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Prospect Theory and the Newsvendor Problem

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The newsvendor problem is a fundamental decision problem in operations management. Various independent experimental studies in laboratory settings have shown similar deviations from the theoretical optimal order quantity. We clarify that Prospect Theory, a prevalent framework for decision making under uncertainty, cannot explain the consistent empirical findings.

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1. Introduction

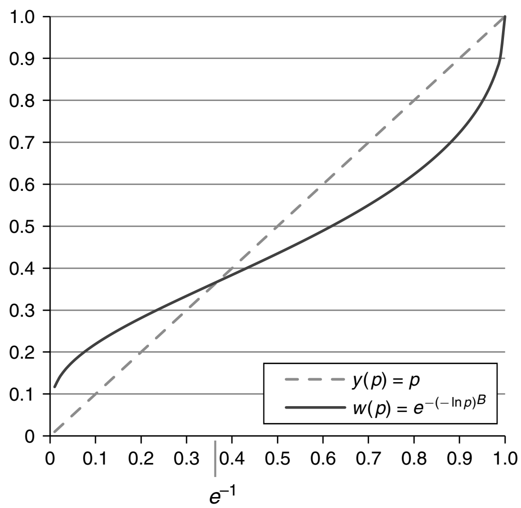
The newsvendor problem is a classic example of decision making under uncertainty. It describes a single-period inventory problem in which items are purchased from a wholesaler at c dollars per unit to be resold at a retailer for r dollars per unit. Retail demand, uncertain at the time of purchase from the wholesaler, is characterized by a cumulative distribution function $F(\cdot)$. For a risk-neutral newsvendor, the optimal order quantity, q^*, is the well-known "critical fractile solution" that solves $F(q^*) = (r-c)/r$.

Extensions of the basic newsvendor problem have examined various behavioral considerations in choosing q. For example, under an expected utility theory (EUT) framework, Eeckhoudt et al. (1995) show that a risk-averse newsvendor would order fewer items than a risk-neutral newsvendor. Agrawal and Seshadri (2000) examine the risk-averse newsvendor who also decides on the selling price and find that the risk-averse newsvendor may order more or less than the risk-neutral newsvendor, depending on how price affects the demand distribution. Wang et al. (2009) raise concerns about whether an EUT framework is even appropriate in this setting because it would lead to the anomalous result that a risk-averse newsvendor would order less as the selling price increases.

Of course, EUT has been called into question as a descriptive framework for decision making under uncertainty ever since the famous Allais paradox (Allais 1953). The development of Prospect Theory (PT) (Kahneman and Tversky 1979) resolved this paradox and alleviated some other issues surrounding EUT. PT differs from EUT in the following important respects: (1) outcomes are valued as gains or losses relative to a current reference point instead of final levels of wealth; (2) the disutility of a loss is greater than the utility of an equivalent gain (referred to as *loss aversion*); (3) decision makers are risk averse over gains but risk seeking over losses; (4) the value of an outcome is weighted not by the probability of its occurrence, p, but rather by a weight of the probability, $w(p)$, where $w(p) > p$ for p near 0 and $w(p) < p$ for p near 1 (i.e., small probabilities are overweighted and large probabilities are underweighted, which is referred to as the *possibility effect* and the *certainty effect*, respectively; see Figure 1); and (5) there is an editing phase in which outcomes and their probabilities may be simplified before applying the evaluation phase (Kahneman and Tversky 1979). In addition to risk aversion, the second item, loss aversion, has also been considered in the newsvendor setting; both Schweitzer and Cachon (2000) and Wang et al. (2009) show that a loss-averse newsvendor would order fewer items than a risk-neutral newsvendor.

