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RESEARCH ARTICLE

From the St. Petersburg paradox to the dismal theorem

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Abstract
This paper aims to consider the meaning of the dismal theorem, as presented by Martin Weitzman [(2009) On modeling and interpreting the economics of catastrophic climate change. *Review of Economics and Statistics* **91**, 1–19]. The theorem states that a standard cost–benefit analysis breaks down if there is a possibility of catastrophes occurring. This result has a significant influence on debates regarding the economics of climate change. In this study, we present an intuitive similarity between the dismal theorem and the St. Petersburg paradox using a simple discrete probability distribution.

Keywords: climate change; catastrophe; fat-tailed distribution; uncertainty

JEL classification: D61; D63; D81; Q54

1. Introduction

1.1. Motivation

Weitzman (2009) presented the 'dismal theorem', which states that a standard cost-benefit analysis may break down if there is a possibility of catastrophes occurring. In particular, the theorem states that owing to a fat-tailed distribution, the *stochastic discount factor*, which corresponds to a willingness to pay for an infinitesimal certain transfer to the future, can be infinite if there is a risk of catastrophic damage. Weitzman (2009) illustrated this problem in the context of climate change: catastrophic damage is assumed to be associated with a very low level of consumption due to high greenhouse gas concentrations.[1] This result has caused much debate in the field of the economics of climate change; Wagner and Weitzman (2016) presented general discussions on this subject. Indeed, many researchers have examined the meaning and significance of the dismal theorem (Millner, 2013; Arrow and Priebsch, 2014; Weitzman, 2014). In addition, some researchers have provided simplified versions of the theorem (Nordhaus, 2009; Pindyck, 2011; Horowitz and Lange, 2014; Weitzman, 2014).

[1]Originally Geweke (2001) showed the dismal theorem, but he did not provide an application to climate change. Weitzman (2009) connected the result with the economics of climate change.

The purpose of this paper is to present an intuitive similarity between the dismal theorem and the St. Petersburg paradox, which is a well-known critique of the expected value theory.[2] The paradox is about a simple game. Toss a coin repeatedly until tails appears for the first time and then stop. If tails appears on the nth toss, then the player gets 2^n dollars. The expected monetary value associated with the game can be extremely large, although with probability 1, the player will get a finite sum as the result of this game. Bernoulli (1954) found a resolution of this paradox by introducing expected utility theory. However, as shown by Menger (1934), this does not fully resolve the paradox. Even if an individual follows the expected utility hypothesis, there is some 'risky game' that causes a similar paradoxical consequence.[3] We show that a result similar to the dismal theorem can be obtained from a variation of the St. Petersburg paradox or Menger's paradox.

Because the St. Petersburg paradox is very simple and well-known, our argument employs only very elementary mathematics. Although continuous probability distributions are employed in existing versions, a geometric distribution – which is discrete – is employed in our formulation. The point is that the geometric distribution in the St. Petersburg paradox can be regarded as a type of fat-tailed distribution, and that the distribution is a natural representation of independent trials. Moreover, as in Weitzman's dismal theorem, our result employs a utility function with constant relative risk aversion. This class of utility functions is quite common in most fields of applied economics. Also, we generalize our result by utilizing a result obtained by Seidl (2013) with regard to the St. Petersburg paradox. We clarify conditions under which the dismal-theorem-like result holds. Thus, our results can be useful for understanding the mechanism behind the dismal theorem, although the dismal theorem and our result are not mathematically the same.

1.2. The dismal theorem

Here we briefly review Weitzman's dismal theorem. We consider a model with two periods: the present and the future. There is a representative agent whose welfare is dependent on consumption levels in these periods. The current consumption level is fixed, and thus it is normalized at 1. The future consumption level is a random variable, which is given by C. The agent has a *constant relative risk aversion (CRRA) utility function* as a periodic utility function:

$$U(C) = \frac{C^{1-\sigma}}{1-\sigma}. \tag{1}$$

Then, given a discount rate $\beta \in (0,1)$, social welfare is given by

$$W = U(1) + \beta E[U(C)].$$

The *stochastic discount factor* S is defined as:

$$S = \frac{\beta E[U'(C)]}{U'(1)}.$$

This value represents the marginal willingness to pay for future consumption obtained by sacrificing current consumption. Given the CRRA form, we have $S = \beta E[C^{-\sigma}]$.

