SYSC 5104

Macaque Pathogen Transmission using Cell-DEVS

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Abstract

To aid in understanding of pathogen transmission patterns amongst long-tailed macaques, a Cell-DEVS model is designed to mimic movement behaviors of macaques. Macaques can move to surrounding environment randomly, they may or may not carry pathogen, and can be infected by nearby neighbors. This model has different layers, considering many factors that could affect the transmission, including landscape, temple, gender and so on. In addition, this model use different phases to realize probabilistic random movement. Different parameters scenarios can be analyzed by simply modifying the configuration macro file. In future, the landscape information can be obtained from GIS, and pathogen life cycle/parameters can be extended by modifying the rules.

Introduction

Several zoonotic diseases have recently emerged on the Asian landscape; macaques have been affected by landscape changes caused by humans. These changes have increased the incidence of human interaction, potentially leading to bi-directional pathogen transmission events to macaques. Here we want to evaluate how landscape changes might influence pathogen transmission patterns, based on the behavior and dispersal patterns of long-tailed macaques. Specifically, we need to address the following basic research questions:

1) How to mimic macaques movement, considering their race characteristic and surrounding environment? We should know how macaques would move, with what preference and possibility, and how this movement would be affected by landscape (forest/blue), and how their race characteristic would influence their movement (birth temple, gender).

2) How are potential routes of pathogen transmission along with macaques' movement, given certain pathogen rates and life cycle? We should know what are the pathogen transmission life cycle, how each state would transfer to another state, the duration of each state, and how macaques would get infected by neighbors.

If we can answer the above questions by using modeling and simulation, we can reuse the model by using true landscape information and more accurate pathogen transmission parameters, and then simulate different scenarios to find finally the impact of human interaction.

Model

Conceptual Model

In this model, our agents are macaques, each with their own properties, such as location, gender, natal temple and infection status. Macaques move in accordance to their surrounding environment, interact with other macaques. This movement is influenced by their properties. As shown in Figure 1, there are movement probabilities related with landscape features. Macaques can move randomly to neighbors, a macaque would be more likely to enter a forest (green) than a river (blue).

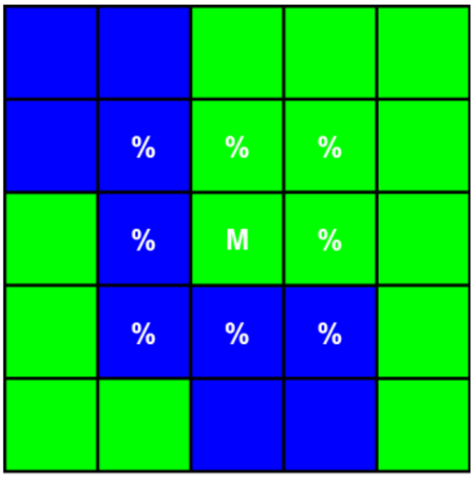

Figure 1. Macaque Movement Probability

Besides, macaques live within their temple (birth temple), as shown in figure 2, gray cells represent temple border. Males (M) may across their temple entering to other temples; while females remain in their temple and never leave to others.

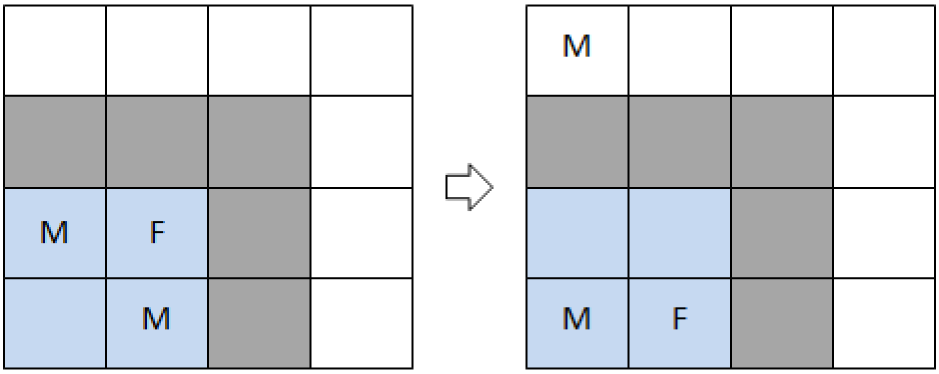

Figure 2. Male macaque may move across temple

All macaques have the ability to carry pathogens and can transmit pathogens when they are moving. Pathogen has four important states. Susceptible refers to the macaque is vulnerable and can be infected. Latent Infection refers to how long a macaque takes to become symptomatic after becoming infected by neighbor macaques that is in state of infection or immunity. Symptomatic infection refers to the duration macaque suffering the disease. Acquired Immunity refers to the amount of time a macaque is clear of a pathogen. To the simplicity, in our model, we use the state diagram shown in Figure 2. Note that pathogen transmission could be more complicated than this way, which could be improved in the future.

