ACOUSTICS OF THE SALT LAKE TABERNACLE

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Introduction

During the summer months from 500 to 2000 tourists from all over the world visit the Salt Lake tabernacle daily. Guides are furnished who conduct them through the building, explaining as they go the method of and difficulties attending its construction, its dimensions, seating capacity, etc., and conclude by giving them a demonstration of some of its acoustic properties. An attendant drops a pin on a wooden rail, drops it in his stiff hat, rubs his hands, and whispers toward and away from the visitors who are in the balcony at the rear of the building nearly 200 feet away. All of these demonstrations are heard distinctly. The result is that the "Mormon" tabernacle has a very extended reputation of being one of the most acoustically perfect buildings in the world. Being a "whispering gallery" of eminence, however, is not sufficient evidence to determine the perfectness of the acoustics of any building, but rather the hearing must be good in all positions in the auditorium and under all conditions as to the nature of the source emitting the sound.

Because of the widespread reputation of the Salt Lake tabernacle as an auditorium of extraordinary acoustical qualities, and because of its historical significance, the author became interested in carrying out certain acoustical experiments in the building.

An attempt was made therefore to—

I. Determine the variation of reverberation with a variation of:
   (a) Absorption power,
   (b) Position of observer in auditorium,
   (c) Pitch,
   (d) Intensity;

II. Determine to what extent and under what conditions echoes are produced in the auditorium;

III. Determine the distribution of the intensity of sound throughout the auditorium;

IV. Determine the per cent of words articulated in the building under varying conditions.

Method

The method used on all reverberation measurements was essentially that of Sabine. The source of sound was the tabernacle organ itself which could be made to operate, by a proper adjustment of stops, 1, 2, 3, or 4 pipes (of the same pitch and practically of the same quality and intensity) by pressing but one key. The key used in the main was Middle C, vibrating 261 times per second. A determination of the period of reverberation consisted of an average of 20 observations. To eliminate the interfering effect of extraneous noises all determinations were made from 1 to 5 o'clock in the morning. The agreement of determinations taken by one observer on the same date, those taken on different dates, and those taken by a different observer are given in Table no. 1.

Table 1.

First:—Agreement of Observations Obtained at One Setting

Determination	Average Time for 20 Observations	Departure from Mean
1	4.62 sec.	−.05 sec.
2	4.62 "	−.05 "
3	4.68 "	+.01 "
4	4.68 "	+.01 "
5	4.80 "	+.13 "

Average deviation from mean .05 sec. Maximum deviation from mean .13 sec. Probable error less than .05 sec.

Second:—Agreement of Observations Obtained on Different Nights by the Same Observer and Under Similar Conditions

Date	Reverberation
June 23	4.67 sec.
June 26	4.73 "
July 11	4.66 "
July 14	4.75 "

Third:—Agreement of Independent Observations Made by Different Persons

Date	Name of person	Reverberation
July 29	J. J. Toronto	4.69 sec.
		4.68 "
		4.62 "

Reverberation and Absorption Power

By making use of Sabine's formula

$$at = k, \tag{1}$$

(a) being the total absorbing power of walls etc., t the period of reverberation, and k a constant depending upon the volume of the building according to

$$k = .164V, \tag{2}$$

and by opening the many doors and windows in the building we had means of determining (a) and (k). If (x) = the number of square meters of open window space and therefore their respective absorbing power, then,

$$(a+x)t = k' \tag{3}$$

x was made to vary from 0 to 137.7 sq. meters and t varied from 5.07 sec. to 4.30 sec. respectively. By substituting these various values of x and t in equation (3) and solving for (a) and k' we obtain an average for

$$a = 629 \qquad k' = 3190.$$

The detailed results are given in Table No. 2.