[2] For surveys of this paradox, see Samuelson (1977) and Seidl (2013).

[3] Arrow (1974) provided conditions that make the expected value of utilities finite.

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Weitzman's dismal theorem is stated as follows:[4] the stochastic discount factor S is infinite, that is, the expectation does not converge if:

(i) $\sigma > 1$;
(ii) $y := \log(c)$ is distributed according to a probability density function (PDF) $h(y \mid s) = 1/s \times \phi((y-\mu)/s)$;
(iii) the prior PDF of s is given by $p(s) \propto s^{-k}$ for some positive number k, and n independent observations of y are given.

Here note that y is interpreted as the growth rate of consumption. A function ϕ is a normalization function, and s and μ are structural parameters. There is what Weitzman called 'structural uncertainty', i.e., there is uncertainty about s. A finite set of observations is used to obtain the posterior-predictive PDF of s. Given this setting, it is shown that the marginal willingness to pay approaches infinity; this implies that the agent is willing to sacrifice an extremely large amount of current consumption to get a small amount of future consumption.[5] The key point of this theorem is that policies are crucially dependent on a catastrophic outcome with a very small probability; even if the probability is small, the distribution of certain future consumption is fat-tailed. Because of this, the standard method of cost-benefit analysis breaks down. In the next section, we show a similar result by using the St. Petersburg paradox.

2. The St. Petersburg paradox and the dismal theorem

The well-known resolution of this paradox is to introduce the expected utility theory. If the agent has the CRRA utility function given by (1), then the expected utility is calculated as:

$$\begin{aligned} EU &= \frac{1}{1-\sigma}\left[\frac{1}{2}2^{1-\sigma} + \frac{1}{2^2}2^{2(1-\sigma)} + \cdots + \frac{1}{2^k}2^{k(1-\sigma)} + \cdots\right] \\ &= \frac{1}{1-\sigma}\left[2^{-\sigma} + 2^{-2\sigma} + \cdots + 2^{-k\sigma} + \cdots\right] \\ &= \frac{1}{1-\sigma}\lim_{n\to\infty}\frac{2^{-\sigma}(1-2^{-n\sigma})}{1-2^{-\sigma}}. \end{aligned}$$

If $\sigma > 1$, the value of EU is finite.[6] Thus, the agent avoids participating in this risky situation if the fee is sufficiently large.

Next we present a result that has a similar property to the dismal theorem, along with a small modification of the St. Petersburg paradox. Consider another agent who has one million dollars of wealth. He/she risks losing 50 per cent of the wealth with probability 1/2; 75 per cent with probability $1/(2)^2$; 87.5 per cent with probability $1/(2)^3$; and so on.[7] That is, the agent loses a fraction $1 - 1/(2)^k$ of the wealth with probability $1/(2)^k$

[4] Millner (2013: 312) concisely presented the dismal theorem. Here, we follow his way of presentation.

[5] In Weitzman's original argument, a distinction between pointwise and uniform convergences was emphasized (Weitzman, 2009: 8 and 11–15). A counterintuitive result can occur because S is pointwise convergent but not uniform convergent. To get a robust political implication of the dismal theorem, specifying the limiting convergence process is very important.

[6] This also implies that if $\sigma < 1$, the expected utility is infinite.

[7] Here, he/she is a representative agent of the society.

