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A Further Extension of Osuna's Model for Psychological Stress

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Abstract

In 1985 Osuna presented a mathematical model to describe how stress is built up by an individual waiting for a service to take place. It can be a customer in a queuing system (or a passenger at an air terminal or train station). That study included an analysis of the issue of when to announce service in such a way as to minimize stress. Here we present an extension of the original model to include the situation in which the customer has a maximum time (personal threshold) below which she/he does not build up stress, and once that threshold is reached, the customer begins to accumulate stress. We shall explore the properties of the accumulated stress in this case, and we will show that psychological stress for waiting can be reduced by appropriately announcing when service is to occur, and that the optimal announcement time will depend on both, the personal threshold and the service time. In the case of waiting passengers, we can develop optimal policies for the time to provide them with information about the departure time of their delayed flight or the arrival time of their train, and to reduce the accumulated stress of waiting. The results can be applied to any queuing system in which the system manager has the resources for providing users with information regarding the time they will have to wait.

Keywords: waiting time, stress accumulation, psychological cost of waiting

1 Introduction and Preliminaries

In the first part of this introduction we describe the problem and the contents of the paper, whereas in the second we gather some mathematical preliminary results.

1.1 Introductory remarks

In Osuna (1985), one of us proposed a mathematical model to describe the build up of psychological stress, and particularized it to the case of a customer that has to wait in a queuing system before being served. In any physical or psychological (emotional) stressing situation, there are two factors involved: the intensity of the stimulus and the time that the stimulus acts on the subject. As a result of this situation there will be what we call *accumulated stress*. This accumulated stress is what can be considered as a menace to the health (physical or psychological) of the subject. In the particular case of waiting in a queue, to board a train or a plane, the cause of the anxiety is the anticipation of a loss due to the time wasted in queue. The (instantaneous) intensity of psychological stress, or stress accumulation rate - which we will denote by $s(t)$, will be the expected loss perceived by the individual at that particular moment. The accumulated stress -which we will denote by $S(t)$, will be an integral over time of the intensity from the moment, taken to be $t = 0$, that he arrives to the system, up to current time t. The stress accumulation process continues until the time that the customer is served. In Osuna (1985) several aspects of the stress accumulation process were explored.

Form the point of view of the system manager, an interesting result proved there that stress drops as soon as the precise service time is known or announced. Probably, this is why elevators display the position of the cabin, some underground stations display time until arrival of the train and so on.

In this note we further extend the original setup, and suppose that waiting customers may concede the system, or themselves, a grace period before they start building up stress. This period or "threshold" will be modeled by a positive random variable. It is reasonable to suppose that each customer in the system has its own threshold, that is, the statistical nature of the threshold may change from customer to customer. For any given customer such threshold will depend upon his expectations about the serving system. We explore the stress build up problem from both the point of view of a customer that knows his own threshold before starting to get stressed, and that of the manager that may reduce the collective stress by announcing when service will take place. This last part may be of interest to airport or train station managers or to any queuing system where an operator has the capability of providing customers with information regarding the time that they will be served.

Actually, individuals may have opposite reactions to waiting. For example, when waiting is minimal, they may be satisfied, as pointed out by Kumar, Kalwani and Dada (1997). But the opposite may also be true, as Buell and Norton (2011) point out. People may tend associate longer service time with thoroughness.

Anyway, the results in the original paper seem to be of interest in a variety of fields. For example, in perception of time problems, see Fleizig, Ginzburg and Zakay (2009), in behavioral science Klapproth (2008), in consumer research, see Miller, Khan and Luce (2008), in applied psychology See Munichor and Rafaelli (2007) or Rose, Meuter and Curran (2005), in decision making processes, see Easton and Goodale (2005) or Soman (2001), in queuing system management, see Shimkin and Mandelbaum (2004). A few dealing with issues more related to the original theme are Zohar, E., A. Mandelbaum and N. Shimkin (2002), Soman D. and M. Shi (2003), Boivin and Lancastle (2010) where several forms of stress are studied, Wu, Levinson and Liu (2009), Zhou and Soman (2003) and Carmon, Shanthikumar and Carmon (1995), and specially the report by Carmon and Kahneman (1995) where some interesting experiments are described.