TABLE 2.
ABSORPTION AND REVERBERATION TABLE

Determination	No. of doors open	Area of openings	Absorbing power	Absorbing power corrected x	Reverberation in seconds t
1	0	0	0	0	5.07
2	2	13.4	13.4	12.6	5.05
3	4	26.8	26.8	25.2	4.92
4	6	39.7	39.7	37.3	4.78
5	8	51.5	51.5	48.4	4.70
6	10	62.4	62.4	58.6	4.61
7	12	72.3	72.3	67.9	4.42
8	14	82.0	82.0	77.0	4.53
9	14 doors 27 windows	137.7	137.7	132.2	4.30
10	27 windows	55.5	55.5	54.0	4.66

An opportunity was given during an organ recital to measure just how the reverberation would be affected by an audience in the tabernacle. With 1004 people in the balcony, all windows open, ($x = 55.5$) and at noon competing with extraneous noises, ($t = 3.20$ sec.), equation (3) now becomes

$$(684+W)3.20 = 3190.$$

W = 313 open window units. This gives absorbing power per person = .31 and absorbing power per square meter of audience = .73 as compared with Sabine's values of .44 and .96 respectively.

Reverberation and Position of Observation

Determinations of reverberation were made in 11 different positions in the building: in the balcony, under the balcony and in the main body of the auditorium. All determinations agreed within .15 sec. to the average period of 4.76 sec., which shows that the period of reverberation is practically independent of the position in the tabernacle of the auditor.

Reverberation and Pitch

After an abrupt cessation of a chord on an organ, piano, or from an orchestra in an auditorium one notices the changing quality of the residual sound as it decays to minimum audibility. This is due to three causes: First, the materials in the building have a selective absorption

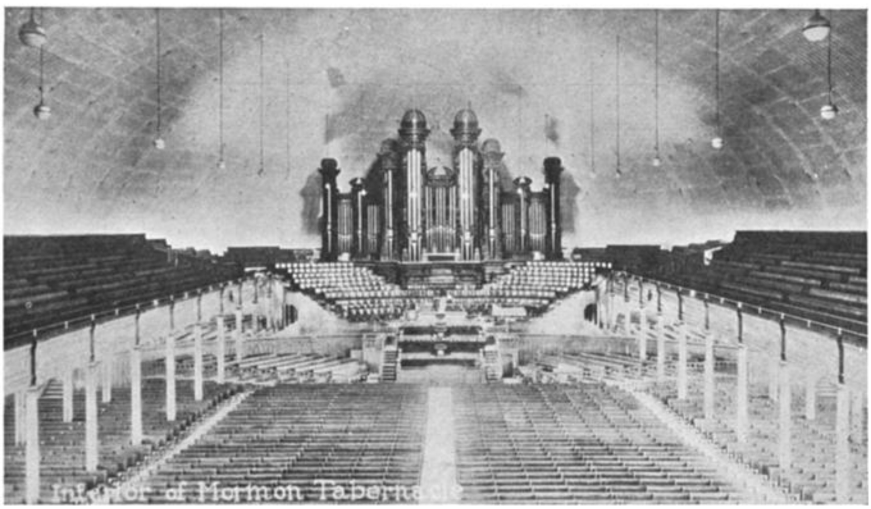

Fig. 1. *Interior of Mormon Tabernacle.*

characteristic. This tends to eliminate by absorption some notes much more rapidly than others, leaving the prolonged notes of a purer tone quality. Second, the intensity of the sound energy varies with pitch. Lord Rayleigh gives the formula for the energy per cu. cm. as $E = 2\pi^2 dn^2 a^2$ where d = density of medium, n = frequency and a = amplitude. Third: the sensitivity of the ear varies with pitch. To show the individual effect of any one of these three factors could not be attempted in this experiment. The results, therefore, show only the combined effect.

Determinations were made for 16 different notes, all in the same set of pipes and blown with the same pressure, namely, .54 pounds per square inch. The period of reverberation varied from $t=1.63$ sec. for C_4, 16 v.p.s. to a maximum of $t=5.21$ sec. for F, 348 v.p.s., thence down to $t=0.97$ sec. for C^v, 8,368 v.p.s. These results show that the duration of residual sound under these conditions varies greatly with pitch, being relatively short for the high and low frequencies as compared with the time for the note F, 348 v.p.s. They are shown graphically in Figure 2.

