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HOW TO PREDICT FUTURE DURATION FROM PRESENT AGE

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The physicist J. Richard Gott has given an argument which, if good, allows one to make accurate predictions for the future longevity of a process, based solely on its present age. We show that there are problems with some of the details of Gott's argument, but we defend the core thesis: in many circumstances, the greater the present age of a process, the more likely a longer future duration.

I. INTRODUCTION

I.1. *A story*

'Welcome to Geyser Intergalactic Park.' Although you have been planning this trip for some time, you realize as you enter the park that you actually know very little about geysers. You know that at some time a geyser starts shooting liquid, and at some time later it stops, but you know nothing about how long the process lasts. While reflecting on what your prior probability distribution over the temporal length of such a process is, you wander round the park, and eventually find yourself in front of a shooting geyser. Just as you begin to wonder how long it has been shooting for, you see a sign adjacent to the geyser. It says 'This geyser has been shooting for' and there is an advancing digital stopwatch underneath, which reads '10 minutes'. Looking around, you notice a second geyser nearby, with another sign and stopwatch: 'This geyser has been shooting for 10 years'.

If you had not seen the signs, your guess about how long the two geysers would continue to shoot would be the same. But it seems natural to take the signs to give you some evidence regarding how long the geysers will continue to shoot. If you stood around for a few minutes and the first geyser you saw stopped shooting, you would not be surprised – after all, it just started shooting a few minutes before. But if the second geyser stopped shooting just then, you would be surprised – it had been shooting for years, and you were lucky enough to come at just the right time to witness the end!

So if you had to guess, you should guess that the second geyser will continue to shoot for a longer time than the first geyser. To put it more precisely, your probability distribution over future durations for the second geyser should have more weight on longer time intervals than your probability distribution over future durations for the first geyser. Without seeing the stopwatches, your probability distribution over future durations for the two geysers would have been the same, but the information about present age produces a probability shift.

We shall call this shift a *Gott-like shift*, in honour of the physicist J. Richard Gott, who (as far as we know) was the first person to provide a general argument that the present age of a process is an indicator of future duration: the greater the present age, the more likely a longer future duration. While we disagree with some of the details of Gott's reasoning, we think the core thesis is correct. The goal of this paper is to examine Gott's argument carefully, both to highlight its (under-appreciated) virtues and to explain its problems. In doing so we shall defend the basic idea that in many circumstances present age is an indicator of future duration.

I.2. *Gott's argument*

Gott begins what he calls the 'delta t argument' as follows, where t_{begin} is the time at which the phenomenon whose lifetime we are interested in begins, and t_{end} the time when it ends:

> Assuming that whatever we are measuring can be observed only in the interval between times t_{begin} and t_{end}, if there is nothing special about t_{now} we expect t_{now} to be located randomly in this interval.[1]

This is an application of the so-called 'Copernican principle' that (in the absence of evidence to the contrary) we should not think of ourselves as having a special position in the universe. Gott's argument continues:

> If $r_1 = (t_{now} - t_{begin})/(t_{end} - t_{begin})$ is a random number uniformly distributed between 0 and 1, there is a probability $P = 0{\cdot}95$ that $0{\cdot}025 < r_1 < 0{\cdot}975$.

Letting $t_{future} = t_{end} - t_{now}$ and $t_{past} = t_{now} - t_{begin}$, it takes a few lines of calculation[2] to show that the consequent of the statement above is equivalent to

1. $(1/39)\ t_{past} < t_{future} < 39\ t_{past}$ (with 95% confidence).

We can apply this reasoning to the geyser story presented above. For the first geyser, Gott would assign probability 0·95 to the proposition

[1] J.R. Gott, 'Implications of the Copernican Principle for our Future Prospects', *Nature*, 363 (1993), pp. 315–19, at p. 315.

[2] Rewriting the inequality for r_1, we get $39/40 > t_{past}/(t_{past} + t_{future}) > 1/40$, and by taking the inverse, multiplying by t_{past} and then subtracting t_{past} we get equation (1).

$10/39$ minutes $< t_{future} <$ 390 minutes,

while for the second he would assign probability 0·95 to the proposition

$10/39$ years $< t_{future} <$ 390 years.

Thus information about present age leads Gott to make very different predictions about the future duration of the geysers.

There is nothing special about the 95% confidence interval. The inequality

2. $a\, t_{past} < t_{future} < b\, t_{past}$

is equivalent to

3. $1/(b + 1) < r_1 < 1/(a + 1)$

and hence according to Gott's line of reasoning the probability associated with (2) is $1/(a + 1) - 1/(b + 1)$.

The best known application of Gott's argument is to the phenomenon of intelligent life on Earth.[3] Intelligent life has been around for about 200,000 years, so setting t_{past} = 200,000 years, equation (1) gives (to the nearest year)

4. 5,128 years $< t_{future} <$ 7,800,000 years (with 95% confidence).

Gott's argument is sometimes called a 'doomsday' argument, presumably because it can be used to make a prediction for the end of intelligent life. It is importantly different from the much discussed Carter–Leslie doomsday argument.[4] According to the latter, taking into account the present age of intelligent life should lead you to shift your probabilities in favour of intelligent life ending sooner than you had thought: the probability shift is always in favour of doom sooner. The Carter–Leslie argument is compatible with a wide range of personal prior probability functions. In Gott's argument, by contrast, there is no room to input your personal prior probability function: the argument itself specifies the prior probability function (we shall explain this below). So if you are following Gott's argument, then as long as you agree with him on the value of t_{past} you get the result given by equation (4).

It follows that there is a sense in which Gott's argument is more optimistic than the Carter–Leslie argument. For example, some people might think

[3] For popular discussions of this aspect of Gott's argument, see for example E.J. Lerner, 'Horoscopes for Humanity?', *New York Times*, 14 July 1993, p. A19; Gott, 'The Chances Are Good You're Random', *New York Times*, 27 July 1993, p. A12, and *Time Travel in Einstein's Universe* (Boston: Houghton Mifflin, 2001); T. Ferris, 'How to Predict Everything', *New Yorker*, 12 July 1999, pp. 35–9.

[4] B. Carter, 'The Anthropic Principle and its Implications for Biological Evolution', *Philosophical Transactions of the Royal Society*, A 310 (1993), pp. 347–63; J. Leslie, 'Is the End of the World Nigh?', *The Philosophical Quarterly*, 40 (1990), pp. 65–72, and *The End of the World: the Science and Ethics of Human Extinction* (London: Routledge, 1996).

that there is almost no hope of intelligent life lasting more than one million years. If such people apply Gott's argument, however, they will become more sanguine.

