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Reserve capacity and exit choosing in pedestrian evacuation dynamics

Hui Zhao and Ziyou Gao

Institute of System Science, School of Traffic and Transportation, Beijing Jiaotong University, Beijing, 100044, People's Republic of China

E-mail: zhaohui@jtys.bjtu.edu.cn and gaoziyou@jtys.bjtu.edu.cn

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Abstract

A modified cellular automata model is proposed to simulate the pedestrian evacuation behavior in a room with multiple exits by considering the reserve capacity of the exit. The main idea is motivated by the original concept of minority game, which means less congested exits may be preferentially chosen together with the floor fields. The model outperforms previous ones under the condition in which pedestrians are distributed heterogeneously. Simulation results show that wise exit choosing with the consideration of reserve capacity may reduce the evacuation time apparently, which is more realistic. Furthermore, the impacts of the room geometry and parameter settings are investigated extensively.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction

Recently, pedestrian dynamics have attracted many interests of physicists and traffic engineers [1]. Actually, numerous collective behaviors and self-organization phenomena have been observed in pedestrian dynamics, such as arching, clogging, panic, faster-is-slower, lane formation, spontaneous symmetry breaking, etc. Furthermore, in the field of traffic engineering, understanding the pedestrian dynamics is of great importance in public facilities design.

Because evacuation dynamics is much more difficult to observe than pedestrian dynamics in normal conditions, various macroscopic and microscopic modeling approaches are highly encouraged. Macroscopic models, such as the fluid-dynamic models [2, 3], attempt to describe dynamics of large-scale crowds. Microscopic models, including many-particle force models [4–6], lattice gas models [7–11], cellular automata models [12–16] etc, can describe the details

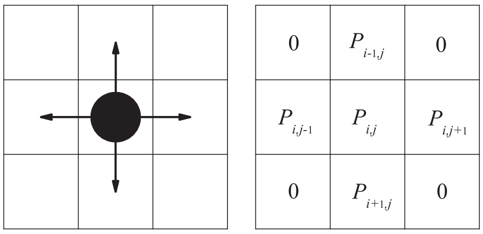

Figure 1. The possible transitions and corresponding transition probabilities of a pedestrian with a relative position.

of pedestrian behavior. In this paper, one of the most important cellular automata models, the floor field model is focused to investigate the pedestrian evacuation dynamics in a room with multiple exits.

Though there are many models that can characterize the pedestrians dynamics, to the extent of our knowledge, evacuation in a room with multiple exits is less investigated [15–17]. Furthermore, most of the models cannot simulate the evacuation process accurately enough when the pedestrians are distributed heterogeneously. In fact, there are instances that some people assemble much more densely in a specified zone of a room. For this consideration, an improved floor field model by considering the exit choosing behavior is presented here to simulate the heterogeneously distributed pedestrians evacuation dynamics. The concept of reserve capacity is introduced from the field of traffic engineering to characterize the exit choosing behavior. The impacts of the room geometry and the parameter settings including the scale of reserve capacity, initial distribution of the pedestrians, etc, are also investigated. It is shown that wise exit choosing by considering the reserve capacity may reduce evacuation times considerably. This paper can be organized as follows. In section 2, the generalized floor field model is introduced in detail. Simulation results, especially in scenarios when pedestrians are distributed heterogeneously, are shown in section 3. Additionally, the impacts of room geometry and parameter settings are investigated extensively. In section 4, conclusions are included.

2. The model

Analogous as in previous models, the space is represented by two dimensional square lattices [13–16]. Each lattice site is approximately 40×40 cm^2 in size and can be either empty or occupied by exactly one pedestrian. Pedestrians may be distributed either homogeneously or heterogeneously in the room at the initial state. In each time step, all pedestrians can move to one of its neighbor lattices with a fixed velocity in one of the four directions, say forward, backward, left and right, or remain stay-stand according to a certain transition possibility.

