Emergency Evacuation Assistance

John Lee
Department of Electrical and Computer Engineering
Indiana U. Purdue U. Indianapolis
Indianapolis, USA
johnlee@iu.edu

Dan Koo
Department of Engineering Technology Construction Management Program
Indiana U. Purdue U. Indianapolis
Indianapolis, USA
dankoo@iu.edu

Dinaol Tadesse
Computer Engineering Department
Jackson State University
Jackson, Mississippi
J00845627@students.jsums.edu

Atharv Jain
Computer Science Department
The University of Texas at Dallas
Dallas, USA
atharvpjain@gmail.com

Sushmitha Shettar
Department of Electrical and Computer Engineering
Indiana U. Purdue U. Indianapolis
Indianapolis, USA
sshettar@iu.edu

Dongsoo Kim
Department of Electrical and Computer engineering
Indiana U. Purdue U. Indianapolis
Indianapolis, USA
dskim@iu.edu

Abstract—**There have been more than necessary casualties due to a lack of intelligence in emergency evacuation mechanisms such as exit signs. Although large or complex buildings and facilities have many exit doors, in case of emergency, people may not be able to escape quickly enough due to sudden loss of directions and difficulty in finding safe routes to exit doors. If you were ever in such a situation, you would wish that if there were ever smart escape route assistance mechanisms available or at least smart exit signs available that safely and quickly guide you to a safe haven. It is what we try to make such a wish come true. In this paper, we propose a graph mapping scheme and a new safe evacuation route algorithm for safe emergency evacuation assistance, with the aid of recent technology called Internet of Things (IoT). The gist of our approach is that people are not allowed to pass through or even go towards any area where fire or toxic gas is detected by controlling the direction signals installed on exit signs. The experiments performed with our methodology shows that the proposed technology may be able to save more lives.**

Keywords—fire safety, emergency evacuation, IoT, graph algorithm

I. Introduction

Recent trends such as re-emergence of downtown development, high-rise building construction, increasing baby boomer retirement and assisted living facilities, and large-scale high technology manufacturing facilities expose greater risk in emergency response and escape. Fire and its complicated threats such as toxic substance discharge are the primary risks for public death, especially in mass occupancy buildings and facilities. The traditional fire alarm technology is often insufficient to save people's lives from the labyrinth of high-occupancy indoor structures. Another common dangerous hazard-exposed situation occurs in biological and chemical labs. In recent years, there are a few catastrophic lab accidents in university labs. Fatal fires, explosions, and toxic substance discharge have occurred at UCLA, Texas Tech, Yale, and other university labs.

The current fire alarm system consists of fire and smoke sensors, a fire protection control system controlling audible alarm, fire suppression, mass notification, and pull stations. The fire evacuation plan is pre-planned and performed with evacuation drills based on the pre-determined evacuation plan. The evacuation is unilateral and only provides a fire alarm and a strobe light to occupants. Lab safety rules and evacuation procedures can be improved, but those are severely inadequate to deliver real-time hazard information and to guide effective evacuation route. The effective and efficient fire/hazard evacuation is always prioritized to all facility managers and fire departments. However, the current technology deployed in most existing buildings/facilities is a reactive system in which a fire alarm is activated when fire sensors detect local hazards or manually pulling an alarm switch. Then, signals go to an annunciator panel and a fire protection control panel. Alarm and strobe lights go off, and occupants must be evacuated by pre-planned evacuation route. Unfortunately, most people in the buildings/facilities, including but not limited to, hospitals, education buildings, hotels, convention centers, long-term care facilities, retail stores, subway stations, and airports are not aware of the pre-planned evacuation plan and not trained to avoid inexorable panic situations.

Many victims of the fire/hazards could be saved if they are effectively notified safe direction of evacuation, types of hazards on the pre-planned evacuation route, and magnitude of fire/hazards on the evacuation route. Notification must be real-time updated, and therefore, the proposed IoT sensor system with an independent wireless network system can play a significant role to provide critical evacuation information on the evacuation route.

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The paper proposes a new paradigm to develop a new information technology using IoT sensors, advanced analysis of hazard data, and a notification system, and it will play a vital role to overcome the aforementioned limitations and challenges. Various sensors are integrated to overcome the barrier. Data collected from the sensors are sent to gateways through wireless networking. The machine learning process calculates and determines evacuation route and commands a notification system that displays information on the exit signs and monitoring stations.