There has been significant interest in the past decade or so in how people make operational decisions in practice and what might explain their behavior. To our knowledge, the earliest work in this area is Schweitzer and Cachon (2000), who study how participants in a laboratory respond when faced with a newsvendor problem. Subjects chose order quantities under different experimental setups (i.e., demand distribution, purchase price, resale price). The results demonstrated the following insights: When the optimal order quantity, q^*, of a (risk-neutral) newsvendor is less than the average, μ, of a symmetric demand distribution (i.e., $c > 0.5r$, or what the authors refer to as the "low-profit" regime), people tend to choose an order quantity $\hat{q}$ such that $q^* < \hat{q} < \mu$. Conversely, when $q^* > \mu$ (i.e., $c < 0.5r$, the "high-profit" regime), people often choose $\hat{q}$ such that $\mu < \hat{q} < q^*$. Other

Figure 1 **Example of PT Weighting Function**



Notes. The solid curve, $w(p)$, shows a typical weighting function from PT ($\beta = 0.5$ in the figure), along with the usual weighting function of EUT ($y(p) = p$) shown by the dashed line. In this example, the PT weighting function overweights (underweights) probabilities less (greater) than e^{-1}.

studies have independently confirmed similar findings (Benzion et al. 2008, Bolton and Katok 2008, Kremer et al. 2010).

In addition to observing *which* order quantity subjects choose in various settings, there have been attempts to understand *why* subjects choose such order quantities. For example, Gavirneni and Isen (2009) record and analyze the responses of subjects who verbalized their thought processes so as to understand explicitly how they arrived at their newsvendor order quantity. Schweitzer and Cachon (2000) discuss several stylized models of decision making to investigate whether each could implicitly explain their empirical findings. The authors note that although PT could explain the observed behavior for the case when both positive and negative profits are possible (because of the PT assumption of risk-seeking behavior in the domain of losses), it cannot explain the findings when only positive profits are possible (which they ensure through their choice of newsvendor problem parameters). Their reasoning is that in the domain of gains and under the standard PT assumption of risk aversion for positive outcomes, the newsvendor would order less than the risk-neutral one (as demonstrated in Eeckhoudt et al. 1995). Ultimately, they conclude that their findings could be explained by a desire to reduce ex post inventory error (i.e., the difference between what is ordered and the demand that is realized) or a by a heuristic in which subjects anchor (to the mean) and then insufficiently adjust their quantities toward q^*.

In an extension to the behavioral models considered in Schweitzer and Cachon (2000), Ho et al. (2010) propose another behavioral theory and parameterize it based on empirical data. A key feature of their model is that it incorporates a reference-dependent psychological disutility for experiencing a stockout or surplus after demand is realized and compared with the order quantity. They find that their model predicts order quantities better than a model that minimizes ex post inventory error (Schweitzer and Cachon 2000) and can explain the stronger pull-to-center bias of the high-profit conditions compared with the low-profit conditions.

Su (2008) presents a bounded rationality model of decision making to explain the empirical findings of the newsvendor problem (specifically, of Bolton and Katok 2008). The boundedly rational newsvendor in this setting maximizes expected profit but cannot determine the optimal order quantity q^*. Instead, her order quantity is described probabilistically so that order quantities with an expected profit that is closer (farther) from the expected profit of q^* have a higher (lower) chance of being selected. Assuming a uniformly distributed demand density, the author shows analytically that the expected order quantity of the boundedly rational newsvendor is greater (less) than q^* when $q^* < (>)\mu$. Therefore, the boundedly rational model could explain how the *average* q across subjects is consistent with empirical findings reported in the literature. However, it appears that this particular model is not a good description of decision making at the individual level because it significantly overestimates the proportion of subjects that would order less than q^* in the low-profit regime or more than q^* in the high-profit regime (Katok 2011). Furthermore, as discussed in Kremer et al. (2010), the form of this random choice model suggests that the choice behavior should depend only on the relative expected profits of the different decisions and not on the context in which they are presented. However, the results of their experiments suggested otherwise.

Our objective here is to revisit what PT can or cannot say about the empirical findings of the newsvendor problem. Given that PT is one of the most popular frameworks for modeling decision making under uncertainty, we believe it deserves a careful and comprehensive treatment in evaluating what is also perhaps the most well-known operations management decision under uncertainty. Previous authors have considered the first three features of PT mentioned above, but to our knowledge, no one has considered the last two features: the weighting of probabilities and the editing of prospects. Because the editing of prospects is not often well defined and possibly depends heavily on the context, we focus on the weighting of probabilities; we comment further on editing in §4.

The overweighting (underweighting) of small (large) probabilities is an integral component of the original PT and has a major effect on choice behavior.

