**CELL-DEVS MODELS FOR DYNAMIC CO2 GENERATORS**

AN EXTENTION OF: CELL-DEVS MODELS FOR CO2 SENSORS LOCATIONS IN CLOSED SPACES

**Assignment 2: Deliverable 2**

**SYSC 5104**

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**Introduction**

Heating, ventilation, and air conditioning (HVAC) is one of the most energy consuming functions in a building. An intuitive way of reducing HVAC energy consumption is by offering it on demand rather than on a schedule by using sensors to detect the current occupancy of a room. This could be done by using a CO2 sensor since they are non-intrusive, passive, and already exist within most buildings in compliance with health and safety codes. Unfortunately, the detection accuracy of these sensors is severely affected by both the environment and their placement. Ventilation, room layout, and a person’s placement within the room can cause a higher detection latency or even lead to no detection. The paper CELL\_DEVS models for CO2 sensors location in closed spaces simulated CO2 dispersion in a room using a CELL-DEVS simulation model, followed by the determination of the optimal location and detection latency of a CO2 detector within a room. This expansion seeks to expand and complicate the model by adding a dynamic behavior to the CO2 generator to better simulate the real world.

1. **Summary of Previous Work**

In this first part of the document, a summary of the article by Hoda Khalil, Gabriel Wainer and Zachary Dunnigan will be presented to ensure a deeper understanding of the model that was expanded upon.

**1.1 Model Description**

A closed space was structured as a set of neighboring cells representing the 2D layout of a room. Each individual cell was comprised of one of six models, each representing CO2 levels measured in particles per million (ppm) based on a set of gas diffusion rules: (0) open-air space (constant 500 ppm CO2 level); (1) CO2 source (fixed amount of CO2 added at the average breathing interval (AVI)); (2) walls (no CO2 diffusion); (3) open door, (4) window, and (5) vent (CO2 diffusers with backgrounds of 500, 400, and <300 ppm respectively). Each cell’s behavior was determined by its underlying model, which had a set of basic rules about its behavior and its effect on neighboring cells. Notably, diffuser cells could not be affected by its neighbors’ increased levels of CO2. Furthermore, “CO2 source” modeled an occupant in the room, at rest, with an AVI of 5 seconds. Finally, the diffusion interval was arbitrarily set to be one second.

In the formalization of the model, S = type: {0,1,2,3,4,5} with each type representing one of the six different models described above. Each cell had two state variables, “type” and “conc”, which represented the type of cell and the level of CO2 in ppm respectively. As mentioned above, the delay value (D(S)) was five seconds for CO2 generator cells (type 1) and one second for any other type.

**1.2 Experimental Framework**

To begin, the CELL-DEVS model was validated to ensure that it correctly represented the expansion and diffusion of CO2. First, a single CO2 producer was set in the center of an empty 14 x 23 cell room. After 30 minutes of simulation, the entire room was saturated with high levels of CO2. Next, the layout of the room was modified to resemble workspace cubicles with either one or two CO2 producers residing in their respective cubicles. With a single CO2 producer in his respective cubicle, after 30 minutes of simulation, his cubicle was saturated with CO2. However, the walls mostly isolated the CO2, such that the cells in the neighboring cubicle were unaffected.

Once the distribution of CO2 within the model was validated, diffusion cells in different configurations were added to investigate varying distribution and diffusion patterns, allowing for the analysis of CO2 sensor placement. Two CO2 sensor cells were added to both the left and right walls of the cubical room configuration boasting a window, door, and vent. A single CO2 generator was placed in the right cubical. The CO2 levels of the sensor cells were analyzed against time to see the level of CO2 that reached them along with the time it took to detect a significant increase. As described above in the one generator in a cubicle simulation, the walls, now bolstered by ventilation units, kept the CO2 from spreading to the other side of the room. After 30 minutes of simulation, only the sensor on the side of the CO2 generator experienced increased levels of CO2.

**1.3 Conclusion**

The experimental framework provided basic analysis of CO2 diffusion in a simplified setting. CO2 behavior is strongly dependent on initial room configuration since CO2 cannot diffuse through walls. As seen in the simulation results, a sensor placed in a cubical opposing the CO2 generator senses a negligible change in CO2 levels, even after 30 minutes of simulation. This confirms the importance of CO2 detector placement as detection delay must be mitigated to allow it to act as an HVAC detection sensor. However, the current CELL-DEVS model is a simplification of a much more complicated environment and must be improved in later iterations to better model the real world.