II. Prior Work

There has been little published targeting the algorithm-based smart fire evacuation using IoT sensor deployment, data acquisition, and evacuation assistance. Many previous studies remain at the conceptual development stage. Zhang et al. proposed a new framework of intelligent evacuation system of buildings [1]. S. Yang and P. Frederick suggested a wireless sensor network to assist fire evacuation [2]. In another study, an IoT-based fire emergency monitoring system is proposed using a mesh network of smart fire alarms and path planning algorithms using IoT sensors and S.A.F.E emergency alarm system [3]. Han et al. studied an evacuation route analysis based on real-time data acquisition and risk calculation [4]. S. Park et al. used an augmented reality visualization technology to guide occupants in case of disaster conditions including fire [5]. However, the actual application of many emerging technologies in the field of the smart evacuation system is still in its infancy stage. NFPA 72's National Fire Alarm Code (2019) [6] only defines new technologies for occupant notification systems, but is unable to provide any details for guidance and control in the code. This indicates that the future code update is largely dependent on technological development in this field.

III. System Architecture

The proposed system architecture consists of smart exit signs, Wi-Fi routers, LoRa gateways, and one or two central server(s) for redundancy. Communication utilizes both Wi-Fi and Long Range Wide Area Network (LoRaWAN) [7] for enhancing fault tolerance. Messages between sensor devices (in exit signs) and a central server are exchanged with MQ Telemetry Transport (MQTT) [8] protocol as it is one of the most widely used message communication protocols for IoT and can support various payload forms including JavaScript Object Notation (JSON) objects. MQTT is used for the following objectives in the system: (i) to deliver sensor data to servers and (ii) to deliver escape guidance signals from servers to devices. To reduce the amount of communication data during emergency, messages sent are only the signals used to block those hallways that are harmful. Finally, accommodating various tasks on the devices (installed on exit signs) such as sensing, communicating, and alarming, a multi-tasking real-time operating system called FreeRTOS [9] has been adopted for supporting concurrent tasks and inter-task communication. The following describes system components in detail.

A. *Exit signs*

The exit signs in our design have a microcontroller-based smart system that communicates with a central server. For the main controller of our smart exit sign, we chose ESP32LoRa module [10] because it supports LoRa, WiFi, and has a Li-Ion battery charger.

Various sensors are used to detect fire or toxic gas, and direction signals are used for evacuation guidance (e.g., directional LEDs that tell safe-to-go to right or left). The signals (indicators) can have combinations of six directions, namely east, west, north, south, up (toward the upper floor), down (toward the lower floor). For example, an exit sign installed on a 3-way junction in hallway would have three directions such as east, west, and south that the signals can tell people to go. In this case, the exit sign will have three signals directing the available three hallways. Each indicator has two options: allow to go towards that direction or not allow to go (because you will see hazard). The signals are normally set to allow to pass.

B. *The RTOS (FreeRTOS)*

We utilize mainly four Real-Time Operating System (RTOS) components, namely tasks, queues, events, and timers. The tasks include sensor reading, MQTT publishing, MQTT subscribing, and signal control (for direction guidance). Our microcontroller system has two queues, namely InputQueue and OutputQueue, which are explained in detail below. Our RTOS system also has several events to handle and coordinate the connections and communications of Wi-Fi as well as LoRa.

Regarding tasks, the sensor reading task reads various sensors such as temperature, humidity, toxic gas, and motion. It then pushed the data to InputQueue. The MQTT publish task dequeues data from InputQueue and publishes them, which will be sent to the server through an available communication network. The MQTT subscribe task receives control commands from the server for the direction signals (ports) and enqueues into OutputQueue. Lastly, the signal control task dequeues the signal commands from OutputQueue and turn on or off the direction signals.

We also custom-designed a Printed Circuit Board (PCB) in order to fit our device-side system inside commercial off-the-shelf exit signs.

