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The study of the influence of obstacles on crowd dynamics

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Abstract
This paper presents the research on the influence of obstacles on crowd dynamics. We have performed experiments for four base scenarios of interaction in crowd: unidirectional flow, bidirectional flow, merging flows and intersection. Movement of pedestrians has been studied in simple shape areas: straight corridor, T-junction and intersection. The volumes and basic directions of pedestrian flows were determined for each of the areas. Layout of physical obstacles has been built from different combinations of columns and barriers. In order to acquire characteristics of the crowd dynamics a set of simulations was conducted using PULSE simulation environment. In the result, we have managed to obtain several dependences between layout of obstacles and crowd dynamics were obtained.

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Keywords: pedestrian crowd dynamics; obstacles layout; agent-based modeling

1 Introduction

Mass gatherings are an essential part of our lives. Public events are held more often, moreover, the scope of events and the number of participants increase. There are several types of activities that may bring large numbers of people together: sports (Olympic Games, world championships), religious (Kumbh Mela, The Hajj), cultural (concerts and festivals) and political events (mass meetings and strikes). Each type has its own characteristics: behavior and purposes of the participants, place and time.

Crowd managers should consider a lot of details to organize a safe and secure event. Soomaroo and Murray [1] have analyzed previous cases of disasters for the period between 1971 and 2011. Overcrowding and crowd control were defined as one of the key areas for preparation of mass events. There are several potential hazards related to crowd movement: suffocation, crushing, trampling.

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These can lead to a large number of casualties. In recent years, there have been several dangerous accidents during mass gatherings. One of the biggest stampede occurred during the annual Hajj pilgrimage in Mina (Mecca, Saudi Arabia) in 2015: more than 2000 pilgrims died and more than 900 pilgrims were injured. The stampede occurred when two large groups of pilgrims with different directions of motion collided faced at the crossroad. Another deadly stampede occurred in Cambodia in 2010 during the Khmer Water Festival. 347 people were killed and 755 people were injured. The crush occurred on a narrow passage of the bridge: some people were trampled, some people drowned in river. In stampede people lose their balance, fall down and may turn into obstacles for others pedestrian because pushing crowd is not controllable.

Installment of physical obstacles to navigate pedestrian flows is a common crowd control and management tool. Such obstacles include crowd control barricades, barriers, line management systems, temporary fencing, and entry control systems [2]. It is widely accepted that temporary obstacles coupled with permanent architectural design solutions and can increase the safety of mass events. The aim of this paper is to identify dependences between various types of obstacles and the main characteristics of the crowd's movement in various types of interaction between flows. It can provide considerations when planning for future events in terms of security and crowd control.

In this work, we describe the method and first results of the study of obstacles influence on the crowd dynamics. Some background information and related works are presented in section 2. Section 3 contains description of selected scenarios and scheme of our approach. In section 4, we present the data obtained from the simulation. Section 5 presents conclusions and a discussion of further research.

2 Related works

The study of dynamics of the crowd movement and influence of different layouts and forms of obstacles have an interdisciplinary nature. On the one hand, one should take into account the experience of crowd managers of mass gatherings, on the other, relevant developments (methods and tools) from the field of crowd movement modeling.

Scientific and practice-oriented organizations worldwide study features of mass gatherings and investigate the causes of dangerous incidents [3]. This becomes the basis for the publication of standards and regulations of safety during mass events. For instance, the British "Health and Safety Executive" organization [4] identifies two types of hazard factors: crowd and venue-related. In the first group hazards may be caused by crushing, aggressive and dangerous behavior, such as climbing on barricades or buildings. Hazards associated with a venue are the following: collapse of structures, such as a fences or barriers, which may crush people, moving vehicles sharing the same route as pedestrians, failure of equipment, such as turnstiles and so on. Therefore, pedestrians face a variety of permanent and temporary obstacles, which can interfere with their movement. From another perspective, temporary structures like barriers are one of the ways to control pedestrians' behavior. According to the guide [5], there are several main purposes of barriers: pedestrian flow control, flow direction management, blocking, and area delineation (separation of groups, boundaries marking etc.).

