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Symmetry Breaking in Escaping Ants

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abstract: The phenomenon of herding is a very general feature of the collective behavior of many species in panic conditions, including humans. It has been predicted theoretically that panic-induced herding in individuals confined to a room can produce a nonsymmetrical use of two identical exit doors. Here we demonstrate the existence of that phenomenon in experiments, using ants as a model of pedestrians. We show that ants confined to a cell with two symmetrically located exits use both exits in approximately equal proportions to abandon it in normal conditions but prefer one of the exits if panic is created by adding a repellent fluid. In addition, we are able to reproduce the observed escape dynamics in detail using a modification of a previous theoretical model that includes herding associated with a panic parameter as a central ingredient. Our experimental results, combined with theoretical models, suggest that some features of the collective behavior of humans and ants can be quite similar when escaping under panic.

Keywords: behavior, ants, herding, escape dynamics, self-organization, complexity.

Panic propagates rapidly by imitation. The words of a tourist in Jamaica a few hours before the passing of "extremely dangerous" Hurricane Ivan in September 2004 are very convincing: "Seeing other people panicked, I panicked as well" (James 2004).

In particular, it is not possible to overestimate the importance of the study of crowd stampede induced by panic, such as that taking place when people try to escape from a burning room, where the "follow-the-crowd" effect associated with imitation may have grave consequences. Helbing et al. (2000) recently made an important step forward in a theoretical article where simulations of individuals escaping from a closed room were presented. That work has been rapidly followed by further theoretical models (Burstedde et al. 2001; Tajima and Nagatani 2001; Kirchner and Schadschneider 2002; Perez et al. 2002) and by experiments in rats (Saloma et al. 2003) and humans (Helbing et al. 2003), with no control in the panic level. One of the most unexpected phenomena predicted in the article by Helbing et al. (2000) is the panic-induced symmetry breaking in the escape from a room with two exits. When individuals under panic try to escape from a room with two symmetrically located exits, one of them is more used than the other one. Here we demonstrate the correctness of such prediction through experiments in which we have been able to examine low- and high-panic scenarios, using ants as model pedestrians. In addition, we report the details of the temporal evolution in their escape in low- and high-panic conditions and show that it can be described by a simple computer model inspired by that reported by Helbing et al. (2000). Our experiments show that escape behavior under panic can be amazingly similar from invertebrates to vertebrates.

Methods

Workers from the Cuban leaf-cutting ant *Atta insularis* (common name *Bibijagua*; Bruner and Valdés-Barry 1949; Pintera and Zorrilla 1981) were collected manually by picking the ants one by one from several nests scattered in an area of approximately 400 m^2. The collection took place during the daytime, in the period from June 2004 to June 2005. The individuals were rapidly transferred to the laboratory in plastic containers so that the experiments typically started 30 min after collection. One hundred in-

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dividuals were randomly selected from the ants under study, and their head widths (i.e., the largest lateral dimension of the individual) were measured using calipers, with an accuracy of 0.02 mm in order to have an idea of the variability of the population.

Two types of experiments were performed. In the first (experiment 1), we simultaneously introduced a group of 66 ants collected from the same nest into a circular cell with two exits symmetrically situated at left and right, which were initially blocked. The cell was an acrylic drum of 8 cm diameter and 0.5 cm height, and the exits were 1 cm wide. The cell rested on a circular piece of filtering paper laying on a horizontal surface and was covered by a flat glass plate of 0.3 cm thickness, with a hole of 0.2 cm diameter situated at the center of the drum. Once the ants were introduced and covered by the glass plate, we opened the exits synchronously so that the ants were able to escape. The whole process was recorded until the end of the escape activity using a video camera situated approximately 20 cm above the cell, and the image analysis was made afterward in slow motion mode.