Figure 1 presents the allowed motions and corresponding transition probabilities for a pedestrian in each time step. The transition probability P_{ij} that a pedestrian intends to leave the room from the doors represents the possibility of selecting the neighboring lattice (i, j). Similar to the previous floor field models [13–16], the probability can be determined by the local dynamics and the floor fields at that specified lattice site. What should be emphasized is that here the definition of *reserve capacity* for each exit, which was discussed in the field of traffic engineering before [18], is introduced to help to characterize the pedestrians' exit choosing behavior. The reserve capacity C_r^m of exit m can be analogously defined as the number of unoccupied cells in the effect area [19] of exit m with radius r. The effect area is the

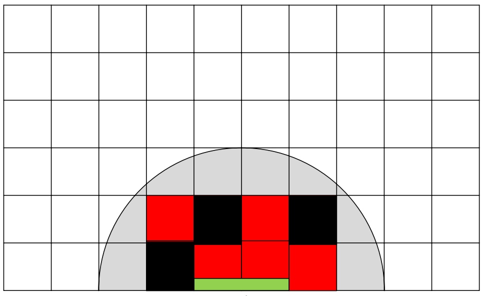

Figure 2. Illustration of the calculation of the reserve capacity C_r^m. The width of the exit (green colored, signed) is 2 (cells).

special region around the exit which is considered to calculate the reserve capacity. As stated in [19], the effect area can be defined in some other ways and there is no limitation of shape and size of the area. Figure 2 gives an illustration of the calculation of the reserve capacity C_r^m. As shown in the example, the effect area contains eight cells (red and black colored) which are located in a half-round with radius 2 (gray colored cells are added). The three occupants are represented by black colored cells. Then the reserve capacity C_r^m is $8 - 3 = 5$ (red colored cells). It is obvious that if a lot of pedestrians jammed near a exit, the reserve capacity of the specified exit may have a rather small value. For detailed information of the reserve capacity, one can refer to one of our previous works [18] and references therein. Unlike in the previous exit choosing strategies [15, 16], in this model, the pedestrians choose their target exits according to the reserve capacity of exit m dynamically in each time step.

Our main idea is motivated by the original concept of minority game. The minority game is a widely used model for characterizing the collective behavior of the agents which have to compete for finite resources [20, 21]. In the evacuation process, if numerous pedestrians approach the same exit, a jam occurs, and it may take a rather long time to evacuate from the exit. Actually, there may exist some farther but un-congested exits, which if chosen, it may take less time to evacuate. In addition, the distance to alternative exits is also an important consideration in evacuation, especially in places with special geometries, e.g. long corridors. Then those un-congested exits may be chosen by the pedestrians who are not very far from them. It is reasonable to consider that each pedestrian may make his/her decision according to the reserve capacity and distance to alternative exits in each time step, together with the static and dynamic floor field accordingly. In the next section, it can be shown that this exit choosing mechanism may lead to less evacuation time.

In each time step, transition probabilities of the pedestrian to the four directions, namely U(up), D(down), L(left) and R(right) at site (i, j) can be determined by

$$P_{ij}^{\mathrm{U}} = N_{i,j} \exp\left(k_S S_{i-1,j} + k_D D_{i-1,j} + \sum_{m \in U}\left(k_C C_r^m + \frac{k_E}{E_{i-1,j}^m}\right)\right)(1 - \mu_{i-1,j})\xi_{i-1,j}, \quad (1)$$

$$P_{ij}^{\mathrm{D}} = N_{i,j} \exp\left(k_S S_{i+1,j} + k_D D_{i+1,j} + \sum_{m \in D}\left(k_C C_r^m + \frac{k_E}{E_{i+1,j}^m}\right)\right)(1 - \mu_{i+1,j})\xi_{i+1,j}, \quad (2)$$

$$P_{ij}^{\mathrm{L}} = N_{i,j} \exp\left(k_S S_{i,j-1} + k_D D_{i,j-1} + \sum_{m \in L}\left(k_C C_r^m + \frac{k_E}{E_{i,j-1}^m}\right)\right)(1 - \mu_{i,j-1})\xi_{i,j-1}, \quad (3)$$

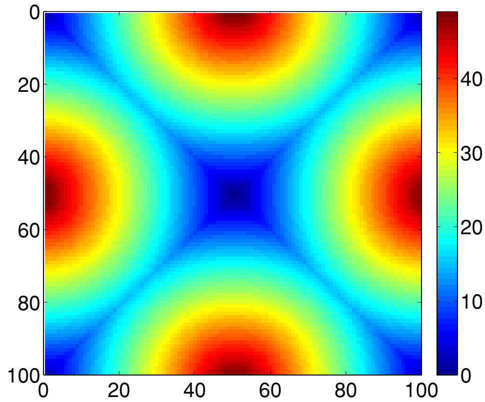

Figure 3. Static floor field S for a lattice of 100×100 with four exits of width four cells each. The value of static floor field is represented by different chroma accordingly.