I.3. *Applicability*

To what processes is Gott's argument applicable? He has applied it to a wide range: examples are the Berlin Wall, the Soviet Union, Stonehenge, the journal *Nature*, the human spaceflight programme, New York City plays, and even individual people. He has also applied it to non-temporal matters: for example, he predicts with 95% confidence that the longitude of one's birthplace is in the middle 95% of range of longitudes of the country one was born in.[5] Are there any limits to the applicability of Gott's argument?

This point is worth addressing, because there has been some confusion about this issue in the literature. Carleton Caves, for example, writes that Gott's reasoning is 'put forward as a universal rule, applicable no matter what other information one has about the phenomenon in question'.[6] Caves puts the point dramatically: Gott 'rejects as irrelevant the process of rational, scientific enquiry, replacing it with a single, universal statistical rule'. We intend to make clear that this is not the right way to understand Gott's argument, and, moreover, Gott makes pretty clear that this is not the right way to understand it.

To read Gott's argument in the way Caves describes is uncharitable, because under that reading it is obviously flawed. There are all sorts of processes we come across where we know the future duration of the process. For example, if Brian comes across a colleague teaching at 10:45 a.m., he knows that this class has been going on for about 45 minutes and will last only about another 5 minutes. It would be silly for him to apply Gott's argument in this case. One might think that the prediction he would make via Gott's argument would be confirmed, since he would predict that

$$45/39 \text{ minutes} < t_{future} < 1755 \text{ minutes (with 95\% confidence)}$$

and $t_{future} = 5$ minutes falls within that interval. But in fact Brian could make many other predictions using Gott's reasoning. For example, he could predict that there is a 50% chance that the class will last at least another 45 minutes, since

$$45 \text{ minutes} < t_{future} < \infty \text{ minutes}$$

[5] The first four examples are from Gott's 1993 *Nature* paper (p. 315); the other four are in his 'Our Future in the Universe', in V. Trimble and A. Reisenegger (eds), *Clusters, Lensing, and the Future of the Universe* (San Francisco: Astro. Soc. of the Pacific, 1996), pp. 140–51, at pp. 145, 149.

[6] C. Caves, 'Predicting Future Duration from Present Age: a Critical Assessment', *Contemporary Physics*, 41 (2000), pp. 143–53, at p. 144.

is equivalent to

$$t_{past} < t_{future} < \infty\ t_{past}$$

which by equation (3) is equivalent to

$$0 < r_1 < 1/2.$$

Given that Brian knows that the class will last only about another 5 minutes, it would be ludicrous for him to assign probability 0·5 to the proposition that it will last at least another 45.

The lesson here is that Gott's argument does not have universal applicability. Gott is well aware of this: he says that his argument should only be applied in cases where one does not have information about the longevity of the process in question. For example, he considers the exponential decay of a radioactive particle.[7] He makes it clear that if you knew the rate of decay, then that would determine the probability distribution for t_{future} 'independently of the particular observed value for t_{past} in this case'. In other words, because one has information about the actual decay rate, the value of t_{past} is irrelevant in predicting t_{future}. Thus Gott is aware that present age is not always an indicator of future duration: whether it is or not depends on whether other information is known about the longevity of the process.

Here is another example of Gott demonstrating awareness of this. Regarding the prediction for the future of intelligent life given in equation (4) above, he writes (in his 1993 *Nature* article, p. 319) 'Short of having actual data on the longevities of other intelligent species, [the prediction in equation (4)] is arguably the best we can make'. He recognizes that if we had such data, this could give us empirical information on the longevity of our species (and intelligent life descended from our species), and this empirical information might contradict the information given by Gott's argument. He makes it clear that if we have the choice of basing our opinion on empirical information or the predictions of his argument, we should base our opinion on empirical information.

Thus Gott's argument is meant to apply in situations where we do not have empirical information about the longevity of the process in question. Elliott Sober gives an interesting criticism of the argument on precisely these grounds, which we now turn to discuss.[8] Considering the applicability of Gott's argument to species, Sober writes 'in the absence of data, we are told to follow Gott's [argument]. I'd expect most biologists to say something different – in the absence of data, you should go out and get some.' It is

[7] Gott, 'Future Prospects Discussed', *Nature*, 368 (1994), p. 108.

[8] E. Sober, 'An Empirical Critique of Two Versions of the Doomsday Argument – Gott's Line and Leslie's Wedge', *Synthese*, 135 (2003), pp. 415–30, at pp. 420–1.

clear from the context that Sober is on the hypothetical biologists' side. As far as we can tell, he is serious about this: in the absence of empirical data going beyond the value of t_{past} one should make no predictions about future longevity. Sober says that Gott's sampling assumption (that t_{now} is located randomly in the interval between t_{begin} and t_{end}) is an empirical claim, which should not be endorsed *a priori*. Instead, he says, '*all* claims about the relationship of prior duration to longevity must be judged empirically'.

Sober's dictum, that in the absence of empirical data 'you should go out and get some', is not very helpful. Gott admits that predictions based on empirical evidence trump predictions based on his delta *t* argument. He wants to use his delta *t* argument to make predictions for processes where one does not have empirical evidence. If empirical evidence were easily obtainable, it might make sense to follow Sober's dictum instead of Gott's argument. But Gott clearly thinks that there are some processes for which empirical evidence is not easily attainable, and that thought seems plausible. Also, even if empirical evidence is easily attainable, it still seems permissible to utilize Gott's argument in the time interval before one gets the empirical evidence.

The geyser story may show how extreme Sober's stance is. Suppose he encounters these two geysers, and stands around for a few minutes to see if they will stop shooting. Since, by assumption, he has no empirical information about geysers, he will make no predictions about when they might end. Thus he will be equally unsurprised whether he sees the first geyser or the second stop shooting, regardless of how different the present ages of the two geysers are. For example, suppose the first geyser has been shooting for 10 seconds, while the second geyser has been shooting for 100 million years. Sober would be as unsurprised to see the 100-million-year-old geyser stop shooting as he would be for the 10-second geyser. But imagine how amazed you would be to come across a geyser that has been shooting for 100 million years, only to have it finally stop shooting right before your very eyes! It seems strange for Sober to treat that experience in the same way as he would treat the experience of seeing the 10-second geyser stop shooting.