C. *The server*

The central server collects and analyzes sensed data from devices installed on exit signs. In a case that there is a sequence of abnormality, it determines emergency evacuation routes to avoid the endangered areas. It runs a database for storing the following information:

- Devices: Theses are exit signs with sensors and direction signals. These also have relative location information inside a building with x,y,z coordinates where z means which floors.
- Ports: These are direction signals attached to devices, and also used for representing connections to other exit signs.
- Connections: These represent how the ports of one exit sign are connected to the ports of other exit signs. The database stores all available connections of all ports of exit signs, which are used to draw graphs.
- Virtual nodes (VN): In some locations of buildings, although there exists no exit sign, when two hallways meet or where a corner is, there can be two, three, or four ways of direction changes. To deal with such cases while constructing a building model graph, a VN is placed.
- Safe zones (SZ): As the name suggests, these are safe places where people can escape through such as exit doors of a building or a fire/toxic-gas proof room.
- Sensor data: All of the sensed data from all sensors of all devices will be stored in the server and used by a machine-learning algorithm to determine hazardous situations.

IV. Methodology

A. Under Emergency

Exit-sign nodes periodically send sensor data to a central server(s). Exit nodes do not make decision. The server detects emergency situations such as fire or toxic gas leak through an abnormality detection algorithm (not described in this paper). It then computes safe routes and sends out the messages used to control guidance signals for safe evacuation of people.

B. Graph Model

An example is shown in Figure 1. A device connects to other devices in the graph by introducing one port for each other device if they are physically connected through such as hallways and stairs. Thus, ports in the graph are a representation of direction signals in real world. Virtual nodes are introduced to overcome some special connections without an exit sign. An edge can be expanded by adding a virtual node. There could be multiple safe zones (SZes) which can be combined to one with a virtual node. As a summary, in a graph, exit signs (devices), ports, VNs, and SZes will be nodes, and hallways and stairs will be edged with weights (for distance and/or difficulty to access).

C. Emergency situation

In case of emergency, one or more exit-sign devices (nodes in a graph) detect an abnormality, and the central server declares emergency. Any exit node that detected fire or toxic gas will be marked ‘unsafe’ in the graph.

