ABSENCE OF SEAT-DIP IN THE STALLS OF THE TEATRO COLÓN IN BUENOS AIRES

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1 INTRODUCTION

The Teatro Colón in Buenos Aires, designed in stages by the architects Francesco Tamburini, Vittorio Meano and Jules Dormal, opened in May 1908. The hall follows the Italian horseshoe opera house model with seven levels of boxes above the stalls. It currently has a total capacity of 2,474 people, although it can be increased by placing around 500 standing people in specifically designated spaces on some levels. The orchestra pit can accommodate around 100 musicians.
Opinion polls on the acoustic quality of the Teatro Colón show a great consensus in highlighting the warmth, clarity and definition of low-frequency sounds. In particular, they emphasize the quality of the bass sounds on the main floor, where there's no perceptible seat-dip. The warmth associated with bass sounds is a very complex perceptual trait that, although related to the presence and acoustic power of low-frequency signals, also involves the temporal development and the spectral and spatial distribution of acoustic energy.
Due to the diffraction grid created by the rows of seats in front of an audience member seated in the stalls, the appearance of spectral minima in the low-frequency response is inevitable due to grazing waves coming from the stage. Whether or not these spectral minima are perceived, or even whether they can be beneficial for the quality of bass sounds, depends on a number of factors, including the frequency and quality factor of the seat-dip spectral minimum, its duration, and the restitution of low-frequency energy during the first milliseconds after the arrival of the direct sound.

Although no formal surveys have been conducted to date, inquiries of musicians, critics, and the general public over more than forty years have not recorded a single mention of loss of bass from an audience seat.[1] The causes of this behaviour have yet to be determined. To do so, each source/seat pair had to be studied individually, since the effect cannot be deduced from global statistical values. Due to the quantity and quality of the records, we chose to analyse the results of the impulse responses measured during the 2006-2010 restoration.

2 SET-UP OF THE MEASUREMENTS

The main locations of the sources and receiving points in the stalls can be seen in Figure 1, although several positions not indicated in said figure were also measured. The perimeter seats were discarded due to the risk of the appearance of comb filters caused by the powerful reflection of the direct signal on the marble wall surrounding the stalls.

An omnidirectional source was located in two positions, S02 and S03, one on the raised orchestra pit platform and the other on the proscenium. The absorbent textile curtain was kept closed to minimize the possibility of very early reflections in the stalls that may distort the data under analysis.

[1] The procedure was always the same: the interviewee was asked to listen to an acoustic source with a large amount of low-frequency energy while standing in front of the seat, and then to sitting in the seat. To date, no one has reported a decrease in loudness or bass presence when doing so.

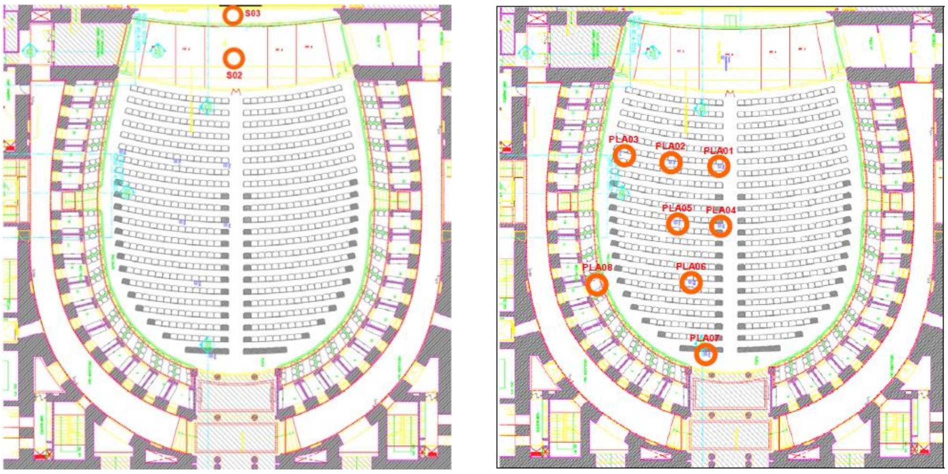

Figure 1. Locations of the sources and measurement points in the stalls. Source S02 on the raised orchestra pit platform and S03 on the proscenium (from IADAE, 2010).