As far as we can tell, there is nothing rationally impermissible about Sober's studied agnosticism, at least in so far as there is no logical infelicity in his position and he is not necessarily being probabilistically incoherent. It is an agnosticism that seems hard to maintain in practice, though, and it is an agnosticism that we do not share. If you share our intuitions about the geyser case, then you too should reject Sober's agnosticism.

To be charitable, we can guess how Sober would respond to our charge of counter-intuitiveness. He would emphasize that in the geyser story, by assumption you know nothing about the lifetimes of geysers. Thus for all you know, almost all geysers last for slightly more than 100 million years, and only a very few last for just somewhat more than 10 seconds. Also, for all you know, most geysers in the park started about 100 million years ago, so that it is currently commonplace to witness the end of one. Thus for all you know, it is the end of the 10-second geyser that is the unusual event. Since you have no empirical data, you do not know whether to be surprised at witnessing the end of the 100-million-year geyser or at witnessing the end of the 10-second one. Sober would conclude that you should remain agnostic.

Here is our response to this imagined defence from Sober. It is true that one possibility is that described in the previous paragraph, where witnessing the end of the 100-million-year geyser is not surprising. But there are many other possibilities where witnessing the end of that geyser is surprising. It simply seems more likely to us that one of those latter possibilities is the one that applies – intuition certainly supports that, because intuition dictates that one should be surprised.

Here is our diagnosis of the central disagreement between Sober and Gott. Sober says that the disagreement arises because Gott is willing to make probability judgements without empirical information. But Gott could legitimately reply that he has empirical information: he has the value of t_{past}. What Sober really wants empirical justification for is the prior probability function Gott is relying on to justify his sampling assumption. Gott maintains that in the absence of evidence, this prior probability function should be chosen *a priori*. We now take up this issue about how to justify the prior.

II. GOTT'S ARGUMENT IS BAYESIAN

II.1. *The prior*

In the 1993 *Nature* paper where Gott first presented his argument, there is no mention of prior probability functions, conditionalization, or anything that would lead the casual reader to think the argument is a Bayesian one. But in fact the argument can be given in Bayesian form, as Gott explains in his 1994 *Nature* follow-up.

Let T_{total} be the proposition that the total longevity of the process in question is t_{total}, where t_{total} is $t_{past} + t_{future}$. Gott assumes a prior probability function

$$P(T_{total}) \propto 1/t_{total}$$

where $\propto$ indicates proportionality. We shall discuss below this choice of prior, but first we shall show how this prior reproduces the predictions of Gott's argument.

Starting from this prior probability function P, the evidence one conditionalizes on is T_{past}, the proposition that the present age of the process in question is t_{past}. By Bayes' rule, the posterior probability $P^*(T_{total})$ is given by

$$P^*(T_{total}) = P(T_{total} \mid T_{past}) \propto P(T_{past} \mid T_{total})\, P(T_{total}).$$

Given the specified prior, $P(T_{past} \mid T_{total}) \propto 1/t_{total}$ as long as $t_{past} < t_{total}$; otherwise the value is 0. It follows that

$$P^*(T_{total}) \propto 1/(t_{total})^2, \text{ as long as } t_{past} < t_{total}.$$

To calculate the probability that t_{total} is in some particular range of values, one must integrate the function $P^*(T_{total})$ over that range of values, and normalize. For example, for the first geyser encountered, let $T^{10}{}_{total}$ be the proposition that the total longevity of the geyser is at least 10 minutes. We know that this probability is 1, so this will allow us to establish the normalization factor.

$$\begin{aligned} P^*(T^{10}{}_{total}) &\propto \int_{10}^{\infty} 1/(t_{total})^2\, \mathrm{d}t_{total} \\ &\propto 1/10 - 1/\infty \\ &\propto 1/10 \end{aligned}$$

Thus the normalization factor is 10. We can now verify that the prediction of Gott's argument is reproduced, that the probability is 0·95 that 10/39 minutes $< t_{future} <$ 390 minutes. In other words, we are evaluating the probability of the proposition $T^{\#}{}_{total}$ that the total longevity is between (10 + 10/39) minutes and 400 minutes.

$$\begin{aligned} P^*(T^{\#}{}_{total}) &= 10\left(\int_{10+10/39}^{400} 1/(t_{total})^2\, \mathrm{d}t_{total}\right) \\ &= 10(1/(10 + 10/39) - 1/400) \\ &= 0{\cdot}95. \end{aligned}$$

We leave it to the reader to verify that there is nothing special about this example; the predictions of Gott's argument are the same regardless of whether one uses the delta *t* argument discussed in §I.2 or the Bayesian formulation discussed in this section.

We now turn to the justification of the prior probability function which Gott chooses. The prior he utilizes is due to Jeffreys, who recommends this prior for situations where we do not know the value of some positive but unbounded magnitude.[9] As Rosenkrantz points out, it is standardly thought that Jeffreys did not provide a compelling rationale for his prior: his justification appears to rely on a discredited version of the principle of indifference.[10] This makes salient the question: what rationale does Gott give for his use of the Jeffreys prior?

[9] H. Jeffreys, *Theory of Probability* (Oxford UP, 1939).

[10] R. Rosenkrantz (ed.), *E.T. Jaynes: Papers on Probability, Statistics, and Statistical Physics* (Dordrecht: Kluwer, 1983), p. xiii.

Gott calls the prior he uses 'the appropriate vague Bayesian prior', but he does not give an elaborate justification for his choice.[11] He does say that 'it is hard to argue that we can produce a "smarter" prior than this on the basis of speculation alone', but this in itself does not constitute an argument. In fact, as far as we can tell, besides pointing out that his prior is often used and is endorsed by others, the only *argument* Gott gives is as follows:

> The vague Bayesian prior can be used by any intelligent observer. Its results are in agreement with the Copernican principle. This agreement is not accidental – the appropriate vague Bayesian prior would be agreed to by any intelligent observer and if they all use it then the results, to be correct, must be consistent with the Copernican principle (take a poll of all observers).[12]

This is an interesting argument. Gott is pointing out that there is a match between the Copernican principle and the Jeffreys prior. For anyone who antecedently endorses the Copernican principle, this would provide a compelling justification for the Jeffreys prior. But for someone who is looking for independent justification of the delta *t* argument, Gott's reasoning here is circular.

