DETAILS ON STAGE AND ENSEMBLE GEOMETRY RELATED TO MASKING EFFECTS

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INTRODUCTION

This brief article is an addition to Chapter 5 of the author's PhD thesis (Dammerud, 2009). Chapter 5 investigated how the overall dimensions and shape of a stage enclosure affect to what degree the acoustic difficulties implied by the orchestra itself are effectively improved. The acoustic difficulties implied by the orchestra itself were related to loud instruments, particularly percussion and brass, making weaker instruments difficult to hear, due to perceptual masking effects. The masking effects were related to differences in sound levels, directivity of radiated sound and time arrival based on how the orchestra synchronise. The discussion on how a stage enclosure can improve the conditions was based on a large symphony orchestra. In this article the effect of the size of the ensemble and arrangement of the musicians on stage is discussed, simply measured as the width and depth of the ensemble. Some background and overall results regarding beneficial stage enclosure design is given below.

BACKGROUND

For acoustic ensembles the musicians spread sideways across the stage have to start their note simultaneously for the sound to be in time for the audience. These players will experience that the direct sound waves (the sound wave travelling the shortest path from the source to the receiver) from other players at the side(s) are delayed due to the limited speed of sound (approximately 3 milliseconds delay introduced per each metre propagated). If the players spread sideways on stage play adjust their timing based on the acoustic sound from the others, the music will easily slow down. Instead these musicians have to force/train themselves to follow visual cues – from the other players or a conductor – to play synchronised. The string players at the front of the stage can watch the bow of other players to keep track of timing relative to the other players. For a symphony orchestra the string players are normally sitting at the front half of the stage. Towards the back of stage we normally have percussion and brass. The sound of percussion and brass is also delayed and the players at the back have to anticipate the beat relative to the string players at front to provide sound in time for the audience. This means that for the string players at the front half of stage, the sound from percussion and brass will appear at their ears at very much the same time as they produce their own sound, while the sound from fellow string players is significantly delayed. This is illustrated in Figure 1. If the orchestra itself is 16 m wide the sound from the opposite side will be approximately 48 milliseconds delayed relative to sound from percussion and brass sitting in the direction directly behind.

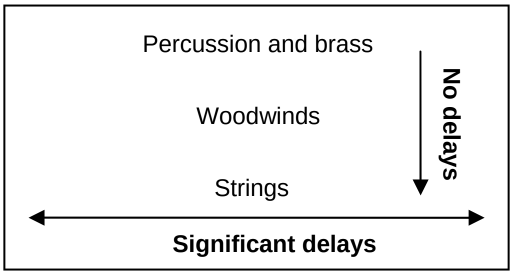

Figure 1: Delays on the direct sound within a symphony orchestra.

On many stages the string players report problems with communicating acoustically within their own group. It is believed that this problem is related to the delay on the string sound, as well as the level other string players being low due to large distance and objects on stage blocking the mutual direct sound (like other musicians, music stands and instruments). The strings are normally among the weakest sounding instrument group, whereas the percussion and brass usually are loud enough or too loud for the orchestra. One of the hypotheses that evolved from the PhD work is that perceptual masking is significant for perceived level balance between instrument groups. Loud sounds appearing at the same time as weaker sounds will easily mask the weak sound and make the weak sound inaudible. This will also include reflections provided by the stag enclosure: it appears detrimental to beneficial level balance if reflections of percussion and brass appear before the delayed direct sound from strings at the sides. Reflections that can mask weak sound were called competing reflections in the PhD thesis, whereas reflections that help to reinforce the weak sound were called compensating. By adjusting the distance reflecting surfaces have to the orchestra, the delay of reflections from different directions will vary. Typically a ceiling reflection of percussion and brass can appear at the string players' ear at the same time as the delayed string sound. Based on this and empirical evidence a too low ceiling was for the PhD work found detrimental for the players' abilities to hear each other clearly, in particular the strings. Under a low ceiling the string players may only able to hear the nearest strings before the reflection of percussion and brass appears and masks the direct sound from the farther string players.

