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**A characterization of S-shaped utility functions displaying loss aversion**

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# A characterization of S-shaped utility functions displaying loss aversion\*

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## Abstract

This paper deals with utility (or value) function for *reference dependent* models. A new characterization of S-shaped utility functions displaying loss aversion is put forward. Then it is used to analyze some standard forms commonly used in the literature. It is shown that, unless some parameters' restrictions are imposed, power and exponential S-shaped utilities can lead to prefer fair symmetric games to the status quo and do not display loss aversion. Finally two new examples of simple S-shaped utility functions exhibiting loss aversion are presented.

Keywords: reference dependence utility, loss aversion.

JEL Classification: D81

AMS (2000) Classification: 91B16.

## 1 Introduction

Reference dependent theory affords a framework where rational and psychological factors explicitly enter the decision problem. Various works have proved that decisions are taken evaluating separately gains and losses rather than consider the final wealth as a whole: this happens because people differently perceive improvements or deterioration of their reference wealth (see, e.g., Kahneman and Tversky (1979), Thaler (1980), Tversky and Kahneman (1992), Kahneman et al. (1991) and Benartzi and Thaler (1995)). The observation that losses matter more than gains is defined as *loss aversion*. Furthermore, the fact that the perception of a change in wealth decreases with its distance from the reference point is termed *diminishing sensitivity* and can be modelled by utility (or value) functions that are concave for gains and convex for losses: precisely *S-shaped* utility functions. In this field some problems have not already been fixed, such as a generally accepted formal definition of loss aversion and

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its measurement. Different proposals may be found in Kahneman and Tversky (1979), Bowman et al. (1999), Köbberling and Wakker (2003) and Neilson (2002).

In standard utility theory there exist various classes of utility functions that can describe different features of the behavior towards risk (for instance CARA and CRRA functions), or that are endowed with some useful properties for dynamical programming purposes (e.g. the HARA functions). In prospect theory general results are available, but only a few functional forms of utility functions have been presented, all can be derived by modifying some standard non-S-shaped functions: the linear, the power, the exponential ones. Among them the power function can be adopted by resorting to the widely observed power law of perception. In fact, the psychological perception theory, developed by Cognitive Psychology and Psychophysics, has shown that power laws generally describe the sensorial stimuli perception: brightness, loudness, sweetness, duration, etc., and – why not? – utility.

This paper aims to present a characterization of S-shaped utilities displaying loss aversion. This characterization is then used to check the suitability of some analytical forms of utility functions. The results can be a step towards a better understanding of the tools to be employed in reference dependent expected utility theory.

I use standard notation, with  $u'(x)$  for the usual derivative with respect to  $x$  of a utility function  $u = u(x)$ . The expressions  $f(x_0^-)$ ,  $f(x_0^+)$ ,  $f(+\infty)$  and  $f(-\infty)$  are shorthands for the right and left side limits at  $x = x_0$  and the limits of a function  $f$  for  $x$  diverging to  $+\infty$  and  $-\infty$ , respectively. All functions I will employ are assumed to be smooth enough to admit the required derivatives.

## 2 Loss aversion

There exist various definitions of loss aversion. Some of them are linked each other. From Kahneman and Tversky (1979), a utility function (or value function)  $u = u(x)$  of a loss averse individual is defined on the difference  $x$  between final wealth and a reference wealth level (*reference dependent utility*) with  $u(0) = 0$  and is endowed with the following properties:

1.  $u$  is strictly increasing;
2.  $u$  is convex for  $x < 0$  and concave for  $x > 0$ , i.e. it is S-shaped;
3. fair symmetric games are refused (if compared with the status quo):  $u(x) < -u(-x)$ ,  $\forall x > 0$ ;
4.  $u'(x) < u'(-x)$ ,  $\forall x > 0$ .

I remark that the last steepness condition can be characterized in a more general sense that does not need differentiability (see by Wakker and Tversky (1993)). In the present paper, however, the differentiability is assumed. The following other definitions of loss aversion can complete the picture and provide a deeper understanding of loss aversion:

5. Köbberling and Wakker (2003) propose to define loss aversion as the property  $u'(0^-) \geq u'(0^+)$ . This allows also to define an index of loss aversion  $\lambda = \frac{u'(0^-)}{u'(0^+)}$ .
6. Neilson (2002) introduces the concept of *weak loss aversion*:  $\frac{u(z)}{z} \geq \frac{u(y)}{y}$ ,  $\forall z < 0$  and  $\forall y > 0$ .
7. Bowman et al. (1999) recognize loss aversion if  $u'(z) \geq u'(y)$ ,  $\forall z < 0$  and  $\forall y > 0$ . This properly corresponds to the *strong loss aversion* proposed in Neilson (2002).