As mentioned in the abstract, the work of Suck and Holling (1997) and Denuit and Genest (2001) is of interest to us for they explore further mathematical aspects of Osuna's (1985) paper. They both obtain a characterization of the expected stress accumulated up to the time of service. We shall show that such characterization holds true even when the customer grants (himself or the system) a grace period before beginning to accumulate stress. Both papers contain a variety of comparison results. Suck and Holling also examine some basics assumptions made in the literature up to 1997, namely the duration hypothesis (a situation with greater expected waiting time causes more stress than a situation with less expected time), the variability hypothesis (a situation with constant waiting time is less stressful than a situation with random waiting time with the same mean) and the generalized variability hypothesis (in two situations with the same mean waiting time, the ne with more variability is more stressful).

Denuit and Genest propose an interesting generalization of the stress intensity rate. We comment further on their work after introducing definition (2) and the statement of theorem (2.1) below.

The rest of the paper is organized as follows. In the following subsection we gather some preliminary mathematical results. It is in sections 2, 4 and 5 where the extension of Osuna's original model is carried out. In section 2 we explore some properties of intensity or expected stress accumulation rate. In sections four and five the process of stress reduction is examined. First, the effect of the announcement of service time on the customer is examined, and then, in section five, the problem is examined form the point of view of the service provider, namely, when should he announce to a given customer that he is to be served so as to reduce his stress. We should point our that when the exact service time is known, the customer ceases to accumulate stress. It is in section three that mathematical properties of the expected accumulated are examined. Here we obtain a result (Theorem 3.1) which is a variation on a theme in by Suck and Holling(1997) and by Denuit and Genest(2001). A few concluding remarks are offered in section 6.

1.2 Mathematical preliminaries

Throughout we will deal with two positive random variables, which may fairly enough be supposed to be independent, although we shall not deliberately assume to be so. One of them, W denotes the waiting time, describing the time a "customer" has to wait before being served. The other, T, denotes a threshold, the time that passes before the customer begins to feel and build up stress. As sample space we may consider $\Omega = [0,\infty) \times [0,\infty)$ together with its Borel sets $\mathcal{B}$ as carriers of the information about the model.

In this model we can identify $W, T : \Omega \to [0,\infty)$ with the coordinate maps, that is, $W(w,\tau) = w$, and $T(w,\tau) = \tau$. We can also identify $\mathcal{B}$-measurable random variables with functions $X(W,T)$. We shall assume to be given a probability $\mathbb{P}$ on $(\Omega,\mathcal{B})$ determining the cumulative distribution functions F_W and F_T respectively of W and T. We shall also use the standard notation $E[X|T] = E[X|\sigma(T)]$, etc.

We know, see sections 10.2 and 10.3 of Bauer's (1972) or section 4.2 of Durrett's (1996), that there exists a kernel $P : \Omega \times [0,\infty) \to [0,1]$ which realizes the regular version of the conditional probability $\mathbb{P}[\bullet|T]$. It satisfies X, $E[X|T] = \int X(w,T)P(dw,T)$ for every integrable X, or to use a more standard notation, $E[X|T=\tau] = \int X(w,\tau)P(dw,\tau)$.

For notational convenience, we shall write P_T or P_τ for the regular version, and E_T or E_τ for integration with respect to it. The purpose of the next lemma is to formalize the meaning of symbols like $E_T[X|W > t \vee T]$. For our purposes it will suffice to consider a set $B \in \sigma(W)$, and the σ-algebra $\mathcal{G} = \{\emptyset, B, B^c, \mathbb{R}_+\} \otimes \sigma(T)$.

Lemma 1.1 *Let X be any integrable random variable. Then there exist $\sigma(T)$-measurable functions $E_\tau[X|B]$ and $E_\tau[X|B^c]$ such that*

$$E[X|\mathcal{G}] = E_\tau[X|B]I_B + E_\tau[X|B^c]I_{B^c}.$$

An alternative notation could be $E_\tau[X|B] = E[X|B, T=\tau]$. Using this representation it is an exercise to verify

$$E_\tau[X|W>t] = \int_t X(w,\tau)\frac{P(dw,\tau)}{P(W>t,\tau)} = \int_t X(w,\tau)\frac{P_\tau(dw)}{P_\tau(W>t)}. \qquad (1)$$

For the next statement, suppose that $F(t)$ and $G(t)$ are two increasing, right continuous functions defined on $[0, infty)$. When F and G have no jumps in common, a standard integration by parts formula that appears as exercise 6.4 of 4.6 in Durrett (1996), or in problem 6, section XIII.21 of Dieudonné's (1970) reduces to the result following result in also proved in Widder (1946).