In this work, we will analyse the most significant results of the measurements and try, when possible, to account for their physical causes. The study is divided into two parts: the early establishment of the seat-dip and its subsequent temporary development.

3 EARLY ESTABLISHMENT OF THE SEAT-DIP

As expected in such complex acoustic fields, there are several spectral minima below 300 Hz, which appear and fade in a few milliseconds that are not significant in the seat-dip analysis. Therefore, only the minima that are sustained for at least 30 ms with a minimum quality factor Q of 15 were considered. In most of the measured locations in the stalls, the seat-dip is established very early, between 20 and 40 ms after the arrival of the direct signal. In some positions, no spectral minima compatible with the phenomenon were observed.

Three recurrent values of frequencies compatible with the seat-dip phenomenon were found in different positions: around 80, 120 and, to a lesser extent, 200 Hz. The time necessary to establish the seat-dip did not exceed 50 ms in any case. Rectangular temporal windows were used and the cutoff frequencies to determine the quality factor Q were set 6 dB above the spectral minimum. In all the cases considered, the valleys corresponding to the seat-dip were narrow-band, with Q above 20.

The most likely cause of this early seat-dip is the diffraction grating formed by the rows of seats located between the source and the receiver[1,2]. In the stalls of the Teatro Colón, the vertical incidence angles, for a source located on the proscenium 1.5 m above the stage floor level, range from 6° in the first rows of seats to 2° in the back. These angles are lower than 10°, the angle below which the specialized literature consider the effect to occur.

3.1 Characteristics and effects of the stall seats

The seats in the stalls of the Teatro Colón are made of wrought iron, with a seat, backrest and armrests made of wood covered with a textile material –prior to the restoration a vegetable fibre, and afterwards sheep's wool velvet. The backrest, as can be seen in Figure 2, does not reach the floor and leaves a generous open space under the seat.

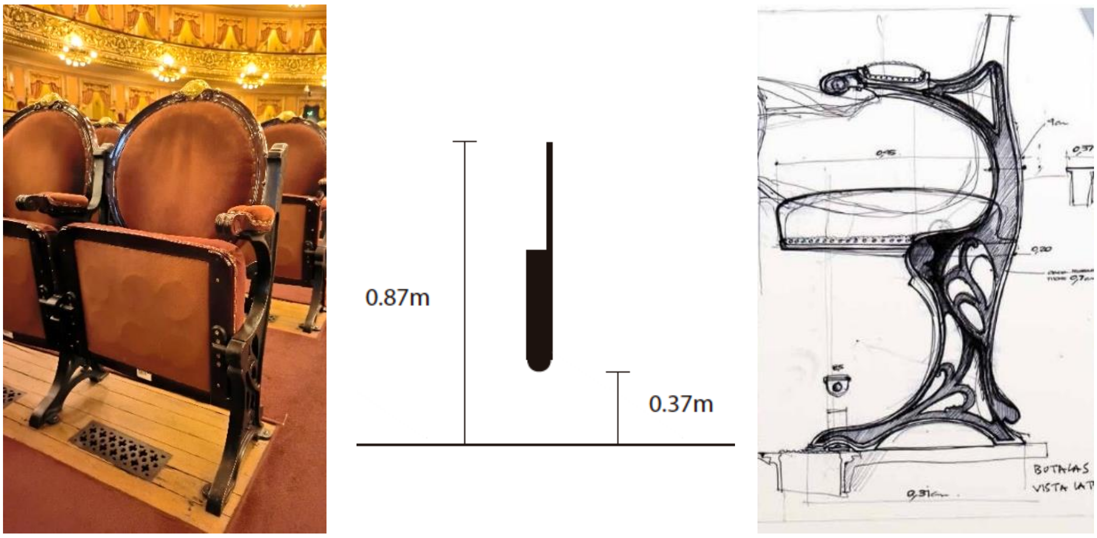

Figure 2. Characteristics and main dimensions of stall seats (Drawings by Architect Claudio Dorado).

The complex curved backrests of the stall seats constitute an acoustic barrier and their effective height depends on the horizontal angle of arrival of the signal from the stage. Such design allows for the coexistence of several possible paths for the grazing waves that diffract in the arrangement of seats.