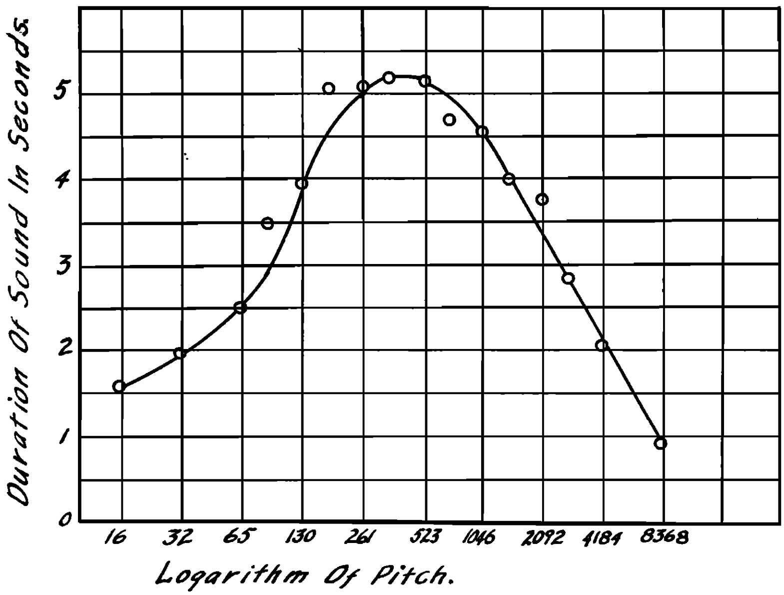

FIG. 2. *Curve showing variation of reverberation with variation of pitch.*

REVERBERATION AND INTENSITY

This part of the experiment was attended with some uncertainties. To obtain accurate results one should have four exactly similar pipes which when blown by the same pressure will give notes of equal intensity, and when blown together will give intensities 2, 3 and 4 times greater than one alone, providing the vibrations of one are not affected by that of another. Not having four similar pipes giving notes of equal intensities and quality on the Tabernacle organ, the writer used four notes which were as much alike as could be obtained. The pipes were all of the same pitch, Middle C 261 v.p.s., and blown by an air pressure of .54 lbs. per sq. in.

By determining the duration of residual sound when first one pipe is blown alone and then two, three, and four pipes together, some very interesting facts may be determined. They are:

(1) The initial intensity (I_1) of the sound in terms of the intensity of minimum audibility (i').

(2) The constant of decay (A) under different absorbing conditions.

(3) The mean free path of sound between reflections.

(4) The determination of the volume of the building which will serve as a check on actual measurement of the volume.

In making these determinations use was made of the following formulae taken from Sabine's work:

$$I_1 = i'e^{At} \quad (4) \qquad At_n = \log \frac{nI_1}{i'}, \quad (5)$$

$$A = \frac{\log n}{t_n - t_1} \quad (6) \qquad A = \frac{va}{pS} \quad (7)$$

$$p = \frac{v.164V}{AST} \quad (8) \qquad k = \frac{k'T}{t} \quad (9)$$

where I_1 = intensity of sound at the stopping of the sounding pipe

i' = intensity of minimum audibility
$I = 1{,}000{,}000\ i'$
A = constant of decay
n = number of pipes in operation
v = velocity of sound, 343 m. per sec. at 22°C.
V = volume of tabernacle = 35,300 c. m. from direct meas.
S = absorbing surface = 9,350 sq. meters from direct meas.
p = mean free path between reflections
t_n = period of reverberation for n pipes
T = period of reverberation for $I = 1{,}000{,}000\ i'$
k = hyperbolic parameter for $I = 1{,}000{,}000\ i'$

Observations and computations are given in Table no. 3.

Sabine proved experimentally that in irregularly shaped rooms, the mean free path is proportional to the cube root of the volume. Two rooms in the Boston Public Library of which he makes record have volumes 2,140 cu. meters and 63.8 cu. meters and mean free paths 7.8

TABLE 3.

	Square Meters of Open Windows			
	$W=0$	$W=54$	$W=132$	Average
$^*t_1=$	4.86	4.59	4.44 sec	
t_2	5.67	5.17	5.02 "	
t_3	5.83	5.34	5.11 "	
t_4	5.97	5.43	5.30 "	
A (average) from (6)	1.23	1.43	1.53	
I_1	$437i'$	$702i'$	$898i'$	
T for $I=1{,}000{,}000i'$	9.37	8.05	7.53 sec	
k for $I=1{,}000{,}000i'$	6,040	5,600	5,400	5,680
p from (7) in meters	18.8	17.6	18.2	18.2
p from (8) in meters	18.4	18.5	18.4	18.4
V from $k=.164V$	36,800	34,200	32,900	34,630
V from direct measurements=				35,300

* t_1 was slightly different for each of the 4 pipes used.

and 2.27 meters, respectively. The mean free path in the tabernacle determined by comparison with these give 19.9 and 18.6 meters. This becomes an interesting check upon measurements recorded in this paper.