Lemma 1.2 *With the notations introduce above, let F denote a probability distribution function, then*

$$\int_{(0,\infty)} G(t)dF(t) = \int_{(0,\infty)} \Big(1 - F(t-)\Big)dG(t) + (1 - F(0))G(0).$$

2 The expected stress accumulation rate

The object of interest in this section will be the quantity

$$E_\tau[H(W - \tau)|W > t] \tag{2}$$

where $H : [0, \infty) \to [0, \infty)$ is increasing and right continuous function. In Osuna (1985) H was called the subjective cost (or disutility) function, and quantity in (2) denotes an expected stress rate function which in Osuna (1985) was called the (stress) intensity or rate of change of psychological stress of waiting per unit time function. The two ingredients of (2) are clear: It is the best predictor of the rate of stress build up, for an individual that does not build stress below a threshold, given that the wait is to be longer than some time not smaller that the threshold. Note that The conditioning occurs with respect to the law P_τ, and this makes sense because each individual knows how much grace time she/he is willing to give to the system.

It is also of interest to note that the conditional distribution $\mathbb{P}_\tau(W \leq w|W > t)$ vanishes for $w < t$. This means that stress does not build up for times less than threshold time.

The analogue of theorem 1 in Osuna's paper is now

Theorem 2.1 *For an increasing cost function H, the intensity function (2) is an increasing function of the time t the customer has waited.*

Proof Exactly the same arguments as in Osuna's paper, based on a simple application of the corollary (1.1). The F appearing there is to be taken as $F(w) = P_\tau(W \leq w|W > t)$. □

Comment 2.1 *At this point we mention that instead of $H(W)$ Denuit and Genest consider a random variable C and suppose that the joint distribution of (W, C) is known. They prove that when $P(C \leq c|T > t)$ is decreasing (i.e., when C is right tail increasing in T), then the analogue of the previous* *theorem holds, namely that,* $E[C\,|T > t]$ *is increasing in* t. *Furthermore, when* $P(T = 0) = 0$, *then* $E[C\,|T > t] \geq EC$.

Suck and Holling present a shorter and simpler proof of the same result.

The next result is an analogue of theorem 2 in Osuna's (1985), and asserts that the rate of stress build up may be higher just before we are served than when we know with certainty when we will be served.

Theorem 2.2 *Suppose that* H *is increasing and continuous. Suppose we know* W, *or that* $W = w$, *then for small enough* h

$$E_\tau[H(W-\tau)|W > (w-h)] \geq E_\tau[H(W-\tau)|W = w] = H(w \vee \tau - \tau).$$

Proof Proceed as in Osuna's first paper. Consider the random variable $W^* = W|_{W>(w-h)}$ which has distribution function with respect to P_τ given by

$$F_{W^*}(u) \equiv P_\tau(W^* \leq u) = \begin{cases} 0 \text{ when } u < (w-h) \\ \frac{P_\tau(W \leq u) - P_\tau(W \leq (w-h))}{P_\tau(W>(w-h))} \end{cases}$$

Consider now

$$E_\tau[H(W-\tau)|W > (w-h)] = \int_{((w-h)),\infty)} H(u-\tau)dF_{W^*}(u),$$

Since H is increasing. $H(u-\tau) \geq H((w-h)-\tau)$ on the range of integration, and the total mass F_{W^*} puts on $((w-h)),\infty)$ is 1, we have

$$E_\tau[H(W-\tau)|W > (w-h)] \geq H((w-h) \vee \tau - \tau),$$

from which the claim drops out. □

Comment 2.2 *Observe that if* $w < \tau$ *the right hand is* 0, *which is to be interpreted as meaning that if one knows he is to be attended before the threshold, no stress is build up.*

Corollary 2.1 *With the notation of the theorem, if* H *is strictly increasing after* $w \vee \tau - \tau$, *then the inequality in the theorem becomes strict, i.e.,*

$$E_\tau[H(W-\tau)|W > (w-h) \vee \tau] > E_\tau[H(W-\tau)|W = w] = H(w \vee \tau - \tau).$$

We also have the following result, analogous to theorem 3 in Osuna's (1985). If we know that we have to wait more than the grace time, then the intensity of the stress is larger or equal than the expected stress rate before arriving to the system.