1. **Extension on Previous Model**

As described in the summary, the current CELL-DEVS model is a simplification of a much more complicated environment. In this section, the implementation and testing of a dynamic CO2 generator will be described.

**2.1 Analysis and Problem Statement**

The model described above models a static CO2 generator that adds CO2 every five seconds to the room it is placed in. This model is practical as a proof of concept for the validation of CO2 expansion and dissipation as well as the measurement of the delay of CO2 detection. However, there are three specific shortcomings with a static CO2 generator. The first is that a static model describes only a very specific situation where a person is static for extended periods of time (ex. watching a movie or working at a desk), making it difficult to expand and simulate longer or more relevant simulations. The second shortcoming is that the dissipation of CO2 and the delay of detection after a person leaves is not measured. However, this could be simulated in the current model by adding a schedule to indicate when the CO2 generator stops producing. The third important shortcoming is the possible effects of dynamic movement such as traveling to a different location in the room. Depending on the layout of the environment, moving can have a significant affect on the CO2 dissipation as they move around walls or closer to ventilation units.

**2.2 Model Description**

In this expansion of the CELL-DEVS CO2 model, a dynamic CO2 generator was modeled to complicate the current model and expand upon its experimental framework. However, to achieve this, two changes to the formal model description had to be made. The first was a change in D(S). The previous model’s D(S) values were as follows: all dissipation type cells would have a delay of 1 second while the CO2 generator cells had a delay of 5 seconds to represent the AVI. However, this presented timing problems when changing a type 0 cell (open air) with a delay of 1 second to a type 1 cell (CO2 generator) with a delay of 5 seconds and vice versa. Due to the cell-type variation in D(S), at times a type 0 cell would become a type 1 cell and the neighboring type 1 cell would not concurrently become a type 0, creating an unwanted second CO2 generator. Alternatively, a type 1 cell could become a type 0 before its neighbor became a type 1, meaning the CO2 generator would disappear from the simulation. To resolve these two problems, the D(S) of type 1 cells was changed to 1 second like the other cell types, and a state variable “counter” was added to ensure timing. A secondary advantage of the addition of a “counter” state variable and the change in D(S) was that variable breathing patterns could now be modeled by changing the timing of CO2 using “counter”.

The second change to the previous model was the addition of a “direction” state variable. The previous model used a von numen neighborhood, meaning the direction state variable was split into 4 ranges out of 100. If “direction” was smaller than 25, its direction was down; if 25 < “direction” < 50, it represented left; “direction” values between 50 and 75 meant right; and “direction” > 75 meant up. The “direction” state variable could be determined two different ways. The first was through random selection of a direction using a uniform distribution every time the CO2 generator moves cells. The second was schedule based, where at a specific time, a specific direction was chosen. This mode was used for the simulation of specific movement within the environment. In both modes however, each step was taken every 5 seconds except, the first which was taken at time 00:00:02.

With the addition of the state variables “counter” and “direction”, each cell had a total of 4 state variables: concentration, type, counter, and direction. These variables were used to define a set of rules for each cell and their type to be used in CD++. The rules were structured as follows:

[rule]

% set of rules to ensure the CO2 generator does not run through a wall.

rule : {set direction in the opposite direction;} 1000 {if cell type 1 and a neighbor is type 2 (wall)} (4 rules)

% set of rules for CO2 generator

rule : {counter += 1;} 1000 {if cell type 1 AND counter != 2 OR 5}

rule : {type = 0; add 12.16ppm of CO2; counter += 1;} 1000 {if cell type 1 AND counter = 2}

rule : {add 12.16ppm of CO2; counter = 0;} 1000 {if cell type 1 AND counter = 5}

% set of rules of type 0 cells to become type 1

rule: {type = 1; counter = neighbors counter; direction = randInt(100) or neighbor direction; (depends if scheduled or random movement)} 1000 {if cell type 0 AND neighbors(counter = 2 AND type = 1 AND direction is correct)} (4 rules)

