2017-01-01

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Nataša Janjić, Darko Kapor, Dragan Doder, Aleksandar Petrović, and Radoslava Doder. 2017. A Model for Determining the Effect of the Wind Velocity on 100 M Sprinting Performance. Journal of Human Kinetics 57(1): 159–167. doi: 10.1515/hukin-2017-0057.

https://open.uns.ac.rs/handle/123456789/3646

Journal of Human Kinetics volume 57/2017, 159-167 DOI: 10.1515/hukin-2017-0057
Section III – Sports Training

A Model for Determining the Effect of the Wind Velocity on 100 M Sprinting Performance

by
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This paper introduces an equation for determining instantaneous and final velocity of a sprinter in a 100 m run completed with a wind resistance ranging from 0.1 to 4.5 m/s. The validity of the equation was verified using the data of three world class sprinters: Carl Lewis, Maurice Green, and Usain Bolt. For the given constant wind velocity with the values + 0.9 and + 1.1 m/s, the wind contribution to the change of sprinter velocity was the same for the maximum as well as for the final velocity. This study assessed how the effect of the wind velocity influenced the change of sprinting velocity. The analysis led to the conclusion that the official limit of safely neglecting the wind influence could be chosen as 1 m/s instead of 2 m/s, if the velocity were presented using three, instead of two decimal digits. This implies that wind velocity should be rounded off to two decimal places instead of the present practice of one decimal place. In particular, the results indicated that the influence of wind on the change of sprinting velocity in the range of up to 2 m/s and was of order of magnitude of 10^{-3} m/s. This proves that the IAAF Competition Rules correctly neglect the influence of the wind with regard to such velocities. However, for the wind velocity over 2 m/s, the wind influence is of order 10^{-2} m/s and cannot be neglected.

Key words: *mathematical modelling, track sprinting, wind.*

Introduction

The research into the effects and contribution of the wind on the change of sprinter's velocity in a 100 m run has resulted in numerous scientific publications over the last 40 years (Dapena and Feltner, 1987; Davies, 1980; Linthorne, 1994; Mureika, 2003; Ward-Smith, 1999). This research was primarily directed towards the analysis and formulation of a mathematical model which would describe the influence of air resistance as a medium in the ground layers of the Earth's atmosphere, and the effect of wind resistance in track sprinting. Indeed, the majority of the afore-mentioned research have performed an analysis based on the mathematical model where the resulting velocity of the sprinter and the wind $v_t \pm w_t$ is squared. However, in our opinion, this is extremely difficult for both understanding and application by the athletic experts in practice. That is the reason why we propose a hypothetical simplified model where only the wind velocity w is squared.

We undertook the study with this in mind, in addition to continuing our previous research regarding the influence of air resistance on sprinting velocity (Janjic, 2014, 2016). The aim was to obtain a mathematical model which would

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Authors submitted their contribution to the article to the editorial board.
Accepted for printing in the Journal of Human Kinetics vol. 57/2017 in June 2017.

allow to produce an adequate equation unifying the effects of the medium (air) resistance and the influence of wind velocities of up to 4.5 m/s (16.2 km/h, breeze volume 2 per Beaufort scale) to the change of the sprinting velocity during the 100 m run.

Furthermore, by knowing a sprinter's maximal segment velocity, as well as the corresponding wind velocity and appropriate resistance coefficients, it is possible to determine the horizontal component of the resulting force. It arises as the vectorial composition of gravity (weight) directed downwards and the ground reaction force, responding to the leg extensor muscle force. The horizontal component of the resultant force is directed towards the desired direction of motion and its intensity governs sprinting velocity (Brughelli et al, 2011; Morin et al 2011, 2012). The main contribution of the present study is the fact that the force, although a dynamical quantity, is evaluated within the proposed model by using measured data for kinematical quantities of distance and time.