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(we call this situation A). Then, he or she loses a very large amount of wealth with a very small probability, corresponding to a catastrophe. Here our question is: what share of his/her wealth should the agent be ready to pay to eliminate this risk? Note that the expected amount of money associated with this risk is:

$$\frac{1}{2^2} + \frac{1}{2^4} + \frac{1}{2^6} + \cdots = \frac{1}{3}.$$

We consider the following utility function, which is a particular case of a class of CRRA utility functions (where σ is chosen to be 2):

$$U(C) = -\frac{1}{C}.$$

The expected utility is:

$$EU = \frac{1}{2}(-2) + \frac{1}{2^2}(-2^2) + \frac{1}{2^3}(-2^3) + \cdots + \frac{1}{2^k}(-2^k) + \cdots = -\infty. \qquad (2)$$

Therefore, (2) is the opposite of the St. Petersburg paradox. The answer to the above-mentioned question is that the agent is willing to pay 100 per cent of the wealth in order to eliminate the risk (in spite of the fact that the actual loss is almost surely smaller than 100 per cent). This is a dual version of the St. Petersburg paradox, which is in the same spirit as the dismal theorem.[8]

The essence of the dismal theorem is obviously related to the dual version of the paradox. However, the dismal theorem is about *marginal* benefit and cost. That is, it is about a trade-off. On the other hand, the dual version is about absolute levels of benefit. Since this difference is crucial, we introduce a certain trade-off, which shows that classical insights from the paradox can be applied to resolving the dismal theorem. Here we consider a marginally more attractive risky situation (situation B). Take a very small number $\varepsilon > 0$. Suppose that if the government pays some cost, then the situation becomes:

(i) $50(1+\varepsilon)$ per cent of wealth remains with probability $1/2$;
(ii) $25(1+\varepsilon)$ per cent of wealth remains with probability $1/2^2$;
(iii) $12.5(1+\varepsilon)$ per cent of wealth remains with probability $1/2^3$;

and so on. That is, $(1+\varepsilon)/2^k$ remains with probability $1/2^k$. In each event, the remaining wealth is increased by 100ε per cent. This means that the agent loses $100(1-(1+\varepsilon)/2^k)$ per cent with probability $1/2^k$. It is easy to see that this change yields an increase of 100ε per cent in the expected amount of money: $(1+\varepsilon)/3$. Let $EU(\varepsilon)$ be the expected utility under this situation:

$$\begin{aligned} EU(\varepsilon) = {} & \frac{1}{2}\left(-\frac{2}{1+\varepsilon}\right) + \frac{1}{2^2}\left(-\frac{2^2}{1+\varepsilon}\right) + \frac{1}{2^3}\left(-\frac{2^3}{1+\varepsilon}\right) \\ & + \cdots + \frac{1}{2^k}\left(-\frac{2^k}{1+\varepsilon}\right) + \cdots = -\infty. \end{aligned}$$

[8]This leading example is shown in an expository work by Cato (2019), which argues practical and philosophical implications of the dismal theorem. In particular, Cato claims that the assumption on utility functions is associated with a matter of ethics.

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Thus the expected value is still infinite. Now we can evaluate the difference between $EU(\varepsilon)$ and EU in (2) by comparing the kth terms in the two situations:

$$\frac{1}{2^k}\left(-\frac{2^k}{1+\varepsilon}\right)-\frac{1}{2^k}(-2^k)=\frac{\varepsilon}{1+\varepsilon}.$$

This implies that:

$$EU(\varepsilon)-EU=\infty.$$

Thus the expected benefit from this small improvement in terms of the expected amount of money is incredibly large; the agent is willing to pay an extremely large amount of money to obtain this small improvement from A to B. We note that for any small $\varepsilon > 0$, this carries over. This negative implication of the cost-benefit analysis is roughly and intuitively similar to that of the dismal theorem. That is, by using extensions of the St. Petersburg paradox, we get a conclusion similar to the the dismal theorem.