In addition to those mentioned in the works of Ishida[3], Economou and Charalampous[4], the extra path generated in the reflection of the floor of the air space under the floor of the stalls should be included. Figure 3 shows the two paths that, according to our analysis, would generate the most frequent spectral minima in the stalls of the Teatro Colón.

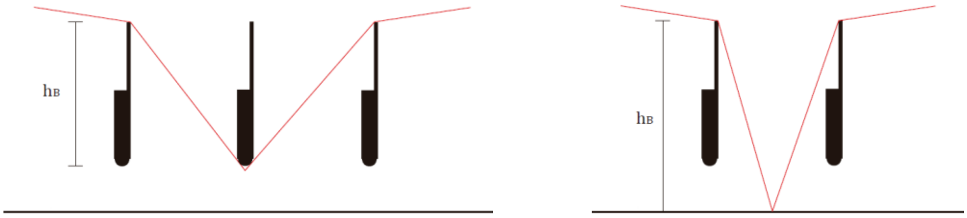

Figure 3. Main paths of grazing waves over the stall seats. Left: through the underpass; right: full seat height.

The curved top of the backrest makes it extremely difficult to determine the effective height h_B of the barrier. To begin with, this height will depend on the horizontal angle of arrival of the direct signal: higher for sources in line with the axis of the seat and lower for signals that arrive from non-frontal sources. From the geometry and dimensions of the seats, it is possible to calculate the main attenuation frequency corresponding to the main paths of the diffracted wave shown in Figure 3:

$$f_{min,n} = \frac{n\,c}{\lambda_{máx}} = \frac{n\,c}{4(h_B + cg)} \qquad (1)$$

where n is the harmonic number, c is the speed of sound, h_B is the effective height of the barrier, and cg is the geometric correction that incorporates the differences between the simplified vertical path and the one actually taken by the diffracted wave. Both the effective height h_B and the geometric correction cg depend on the path analysed.

3.2 Main attenuation frequencies around 120 Hz

Figure 4 shows the early spectral minimum at f = 120 Hz measured for the pair S02/PLA01. This is the valley that appears most often, with a frequency variation of ± 5 Hz.

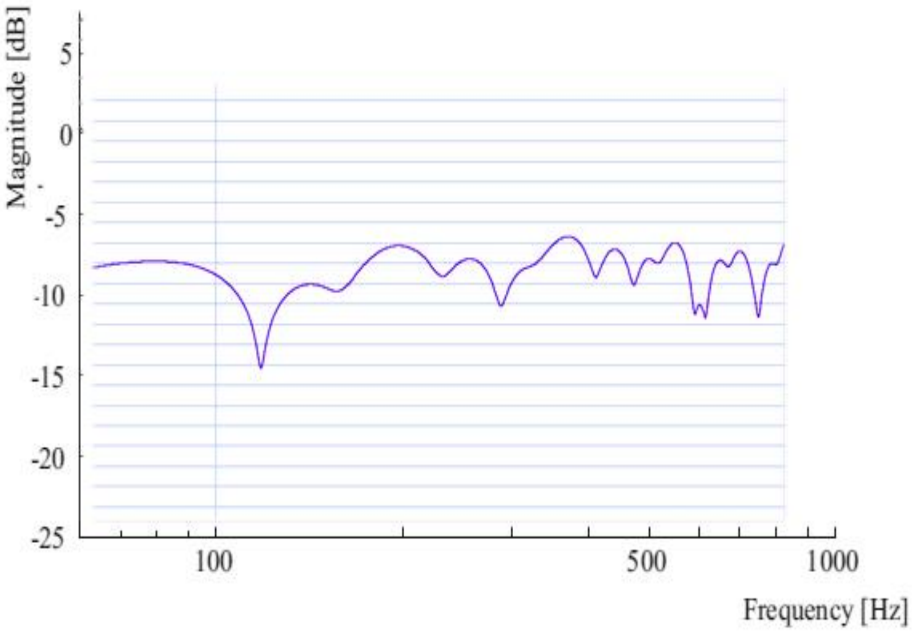

Figure 4. Early establishment of the 120 Hz seat-dip in the centre of the main floor (S02/PLA01 pair). The figure shows the result of the rectangular window at 30 ms after the direct sound. The minimum appears at 20 ms and persists until 90 ms.

