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ZAHMAH SOCIAL FORCE MODEL FOR PEDESTRIAN MOVEMENT

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ABSTRACT

The Social Force Model is one of the well-known approaches that could successfully simulate pedestrian's movement realistically. However, it is not suitable to simulate a complex pedestrian movement. Hence, this research proposed a novel model which improved the Social Force Model for simulating high density crowd such as Tawaf. Tawaf is an Islamic ritual, which requires agents to encircle the Kaabah. This ritual has been complex yet unique, due to its capacity, density, and various demographic backgrounds of the agents. A certain set of rules that must be followed by each agent, which introduces anomalies in the flow around the Kaabah. The agents also will be assigned with unique attributes such as; gender, walking speed and intention outlook to make the simulations more realistic. The findings of this research will contribute to the simulation activities of pedestrians in a highly dense population.

Keywords: *Autonomous Agents, Behaviour, Force, Tawaf, Pedestrians.*

1. INTRODUCTION

The crowd in general can be defined as a large number of people gathered together in a disorganized or unruly way. It is also can be defined as a group of people who are linked by a common interest or activity, such as sport event, political rally or religious ceremony [1,2,3].

Based the definition alone shows that by using the conventional Social Force Model does not fulfil the requirement of being a crowd. It is because, Social Force Model just assumes that everyone within the crowd have the same characteristics, which make the pedestrians within the crowd simulation by using the Social Force Model move in unison without any hectic behaviour of a typical crowd [4,5].

In order to cope with this problem, this research innovated Zahmah concept. Similar to the crowd, Zahmah also means crowd or traffic in Arabic [6,7]. However, this is where the similarities end. Zahmah is a concept which controls the behaviour of the crowd as individuals. Yet it still manages to control the crowd to move together as a whole. Controlling the behaviour of the crowd as a whole is a lot simpler because it can be treated as one organization that has a same direction and purpose. However, it will lack of individuality and uniqueness of each person within the crowd [8,9]. Therefore, Zahmah concept was introduced, in order to give each person in the crowd with their own identities and personalities without sacrificing the interaction between each of them. It means that although they have their own characteristic they still can move and interact with other people in the crowd. Not just a group of people walking alone within the crowd without any interaction with each other at all [10,11,12].

Zahmah is also unique compared to the other common crowd, based on the several key characteristics. Firstly, is the size of the population in Zahmah is relatively huge compared to the other common crowd. Indirectly it will cause the crowd to be very dense and congested. Other than that, time duration for Zahmah is almost indefinitely due

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to the event occurs continuously without a time limit or constraint. As people come and goes replacing the person who left the place. People or agents in Zahmah also have a diverse demographic background since they all come from all over the world. Meaning, each agent within the crowd has different age, gender and ways of interactions. In Zahmah all agents mostly have the same common goal and purpose [13,14]. Hence, the flow of pedestrian generally will be in one flow. However, some of them may move against the flow or other directions which cause the pedestrians flow more chaotic compared to other crowd situations. Besides, the pedestrians in Zahmah sometime come in small groups consist of two of more people within a group. Each person within the same groups will have the tendency to move around closely together. This will make the flow of the crowd even more unique and hectic [15,16,17].

One of the situations that suitable for the Zahmah concept to be applied is Tawaf. Tawaf is one of the Islamic rituals that can only be done in Makkah, Saudi Arabia. Tawaf means circling the Kaabah seven times starting from Hajarul Aswad (Black Stone) and end at the same point, according to its rules [18,19]. Although this ritual seems very simple, it is challenging than it looks. It is mainly due to the vast number of pilgrims whom doing the ritual together especially during Hajj season. Other than that, it is also because of the Tawaf rules which make this scenario more interesting. One of the rules is preserving wuduk (ablution). During Tawaf each pilgrim needs to preserve their wuduk until they complete the ritual, if they nullify it, they have to repeat the ritual all over again. However, it is quite hard to preserve it in a dense and crowded area since touching a different gender can nullify the ablution. Thus, they will try to avoid each other whenever they encounter pilgrim with the opposite gender. Although Ulama had stated that this will not cause the ablution to be nullified, most pilgrims will still keep their distance from each other [20,21,22].