We believe that the strongest argument one can give for the Jeffreys prior is due to E.T. Jaynes.[13] Jaynes proves that if one is assigning a prior probability function to a positive unbounded magnitude, and one wants the predictions one gets using the prior to be invariant under location and scale transformations, then one must assign the Jeffreys prior.

To explain this result, we start by illustrating location invariance. If the predictions you make for how long the shooting of the 10-minute geyser will last depend on when you arrived, then the predictions are not location invariant. (Since we are predicting the temporal length of a process, 'location' in this context means 'location in time'.) For example, in the situation where you know that t_{past} = 10 minutes, if you would make different predictions based on whether it was Monday *vs* Tuesday, or night-time *vs* daytime, then the predictions are not location invariant.

Now we shall illustrate scale invariance. For the geyser that has been shooting for 10 minutes, Gott's argument assigns probability 0·95 to the prediction that 10/39 minutes < t_{future} < 390 minutes. Suppose it turns out that you have misread the stopwatch: it actually says '10 years'. If you are unwilling to replace 'minutes' with 'years' in your prediction, while keeping the numbers the same, then your prediction is not scale invariant.

[11] Gott, 'Future Prospects Discussed'; and 'Our Future in the Universe', p. 143.

[12] See 'Our Future in the Universe', pp. 143, 148.

[13] E.T. Jaynes, 'Prior Probabilities', *IEEE Transactions on Systems Science and Cybernetics, SSC–4* (1968), pp. 227–41, repr. in Rosenkrantz (ed.), *E.T. Jaynes*, pp. 114–30. The relevant discussion is at pp. 125–6.

In the story of §I.1, it is reasonable for your predictions to be location and scale invariant. Since we specified that you have no prior knowledge regarding the longevity of geysers, it is reasonable for your predictions to be the same regardless of when you arrive at the park. Further, it is reasonable for you to make numerically the same predictions regardless of whether you are contemplating the geyser that has been shooting for 10 minutes or the geyser that has been shooting for 10 years. In the geyser example, then, the Jeffreys prior is a reasonable choice, since it is the only prior that satisfies location and scale invariance.

Nevertheless, the argument for the Jeffreys prior is not conclusive. There are many processes for which it would be inappropriate to make the assumption of location and scale invariance. For example, it may be inappropriate to make that assumption regarding geysers: it may be unrealistic to assume that one has no prior knowledge regarding their longevity. We discuss this issue in §III.2 below, and we shall show that in many cases where it is inappropriate to make the assumption of location and scale invariance, a generalization of Gott's argument is still applicable.

Before moving on to the next section, we shall discuss two concerns a reader might have about Gott's use of the Jeffreys prior. As we shall explain, we do not find these concerns moving.

It might be a concern that the Jeffreys prior is non-normalizable – the probabilities assigned to the various disjoint possibilities cannot sum to a finite number, like 1. But this is unproblematic, for two reasons. First, the posterior probability functions one gets from Gott's argument are normalizable, so they can unproblematically be used to represent an agent's opinion. Secondly, there are no technical barriers to dealing with non-normalizable priors – for example, they can be handled by the Rényi axiom system, where all probabilities representing opinions are conditional.[14] Even though we are claiming that non-normalizable prior probability functions are unproblematic, this is a controversial issue: for dissent, see, for example, Howson and Urbach.[15] Below we shall consider ways of modifying Gott's argument to accommodate those who reject non-normalizable priors.

Secondly, one might be concerned that Gott's argument seems non-Bayesian, because each time one wants to apply Gott's argument, one starts from the Jeffreys prior. In a standard Bayesian model, by contrast, one utilizes an *a priori* prior probability function only once; the resulting posterior

[14] A. Rényi, *Probability Theory* (New York: American Elsevier, 1970), p. 70. For discussion see S.J. Press, *Bayesian Statistics: Principles, Methods, and Applications* (New York: John Wiley & Sons, 1989), pp. 10–12.

[15] C. Howson and P. Urbach, *Scientific Reasoning: the Bayesian Approach*, 2nd edn (Chicago: Open Court, 1993), p. 415.

probability function becomes the new prior when one wants to conditionalize on more evidence. For example, suppose that for the first geyser you encounter t_{past} = 10 minutes. Suppose that you wait around another 10 minutes, and this geyser is still shooting. At that point t_{past} = 20 minutes, and you apply Gott's argument using the Jeffreys prior again. But what if instead of simply applying Gott's argument at the 20 minute mark you took the posterior probability function generated when you applied Gott's argument at the 10 minute mark, and then conditionalized on the proposition that the geyser is still shooting 10 minutes later? Will you get the same probability function regardless of which method you choose?

It turns out that the two methods produce the same result, as we shall now show. We shall first consider applying Gott's argument directly, and then evaluate what happens when one conditionalizes.

Let us establish a date scheme such that now, when t_{past} = 10 minutes, is the start of Minute 10. The geyser started shooting at Minute 0. Ten minutes from now, if the geyser is still shooting, t_{past} = 20 minutes, so Gott's argument assigns probability 0·95 to

$$20/39 \text{ minutes} < t_{future} < 780 \text{ minutes.}$$

Let C be the proposition that the process will end between Minute (20 + 20/39) and Minute 800. Ten minutes from now, if the geyser is still shooting, Gott's argument specifies that the probability of C is 0·95.

What probability does Gott's argument assign to C considered from now, when t_{past} = 10 minutes? We must assign a probability to the inequality

$$10 + 20/39 \text{ minutes} < t_{future} < 790 \text{ minutes.}$$

This is equivalent to

$$(10 + 20/39)/10\ t_{past} < t_{future} < 79\ t_{past}.$$

It follows (via equation (3)) that, considered from now, $P(C)$ = 0·475.

In addition to proposition C, there are three other propositions worth considering:

A. The process ends between Minute 10 and Minute 20
B. The process ends between Minute 20 and Minute (20 + 20/39)
D. The process ends after Minute 800.

Applying Gott's argument now, $P(A) = 1/2$, $P(B)$ = 0·0125, $P(C)$ = 0·475, and $P(D)$ = 0·0125. Now suppose that 10 minutes from now, you learn that the geyser has not stopped, so you conditionalize on $\sim A$. The probability of A drops to 0 and the probabilities of the other three propositions double (thus ensuring that the ratios between the probabilities for B, C and D stay the same, this being a requirement of Bayesian conditionalization). It follows that $P(C) = 0{\cdot}95$, thus reproducing the result one gets if one directly applies Gott's argument.

We leave it to the reader to verify that there is nothing special about this example. We conclude that starting from the Jeffreys prior each time one applies Gott's argument does not make his argument non-Bayesian.

