In-situ Sound Insulation Performance of Interior Doors with Slit-shaped Apertures

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Abstract
In a building, doors are one of the weakest building elements regarding sound insulation, which is mainly due to inevitable sound leaks. Although there are some studies based on laboratory experiments, the influence of the aperture on the sound insulation performance under real building conditions have rarely been discussed. This work focused on the total sound insulation of doors with slit-shaped apertures at the bottom. Both in-situ measurements and theoretical predictions were performed on 30 interior doors. The total sound insulation through the door leaf and the aperture was acquired by measurement, and the relationship between the sound insulation performance and the width of aperture was found. The predictions on the total sound insulation were calculated by Gomperts' theory, and were compared with the in-situ measurements. In addition, the effects and the limits of $m$ and $n$, the numbers indicating the incidence sound field and the aperture position, on prediction were investigated. Accordingly, the proper numbers of $m$ and $n$ were recommended for better prediction of the sound insulation of interior doors.

Keywords: total sound insulation; sound insulation performance; transmission; door; aperture

1. Introduction
Narrow gaps or apertures around building elements, such as doors, window sashes and partition walls, are a major cause for the deterioration of sound insulation performance. In particular, the door is one of the weakest building elements due to its inevitable sound leaks at the perimeter. It is common for typical interior doors of residential buildings in Korea to have an aperture at the door's bottom in the form of a straight-edged rectangular slit, and it is a main path for sound transmission. Therefore, this aperture plays a leading role in the sound insulation performance of interior doors. Despite the frequent use of doors in daily life, the effect of a door's aperture on sound insulation is rarely studied by both experimental and theoretical approaches under real building conditions.

Several theoretical estimates for sound transmission through a slit-shaped aperture or a circular aperture have been made. One of the pioneering studies was conducted by Gomperts (1964, 1967), Wilson (1965), etc. Gomperts derived the formulae for the transmission coefficient for both circular and slit-shaped apertures in a thick wall. The author related the velocity potential in a slit-shaped aperture to the velocity potential of cylindrical waves in order to describe the transmission coefficient as a trigonometric function. For slit-shaped apertures, he concluded that average trends between theoretical and experimental results were in good agreement. Another approximate method was derived by Wilson et al. (1965), who considered the normal incidence transmission loss of circular apertures in a wall of finite thickness. They reported that the approximate solutions were in good agreement with the experimental results within the expected limits of experimental error. In these two models, the propagating wave inside the aperture is assumed to be a plane wave.

The previous theoretical models have been experimentally validated and reviewed by others. Oldham et al. (1993) measured the transmission loss of both circular and slit-shaped apertures in walls using the sound intensity technique. Their experimental results agreed very well with the Wilson-Soroka (1965) approximate model for circular apertures and with the Gomperts-Kihlman (1967) model for slit-shaped apertures. Hongisto et al. (2000a) applied Gomperts' model to calculate the sound reduction index (SRI) of one steel door with a slit-shaped aperture at the door's bottom. His results showed that the measured SRI curve conformed to the calculated SRI curve below the slit resonance frequency, but the position of the slit resonance frequency was not correct. Kim et al. (2009) recently compared the results by laboratory test with Gomperts' solutions in eighteen cases of slit-shaped aperture dimensions which can occur in a real door. They suggested that the accuracy between two values was within 2 dB in terms of the weighted SRI.

Some studies (Gomperts, 1964; Oldham et al., 1993; Kim et al., 2009) showed that the depth-to-width ratio...
of slit-shaped apertures was closely related to the sound transmission through an aperture. Considering the depth of the aperture decided by the thickness of the interior door, however, the sound insulation of the door generally depends on the width of the aperture. Actually, for architects and acoustical engineers, it is important to perceive the extent to which the aperture width could lead to the deterioration of the door's sound insulation and how the aperture width should be controlled to satisfy the criteria of sound insulation performance. Above all, useful information, such as various experimental results and theoretical applications under field conditions, should be provided. Despite the importance of these issues, relatively few authors have dealt with these concepts, although some have studied the transmission of an aperture under laboratory conditions.