2. PREVIOUS WORK

One very advanced microscopic approach for simulating pedestrian motion is the Social Force Model. This model solves the Newton's equation for each individual. Repulsive interaction, friction forces, dissipation and fluctuations are among the existing forces within the Social Force Model. This model has been proven to simulate real world scenarios in pedestrian movement successfully [23,24].

Relative to Cellular Automata Model and Rule-Based Model, The Social Force Models can realise the pedestrian behaviour more convincingly and more natural. However, they he Social Force Model is designed to be as simple as it can be. Thus, every agent within the crowd simulation is represented by a circle with its own diameter and the model describes continuous coordinates, velocities and interactions with other objects. Each parameter has a natural interpretation, is individual for each pedestrian, and is often chosen randomly within some empirically found or otherwise plausible interval [25,26,27]

The social forces model describes the human crowd behaviour with a mixture of socio psychological and physical forces [28,29]. The most important social forces model is the Helbing's model.

Most of other researchers prefer using the social force model as their base model to simulate the Tawaf ritual; for example, researchers which also from Universiti Sains Malaysia [30,31] used to simulate the flow of pilgrims in the Tawaf Area. They simulate the flow of pilgrims getting inside into the mosque and getting out from the mosque. The flows of the pilgrims are bidirectional and towards each other and it shows a congested area in the main entrance. Thus, these researchers are proposing a new design for the entrance [32,33].

3. METHODOLOGY

a. Fundamentals of Social Force Model

The social force model can be applied to simulate pedestrian movement similar to the real world. In comparison to the other model such as cellular automata and ruled based model, the social force model simulates pedestrian flow more realistically. However, they are designed to be as simple as possible. Every agent is represented by a circle with its own diameter and the model describes continuous coordinates, velocities and interactions with other objects as shown in Figure 1. This model will be used as the basic model for this research.

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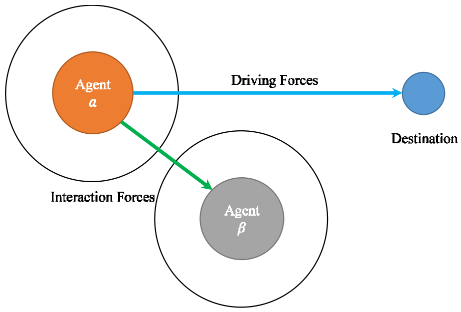

Figure 1 : Social Force Model

Each pedestrian in crowd simulation are called agents and each agent position are defined in two dimensions, x-axis and y-axis. The position is represented on x-axis is x_α and the position on the y-axis is y_α. Agents do not have the third dimension because they mostly just walk on a flat surface.

$$p_\alpha = \{x_\alpha, y_\alpha\}$$

The main force in the social force model is the driving force. This force describes as the motivation of the agent α to move towards desired direction, d. The agent will move according to his or her desired walking velocity, v_α. Where v_c is the actual walking velocity of the agents and τ_a is the relaxation time for agent α.

$$f_{derive} = \frac{v_\alpha . d_\alpha}{\tau_a} - \frac{v_c}{\tau_a}$$

In order to get the desired direction, d_α of agent α was by calculating the distance between the goal position of agent α, g_α and current position of agent α, p_α. Goal position is the main objective which motivates agent α to walk at first, while the current position is the position of agent α at that time. All of this was controlled by a scaling parameter, w.

$$d_\alpha = w \frac{g_\alpha - p_\alpha}{\|g_\alpha - p_\alpha\|}$$

The second force is the repulsion forces between agents within the crowd. This force is important so that the agents do not collide with each other. Each agent will have their own, repulsion strength. The strength depends on the distance between agents with another agent in that scenario. For example the position of agent α, p_α and position of agent β, p_β, which shown in figure 2. The closer agent α towards agent β, the higher repulsion strength will be. Each agent also will have their own radius of interaction, r which determines the distance for each interaction start. Lastly, $n_{\alpha\beta}$ is the normalized vector pointing from agent α towards agent β.