The main attenuation dip around 120 Hz was measured in seats close to the longitudinal symmetry axis of the stalls, which receive the acoustic waves frontally. The path of the grazing frontal wave travelling through the underpass of the seat can be seen in Figure 3. In this case, the effective height h_B is

h_B = maximum backrest height – height of the underpass = 0.87 – 0.37 m = 0.50 m

For a distance between rows of 1.00 m, the geometric correction factor cg is

$$cg = \sqrt{(0.5m)^2 + (0.5m)^2} - 0.5m = 0.207m$$

Substituting in (1)

$$f_{min1,n} = \frac{n\,c}{4(h_B+cg)} = \frac{n \cdot 343\ m/s}{4\ (0.50m+0.207m)} = n \cdot 121\ Hz$$

This result is valid for a frontal source. The second harmonic, with a frequency of 242 Hz, and the higher ones, are above the frequency band under analysis.

It is interesting to compare this value with the one measured in a seat close to the side of the stalls, in which the waves arrive following the path determined by the lower part of the backrest of the seats. Figure 5 shows the main attenuation frequency measured from the S02/PLA03 pair, with a horizontal arrival angle of 42°, which meets such condition. The frequency of the spectral minimum was 135 Hz.

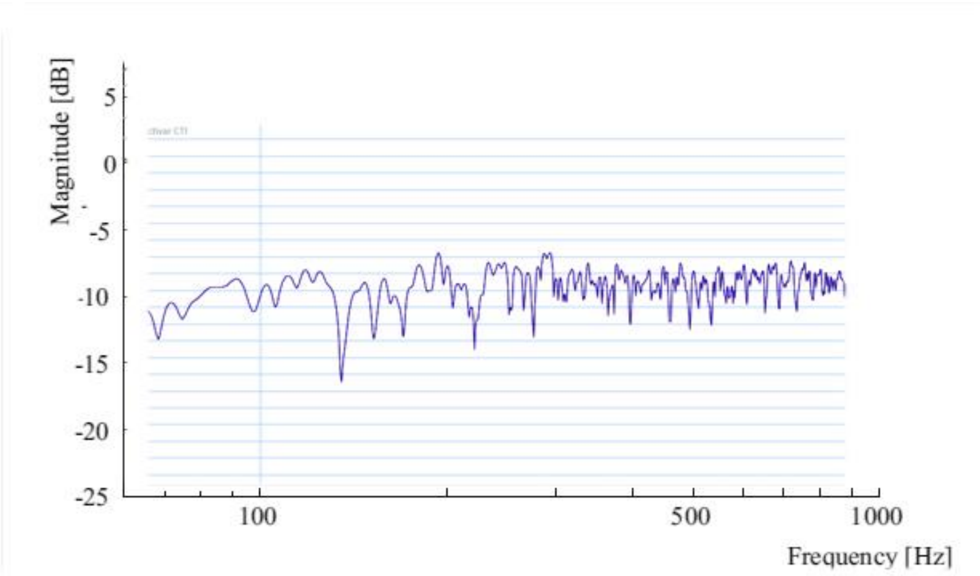

Figure 5. Early establishment of the 135 Hz seat-dip in a non-frontal position (S02/PLA03 pair). The figure shows the result of the rectangular window at 30 ms after the direct sound. The minimum appears at 30 ms and persists until 80 ms.

Given the location of the PLA03 seat, special care was taken in order to rule out the possible appearance of a comb filter caused by the reflection of the direct signal from the marble wall surrounding the stalls.

On the main floor of the Teatro Colón, the horizontal angle of arrival varies between 0 and 60°. It is therefore expected to find minimum frequencies between approximately 120 and 135 Hz for the path under analysis. As an example, for a source located on one side of the stage, with waves reaching the seat at a horizontal angle of 30°, the effective height h_B is reduced to

h_B = minimum backrest height – height of the underpass = 0.72 – 0.37 m = 0.30 m

For a diagonal distance between rows of 1.14 m, the geometric correction factor cg is

$$cg = \sqrt{(0.35m)^2 + (0.57m)^2} - 0.35m = 0.318m$$

Substituting in (1)

$$f_{min2,n} = \frac{n\,c}{4(h_B + cg)} = \frac{n \cdot 343\ m/s}{4\,(0.35m + 0.318m)} = n \cdot 128\ Hz$$

This result approximately coincides with the one measured at position PLA03.