For example, the nonlinear weighting function helps explain why people would be risk seeking when there is a low probability of a large payoff (e.g., lottery tickets) or risk averse when there is a low probability of incurring a large expense (e.g., insurance) (Prelec 1998). The weighting function is also specifically the feature of PT that helps resolve the equity premium puzzle (Mehra and Prescott 1985) as well as the Allais paradox (similar to other research in nonexpected utility theory; see Rabin 2003).

We confirm earlier sentiments that PT cannot explain the experimental data by showing that a decision maker applying PT in the low-profit regime would necessarily order less than the usual newsvendor order quantity, q^*. We also show that for most commonly cited parameters for utility functions and probability weighting functions, the decision maker applying PT in the high-profit regime would order more than q^*. This further strengthens the argument that PT cannot explain peoples' ordering decisions because it predicts the *opposite* of what they do (which is to order more than q^* in the low-profit regime and less than q^* in the high-profit regime).

2. The Newsvendor Problem as a Choice Among Prospects

The development of EUT and PT grew out of studies of how people choose from among different gambles (or "prospects" in the language of PT). Although it is not commonly described in such terms, the newsvendor problem is a choice from among gambles. Consider the following newsvendor setup of Schweitzer and Cachon (2000), which ensures that the newsvendor has a positive profit, regardless of the demand outcome. Demand for an item is (discretely) uniformly distributed between 901 and 1,200. The resale price of the item (r) is \$12, and the purchase price (c) is either \$9 (in the low-profit case) or \$3 (in the high-profit case).

The traditional notation for a prospect is $(x_1, p_1; x_2, p_2; \ldots; x_n, p_n)$, where x_i is the ith possible outcome, which occurs with probability p_i. Table 1 displays this information for each order quantity between 901 and 1,200 (in the low-profit case, where $c = 9$ and $r = 12$). For example, the order quantity $q = 901$ can be represented by the prospect $(2{,}703, 1)$; the newsvendor will certainly sell the 901 papers ordered at a profit of 3 each, for a total profit of \$2,703, which he earns with a probability of one. Note that we made an implicit editing assumption; because there are 300 different possible demand scenarios, one might technically represent the prospect as $(2{,}703, 0.0033; 2{,}703, 0.0033; \ldots; 2{,}703, 0.0033)$ for the profit realized if demand comes in at $901, 902, \ldots, 1{,}200$. Instead, we aggregated all the probabilities for identical outcomes. (The final profit shown for each q in Table 1 is associated with probability demand $\geq q$.) For example, the order quantity $q = 902$ is represented by the prospect $(2{,}694, 0.0033; 2{,}706, 0.9967)$ because if demand comes in at 901 (with probability $1/300$), the newsvendor profits \$2,694, and if demand comes in greater than or equal to 902 (with probability $299/300$), the newsvendor profits \$2,706.

2.1. Evaluating Prospects

The earliest version of PT, known as the Original Prospect Theory (OPT), focused entirely on prospects with at most two nonzero outcomes, x_1 and x_2, which occur with probabilities p_1 and p_2, respectively (Kahneman and Tversky 1979). The evaluation of the prospect is then calculated as

$$V(x_1, p_1; x_2, p_2) = u(x_1)w(p_1) + u(x_2)w(p_2), \tag{1}$$

where $u(x)$ is the utility associated with outcome x and $w(p)$ is the weight associated with probability p.

Table 1 **The Newsvendor Problem of Schweitzer and Cachon (2000), Represented as an Explicit Choice Among Prospects ($c = \$9$, $r = \$12$; Demand Is a Discrete Uniform Distribution Between 901 and 1,200)**

If $q =$														
901		902		903		904		...	1,198		1,199		1,200	
Profit	Prob	Profit	Prob	Profit	Prob	Profit	Prob		Profit	Prob	Profit	Prob	Profit	Prob
2,703	1	2,694	0.0033	2,685	0.0033	2,676	0.0033		30	0.0033	21	0.0033	12	0.0033
		2,706	0.9967	2,697	0.0033	2,688	0.0033		42	0.0033	33	0.0033	24	0.0033
				2,709	0.9933	2,700	0.0033		54	0.0033	45	0.0033	36	0.0033
						2,712	0.99		66	0.0033	57	0.0033	48	0.0033
									.		.		.	
									.		.		.	
									3,582	0.0033	.		.	
									3,594	0.01	3,585	0.0033	.	
											3,597	0.0067	3,588	0.0033
													3,600	0.0033

Note. For example, order quantity $q = 901$ is certain to give a profit of \$2,703, $q = 902$ is equivalent to a gamble that pays \$2,694 with probability 1/300 and \$2,706 with probability 299/300, and so on.