The aim of this work is to investigate the total sound insulation of interior doors by means of in-situ measurements and theoretical predictions to understand the effect of the door apertures on sound transmission under real building conditions. This work focuses on the slit-shaped aperture at the door's bottom. The measurements are taken from a total of 30 doors in residential buildings, and the total sound insulation through each door leaf and the aperture is presented. The relationship between the total sound insulation performance and the aperture size is analyzed, and the effect of the aperture is discussed. Predictions for all 30 doors are calculated by Gomperts' model which can be used for sound transmission through a slit-shaped aperture, and are compared with the in-situ measurements. Additionally, the effects of \( m \) and \( n \) indicating the incidence sound field and the aperture position on predictions are investigated.

2. Theory and Methods
2.1 Theoretical model for sound transmission through a slit-shaped aperture

When the size of an aperture on a structure is small compared to the acoustic wavelength of interest, the transmission coefficient through the aperture depends on the frequency according to the relationship between the thickness of the structure and the size of aperture. The transmission coefficients, \( \tau_{\text{slit}} \), through a slit-shaped aperture based on Gomperts' model (1964) can be expressed as the following:

\[
\tau_{\text{slit}} = \frac{m K \cos^2(Ke)}{2n^2 \left[ \sin^2(K(X + 2e)) + \frac{K^2}{2n^2} [1 + \cos(KX) \cos(K(X + 2e))] \right]}
\]

(1)

where \( K \) is the product of the wave number and the width of the slit \((=kw)\); \( X \) is the depth-to-width ratio of the slit \((=d/w)\); \( e \) is the end correction factor for a straight-edged slit assuming a slit of infinite length in an infinite structure and can be expressed as \( e = (1/n) [\ln(8/K)] \cdot 0.57722 \); \( m \) is a constant dependent on the nature of the incident sound field \((m = 8\) for a diffuse field and \( m = 4 \) for a plane wave at normal incidence\)); \( n \) is a constant dependent on the position of the aperture in the wall \((n = 1\) for a slit in the middle of the wall and \( n = 0.5 \) for a slit in the edging of two walls at right-angles to each other).

In this work, Gomperts' model for a slit-shaped aperture, equation (1), is used to predict the sound insulation performance of interior doors with apertures at the bottom. The transmission loss curve through a slit by equation (1) has dips at the frequencies where the sum of the aperture depth and the end correction corresponds to an integral number of half-wavelengths.

In typical residential buildings in Korea, most inner walls with interior doors are made of reinforced concrete between 140-160 mm thick. In addition, the widths of the door frames are slightly thicker than the thickness of the reinforced concrete wall. Therefore, the sound transmission through the inner wall and the door frame can be ignored because the transmission coefficients of these two components are very small compared with that of the interior door leaf and aperture. Ultimately, the sound transmission through a door with an aperture can be divided into two paths. One path is the structure transmission through the door leaf, and the other is the slit transmission through a slit-shaped aperture as shown in Fig.1.

Fig.1. Configuration of Two Sound Transmission Paths on an Interior Door with an Aperture

The total transmission loss of a door through both paths can be expressed by the area-weighted sum of transmission coefficients, as shown in equation (2) (Hongisto, 2000b):

\[
TL_{\text{total}} = 10 \log \left( \frac{1}{\tau_{\text{total}}} \right) = 10 \log \left( \frac{S_{\text{structure}}}{S_{\text{slit}}} \cdot \frac{S_{\text{total}}}{S_{\text{structure}} + S_{\text{slit}}} \right)
\]

(2)

where \( TL \), \( \tau \), and \( S \) are the sound transmission loss, transmission coefficient, and area, respectively. The subscript 'structure' and 'slit' indicate each sound path, and the subscript 'total' indicates the sum of both paths.

2.2 Survey of interior door and its aperture

The interior door in this work indicates a barrier-free designed door without a doorsill for the elderly
and the handicapped, which is typical of doors in domestic residential buildings. Most interior doors are formed from a plate-cavity-plate system on a frame. Door leaves are primarily made of MDF (medium density fiberboard) approximately 4.5 mm thick with 700 kg/m$^3$ density, but the cavities are installed with slightly different thicknesses. Timber lath and stud or paper honeycomb is installed in the cavity between the MDF on both sides for support. Fig.2. shows the sections of a typical interior door as an example. The typical width, height and thickness of interior doors range between 800-900 mm, 2,000-2,200 mm, and 35-45 mm, respectively. Door frames are typically 160-220 mm wide and 20-50 mm thick and made of a plate and board. They are generally installed at the edge of the door opening, except for the bottom. A door stopper is also installed on the doorframe.