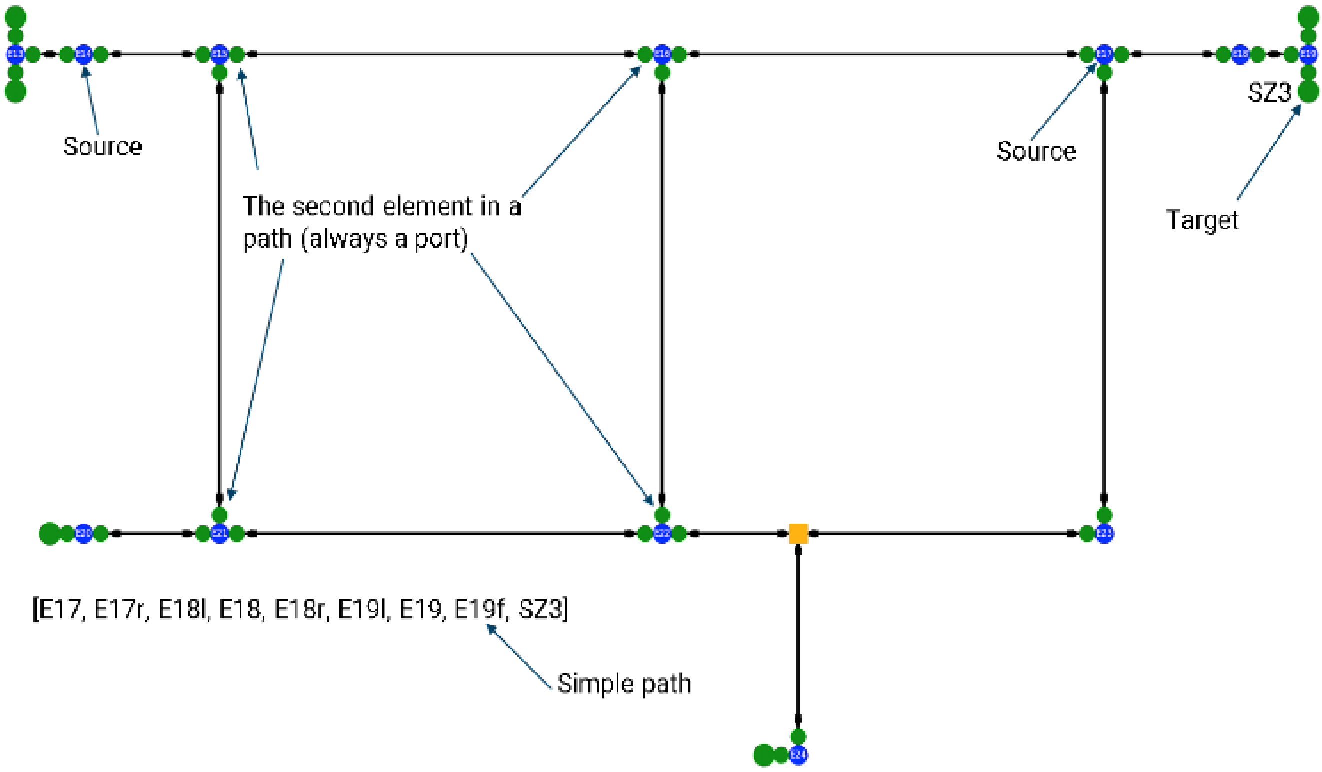

Figure 1. Graph example for the first floor of the experimented building (larger blue circles with IDs are exit signs; smaller green circles are ports; larger green circles are safe zones; the yellow square is a virtual node)

However, this is not enough for safe evacuation of people. It is important to consider that people under emergency circumstances often forget directions and thus easily get lost. Furthermore, they may not know the location of hazard and might accidentally go toward the hazardous area. This is critical. Now question is how we can prevent this from happening.

In order not to lead people to hazards, the sensing device detecting hazards propagates the information to a central server that computes safe evacuation routes for all devices. Our idea is that not only the exit signs detected hazards are set 'unsafe', but we also set some signals (ports) of other exit signs to not-safe-to-go toward certain directions that directly lead to hazards. However, the challenge is that the other exit signs not under hazards have no idea what to do.

D. *The algorithm*

For the aforementioned reason, we implement a smart algorithm. The objective is to set all the direction signals of all exit signs such that coordinated guidance does not lead people toward any hazardous area but guides them to avoid the area and then be safely evacuated.

The followings are the inputs to the algorithm. Device-List contains all the devices (exit-sign nodes) not on fire in the graph. Temp-Port-List initially contains a list of all ports (signals). Safe-Zone-List contains a list of all safe zones in the system.

The algorithm utilizes a graph theory to find all safe paths that do not allow people to pass or even go toward the hazardous area in which exit-sign nodes are marked unsafe.

Figure 2 shows the flowchart of our algorithm. The following is its legend. It may be better to see together with Figure 1. 'Source' means the starting point for a path and always an exit-sign node. 'Target' means the ending point for a path and always a safe zone. 'Simple path' is from a source to a target, and always starts at a device and ends at a safe zone. 'Combined-Paths' means a list of all simple paths joined together. Also 'Element' means a single node or port in the graph. The second element of a path starting from a device is always a port.

The algorithm considers all simple paths from all sources to all targets, but as noted in the input description, any exit-sign nodes on hazard are excluded. Then, it generates a list of deactivated ports where 'deactivate' means people are not allowed to pass or go forward to the direction. Then, the server sends out signal control messages to those exit-sign nodes with the deactivated ports so that they are set to the corresponding signals to not-to-safe-to-go-toward. Note that the run-time complexity of our algorithm is $O(n^4)$ where n is the number of nodes. We plan to improve and reduce this run-time complexity in the future.