Extending (1) to prospects with many outcomes can be problematic, especially when many of them have small probabilities (Fennema and Wakker 1997). As seen in Figure 1 and Table 1, the issue of overweighting several small probabilities would arise if we use OPT to evaluate the newsvendor problemsince all outcomes associated with a given order quantity have a probability of 0.0033, except for the largest outcome.

To better handle the evaluation of multioutcome prospects, Tversky and Kahneman (1992) develop an updated form of PT, known as the Cumulative Prospect Theory (CPT). In CPT, if all possible outcomes are positive, they are weighted by differences in the weights of cumulative probabilities, as shown in the CPT valuation of a prospect with n possible outcomes:

$$V(x_1, p_1; x_2, p_2; \ldots; x_n, p_n) = \sum_{i=1}^{n} u(x_i)\left[w\left(\sum_{j=i}^{n} p_j\right) - w\left(\sum_{j=i+1}^{n} p_j\right)\right]. \quad (2)$$

As an example, the CPT evaluation of the prospect $q = 903$ in Table 1 is

$$\begin{aligned} V(2{,}685, 0.0033; 2{,}697, 0.0033; 2{,}709, 0.9933) &= \sum_{i=1}^{n} u(2{,}685)[w(1) - w(0.9967)] \\ &\quad + u(2{,}697)[w(0.9967) - w(0.9933)] \\ &\quad + u(2{,}709)w(0.9933). \end{aligned} \quad (3)$$

The CPT evaluation of prospects involving both negative and positive outcomes is handled differently, but note that we use a newsvendor problem setup that can only result in positive profits. We refer the reader to Tversky and Kahneman (1992) for more on the case of mixed-outcome prospects.

We apply models of utility and weighting functions that are commonly seen in the PT literature. For utilities, we use the power utility function, $u(x) = x^{\alpha}$ $(0 < \alpha < 1)$ for $x \geq 0$ (for example, see Camerer and Ho 1994, Tversky and Kahneman 1992, Wu and Gonzalez 1996). We use the probability weighting function proposed by Prelec (1998), $w(p) = e^{-(-\ln p)^{\beta}}$ $(0 < \beta < 1)$. This function has several desirable theoretical properties, is widely accepted, and has strong empirical evidence. Although there are several other forms of utility and weighting functions discussed in the literature, Stott (2006) fits several combinations of them to experimental data and finds that the model with the best explanatory power used the power utility function and the Prelec weighting function. Therefore, we focus on these functional forms.

In what follows, it will be helpful to characterize the different order quantities a choice model would predict relative to the usual newsvendor solution of the low-profit and high-profit scenarios (which we label q^*_{LP} and q^*_{HP}, respectively). Schweitzer and Cachon (2000) find that subjects chose what we will call the RL ("right/left") combination. That is, in the low-profit case, they chose $q > q^*_{\mathrm{LP}}$, and in the high-profit case, they chose $q < q^*_{\mathrm{HP}}$. They then ruled out PT as an explanation for their empirical findings because all possible profits were positive, people are risk averse over gains, and a risk-averse utility function would imply an LL solution. (Optimal order quantities for the risk averse newsvendor that are to the left of q^*_{LP} in the low-profit situation and are also to the left of q^*_{HP} in the high-profit situation). However, this only considers the utility function of PT and ignores the effect of the weighting function. To evaluate a prospect, one needs both.