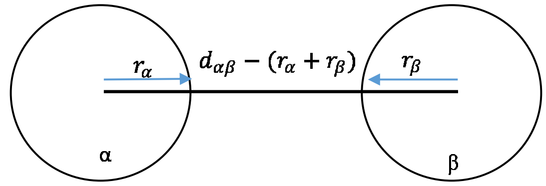

Figure 2 : Repulsion forces between to agents

The third and last force is the attraction forces between agents. Agents usually walk in groups, especially in crowded areas, to avoid getting lost and isolated. Agents from the same group tend to walk together and if they get separated, they will regroup again if possible. This attraction forces can be done by manipulating the c, scaling parameter of attraction forces between agents from the same group.

$$f_{attraction} = c n_{\alpha\beta}$$

In conclusion, the social force model consists of several forces that works together in order to determine the next position of the agent during that period of time. This is a continuous process until all the agent arrived at their own goal position. This sum of all forces, describes the movement and direction of the agent as shown in the equation below.

$$f_{social} = f_{drive} + \sum_{\beta=0}^{n} f_{repulsion} + \sum_{\beta=0}^{n} f_{attraction}$$

b. Fundamentals of ZS Force Model

This research has developed a novel model called Zahmah Social Force Model (ZS Force Model). ZS Force Model modified the existing Social Force Model by making the three main forces as the fundamental forces in ZS Force Model, which are driving force, repulsion force and attraction force. This model also enhanced the mathematical formula of each force to make it more suitable for large population crowd scenarios. These modifications were based on several factors such the goal position, agents' gender and walking speed diversity.

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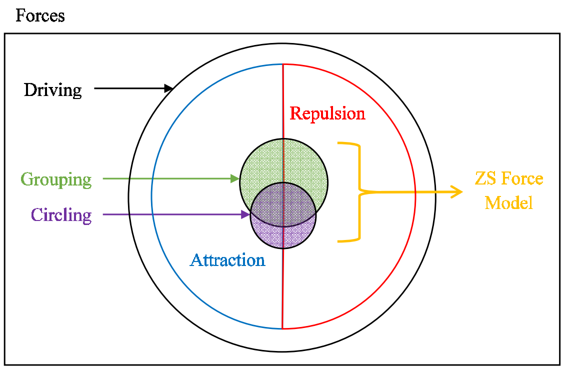

Figure 3 : ZS Force Model

Based on the Figure 3, shows that basically ZS Force Model was consisted of a few forces that works together in order to make an agent move. The most important force is the driving force. This is because without the drive to go to somewhere the agents do not need to even move in the first place. After the agents find their drive and start walking, the agents will need a repulsion force to avoid other agents or objects along their journey toward their destination. The agents also might need an attraction force if they found something that grabs their attention along the journey. Other than that, if the agents walk within a small group of a few agents, group force is needed to keep these agents sticks together among all the other agents outside the small group. Lastly, since ZS Force Model is applicable to Tawaf situation, each agent also needs the circling forces to keep each agent circumambulate the Kaabah until they complete the ritual.

i. Goal

One of the main forces in this new model is the goal force. The goal is the desired position that each agent wants to go. The goal position is different for each agent. For example, in the real world, some people want to go to the store, some want to go home and some other places. The desire to arrive at the goal position will make the pedestrian move from their current position to their goal position. However, in Tawaf everybody have the same main goal, which is to circle the Kaabah 7 times. As we can see in Figure 4 shows that the agent will start circling at the Hajarul Aswad (Black Stone) and move in counter clockwise rotation. This is different from any other situation that every agent will have their own different goal, which makes the Tawaf situation unique.

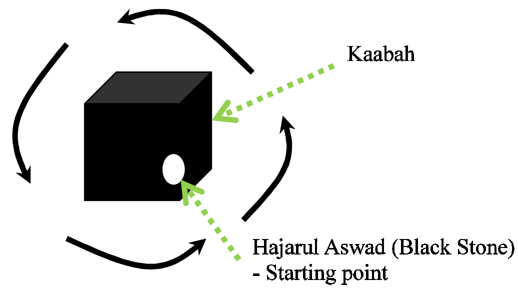

Figure 4 : Tawaf pedestrian movement flow

$$g_a = p_a + \frac{d(t-p_a)\times Y}{|(t-p_a)\times Y|}$$

This goal force was the extended version of the driving force in the Social Force Model. During Tawaf, agents need to circle around the Kaabah, thus makes it as the epicentre of the circumambulation, t. Other than that, since the agents are moving around the Kaabah, so is the goal position of the agents. Thus, in ZS Force Model the goal position, g_a will constantly move around to make the agents circle around the Kaabah, as shown in figure 5. Parameter d is the distance which the goal will be repositioned each time pedestrians reach at their goal position. The smaller the distance value, d the more accurate the rotation calculation around the Kaabah will be.