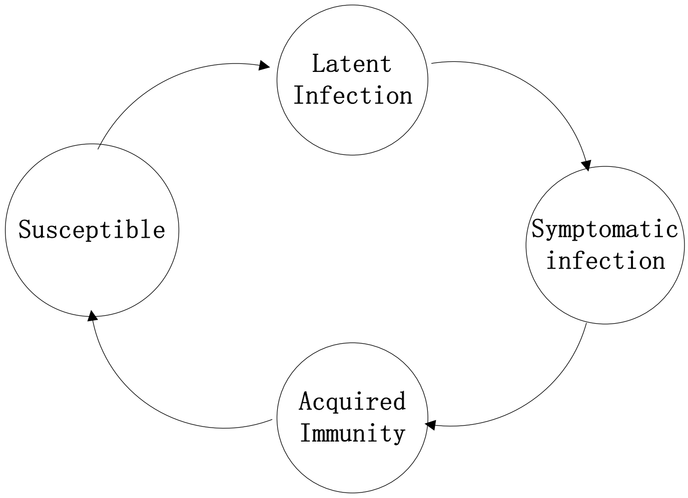

Figure 2. Pathogen Transmission State Diagram

In a short, our pathogen transmission model would cover the following main characteristics:

1. Macaques can move to surrounding environment randomly. They can move to eight surrounding neighbors, with high probability into forest and lower probability into river.

2. Female macaques cannot across their temple.

3. Macaques may or may not carry pathogen when they moving, the state of pathogen would follow pathogen life cycles as timing going. If they were in the state of infection or immunity, they would be infected by nearby neighbors.

Formal Specification

We use Cell-DEVS to model the pathogen transmission problem.

<u>Layers</u>

The model uses three-dimensional cells to store different cells states. It has five layers. From the top view, each layer has MxN cells, and each cell represents a square place associated with physical geographical location. From the vertical view, each cell is subdivided into five different planes (Figure 5) to store different state variables. They are landscape, temple, movement, gender and pathogen information respectively.

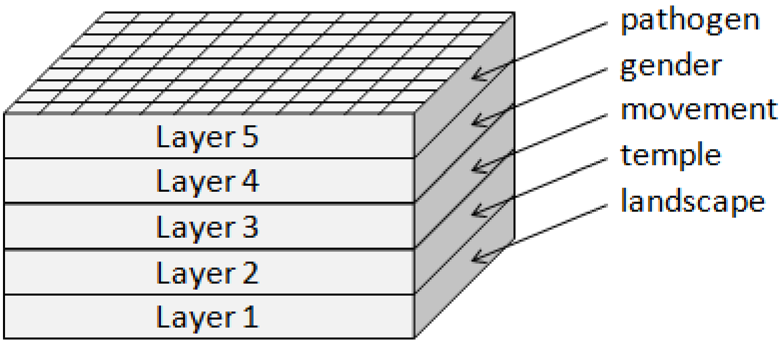

Figure 3. Five Layers of cells

Cell States

Table 1. Cell states of different layers

Cell State	State Name	Cell Color
Layer 5 : Pathogen		
1	Susceptible	
2	Latent Infection	
3	Symptomatic Infection	
4	Acquired Immunity	
Layer 4 : Gender		
1	Male	
2	Female	
Layer 3 : Movement		
0	Not occupied	
1	Occupied	
11-18	Intent direction E(1),NE(2),N(3),NW(4),W(5),SW(6),S(7),SE(8)	
21-28	Choose: intended cell got accepted	
31-38	Constraint: intended cell got accepted	
39	Constraint: intended cell got rejected	
41-48	Choose: empty cell acceptance W(1),SW(2),S(3),SE(4),E(5),NE(6),N(7),NW(8)	
51-58	Constraint: empty cell acceptance	
Layer 2 : Temple		
0	Temple Inside	
8	Temple Border	
Layer 1 : Landscape		
5	Coast	
6	River	
7	Forest	

From the top view, the status of each cell is stored by different layers. From Table 1, layer 1 stores landscape information: they are coast-5 (the border of landscape), river-6, and forest-7. Layer 2 stores temple information: temple border-8. Layer 3 records all the movement related information: 0 represents the current cell is not occupied while 1 means occupied, the remaining states are related with phases (details discussed later). Layer 4 records gender information: 1 means male and 2 means female. Layer 5 stores all pathogen related information: they are shown with different states within the pathogen life cycle during movement (details discussed later).

Neighbors

In this model, spatial movement is based on an expended Moore neighborhood (see Figure 4), with allowance for larger neighborhoods. The basic neighborhood is nine Moore neighbors ((-1,-1,0)…(1,1,0)). To determine the movement, we need to know the landscape and temple information, which are stored in (0,0,-1) and (0,0,-2). When the empty cell want to choose an intended cell to come into, we need to know the corresponding neighbor's gender, so we need another nine Moore neighborhood of upper layer ((-1,-1,1)…(1,1,1)).