The theoretical analysis presented in the paper was tested using the results of Carl Lewis (1988), Maurice Green (2001) and Usain Bolt (2009), who according to IAAF, have achieved three of the best performances in the 100 m sprint. We aimed to confirm, based on the obtained results, the correctness of the IAAF Competition Rules (IAAF, 2014a, 2014b) neglecting the effect of wind velocities up to 2 m/s (7.2 km/h) on sprinting velocity. These rules were established in the second half of the 20th century, when mechanical measuring devices provided measurement accuracy up to two decimal places. The empirical data showed that wind velocities over 2 m/s would influence the second decimal place, so that is where the noted limitation was derived. Nowadays, digital instruments offer better measurement accuracy so we propose that the official representation of the results of sprinter velocity should use three instead of two decimal places. The performed analysis implied that the limit for the neglect of wind influence on sprinting velocity could be safely changed from 2 m/s to 1 m/s, which would provide more exact values for velocity and time. This would demand rounding off the wind velocity to two, instead of one decimal place.

Material and Methods

Participants

The mathematical analysis presented herein was based on the data (measured values of the 10 m segment times and wind velocity) from the 100 m sprint races run by Carl Lewis at the 1988 Olympic Games in Seoul, Maurice Green at the 2001 IAAF World Championships in Edmonton in 2001, and Usain Bolt at the IAAF World Championships in Berlin in 2009. These data are made freely available to the public by the IAAF (IAAF, 2014a). Nevertheless, the study design conformed to the ethical standards of the Declaration of Helsinki and sport and exercise science research described by Harriss and Atkinson (2011).

Theoretical model

Let us assume that in a 100 m run, a sprinter with the mass m moves along a straight line under the action of the following forces:

- $F(t)$ = horizontal component of the resulting force. It arises through the vectorial composition of gravity (sprinter's weight) directed downwards and the reaction force of the ground, induced by the leg extensor muscle force with which a sprinter rebounds from the ground. The sprinter maintains the position in such a manner that the resulting force is practically horizontal so that the horizontal component of the resulting force pushes him/her forwards,
- F_v = force of the resistance of the ground layers of the atmospheric air (medium resistance), which is proportional to the sprinting velocity v_s and equal to $-kv_s$ with k = coefficient of the air resistance,
- F_w = wind force proportional to the square of the wind velocity w, i.e $\pm lw^2$, the tail wind (sign +) or head wind (sign -) and the coefficient $l = c_d \rho A/2$. Taking $c_d=0.5$ as the typical value of the drag coefficient (Keller, 1973; Mureika, 2001), ρ= 1.2 kg/m^3 for the air density, and a cross section of A A = 1 m^2 (Helene and Yamashita, 2010), we obtain l = 0.3 kg/m.

Taking all the above into account, one can assume that the motion of a sprinter is performed under the action of the resulting $F_s = F(t) - F_v \pm F_w$.

$$m\frac{dv_s}{dt} = F(t) - kv_s \pm lw^2 \qquad (1)$$

A rearrangement produces a differential equation of motion

$$\frac{dv_s}{dt} + \frac{k}{m}\, v_s = \frac{F(t)}{m} \pm \frac{l}{m} w^2 \qquad (2)$$

Equation (2) is the first order differential equation of which solution, with an initial condition $t=0$, $v_s=0$, gives a general expression for the instantaneous velocity v_s

$$v_s = e^{-\frac{k}{m}t}\left[\frac{1}{m}\int d\,t\,F\,(t)e^{\frac{k}{m}t} - \frac{1}{m}\left(\int d\,t\,F\,(t)e^{\frac{k}{m}t}\right)_{t\,=\,0}\right] \pm \frac{l}{k}w^2\left(1 - e^{-\frac{k}{m}t}\right) \qquad (3)$$

In the special case when $F(t) = F = const$, equation (3) turns into the equation of the following form:

$$v_s = \left[\frac{F}{k} \pm \frac{l}{k}w^2\right]\left(1 - e^{-\frac{k}{m}t}\right) \qquad (4)$$

with $\left[\frac{F}{k} \pm \frac{l}{k}w^2\right] = v_m$ i.e

$$\frac{F}{k} = v_{ms} \mp \frac{l}{k}\, w^2 \qquad (5)$$

where $v_{ms} = \Delta S/\Delta t$ is the maximum segment velocity (Janjic, et al., 2014, 2016).

Equation (4) can be rewritten as

$$v_s = \frac{F}{k}\left(1 - e^{-\beta t}\right) \pm \frac{l}{k}w^2\left(1 - e^{-\beta t}\right) \qquad (6)$$

with time t, coefficient $k=m\beta$, here m is the sprinter mass, β is the coefficient determined from the measured data for the transient segment times of the sprinter following the procedure described in Janjic, et al. (2014, 2016), and w is the wind velocity.