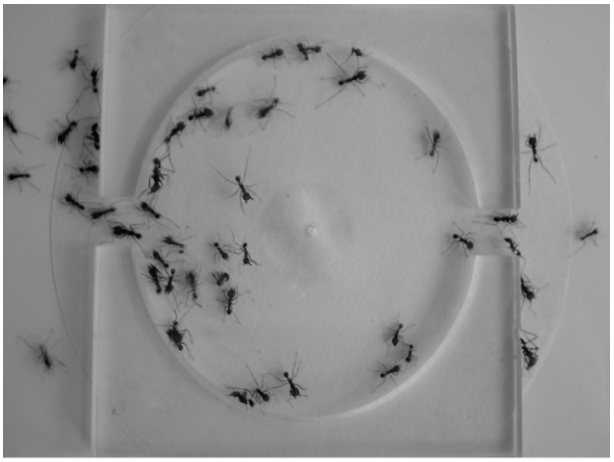
In the second kind of experiment (experiment 2), everything took place as in experiment 1, with the important difference being that a few seconds before opening the doors, a dose of 50 μL of an insect-repelling liquid (citronella, Labiofam, Cuba) was rapidly injected into the cell through the hole in the cover glass, producing a disk-shaped spot of the substance at the center of the filtering paper on which the whole setup rested.

Experiments 1 and 2 were repeated 30 times. In each repetition, a new group of ants collected from a single nest was used. Video 1 (in the online edition of the *American Naturalist*) shows a typical run of experiment 2.

It should be noted that it was impossible to make sure that the totality of the ants escaped from the cell because some of them were eventually injured because of their interaction with the crowd or because of immersion in the repellent fluid if they were located under the central hole in the glass plate at the beginning of the experiment. So, the total number of escaping ants was impossible to control in detail and fluctuated between 52 and 66 ants, depending on the repetition (the average number of ants that managed to escape was 60, with a standard deviation of 3.3).

Results and Discussion

On the basis of size measurements of 100 ants randomly selected, the mean and standard deviation for the head width were 1.68 and 0.05 mm, respectively. Tables A1 and A2 present the total number of ants abandoning the cell through each exit as counted from the slow-motion videos taken in the 30 repetitions of experiments 1 and 2, respectively. The final column of each table reports the percentage difference in use between the two doors, calculated as



Video 1: Still photograph of experiment 2 associated with a video (available in the online edition of the *American Naturalist*) that illustrates symmetry breaking. A few dozen individuals of the species *Atta insularis* (*Bibijagua*) escape from a cell with two symmetrically located exits after introducing 50 μL of a repellent fluid at the center and then opening the exits. As can be seen, most of the ants spontaneously escape through the left door, so the symmetry is broken. The inner diameter of the cell is 8 cm, and the exits are 1 cm wide.

$$\frac{|\text{total of ants escaping left} - \text{total of ants escaping right}|}{\text{total of escaping ants}} \times 100.$$

We will use this definition for the percentage difference in use between the two exits to express all our experimental and theoretical results, except when otherwise stated.

In figure 1 we present histograms based on those columns for low- and high-panic conditions, with means and standard deviations of 12.4 (11.19) and 38.3 (19.9), respectively. A simple inspection of the histograms and the corresponding means strongly suggests that symmetry breaking appears as a consequence of the addition of the repellent fluid. Let us examine in more detail the symmetry in door use for the two types of experiments. If both exits are used with equal probability, we say that there is no symmetry breaking. In such a scenario, the distribution of ants exiting through each door is expected to be binomial with $P = 0.5$ (and $q = 1 - P = 0.5$). If one of the doors is used preferentially, we say that there is symmetry breaking, and we would expect binomial distributions with statistically significant $P \neq 0.5$. To investigate this, hypothesis tests for the distribution of ants exiting through both doors for experiment 1 and experiment 2 were performed, taking $P = 0.5$ as an alternative hypoth-