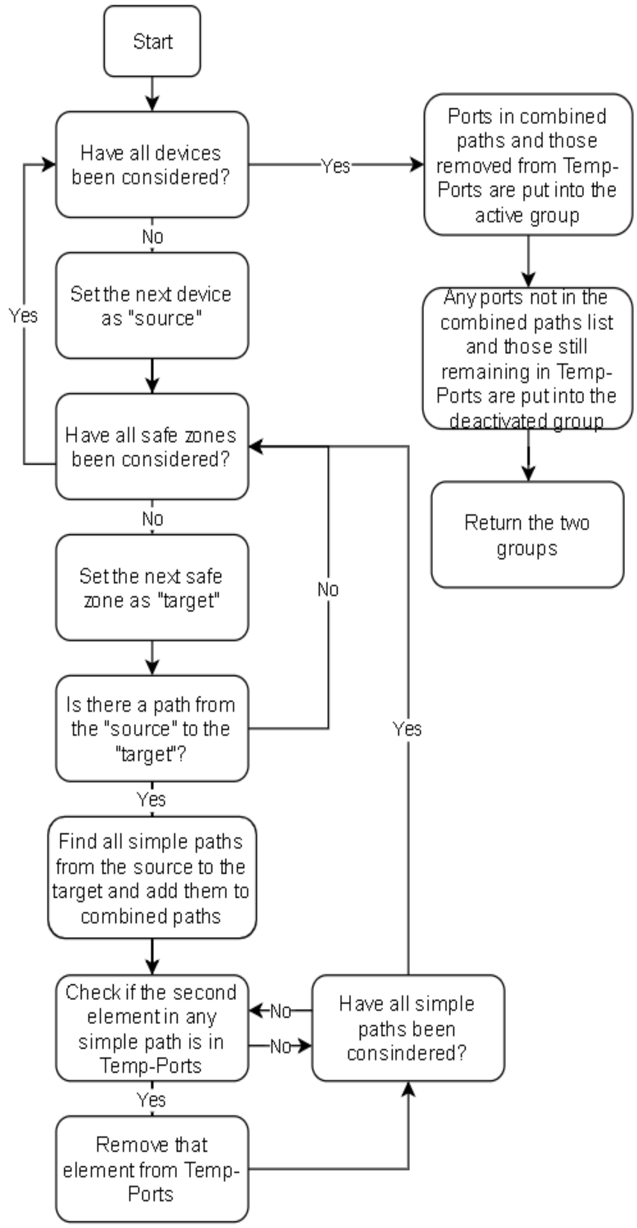

Figure 2. Our safe path search algorithm.

To test the algorithm, we create various situations with different as well as multiple fire locations and validate whether the algorithm correctly finds all possible routes to safe zones from each and every node.

V. EXPERIMENTATION AND RESULTS

We implemented the system and set up communication links between exit-sign devices and a central server. Although not introduced in this paper, we also developed a Graphical User Interface (GUI) tool to map the exit signs, exit doors, hallways, corners, and stairs of a building into a graph. Using the GUI, the information is entered into a database and rendered .

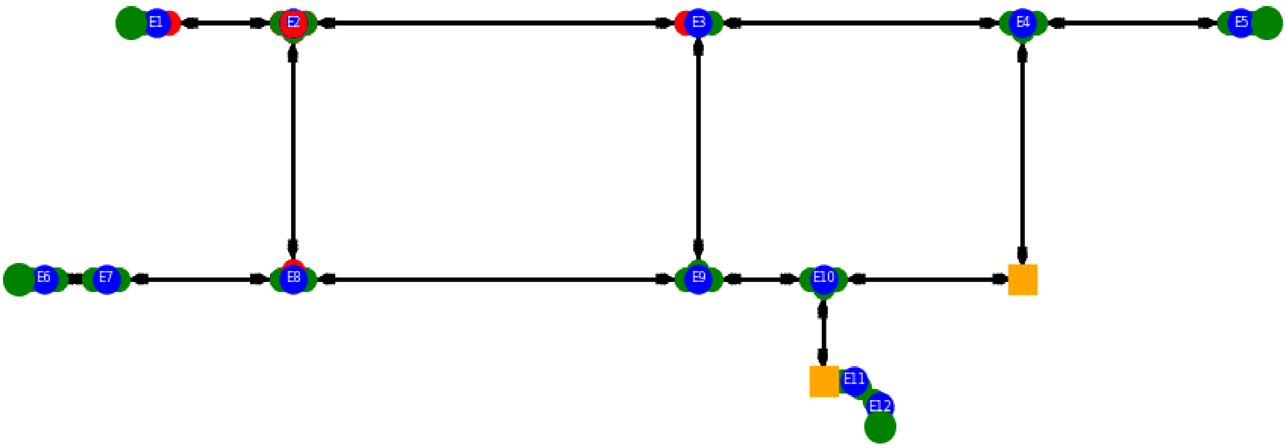

Figure 4. The output of our safe path search algorithm.