II.2. *Inference to the best explanation*

There is a further respect in which Gott's argument is Bayesian, one worth emphasizing. This consists in the fact that it is independent of inference to the best explanation (IBE). We shall begin with this independence, then turn to why it bears emphasizing, and finally explain in what sense this contributes to the Bayesian character of Gott's argument.

As we have shown in the previous section, Gott's argument works by beginning with a certain prior probability distribution for T_{total} and then updating with information about the minimum duration of the process in question. Whether or not such updating amounts to IBE will depend on the nature of the prior probability distribution. But the prior Gott utilizes, namely $P(T_{total}) \propto 1/t_{total}$, merely represents one kind of principle of indifference, *viz* the one which satisfies location and scale invariance. Thus the conditional probabilities one gets from this prior will fail to have the character necessary in order for the corresponding conditionalization to be treated as IBE.

This bears emphasizing, since, when Gott himself is trying to present his argument as plausible, it may seem that he illicitly appeals to IBE. For one example, in applying his argument to the longevity of the Wonders of the World, Gott writes:

> The famous list of the Seven Wonders of the World can be traced back to approximately 150 BC, the time of Antipater of Sidon. Two of the seven wonders (the hanging gardens of Babylon and the Colossus of Rhodes) no longer existed at the time the list was made, but five still did: the statue of Zeus at Olympia, the temple of Artemis at Ephesus, the mausoleum at Halicarnassus, the pharos of Alexandria, and the pyramids of Egypt. Of the first four wonders that had each been in existence for less than 400 years at the time the list was made, not one is still here today. But the oldest, the pyramids, which were then 2,400 years old, have survived. *Things that have been around for a long time tend to stay around a long time. Things that haven't been around long may be gone soon.*[16]

Since applying Gott's argument will lead an agent to 95% confidence in an interval for future duration which is proportional to past duration, the

[16] Gott, *Time Travel in Einstein's Universe* (Boston: Houghton Mifflin, 2001), at pp. 218–19; our italics.

argument seems to receive intuitive support from this discussion. However, in so far as what Gott says is plausible, that may be the result of a covert appeal to IBE. The best explanation for the lengthy past existence of some given thing like an Egyptian pyramid may be extremely sturdy construction or something else, but whatever it is, it is likely to be something which will make a lengthy future existence probable. The same cannot be said for the brief past existence of other things.

Compare an IBE treatment of a schematic instance of enumerative induction: all 100 Fs observed so far have been Gs; the best explanation of this is that it is a law that all Fs are Gs; and this entails the mere generalization that all Fs are Gs. The final conclusion is reached in two steps, the first step being an inference to the best explanation, the second an extrapolation from the postulated explanation. The reasoning sketched at the end of the previous paragraph takes a similar two-step form. The first step is a highly general instance of IBE, which goes something like this: the best explanation of the lengthy past existence of the thing in question meets the description 'a single structural feature of, or single process interacting with, the thing in question, itself durable or long-lived, which explains the thing's long life so far'. The second step is then an extrapolation from this postulated explanation: this explanation makes lengthy future existence probable, since whatever in fact satisfies the description 'a single structural feature of, or single process interacting with, the thing in question, itself durable or long-lived, which explains the thing's long life so far' is likely to lead to lengthy future existence.

Another example is Gott's discussion of seaworthiness (*Time Travel*, p. 222). There he offers the recommendation 'To be on the conservative side, if you go to the dock to take an ocean voyage, don't pick a ship that has not already completed at least 39 such voyages successfully'. But the reasonableness of this recommendation may involve IBE: whatever best explains the past 39 successful voyages is likely to lead to many more successful voyages. In a similar vein, one might suggest that the intuitions we solicit about our own geyser example have, at least partly, an IBE source. There may be something to this, but our point here is simply to make clear the distinction between Gott's official argument and IBE. Having made this distinction, we can further note that the predictions in question – about our geyser example, and about pyramids and ships – can all be accounted for via Bayesian reasoning which begins with the Jeffreys prior.

So Gott's argument, despite the fact that his own discussion of it might lead one to suppose otherwise, is independent of IBE. How does this constitute a respect in which it is Bayesian? We recognize that IBE can be represented as Bayesian by suitably tailoring an agent's prior probability function. But although accurate in certain senses, this is a psychological misrepresentation, since it represents what is psychologically an inference to the best explanation as nothing more than a coherence-preserving inference. Gott's argument is different, and in that sense straightforwardly Bayesian. An agent who applies it in a given instance is accurately represented psychologically as engaging in a coherence-preserving inference. The agent begins by treating no temporal location, and no scale, as special – in other words, begins with the Jeffreys prior. The agent then leaves this state of indifference by learning information which excludes certain possibilities, with a resultant coherence-preserving realignment of probabilities which preserves indifference among the remaining possibilities.

III. GOTT'S ARGUMENT: ITS SCOPE AND LIMITS

Now that we have presented Gott's argument in a Bayesian fashion, we return to its applicability. We accept Gott's appeal to Bayesian rules of inference, so the question of applicability boils down to the question: under what circumstances is that specific Bayesian framework applicable?[17] For example, under what circumstances is the Jeffreys prior a reasonable prior to start from? We shall first argue that observational selection effects sometimes render Gott's argument completely inapplicable. We shall then show that in many circumstances where it is not applicable, one can still apply a Gott-like argument to get predictions similar to those which he makes. Finally, we shall show that a purported refutation of Gott's argument, due to Caves and Olum, is only relevant in some circumstances.

III.1. *Observational selection effects*

Gott specifies that to apply his argument, there must be nothing special about t_{now}: we must be able to treat t_{now} as located randomly in the interval between t_{begin} and t_{end}. He points out (*Time Travel*, p. 219) that this requirement puts a limit on the applicability of his argument:

> Don't wait until you are invited to a friend's wedding, and then, one minute after the vows are finished, proclaim that the marriage has less than 39 more minutes to go.

[17] Gott's argument is essentially indexical; it involves conditionalizing upon T_{past}, which is the proposition that the present age of the process in question is t_{past}. There is a real question whether Gott's extension of Bayesian probability theory to indexical propositions is correct. But like nearly everyone else who writes on probability issues involving indexical propositions (such as doomsday arguments, the Sleeping Beauty problem, and so on), we here simply assume that it is. For one way of rejecting Bayesian conditionalization for indexical propositions, see our 'Minimizing Inaccuracy for Self-Locating Beliefs', *Philosophy and Phenomenological Research*, 70 (2005), pp. 384–95.