$$f_{goal} = v_\alpha . d_\alpha / \tau_a - v_c / \tau_a \}$$

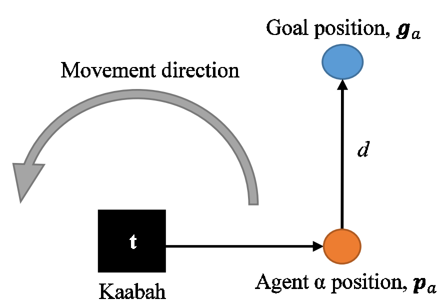

Figure 5 : Movement of agent's position and goal position

ii. Gender

Gender plays an important role in crowd simulation. This is because it will influence the behaviour of the agent in term of interaction with other agents. During Tawaf, there are several rules that need to be followed by each pedestrian. One of the rules is that, agents with different gender cannot

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touch each other. If they touched each other, both of them have to restart their Tawaf ritual all over again. Thus, pedestrians will try to avoid each other if they encounter different gender agents.

None of the previous researchers are focusing on simulating the different interaction between both genders. This is because mostly in other situation there are only minor differences between both interactions. However, in Tawaf scenario, it plays a very important part in order to simulate the situation precisely.

$$f_{gender} = s\exp[\frac{p_\alpha - p_\beta}{r}]n_{\alpha\beta}$$

In order to simulate this situation, the interaction force equation will be enhanced, as can be seen in Table 1. Each agent has their own interaction forces and interaction threshold. Interaction force is the repulsion strength towards other pedestrians, so that they do not collide with each other. While, interaction forces are the distance which the interaction forces will begin to trigger. If different genders pedestrians meet with each other, both of them will have a higher force of interaction compared to the interaction force if they have the same gender. However, their threshold of interaction will remain the same distance for both interactions. The threshold of interaction remains the same because people mostly have similar distance of interaction, even though the force of interaction is different. The interaction forces also increase the closer the agents towards each other.

Table 1: Parameter modification

Condition	Parameters	
	Interaction Force	**Interaction Threshold**
Same Gender	F1 = 0.015f F2 = 0.005f F3 = 0.0025f	D1= 0.5f D2 = 1.0f D3 = 2.0f
Different Gender	F1 = 0.019f F2 = 0.009f F3 = 0.0029f	D1= 0.5f D2 = 1.0f D3 = 2.0f

iii. Walking Speed

Everybody has their own desired walking speed. It is influenced by many factors such as intention outlook, age, and gender. For example, a younger man will have a faster walking speed compared to an old lady. However, this can be completely the opposite if the intent of the old lady differs from the younger man. For instance, if the old lady is in an emergency situation, she will try to walk as quickly as she can. Meanwhile, a younger man without any emergency will walk slowly than the old lady.

During Tawaf, there are a lot of agents walking in the same place at the same time. Some of them want to finish faster, will walk faster compared to the other agents. The driving force equation will be manipulated in order to realize this behaviour. In order to get the min value for walking speed actual walking speed, v_α will be subtracted from the desired walking speed, v_c of each agent. While getting max value for walking speed, desired walking speed, v_c will be subtracted from the actual walking speed, v_α.

$$f_{speed} = v_\alpha . d_\alpha / \tau_a - v_c / \tau_a \}$$

Since every agent has their own desired walking speed, it must be distributed evenly among the agents within the crowd simulation. Thus, the walking speed will be distributed accordingly by using the Gaussian distribution model (figure 6). The Gaussian distribution model is used because it is one of the most popular models to distribute a normal distribution similar to the real world scenarios. A random number generator cannot be used in this simulation due to the distribution might be awkward and does not simulate the real world situation.