We consider the combined effect of risk aversion and nonlinear probability weighting through the continuous form of CPT (see He and Zhou 2011 for another example that uses the continuous form of CPT) and denote the valuation of an order quantity q by $L(q)$. Assuming nonnegative profits, we have

$$L(q) = \int_0^q (rx - cq)^{\alpha}[-w'(\bar{F}(x))]\,dx + [q(r-c)]^{\alpha} w(\bar{F}(q)), \quad (4)$$

where $w'()$ indicates $(d/dx)w()$. The above expression merits a short discussion. First of all, note that when $\alpha = 1$ and $\beta = 1$, Equation (4) is the usual risk-neutral newsvendor expression. When $\alpha < 1$ and $\beta = 1$, $L(q)$ describes the risk-averse variant of the newsvendor expression. When $\alpha < 1$ and $\beta < 1$, $L(q)$ continues to have useful properties such as concavity and differentiability (almost everywhere if the underlying demand is discrete). The former can be verified directly by taking the second derivative or by noting that $L(q)$ is an infinite sum of concave functions that are positively weighted. Alternatively, one notices from Equation (2) that the newsvendor valuation of an order quantity in a discrete version of CPT is concave because it is a finite sum of positively weighted concave functions. The continuous variant described by $L(q)$ is a limit of such functions. If one assumes that q is from a compact set, we have $L(q)$ as the limit of a sequence of uniformly converging concave functions, which is concave.

Our next result establishes that in the low-profit regime with nonnegative profits, PT indeed cannot explain the empirical results of ordering more than q^*_{LP} when $0 < \alpha \leq 1$ and $0 < \beta \leq 1$. In the spirit of Schweitzer and Cachon (2000), we ensure nonnegative profits by assuming $rx - cq > 1$ for any combination of realized demand, x, and order quantity, q. Denoting the minimum and maximum demand by $d_{\min}$ and $d_{\max}$ and noting that one would never order more than the maximum possible demand, we assume $rd_{\min} - cd_{\max} > 1$. For technical reasons in the proof, we require the inequality ">1" rather than "≥ 0." (In the experiments of Schweitzer and Cachon 2000, the smallest possible profit was $12(901) - 9(1{,}200) = 12$.) Let q^*_{PT} denote the optimal order quantity based on the PT evaluation in (4) for arbitrary α and β.

Proposition 1. *Let $0 < \alpha \leq 1$ and $0 < \beta \leq 1$ for the utility function $u(x) = x^\alpha$ and weighting function $w(p) = e^{-(-\ln p)^\beta}$, respectively. Suppose positive profits are guaranteed through the condition $rd_{\min} - cd_{\max} > 1$ and that $c/r > 0.5$ (i.e., the newsvendor is in the low-profit regime). Then $q^*_{\mathrm{PT}} \leq q^*_{\mathrm{LP}}$.*

Proof. Let $q^*(\alpha, \beta)$ maximize (4) for a given combination of α and β. First we show that when $\alpha = 1$, $q^*(\alpha, \beta)$ increases in β. Then we show that for any β, $q^*(\alpha, \beta)$ increases in α. Taking the derivative of (4) with respect to q, we obtain

$$L'(q) = \int_0^q c\alpha(rx - cq)^{\alpha-1} w'(\bar{F}(x))\, dx + \alpha q^{\alpha-1}(r-c)^\alpha w(\bar{F}(q)). \tag{5}$$

It is easy to show that when $\alpha = 1$, the unique maximizing $q^*(\alpha, \beta)$ of (4) is obtained as the solution of

$$\bar{F}(q) = e^{-(-\ln(c/r))^{1/\beta}}. \tag{6}$$

Taking the derivative of (6) with respect to β, we have

$$\frac{d}{d\beta}\bar{F}(q) = e^{-(-\ln(c/r))^{1/\beta}}(-1)\left(-\ln\frac{c}{r}\right)^{1/\beta} \cdot \ln\left(-\ln\frac{c}{r}\right)(-\beta)^{-2}. \tag{7}$$

It is easy to check that (7) < 0 if $0.5 < c/r < 1$. The proof follows from the monotonicity of $F(\cdot)$.

Now fix an arbitrary $0 < \beta \leq 1$. We show $q^*(\alpha, \beta)$ increases in α. Taking the derivative of (5) with respect to α yields

$$\frac{d}{d\alpha}L'(q) = \int_0^q \left[w'(\bar{F}(x))c(rx - cq)^{\alpha-1}[1 + \alpha\ln(rx - cq)]\right] dx + \frac{w(\bar{F}(q))}{q} q^\alpha (r-c)^\alpha [1 + \alpha \ln(q(r-c))]. \tag{8}$$

Since the weighting function $w()$ and its first derivative are nonnegative, $rx - cq > 1$ (by assumption), and $r > c$, it follows that $(d/d\alpha)L'(q)$ is nonnegative, and thus $q^*(\alpha, \beta)$ increases in α. Therefore, for $\alpha_2 \leq \alpha_1 = 1$, it follows that $q^*(\alpha_2, \beta) \leq q^*(\alpha_1, \beta)$.