Most interior doors have an aperture at their perimeter. In general, a simple rectangular slit is formed between the bottom of the door leaf and the flooring. An L-shaped slit is formed at the upper end and both vertical sides of the perimeter by the door leaf, door frame and door stopper. The L-shaped slit, with one internal bend, maintains a tortuous route through a more complex cross-section than the rectangular slit.

First of all, the survey on the sizes of apertures was performed in residential buildings located in the Seoul metropolitan area. The width of the rectangular slit at the bottom of the door was measured for 67 doors in 7 different apartment complexes, and the L-shaped slit was measured in 12 doors of one apartment complex. For delicate measurements, a feeler gauge and a scale ruler were used. The width of the rectangular slit and L-shaped slits for individual doors were calculated by averaging the measured values from 3-5 points for each slit. The measurements for each apartment building are shown in Table 1. These results showed that the interior doors have varied slit widths of 3.2-13.6 mm (avg. 7.1 mm) for the rectangular slit and 1.5-4.7 mm (avg. 2.9 mm) for the L-shaped slit. Accordingly, it seems clear that the rectangular slit will be a primary sound path based on its shape and width. In addition, it is inferred that the reason for various slit widths is mainly due to poor workmanship and the absence of guidelines for determining the minimum slit width for sound insulation.

### 2.3 In-situ measurements

The purpose of the in-situ measurements is to obtain useful data on the sound insulation of doors under real building conditions. Considering the typical floor plan of residential units in Korea, bedrooms are usually connected with the living room or the corridor coupled with a living room. In many cases, the bedrooms, the living rooms and the corridors do not provide sufficient room volume which can minimize the effect of room modes and have various shapes; so, it is hard to make a truly diffuse sound field and to measure a reliable reverberation time. Thereby, in this work, the sound pressure level (SPL) difference between two points, $D_p$ is measured in accordance with Korean Standard (KS) F 2809 Annex 2 considering these measurement conditions. This annex is applied to find the airborne sound insulation between two specific points in the building when the measurement conditions are not able to comply with the body of KS F 2809 (this is similar to ISO 140-4). The annex recommends that the measurements should be done under the ordinary use of the building. After the SPL difference $D_p$ is acquired from the measurement points in the source area and receiving area, the weighted SPL, $D_{p, w}$ is evaluated in accordance with KS F 2862 (this is similar to ISO

| Name of Apt. | No. of doors for meas. | Measured slit width (mm) | Slit position at door perimeter |
|--------------|------------------------|--------------------------|--------------------------------|
| D            | 6                      | 8.1                      | 11.4                           | 9.5                           | 1.13                           | lower part                      |
| T            | 21                     | 3.7                      | 12.8                           | 6.3                           | 2.16                           |
| K            | 9                      | 3.2                      | 4.9                            | 3.9                           | 0.55                           |
| S            | 11                     | 4.2                      | 13.6                           | 7.8                           | 3.23                           |
| P            | 6                      | 5.7                      | 11.5                           | 8.9                           | 2.56                           |
| H1           | 2                      | 7.4                      | 11.9                           | 9.7                           | 3.18                           |
| W            | 12                     | 4.5                      | 10.5                           | 7.9                           | 2.07                           |
| W            | 12                     | 1.5                      | 4.5                            | 3.0                           | 0.90                           | upper part                      |
| W            | 12                     | 1.5                      | 4.7                            | 2.8                           | 0.93                           | vertical part                   |

**Table 1. Measured Slit Widths of Door for 7 Apt. Buildings**

![Fig.2. Section View of a Typical Door: (a) Cross Section, (b) Vertical Section; unit (mm)](image_url)
717-1) to review the sound insulation performance of the measured door as a single-number value. For measurements, white noise is generated from the omnidirectional loudspeaker (AP600, CESVA) and the SPL is measured using the four-channel signal acquisition system (Harmonie, 01dB).

Measurements for the sound insulation performance of interior doors were carried out for 30 doors in four different apartment complexes (D, H, S, and P). All these complexes are new buildings, and measurements were performed just before the residents moved into the buildings to provide the optimum conditions for measurement. The partition wall in the bedroom consists mainly of a concrete wall and interior door. The effect of the sound transmission through the concrete wall is not reviewed directly in this work. However, according to the basic properties of materials for sound insulation, the sound transmission through the concrete wall as a franking path can be ignored.