ECHOES IN THE TABERNACLE

If the source of sound in a room is a short, sharp impulse, it will spread out in all directions as a group of waves. If the room is a large one and if an observer is standing in the center, he will very likely hear two or three repetitions of the same impulse, the first one coming direct from the source, the others being a reflection and double reflection from the walls and ceiling. If he be seated in a position where the difference in path of the direct impulse and the reflected impulse is less than 75 feet he will perceive the two portions of the wave in the form of a single sensation of hearing, each louder than the effect which either part would have produced alone. In this case, instead of hearing an echo, the original impulse was reinforced. If the wall is curved the effect is generally either a more pronounced echo or increased reinforcement. In an auditorium the size and shape of the tabernacle one would expect both of these phenomena to be present. This is why a listener can hear so much better in the rear end of the balcony than in the middle of the main floor where he is from 50 to 100 feet closer to the speaker. In the balcony he hears the original impulse reinforced by reflections from behind, above and on both sides. In the center of the building and for some distance behind a direct impulse of one syllable reaches the ear of the listener at the same time that the reflected impulse of the syllable that just preceded. The result is confusion or strained attention which becomes wearisome to the extreme if long maintained.

An effort was made to determine to what degree successive echoes were produced in the tabernacle. The source of sound was a highly damped clap produced by the impact of a block of wood and a block of iron. An attendant of the building operated the source at the main pulpit, while the author made observations at every point on the main floor and in the balcony. Nowhere were successive echoes perceived except down the center aisle, from a point very near the center of the floor to a point 30 feet back. In this region three audible successive echoes were heard. Fifteen feet on either side of this region there existed a phenomenon which could hardly be called echo but could be better described as a throbbing reverberation. It is in this region, probably 50 feet square, where hearing is attended with greatest difficulty because of the interference produced by successive reflections or echoes. Other places were equally bad but they are a result of low intensity rather than interference due to echo.

When the source of sound was carried by the observer, four points in the balcony symmetrical with respect to the center line of the building were strikingly singular. At these points as many as 14 distinct successive echoes could be heard all within 3 seconds after the clap of sound was made. This phenomenon is not a serious acoustical defect of the building since a source of sound is never at these points.

Distribution of Intensity of Sound in the Tabernacle

The method used in this part of the experiment was one suggested by Dr. Harvey Fletcher and used on similar experiments in the Bell Telephone laboratories. The source of sound was a vacuum tube oscillator, vibrating 806 times per second, located at the main pulpit. Two telephone receivers, mounted on a head support and held $1\frac{1}{2}$ inches from the ear by a wire cage, were carried to all parts of the building. These head phones were shunted across a potentiometer arrangement by which the current in them and likewise the intensity of the sound emitted by them could be varied to any degree desired. The current was first sent through the stationary receiver and then through the head receivers. The potentiometer was adjusted until the intensities were the same from both sources. When this balance is made it can be shown that the intensity of the sound produced varies directly as the square of the shunt resistance. The unit of intensity was taken as the intensity of sound when the head phones were one meter from the pulpit receiver. Use was made throughout of the formula:

$$I_n = \left(\frac{R_n}{R_0}\right)^2$$

where R_o is the balance resistance one meter from the source R_n the balance resistance at ony other station in the auditorium and I_n is the corresponding intensity. Observations were made at 37 different positions in the building. These showed variations in intensity from 15 per cent to 4.2 per cent of the intensity one meter from the source. R_m for minimum audibility was found to be 0.10 ohms.

The following table no. 4 gives a few of the stations observed. Stations numbered 1 to 5 were down the center aisle. The last 4 were on the north side under the balcony. Each determination for any station represents an average of 10 settings for R_n.

TABLE 4.