3.3 Main attenuation frequencies around 80 Hz

The second group of minimum frequencies, compatible with the seat-dip phenomenon, was measured around 80 Hz, as can be seen in the impulse response for the S02/PLA05 pair in Figure 6. The spectral minimum of 81 Hz appears at 30 ms and persists until 100 ms after the direct signal.

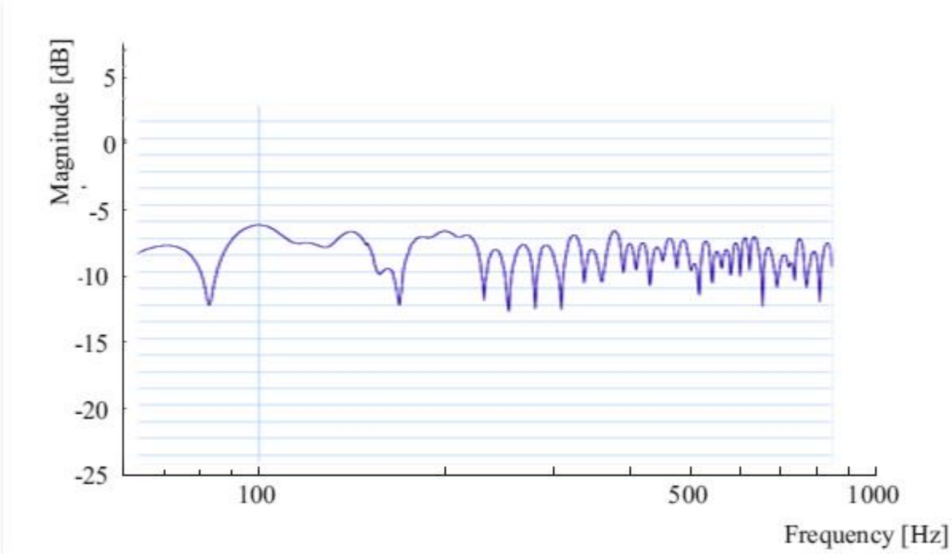

Figure 6. Early establishment of the 83 Hz seat-dip in the centre-left of the main floor (S02/PLA05 pair). The figure shows the result of the rectangular window at 40 ms after the direct sound. The minimum appears at 30 ms and persists until 100 ms.

The possible origin of that attenuation dip is the full-back path of the grazing frontal wave shown in Figure 3. In this case, the entire height of the backrest acts as the effective height h_B:

h_B = maximum backrest height = 0.87 m

For a distance between rows of 1.00 m, the geometric correction factor cg is

$$cg = \sqrt{(0.5m)^2 + (0.87m)^2} - 0.87m = 0.133m$$

Substituting in (1)

$$f_{min3,n} = \frac{n\,c}{4(h_B+cg)} = \frac{n \cdot 343\ m/s}{4\,(0.87m+0.133m)} = n \cdot 85.5\ Hz$$

The second harmonic, with a frequency of 171 Hz, falls within the range of possible seat-dip. The third, at 256.5 Hz, is above the frequency band under analysis.

For non-frontal source/receiver pairs, the full-path minimum reaches 94 Hz when the grazing wave reaches a seat from a horizontal angle of 30°.

Among the many possible paths, the two above —and to a lesser extent, the one crossing the air space under the stalls— stand out when establishing the early seat-dip on the main floor of the Teatro Colón.

4 TEMPORAL RECOVERY OF THE SEAT-DIP IN THE STALLS OF THE TEATRO COLÓN

Having seen and analysed the inevitable early establishment of seat-dip, the fundamental question remains to be answered: why is no seat-dip perceived on the main floor of the Teatro Colón? We believe that the key lies in the rapid temporal recovery which, in the measured positions, is reached at the most 130 ms after the arrival of the direct signal[5]. After that moment, the frequency response remains relatively smooth, with local fluctuations coming in and out over a few ms. There is also no trace of seat-dip in the temporal development of the late reverberant field in the stalls.

All the measurements analysed showed a rapid recovery of the seat-dip. As an example, Figure 7 shows a time-frequency graph measured in the S02/PLA04 pair, in which the evolution of the impulse response was segmented at 20 ms intervals, between 20 and 200 ms from the arrival of the direct signal[6].