The measurement conditions and arrangements are shown schematically in Fig.3. The bedroom was selected as a source area, and a loudspeaker was placed in the corner of the bedroom to provide a sound field as diffuse as possible. The measurement points of source area and receiving area were respectively set at positions 1 m apart from the measured door with three heights of 0.5 m, 1.2 m and 1.9 m from the floor level. The reverberation times in the receiving area were between 0.70 sec and 1.19 sec at 500 Hz.

The outline of the measured doors is shown in Table 2. The doors for each apartment are of the same structure. All measured doors had similar features in terms of dimension, material, structure and installation method. However, in the case of five doors from the H apartment building (H2), an adjustment plate of 890x2,120x40 (height) x (length) x (width) x 3-6mm (thickness) was experimentally installed on the flooring just under the door leaf to control the width of the slit-shaped aperture within 3 mm as a minimum clearance. The door apertures were controlled using two seal perimeters was measured in four apartment buildings. The sound insulation of 30 doors sealed at their perimeters was measured in four apartment buildings. This measurement intended to estimate not only the deterioration in the door's sound insulation due to any possible apertures, except for the slit-shaped aperture at the door's bottom, were meticulously sealed with double taping on both sides of the door. In addition, to check the sound transmission loss through the door leaf only, $T_{L,\text{door}}$, a slit-shaped aperture at the door's bottom was also sealed with double taping on both sides of the door after inserting a foam rubber densely into the aperture.

3. Measured Results and Discussion

3.1 Sound insulation of sealed doors

The sound insulation of 30 doors sealed at their apertures. The weighted SPL differences for 30 doors showed 32±1 dB in the weighted SPL difference.

### Table 2. Outline of the Measured Doors

| Name of Apt. & No. of meas. door | Dimension [wide x height x thickness] | Description of door structure |
|---------------------------------|--------------------------------------|------------------------------|
| D 6 875 x 2,090 x 36             | MDF 4.5 + Air Cavity 15 to 27 (support honey-comb paper and support lath) + MDF 4.5 + MDF 4.5 |                           |
| H (H1) 2                        | MDF 4.5 + Air Cavity 31 (with honey-comb paper and support lath) + MDF 4.5 |                           |
| (H2) 5 890 x 2,120 x 40          | The door (H2) has the same structure as the door (H1), and additionally the adjustment plate is installed on the flooring just under the door leaf. |                           |
| S 11 875 x 2,210 x 24 to 36      | MDF 4.5 + Air Cavity 15 to 27 (15: in the middle of a door leaf with an area of 665x1910, 27: in the edge of door leaf with the other area) + MDF 4.5 |                           |
| P 6 830 x 2,150 x 40             | MDF 4.5 + Air Cavity 31 (support lath and stud) + MDF 4.5 |                           |

Fig.3. Floor Plan Indicating the Measurement Conditions and View of Measurement; unit (mm)
3.2 Total sound insulation of doors with slit-shaped apertures

Fig. 5. indicates the measured SPL differences, $D_p$, for the doors from four apartment buildings (D, H1, S, and P). The average slit widths for each apartment ranged between 7.8 mm and 9.7 mm (see Table 1.). In Fig. 5., the top and bottom of the vertical bars indicate the maximum and the minimum value, respectively, while the dot symbol indicates the average value. Compared with the results from the doors without apertures, as expected, the SPL differences noticeably decreased, especially at high frequencies. For each apartment, the highest SPL differences were obtained at the mid-frequency range between 1,000 Hz to 1,600 Hz, and the dips in the average curves were commonly observed around 3,150 Hz. Considering the fact that the thickness and the slit width of typical interior doors are 35-40 mm and 2-15 mm, respectively, the lowest resonance frequency by the Gomperts' theory can be obtained at 3,150 Hz or 4,000 Hz for 1/3 octave-band frequency. Therefore, it can be explained that the dips in the measured curves at 3,150Hz are due to the resonance effects from the slit-shaped aperture of the door.