Theorem 2.3 *With the notations introduced above*

$$E_\tau[H(W-\tau)|W>\tau] \geq E_\tau[H(W-\tau)].$$

Proof It consists of a simple comparison starting with

$$E_\tau[H(W-\tau)|W>\tau] = \int_{(\tau,\infty)} H(w-\tau)dP_\tau(W \leq w|W>\tau) = \int_{(\tau,\infty)} \frac{P_\tau(W>w)}{P_\tau(W>\tau)} d_w H(w-\tau)$$

where at the second step we invoked the corollary to the integration by parts lemma, since $P_\tau(W>w)/(P_\tau(W>\tau) \geq P_\tau(W>w)$, we obtain that

$$E_\tau[H(W-\tau)|W>\tau] \geq \int_{(\tau,\infty)} P_\tau(W>w)dH(w-\tau) = E_\tau[H(W-\tau)]$$

thus proving our claim. □

3 The accumulated stress process

As we are concerned here with the stress build up process taking place in an individual when he is subjected to some stressing stimulus (in particular to the psychological cost of waiting) for a certain time, we shall think of the accumulated stress as the accumulated psychological cost of waiting.

From the point of view of an individual that does not build up stress before some threshold, the total accumulated stress is defined by

Definition 3.1 *The accumulated stress for an individual with threshold T is, when the current time w is larger than T*

$$S_a(w) = \int_T^w E_T[H(W-T)|W>t]dt.$$

and if we denote by $S_o(T) \geq 0$ the individual's prior stress (the stress with which an individual comes into the queue, the total accumulated stress at $w>T$ can be defined by

$$S(w) = S_o(T) + S_a(w).$$

For $w \leq T$ we may convene on setting $S(w) = S(0)$, and say that the individual does not accumulate stress prior to his threshold. Thus, the total accumulated stress may be represented by

$$S(w) = S_o(T) + I_{\{w>T\}} S_a(w). \tag{3}$$

where we use the standard notation $I_A(x)$ to denote the indicator function of the set A. To sum up, after being served, an individual leaves the system with his prior stress $S_o(T)$ if $W \leq T$ or with a total stress $S(W)$ if $W>T$.

Theorem 3.1 *With the notations introduced above, the expected accumulated stress up to the time she is served is*

$$E_T[S_a(W)] = E_T[(W-T)H(W-T)]$$

Proof It is a standard computation based on Fubini's theorem. Note that on $\{W > T\}$

$$S_a(W) = \int_T^W dt \int_t^\infty H(s-T)\frac{d_sP_T(t < W \leq s)}{P_T(W > t)}$$

Therefore

$$\begin{aligned}
&E_T[S_a(W)] = \int_T^\infty d_wP_T(W \leq w)\int_T^W dt \int_t^\infty H(s-T)\tfrac{d_sP_T(t<W\leq s)}{P_T(W>t)} \\
&= \int_T^\infty dt \int_t^\infty \tfrac{d_wP_T(W\leq w)}{P_T(W>t)} \int_t^\infty H(s-T)d_sP(W\leq s) = \int_T^\infty dt \int_t^\infty H(s-T)d_sP(W\leq s) \\
&= \int_T^\infty H(s-T)d_sP(W\leq s)\int_t^s dt = \int_T^\infty (s-T)H(s-T)d_sP(W\leq s) \\
&= E_T[(W-T)H(W-T)]
\end{aligned}$$

which concludes our proof. □

4 Stress reduction when service time is announced

If an individual waiting to be served is provided information at time t_0 that he is going to be served at a specific time w, his stress build up rate changes from that time on to $E_T[H(W-T)|W=w] = H(w-T)$, and also his total stress function changes. To examine the different possibilities note that

4.0.1 Case 1

If $w \leq T$, that is, if the announced service time is less than his threshold, then his stress build up rate is zero and the accumulated stress stay constant at $S_o(T)$.