$$P_{ij}^{\mathrm{R}} = N_{i,j} \exp\left(k_S S_{i,j+1} + k_D D_{i,j+1} + \sum_{m\in R}\left(k_C C_r^m + \frac{k_E}{E_{i,j+1}^m}\right)\right)(1-\mu_{i,j+1})\xi_{i,j+1}, \tag{4}$$

where $N_{i,j}$ is a normalization factor to ensure that $P_{ij}^{\mathrm{U}} + P_{ij}^{\mathrm{D}} + P_{ij}^{\mathrm{L}} + P_{ij}^{\mathrm{R}} = 1$. As defined in [13, 15, 16], S_{ij} and D_{ij} are the values of the static and dynamic floor field at lattice site (i, j) and k_S and k_D are two sensitivity parameters for scaling S_{ij} and D_{ij} respectively. The static floor field S_{ij} does not evolve with time and can be determined at the beginning of the evacuation. Actually, there are several approaches to define the static floor field [13, 15, 16]. In this paper, the static floor field S_{ij} is calculated from [15]

$$S_{ij} = \min_{(i_{T_s}, j_{T_s})}\left\{\max_{(i_l,j_l)}\left\{\sqrt{(i_{T_s}-i_l)^2 + (j_{T_s}-j_l)^2}\right\} - \sqrt{(i_{T_s}-i)^2 + (j_{T_s}-j)^2}\right\}, \tag{5}$$

where (i_l, j_l) runs over all lattices to reach the maximal value of the distance to all the exit cells (i_{T_s}, j_{T_s}). As illustrated in figure 3, there are four exits in a room and the static floor field increases in the four directions to all the exits. The dynamic floor field D_{ij} adopted here is defined as the number of bosons in the lattice site (i, j) and updated at each time step [15]. The bosons characterize the virtual traces left by moving pedestrians and their own dynamics proceed through diffusion and decay. Initially, the dynamic field D_{ij} of all lattices are zero. When a pedestrian moves from the lattice (i, j) to one of the neighboring lattices, the number of bosons increases by 1: $D_{ij} \to D_{ij} + 1$. Furthermore, each boson decays with probability δ and those bosons which have not decayed may diffuse (randomly move to one of the neighboring lattices) with probability α in each time step. As mentioned above, C_r^m represents the reserve capacity of the exit m in the effect area with radius r and k_C is the sensitivity parameter for scaling C_r^m. The distance between the cell (i, j) and the exit m can be measured by using the metric $E_{i,j}^m$, and the parameter k_E used in (1)–(4) is also a sensitivity parameter for scaling $E_{i,j}^m$. Notations U, D, L and R represent the exit set on the 'up', 'down', 'left' and 'right' side of the room. In (1)–(4), the occupation number μ_{ij} indicates whether the neighboring lattice (i, j) is occupied or not. It has a value 1 if the lattice is occupied and 0 otherwise. The obstacle number ξ_{ij} is related to the existence of obstacles. It is 0 if the neighboring lattice site (i, j) is a forbidden lattice, e.g. walls and 1 otherwise.

To define the reserve capacity as the number of unoccupied cells in the effect area of exit m with radius r is reasonable. In fact, the effect area usually contains cells with a high static

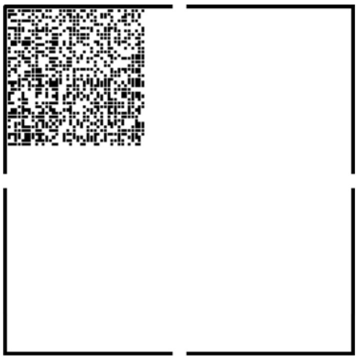

Figure 4. Initial stage of the evacuation with 900 pedestrians distributed heterogeneously in a specified zone (size 40 × 40 cells) of the room.

floor field. Then the number of unoccupied cells in the effect area can be seen as the level of chance to reach the area of high static floor field. Next, extensive simulations will be carried out to investigate the impact of the reserve capacities on the evacuation dynamics.

