suggest that this very kind of case might correspond to the kind of scenario we have been considering: a case in which [2]–[8] are met and (a) certain people endorse 'E is evidence for H' and 'E is evidence for H^+' whilst (b) others endorse 'E is evidence for H' but 'E *is not* evidence for H^+'. Explanation? The (a)-people are thinking about incremental confirmation whilst the (b)-people are thinking about absolute confirmation. I do not think this works. Granting Carnap's point for sake of argument, we can just rerun the eliciting of intuitions with expressions such as 'E contributes to supporting H' or 'E lends weight to H' (or even, why not, 'E incrementally confirms H'). This forces a reading in terms of incremental confirmation. With this in place, my intuitions still place me in the (b) camp. Those Bayesians cited in footnote 5 will also side with me here: after all, they explicitly formulated the tacking problem in terms of incremental confirmation.

[2] $\Pr(E|H\&X) = 1$ *(from [1])*

[3] $\Pr(H|E) = \Pr(E|H) * \Pr(H)/\Pr(E)$ *(axioms of prob. calc.)*

$\leftrightarrow \Pr(H|E)\Pr(E) = \Pr(E|H) * \Pr(H)$

[4] $\Pr(H|E)\Pr(E) = \Pr(H)$ *(from [1] and [3])*

[5] $0 < \Pr(E) < 1$ *(premise)*

[6] $\Pr(H) > 0$ *(premise)*

[7] $\Pr(H|E) > \Pr(H)$ *(from [4], [5] and [6])*

[8] TB: C(H, E) iff $\Pr(H|E) > \Pr(H)$ *(premise)*

[9] C(H, E) *(from [7] and [8])*

Furthermore:

[10] $\Pr(H\&X|E) = \Pr(H\&X\&E)/\Pr(E) = \Pr(E|H\&X) * \Pr(H\&X)/\Pr(E)$ *(axioms of prob. calc.)*

[11] $\Pr(H\&X|E) * \Pr(E) = \Pr(H\&X)$ *(from [2] and [10])*

[12] $\Pr(H\&X) > 0$ *(premise)*

[13] $\Pr(H\&X|E) > \Pr(H\&X)$ *(from [5], [11] and [12])*

[15] C(H&X, E) *(from [8] and [13])*

Appendix B: Proof of Theorem 2

[1] $\Pr(H|E) > \Pr(H)$ *(premise)*

$\leftrightarrow \Pr(E|H)\Pr(H)/\Pr(E) > \Pr(H)$

$\leftrightarrow \Pr(E|H)/\Pr(E) > 1$

$\leftrightarrow \Pr(E|H) > \Pr(E)$

[2] $\Pr(H|H^+) = 1$ *(premise)*

[3] $\Pr(E|H\&H^+) = \Pr(E|H)$ *(premise)*

[4] $\Pr(H^+|E) > 0$ *(premise)*

[5] $\Pr(E|H^+) = \Pr(E|H)$ *(from [2] and [3])*

[6] $Pr(H^+ |E) = Pr(H^+\&E)/Pr(E) = Pr(E|H^+) * Pr(H^+)/Pr(E)$ *(axioms of prob. calc.)*

[7] $Pr(H^+|E) = Pr(E|H) * Pr(H^+)/Pr(E)$ *(from [5] and [6])*

$\leftrightarrow Pr(H^+|E) * Pr(E) = Pr(H^+) * Pr(E|H)$

[12] $Pr(H^+|E) > Pr(H^+)$ *(from [1] and [7])*

[13] TB: C(H, E) iff $Pr(H|E) > Pr(H)$ *(premise)*

[14] $C(H^+, E)$ *(from [12] and [13])*

Appendix C: Proof of Theorem 3

[1] $Pr(H|H_1^+) = 1$ *(premise)*

[2] $Pr(H|H_2^+) = 1$ *(premise)*

[3] $Pr(E|H \& H_1^+) = Pr(E|H)$ *(premise)*

[4] $Pr(E|H \& H_2^+) = Pr(E|H)$ *(premise)*

[5] $Pr(E|H_1^+) = Pr(E|H) = Pr(E|H_2^+)$ *(from [1], [2], [3] and [4])*

[6] $Pr(\sim E|H_1^+) = 1 - Pr(E|H_1^+) = 1 - Pr(E|H_2^+) = Pr(\sim E|H_2^+)$ *(from [5])*

