2013 IEEE/RSJ International Conference on
Intelligent Robots and Systems (IROS)
November 3-7, 2013. Tokyo, Japan

Tactile Bump Display using Electro-rheological Fluid

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Abstract— **This study proposes a novel technique to display tactile sensation using electro-rheological fluid (ERF). ERF changes its rheological characteristics according to the electric field applied. The ERF used in this study generates relatively high yield stress and behaves as a solid when subjected to a strong electric field. Using this solid-liquid phase transition, we propose a novel device which provides a tactile sensation, i.e., tactile bump display. Applying electric field at a specific position in an ERF chamber, the corresponding ERF behaves as solid at the position. This solid-state ERF gives tactile sensation like a physical bump to a user. We fabricate in this study a prototype, which may realize the above-mentioned idea, and characterize it. We obtained the following results by experiments. First, the tactile bump display could make the users recognize their finger position on a flat surface by creating a tactile bump. Second, we confirmed that the tactile bump might significantly improve the accuracy and the precision of touch typing.**

I. Introduction

Touchscreen interfaces are widely used for electronic devices, such as smart phones and tablet computers [1]. Although the most important advantage of touchscreens is the design flexibility of the user interface which enables the users for their intuitive operation [2], touchscreens still have some potential problems. One is the lack of haptic feedback which could be perceived from mechanical buttons on conventional interfaces such as mouse and keyboard. This problem results in lower operability of touchscreens than conventional interfaces.

It is known that the feedback from general input operation contributes a significant decrease of error rates [3,4]. Furthermore, the feedback of multimodal interaction, such as visual-auditory and visual-tactile feedback, significantly increases operating efficiency than the single modal feedback [5]. With these backgrounds, several investigations about an influence of haptic feedback upon operability of touchscreens have already been conducted. Some investigations revealed that the haptic feedback together with touchscreens contributes to reduction of error rate and operating time [6,7]. Thus, it is essential to give an appropriate haptic feedback to users in order to improve the operability of touchscreens.

Generally, haptic sense is created by tactile and kinaesthetic stimuli, however, tactile stimulus is especially important in haptic feedback of mechanical buttons, because our pilot study has revealed that spatial resolution of human finger is smaller than stroke of general mechanical button. Hence, we neglect kinaesthetic stimulus in this study when considering an appropriate stimulus which should be displayed on touchscreens, and classify tactile stimulus given by mechanical button into two types, i.e., dynamic and static tactile stimuli. A feedback of dynamic tactile stimulus enables users to know whether operation is conducted successfully or not. For example, users are able to recognize the success of mouse clicking input by perceiving clicking vibration, which is the dynamic tactile stimulus. On the other hand, a feedback of static tactile stimulus enables users to know whether the position of operating finger is correct or not. For example, users are able to know the home position on keyboard by perceiving bumps on "F" and "J" keys, which is the static tactile stimulus. Several techniques, which displays dynamic tactile stimulus on touchscreen, have already been developed [8,9]. In addition, there are some products utilizing this technique [10]. In contrast, there is no effective technique, which displays static tactile stimulus on touchscreens.

As other aims than displaying tactile information on touchscreens, several tactile information display techniques have already been developed. One is the technique using many pin actuators (vibration, linear or pneumatic actuators) arranged in a matrix pattern [11-13]. However, this technique is not suitable to be integrated with touchscreens because the configuration of the device becomes complicated. Another technique is to apply electrical current to the finger pad, which directly stimulates tactile mechanoreceptors [14]. Although the device can be simple by using this technique, it still has some problems for practical use. For example, the tactile sensation given by this technique is greatly influenced by several conditions such as thickness of contacting skin, local amount of sweat etc.

Although there are still other tactile information display techniques than mentioned above, most of them are not suitable for the integration with touchscreens. Therefore, a novel technique is required especially to display static tactile information on touchscreens.

We believe that it is necessary to create physical bumps on touchscreens rather than to imitate the tactile sense of bumps by using of vibration, electrical current etc. In this viewpoint, Tactus Technology, Inc. developed a suitable interface, which changes physical shape of touchscreen surface [15]. This technology, however, displays physical bump of a particular pattern and all bumps simultaneously. This could impair the most important advantage of touchscreen, that is, the design flexibility of user interface. Hence, to develop novel tactile display for touchscreen is still expected to be realized. In order to do so, this study proposes a novel tactile display technique using an electro-rheological fluid (ERF). The ERF is a kind of functional fluids, whose rheological characteristic changes according to the electric field applied [16-19]. By using the ERF, physical bumps can be created on the surface of a flat device. We fabricated a prototype, which we call a tactile bump display, and investigated the effectiveness of our technique by two experiments.