In order to use equation (6) to determine the force F, one must have in mind that in principle it changes during a run, so we shall observe it at the level of a segment of length ΔS during the segment interval Δt when one can assume that $F = const$. It follows from relation (5) that

$$F = v_{ms}\, k \mp l w^2 \qquad (7)$$

Considering (6), let us denote by v_t the first term which provides sprinting velocity with atmospheric air resistance and neglects the wind influence, i.e.

$$v_t = \frac{F}{k}\left(1 - e^{-\beta t}\right) \qquad (8)$$

and let us denote the second term, which contributes to the change of sprinting velocity due to the effect of the wind blowing with the velocity w, by w_t, i.e.

$$w_t = \frac{l}{k} w^2\left(1 - e^{-\beta t}\right) \qquad (9)$$

Then (6) can be represented as

$$v_s = v_t \pm w_t \qquad (10)$$

One should stress that the contribution of the first term v_t is dominant for determining the velocity v_s. The other term w_t, which according to (9) depends on the square of the wind velocity w, plays the role of a correction factor of sprinting velocity v_s since it has either positive or negative contribution depending on the direction of the wind.

Equation (10) provides a theoretical possibility to calculate independently each of the two terms, following (8) and (9) and then study their contribution to sprinting velocity v_s. This was performed in this paper for the three sprinters mentioned above.

The coefficient β in the exponent of the function $e^{-\beta t}$ is determined from the expression

$$\beta = \frac{9.210340372}{t_o} \qquad (11)$$

where t_0 is the time necessary for the sprinter to reach the maximum velocity v_{smax}.

Results

In order to verify and test the applicability of the proposed mathematical model (6), we considered the measured values of the segment times and wind velocity for the final 100 m sprint at the 1988 Olympics in Seoul run by Carl Lewis, as well as the values related to Maurice Green's 2001 final run at the IAAF World Championships in Edmonton, and Usain Bolt's 2009 final run at the IAAF World Championships in Berlin. These data, obtained from IAAF (2014a), are presented in Tables 1-3.

The determination of the instantaneous or final velocity v_s according to equation (10) turns in practice to the sum of two independent, although functionally related algebraic terms, v_t and w_t each having its own analytic expression, meaning and contribution. This was performed for all three sprinters, but simple algebra shows that the final sum must be equal to $v_{ms}=\Delta S/\Delta t$. The relation (8) demands the knowledge of the horizontal component force F which is obtained from relation (7) using the data from Tables 1-3. The results obtained for the segment velocity v_t (8), w_t (9) and v_s (10) for the wind velocity + 1.1 m/s for Lewis and + 0.9 m/s for Green and Bolt together with the values of the necessary variables are presented in Tables 1-3.

The analysis of the results presented in Tables 1-3 for each of the sprinters indicates that the wind velocity during the run was constant. The effect of wind influence was higher for the velocity of + 1.1 m/s when compared to the velocity of + 0.9 m/s. Using the equation (9) with the values of the constants from Tables 1-3, and the arbitrary values for the wind velocity w (within the range + 0.1 – 4.5 m/s) we could calculate the values for the effect w_t of the wind influence to the final velocity v_s achieved in the 100 m run. The results for all three sprinters are presented in Table 4. This calculation is an approximation, since the variation of the wind velocity would definitely influence the final result, changing the parameter β.

Table 1

The values of the instantaneous and final sprinting velocity v_s in the 100 m run under the wind influence for Carl Lewis

C. Lewis. 1988

S(m)	t(s)	Δt[s]*	F(N)	v_t[m/s]	w_t[m/s]***	v_s[m/s]
0	0					v_0=3.45
		1.89	671.80			
10	1.89			4.99	$2.8\cdot10^{-3}$	4.99
		1.07	1149.23			
20	2.96			9.24	$2.9\cdot10^{-3}$	9.24
		0.94	1308.22			
30	3.90			10.61	$2.9\ 10^{-3}$	10.61
		0.89	1381.73			
40	4.79			11.23	$2.9\ \cdot10^{-3}$	11.23
		0.86	1429.95			
50	5.65			11.63	$2.9\cdot10^{-3}$	11.63
		0.83	1481.64			
60	6.48			12.05	$2.9\cdot10^{-3}$	12.05**
		0.85	1446.77			
70	7.33			11.77	$2.9\cdot10^{-3}$	11.77
		0.85	1446.77			
80	8.18			11.77	$2.9\cdot10^{-3}$	11.77
		0.86	11429.95			
90	9.04			11.63	$2.9\ \cdot10^{-3}$	11.63
		0.88	1397.44			
100	9.92			11.36	$2.9\cdot10^{-3}$	11.36