> You attended the wedding precisely to observe a *special* point in the marriage – its beginning.

While we agree that Gott's argument should not be applied to this particular process, let us make it clear *why* it cannot be applied. We shall argue that it is applicable in some situations where one knows one has observed a special point in the process. We shall then explain why the argument is sometimes not applicable.

Back at Geyser Intergalactic Park, you run into a park ranger, who says, before you get a chance to ask anything about the longevity of geysers, 'Follow me – Geyser 17 is going to start shooting purple liquid soon, and it's quite a sight'. The ranger explains that exactly once during the time while this geyser is shooting, it shoots purple liquid. You get there just in time to catch the purple phase of the shooting; it is quite a sight. You notice that at the time when the geyser shoots purple liquid, the sign and stopwatch next to the geyser tell you that it has been shooting for 30 minutes.

Is Gott's argument applicable to this geyser? We maintain that it is – or at least, we maintain that if the argument is applicable in general to geysers in Geyser Intergalactic Park, then it is applicable in this case. You start with the Jeffreys prior for the geyser, and then you conditionalize on the information that exactly once during the shooting process it shoots purple liquid. Since this gives no information about the longevity of the geyser, the prior is unchanged. You also conditionalize on the information that the ranger knows when the geyser will shoot purple liquid, but again that does not give you any information on its longevity. When you conditionalize on the fact that the purple liquid shoots at 30 minutes, this gives the present age of the geyser, but it does not give you any more information than this. You have no information, for example, about whether purple liquid shoots happen early or late in the stage of a geyser, or about what sorts of geysers shoot purple liquid. Thus Gott's argument is applicable – to predict the longevity of this geyser, you start with the Jeffreys prior, and conditionalize on the proposition that the present age of the geyser shoot is 30 minutes.

So Gott's argument is applicable to this geyser, even though you have been brought to the geyser to observe a special point in its process – the point when it shoots purple liquid. So why is Gott's argument not applicable to the marriage? The reason cannot simply be that you have been brought there to observe a special point in the process. The problem is that the special point is *temporally* special – the special point is such that t_{now} cannot be treated as located randomly in the interval between t_{begin} and t_{end}.

But why is Gott's argument not applicable in cases where one observes a temporally special point? The reason is that in such cases, there is an *observational selection effect*. Observational selection effects have been extensively discussed as far back at least as Eddington, with a notable recent discussion by Bostrom.[18] The basic idea is that sometimes observations we make are biased because of a selection effect – we are only capable of making certain types of observations. For example, if we cast a net in a pond and catch only big fish, we might be tempted to conclude that all the fish in the pond are big. But if our net lets small fish go free, then that conclusion would not follow from our evidence.

The relevance of observational selection effects emerges from an alternative version of the geyser story, where you know that all geysers shoot either for 1 hour or for 100 years, but you do not know which. The first thing you do at the park is take a tour bus ride, and you are brought to a geyser specifically to see it start to shoot. After 10 minutes, the tour bus departs. Should the fact that this geyser has been shooting for 10 minutes lead you to shift your probabilities in favour of the hypothesis that geysers last 1 hour? No, it should not. The reason is that there is an observational selection effect: you would have observed this geyser shooting for 10 minutes, regardless of whether it was going to shoot for 1 hour or for 100 years.

The point can be put in Bayesian terms: the posterior probability of the hypothesis h that the total longevity of geysers is 1 hour is given by the prior probability of that hypothesis conditional on the evidence e that you were brought to this geyser to observe it shoot for the first 10 minutes. In other words, $P^*(h) = P(h|e)$. But you got on the tour bus and were taken to the geyser specifically to see it start to shoot, and you knew that it was going to shoot for at least 10 minutes. It follows that $P(e) = 1$, and hence $P^*(h) = P(h)$; your probability for h is unchanged.

Imagine now that the tour bus happens to drive past a geyser that has been shooting for 10 minutes. Seeing this *does* provide evidence in favour of h, since you would be more likely to observe a geyser that has been shooting for 10 minutes under the hypothesis that geysers shoot for an hour than you would under the hypothesis that geysers shoot for 100 years. In that situation there is no observational selection effect: you randomly came across this geyser, and it could have been shooting for any length of time. We conclude that when there is no observational selection effect, present age can provide evidence of future duration.

III.2. *Gott-like shifts*

Above we discussed the example of how Gott's argument should not be used to predict the future duration of a marriage if one is present at the beginning. Following the reasoning of the previous section, we can conclude that

[18] A. Eddington, *The Philosophy of Physical Science* (Cambridge UP, 1939); N. Bostrom, *Anthropic Bias: Observation Selection Effects in Science and Philosophy* (New York: Routledge, 2002).

at least one reason why Gott's argument is inapplicable in this case is that there is an observational selection effect associated with the fact that one did not randomly come across this marriage: one was specifically invited to be present at the wedding.

This leads to the natural question: what happens if one *does* randomly come across a marriage, and the present age of the marriage is just one minute? Would it be legitimate to apply Gott's argument to this marriage, and predict, for example, that there is a 50% chance that the marriage will end in the next minute?

Clearly, this would not be legitimate. But why not? The reason is that we have information about the longevity of marriages; this information gives us a prior probability function for longevity which is not the same as the Jeffreys prior. At the moment when a couple gets married, one's prior probability function is such that one assigns probability of almost 0 to the proposition that the marriage will last less than one minute. Thus, after one minute, when one conditionalizes on the proposition that the marriage has lasted a minute, this produces almost no change in one's opinions regarding future longevity.

A marriage is not the sort of process to which it is appropriate to apply Gott's argument, since the Jeffreys prior is an unreasonable prior to use for the longevity of a marriage. Sometimes Gott says things which suggest that he recognizes this, for example, 'My Copernican principle is most useful when examining the longevity of something, like the human race, for which there are no actuarial data available'.[19] But sometimes he seems to ignore the restriction, for example, 'you can use the 95% Copernican formula right now to forecast the future longevity of your current relationship'.[20] If his argument were applicable to relationships, then one could predict for a couple who have been married for 10 years that there is a 2·5% chance that the relationship will last for longer than 390 years. This is clearly not correct.