% set of rules if type 0 for CO2 dissipation

rule: {calculate average concentration of all surrounding cells} 1000 {if cell type 0} (9 rules)

% set of rules for type 2,3,4,5

rule: {maintain preset CO2 concentration;} 1000 {if cell type 2,3,4,5}

%default rule

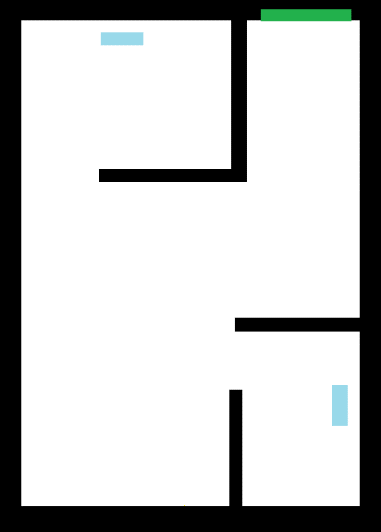
rule: {counter += 1;} 1000 {any type}

Since each cell traversed through this list of rules sequentially from top to bottom, the order of the rules was important. The (4 rules) or (9 rules) meant that that rule was implemented using 4 or 9 rules that covered each neighboring cell or combination of cells to account for all possibilities. Furthermore, as described previously, the “direction” state could be set either by random integer generation or via a schedule. When set using a schedule, the state of “direction” was passed from cell to cell as they became producers. A new list of rules that changed the state of direction for producer cells at a given count number was then produced to simulate a specific path. Finally, when using a schedule, the rules that ensured a CO2 generator does not go into a wall were removed to avoid interfering with the schedule.

**2.3 Experimental Framework**

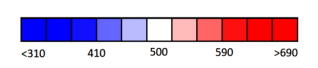
Testing the dynamic CO2 producer was completed in two parts. The first series of simulations verified if random movement was a viable way of simulating movement and CO2 distribution. The second set of simulations used a scheduled path representing a person arriving in their home and traveling to the bedroom, the kitchen and then the bathroom.

To complete these simulations, a 21 x 30 cell representation of a bachelor style apartment was produced. A door and two vents, one in the kitchen and the other in the bathroom, were added to help dissipate the CO2 produced. Furthermore, as it can be seen in the set or rules, the CO2 generator adds 12.16ppm at times 2 and 5, meaning that the breathing rate for these simulations is every 3 seconds. This was done to simulate an active breathing rhythm rather than one at rest.