In the next section I will try to put together all the relations above, looking for some links and transfer them into formal conditions on  $u$ .

### 3 A unified approach

Define the general reference dependent utility function  $u(x)$  as follows

$$u(x) = \begin{cases} u_+(x) = v(x), & x \geq 0 \\ u_-(x) = -v(-x) - \ell(-x), & x < 0, \end{cases} \quad (1)$$

being  $v$  and  $\ell$  continuous functions defined on  $x \geq 0$ , vanishing at  $x = 0$  and with  $v$  strictly increasing and concave:

$$v(0) = 0, v'(x) > 0, v''(x) \leq 0, \forall x > 0. \quad (2)$$

This way  $u$  is null and continuous at  $x = 0$ , with first and second derivatives

$$u'(x) = \begin{cases} v'(x), & x > 0 \\ v'(-x) + \ell'(-x), & x < 0 \end{cases}, \quad u''(x) = \begin{cases} v''(x), & x > 0 \\ -v''(-x) - \ell''(-x), & x < 0. \end{cases}$$

Now I translate the properties presented at the end of section 2 into corresponding properties on  $\ell(x)$ .

**Property 1.**  $u'(x) > 0, \forall x$ : for  $x > 0$  it is verified by assumption, whereas for  $x < 0$ , this requires  $v'(x) + \ell'(x) > 0, \forall x > 0$ .

**Property 2.** S-shapedness, i.e.  $u''(x) \leq 0, \forall x > 0$  and  $u''(x) \geq 0, \forall x < 0$ : the first part is verified by assumption; the second one requires  $\ell''(x) \leq -v''(x), \forall x > 0$ .

**Property 3.**  $u(x) < -u(-x), \forall x > 0$ : this means  $\ell(x) > 0, \forall x > 0$ .

**Property 4.**  $u'(x) < u'(-x), \forall x > 0$ : that is  $\ell'(x) > 0, \forall x > 0$ . Under definition (1) and properties (2), this property implies property 1.

**Property 5.**  $u'(0^+) \leq u'(0^-)$  means  $\ell'(0^+) \geq 0$ .

**Property 6.** Weak loss aversion may be written as

$$\sup_{x>0} \left\{ \frac{u(x)}{x} \right\} \leq \inf_{x<0} \left\{ \frac{u(x)}{x} \right\}.$$

When  $u$  is S-shaped (property 2), this is equivalent to

$$u'(0^+) \leq \lim_{x \rightarrow -\infty} \frac{u(x)}{x},$$

and also, thanks to (1),

$$\ell'(+\infty) \geq v'(0^+) - v'(+\infty). \quad (3)$$

Moreover the sign and the concavity of  $v$  (see (2)) imply that  $v'(+\infty)$  is finite and not greater than  $v'(0^+)$ . If  $v$  is not linear, condition (3) is satisfied only if  $\ell(x)$  is unbounded above for  $x \rightarrow +\infty$ . If the *Inada condition* at  $+\infty$  is verified (i.e. if  $u'(+\infty) = 0$ ), it remains to control whether the relation  $\ell'(+\infty) \geq v'(0^+) > 0$  holds.

**Property 7.** Strong loss aversion may be written as

$$\sup_{x>0} \{u'(x)\} \leq \inf_{x<0} \{u'(x)\},$$

and again, the sign and the curvature of  $u$  guarantee that this is equivalent to

$$u'(0^+) \leq u'(+\infty).$$

Thanks to definition (1), this can be written as  $v'(0^+) \leq \lim_{x \rightarrow -\infty} (v'(-x) + \ell'(-x))$ , and a condition identical to (3) is obtained. Obviously the comment following relation (3) applies here as well.

Starting from the utility function

$$u(x) = \begin{cases} u_+(x), & x \geq 0 \\ u_-(x), & x < 0, \end{cases}$$

it is easy to recover  $\ell(x)$ :

$$\ell(x) = -u_+(x) - u_-(-x), \quad x > 0.$$

So the relations summarized in table 1 may be useful in investigating the properties of a given utility function. It is clear that property 1 is implied by property 4, and that properties 6 and 7 are equivalent for S-shaped functions (for a different derivation of this last result, see Neilson (2002)). Moreover, under assumption 0, property 4 implies property 3.