As shown in Table 3., the average weighted SPL differences for each apartment showed a range from 21.5 dB to 24.3 dB except for the doors with 28.8 dB of the H2 apartment which had an adjustment plate intentionally installed to reduce the slit width. For curve fitting to determine the single-number value, it was found that the maximum unfavorable deviations between the measured curve and the reference curve were mostly observed at high frequency, including the lowest resonance frequency by the slit.

Based on the measured results for all 30 doors with different slit widths, the relationship between sound insulation performance and slit width was reviewed. Fig. 6. shows the sound insulation performances, $D_{p,w}$, according to the widths of the slit-shaped aperture. As the width of the aperture ($x$) increased, the sound insulation performance ($y$) obviously decreased with the relationship $y = -0.73x + 29.97$, and the coefficient of determination ($R^2$) for the linear correlation function was 0.7102. Based on this relationship acquired from real building conditions, it is summarized that a decrease of 1 mm in the width of the slit-shaped aperture provides a 0.7 dB increase in sound insulation performance.
4. Predicted Results and Discussion

4.1 Influence of the numbers in theory for the incidence sound field and the position of aperture

For a slit-shaped aperture, three combinations of the numbers \(m=4, n=1\); \(m=8, n=1\); and \(m=8, n=0.5\) are suggested according to the incidence sound fields and the positions of the slit (Gomperts, 1964; 1967). However, there are few studies to verify the influence of these numbers on the sound transmission loss (TL) in a building. To review the effect of these numbers, the total TLs of the doors using these three combinations are predicted and discussed.

Fig. 7. shows the predicted TLs through slit-shaped apertures, \(TL_{slit}\), with three different widths. The depth of each aperture was fixed at 40 mm in consideration of the typical thickness of interior doors. The predicted TLs showed that the smaller the aperture width, the deeper the dips in the resonance frequencies made by the slit-shaped aperture. It can be observed from the three curves of different widths that the TL curve tended to be flat converging at 0 dB as the slit width increases. Fig. 7 also shows that the diffuse field TL, with \(m=8\) and \(n=1\), is always 3 dB lower than the normal incidence TL, with \(m=4\) and \(n=1\), regardless of the slit dimension and the frequency. Sgard et al. (2007) mentioned that the difference between the diffuse field TL and the normal incidence TL was 2.2 dB at low frequencies if the value of the limit angle for diffuse field integration is 78°. They also showed that it is sufficient to use the normal incidence TL with an acceptable error. Kang et al. (2001) applied the normal incidence, with \(m=4\), to predict the sound insulation of partitions with a slit-shaped aperture between typical cabins in a ship based on some theoretical and experimental evidence that the normal incidence component plays a major role in sound transmission. Taken together, as the numbers for the incidence sound field, either \(m=4\) or \(m=8\) can be used to predict TL within 3 dB depending on the frequency.

Regarding the position of the slit in Fig. 7., the results show that below the lowest resonance frequency, the TL of the slit-shaped aperture always tends to be lower when the slit is situated in the edging of two walls at right-angles to each other, with \(m=8\) and \(n=0.5\), rather than when the slit is situated in the middle of a wall, with \(m=8\) and \(n=1\). The difference between these two predicted TLs was shown in a range from 5.0 dB to 6.0 dB at 500 Hz for 1/3 octave-band, while the differences were small around the resonance frequencies. The reason for this relates to the fact that the position of the slit in the wall of a room is taken into account using reciprocity considerations in Gomperts’ model. His calculation assumes that a source situated in the immediate vicinity of a flat surface or an edge of two perpendicular flat surfaces radiates twice or four times, respectively, which has as much power as the same source situated in an unconfined space.

4.2 Predicted results and comparison with the measured results

The prediction for the total transmission loss, \(TL_{total}\), was performed using equation (2) after estimating the transmission coefficient through a slit, \(\tau_{slit}\), in accordance with equation (1) by Gomperts’ model.
The transmission coefficient through a door leaf, $\tau_{\text{struct}}$, was obtained from the measured sound insulation of the door with complete seal treatment. All three combinations of numbers suggested by Gomperts' model for a slit-shaped aperture ($m=4$, $n=1$; $m=8$, $n=1$; and $m=8$, $n=0.5$) were considered to verify which combination provides a good agreement with the measured results in real buildings.