w_t***	+1.1 (m/s)
l	0.3 (kg/m)
β	1.5186 (s^{-1})
m	81 (kg)
k	123. 007 ($kg.s^{-1}$)
v_{smax}**	12.05 (m/s)

*segment time, **maximum velocity, *** wind velocity

Table 2

The values of the instantaneous and final sprinting velocity v_s in the 100 m run under the wind influence for Maurice Green

M. Green. 2001

S(m)	t(s)	Δt(s)*	F(N)	v_t(m/s)	w_t(m/s)***	v_s(m/s)
0	0					v_0=3.61
		1.83	654.93			
10	1.83			5.15	$1.9 \cdot 10^{-3}$	5.15
		1.00	1198.73			
20	2.83			9.88	$2.0 \cdot 10^{-3}$	9.88
		0.92	1302.99			
30	3.75			10.84	$2.0 \cdot 10^{-3}$	10.84
		0.89	1346.91			
40	4.64			11.23	$2.0 \cdot 10^{-3}$	11.23
		0.86	1393.91			
50	5.50			11.63	$2.0 \cdot 10^{-3}$	11.63
		0.83	1444.30			
60	6.33			12.05	$2.0 \cdot 10^{-3}$	12.05**
		0.83	1444.30			
70	7.16			12.05	$2.0\ 10^{-3}$	12.05
		0.86	1393.91			
80	8.02			11.63	$2.0\ 10^{-3}$	11.63
		0.89	1346.91			
90	8.91			11.24	$2.0 \cdot 10^{-3}$	11.24
		0.91	1317.31			
100	9.82			10.99	$2.0 \cdot 10^{-3}$	10.99
w_t***			+0.9 (m/s)			
l			0.3 (kg/m)			
β			1.55712 (s^{-1})			
m			77 (kg)			
k			119.897 ($kg.s^{-1}$)			
v_{smax}**			12.05 (m/s)			

*segment time, **maximum velocity, ***wind velocity

Table 3

The values of the instantaneous and final sprinting velocity v_s in the 100 m run under the wind influence for Usain Bolt

U. Bolt. 2009						
S(m)	t(s)	Δt(s)*	F(N)	v_t(m/s)	w_t(m/s)***	v_s(m/s)
0	0					v_0=3.42
		1.89	625.74			
10	1.89			4.90	$1.9 \cdot 10^{-3}$	4.90
		0.99	1194.81			
20	2.88			9.91	$2.0 \cdot 10^{-3}$	9.91
		0.90	1314.32			
30	3.78			11.05	$2.0 \cdot 10^{-3}$	11.05
		0.86	1375.46			
40	4.64			11.61	$2.0 \cdot 10^{-3}$	11.61
		0.83	1425.18			
50	5.47			12.04	$2.0 \cdot 10^{-3}$	12.04
		0.82	1442.56			
60	6.29			12.19	$2.0 \cdot 10^{-3}$	12.19
		0.81	1460.38			
70	7.10			12.35	$2.0 \cdot 10^{-3}$	12.35**
		0.82	1442.56			
80	7.92			12.20	$2.0 \cdot 10^{-3}$	12.20
		0.83	1425,15			
90	8.75			12.05	$2.0 \cdot 10^{-3}$	12.05
		0.83	1425.18			
100	9.58			12.05	$2.0 \cdot 10^{-3}$	12.05

w_t***	+0.9 (m/s)
l	0.3 (kg/m)
β	1.3757 (s^{-1})
m	86 (kg)
k	118.310 ($kg \cdot s^{-1}$)
v_{smax}**	12.35 (m/s)