As described by [1–4], the basic dynamics of a pedestrian can be characterized by the static floor field, dynamic floor field, reserve capacity and the distance to alternative exits. If conflicts arise by any two or more pedestrians attempting to move to the same target cell, it can be resolved by probabilistic method used in [13, 15]. Since the normalization factor N_{ij} may be different at each site (i, j), here we adopted the un-normalized value and transform them into the proper relative probabilities. Next, we will focus on the role of the reserve capacity in exit choosing, especially in the case when the pedestrians are distributed heterogeneously in a room.

3. Simulation results

To understand the role of the reserve capacity in exit choosing, the evacuation process of the heterogeneously distributed pedestrians is simulated extensively. The room is set to be represented by 100 × 100 lattices with four exits. The width of the exit is 4 cells each. As shown in figure 4, there are 900 pedestrians randomly distributed in a specified zone attempt to escape from the room. The specified zone is represented by 40 × 40 lattices. Actually, the scene can usually be seen when some people are assembling or meeting in a relatively large hall. And for such a hall, there usually exists more than one exit. Then to investigate the evacuation dynamics under this circumstance is meaningful. The time step adopted here is 0.3 s, which implies a walking speed of approximately 1.33 m s^{-1}. The transition probability of each pedestrian can be determined by (1–4) with $k_E \neq 0$ and the procedure uses a parallel update to simulate the evacuation dynamics.

To validate the proposed model, well-known collective behaviors, e.g. arching and clogging in the evacuation process, are tested. The sensitivity parameters adopted here are $k_S = 2$, $k_D = 1$, $k_C = 0.1$ and $k_E = 2$. The static floor field S_{ij} and the dynamic floor field D_{ij} are calculated by using the algorithm proposed in [15] with $\alpha = 0.5$ and $\delta = 0.5$. The radius of effect area r considered here is 10 (cells). Three typical stages of the evacuation at time step 100, 150 and 500 are shown in figures 5(*a*), (*b*) and (*c*). As reported in figure 4(*a*), congestion occurs near the two exits (say the ‘up’ and ‘left’ ones) in time step 100. Furthermore, the other two farther but un-congested exits (say the ‘down’ and ‘right’ ones) are chosen as targets by a number of pedestrians. As reported in figure 4(*b*), in time step 150, congestion occurs near

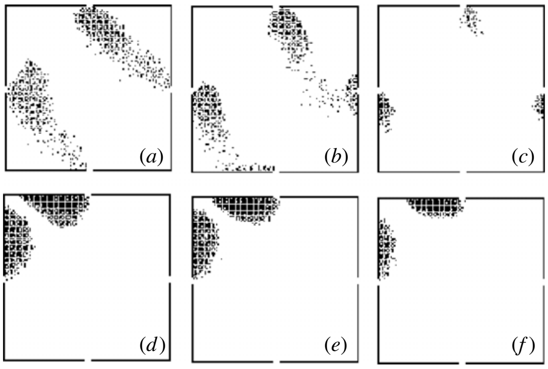

Figure 5. Typical stages of the pedestrians evacuation with exit choosing behaviors by considering the reserve capacity at (*a*) 100, (*b*) 150 (*c*) 500 time step, and stages with exit choosing behaviors only considering the the shortest path at (*d*) 100, (*e*) 150 (*f*) 500 time step.

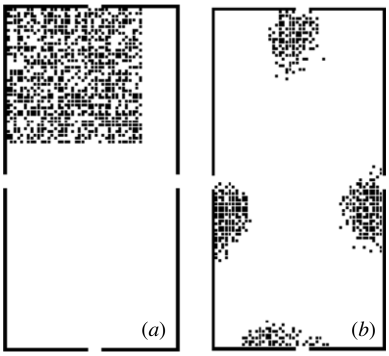

Figure 6. (*a*) Initial stage of the evacuation with 900 pedestrians distributed heterogeneously in a specified zone (size 40 × 40 cells) of the corridor-like room. (*b*) Typical stage of the pedestrians evacuation with exit choosing behaviors by considering the reserve capacity at 150 time step.

all of the exits. Due to the attraction of the exits and interactions between the pedestrians, arch-like clogging is shaped, which is supported by empirical results [1]. And in the end of the evacuation, migration behaviors terminate because of the high travel times/costs. Even if there exist some un-congested exits (e.g. the 'down' exit in figure 5(*c*)), no pedestrians choose these. By comparison, three typical stages of the evacuation dynamics with exit choosing only according to the shortest path in time step 100, 150 and 500 are presented in figures 4(*d*), (*e*) and (*f*). From the illustrations, it can be checked that during the whole evacuation process, no pedestrians choose the un-congested alternative exits, which is not realistic at all.