In practice the players may not synchronise this perfect, depending on the quality of performance of the orchestra. Being able to fully anticipate the beat and playing really in time for the audience according to Figure 1 may be relevant only for the best orchestras. Such orchestra may clearly discover the problem with the masking ceiling reflection. Orchestras not being able to adjust their timing to such a level may not have similar problem with the ceiling reflection. If the players at the back do not fully anticipate the ceiling reflection will be more delayed relative to the string sound. For the same reasons some orchestras under a low ceiling may have problems with or avoid playing in time for the audience since that makes it easier to hear the strings (each other).

The stage enclosure can provide reflections from above, the sides and from the back. Reflecting surfaces at the sides close to the strings appear beneficial to boost the low direct sound levels of string. The surfaces at the sides can be designed and angled to give priority to feed string sound back into the orchestra, not so much the louder instruments at the back. Additionally it appears beneficial for the double bass to be close to a wall to raise the levels of double bass for low notes. The surfaces at the sides may also reflect the loud sound from the back of the stage, but with a rather small delay from players close to the side walls. Such reflections will appear together with loud direct sound that will mask weak sounds anyway. The back wall will mainly reinforce the instruments close to it, the percussion and brass, and work as competing reflections. The back wall can be made absorbing or diffusing at the critical frequency range (approximately above 500 Hz). A reflecting back wall at low frequencies may contribute to a fuller sound like for the double basses. The ceiling can provide a delayed reflection of loud percussion and brass at the same time as the delayed string sound, and therefore make it difficult to hear the strings, particularly within the string section. The ceiling reflection can also provide compensating reflections for string. But since the ceiling will provide both competing and compensating the net effect of compensating reflections appears reduced compared to side reflecting surfaces. Additionally, it appears easier to perceptually isolate sound components that are vary spatially in the horizontal plane. We struggle to locate sound waves in the vertical plane and this may contribute to more problems isolated source with reflections from above.

The results and mechanisms at work described above led to one of the major result from the PhD thesis: a narrow and high stage enclosure appears to the best starting point for a beneficial stage enclosure for the orchestra. By having a sufficiently high ceiling the reflection of the loud instruments at the back will arrive after the weak string sound from the opposite side and perceptually open up for the string sound. There may though be some elements above the orchestra at lower height as long as these elements do not significantly reflected percussion and brass directly down towards the strings with a too small delay. A very high ceiling may though not be beneficial as it can produce a too late arriving reflection for the orchestra. Some early reflections can be beneficial as long as they open up for the string sound. Additionally, a high ceiling will make the stage to a large degree acoustically coupled with the main auditorium. This will allow the players to hear the response from the main auditorium on the sound they produce, and not feel acoustically detached from the audience. To what degree is the empirical finding of narrow and high being beneficial linked to temporal masking effects on early sound versus acoustic coupling with the main auditorium? This answer was not answered within the PhD study, but a likely answer is maybe that both aspects are relevant. A high ceiling will in many cases contribute to more acoustic coupling, but also the use of reflectors and the reflectors' shape and angle will affect the balance of stage response back to the orchestra compared to acoustic coupling. The necessary ceiling height of rehearsal hall may be interesting to reveal the importance of ceiling height for internal communication, since acoustic communication with the audience area is in this case not relevant.

Instead of a high ceiling the ceiling may be made absorbing to reduce the level of the reflection. But a low ceiling will lead to the response from the main auditorium having problems reaching the orchestra. Another alternative is to tilt the ceiling so that the reflections of the orchestra are directed towards the main auditorium, not down towards the orchestra. This can make the ceiling appear higher than it actually is and maintain the acoustic coupling with the main auditorium. But in certain circumstances the ceiling is flat, low and reflective and cannot easily be changed. An apparently clever option in such a case, published by Arau-Puchades (2012), to add a grid over the orchestra that will block the direct path for the ceiling reflection within what appears to be the most critical frequency band, within 500 to 2000 Hz. The increased path adds delay and lowers the level of the ceiling reflection, but the acoustic coupling with the main auditorium is likely to be reduced. Figure 2 illustrates the different options to avoid competing reflections from the ceiling while maintaining acoustic coupling with the main auditorium.