The discussion above allows to state the following proposition and corollaries that synthesize the results above. Their proofs directly stem from the relations listed in table 1, where the conditions in the third column are equivalent to the corresponding property in the second one.

basic properties		
0	$u(0) = 0$	$\ell(0^+) = 0$
1	$u$ strictly increasing	$v'(x) + \ell'(x) > 0, \forall x > 0$
2	$u$ S-shaped (convex/concave)	$\ell''(x) \leq -v''(x), \forall x > 0$
3	$u(x) < -u(-x), \forall x > 0$	$\ell(x) > 0, \forall x > 0$
4	$u'(x) < u'(-x), \forall x > 0$	$\ell'(x) > 0, \forall x > 0$
additional properties		
5	$u'(0^+) \leq u'(0^-)$	$\ell'(0^+) \geq 0$
6	weak loss aversion (provided 1 and 2)	$\ell'(+\infty) \geq v'(0^+) - v'(+\infty)$
7	strong loss aversion (provided 1 and 2)	$\ell'(+\infty) \geq v'(0^+) - v'(+\infty)$

Table 1: Properties

**Proposition 1** *Assume that the continuous utility function*

$$u(x) = \begin{cases} u_+(x), & x \geq 0 \\ u_-(x), & x < 0, \end{cases} \quad (4)$$

*satisfies  $u(0) = 0$  and let  $u_+(z)$  and  $u_-(-z)$  be twice differentiable for  $z > 0$ . Define the function*

$$\ell(x) = -u_+(x) - u_-(-x), \quad x > 0. \quad (5)$$

*Then the function  $u$  fulfils the property 1 to 4 if and only if  $\ell$  is positive, increasing, vanishing at  $x = 0^+$ , and its second derivative satisfies*

$$\ell''(x) \leq -u_+''(x), \quad \forall x > 0.$$

*Moreover, for S-shaped utilities weak and strong loss aversion are equivalent and hold if and only if*

$$\ell'(+\infty) \geq u_+'(0^+) - u_+'(+\infty).$$

**Corollary 2** *Provided that properties 1 to 4 are satisfied,  $u$  displays weak or strong loss aversion if and only if one of the two following cases occurs: either  $u_+$  given in (4) is linear, or  $\ell$  is unbounded above (i.e.  $\ell(+\infty) = +\infty$ ). In any case,  $u_-(x)$  must be unbounded below:  $u_-(-\infty) = -\infty$ .*

**Corollary 3** *Provided that properties 1 to 4 are satisfied, if the Inada condition  $u'(+\infty) = 0^+$  holds, then  $u$  enjoys weak or strong loss aversion if and only if  $\ell'(+\infty) \geq v'(0^+)$ .*

The proposition 1 can be interpreted as a characterization of S-shaped utility functions displaying loss aversion. Moreover, given a utility function, it provides a tool helping the check of S-shapedness and loss aversion. For instance, a simple linear  $\ell(x) = \lambda x$ , with  $\lambda > 0$ , satisfies the properties 1 to 5. In addition, if the coefficient is greater enough ( $\lambda \geq u_+'(0^+)$ ), properties 6 and 7 are verified as well.

power S-shaped	
$\ell(0^+) = 0$	✓
$\ell(x) > 0$	only for $x > \lambda^{\frac{1}{\alpha-\beta}}$
$\ell'(x) > 0$	only for $x > \left(\lambda \frac{\beta}{\alpha}\right)^{\frac{1}{\alpha-\beta}}$
$\ell''(x) \leq -u''_+(x)$	✓
$\ell'(+\infty) \geq u'_+(0^+) - u'_+(+\infty)$	no

Table 2: Power function

## 4 Some standard S-shaped utility functions

Proposition 1 can be applied to focus the properties of some S-shaped utility functions proposed in literature, namely: the power utility, the kinked linear utility, and the exponential utility.

### 4.1 The power S-shaped utility function

The power S-shaped utility function (Benartzi and Thaler (1995), Thaler et al. (1997), Fennma and Van Assen (1999), Tversky and Kahneman (1992) and Wakker and Zank (2002))

$$u(x) = \begin{cases} x^\alpha, & x \geq 0 \\ -\lambda(-x)^\beta, & x < 0, \end{cases} \quad (6)$$

with  $0 < \alpha \leq \beta < 1$  and  $\lambda \geq 1$ , is associated, through proposition 1, to the following

$$\ell(x) = -x^\alpha + \lambda x^\beta, \quad x > 0.$$

As table 2 shows, the utility function (6) is continuous, increasing and S-shaped, but does not fulfil some loss aversion features. Namely, although  $u'(0^+) \leq u'(0^-)$ , the first derivative satisfies  $u'(x) < u'(-x)$  only for  $0 < x < \left(\lambda \frac{\beta}{\alpha}\right)^{\frac{1}{\alpha-\beta}}$ ; moreover, fair symmetric games are not refused if the stake is small enough (i.e. if  $x < \lambda^{\frac{1}{\alpha-\beta}}$ ).