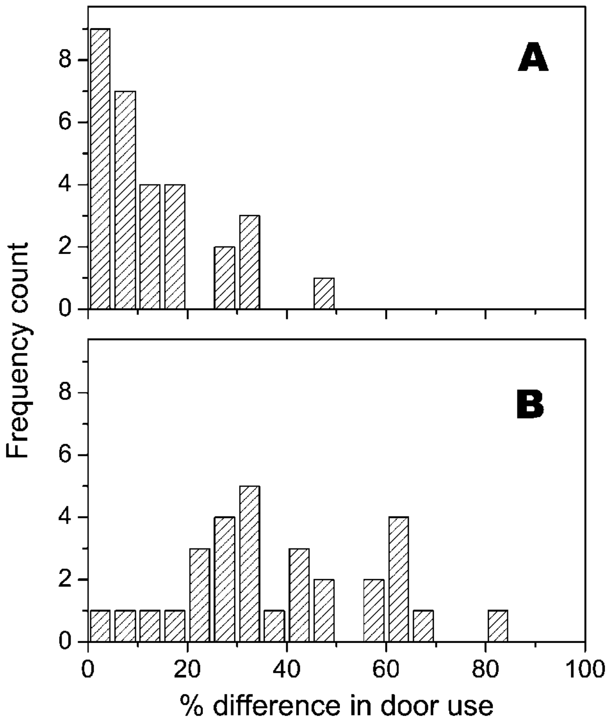


Figure 1: Histograms showing the percentage difference in the use of the two doors for (*A*) low-panic and (*B*) high-panic conditions.

esis (two tails). In the case of low panic, the calculated probability of the observed distribution was 0.336, well above the standard confidence limit of 0.05, so the null hypothesis cannot be rejected: there is no symmetry breaking in low-panic conditions. For the panic experiments, the situation is quite different. The probability of obtaining the experimental distribution of ants in the exits under the null hypothesis is 0.0062, well below 0.05. So, the null hypothesis is rejected: symmetry is broken in panic conditions. As a complementary test, we compared the results of both types of experiments using the Kolmogorov-Smirnov test for two samples (Lindgreen 1968), assuming as the null hypothesis the case where the two samples are extracted from the same population and, as an alternative hypothesis, that the populations are different. We then applied the test to the percentage difference in door use. The experimental value was $D_{\mathrm{exp}}(0.05) = 0.997$, while the theoretical value was $D_{\mathrm{th}}(0.05) = 0.254$. Because $D_{\mathrm{exp}} > D_{\mathrm{th}}$, the null hypothesis is rejected, so the percentage difference in door use is significantly different between low- and high-panic situations.

Hence, our experiments demonstrate quantitatively that panic induces symmetry breaking in the escape of ants from a room with two symmetrically located exits. It is important to note that examined over all repetitions of experiment 2, neither the left nor the right exit was consistently favored when symmetry was broken; that is, the symmetry breaking was independent from any experimental artifact related to the lack of symmetry in the setup. Furthermore, there was no evident connection between the ant spatial distribution inside the cell at $t = 0$ (i.e., when the exits are opened) and the exit used by the majority of ants in a specific repetition (however, we did not perform any quantitative test in this respect).

In addition, we performed 10 repetitions of experiments 1 and 2 combining ants from different nests in each repetition, data that are not shown here. The application of statistical tests similar to the ones described for the experiments with ants from the same nest produced analogous results. This suggests that the symmetry breaking effect is independent of the level of genetic relation between ants.

Figure 2*A* and 2*D* show still pictures of the ant distributions inside the cell during one sample repetition of experiment 1 and one of experiment 2, respectively. The distributions illustrate symmetric and nonsymmetric scenarios for low- and high-panic conditions, respectively. In order to get insight into the escape dynamics, we also extracted from our video records the temporal evolution of the number of ants escaping through each door. The general shape of the resulting curves within each type of experiment was qualitatively similar for all repetitions, so we present only typical curves for one repetition of experiment 1 (fig. 2*C*, *circles*) and one repetition of experiment 2 (fig. 2*F*, *circles*). Notice that at the end of these specific repetitions, the absolute difference in use between the two exits is six ants for figure 2*C* and 27 ants for figure 2*F*, which corresponds to percentage differences of 10% and 50%, respectively. We constructed a computational model inspired by that presented by Helbing et al. (2000) as follows. Sixty ants are introduced into a circular cell like the one used in the experiment. The initial positions of the ants and directions of movement are chosen randomly, while their size and initial velocity distributions are Gaussian, with average values $\langle s\rangle$ and $\langle v\rangle$ and standard deviations σ_s and σ_v, respectively. Starting at $t = 0$ (i.e., when the exits are opened in the actual experiment), the virtual ants are allowed to move always at the initially assigned velocities using the following rules: when an ant hits a wall of the cell, it is reflected; when two ants meet, they "bounce" against each other in random directions during several computer steps until each one is able to continue along its original direction before the encounter; and if an ant gets closer to one of the exits than a certain critical radius, R_e, it escapes through that door. In the following results, we assigned approximate values to the simulation parameters (based on rough measurements from video images) to demonstrate the plausibility of the