Crowd consists of separate groups of pedestrians or flows gathered together by a common interest or activity. These groups or flows have different characteristics of movement. Duives describes the taxonomy of base cases of crowd movement and distinguishes two types of flows [6]: unidirectional and multidirectional. Unidirectional flows can be straight, rounding corners or entering, exiting. Multi-directional flows can be parallel or crossing with focal point or random. This taxonomy helps to define base scenario of flow's interaction for investigating crowd motion.

There are two main methods to study the dynamics of the crowd: the experiment with people and crowd simulation. Lots of experiments have been devoted on objects of various shapes with the help of volunteers. For example, Helbing [7] conducted experiments for corridors with single or two opposite flows passing a short or long bottleneck. Authors [8] study various forms of ordering in bidirectional pedestrian stream. Case of T-junction was investigated by Zhang [9] and Shiwakoti [10]. Intersection of two flows on crossroad was investigated in [7].

It seems that the movement of the crowd is difficult to define and describe by computer model. This is probably true then we consider new or complex situations. In such situations, the behavior has probabilistic character. But in standard or simple situations the behavior of human is well predictable and can be described by computer model [11]. One of the widely-used models in studies of crowd dynamics is a social agent-based model (ABM). Cioffi-Revilla [12] defines three main components of ABM: agents (autonomous, interacting, goal-oriented), rules and environments where agents are simulated. Thus, agents can perceive information and make decisions. In work [13] a pattern-based approach is proposed to simulate human-like pedestrian steering behavior of agents.

ABM provides unprecedented opportunities for investigation of behavior of people in critical events including studies of information spread [14], analysis the effectiveness of wearable wireless sensors in controlling density of crowd [15], evacuation scenarios [16] etc. In the latter example, the main purpose of analysis is optimal layout of obstacles for minimization of evacuation time. Jiang [17] uses ABM based on Social Forces [11] and genetic algorithm to obtain best designs of architectural entities to host large crowds. More detailed approach has been proposed by Zhao [18]. He uses Social Force model and a robust differential evolution to optimize the geometrical parameters of differently shaped (pillar and panel) obstacles in order to achieve an optimal evacuation performance.

From the survey of the existing literature on the matter, we may conclude that different obstacles can help control and regulate motion of pedestrians in crowds. However, there is clear lack of systematic research on how different characteristics of obstacles shape the movement of the crowd. The articles discussed above study the following characteristics of the motion: density, velocity, flow and crowd pressure. For visualization of the relationship between some characteristics fundamental diagrams [19] may be used.

3 Method

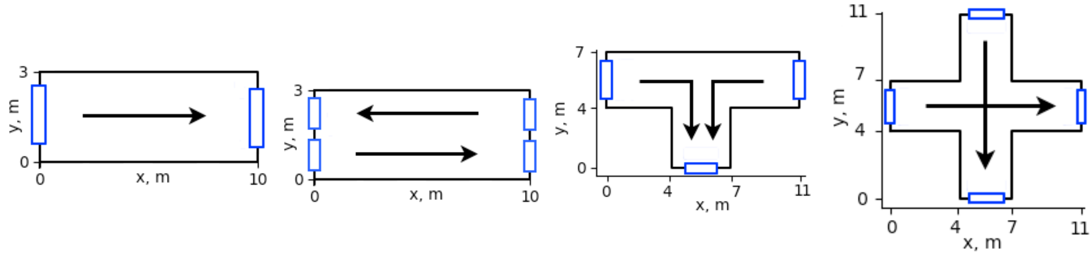
This section contains the description of the approach used in the study. In the first part, we describe the set of experimental scenarios and their characteristics. The second part is dedicated to description of the modeling tools used.

3.1 Description of the base cases

Mass gatherings may occur in different places. Depending on the specifics of the event it may be a stadium or a group of sports objects, town square or another urban area, various suburban areas etc. The territory of events and public places may be of a complex shape and can be divided into separate zones in regard to functional, spatial and other characteristics. Thus, the space can be reversely decomposed into units, based on the following features:

- geometric shape;
- number of inputs;
- number of outputs;
- directions of movements between inputs and outputs.