Nevertheless, for processes like marriages, it can be reasonable to take present age as an indicator of future longevity. When one comes across two couples, one married for 5 weeks and the other for 5 years, it is reasonable to predict that the marriage of the first couple will not last as long as the marriage of the second couple. One's predictions for future longevity change once one takes into account the present age of the processes, but the predictions are not exactly the predictions one would make by applying Gott's argument. Nevertheless, because the probability shifts are such that the process which has greater present age is predicted to have greater future

[19] Gott, 'A Grim Reckoning', *New Scientist*, 15 November 1997, pp. 36–9, at p. 39.
[20] *Time Travel and Einstein's Universe*, p. 219.

longevity, we maintain that such probability shifts are in the spirit of Gott's argument. This is why we call them *Gott-like shifts*.

The reason why the predictions are not the predictions one would make by applying Gott's argument is that one is starting with a different prior. This prior (unlike the Jeffreys prior) is arrived at *a posteriori*. The exact features of this prior would depend on the opinions of the individual agent, but there are certain features we would expect in it. For example, for a marriage, it would be reasonable to assign probability 0 to the proposition that the marriage will last for longer than some long period, like 200 years. In fact, for many of the processes we encounter it would be reasonable to assign some sort of cut-off. For example, our sun has a finite lifetime, and arguably that imposes an upper boundary for the lifetime of processes on Earth. Thus it would be reasonable to assign probability 0 to the hypothesis that any Earth-bound process (like a shooting geyser) lasts for longer than, say, 100 billion years. The fact that we typically impose such upper bounds on prior probability functions for longevity entails that our prior probability functions are (at least typically) normalizable. This addresses the concern discussed in §II.1, that the Jeffreys prior is unnormalizable. The prior probability functions for longevity we actually use are similar in certain ways to the Jeffrey prior, but one way in which they often differ is by having an upper bound.

At this point the reader may wonder: what about Jaynes' location and scale invariance argument, which we used to provide a reason for adopting the Jeffreys prior? Our reply to that argument is that for many of the processes one encounters, one does not endorse scale invariance because one possesses relevant empirical evidence. For example, for the geysers, it would be reasonable to endorse scale invariance in a limited way: it would be reasonable to make numerically the same predictions whether one is dealing with a scale of minutes or years (for a normal range of numerical values). But once one considers a scale of billions of years, for example, the upper boundary comes into play. If one assigns probability 0 to the proposition that the geyser will last for more than 100 billion years, then for a geyser that has been shooting for 10 billion years one would not follow Gott's argument in assigning probability 0·025 to the proposition that it will last for more than 390 billion years. We conclude that while Jaynes' justification for the Jeffreys prior is a beautiful result, it is not typically applicable in practice.

In addition to Gott-like shifts, we should also point out that there are *anti-Gott-like shifts*, cases where the longer the present age of a process, the shorter the future duration is predicted to be. This should not be surprising: lots of processes work in this way. For example, for people past the age of infancy, the greater one's present age, the shorter one's future duration is predicted to be.

What this shows is that it is one's prior probability function that determines whether present age gives any information about future longevity. Assuming that present age does give information about future longevity, one's prior also determines whether one gets a Gott-like shift or an anti-Gott-like shift. For circumstances where one does not have *much* information about longevity, it would be reasonable to choose a prior similar to the Jeffreys prior, and hence the predictions one makes about longevity would be similar to the predictions one gets from Gott's argument. But for circumstances where one does have significant information about longevity, the predictions one makes depend on the detailed information which is used to generate one's prior probability function.

III.3. *Does anthropic reasoning refute Gott's argument?*

Caves and Olum believe that for processes where one does not have empirical information about longevity, one cannot use present age to make predictions about future duration.[21] They maintain that Gott's argument is flawed because he does not take into account how likely it is to come across a particular process. They argue that one is more likely to come across processes that have longer total duration, and once one takes that anthropic factor into account, present age gives no information about future duration.

Specifically, the Caves–Olum objection is as follows (our presentation of the objection is an improved version of that given by Olum, pp. 175–6): Gott's prior probability function $P(T_{total})$ represents the probability that if a process were chosen randomly out of all the processes in the class under consideration ever to exist, that process would have total longevity of t_{total}. For example, for the geysers, $P(T_{total})$ represents the probability distribution over longevity for all the geysers that ever exist, past, present or future. What Gott ignores, according to Caves and Olum, is that one is more likely to encounter longer-lived processes, because longer-lived processes are more likely to exist now. Caves and Olum thus maintain that the prior probability function for total longevity of all *currently existing* processes in the class under consideration, $P_{currently\ existing}(T_{total})$, is not the same as $P(T_{total})$. Instead, a t_{total} anthropic factor is required, which takes into account that the longer the total longevity of a process, the more likely it is to exist now. In other words,

$$P_{currently\ existing}(T_{total}) \propto t_{total}\, P(T_{total}).$$

Conditionalizing on T_{past}, Bayes' rule establishes that the posterior probability is

[21] Caves, 'Predicting Future Duration'; K. Olum, 'The Doomsday Argument and the Number of Possible Observers', *The Philosophical Quarterly*, 52 (2002), pp. 164–82.

$$P^*_{currently\ existing}(T_{total}) \propto t_{total}\, P(T_{past} | T_{total})\, P(T_{total}).$$

Since $P(T_{past} | T_{total}) \propto 1/t_{total}$ as long as $t_{past} < t_{total}$, it follows that

$$P^*_{currently\ existing}(T_{total}) \propto P(T_{total})$$

as long as $t_{past} < t_{total}$. Once one incorporates the t_{total} anthropic factor, one's posterior probability function is the same as one's prior (except for the information that $t_{past} < t_{total}$). As Olum concludes (p. 176), 'we do not learn anything new from knowing the past lifetime, other than that the total lifetime must be at least as large as what we have observed'.

We have three replies to the Caves–Olum objection. First, Caves and Olum illegitimately assume that the prior probability function Gott utilizes represents the probability distribution for longevity for all the processes that ever exist in the class under consideration. But we see nothing in Gott's presentation of his argument to mandate that reading. Instead, the prior probability function could be taken to represent one's subjective probability distribution for longevity for *currently existing* processes in the class under consideration. In other words, the anthropic factor could already have been taken into account when Gott gives his prior probability function.