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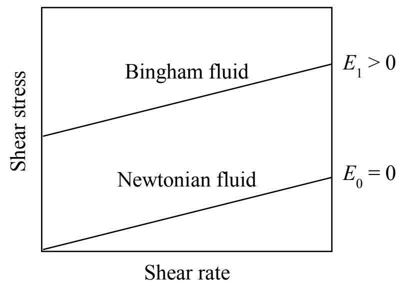

Fig. 1 Relations between shear rate and shear stress of ERF in electric field

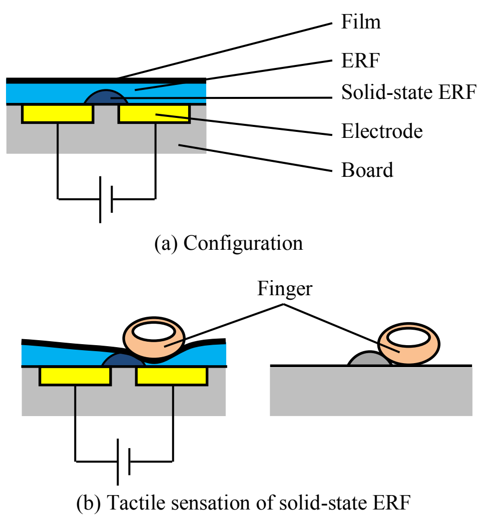

Fig. 2 Principle of tactile bump display

II. Concept

A. Electro-rheological fluid

An Electro-rheological fluid (ERF) changes its rheological characteristics when subjected to electric field. Many investigations on ERF, including fundamental and application researches, have been reported so far [16-19]. Tactile array using ERF has been also developed [20]. Although the ERF is a generic name of fluids which changes their rheological characteristic widely, instantly and reversibly according to the applied electric field [16], the ERF in this paper especially means the colloidal dispersion fluid, which is composed of insulating oil and insulating solid particles. With this kind of colloidal fluid, the liquid/solid phase transition could be possible due to the electric field strength applied.

In order to investigate the change of rheological characteristic of the ERF, several experiments were conducted to measure the shear stress against the electric field. Fig. 1 shows the general theoretic results. When the ERF is not subjected to any electric field, the shear stress is approximately proportional to the shear rate just as a Newtonian fluid. On the other hand, when the ERF is subjected to the electric field, we can observe the yield shear stress at the shear rate of zero just as a Bingham fluid. The value of yield shear stress has, of course, no relation with the shear rate, and increases according to the applied electric field strength [19]. This means that the ERF subjected to an electric field behaves as solid when the shear stress is lower than the yield shear stress.

We focused on this liquid/solid phase transition capability of the ERF in this study in order to realize a novel tactile bump display.

B. Principle of tactile bump display

Fig. 2 shows the principle of a tactile bump display proposed in this study. This display mainly consists of an electrode board and a thin insulator film as shown in Fig. 2(a). The space between the board and the film is filled with the ERF. On the electrode board, there are several electrodes with which the voltage is applied to the ERF. When DC voltage is applied between neighboring electrodes, the electric field is generated around the corresponding electrodes' gap, resulting in the ERF around the gap behaves as solid (solid-state ERF). On the other hand, the ERF located far enough from the gap still behaves as liquid. At this condition, when a finger touches the surface on the film as shown in Fig. 2(b), the solid-state ERF gives a tactile sensation to the finger just as a physical bump. Using this technique, it is possible to display tactile sensation like a physical bump by only applying a voltage to the electrodes without any mechanical motion.