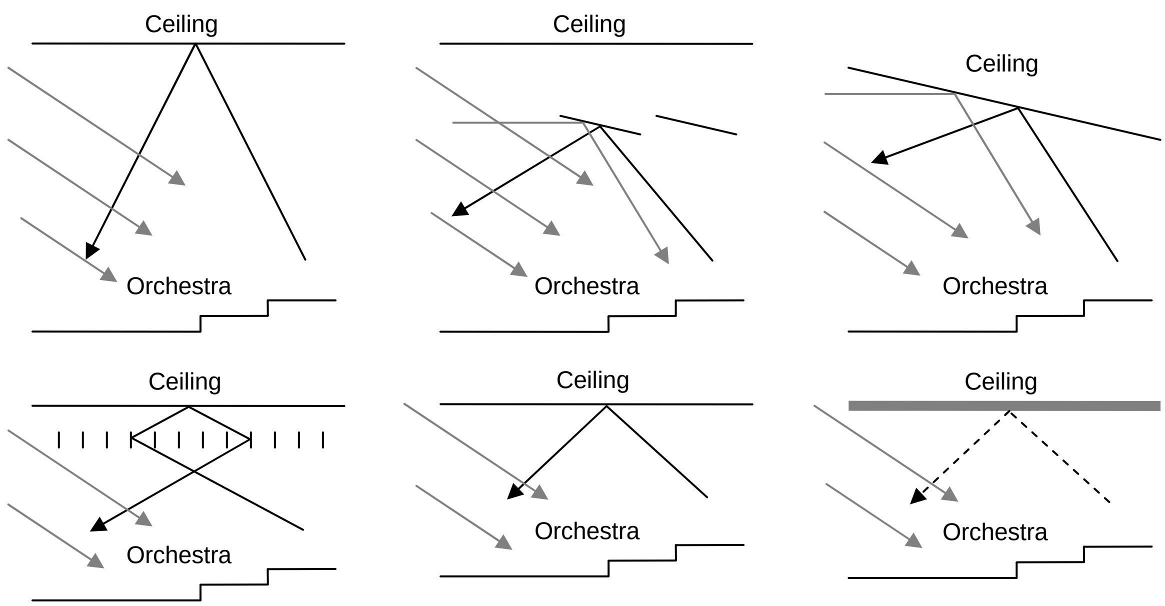

Figure 2: Different stage enclosure designs seen vertically.

As suggested above the optimal ceiling height may be controlled by acoustic coupling as much as avoiding reflections of the loud instruments at the back arriving too loud and early. But it may be useful to investigate how the size of acoustic ensembles and the arrangement of players on stage in general affect the necessary ceiling height to avoid the ceiling reflection of loud instruments at the back arriving before the direct sound of weak instruments at the sides In the PhD thesis the height to any reflecting surface reflecting percussion and brass was denoted H_{rb}. The distance between surfaces likely to reflect strings at the side was denoted W_{rs} (also see Dammerud, 2011 for details). The necessary delay will depend on the size of the ensemble, and consequently also the requirements to H_{rb} and W_{rs}, will be studied into more detail in this article. With a higher ceiling the level of the ceiling reflection will be attenuated (due to the inverse-square law) as well as more delayed. The level reduction due to higher ceiling is therefore also studied in some more detail compared to PhD thesis.

REQUIRED HEIGHT TO SURFACE REFLECTING PERCUSSION AND BRASS

Figure 3 shows a sketch of an acoustic ensemble with a given with W_e and depth D_e. The horizontal surface in Figure 3 represents a simplified representation of the ensemble. The left part of Figure 3 is for a direct sound path from the instruments at the back perpendicular to the side direction, whereas in the right part this path is diagonally across the stage. The diagonal distance is denoted d_e. The required minimum height, H_{min}, to avoid detrimental masking with loud players at the back is found relative to the height of the instruments and the listeners' ears. For the diagonal path some delay is added to the direct sound from the instruments at the back, even if the players at the back fully anticipate the beat.