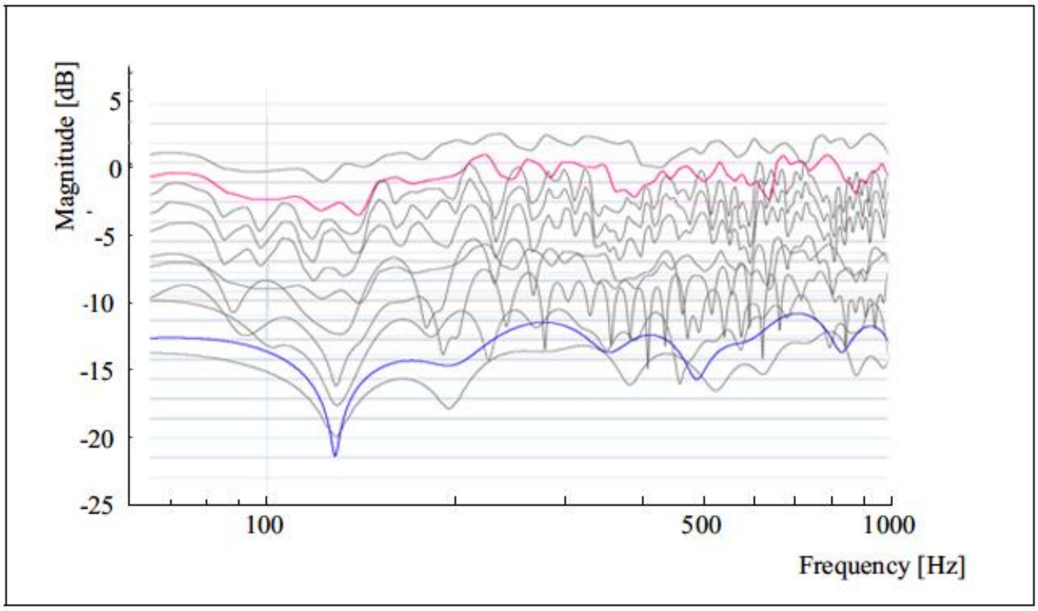

Figure 7. Temporal development of the seat-dip in the centre of the main floor (S02/PLA04 pair) measured at 20 ms intervals. In blue, impulse response at 40 ms; in red, at 200 ms.

The spectral minimum appears at 20 ms and remains until 100 ms after the direct signal. The large low-frequency energy content provided by the early reflections in that location is also noteworthy. A similar recovery pattern was observed in all the measurements in the stalls that presented an early establishment of seat-dip.

Several architectural factors contribute to the recovery by providing a large number of early reflections with non-grazing arrival angles with a broadband spectral content or, at least, with a large amount of energy in the low frequency region[7]. These early reflections originate from the hard surfaces surrounding the stalls, especially the marble wall that runs along its perimeter up to the parapets of the lower boxes and the masonry rear walls of the boxes on all levels. The reflections are directed towards the stalls thanks to the shape of the horseshoe plan of the Teatro Colón, which is slightly different to those of other Italian opera houses, the height and depth of the boxes and, to a lesser extent, the shape of the avant-scène boxes[8].

5 SUMMARY

The early establishment of the seat-dip in the stalls of the Teatro Colón is caused by a multiplicity of factors that combine in different ways depending on the source/seat pair under analysis. In some cases, sound waves passing underneath the seat seem to dominate, while in others, reflections from the floor of the stalls prevail. The effective heights of these paths vary depending on the seat position, resulting in different periodic spectral patterns. The causes of each of these reflections are independent, since they arise from different geometric characteristics, so the fundamentals of the associated harmonic series are not necessarily correlated. In the stalls of the Teatro Colón, the distribution of fundamentals is spaced enough apart to achieve a uniform and relatively smooth spectrum, except when one factor predominates and stands out from the rest, cases wich were described in this work.

The early spectral minima are rapidly compensated for by the arrival of a large number of non-grazing early reflections, which carry a significant amount of bass frequency energy. The rapid and effective early recovery of the seat-dip is apparently the reason that explains the te non-existence of perceptual seat-dip in the stalls of the Teatro Colón.

It is not always easy to find the cause of the early establishment of each seat-dip. Given the complexity of the phenomenon, there may be other factors not considered in this work that could account for a particular occurrence.

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