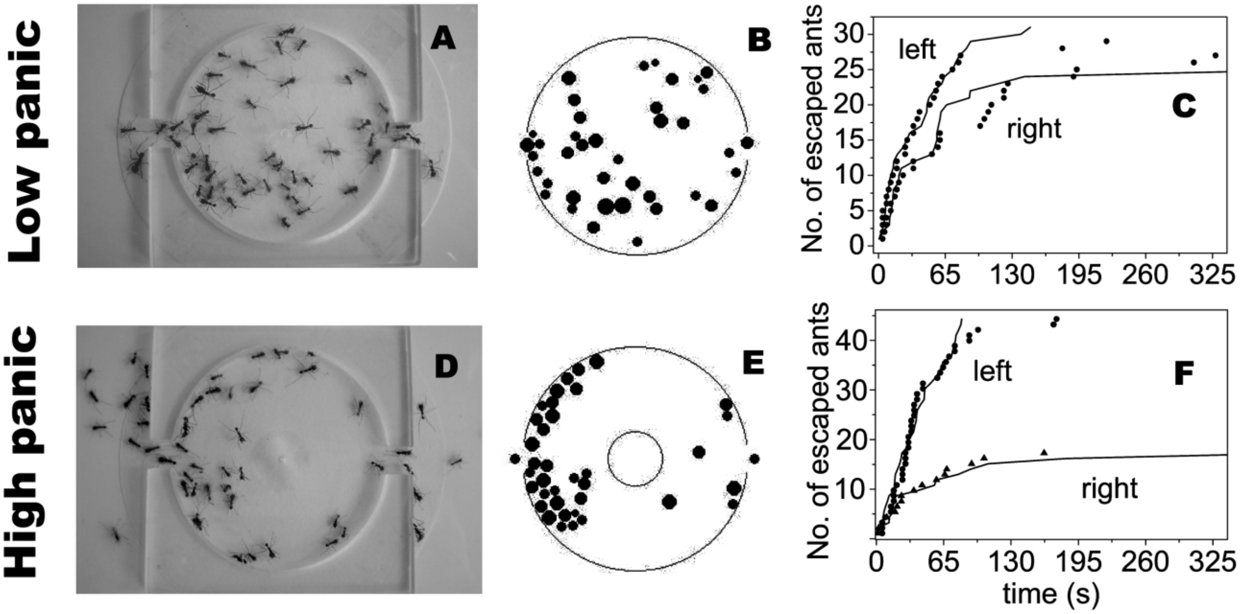


Figure 2: Escape of ants from a cell with two symmetrically located exits in low- and high-panic conditions. Low panic: *A*, Ant distribution several seconds after opening the exits at $t = 0$. *B*, Typical ant distribution during one run of the computer simulation described in the text. *C*, Number of ants abandoning the cell as a function of time. High panic: *D*, Ant distribution several seconds after adding 50 μL of an insect repellent fluid through the central hole and then opening the exits at $t = 0$ (note a circular spot of repellent fluid of approximately 2 cm diameter at the center of the cell). *E*, Typical ant distribution during one run of the computer simulation described in the text. *F*, Number of ants abandoning the cell as time goes by, quantitatively demonstrating the symmetry breaking when repellent is added as a function of time. In *C* and *F*, symbols correspond to the experiment, while full lines follow computer simulations described in the text.

simulation rules for our case. Figure 2*B* shows a picture of a typical ant distribution during one computer run of the simulation, performed using the following set of parameters: $\langle s\rangle = 0.42$ cm, $\sigma_s = 0.07$ cm, $\langle v\rangle = 0.5$ cm/s, $\sigma_v = 0.25$ cm/s, and $R_e = 0.5$ cm. The full lines in figure 2*C* display the corresponding temporal evolution of ants escaping. They fit the data well. In order to understand the precise dynamics of experiment 2, we added two further rules to the simulation described above: if the prolongation of the direction of movement of one ant located outside the central repellent spot "hits" the spot, a new direction of movement is randomly chosen and at computer step denoted by integer *k*, the direction of the velocity of an ant is given by a unit vector calculated as

$$\vec{e}_k = \frac{(1-p)\vec{e}_{k-1} + p\left\langle \vec{e}^{\,\text{herd}}_{k-1}\right\rangle}{\left|(1-p)\vec{e}_{k-1} + p\left\langle \vec{e}^{\,\text{herd}}_{k-1}\right\rangle\right|} \qquad (1)$$

(Vicsek et al. 1995; Helbing et al. 2000).