In most cases, crowd consists of unidirectional and multidirectional flows. For multidirectional cases, there are several possible types of interaction between individual flows: movement in opposite direction, merging, intersecting. Other forms of interaction can be obtained by their combination. For investigation of the scenarios based on these interactions we suggest considering the cases of simple shape: straight corridors for unidirectional and bidirectional flows, T-junctions for merging and crossroad for intersection (Fig.1). The width of the corridor has been selected in accordance with the rules of urban planning developed by the Ministry of Regional Development of Russia [20] for sidewalks (in streets with adjustable movement).



(a) (b) (c) (d)

Figure 1: The base cases and the directions of motion: (a) corridor with unidirectional flow; (b) corridor with bidirectional flow; (c) T-junction; (d) intersection area; the arrows indicate directions of motion; blue rectangles denote portals where agents appear or disappear.

Selection of cases was based on the work of studying the flow in simple shaped areas and described in section 2. For the unidirectional flow, the following layouts of obstacles were chosen: parallel, zigzag-shaped barriers and barriers which create narrow passage. In order to investigate the influence of a narrow passage two scenarios with a column and constriction were added.

Corridor with bidirectional flow is a typical situation: these can be found in corridors in buildings, sidewalks on the streets, approaches to events, etc. Two flows can be artificially separated by one barrier or a series of obstacles like columns or short barriers. Second type of obstacles are permeable. Such designs allow pedestrians to use the other side of corridor, if necessary. In addition to that, cases for zigzag-shaped barriers and narrow passages were added.

Table 1 contains the possible scenarios of obstacle's layout for the corridor case.

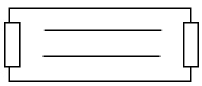
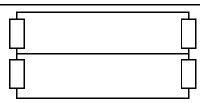
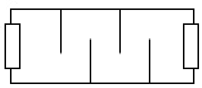
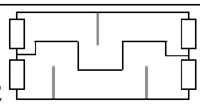
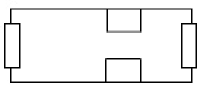
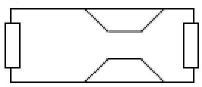
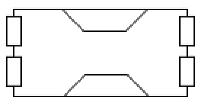
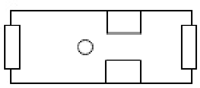
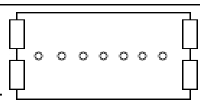
Scenarios	Corridor with unidirectional flow	Corridor with bidirectional flow
Straight line of barriers	a.1 	b.1 
Zigzag-shaped barriers	a.2 	b.2 
Narrow passage	a.3  a.4 	b.3 
Columns	a.5 	b.4 

Table 1: Scenarios for corridor

T-junction and intersection represent cases of merging and crossing of pedestrian flows. Columns and lines of barriers on crowd's way are assumed to alter the direction of crowd movement and place of collision. These obstacles have been added to T-junction and intersection. In addition to that, the scenario of a narrow corridor for the merging and scenario with a circular motion around the column for interaction were added. Table 2 contains scenarios for these cases used in the experiments conducted for this research.

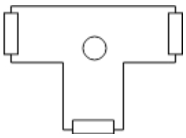
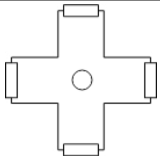
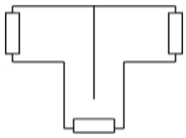
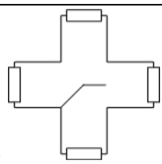
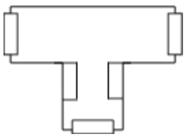
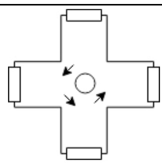
Scenarios	T-junction	Intersection
Column	 c.1	d.1 
Barrier	 c.2	d.2 
Other	 c.3	d.3 

Table 2: Scenarios for T-junction and intersection

3.2 The method's scheme and simulation environment

This section presents the method's scheme and its main components (Fig. 2). First part of input data is a set of cases (the corridor, T-junction and intersection area). For each case, different obstacles were selected in section 3.1. In order to calculate the characteristics of the motion, we use virtual sensors. The sensors are parts of the area where characteristics of motion are measured.

In normal situations, the desired velocity is approximately Gaussian distributed with a mean value of 1.3 m/s and a standard deviation of around 0.3 m/s [7]. This distribution has been used for defining desired velocity of each agent. Probability of generating agents defines in each case and it is the same for different layouts of obstacles in each case. This determines the number of agents in the area.