*segment time, **maximum velocity, ***wind velocity

Table 4

Theoretical values of the effect w_t of the wind velocity w in the range 0.1-4.5 m/s on final velocity v_s achieved in the time t in the 100 m run

w [m/s]	C. Lewis	M. Green	U. Bolt
	w_t m/s t = 9.92 (s)	w_t m/s t = 9.82 (s)	w_t m/s t = 9.58 (s)
0.1	$2.44 \cdot 10^{-5}$	$2.50 \cdot 10^{-5}$	$2.53 \cdot 10^{-5}$
0.2	$9.75 \cdot 10^{-5}$	$1.00 \cdot 10^{-4}$	$1.01 \cdot 10^{-4}$
0.3	$2.19 \cdot 10^{-4}$	$2.25 \cdot 10^{-4}$	$2.28 \cdot 10^{-4}$
0.4	$3.90 \cdot 10^{-4}$	$4.00 \cdot 10^{-4}$	$4.05 \cdot 10^{-4}$
0.5	$6.09 \cdot 10^{-4}$	$6.25 \cdot 10^{-4}$	$6.34 \cdot 10^{-4}$
0.6	$8.78 \cdot 10^{-4}$	$9.01 \cdot 10^{-4}$	$9.13 \cdot 10^{-4}$
0.7	$1.19 \cdot 10^{-3}$	$1.20 \cdot 10^{-3}$	$1.24 \cdot 10^{-3}$
0.8	$1.56 \cdot 10^{-3}$	$1.60 \cdot 10^{-3}$	$1,62 \cdot 10^{-3}$
0.9	$1.97 \cdot 10^{-3}$	$2.03 \cdot 10^{-3}$	$2.05 \cdot 10^{-3}$
1.0	$2.44 \cdot 10^{-3}$	$2.50 \cdot 10^{-3}$	$2.53 \cdot 10^{-3}$
1.1	$2.95 \cdot 10^{-3}$	$3.03 \cdot 10^{-3}$	$2.79 \cdot 10^{-3}$
1.5	$5.49 \cdot 10^{-3}$	$5.62 \cdot 10^{-3}$	$5.70 \cdot 10^{-3}$
1.9	$8.80 \cdot 10^{-3}$	$9.03 \cdot 10^{-3}$	$9.15 \cdot 10^{-3}$
2.0	$\boldsymbol{9.75 \cdot 10^{-3}}$	$\boldsymbol{1.00 \cdot 10^{-2}}$	$\boldsymbol{1.01 \cdot 10^{-2}}$
2.1	$1.07 \cdot 10^{-2}$	$1.10 \cdot 10^{-2}$	$1.12 \cdot 10^{-2}$
2.2	$1.18 . 10^{-2}$	$1.21 \cdot 10^{-2}$	$1.23 \cdot 10^{-2}$
2.5	$1.52 \cdot 10^{-2}$	$1.56 \cdot 10^{-2}$	$1.58 \cdot 10^{-2}$
3.0	$2.19 \cdot 10^{-2}$	$2.25 \cdot 10^{-2}$	$2.28 \cdot 10^{-2}$
3.5	$2.98 \cdot 10^{-2}$	$3.06 \cdot 10^{-2}$	$3.10 \cdot 10^{-2}$
4.0	$3.90 \cdot 10^{-2}$	$4.00 \cdot 10^{-2}$	$4.06 \cdot 10^{-2}$
4.5	$4.94 \cdot 10^{-2}$	$5.07 \cdot 10^{-2}$	$5.13 \cdot 10^{-2}$

Discussion

We can now analyze the meaning of the data obtained for F, v_t , w_t and v_s (Tables 1-3), having in mind that the horizontal component of the resulting force actually governs sprinting velocity. This is confirmed by the variation of the value of this force before and after reaching the maximal velocity v_{max} which is presented in the Tables 1-3. It is very important to note that the values of the resulting force appearing here are close to the values obtained experimentally (Brughelli et al, 2011; Morin et al 2011, 2012). We wish to stress again that the values of the force were obtained via a purely kinematical manner.