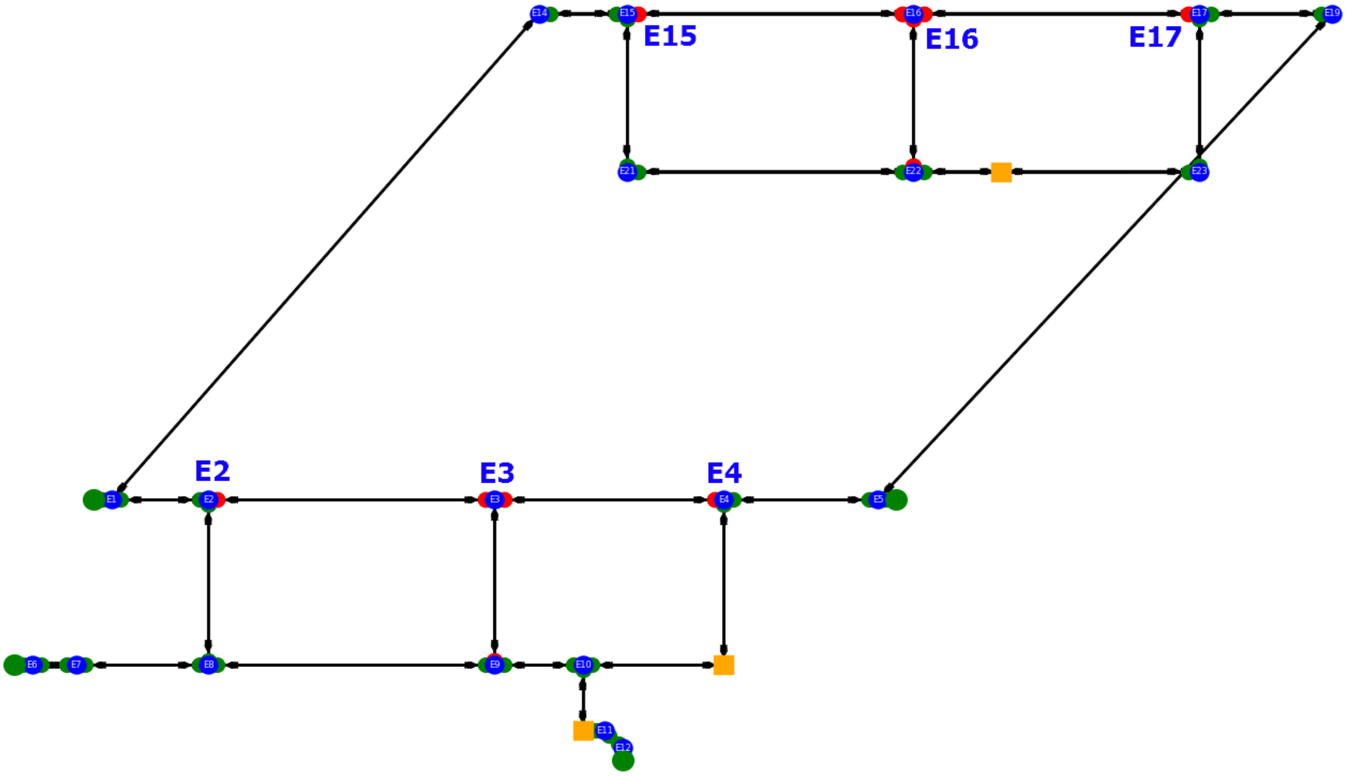

Figure 3. Another example with two floors and two fires.

To prove the correctness of the algorithm, we simulate various situations with one or more fires on specific exit signs and run the algorithm. Figure 3 shows an example where deactivated ports are correctly marked with three red circles when device E2 is stimulated with a hazard. The red signal on E8 node means that from node E8, people are not allowed to go toward E2. Similarly, from E3, not allowed to go toward E2. Figure 4 is another example where exit signs E3 and E16 are simultaneously on fire. As can be seen, the algorithm correctly indicates that people can escape by following green light signals.

VI. Conclusions

This paper describes a new technical paradigm developing a fire escape assistance technology. It utilizes various types of IoT sensors installed inside existing exit signs, which collect fire or toxic gas hazard data from various building components such as hallways, rooms and spaces, stairs, doors and windows, and walls. Exit signs also serve as an escape guide display. The hazard data from the IoT sensor networks are analyzed and the safe routes to escape are computed by a server and then delivered to exit signs. Although we have not yet mathematically proven the correctness of the proposed algorithm, we tested various cases, and the results were all correct.

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