For multi-agent simulation of crowd behavior in all investigated cases we use PULSE simulation environment [21][22], which is freely available via GitHub[*]. PULSE uses modified HiDAC (High-Density Autonomous Crowd) agent-based model [23], which based on a combination of psychological and geometrical rules with a social and physical forces model. In our model, the perception area for agent has a half ellipse. Each agent in the model is autonomous, has a desired velocity and direction of movement. In addition, other objects may interplay with movement of virtual pedestrians: the distance to the obstacles and distance to other agents shapes the trajectories of agents. For the sake of reproducing uncertainty in agents' behavior, fluctuation of parameters has been added. It can be described as an accidental or deliberate deviation from the usual rules of motion.

[*] https://github.com/vladkar/pulse-project-open

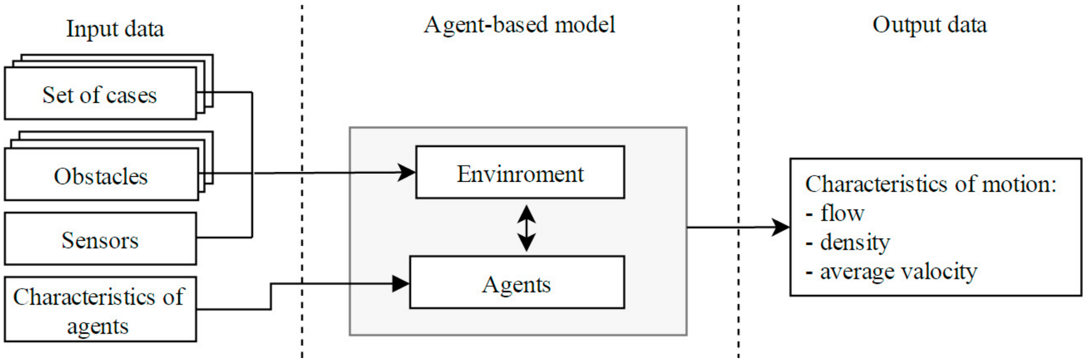


Figure 2: The method's scheme.

Output data and results of simulations were collected using sensors which recorded required parameters at defined part of territory. The following indicators were mesuared for discription of the pedestrian movement: velocity (average velocity of agents), the density (number of agants in square meter) and flow (the number of agents in sensor's zone).

For identifying dependances between the indicators, a metric known as a fundamental diagram of pedestrian movement was used. In this paper, we investigate the relationship between the density of agents and average velocity.

4 Results

30 simulations were conducted for each of the scenarios with 95% confidence level. Data was gathered for periods of 30 seconds, and total time for each simulation run is 600 seconds. The results of experiments are presented below.

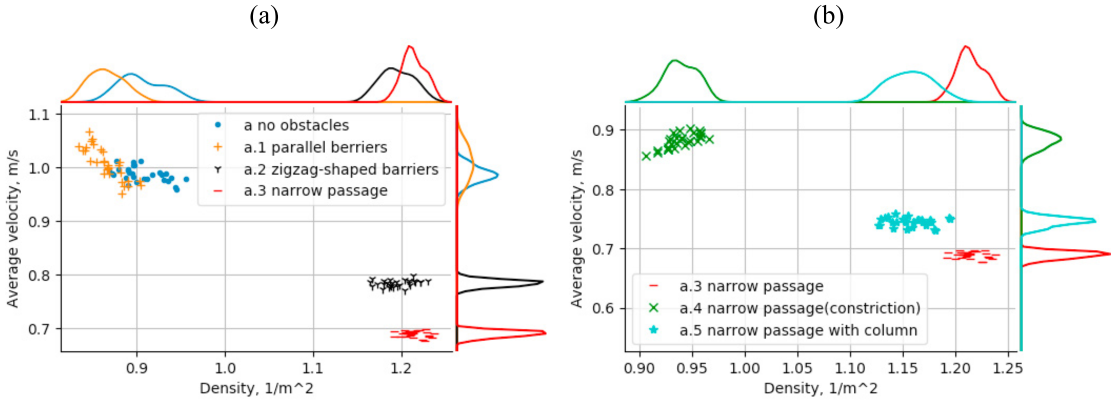


Figure 3: Fundamental diagram of pedestrian motion with unidirectional flow in corridor: (a) relation between density and average velocity; (b) relation between density and average velocity for narrow passage.