According to the IAAF Competition Rules (IAAF, 2014b), the presence of the wind of the velocity up to w =2 m/s and its effect on the final value of the velocity v_s is neglected. The results obtained in this study, according to equation (10), indicate to what extent the neglecting criterion is justified and why it is applicable according to the actual rules. If one analyzes individually the effects of the wind influence on the final velocity achieved in the interval t obtained from equation (9) (Table 4) for the three sprinters, it is obvious that the influence of wind on sprinting velocity increases with the rise of their velocity. As a result, for Green and Bolt at the wind velocity of w = + 0.9 m/s, the contribution to the change of the maximum and instantaneous velocity is 2.0 x 10^{-3} (the third decimal place), and for Lewis at the wind velocity of w = + 1.1 m/s it was 2.9 x 10^{-3} (also the third decimal place). Since the intensity of the velocity v_s according to the IAAF Competition Rules is presented using two decimal places (one hundredth of m/s), and the contribution of the wind influence with the velocities + 0.9 m/s and + 1.1 m/s to sprinting velocity according to the presented analysis appears at the third decimal place (one thousandth of m/s), its contribution could be neglected.

If, however, the results of sprinting velocity were presented using more than two decimal places (e.g. three decimal places), this could provide the basis for a deeper scientific analysis. It might help coaches to instruct sprinters about more efficient movements during running. On the other hand, if sprinting velocity was presented using up to three decimal places, according to our results it would suggest that the influence of the wind velocity was neglected up to1 m/s, and not 2 m/s. In this way, the third decimal place in the value of the final velocity would become important and could influence the final placement of sprinters, diminishing the role of automatic phototiming.

The results presented in Table 4 show to what extent the influence of wind velocity can increase (+) or decrease (-) sprinting velocity v_s in the 100 m run. According to the data from the present study, this contribution to the intensity of the sprinting velocity v_s, for the wind velocities in the range 0.1-2.0 m/s is of the order of magnitude of 10^{-5} to 10^{-3} m/s. This shows that the effect of the wind velocities of up to 2 m/s on the final value of the velocity v_s is such that it is not taken into account by the IAAF, and consequently the wind influence is neglected. Regarding the wind velocity equal to 2 m/s, of which effect to the velocity vs varies in the range 10^{-2} to 10^{-3} m/s, the data from Table 4 indicate that this influence cannot be safely neglected.

For this reason, it could be concluded, as justified by the presented mathematical analysis and the results shown in Table 4, that for the wind velocities less than 2 m/s (excluded), wind does not influence the result of the final sprinting velocity v_s. If sprinting velocity were presented using three decimal places instead of two, that would contribute to changing the limit of neglecting the wind influence on sprinting velocity to 1 m/s instead of 2 m/s. This would consequently demand rounding off wind velocity w to the second instead of the first decimal place.

We present here a final example. The justification for presenting velocity using three decimal places is well illustrated by the results of Green (Table 2). There it was necessary to determine which of the two equal, rounded to two decimal places, segment values of the velocity v_t = 12.05 m/s for the moments t = 6.33 s and t = 7.16 s, corresponded to v_{max}. If the value of velocity for Green is presented using three decimal places, one can see that for t = 6.33 s, v_t = 12.048 m/s and for t = 7.16 s, v_t = 12.049 m/s. This indicates that the third decimal place shows that the maximum velocity was achieved for t = 7.16 s.

To conclude, in our analysis of a model for determining the effect of wind on sprinting velocity, mathematical considerations led to a simple and original equation for the calculation of instantaneous and final sprinting velocity v_s in 100 m run (equation 6). The validity of this equation was verified by the values of measured segment intervals (IAAF 2014a), for three sprinters in 100 m run, Carl Lewis in 1988, Maurice Green in 2001 and Usain Bolt in 2009. The results indicate that the influence of wind on the change of sprinting velocity in the range of up to 2 m/s is of the order of magnitude of 10^{-3} (one thousandth of m/s). This implies that the IAAF Competition Rules correctly neglect the influence of the wind with the velocities up to 2 m/s. The mathematical analysis and the results presented lead to the conclusion that if the velocity were documented using three, instead of two decimal places, that would cause the limit of safely neglecting the wind influence, to move to 1 m/s instead of 2 m/s. If this proposal were accepted, it would contribute to more precise results for the velocity and time, demanding the rounding off of the wind velocity *w* to two instead of one decimal place.

Acknowledgements

The authors wish to thank Prof. dr Jevrem Janjić, for valuable comments and suggestions during this and previous research.

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