The predictions for the total TL of the doors were compared with the measured results, $D_p$, in Fig.8. Even though the predictions were calculated for all 30 doors, just two cases of the doors for each apartment were presented as typical examples. As reviewed above, the predicted total TL for $m=4$, $n=1$ had the highest value, followed by $m=8$, $n=1$ and $m=8$, $n=0.5$. The positions of the dip in the measured curves generally corresponded to the lowest resonance frequency in the predicted curves. In addition, the dips at the resonance frequency were mostly deeper for the predicted values than for the measured values because Gomperts' model assumes that the air inside the slit is non-viscous. On the whole, the measured curve met the two predicted curves for $m=4$, $n=1$ or for $m=8$, $n=1$ with better agreement than the predicted curve for $m=8$, $n=0.5$. This fact can clearly be seen in the single-number values presented on each graph. For all 30 doors, the average deviations at 80-5,000 Hz between the measured curve and the predicted curves were 2.3 dB for $m=4$, $n=1$, 2.1 dB for $m=8$, $n=1$ and 4.8 dB for $m=8$, $n=0.5$.

In predictions of the sound transmission through a slit-shaped aperture at the bottom of the door, $n=0.5$...
should be selected as the number for the slit position, considering the recommendation by Gomperts. However, as we can see from the predicted results, $n=0.5$ results in large deviations from the measured values in comparison with $n=1$. This result means that the sound power radiated from the slit at the junction of two surfaces is excessive in the prediction model. It can be assumed that the main reason for this is that the slit as a source is actually situated inside one surface with a limited length which is equivalent to the door width, while the prediction model assumes that the slit is situated in the immediate vicinity along the infinite edge of two surfaces.

The predicted results from the three combinations of $m$ and $n$ were compared with the measured results in terms of the single-number value as shown in Fig. 9. The single-number values for the predicted and the measured results are represented by the weighted sound reduction index, $R_{w}$, and the weighted sound pressure level difference, $D_{p,w}$, respectively. These are important for architects and acoustic engineers to understand the sound insulation performance of building elements, such as a door, at a glance. In Fig. 9., the closer the data are to the dotted line, the better the predicted value is in agreement with the measured value. On the whole, the predicted values in Fig. 9. (a) and Fig. 9. (b) were generally in good agreement with the measured values, whereas the predicted values in Fig. 9. (c) showed poor agreement. More specifically, based on the average deviation from the measured single-number values for all 30 doors, the predicted values, with $m=4$ and $n=1$, were slightly overestimated by 1.4 dB, whereas those with $m=8$ and $n=1$ were slightly underestimated by 1.8 dB. Additionally, the predicted values using $m=8$ and $n=0.5$ were obviously underestimated by 4.9 dB. Therefore, as many authors have suggested, it is reasonable to use either the normal incidence TL, $m=4$, or the diffuse field TL, $m=8$, with average variations in the single-number value of 2 dB. However, even if $n=0.5$ is recommended by the Gomperts model for cases where the slit is placed along the edge of two surfaces like the slit-shaped aperture at the bottom of the door, the predictions always give underestimated values by up to 9 dB due to the excessive prediction of the sound output through a slit.

5. Conclusions

The sound insulation of interior doors with an aperture was studied by in-situ measurements in apartment buildings. In addition, predictions were performed to understand the effects and the limits for sound transmission through the aperture. This work focused on the slit-shaped aperture at the door’s bottom. The major results are summarized as follows.

The measured sound insulation for 30 doors showed various values depending on their slit width. Based on the measured results with different slit widths in real buildings, it was found that a decrease of 1 mm in the width of the slit-shaped aperture provides an increase of 0.7 dB in sound insulation in terms of the weighted SPL difference, $D_{w}$. In addition, the lowest resonance dip decided by the slit dimension of an interior door was commonly observed around 3,150 Hz in the measured TL curves, and this can be a secondary cause of the deterioration in the sound insulation of a door. The positions of the dip in the measured TL curves agreed reasonably well with the position of the lowest resonance frequency in the predicted TL curves. Compared to the measured results in terms of $D_{w}$, Gomperts’ theory provided good agreement within average variations of 1.8 dB for both cases of $m=4$, $n=1$ and $m=8$, $n=1$. However, even though $n=0.5$ might be the best option for the slit position of the doors’ bottom in accordance with Gomperts’ recommendation, it was found that the predictions of TL were remarkably underestimated.

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