In case of practical use of this display installed in touchscreens, there could be two problems to consider, which are optical transparency and interference with touch sensors. First, for the former problem, the electrode board and the insulator film of the display could be easily made of transparent materials. Namely, optical transparency of ERF would be the matter for the problem. ERF in this display is a kind of colloidal fluid as mentioned above. Generally, colloidal fluid with particles in size of several tens of nanometers has optical transparency. Besides, ERF with such particles displays larger shear stress in electric field than other ERFs with relatively large particles [21]. Therefore, it is possible for ERF, and also whole system of the proposed display, to have optical transparency. Next, interference with touch sensors would be considered. Most of existing touchscreens utilize pressure-sensitive or capacitance touch sensors. For pressure-sensitive touch sensors, the proposed display could be mounted on surface of touch sensors, because the proposed display made of soft materials does not disperse the pressure by pushed force on the surface. For capacitance touch sensors, integrating the electrodes of capacitance touch sensors with insulating film of the proposed display, they could function without any interference.

III. Fabrication

A. Tactile bump display

We fabricated a prototype of the tactile bump display in order to confirm the effectiveness of the proposed concept. Fig. 3 shows the configuration of the tactile bump display.

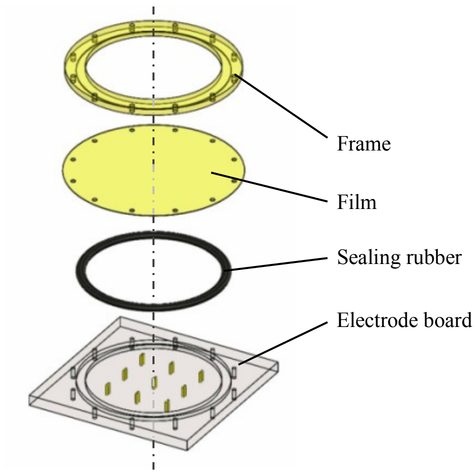

Fig. 3 Configuration of tactile bump display

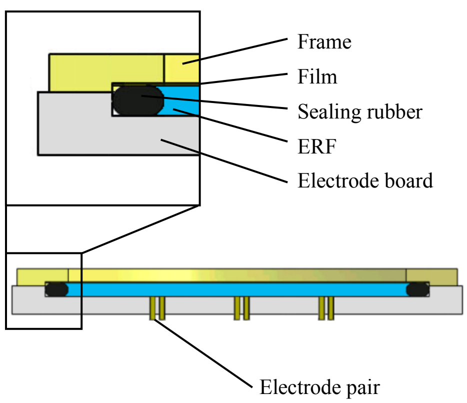

Fig. 4 Cross-section view of tactile bump display

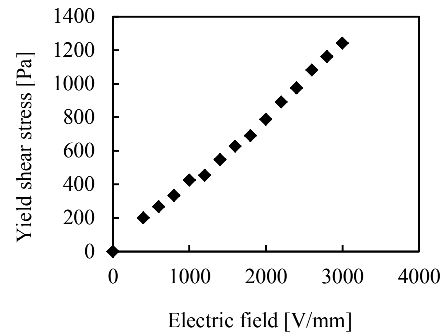

Fig. 5 Characteristic of the ERF used in this study

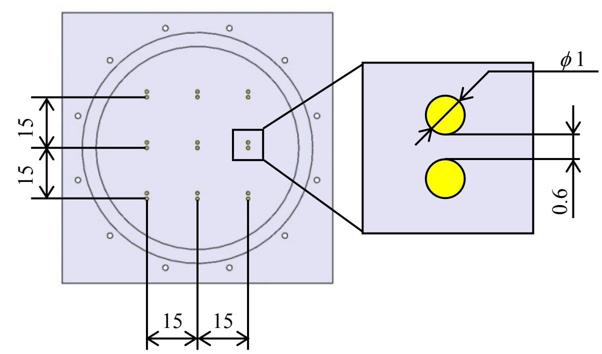

Fig. 6 Electrode pairs

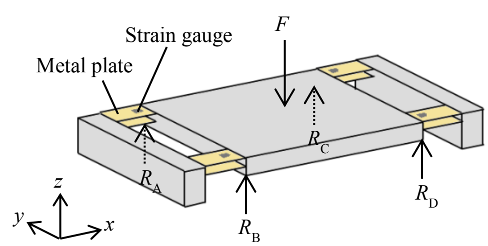

Fig. 7 Pushed position measuring system

This device is mainly composed of a frame, a film, a sealing rubber and an electrode board. The frame and the film are made of polyether imide. The electrode board is made of acrylic resin (base) and brass (electrodes). The film must have insulation properties to avoid electrical discharge on a finger, and at the same time must be thin enough not to weaken the tactile sensation given by the bump created under the film. Considering these requirements, we used a polyether immide film with thickness of 12.5 μm and with insulation breakdown voltage of 4.76 kV. Fig. 4 shows the cross-section view of the device. The components are fixed together with twelve screws, and the space between the film and the electrode board is filled with the ERF. The voltage could be applied to the electrodes from the undersurface side. We use a high density ERF type B (ER tec Co. Ltd., Japan) in this study. Fig. 5 shows the characteristic of the ERF, which is measured by ER tec. In this figure, the horizontal and vertical axes represent the applied electric field and the yield shear stress, respectively.