The effect of the distance to alternative exits $E_{i,j}^{m}$ can be shown in a room with a different geometry. In a corridor-like room represented by 100 × 50 lattices as illustrated in figure 6(*a*), 900 pedestrians are randomly distributed in a specified zone of size 40 × 40 cells initially. Parameter settings adopted here are the same as mentioned above. A typical stage of the evacuation at time step 150 is presented in figure 6(*b*). Though the reserve capacities of the 'right' and 'down' exits are equal at the beginning of the evacuation process, the 'right' exit is chosen preferentially due to the shorter distance. Furthermore, if the corridor is long enough, travel time to those un-congested alternative exits may be longer than the expected evacuation time, migration cannot occur.

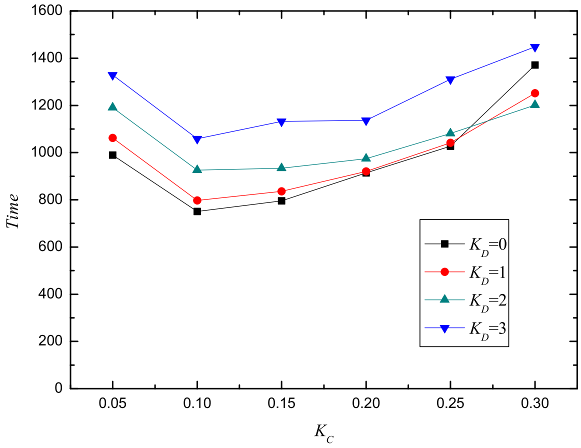

Figure 7. The evacuation times (time steps) against parameter k_C when $k_S = 2$, $k_E = 2$ and k_D takes four different values 0, 1, 2 and 3. Initially, there are 1200 pedestrians distributed heterogeneously in a specified zone (size 40 × 40 cells) of the room (size 100 × 100 cells).

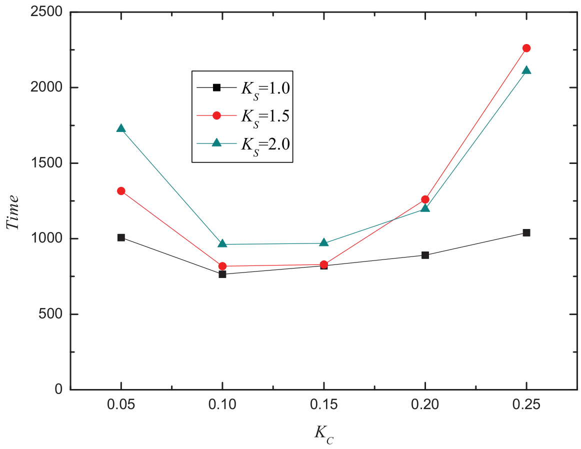

Figure 8. The evacuation times (time steps) against parameter k_C when $k_D = 0.5$, $k_E = 2$ and k_S takes three different values 1.0, 1.5 and 2.0. In the initial state, there are 1200 pedestrians distributed heterogeneously in a specified zone (size 40 × 40 cells) of the room (size 100 × 100 cells).

To investigate the impact of the reserve capacity, the effect of the parameter k_C on evacuation times is investigated. More than 20 independent simulations are conducted for each set of parameters and the mean values are provided in figure 7. As illustrated, when k_S and k_E are fixed, with increasing k_C, the evacuation times vary non-monotonically. Similarly, as presented in figure 8, when k_D and k_E are fixed, non-monotone variations of evacuation times can also be observed with increasing k_C. Interestingly, from the two figures, it seems that evacuation times can be expected to reach its approximate minimum when $k_C = 0.1$.