(a) (b)

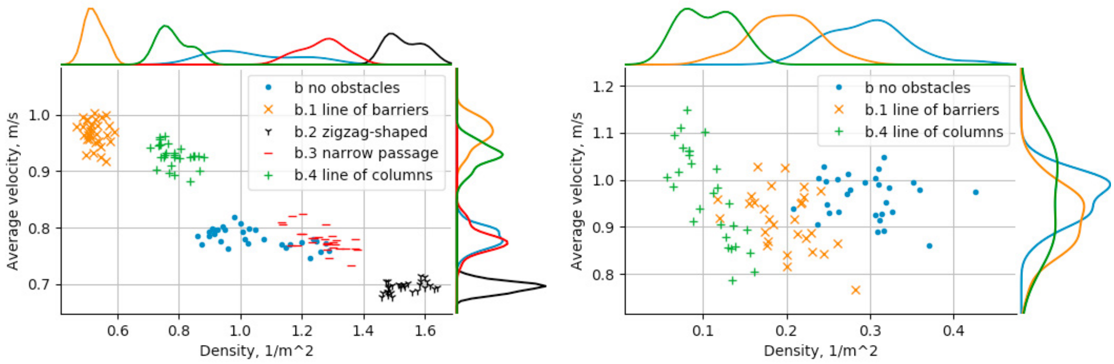


Figure 4: Fundamental diagram of pedestrian motion with bidirectional flow in corridor: (a) relation between density and average velocity; (b) relation between density and average velocity for decreased flows of pedestrians.

Figures 3 and 4 illustrate the results of simulations for a unidirectional and bidirectional flows in corridor case. Conclusion for these scenarios are presented in table 3.

Scenarios	Corridor with unidirectional flow	Corridor with bidirectional flow
Straight line of barriers	a.1: Insignificant decrease of the density	b.1: Increase of average velocity and decrease of density in the case of increasing the number of agents
Zigzag-shaped barriers	a.2, b.2: Significant decrease of the average velocity and increase of density	
Narrow passage	a.3, a.4: Decrease of the average velocity and greatly increase of density, however, gradual constriction reduces this affect	b.3: Decrease of the average velocity and increase of density
Columns	a.5: Increase in the average velocity and decrease of density in the case of a narrow passage	b.4: Increase of average velocity in the case of increasing the number of agents

Table 3: Comparison of scenarios with obstacles and control scenario without obstacles for corridor case.

For the unidirectional flow, the following results were obtained. Parallel barriers seem to separate pedestrians into several flows and decrease density in the crowd. Zigzag-shaped barriers and narrow passages have another effect: pedestrians have to bend around obstacles so dropping the velocity of their movement which leads to an increase in density. In order to increase average velocity for overcoming narrow passage single column in front of passage or gradual constriction can be established.

The scenarios with bidirectional flow and zigzag-shaped barriers or narrow passages produce a similar effect to the one seen in the scenarios for unidirectional flow. For more detailed investigation of obstacles placed in line, simulations with different numbers of agents were conducted. As a result, line of obstacles shows greater influence on agents when their numbers grow and thus helps avoid collision of the latter. The described effect allows to increase the average velocity of agents' movement.