The above results imply that for $\alpha_2 \leq \alpha_1 = 1$ and $\beta_2 \leq \beta_1 = 1$, $q^*(\alpha_2, \beta_2) \leq q^*(\alpha_1, \beta_1) = q^*_{\mathrm{LP}}$ (the usual newsvendor optimal order quantity for the low-profit regime). □

3. Numerical Experiments

Here, we evaluate how various combinations of utility (α) and weighting (β) parameters affect optimal order quantities in the low- and high-profit situations. We use the same newsvendor setup Schweitzer and Cachon (2000) consider, in which only positive profits can be realized: Demand is (discrete) uniform between 901 and 1,200, the resale price of a paper is \$12, and the purchase price is \$9 (in the low-profit setting) or \$3 (in the high-profit setting). These parameters imply $q^*_{\mathrm{LP}} = 975$ and $q^*_{\mathrm{HP}} = 1{,}125$. We test α values of 0.37 (Camerer and Ho 1994), 0.52 (Wu and Gonzalez 1996), and 0.88 (Tversky and Kahneman 1992); β values of 0.60, 0.74, and 0.88. (Wu and Gonzalez 1996 report a pooled estimate of 0.74, with a standard error of 0.14, so we test 0.74 ± 0.14.)

Recall that Schweitzer and Cachon (2000) had ruled out PT as an explanation for the RL empirical results of this newsvendor setup because risk aversion (alone) would indicate an LL solution (as demonstrated in Eeckhoudt et al. 1995). In Proposition 1, we demonstrated that risk aversion combined with the weighting function guarantees an optimal order quantity to the left of the usual newsvendor order quantity in the low-profit regime. Moreover, examining the high-profit regime solutions based on the combination of risk aversion and weighting function (see Table 2), we find that every solution except for one is to the right of the usual newsvendor order quantity in the high-profit regime. Since risk aversion pulls solutions to the left, the weighting function in these cases has a greater effect on pushing solutions to the right (in the high-profit regimes only). Therefore, in some sense, PT is even more at odds with empirical findings than previously thought because

Table 2 **Optimal Order Quantities Under Different Combinations of α and β When Applying CPT Evaluations of the Schweitzer and Cachon (2000) Experiments**

Utility function	Weighting function	Order quantity		
Alpha	Beta	LP	HP	Type
0.37	0.60	933	1,136	LR
	0.74	947	1,129	LR
	0.88	960	1,124	LL
0.52	0.60	934	1,139	LR
	0.74	948	1,131	LR
	0.88	961	1,125	LR
0.88	0.60	935	1,145	LR
	0.74	950	1,136	LR
	0.88	964	1,129	LR

Notes. The "Type" column indicates whether the low- and high-profit solutions are LL or LR. (Proposition 1 rules out the possibility of RL or RR solutions.) For example, when $(\alpha, \beta) = (0.37, 0.74)$, a LR solution results; the low-profit order quantity of 947 is to the left of the risk-neutral optimal of 975; and the high-profit order quantity of 1,129 is to the right of the risk-neutral optimal of 1,125.

it predicts LR solutions rather than the RL solutions found empirically.

4. Discussion

In our analysis, we have used a rigorous framework to show that PT indeed cannot explain the observations in the behavioral operations literature regarding the newsvendor problem. This leads to the natural question of why PT, a well-known and widely accepted framework for decision making under uncertainty, may not apply to a fundamental operations management problem. It may be useful to revisit the problems that motivated the development of PT. Often, these were choices between simple gambles involving just two chance outcomes. The newsvendor problem, however, involves many chance outcomes in its explicit form, and therefore the observed results may be affected by the framing of the problem and how subjects edit the problem information. We are not aware of other work that examines how a PT-based evaluation compares with empirical findings for decisions involving more than a few chance outcomes. This may warrant further consideration given the mismatch between what PT predicts and how people actually behave in an important decision problem under uncertainty.

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