[7] $\frac{Pr(E|H_1^+)}{Pr(E|H_2^+)} = \frac{Pr(\sim E|H_1^+)}{Pr(\sim E|H_2^+)}$ (from [5], [6])

[8] $C(H_1^+, H_2^+, E) \rightarrow Pr(H_1^+|E\&(H_1^+ \vee H_2^+)) > Pr(H_1^+|\sim E\&(H_1^+ \vee H_2^+))$ (premise—from definition of $C(H_1^+, H_2^+, E)$)

[*Lemma*] $Pr(H_1^+|E\&(H_1^+ \vee H_2^+)) > Pr(H_1^+|\sim E\&(H_1^+ \vee H_2^+))$
$\leftrightarrow \frac{Pr(E|H_1^+)}{Pr(E|H_2^+)} > \frac{Pr(\sim E|H_1^+)}{Pr(\sim E|H_2^+)}$

[*Proof*] $\frac{Pr(E|H_1^+)}{Pr(E|H_2^+)} > \frac{Pr(\sim E|H_1^+)}{Pr(\sim E|H_2^+)} \leftrightarrow \frac{Pr(H_1^+\&E)}{Pr(H_2^+\&E)} > \frac{Pr(H_1^+\&\sim E)}{Pr(H_2^+\&\sim E)}$
(axioms of prob calc)

$\leftrightarrow Pr(H_1^+\&E) * Pr(H_2^+\&\sim E) > Pr(H_1^+\&\sim E) * Pr(H_2^+\&E)$

$\leftrightarrow [Pr(H_1^+\&E) * Pr(H_1^+\&\sim E)] + [Pr(H_1^+\&E) * Pr(H_2^+\&\sim E)]$
$> [Pr(H_1^+\&E) * Pr(H_1^+\&\sim E)] + [Pr(H_1^+\&\sim E) * Pr(H_2^+\&E)]$

$$\leftrightarrow Pr(H_1^+\&E) * [Pr(H_1^+\&{\sim}E) + Pr(H_2^+\&{\sim}E)] > Pr(H_1^+\&{\sim}E) * [Pr(H_1^+\&E) + Pr(H_2^+\&E)]$$

$$\leftrightarrow \frac{Pr(H_1^+\&E)}{[Pr(H_1^+\&E) + Pr(H_2^+\&E)]} > \frac{Pr(H_1^+\&{\sim}E)}{[Pr(H_1^+\&{\sim}E) + Pr(H_2^+\&{\sim}E)]}$$

$$\leftrightarrow \frac{Pr(H_1^+\&E)}{Pr(E\&(H_1^+ \vee H_2^+))} > \frac{Pr(H_1^+\& \sim E)}{Pr(\sim E\&(H_1^+ \vee H_2^+))}$$

$$\leftrightarrow \frac{Pr(H_1^+\&E\&(H_1^+ \vee H_2^+))}{Pr(E\&(H_1^+ \vee H_2^+))} > \frac{Pr(H_1^+\&{\sim}E\&(H_1^+ \vee H_2^+))}{Pr({\sim}E\&(H_1^+ \vee H_2^+))}$$

$$\leftrightarrow Pr(H_1^+|E\&(H_1^+ \vee H_2^+)) > Pr(H_1^+|{\sim}E\&(H_1^+ \vee H_2^+))$$

[9] $C(H_1^+, H_2^+, E) \rightarrow \frac{Pr(E|H_1^+)}{Pr(E|H_2^+)} > \frac{Pr({\sim}E|H_1^+)}{Pr({\sim}E|H_2^+)}$ (from [8], [Lemma])

[10] $\sim C(H_1^+, H_2^+, E)$ (from [7], [9])

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