So how can one decide whether the Jeffreys prior should apply to all processes, or to currently existing processes? There is a sense in which there is no right answer: rationality does not mandate that you utilize either approach in order to represent your prior opinion. Nevertheless we have considered an argument for the Jeffreys prior, namely, Jaynes' location and scale invariance argument. Thus the question becomes: does one maintain that location and scale invariance holds for all processes, or for currently existing processes? We believe that it is reasonable to maintain that location and scale invariance holds for currently existing processes – unless, that is, one has relevant empirical information; but even in many such cases it will be reasonable to hold that such invariance holds approximately. For example, in the geyser story, both the geyser where t_{past} = 10 minutes and the geyser where t_{past} = 10 years are currently existing, and yet we argued that it is reasonable to make numerically the same predictions for the two geysers. It follows that one is applying at least approximate scale invariance at the level of currently existing processes.

Here is our second reply to the Caves–Olum objection. Even if our first reply to Caves and Olum is incorrect, all their argument shows is that there is a problem with Gott's argument itself. This still leaves open the possibility of getting Gott-like shifts by conditionalizing on present age. To get their t_{total} anthropic factor in the equation for $P_{currently\ existing}(T_{total})$, Caves and Olum are making a random sampling assumption, that processes in the class under consideration are randomly distributed through time. The assumption is in the spirit of Gott's Copernican hypothesis, but this does not mean that it is correct. Just as one can have empirical information which renders inappropriate the use of the Jeffreys prior, so one can have empirical information which renders inappropriate the prior probability distribution of processes over time that Caves and Olum are assuming. This empirical information could make it inappropriate to use t_{total} as the anthropic factor, and hence the anthropic factor would not cancel out $P(T_{past}|T_{total})$, and hence it would not be the case that $P^*_{currently\ existing}(T_{total}) \propto P(T_{total})$ as long as $t_{past} < t_{total}$.

As an extreme example, one could have the empirical information that all processes in the class under consideration exist now. In that scenario, no anthropic factor at all would be needed, and one could reproduce the predictions of Gott's argument. (Whether one reproduces its predictions in that scenario would depend on whether one uses the Jeffreys prior to represent one's prior probability distribution over total longevity.)

A related example is given by Bostrom (p. 93). Bostrom implicitly rejects our first reply to the Caves–Olum objection:

> in order to legitimately apply Gott's method, you must be convinced that your observation point's sampling interval co-varies with durations of the phenomenon.

In other words, you must be convinced that given that the phenomenon starts at t_{begin} and ends at t_{end}, you can only make an observation in the interval starting from t_{begin} and ending at t_{end}; you must be convinced that it was not possible for you to look some time before t_{begin} or after t_{end} and see that the process was not going on. In this situation, no anthropic factor would be needed, and again one could reproduce the predictions of Gott's argument.

The two examples considered in the previous two paragraphs are somewhat far-fetched. More realistically, one might have empirical information which would make the anthropic factor more complicated than the simple t_{total} factor, without the anthropic factor dropping out altogether. As long as the anthropic factor does not cancel out $P(T_{past}|T_{total})$, the posterior longevity distribution is not given just by the prior. This provides more evidence for our claim that even in cases where Gott's argument itself is not applicable, present age can be an indicator of future duration.

Here is our third response to the Caves–Olum objection. Just as one can have empirical information which vitiates t_{total} as the anthropic factor, so one can have empirical information which calls into question the claim that $P(T_{past}|T_{total}) \propto 1/t_{total}$ as long as $t_{past} < t_{total}$. The assumption that no value of t_{past} should be favoured over any other (as long as $t_{past} < t_{total}$) is a reasonable one, in a situation where one is following the Copernican principle in treating t_{now} as randomly located in the interval between times t_{begin} and t_{end}. But one could have empirical information that would render that random sampling assumption inappropriate. For example, the empirical information could specify that one is more likely to encounter a process at some stages of its lifetime than at other stages. It would follow that it is not the case that $P(T_{past} | T_{total}) \propto 1/t_{total}$ and hence the Caves–Olum anthropic factor would not cancel out $P(T_{past} | T_{total})$, and thus it would not be the case that $P^*_{currently\ existing}(T_{total}) \propto P(T_{total})$ as long as $t_{past} < t_{total}$. Again we get the result that even in cases where Gott's argument itself is not applicable, present age can be an indicator of future duration.

There is a certain irony here in our last two replies to the Caves–Olum objection. Gott's argument has been criticized because it relies on an *a priori* prior probability function; it does not utilize empirical evidence. Caves and Olum rely on that sort of *a priori* reasoning to refute Gott's argument. We have argued that the spirit of Gott's reasoning can be maintained even when one incorporates empirical information into the prior probability function. The irony is that it is just this sort of incorporation of empirical information which can render the Caves–Olum objection ineffective.

IV. CONCLUSION

We agree with the core thesis in Gott's argument: in many circumstances, the greater the present age of a process, the more likely a longer future duration. What makes Gott's argument so fascinating is that one can generate predictions of future longevity based on minimal empirical information: the only empirical input is the present age of the process.

In practice, one often, perhaps always, has more empirical information than just the present age of the process. This empirical information can render the application of a location and scale invariant prior probability distribution inappropriate. But because we have shown that Gott's argument is Bayesian, one knows how to modify it when the Jeffreys prior is inappropriate – simply start with a different prior, and use standard Bayesian reasoning from there.

One of the surprising things about Gott's argument is that one can make powerful predictions from this minimal empirical input of present age. The most discussed prediction of this sort is the prediction of our future prospects on which Gott's paper originally focused. In fact, some discussions of his argument exclusively focus on this doomsday prediction. The problem with this approach is that the doomsday aspect of Gott's argument raises a number of controversial issues that go above and beyond the controversial issues associated with the argument in general. As a result, the merits and drawbacks of Gott's argument itself easily get obscured. We have attempted to rectify that situation with this paper.

To highlight just one doomsday controversy which has recently been discussed in this journal, there is the question of whether the self-indication assumption (roughly, 'Finding that you exist gives you reason to think there are more observers') vitiates the doomsday argument.[22] It would be interesting to explore whether this and other doomsday controversies influence the prediction of our future prospects one gets from Gott's argument. To do so, however, is beyond the scope of this paper.[23]

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[22] For discussion, see Olum's paper, at pp. 181–2; B. Monton, 'The Doomsday Argument Without Knowledge of Birth Rank', *The Philosophical Quarterly*, 53 (2003), pp. 79–82; N. Bostrom and M. Čirkovič, 'The Doomsday Argument and the Self-Indication Assumption: Reply to Olum', *The Philosophical Quarterly*, 53 (2003), pp. 83–91.

[23] We thank J. Richard Gott and an anonymous referee for helpful comments.