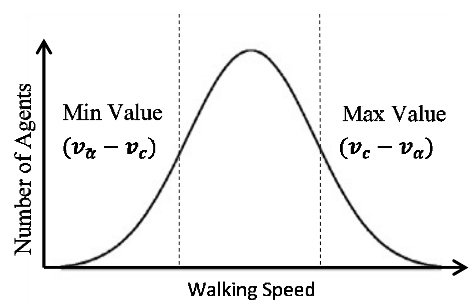

Figure 6 : Walking speed distribution (Gaussian distribution model)

According to Mohamed H. Dridi [34] an average walking speed for pilgrims during Tawaf on average are 1.22m/s for women and 1.37m/s for men (figure 7). Based on this information it shows that the female agent has a slower walking speed than the male agents. Thus, in order to have a better and realistic crowd simulation these data will be included in the ZS Force Model.

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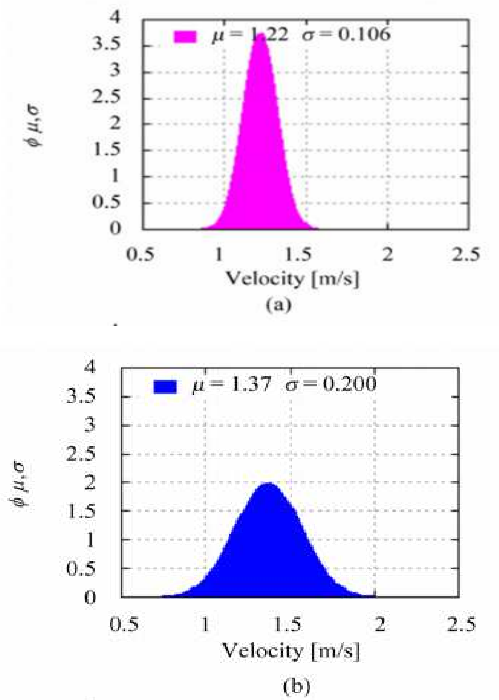

Figure 7 : Walking speed distribution in Tawaf movement. (a)Women. Average walking speed is 1.22 m/s (b) Men. Average walking speed is 1.37 m/s

iv. Grouping

Agents sometime like to walk in groups. Agents within the same group have the tendency to keep close to the other members of the group. Even if they were separated, they will try to reunite of possible. The groups are mostly consisted of two or more agents. These groups also can be a combination of both male and female or just one gender. The interaction forces between members of the group are also weaker than the interaction forces between agents outside the group.

Thus, to realise this situation within the crowd simulation, this research chose the Helbing's Rule-Based Model [35] to be integrated into the ZS Force Model. This model was chosen because it is very suitable to be used to simulate group behaviour; since all the agents within the group have a similar direction and walking speed. As discussed in the previous sections the Rule-Based Model has three main rules which are cohesion, separation and alignment [36-40].

Cohesion is for the formation the group. Each agent location, Pj within the same group will total together and then divided by the number of the group members, m. Hence, the groups will move together to the same position.

$$c_i = \sum \frac{p_j}{m}$$

The next rule is alignment, which is used to make sure that every group member move at the same walking speed. A group cannot have a member who walks too fast or too slow. They must have similar speed in order to move together. Hence, the average speed of the group will be calculated. The total walking speed of each agent, Vj will be divided by the total number of the group members, m.

$$m_i = \sum \frac{v_j}{m}$$

The separation rules will be eliminated because the Repulsion force of the Social Force Model has a better solution for collision detection compared to this Rule-Based Model. In addition, if the separation rule is implemented on top of the Social Force Model will cause redundant of repulsion forces. This will make the agent to move awkwardly and unnaturally.

As a conclusion the grouping force will consist of two rules of Helbing's Rule-Based Model. These rules are cohesion and alignment. These two rules will be integrated with the rest of the ZS Force Model to make a better crowd simulation model.

$$\sum_{\beta=0}^{n} f_{group} = c_i + m_i$$

c. ZS Force Model

As stated above, the Social Force Model consisted of three main forces. These forces were named as driving, repulsion and attraction forces accordingly. For the ZS Force Model, another four forces were added into the equation. Those forces are goal position, gender interaction, walking speed distribution and grouping formation. Details of each new force were explained above. Below is the new combination of equations for ZS Force Model.