4.0.2 Case 2

If $w > T$, then he may accumulate stress for a while according to

$$S(w,t_0) = \begin{cases} S_o(T) + (w-T)H(w-T) \ \text{ if } \ t_0 \leq T \\ S_o(T) + \int_T^{t_0} E_T[H(W-T)|W>t]dt + (w-t_0)H(w-T) \ \text{ if } \ t_0 > T \end{cases}$$

Let us consider the second case, that is, let us examine now what happens when the individual is told at $t_0 > T$, that he is to be served exactly at w, after he is already building up stress since T.

Proposition 4.1 *Suppose that* $E_T[H(W-T)|W>t]$ *is continuously differentiable in* t *for* $t>T$, *and that* $E_T[H(W-T)|W>T]<h(w-T)$. *Then* $S(w,t_0)$ *has a minimum at* t_0^* *such that*

$$\int_T^{t_0^*} E_T[H(W-T)|W>t]dt = H(w-T).$$

Proof From the continuity $E_T[H(W-T)|W>t]$ it follows that $S(w,t_0$ is derivable with respect to t_0. We established above that $E_T[H(W-T)|W>t]$ is an increasing function of t on $t>T$. This guarantees the existence of t_0^*. That the second derivative of $S(w,t_0)$ is positive at t_0^* is clear, thus t_0^* is a minimizer of $S(w,t_0)$. □

We introduce the saved stress due to information by $V(w,t_0)=S(w)-S(w,t_0)$. Clearly, for $t_0>T$,

$$V(w,t_0^*) = \int_{t_0}^{w} E_T[H(W-T)|W>t]dt + (w-t_0)H(w-T)$$

The following is a rather curious result.

Proposition 4.2 *Assume that the announced time is chosen at random with distribution* P_T. *The for any* $t_0>T$ *we have* $E_T[V(W,t_0)]=0$.

Proof The same proof as that of theorem (3.1) yields that

$$E_T[\int_{t_0}^{W} E_T[H(W-T)|W>t]dt] = E_T[(W-t_0)H(W-T)],$$

thus our result. □

Comment 4.1 *This rather curious result holds in case all customers had* $T=0$. *Thus unless the customers are told the truth, it may be better not to say anything for they will save no stress.*

5 Point of view of the manager

As mentioned above, there are two possible ways to interpret the result that follows from the managerial point of view. Either we are analyzing a collective system, like an airport or a train station, or we are analyzing an individual customer with unknown threshold. From the manager's point of view it makes sense to suppose that the distributions of the waiting time and that the individual tolerance are independent. Even though this is not necessary, it nevertheless simplifies the notation. The manager knows that any individual has a stress intensity function

$$s_T(t) = E[(H-T)|W>t] = \int_{t\vee T}^{\infty} H(w'-T)\frac{dF_W(w')}{1-F_W(t)}$$

but he/she does not know T. Recall as well that the accumulated stress at time t of and individual with threshold T is

$$S_T(t) = S_o(T) + I_{\{t>T\}}\int_T^t s_T(t')dt'.$$

The manager predicts, or expects, the accumulated stress t by the individual, or the waiting crowd, up to time t to be

$$S_{av}(t) = \int_0^{\infty} S_o(\tau)dF_T(\tau) + \int_0^t dF_T(\tau)\int_T^t s_T(t')dt'. \tag{4}$$

The manager can also predict the average accumulated stress up to the time the group starts being serviced to be $E[S_{av}(W)]$.

Theorem 5.1 *With the notations introduced above, the accumulated stress until service begins is*

$$E[S_{av}(W)] = E[S_o(T)] + E[(W-T)H(W-T); W>T].$$

Comment This is a rather intuitive result. The first term describes the average prior stress and the second term describes the actual accumulated stress after the grace period.