There are 9 electrode pairs formed in a 3 by 3 matrix with interval of 15 mm on the electrode board as shown in Fig. 6. The surface of this board is smoothed in order to avoid giving any tactile sensation to the users when the voltage is not applied to the electrodes. Each electrode pair consists of two column electrodes with diameter of 1 mm and with the interelectrode gap of 0.6 mm. The dimension of the electrode pair is determined by the following discussion. First, as mentioned in Section II.A, the higher yield shear stress could be obtained with the stronger electric field resulting in making the tactile bump sharper. It is also known from our previous study [22] that the electric field of approximately 5 kV/mm or higher is required to give a tactile sensation with the ERF used in this study. In addition, since the insulation breakdown voltage of the film is 4.76 kV, the applied voltage should be lower than this value. Then, considering these conditions, we determined the electrode gap to be 0.6 mm and the applied voltage to be 3.54 kV. With this condition, the electric field becomes 5.9 kV/mm.

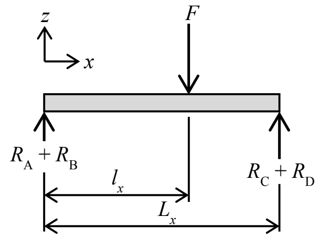

Fig. 8 Two-dimensional view of push position measuring system

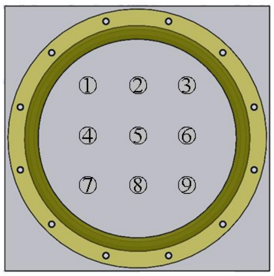

Fig. 9 Identification numbers of electrode pairs

B. *Pushed position measuring system*

In this study, we investigate an influence of tactile bump upon operability of touching action. Hence we constructed a pushed position measuring system in addition to the tactile bump display. Fig. 7 shows a schematic illustration of the system. With this system, the pushed position is estimated from the balance of reaction forces at four corners, each of which is measured by using strain gauges arranged on metal plates (phosphor bronze) located at the corresponding corner. Consider the pushing force F and each reaction forces R_A, R_B, R_C and R_D, and the electrodes board as a rigid body. When considering this system as a two-dimensional beam of x-z level as shown in Fig. 8, l_x representing the pushed position in the x-coordinates is obtained by

$$l_x = \frac{R_C + R_D}{F} L_x = \frac{R_C + R_D}{R_A + R_B + R_C + R_D} L_x \quad (1)$$

where L_x represents the length of device in the x-coordinate. Likewise, l_y standing for the pushed position in the y-coordinates can also be obtained. In addition, the electrode pairs' positions in this paper are defined as point 1 to point 9 as shown in Fig. 9.

Fig. 10 shows the actual view of the whole system. In order to verify the precision of the point detection method mentioned above, we conducted a calibration experiment as follows. The points 1 to 9 are pushed in order in one set of experiment, and the l_x and l_y are calculated each time. Then, totally ten sets of experiments are conducted to verify the precision. As a result, σ_{x0} and σ_{y0}, which stand for the standard deviations of the l_x and l_y, were 0.22 mm and 0.26

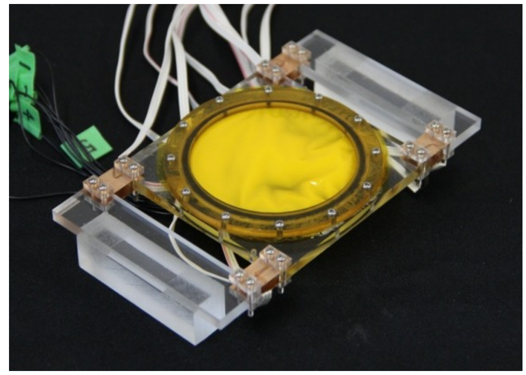

Fig. 10 Actual view of tactile bump display and push position measuring system

mm, respectively. Note that the interval of each point is 15 mm.