In this expression, $\vec{e}_{k-1}$ is the unit vector of the ant's velocity at computer step $k-1$ and $\langle\vec{e}^{\,\text{herd}}_{k-1}\rangle$ is the average unit vector of the velocities of neighboring ants inside the cell located within a radius R_h from the ant under study at computer step $k-1$. Finally, *p* is a parameter that determines the tendency of an ant to "follow the crowd" (the extreme cases are $p = 0$, where the ant acts "individualistically" and keeps moving in the previous direction and $p = 1$, where it reorients to follow the crowd). In the approach of Helbing et al. (2000), *p* should increase with increasing panic, so it is called the "panic parameter." Figure 2*E* shows a typical ant distribution during a run of the simulation with the following set of parameters: $\langle s\rangle = 0.42$ cm, $\sigma_s = 0.07$ cm, $\langle v\rangle = 1$ cm/s, $\sigma_v = 0.5$ cm/s, $R_e = 0.5$ cm, $R_h = 3.75$ cm, and $p = 0.8$. The full lines in figure 2*C* show the corresponding temporal evolution of the escape. As can be seen, it accurately reproduces the symmetry-breaking scenario by fitting the experimental data well. In order to match the timescale of the experiment, the average velocity assigned to this simulation had to be tuned to two times more than the one used in the case of low-panic conditions, which is consistent with experimental observation and also with the considerations of Helbing et al. (2000; i.e., individuals tend to move faster if they are in panic).

It is important to underline that the degree of symmetry breaking (i.e., the vertical gap between the final sections of the two curves in fig. 2*C* and those in fig. 2*F*) is basically controlled by two parameters: the "herding" (or "following") radius, R_h, and the panic parameter, p. To illustrate this point, we can say that 300 simulation runs identical to the one corresponding to the lines of figure 2*C* yield an average gap of 50% ± 4%. By exclusively introducing the changes $R_\mathrm{h} = 0$ and $p = 0$, the average gap between the curves drops to 10.4% ± 0.1%. These percent values match well with the gaps corresponding to the experimental runs presented in figure 2*C* and 2*F*.

It should be noted that in the simulations we have described, all the ants initially introduced in the cell were able to escape within computational time. We have tested a variation of the simulations presented above for panic conditions in which $\langle \vec{e}_{k-1}^{\,\mathrm{herd}} \rangle$ is substituted in equation (1) by the unit vector pointing from the test ant to the center of mass of the rest of the ants located within R_h. When this simulation is run 300 times with the same parameters used to obtain the results displayed in figure 2*F*, the average symmetry breaking is found to be 45.7% ± 1.4%. Different from the previous ones, in these simulations, some ants are typically not able to find the doors within the simulation time, so they remain "frozen" in the cell, a situation that mimics the reality of many experiments. The results obtained with our two types of models suggest that given an expression involving an "individualistic" ingredient with probability $1 - p$ and a "follow-the-crowd" ingredient with probability p, the emergence of symmetry breaking is not necessarily determined by the specific mechanism responsible for the latter.

In summary, our experimental findings coincide well with the theoretical predictions reported by Helbing et al. (2000) for the case of humans. There they defined a panic parameter that induces individualistic behavior (each pedestrian tends to find an exit by himself or herself) when low and herding behavior (pedestrians tend to follow the crowd) when high. Through a simple computational model inspired by that proposed by Helbing et al. (2000), we have been able to reproduce convincingly our experimental findings in ants, including the details of the temporal evolution of escape. Moreover, our simulations suggest that the phenomenon of symmetry breaking is robust relative to the specific mechanism of herding. In spite of the sizable differences between traffic in humans and ants in normal conditions (beautifully illustrated by Burd et al. [2002]), our experiments combined with the theory of Helbing et al. (2000) suggest that some features of the collective behavior of both species can be strikingly similar when escaping under panic.