Proof The proof is again just a computation involving an application of Fubini's theorem. To obtain the first term note that

$$\int_0^{\infty} dF_T(\tau)S_o(\tau) = E[S_o(T)].$$

To obtain the second term consider

$$\begin{aligned}
&\int_0^{\infty} dF_W(w)\int_0 w dF_T(\tau)\int_\tau^w s_\tau(t')dt' = \int_0^{\infty} dF_T(\tau)\int_\tau^{\infty} dF_T(\tau)\int_\tau^w s_\tau(t')dt' \\
&= \int_0^{\infty} dF_T(\tau)\int_\tau^{\infty} dF_T(\tau)\int_\tau^w \int_{t'\vee\tau}^{\infty} H(w'-\tau)\tfrac{dF_W(w')}{P(W>t')} \\
&= \int_0^{\infty} dF_T(\tau)\int_\tau^{\infty} dF_T(\tau)\int_\tau^w \tfrac{dt'}{P(W>t')}\int_{t'}^{\infty} H(w'-\tau)dF_W(w') \\
&= \int_0^{\infty} dF_T(\tau)\int_\tau^{\infty} dt'\int_{t'}^{\infty} \tfrac{dF_W(w)}{P(W>t')}\int_{t'}^{\infty} H(w'-\tau)dF_W(w') \\
&= \int_0^{\infty} dF_T(\tau)\int_\tau^{\infty} dt'\int_{t'}^{\infty} H(w'-\tau)dF_W(w') = \int_0^{\infty} dF_T(\tau)E[(W-\tau)H(w-\tau); W>\tau) \\
&= E[(W-T)H(W-T); W>T],
\end{aligned}$$

thus concluding our proof □

5.1 When to announce time of service

The decrease in stress when an individual is told that he is going to be served is different when computed by the manager, for he/she does not know the waiting individual's threshold, even though he/she knows the time at which service is to be provided. Ditto for the case in which an arrival or departure is to be announced to a collective.

If the announcement is made at t_o, at which time the individual is to be told that service will occur at $w^* > t_o$, his stress accumulation function differs because from t_o to w^* his stress intensity changes. We mentioned above that, when an individual has threshold τ, his accumulated stress up to the announced service time w^* is

$$S_\tau(w^*, t_o) = S_o(T) + I_{\{w^*>\tau\}}\Big(\int_\tau^{t_o} s_\tau(t')dt' + (w^* - t_o)H(w^* - \tau)\Big).$$

The average accumulated stress is therefore

$$S_{av}(w^*, t_o) = \int_0^\infty S_o(\tau)dF_T(\tau)+\int_0^{w^*} dF_T(\tau)\Big(\int_\tau^{t_o} s_\tau(t')dt'+(w^*-t_o)H(w^*-\tau)\Big).$$

We can now state a possible result about characterization of such t_o.

Theorem 5.2 *Suppose that for every τ we have $s_\tau(0) < h(w^* - \tau)$, and that $s_\tau(t)$ is a continuously differentiable function of t. Then t_o exists and satisfies*

$$\int_0^{w^*} dF_T(\tau)s_\tau(t_o) = \int_0^{w^*} dF_T H(w^* - \tau).$$

Proof The arguments are as above. The conditions upon $s_\tau(t)$ ensure that the first order conditions hold, and that if a t_o exists, since $s_\tau(t)$ is increasing, it is a minimizer. That such a t_o exists follows from the other conditions, since $\int_0^{w^*} dF_T(\tau)s_\tau(t)$ is increasing in t for every τ and at $t = 0$ it is less that $\int_0^{w^*} dF_T H(w^* - \tau)$. Notice as well that as $t_o \uparrow w^*$ then $s_\tau(w^*) = E[H(W - \tau)|W > w^*] \geq H(w^* - \tau)$ since H is monotone increasing. The inequality being strict if H is strictly increasing. □

6 Concluding remarks

In Osuna (1985) a model to quantify the process of psychological stress built up by a customer waiting to be served was proposed. The key concept there was the (expected) stress accumulation rate (called there the psychological cost), from which from which the (expected) accumulated stress up to service time is to be computed.

Here we extended the model to incorporate the possibility that each customer concedes the service system a grace period within which no stress is accumulated. This is modeled by a subjective random time, each customer having his own, determined by his expectations about the system.

By appropriate conditioning, we verified that both the modified expected stress accumulation rate and the expected accumulated stress, satisfy the properties that Osuna proposed in his original paper. Besides that, we verified that our model satisfies some additional properties studied by Suck and Holling (1997) and Denuit and Genest (2001).

As far as stress managing goes, we showed that even when the customer has a threshold before building up stress, there may be occasions in which he is better off if no information about service time is provided to him.

From the point of view of the manager who may have to deal with collective anger arising from stress accumulation, there is an optimal time of when to announce service.

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