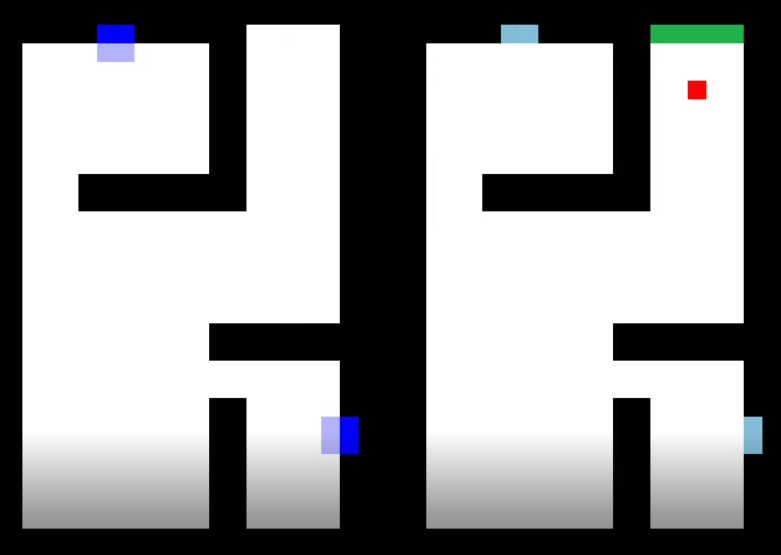
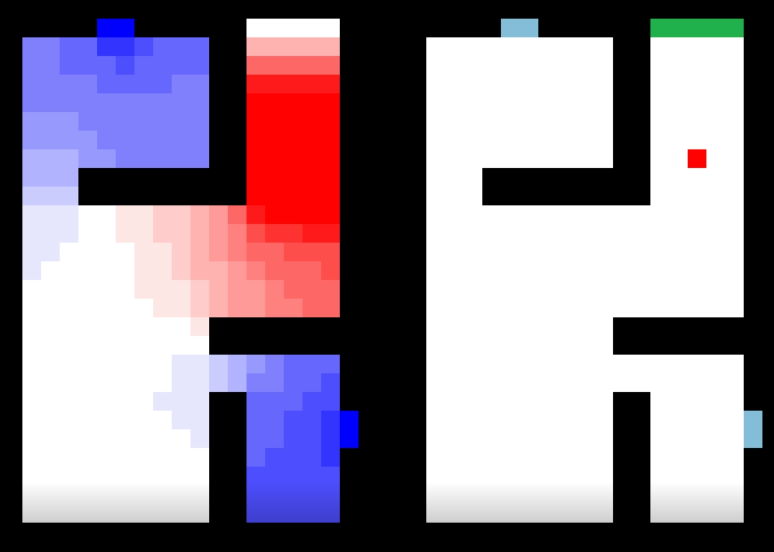
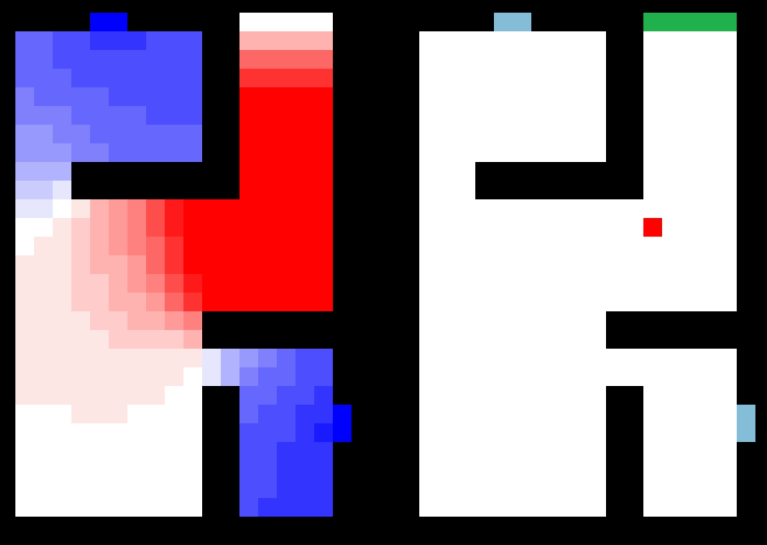


**Figure 1.** **Bachelor style apartment template.** The door (green) and vents (blue) represent routes for CO2 dissipation.