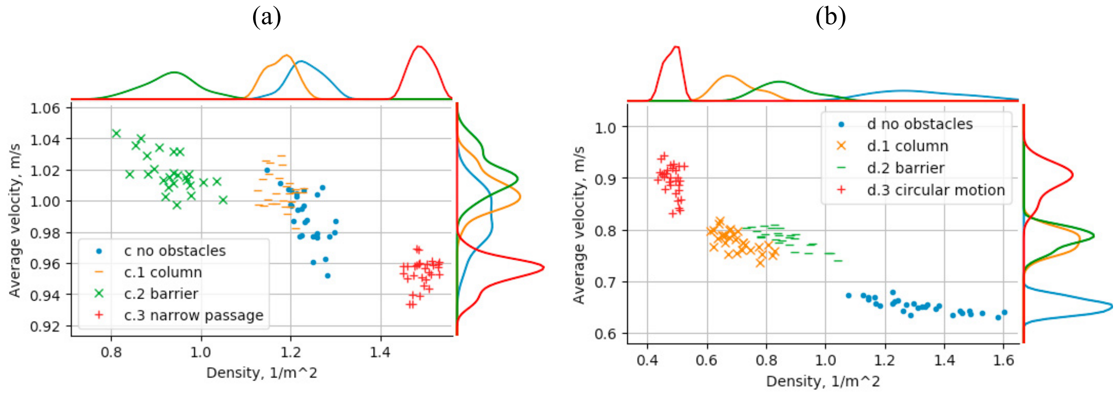


Figure 5: Fundamental diagram of pedestrian motion: relation between density and average velocity: (a) T-junction; (b) Intersection.

Figures 5 illustrate the results of simulations for merging and intersection of flows. Conclusion for these scenarios are presented in table 4.

Scenarios	T-junction	Intersection
Columns and barrier	c.1, c.2: Increase in average velocity and decreased density values	d.1, d.2: Significant increase in density and increase in velocity
Other	c.3: Dramatic increase in density	d.3: Decrease in density values

Table 4: Comparison scenarios with obstacles and base scenario without obstacles for T-junction and intersection.

In scenarios of flows' merging, the barrier or the column between flows have same effect on velocity and density of crowd. These obstacles reducing the angle between the interacting flows. The width of the resulting corridor in case of merging should be enough for pedestrians from two another corridor, because narrow passage is a place of gathering a large number of agents.

Intersection of flows may significantly increase density and decrease average velocity in scenarios without obstacles. For the increasing velocity and decreasing density column or barrier can be installed in the center of intersection. It's important to note, circular motion around column can give more stable value of movement's characteristics.

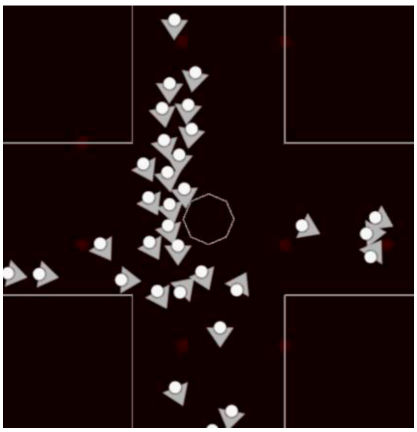


Figure 6: Screenshot from PULSE simulation environment

Figure 6 depicts the screenshot from PULSE simulation environment for the circular motion scenario (d.3) with column in case of intersection. The triangles denote the direction of agent's movement.

5 Conclusion and Discussion

In this paper, we describe the results of the primary study, aimed at formalizing the influence of different layouts of obstacles like barriers and columns on pedestrian dynamics.

Unidirectional and bidirectional flows, merging and intersection of pedestrian's flows were considered as basic scenarios of motion, because other interactions can be obtained by their combination. For investigation, selected scenarios the cases of simple shape were chosen: corridor, T-junction and intersection. During the experiment, we have investigated the several possible layouts of obstacle on crowd's way: single barrier, column or groups of objects. Better understanding of such a processes could help to build better models and use them to achieve better results for different scenario simulations [24] or [25].

In the result of experiments, we came to the following conclusions about impact of obstacles on crowd dynamics. Barriers set in a zigzag shape decrease average velocity and decrease density in the crowd. Narrow passages have the same effect, but it can be reduced by installing additional obstacles: single columns or constriction. Lines of obstacles allow to separate flows in the crowd in order to reduce density. At the same time, there are obstacles that particularly change the characteristics of the movement, for instance, the installation of the column and the organization of circular motion in scenario of intersection reduce density.

Control of movement on the territory of mass gathering is one of challenges for organizers. The knowledge about the influence of different obstacles on the crowd dynamics can help to place barriers, barricades and columns and to organize the movement of different flows of pedestrian more safely.

This is the base for the future work dedicated optimal layouts of barricades for specific situations, which may be a problem of evacuation and minimization of time, a problem of reducing the velocity or density of agents. Besides we plan to conduct more experiments on complex shape areas and study the crowd's pressure characteristic because the density and the velocity does not fully reflect the influence of obstacles and other agents, however, asphyxia is one of the cases of death in stampede.

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