These intriguing similarities between the St. Petersburg paradox and the dismal theorem are obtained under a general formulation of the CRRA utility function given in (1). The expected utility under situation A (before paying the cost) is:

$$\begin{aligned}EU &= \frac{1}{1-\sigma}\left[\frac{1}{2}2^{\sigma-1}+\frac{1}{2^2}2^{2(\sigma-1)}+\cdots+\frac{1}{2^k}2^{k(\sigma-1)}+\cdots\right]\\ &= \frac{1}{1-\sigma}\left[2^{\sigma-2}+2^{2(\sigma-2)}+\cdots+2^{k2(\sigma-2)}+\cdots\right].\end{aligned}$$

After paying some cost, the agent can receive an infinitesimal improvement. In this situation, the expected utility is given by:

$$EU(\varepsilon)=\frac{1}{1-\sigma}\left[\frac{2^{\sigma-2}}{(1+\varepsilon)^{\sigma-1}}+\frac{2^{2(\sigma-2)}}{(1+\varepsilon)^{\sigma-1}}+\cdots+\frac{2^{k2(\sigma-2)}}{(1+\varepsilon)^{\sigma-1}}+\cdots\right].$$

Focusing on the kth term in each situation, we obtain the following difference between the two situations:

$$A(k)=\frac{2^{k2(\sigma-2)}}{\sigma-1}\left[1-\frac{1}{(1+\varepsilon)^{\sigma-1}}\right].$$

Note that $EU(\varepsilon)-EU=\sum_{k=1}^{\infty}A(k)$. Furthermore, if $\sigma \geq 2$, then

$$0 < A(1) \leq A(2) \leq A(3) \leq A(4) \leq \cdots.$$

This implies that $EU(\varepsilon)-EU > \infty$ if $\sigma \geq 2$. Then, for any $\varepsilon > 0$ and any $\sigma \geq 2$, the value of a small improvement is incredibly large, and thus we have a result similar to the dismal theorem.[9]

This argument illustrates that a dismal-theorem-like result can be obtained from an extension of the St. Petersburg paradox. It is helpful to see how traditional discussions on the St. Petersburg paradox are associated with recent arguments in the context of

[9]Weitzman's formulation also employs the CRRA form. He shows that the dismal theorem holds for $\sigma > 1$.

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the dismal theorem. Since the work by Menger (1934), the idea that the boundedness of utilities is crucial for overcoming the St. Petersburg paradox has been discussed. Nordhaus (2009) discussed the utility function employed in the dismal theorem being one of the sources of the consequence. He pointed out that a utility level with near-zero consumption is a key factor for the dismal theorem: indeed, the CRRA utility function we employed is not bounded. More importantly, to derive the dismal theorem, its marginal utility must be unbounded. Recently Millner (2013) pointed out that the dismal theorem does not carry over under a class of harmonic absolute risk aversion (HARA) utility functions, which is defined as:

$$U(C) = \alpha \left(\beta + \frac{C}{\sigma}\right)^{1-\sigma},$$

where $\alpha(1-\sigma)/\sigma > 0$. Here, suppose that $\alpha = -1$, $\beta = 1$, and $\sigma = 2$. In our framework, it is easy to understand the working of this utility function and how a cost-benefit method breaks down. Note that if $\beta = 0$, it corresponds to the CRRA utility with $\sigma = 2$, which we used to derive our dismal-theorem-like result. Then we have $U(C) = -(1 + C/2)^{-1}$. Note that

$$U\left(\frac{1}{2^k}\right) = -\frac{2^{k+1}}{2^{k+1}+1} \quad \text{and} \quad U\left(\frac{1+\varepsilon}{2^k}\right) = -\frac{2^{k+1}}{2^{k+1}+1+\varepsilon}.$$

Then, the expected utility under situation A is:

$$EU = -\left(\frac{4}{5} + \frac{8}{9} + \frac{16}{17} + \cdots + \frac{2^{k+1}}{2^{k+1}+1} + \cdots\right) = -\infty.$$

This implies that the expected utility is not defined. Moreover, it is easy to see that $EU(\varepsilon)$ (expected utility under situation B) is also infinite. However, we can see that

$$\begin{aligned} B(k) &= \frac{2^{k+1}}{2^{k+1}+1} - \frac{2^{k+1}}{2^{k+1}+1+\varepsilon} = \frac{2^{k+1}(2^{k+1}+1+\varepsilon) - 2^{k+1}(2^{k+1}+1)}{(2^{k+1}+1)(2^{k+1}+1+\varepsilon)} \\ &= \frac{2^{k+1}\varepsilon}{(2^{k+1}+1)(2^{k+1}+1+\varepsilon)}, \end{aligned}$$

and $EU(\varepsilon) - EU = \sum_{k=1}^{\infty} B(k)$. Note that

$$\frac{\varepsilon}{2^{k+1}} \geq \frac{2^{k+1}\varepsilon}{(2^{k+1}+1)(2^{k+1}+1+\varepsilon)}.$$