Station	Distance from source in meters	R_n	I_n	I_n/I_m
0	1	41.1	1.00	170,000
1	10	15.9	.150	25,200
2	18	14.3	.121	20,200
3	28	13.9	.114	19,000
4	37	14.3	.121	20,200
5	45	15.0	.133	22,200
21	28	12.1	.086	14,300
20	36	10.3	.063	10,500
19	43	8.47	.042	7,000
16	52	9.43	.053	8,800

If a sound of constant pitch be long sustained in an auditorium, certain trains of waves will traverse a course which will be little different from that traversed by another set. These will overlap and as a result will either reenforce or mutually destroy each other. This phenomenon is called interference and is common in all types of wave motion. The writer discovered early in the course of this investigation that this phenomenon existed in the tabernacle and had to be dealt with. Often it was possible by moving the head six inches to move it from a point of maximum intensity to a point of maximum interference. Measurements were made to determine the relation between maximum and minimum intensities at these points. For a point of maximum intensity $R_n = 16$, and for a region of minimum intensity $R_n = 4$, showing a ratio of intensities of 16 to 1. Throughout the experiment an attempt was always made to have the head of the observer in a region of maximum intensity. By slowly walking down the center aisle of the tabernacle the author counted 45 of these regions of maximum intensity through which the head passed.

Articulation Tests in the Salt Lake Tabernacle

In the spring of 1928 this investigation was extended to determine the per cent of, and the variation of, word and syllable reception with a variation of voice intensity, position of auditor in the building, size of audience, etc. The per cent of increase in word reception when electrical speech amplifiers were used was likewise determined. Twelve to fifteen students from the physics department of the Weber College cooperated with the author in making the investigation. The method used was that in which the author called out 75 nonsense syllables or unrelated words in groups of 3. The time required to sound a particular combination of three syllables or words was two seconds and the time between

Table 5.

	Audience	Voice	Per cent reception		
			Minimum	Maximum	Average
Syllable	None	Normal	23	76	39[3]
Syllable	"	3×Nor.	42	76	52[3]
Word	"	Normal	18	68	36[3]
Word	"	3×Nor.	30	84	52[3]
Consonants	"	Normal	42	88	67[3]
Consonants	"	3×Nor.	80	98	93[3]
[1]Words	3100–½ full	3×Nor.	43	70	59[4]
[2]Words	"	Amplifier	64	88	80[4]

[1] 90 per cent maximum single record.
[2] 97 per cent maximum single record.
[3] Average of 3 records in 12 different positions.
[4] 120 records from all parts of the building in 11 different positions.