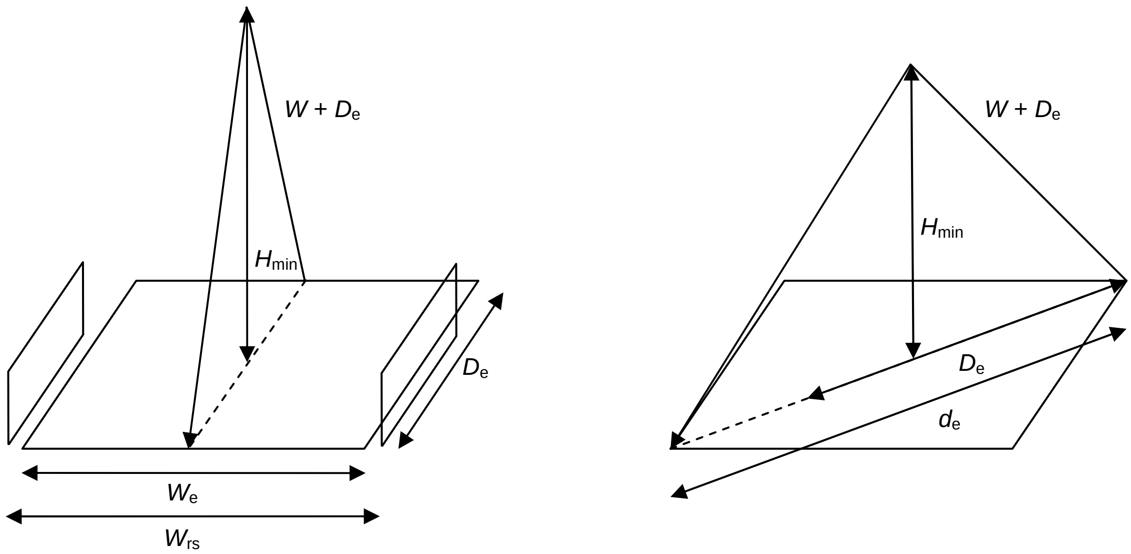

Figure 3: Ensemble dimensions and ceiling height.

The relevant width for the required minimum height to surfaces reflecting percussion and brass, H_{min}, can be either the ensemble with W_e or the distance between surfaces reflecting strings, W_{rs}, as given by Equation (1). Having the relevant width equal to W_{rs} will allow also the side reflection of string players on the outer edge of the orchestra appearing before the ceiling reflection. In principle, the path for the ceiling reflection must be larger than to the total distance of the relevant width and the ensemble depth. To assign the necessary height relative to the stage floor, H_{rb}, 1.6 m has to be added to the minimum height, which corresponds to average instrument and listener height with the instruments the back on a 1 m high riser. Based on the geometry presented in Figure 3 the minimum H_{rb} for the perpendicular path can be found according to Equation (3), while for the diagonal path according to Equation (4).

$$W = W_e \quad \text{or} \quad W = W_e + \left(\frac{W_{rs} - W_e}{2}\right) \cdot 2 = W_{rs} \tag{1}$$

$$H_{rb} = H_{min} + 1.6 \tag{2}$$

$$H_{rb} > 1.6 + \sqrt{\left(\frac{W + D_e}{2}\right)^2 - \left(\frac{D_e}{2}\right)^2} \tag{3}$$

$$H_{rb} > 1.6 + \sqrt{\left(\frac{W + D_e}{2}\right)^2 - \left(\frac{d_e}{2}\right)^2} = 1.6 + \sqrt{\left(\frac{W + D_e}{2}\right)^2 - \left(\frac{\sqrt{W^2 + D_e^2}}{2}\right)^2} \tag{4}$$

In general a compact ensemble will be less demanding on necessary H_{rb}. The diagonal path will result in a smaller value for the required H_{rb}, since d_e always will be larger than D_e. For W = 16 m and D_e = 12 m, H_{rb} must be larger than 14.2 m for the perpendicular path, whereas larger than 11.4 m for the diagonal path. Table I provides some examples of required H_{rb} with risers and on flat floor. With a flat floor only 1.1 m is added to H_{min}, not 1.6 m. with examples. For small ensembles the effect of masking from loud instruments may not be relevant any longer, but small values of W and D_e are nonetheless here included. Figure 4 shows required H_{rb} from on W and D_e, as a 3-dimensional surface. From Figure 4 we see that the width is more 'demanding' on H_{rb} than the depth: the surface is steeper along the W axis compared to the D_e axis.

Table I: Examples of required H_{rb} based on ensemble/stage width W and ensemble depth D_e.