Kahneman and Tversky (1979) estimated the parameter values  $\alpha = \beta = 0.88$  and  $\lambda = 2.25 > 1$ . With  $\alpha = \beta < 1$  and  $\lambda \geq 1$  the function  $\ell(x)$  becomes  $\ell(x) = (\lambda - 1)x^\alpha$ ,  $x > 0$  and it is easy to check (see table 3) that in this case  $u$  displays all properties but weak and strong loss aversion.

### 4.2 Kinked line

A special case of the power utility discussed above is the kinked linear utility function

$$u(x) = \begin{cases} x, & x \geq 0 \\ \lambda x, & x < 0 \end{cases}$$



<b>power S-shaped <math>\alpha = \beta</math></b>	
$\ell(0^+) = 0$	✓
$\ell'(x) > 0$	✓
$\ell''(x) \leq -u''_+(x)$	✓
$\ell'(+\infty) \geq u'_+(0^+) - u'_+(+\infty)$	no

Table 3: Power function with equal exponents

<b>kinked line</b>	
$\ell(0^+) = 0$	✓
$\ell'(x) > 0$	✓
$\ell''(x) \leq -u''_+(x)$	✓
$\ell'(+\infty) \geq u'_+(0^+) - u'_+(+\infty)$	✓

Table 4: Kinked line

with  $\lambda \geq 1$ . It can be obtained from the power utility (6) with  $\alpha = \beta \rightarrow 1$ . In Benartzi and Thaler (1995) and in Thaler et al. (1997) this function is presented as an introductory tool; in Shalev (2000) it is used with only formal differences; in Gneezy and Potters (1997) this function is implicitly used (see section II). The corresponding  $\ell(x)$  is

$$\ell(x) = x(\lambda - 1), \quad x > 0,$$

which is linear. Table 4 shows that the kinked linear utility function, although very simple, enjoys all the required properties.

### 4.3 Exponential

The exponential S-shaped utility function

$$u(x) = \begin{cases} \frac{1 - e^{-\alpha x}}{\alpha}, & x \geq 0 \\ \lambda \frac{e^{\beta x} - 1}{\beta}, & x < 0, \end{cases} \quad (7)$$

with  $0 < \alpha \leq \beta$  and  $\lambda \geq 1$ , is associated, through proposition 1, to the following

$$\ell(x) = -\frac{1 - e^{-\alpha x}}{\alpha} + \lambda \frac{1 - e^{-\beta x}}{\beta}, \quad x > 0.$$

The function (7) is just in the form presented in Köbberling and Wakker (2003). In Schmidt and Zank (2002) the exponential function is used without the normalization here introduced. Table 5 shows that the utility function (6) is continuous, increasing and S-shaped, but does not fulfil some loss aversion features. Namely, although

<b>exponential S-shaped</b>	
$\ell(0^+) = 0$	✓
$\ell(x) > 0$	only for $x < \bar{x}$ if $\frac{\lambda\alpha}{\beta} < 1$ , or $\forall x > 0$ if $\frac{\lambda\alpha}{\beta} \geq 1$
$\ell'(x) > 0$	only for $x < \frac{\ln \lambda}{\beta - \alpha}$ if $\alpha < \beta$ and $\lambda > 1$ , or $\forall x > 0$ if $\alpha = \beta$ and $\lambda > 1$
$\ell''(x) \leq -u''_+(x)$	✓
$\ell'(+\infty) \geq u'_+(0^+) - u'_+(+\infty)$	only if $\lambda \geq \beta \frac{\alpha+1}{\alpha}$

Table 5: Exponential function

$u'(0^+) \leq u'(0^-)$ , the first derivative satisfies  $u'(x) < u'(-x)$  only for  $x > \frac{\ln \lambda}{\beta - \alpha}$  if  $\lambda > 1$  and  $\alpha < \beta$ , or  $\forall x > 0$  if  $\lambda > 1$  and  $\alpha = \beta$ . Moreover, fair symmetric games are not refused if the stake is large (i.e. if  $x > \bar{x}$ , where  $\bar{x}$  is the solution, not obtainable in an explicit way, of  $\ell(x) = 0$ ).