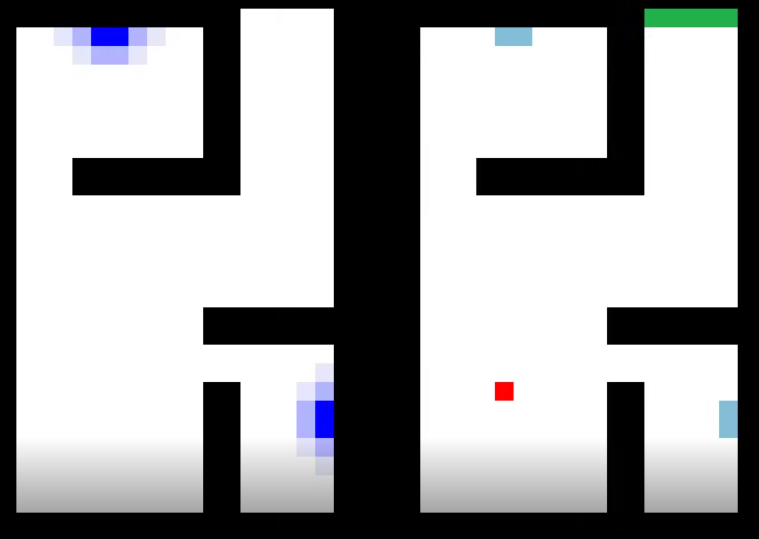
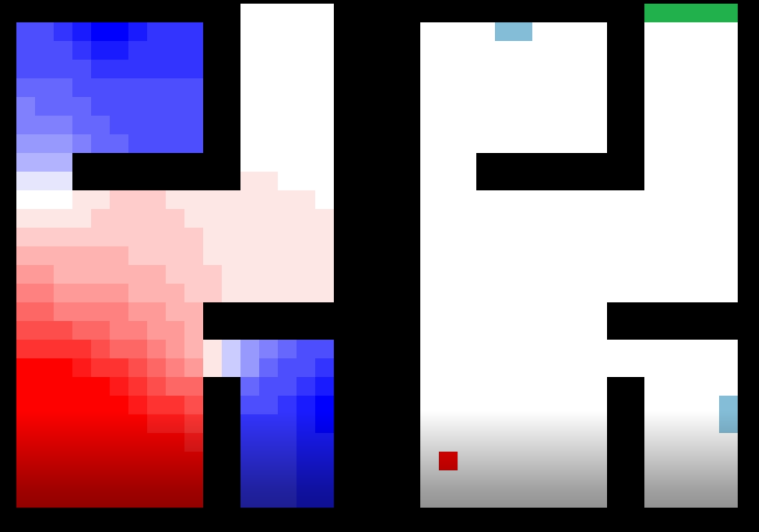
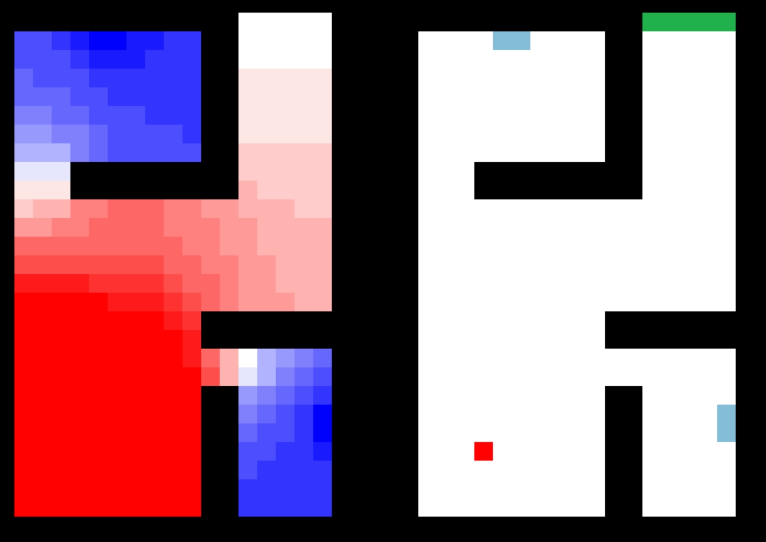
As described above, the first series of simulations modeled random movement. This was done three times with the CO2 producer starting in the entrance hallway (by the green door), in the living room (bottom left space) and finally in the kitchen (top left space). The time elapsed in each simulation was 10 minutes. Images of the simulation at 0, 5, and 10 minutes are presented below.