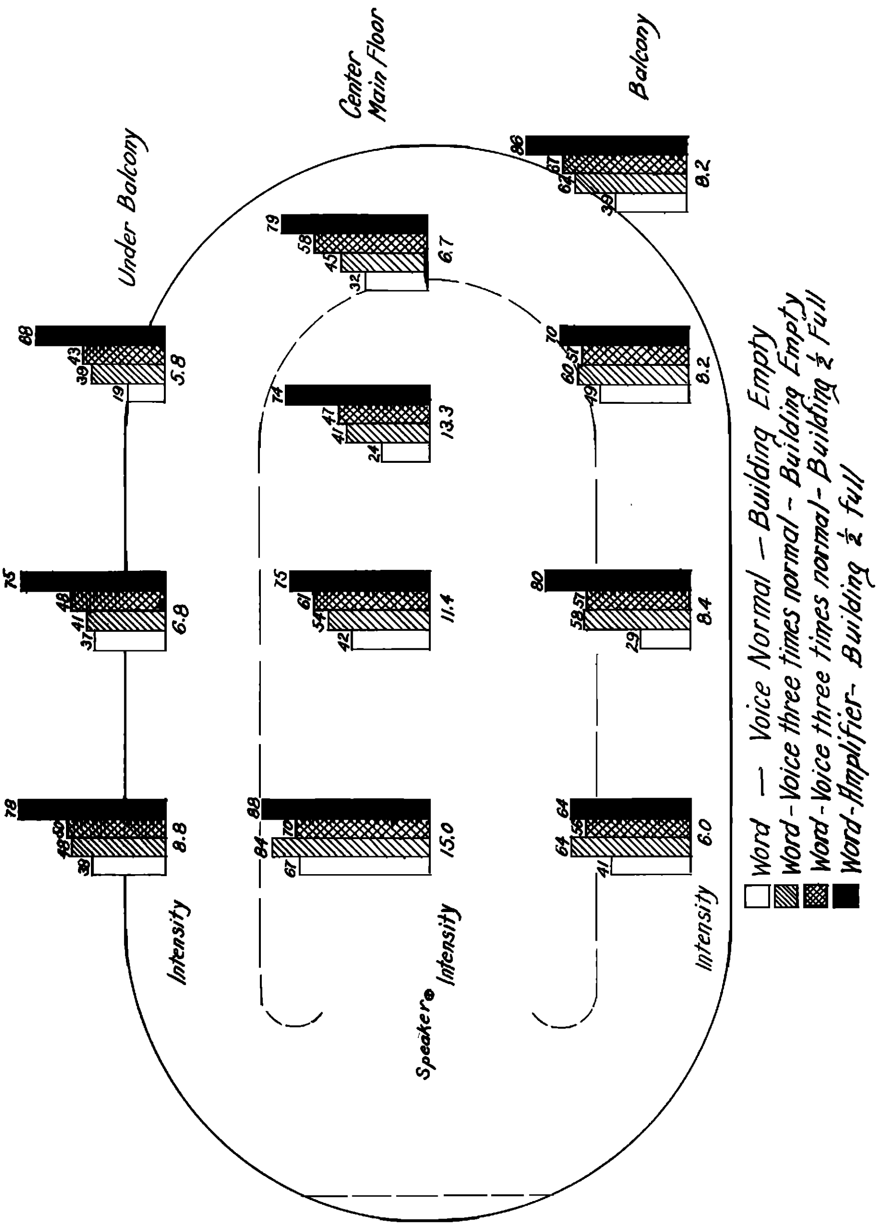

FIG. 3. *Showing variation in word reception with variation in position, voice, intensity, and audience in Salt Lake Tabernacle.*

combinations was approximately $8\frac{1}{2}$ seconds. The auditors (12 to 15 in each position making $12 \times 75 = 900$ syllables heard in each position) wrote what they heard and later compared their results with the originals to determine the per cent of reception. Many preliminary tests were made in various rooms at the Weber College and in the open air to become acquainted with the methods and to standardize the units of loudness.

Two different degrees in the loudness of voice were used—First, that of normal conversation or about 47 sensation units, second, that which was three times normal or that which can be heard three times the distance of normal which would be equivalent to about 57 sensation units.

Results are given in Table 5.

These results are shown graphically in Figure 3.

Conclusions

The conclusions drawn are as follows:

(1) Hearing is obviously best immediately in front of the speaker. It slowly decreases as one recedes down the center aisle and then rises again near the rear.

(2) Hearing is poorest under the balcony and east of the north aisle.

(3) Hearing is better on the whole in the balcony than under the balcony.

(4) Good hearing is fundamentally dependent on loudness of voice increasing from 39 per cent for normal voice to 59 per cent for voice $3\times$ normal and to 80 per cent for the amplified voice.

(5) Good hearing is dependent upon the period of reverberation increasing from 52 to 59 as reverberation decreases from 5 seconds (empty) to 2.3 seconds (3100 persons present).

(6) There is practically no difference in word and syllable articulation in the Salt Lake Tabernacle.

(7) Finally, it is seen that the effects of sound which may exist in a room are loudness or intensity, reverberation, echoes, and interference, the three latter are characteristic of the building itself. It has been shown that the acoustics of any auditorium vary with the number of different factors, namely, volume, absorbing power, audience, pitch, intensity, duration of a sounding source, echoes, interference, etc. In an auditorium the audience may be small, the speaker's voice vary in intensity and pitch and the entertainment a musical number or an

address, all of which produce widely different effects on a listener. The best arrangement for good acoustics can only be a compromise where the average conditions are fulfilled.

For reverberation this compromise seems to have been well met in the construction of the Salt Lake Tabernacle. When an audience fills this auditorium the reverberation is a little more than a second, a period which is about right to produce the best effects on a listener when the entertainment is musical, and which is a little too long for ideal conditions when the entertainment is an address. It is indeed remarkable for an auditorium of this volume to have a reverberation of less than 5 seconds when the building is empty and about one second when filled with an audience.

The interference by successive reflections which was noted in certain sections of the tabernacle could be greatly reduced by placing some efficient absorbing material on the walls. This would lessen to a great extent the intensity of reflected waves. But since an auditor in the rear of the building (and in the balcony) is so dependent on these reflected waves for good hearing, it is doubtful that anything could be gained.

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