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APPENDIX A

Experimental Data

Table A1: Results of 30 repetitions of experiment 1 (no repellent fluid used)

	Total no. ants exiting cell		Percentage difference in door use
Repetition	Left	Right	
1	30	32	3
2	34	28	10
3	29	31	3
4	32	34	3
5	37	28	14
6	37	28	14
7	32	28	7
8	43	22	32
9	32	28	7
10	29	32	5
11	26	30	7
12	41	22	30
13	38	20	31
14	33	24	16
15	32	33	2
16	37	22	25
17	31	30	2
18	24	28	8
19	33	32	2
20	37	25	19
21	37	22	25
22	28	32	7
23	27	30	5
24	45	17	45
25	23	32	16
26	28	34	10
27	30	32	3
28	25	34	15
29	30	29	2
30	31	29	3

Table A2: Results of 30 repetitions of experiment 2 (repellent fluid used)

Repetition	Total no. ants exiting cell: Left	Total no. ants exiting cell: Right	Percentage difference in door use
1	27	37	16
2	26	34	13
3	5	53	83
4	50	9	69
5	28	29	2
6	50	12	61
7	43	22	32
8	43	22	32
9	43	15	48
10	12	48	60
11	47	16	49
12	38	24	23
13	24	38	23
14	42	24	27
15	37	19	32
16	49	12	61
17	37	21	28
18	20	41	34
19	42	18	40
20	19	46	42
21	47	13	57
22	23	39	26
23	12	46	59
24	22	40	29
25	34	21	24
26	17	42	42
27	36	19	31
28	28	24	8
29	44	20	37
30	50	12	61

APPENDIX B

Influence of the Number of Ants

Here we present some theoretical and experimental results to investigate whether the phenomenon of symmetry breaking depends on the total number of ants involved in the experiment. The main results are shown in figure B1. There, filled circles correspond to the percentage difference in the use between the two doors averaged after 300 runs of a simulation with the same parameters used to obtain the results shown by the lines of figure 2*F* but for different initial amounts of ants. The open circles correspond to experimental results averaged over 10 repetitions of each experiment. In both cases, the error bars are given by the standard deviation from the mean. While the theoretical model suggests a discrete increase of the symmetry breaking as the number of ants increases, the experiments show no measurable dependence on the number of ants, given our experimental uncertainty (notice that as the number of ants decreases, fluctuations are more and more important, so a very high number of repetitions is necessary to decrease the error bar). In spite of the fact that formula (1) is a completely deterministic equation for a single ant, the overall rules of the simulation somehow involve the behavior of the whole group of interacting individuals, which may justify the moderate dependence of the symmetry-breaking phenomenon on the ant number (this might be paralleled to certain dynamical, global behaviors in ants' nests that take place only above a certain number of individuals; Solé et al. 2003). While one might be tempted to expect this theoretical tendency in the experiments, we have to take into account that overcrowding in the cell above approximately 100 ants completely changes the dynamics relative to the theoretical scenario.

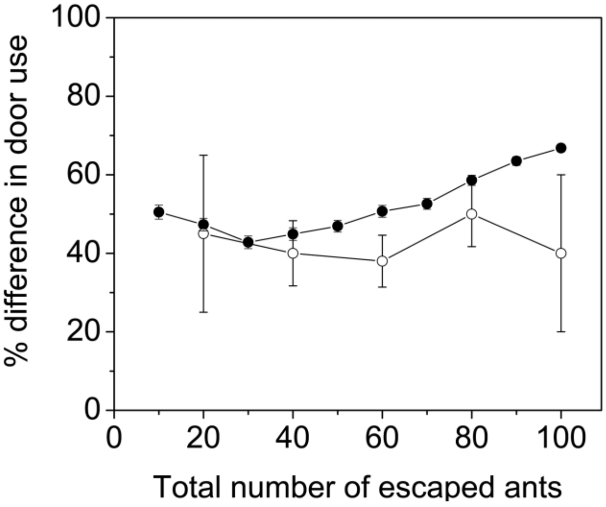

Figure B1: Dependence of the percentage difference in use of the doors with the total number of escaping ants. The filled circles correspond to theoretical simulations with the same parameters producing the continuous lines of figure 2*F*, and the open circles correspond to the experiment.

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