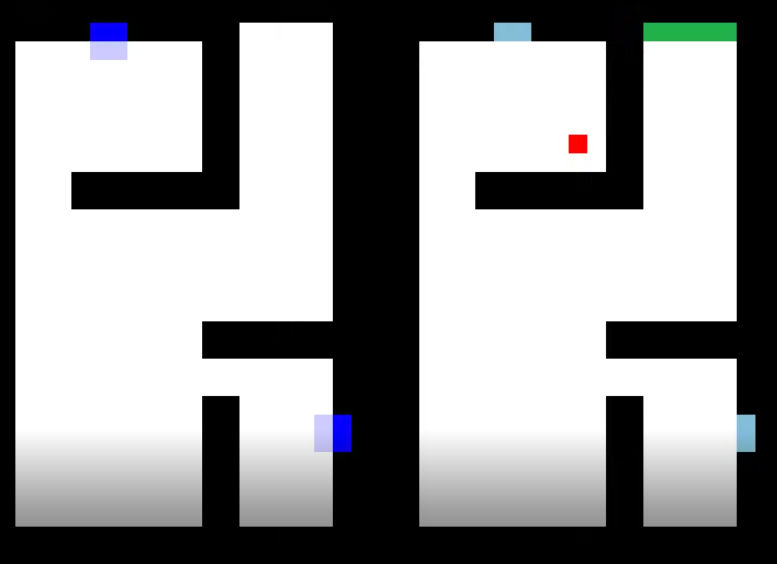
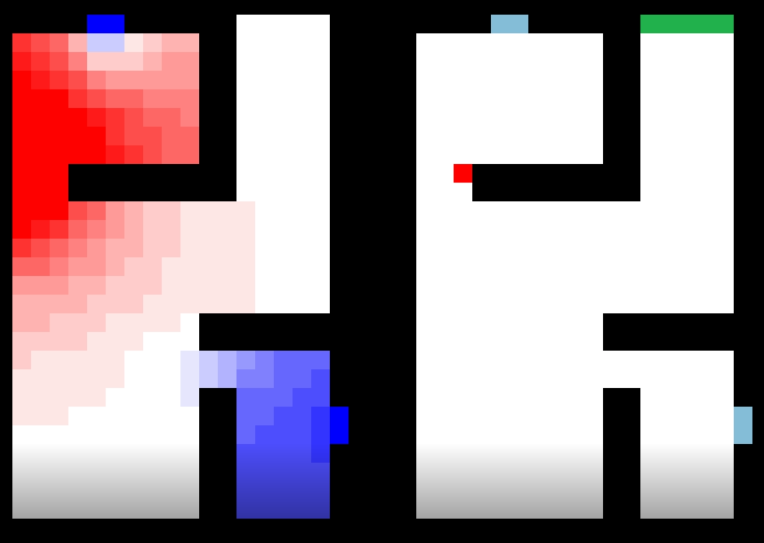
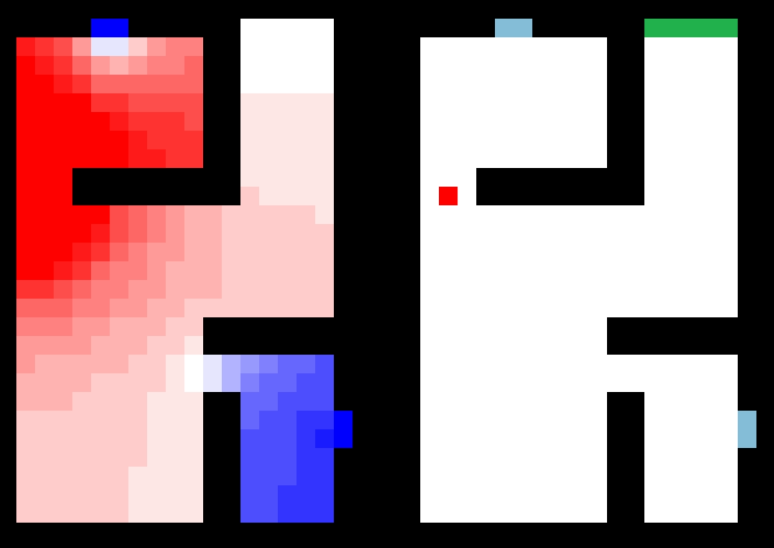
**Figure 2. Color legend of CO2 concentration in ppm [1]**

**Figure 3. Random movement simulation starting in the entrance hallway.** The simulation at 0, 5, and 10 minutes is shown from left to right. In each time point image, the left panel shows carbon level, and the right panel shows the location of the CO2 producer.