## 5 Two new examples

In section (4) three classes of utility functions have been explored, obtaining the following results:

- Unless the two exponents  $\alpha$  and  $\beta$  of (6) are equal, power functions can not describe the behavior of an individual who always refuses fair symmetric games.
- Moreover, if  $\alpha < \beta < 1$ , the fair symmetric games with a small stack are more valuable than the status quo.
- In any case power functions (6) are not feasible to model neither weak nor strong loss aversion as defined in property 6 and 7.
- Kinked linear utility fulfil all the required properties, but it can not describe the behavior of an individual who is risk averse over gains and/or risk seeking over losses.
- Unless if in (7)  $\alpha = \beta$  and  $\lambda > 1$ , exponential functions show a disappointing fact: fair symmetric games with a large stack are more valuable than the status quo. This flaw can be overcome by restricting the admissible values of  $x$  on the interval where this behavior does not appear.
- In any case exponential functions (7) are not feasible to model neither weak nor strong loss aversion.

In order to overcome some shortcomings of the standard functions above, I present below two easy new examples of S-shaped utility functions displaying loss aversion. This shows that it is an easy matter to find a function with the desired properties.

<b>sub-odd function</b>	
$\ell(0^+) = 0$	✓
$\ell'(x) > 0$	$\lambda > 1$
$\ell''(x) \leq -u''_+(x)$	$\lambda > 0$
$\ell'(+\infty) \geq u'_+(0^+) - u'_+(+\infty)$	$\lambda \geq \frac{v'(0^+)}{v'(+\infty)}$

Table 6: Sub-odd function

### 5.1 *Sub-odd function*

Modifying a proposal of Köbberling and Wakker (2003), the following utility function can be defined<sup>1</sup>:

$$u(x) = \begin{cases} v(x), & x \geq 0 \\ -\lambda v(-x), & x < 0, \end{cases} \quad (8)$$

and named *sub-odd* as it recalls an odd function. Thanks to (5) it is straightforward to find

$$\ell(x) = (\lambda - 1)v(x), \quad x > 0,$$

and to verify that property 1 to 4 are fulfilled if and only if  $\lambda > 1$ . Moreover, if  $\lambda \geq \frac{v'(0^+)}{v'(+\infty)}$ , then weak and strong loss aversion are satisfied as well. From table 6 it is clear that an S-shaped utility of the form (8) which satisfies the Inada condition at  $+\infty$  can not display neither weak nor strong loss aversion.

### 5.2 *Loss-linear function*

A simple way to set up a candidate S-shaped loss averse utility is to merge a concave function  $v(x)$  for  $x \geq 0$  and a linear one for  $x < 0$ :

$$u(x) = \begin{cases} v(x), & x \geq 0 \\ \lambda x, & x < 0, \end{cases}$$

so that the corresponding function  $\ell$  is

$$\ell(x) = -v(x) + \lambda x, \quad x > 0.$$

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<sup>1</sup>The function (8) stems from the *basic function* (in the sense of Köbberling and Wakker (2002))

$$u(x) = \begin{cases} v(x), & x \geq 0 \\ -v(-x), & x < 0, \end{cases}$$

which is S-shaped and smooth even at 0.

loss-linear function	
$\ell(0^+) = 0$	✓
$\ell'(x) > 0$	$\lambda > v'(0^+)$
$\ell''(x) \leq -u''_+(x)$	✓
$\ell'(+\infty) \geq u'_+(0^+) - u'_+(+\infty)$	$\lambda \geq v'(0^+)$

Table 7: Loss-linear function

Thanks to the sign and the concavity of  $u_+$ , the equality  $\sup_{x>0} v'(x) = v'(0^+)$  follows, thus properties 1 to 4 are satisfied if and only if  $\lambda > v'(0^+)$ . In this case the weak or strong loss aversion are displayed as well, as in table 7.

## 6 Conclusion

Many definitions for S-shaped utility functions to describe loss aversion are available. I have compared them and clarified their hierarchy. In this scheme of things I have put forward a new characterization of S-shaped utility functions (proposition 1) that allow to deal with S-shapedness and loss aversion in an unified framework. In order to get loss aversion under various definitions, I have shown how to constrain the parameters of the most commonly used S-shaped utility functions (linear, power, and exponential utility). Finally I have presented two simple new examples of loss averse utility functions. I hope that my results can improve the understanding of the tools to be employed in reference dependent expected utility theory.

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