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$$f_{ZSFM} = f_{driving} + \sum_{\beta=0}^{n} f_{repulsion} + \sum_{\beta=0}^{n} f_{attraction} + \sum_{\beta=0}^{n} f_{goal} + \sum_{\beta=0}^{n} f_{gender} + \sum_{\beta=0}^{n} f_{speed} + \sum_{\beta=0}^{n} f_{group}$$

4. RESULT AND DISCUSSION

The experiment in this research is to combine all the forces and test whether each of them can work together within the same model.

The result shows that all the new forces within ZS Force Model can work together in order to make a better crowd simulation. All the forces can simulate a better crowd behaviour, not just for the whole crowd, but also as individuals and also small groups.

The implementation of the ZS Force Model for high density crowd simulation had successfully been done in this section. This method could produce efficient forces to avoid collision between agents without separating agent whom within a group. Other than that, a few of Tawaf rules can be realised successfully in this crowd simulation. Those rules are goal position and gender respectively. Hence, the objective of this research was archived by introducing a novel model which is ZS Force Model to improve the simulation of crowd flow in high density crowd situations.

A crowd usually consists of people from different backgrounds, such as gender, age, and intention outlook. It is also sometime consists of several groups of pedestrians which tends to move together. Previous researchers have proposed several methods to solve this problem; however, their solution does not include each of this attribute together.

In this research a new Model of crowd simulation has been proposed by using the Zahmah concept. As discussed before in previous section Zahmah is a concept of that controls the behaviour of the crowd as individuals, but yet still manages to control the crowd to move together as a whole. The current existing models are not diverse enough in term of demographic background which indirectly influences the behaviour of the crowd [37,38,39].

ZS Force Model was designed to handle these issues by giving each agent in the simulation a different set of attributes, which make every agent unique just like in the real world. Some of the agents are also will be set as groups to replicate the grouping behaviour in crowd simulation. This model has hybrid all the required parameters such as gender, age, and intention outlook, which does not consider by the other models. These attributes were clearly defined from the Zahmah concept which was reflected in the high density crowd environment. This model has been tested in the Tawaf scenario which produces a more accurate simulation result compared to the conventional Social Force Model.

As explained in the previous sections, Tawaf have lots of rules and regulation to be followed by each agent. These rules that make the movement of crowds become more unique and difficult to be simulated. Nevertheless, by using the ZS Force Model a few of these rules had been applied in the crowd simulation. Based on the simulation result, it shows that the ZS Force Model has been successfully simulated some of the Tawaf rules. Those rules are circumambulation and gender interaction.

Based on implementation, this model also applicable for other scenarios; such as in a crowded train station or road intersections. Similar to the Tawaf ritual, these scenarios also have a high density population with various demographic backgrounds. Though, the Tawaf ritual might have a much higher population and density compared to the other scenarios.

5. CONCLUSION

As a conclusion, based on the experimental results this model can simulate high population crowd more accurate than the conventional Social Force Model. All the attributes within this model allow the simulation to be more natural and exhibit the behaviour comparable to the real-world crowd.

Although both proposed model shows great results, it is still far from perfect in capturing the real-world crowd behaviour. Some enhancements need to be made in the proposed method so that the accuracy of the simulation could be improved for future use. In the future works, there will be tons of unique behaviour that only occurs in the high density crowd, which yet to be explored and to be implemented in the crowd simulation. These behaviours can be studied by observation. These studies can be carried out either by watching videos or the real-world situation. Other crowd simulation models such as holonomic behaviour and manoeuvring behaviour also can be added in the future research since these behaviours also normally happen in the dense crowd.

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In order to improve the simulation for the Tawaf ritual, other Tawaf rules can be added along with existing rules within ZS Force Model. To make the simulation more interesting, other agents' behaviour such as getting out from Mataf area, getting into Mataf area or praying can be added into the simulation. With the implementation of these behaviours the crowd flow will become more chaotic and hectic.

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