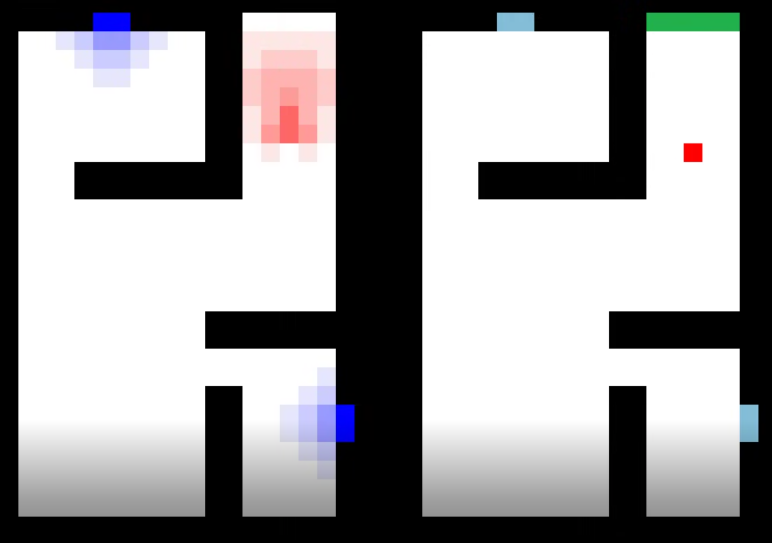
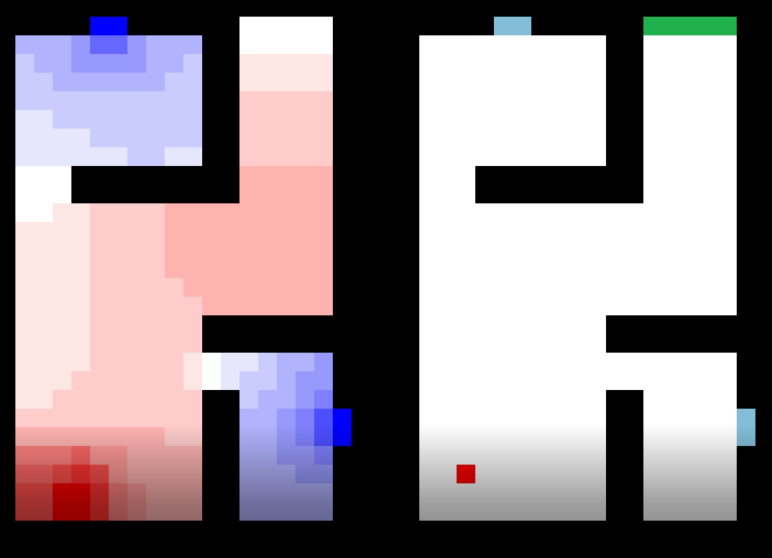
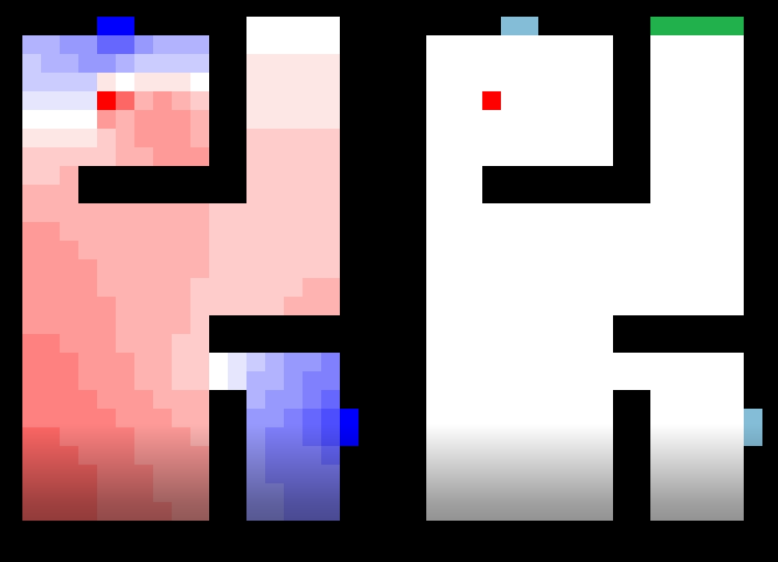
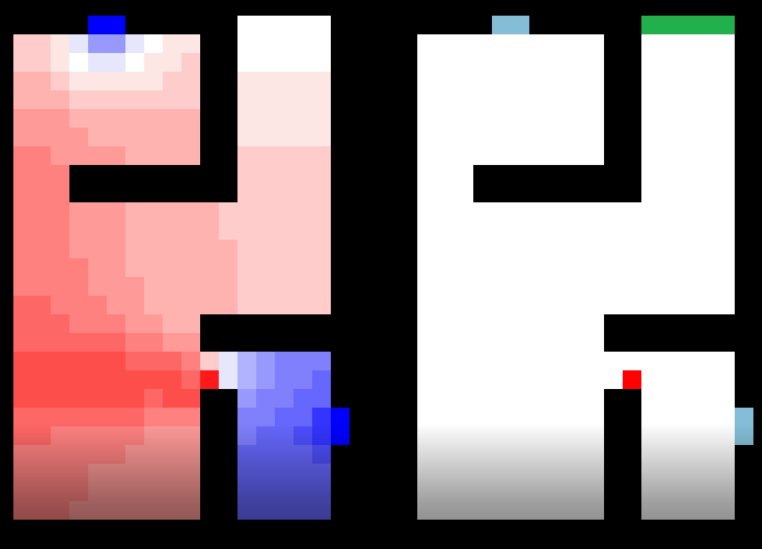
**Figure 4. Random movement simulation starting in the living room.** The simulation at 0, 5, and 10 minutes is shown from left to right. In each time point image, the left panel shows carbon level, and the right panel shows the location of the CO2 producer.