W	D_e	Required H_{rb}	
		Risers	Flat floor
26	12	19.6	19.1
20	12	16.4	15.9
16	16	15.5	15.0
16	12	14.2	13.7
16	8	12.9	12.4
12	8	10.8	10.3
8	6	7.9	7.4
4	3	4.8	4.3

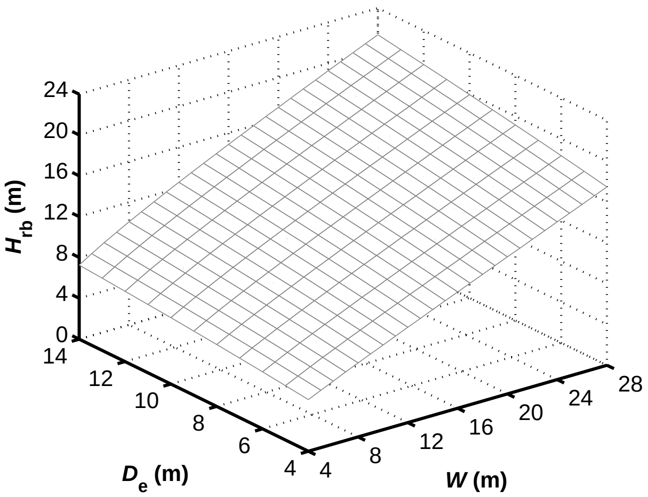

Figure 4: Required H_{rb} based on ensemble/stage width W and ensemble depth D_e.

Figure 5 shows the ratio of required H_{rb} and W as a function of W. With W equal to W_{rs}, the ratio corresponds to H_{rb}/W_{rs}, studied in Dammerud (2009). From Figure 5 we see that narrow ensembles require more a more quadratic relation between H_{rb} and W, while wide ensembles require proportionally lower enclosures. A deep ensemble results in higher values of H_{rb}/W being required.

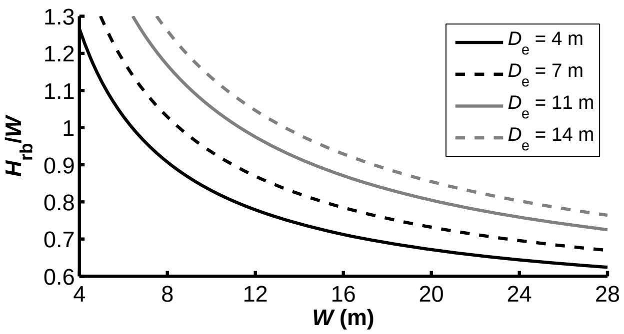

Figure 5: The ratio H_{rb}/W as a function of W, with ensemble on risers.

When increasing H_{rb} the level of the ceiling reduction will be reduced in level as well as more delayed. The level reduction will be due to longer propagation distance, corresponding to a 6 dB level decrease if doubling the propagation distance (inverse-square law). Brass instruments are significantly directional above 500 Hz, leading to lower levels in directions to the sides and above/below compared to directly in front of the instrument, see pages 91 and 92 in Dammerud (2009) for more details. Percussion instruments are often more omnidirectional, with emitted sound level being close to equal in all directions. Equation (5) gives the level of the ceiling reflection, depending of H_{rb} and D_e, solely based on the propagation distance, ignoring the effect of directivity, for the perpendicular case in

Figure 3. The reflection level is here presented as $G_{rb,omni}$ where the level is seen relative to the free-field direct sound level at 10 m distance. The real reduction of brass instruments is therefore expected to be larger than predicted by Equation (5). Figure 6 shows the relation between H_{rb} and $G_{rb,\ omni}$ for four different ensemble depths. The reflection level is most significantly reduced when a low ceiling is raised, and with a low ceiling the ensemble depth D_e has the most significant influence.

$$G_{rb,omni} = 20 - 20 \cdot \log_{10}\left(2 \cdot \sqrt{H_{rb}^2 + \left(\frac{D_e}{2}\right)^2}\right) \qquad (5)$$

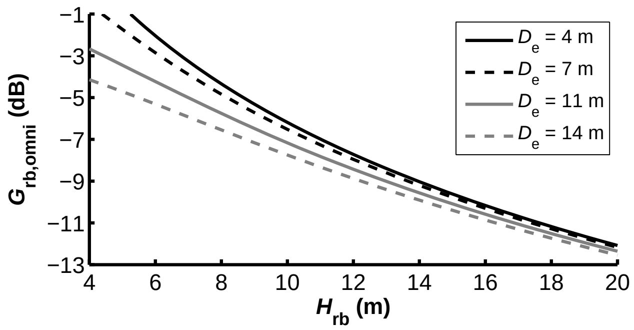

Figure 6: Level of ceiling reflection from percussion and brass.