IV. Experiments

A. *Point display experiment*

First, we verified whether it is possible to let users know their finger position on a surface by the tactile bump.

1) Experimental method: The subjects are 10 people from 20 to 25 of age. First, DC voltage is applied to the electrode pair, and the subject touches the surface of the device. By repeating this action several times, the subject get used to the perception for the sensation of bump. With this practice, the subject knows the positional relations and the identification number of the electrode pairs (point 1 to 9). Next, a black sheet is set between the subject and the tactile bump display in order to avoid the influence of visual information. Then, DC voltage is applied to an arbitrary electrode pair, and let the subject answer the position of bump, which is created on the device. The voltage is applied to each electrode pair three times in random order, which means, there are 27 trials per one subject and totally 270 trials in this experiment.

2) Result: As results of this experiment, there are 265 correct answers out of 270 trials (percentage of correct answers: 98%). This means that it is possible to display a certain position to the user with the tactile bump display developed in this study. 2 of 5 wrong answers are the case that the subjects answered the same point as previous trials. This might be because of the low responsiveness of the ERF used in this study, i.e., the bump created by the ERF remained even after the voltage was turned OFF, and the subject perceived it in the next trial. Hence, it is also verified that there is a problem of responsiveness of the ERF in the tactile bump display, there is slight possibility of false recognition, though. The relaxation time of this phenomenon is not constant for physical conditions, because the dominant factor of relaxation of tactile bump is not own diffusion of particle but flows of ERF occurred by subject's finger motion. In other words, the relaxation time depends on subject's finger motion.

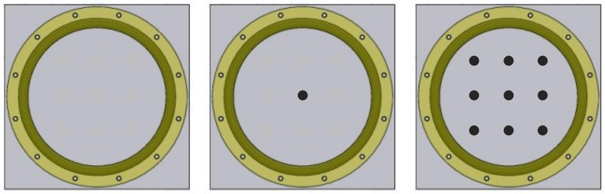

Fig. 11 Three conditions of tactile sensations

TABLE I
The difference, the standard deviations and the searching time

Condition	Difference [mm]		Standard deviation [mm]		Searching time [sec]
	x	y	x	y	
none	2.74	3.07	4.93	4.31	1.97
center	1.79	1.78	2.75	2.42	1.67
all	0.68	0.52	1.23	0.77	2.37
Calibration	-	-	0.22	0.26	-

B. *Pushed position comparison experiment*

Second, we verified the influence of tactile bump upon the accuracy and precision of push action.

1) Experimental method: The subjects are 10 people from 20 to 25 of age. First, with the same practice as in the section IV.A.1, the subject knows the positional relations and the identification number of the electrode pairs (point 1 to 9). After that, a black sheet is again set between the subject and the tactile bump display in order to avoid the influence of visual information. Then, the subject is asked to push a certain button corresponding to the number displayed on a computer screen (Fig. 9) under the three conditions shown in Fig. 11.

In the first condition, we do not apply any voltage to any electrode pairs (condition: "none"). In the second condition, the voltage is only applied to the electrode pair located at center, Point 5 (condition: "center"). On the contrary, in the third condition, the voltage is applied to all electrode pairs (condition: "all"). The subject knows these conditions in advance. In addition, the subject could touch not only the surface but also the frame of the device during the experiments. By doing so, the subject could roughly estimate the position of their fingers even without visual information. For each condition, we conducted 30 trials per subject. This means totally 900 trials of the experiment were conducted with 10 subjects (30 trials/condition/subject).

The pushed position measuring system recorded the pushed position and, at the same time, a searching time, which is an interval of time between when a number is displayed on the computer screen and when the subject pushes the device.