**Figure 5. Random movement simulation starting in the kitchen.** The simulation at 0, 5, and 10 minutes is shown from left to right. In each time point image, the left panel shows carbon level, and the right panel shows the location of the CO2 producer.

In all three iterations of the simulation, the CO2 generator remained in the general location they started in, saturating that part of the bachelor apartment with CO2 while minimally affecting the other regions. This was similar to the results generated by a static CO2 producer. However, the reason for the lack of movement was that a normal distribution was used to determine the direction of travel. Thus, each direction of travel was equally likely to be set, generating a generally circular motion. Therefore, movement could be better represented using a different random number distribution.

The next simulation that was run was the scheduled movement simulation. This simulation represented a person arriving home, leaving the door open, travelling to the living room and then the kitchen, spending around 1 minute and 30 seconds and 2 minutes in each room respectively, and then finally heading to the bathroom. This simulation had a total elapsed time of 4 minutes.

**Figure 6. Scheduled movement simulation.** The simulation at 0, 1.45, 3.45, and 4 minutes is shown from left to right. In each time point image, the left panel shows carbon level, and the right panel shows the location of the CO2 producer.

The CO2 behavior in the scheduled simulation was both expected and surprising. It was expected that the CO2 would spread across the entire apartment fairly quickly as the CO2 generator moved around. However, the duration for which the CO2 lingered in the entrance hallway was unexpected as the open door was dissipating the CO2 concentration. This behavior is important to note since this demonstrates how quickly the CO2 expands and how slowly it dissipates.

**2.4 Discussion**

As is shown in the experimental framework, random movement is not optimal for simulating a dynamic CO2 generator. However, the analysis of a scheduled dynamic CO2 generator yielded interesting results which are ultimately important in studying the expansion and dissipation of CO2 to find the optimal sensor location. When considering the question posed by the paper described in section one regarding the detection latency in sensing the increase and decrease of CO2 levels, it could be said that the latency of detection for increasing CO2 levels would be much shorter than the latency of detection for decreasing levels. As shown in the scheduled movement simulation, the CO2 still lingers a higher than average levels in the entrance way after 4 minutes. Even the presence of a door failed to reduce the level. This could present possible problems in trying to use CO2 sensors to detect the presence of a person since there would be an inflated latency in detecting the departure of a person. Furthermore, in the context of COVID, the lingering of CO2 demonstrates that the practice of limiting the number of people in a location at a time has less beneficial advantages as previously believed. It may be prudent to add a delay before every new entry to allow the CO2 to dissipate. Finally, in a more complicated setting with more rooms, a person could travel to an area without a sensor, resulting in the possibility that the HVAC system would wrongly believe the apartment to be empty. Thus, more complex settings would require many more CO2 sensors then already normal.

**3.0 Conclusion**

The addition of a dynamic element to the previous model of CO2 dissipation in a room yielded interesting results and offers a range of new possibilities for future simulations. The first is the new possibility of adding variable or simply different breathing rates to the simulation. Another is the scheduled movement of one or many CO2 generators within an environment that can be used to simulate the dispersion of CO2 within a workplace or home as people move around. Although this expansion does not answer the questions asked in the original paper by Hoda Khalil, Gabriel Wainer and Zachary Dunnigan, it rather adds an extra degree of realism to the model.

**References**

[1] K. Khalil, G. A. Wainer, Z. Dunnigan, “Cell-Devs Models For Co2 Sensors Locations In Closed Space”, *Proceedings of the 2020 Winter Simulation Conference,* 2020