DISCUSSION

Having many players very close to each other can lead to very high direct sound levels. This suggests there is an optimum ensemble size regarding direct sound levels and temporal masking effects from reflected sound. Given a low ceiling height it may in some cases lead to better abilities to hear the other players with a more compact ensemble setup. Screens and other aids can be used to reduce direct sound levels within the ensemble when the players are sitting close to each other.

Avoiding the perpendicular path for the sound of players at the back may be beneficial. By having the ensemble wider ensemble at the back compared to front, the direct sound from loud instruments can have diagonal stage paths to all players within the string section.

With regard to temporal masking the optimal value of H_{rb}/W_{rs} will depend on the size and proportion of the ensemble. Small ensembles may require a surprisingly high ceiling when compared to the ensemble's width: the required H_{rb} decreases with decreasing W, but when relating the required H_{rb} to W it is actually increased when W is reduced. This may seem counterintuitive. The required vertical room proportion will be a standing rectangle for small ensembles while a lying rectangle for very large ensemble, see Figure 7. The apparent problem with the ensemble occupying a large floor area is that the delay of sound sideways is excessive, combined with poor acoustic coupling with the main auditorium; the orchestra sound can more easily mask the main auditorium's acoustic response to the sound produced by the ensemble. Making the ensemble more compact will require a higher ceiling, but the PhD results suggests that this increase of ceiling height does not have many significant negative effects as long as the height is not well above the required height.

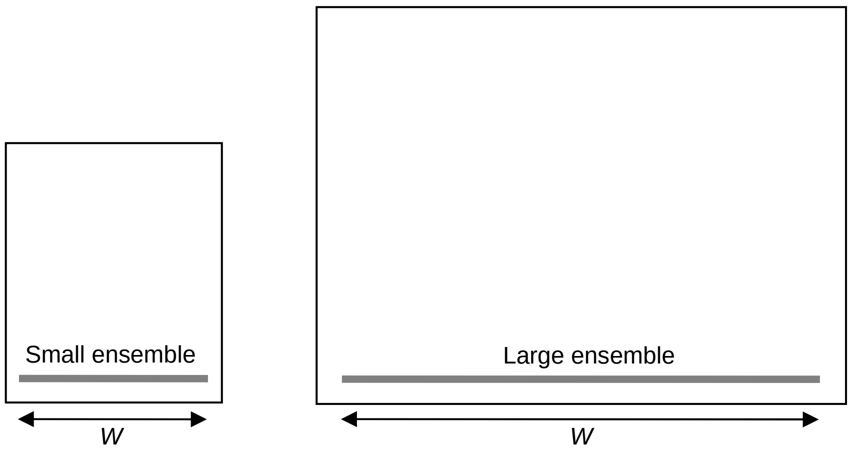

Figure 7: Required stage enclosure/room height-to-width proportions, with regard to avoiding temporal masking.

It is consider useful to have hypothesis regarding perceived acoustic conditions related to physical dimensions that are easy for everyone to observe and test, compared to acoustic measures. Perceived acoustic conditions are believed to relate to perceptual effects like level and temporal masking as well as the cocktail-party effect. The relations between physical conditions and these perceptual effects are not well known. But apparently from the results in Dammerud (2009) simple architectural measures, like W_{rs} and H_{rb}, are more relevant than existing acoustic measures, given that only venues purpose-built for symphony orchestras are studied. Existing acoustic measures mainly sum total acoustic response while ignoring details in time arrival and direction.

CONCLUSIONS

The purpose of this article has been to provide some more details on how the size and proportions of an acoustic ensemble may set requirements to the size and proportions of the stage enclosure or the room the ensemble performs in. The emphasis has been on avoiding loud reflections appearing simultaneously with direct sound from much weaker sound instruments. It is not fully understand the relevance of temporal masking of direct sound from across the stage due to reflections of loud instruments at the back. But as the results are now it should not be ignored, and the results presented in this article may be useful in the search for better acoustic conditions for symphony orchestra or various sized acoustic ensembles in general. Being aware of it can also help to test the hypotheses further in real situations, among both acousticians, musicians, conductors and architects.

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