Thus, it follows that

$$EU(\varepsilon) - EU \leq \sum_{k=1}^{\infty} \frac{\varepsilon}{2^{k+1}} < \infty.$$

This implies that our dismal-theorem-like result disappears. This observation shows how it can be the case that both EU and $EU(\varepsilon)$ are infinite and their difference is finite.

Nordhaus (2009) also pointed out that a fat-tailed distribution is a key factor in the dismal theorem. Weitzman (2009, 2014) noted that the dismal theorem does not happen under a normal distribution. The probability distribution employed in this study can be regarded as a type of fat-tailed distribution. Moreover, in the context of the St. Petersburg paradox, it has been recognized that a combination of a utility function and a probability distribution is quite important. Seidl (2013) provided a general result by utilizing d'Alembert's ratio test. We can provide a general dismal-theorem-like result by modifying Seidl's argument. Let $x : \mathbb{N} \to X \subseteq \mathbb{R}$ be such that $x_k > x_{k+1}$ for all $k \geq 1$. Let $U(x)$ be a non-decreasing function and $p(x) \in [0, 1]$ a probability function such that $\sum_{k=1}^{\infty} p(x_k) = 1$. Let $\varepsilon > 0$ be a small real number. Then we have the following result:

(i) $EU(\varepsilon) - EU < \infty$ if there exists $k^* \geq 1$ such that $p(x_k) = 0$ for all $k \geq k^*$;

(ii) $EU(\varepsilon) - EU < \infty$ if there exists $k^* \geq 1$ such that

$$\sup_{k \geq k^*} \frac{[U((1+\varepsilon)x_{k+1}) - U(x_{k+1})]p(x_{k+1})}{[U((1+\varepsilon)x_k) - U(x_k)]p(x_k)} < 1;$$

(iii) $EU(\varepsilon) - EU = \infty$ if there exists $k^* \geq 1$ such that

$$\inf_{k \geq k^*} \frac{[U((1+\varepsilon)x_{k+1}) - U(x_{k+1})]p(x_{k+1})}{[U((1+\varepsilon)x_k) - U(x_k)]p(x_k)} \geq 1;$$

(iv) $EU(\varepsilon) - EU$ may converge or diverge if

$$\lim_{k \to \infty} \frac{[U((1+\varepsilon)x_{k+1}) - U(x_{k+1})]p(x_{k+1})}{[U((1+\varepsilon)x_k) - U(x_k)]p(x_k)} = 1,$$

where

$$EU = \sum_{k=1}^{\infty} p(x_k)U(x_k),$$

and

$$EU(\varepsilon) = \sum_{k=1}^{\infty} p(x_k)U((1+\varepsilon)x_k).$$

Note that case (iii) corresponds to our dismal-theorem-like result. The key is comparing the growth rate of improvement in consumption and the shrinking rate of probability. As demonstrated by Seidl (2013), his result from the ratio test unifies many observations associated with the St. Petersburg paradox.

In order to apply this result, let us consider a risky situation with a Poisson distribution. Suppose that $100/2^k$ per cent of wealth remains with probability $e^{-\lambda}\lambda^k/k!$, where $\lambda > 0$. That is, the agent loses a fraction $1 - 2^k$ of wealth with probability $e^{-\lambda}\lambda^k/k!$. His/her utility function is assumed to be $U(C) = -1/C$. Note that

$$\frac{[U((1+\varepsilon)x_{k+1}) - U(x_{k+1})]p(x_{k+1})}{[U((1+\varepsilon)x_k) - U(x_k)]p(x_k)} = \frac{2\lambda}{k}.$$

Thus, case (ii) can be applied. The dismal-theorem-like result disappears, and then a standard cost-benefit method works for the Poisson distribution.