2) Result: Figs. 12, 13 and 14 show the experimental results for the pushed position with the conditions of "none", "center" and "all", respectively. In the figures, the horizontal and vertical axes correspond to the x- and the y-coordinate on the surface of the device with the origin at the center electrode pair (Point 5). The plots with numbers correspond to the averaged pushed position when the numbers were displayed on the computer screen. Error bars of the x and the y directions correspond to the standard deviations of the pushed position along the x- and the y-coordinates, respectively. The intersection points of the broken lines represent the positions of the points 1 to 9. We use the difference between the pushed position and the position of electrode pair for evaluation of accuracy, and the standard deviation for evaluation of precision. Table I summarizes the experimental results about the differences, the standard deviations and the searching times, which are averaged with every condition. The differences in Table I were averaged with their absolute value.

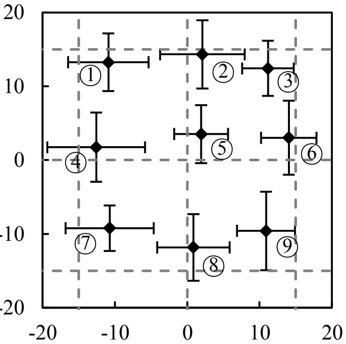

Fig. 12 Pushed positions with condition of "none"

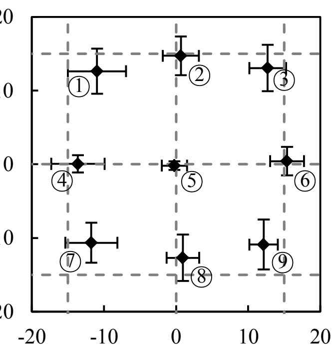

Fig. 13 Pushed positions with condition of "center"

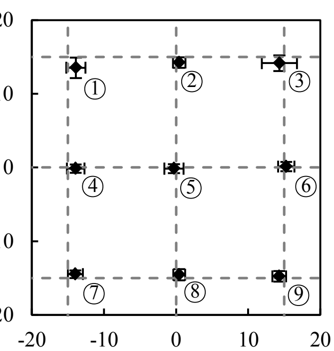

Fig. 14 Pushed positions with condition of "all"

In addition, the standard deviations measured by calibration are shown in this table in order to compare with the potential error of this measuring system.

In Figs. 12, 13, 14 and Table I, the differences and the standard deviations increase in the order of the conditions "none", "center" and "all", which means that the accuracy and the precision of the pushed position become higher in this order. The accuracy and the precision especially in the condition of "all" are the highest with the difference and the standard deviation of smaller than 1.5 mm, which might be smaller than most of virtual buttons commonly displayed on touchscreens. Therefore, it is confirmed that the technique we proposed may significantly improve the accuracy and precision of touch typing on touchscreen.

On the other hand, the searching time decreases in the order of the conditions "all", "none" and "center", which means that the operation under the condition of "center" is quicker than "none", and the operation under the condition of "all" is slower than "none". This suggests that the tactile bump at the center make the subject recognize his/her finer position easily. Accordingly, the subject may push the button as soon as he/she moves his/her finger from the center position. In contrast, with the condition of "all", the subject must touch several bumps to recognize the position of his/her finger because all the bumps have the same tactile stimuli. This searching process takes some amount of time, and as a result, the operation under the condition of "all" becomes the slowest. In addition, we asked the subjects' impression for the developed device after the experiment. Accordingly, the subjects might have got a similar impression for the condition of "all", i.e., they sometimes lost which tactile bump they were touching. In order to improve the operability of the condition "all", we should display the different tactile sensations for the different positions.

V. Conclusion

This study proposed a novel technique to display static tactile stimulus on a flat surface such as touchscreen using the electro-rheological fluid (ERF). We fabricated a prototype, which we call a tactile bump display, and confirmed the effectiveness of the proposed technique using the prototype. First we confirmed that the device could make the users recognize their finger position on a flat surface by creating a tactile bump with liquid/solid phase transition of the ERF. Second, we confirmed that the tactile bump might significantly improve the accuracy of touch typing.

It was also revealed that remains of tactile bump by the relaxation time of ERF could be a problem. Although the relaxation time is difficult to quantify because it depends on finger motion, the relaxation time and also contraction time should be investigated for practical use of proposed technique.

Our future study focuses on improving the response of the liquid/solid phase transition of ERF and creating the different tactile stimuli. In addition, integrating dynamic tactile stimulus together with the static tactile stimulus displayed in this study might be a final goal of our study.

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