The variation of the reserve capacities of the four exits as time passes are presented in figure 9. The parameters are set as $k_S = 2, k_D = 1, k_C = 0.1, k_E = 2, \alpha = 0.5, \delta = 0.5$ and $r = 10$. The room size is 100 × 100 cells and the number of pedestrians is 1200. As

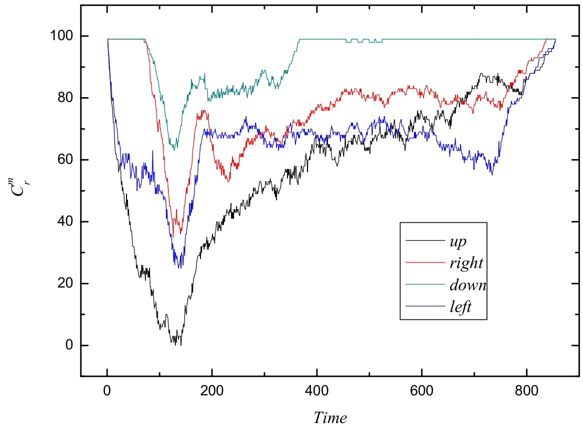

Figure 9. The variations of the four exits' reserve capacities as time passes if the exit choosing behavior is considered.

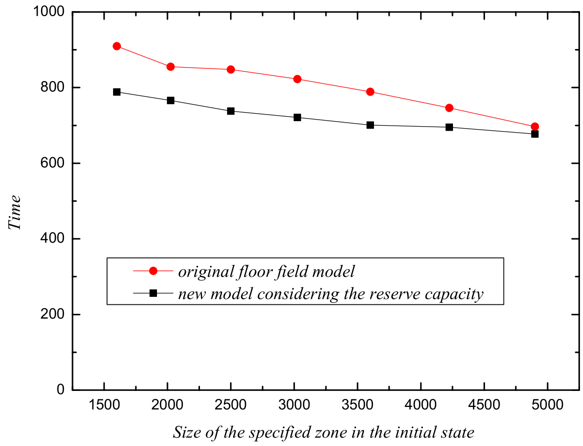

Figure 10. The relationship between the evacuation times (time steps) and the size of the specified zone in the initial state. The parameters are set as $k_S = 2, k_D = 1, k_C = 0.1, k_E = 2, \alpha = 0.5$ and $\delta = 0.5$.

illustrated, in the initial state, all of the four exits are un-congested, the reserve capacities are at their maximum value. As time passes, reserve capacities of the 'up' and 'left' exits decrease considerably. Then a number of pedestrians choose another two exits, which causes the decrement of the 'down' and 'right' exits' reserve capacities. And in the middle of the evacuation, the reserve capacities of the 'down' and 'right' exits recover, which means less pedestrians choose the two exits for the relatively high travel costs. At the end of evacuation, the reserve capacities of all exits recover. Actually, figure 9 can be seen as another description of the dynamics shown in figure 5.

In fact, the initial state, especially the heterogeneous distribution of the pedestrian, may affect the evacuation dynamics apparently. With room size fixed, the heterogeneousness of the distribution can be characterized by the size of the specified zone in the initial state. Figure 10 gives the evacuation times computed by the original floor field model and the new model accordingly with increasing the size of the specified zone in the initial state in a room with 90×90 cells. It can be shown that higher heterogeneousness of the initial distribution may lead to longer evacuation times. And wiser exit choosing strategy, e.g. by considering the reserve capacity, may reduce the evacuation time. Furthermore, with decreasing the heterogeneousness level of the initial distribution, the difference in the evacuation time computed by the two models can get smaller. In the simulation, the number of pedestrians is 900.

4. Conclusions

In this paper, a generalized floor field model is presented to characterize the exit choosing behavior in rooms with multiple exits. The modified model can take advantages in describing the heterogeneously distributed pedestrians' evacuation dynamics. Simulation results show that the evacuation times may reduce apparently if the exit choosing behavior is wisely considering the reserve capacity under proper parameter settings. Self-organization phenomena, e.g. arch-like clogging, can be reproduced. Furthermore, the impact of the room geometry and the parameters is also investigated. The model may have potential applications in the future studies on the evacuation dynamics, especially in a room with multiple exits.

Acknowledgments

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