Consider another case. Suppose that the agent earns $1/d^k$ ($d \geq 1$) dollars with probability $-(1/\log(1-p))(p^k/k)$, where $0 < p < 1$. This is the logarithmic distribution. His/her utility function is assumed to be $U(C) = -1/C$. Note that

$$\frac{[U((1+\varepsilon)x_{k+1}) - U(x_{k+1})]p(x_{k+1})}{[U((1+\varepsilon)x_k) - U(x_k)]p(x_k)} = \frac{k}{k+1}pd.$$

Thus, if $pd > 1$, then the dismal-theorem-like result appears; if $pd < 1$, then the dismal theorem disappears.

3. Expression with environmental damages

We now consider another way of obtaining some dismal-theorem-like result by revisiting the standard St. Petersburg paradox. Consider a society that faces the risk of environmental damage. The society suffers from: (i) 2 units of environmental damage with probability 1/2; (ii) 2^2 units with probability $1/(2)^2$; (iii) 2^3 units with probability $1/(2)^3$; and so on. That is, the environmental damage is 2^k units with probability $1/(2)^k$. The social welfare function is:

$$u(c,d) = \sqrt{c} - d,$$

where c is the consumption level and d is the environmental damage. Here, c is positive and fixed. It is easy to see that $EU = -\infty$ under this utility function. This is the same as the St. Petersburg paradox.

We suppose that the society puts a resource g to make the situation better. The following constraint is imposed:

$$c + g = \bar{c}.$$

Given g, we can obtain the following situation instead of the original one: (i) $2/(1+\varepsilon g)$ units of environmental damage with probability 1/2; (ii) $2^2/(1+\varepsilon g)$ units of environmental damage with probability $1/(2)^2$; (iii) $2^3/(1+\varepsilon g)$ units of environmental damage with probability $1/(2)^3$; and so on. Here, ε is strictly positive. The resulting expected social welfare is:

$$EU(\varepsilon, g) = \sqrt{\bar{c} - g} - \frac{1}{(1+\varepsilon g)}\left[\frac{1}{2}2 + \frac{1}{2^2}2^2 + \frac{1}{2^3}2^3 + \cdots + \frac{1}{2^k}2^k + \cdots\right] = -\infty.$$

In spite of this prescription, the expected social welfare is still negative infinity. However, we have

$$\frac{dEU(\varepsilon, g)}{dg} = \infty,$$

for any $\varepsilon > 0$ and $g \geq 0$. Thus, it is optimal to put all resources $\bar{c}$ into this possibility of improvements. That is, $g = \bar{c}$. Under this choice of the society, the expected social

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welfare becomes

$$EU(\varepsilon,\bar{c}) = -\frac{1}{(1+\varepsilon\bar{c})}\left[\frac{1}{2}2 + \frac{1}{2^2}2^2 + \frac{1}{2^3}2^3 + \cdots + \frac{1}{2^k}2^k + \cdots\right] = -\infty.$$

We now take the difference between $EU(\varepsilon,\bar{c})$ and the expected utility under the original situation,

$$EU(\varepsilon,\bar{c}) - EU(\varepsilon,0) = \infty,$$

where we use the same argument as that in the previous section. This implies that the government is willing to spend an extremely large amount of money to make a very small improvement. We note that a difference is that catastrophe is represented by a very small level of consumption in the original version, while it is represented by a very large level of environmental damage.

4. Concluding remarks

This paper examined Weitzman's dismal theorem, which has attracted attention in the field of climate economics and environmental economics. We showed that a conclusion similar to the dismal theorem can be obtained from a variation of Menger's version of the St. Petersburg paradox. In spite of its long history, there is no absolute resolution of the St. Petersburg paradox.[10] Although many authors have argued about the meaning and significance of the dismal theorem, it is still controversial. We believe that this controversy is due to the nature of the St. Petersburg paradox, whose resolution is still controversial.

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[10]For example, Peters (2011) recently provided a new resolution of the paradox.

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