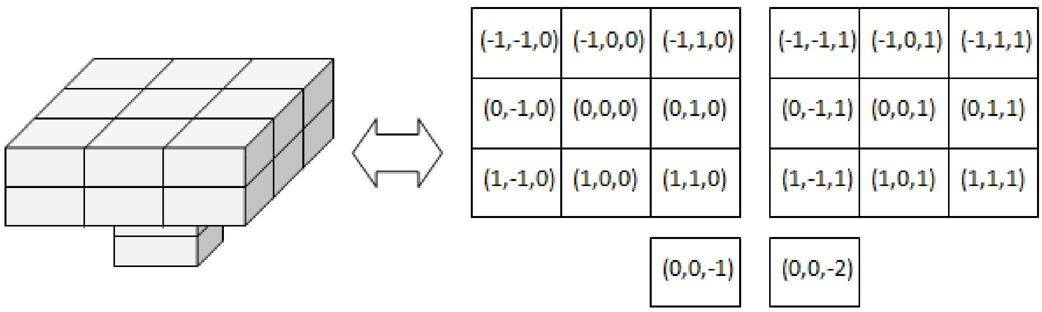

Figure 4. Neighborhood

Movement Phases

In order to realize random movement with different possibilities and temple constrains. The movement behavior is divided into four phases (intent, choose, constraint, and move). The advantages of using different phases are as follows: 1) we need eight directions, in normal case we should use 25 neighbors to avoid collision, but after using phases (choosing and constraint phases take charge of collision control), we can narrow down to 9 neighbors, which is more efficient. 2) it is much easier to modify and control if using phases, as well as bugs handling, because it provides us modularity and better abstraction. 3) it can realize random intention when using phases, specific states of intent phase are generated randomly, and then it can notify neighbors its definite value where it want to go into.

Phase 1: Intent

During this phase, each occupied cell would pick a random direction from eight potential directions. As shown in Figure 5, each direction has a unique value: E(1),NE(2),N(3),NW(4),W(5),SW(6),S(7),SE(8). After the intent phases, the state 1(occupied) would turn to 11-18, the units place corresponds with the unique value of directions. E.g. 11 means the cell want to move towards right. Note here we do not care whether the intended cell is available (empty, border, temple), it would be checked in the following phases.

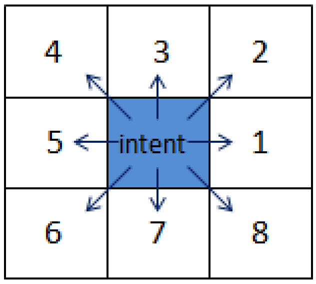

Figure 5. Intent phase - picking up random direction

Phase 2: Choose

After occupied cell picked up intended direction, some cells maybe want to enter into a same cell (collision happens). To handle this problem, each empty cell (not occupied) would choose only one neighbor who want to come in, and change it's state from 0 to 41-48, the units place corresponds with the eight reverse directions (see Figure 6). E.g., 41 means the current cell wants the left neighbor to come in. To mimic different probability to enter into river over forest, in this phase, if the target cell is river, we would use certain probability to change to 41-48 (can move into river) or 0 (cannot move into river). We also use this phase to check all limitations for the movement. Here, we would change the choosing cell (41-48) to 0 if any violation of following conditions: whether the landscape of current cell is out of coast, if the gender is female and current cell is at the border of temple. In order to keep coherence, during the choosing phase, the cells with intent direction (11-18) would change to 21-28, remind that the units place remains unchanged.

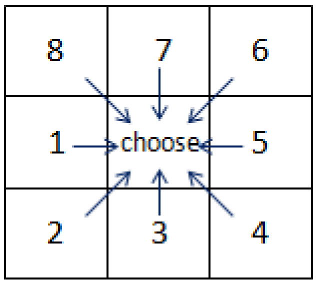

Figure 6. Choose phase – revise directions to choose only one cell

Phase 3: Constraint

We use this phase to authorize the movement after choosing phase, we change the intent cell (21-28) to (31-38) if the target cell state has coherent state (41-48); otherwise (means collision ant target not available), change to 39 to deprive the right of moving. E.g., a cell is 21 and its right cell is 41, we change 21 to 31; otherwise we change it to 39. In order to keep coherence, for choosing cell (41-48), after this phase, we turn it to corresponding (51-58).

Phase 4: Move

So now, we can move the monkey from indented cell to target cell. Every intended cell are 31-38 (approved) or 39 (deprived), we empty the approved cell (0) and remain value (1) for the deprived cell. For target cell, we have already checked the constrains, the cell in (51-58) all are valid to move people into, so we put 1 to it.

Here is an example to show this phase (Figure 7), in phase1, two cells randomly intend to move to the same cell (one with 11 and the other with 12). In phase 2, the target cell check the limitations, if all passed, it chooses the left to come into (changes to 41, and 11 to 21 and 21 to 22); otherwise, it changes to 0. In phase 3, make sure the movement can happen, change 21 to 31 and 41 to 51; otherwise, it changes to 39. In phase 4, we finally move the monkey.

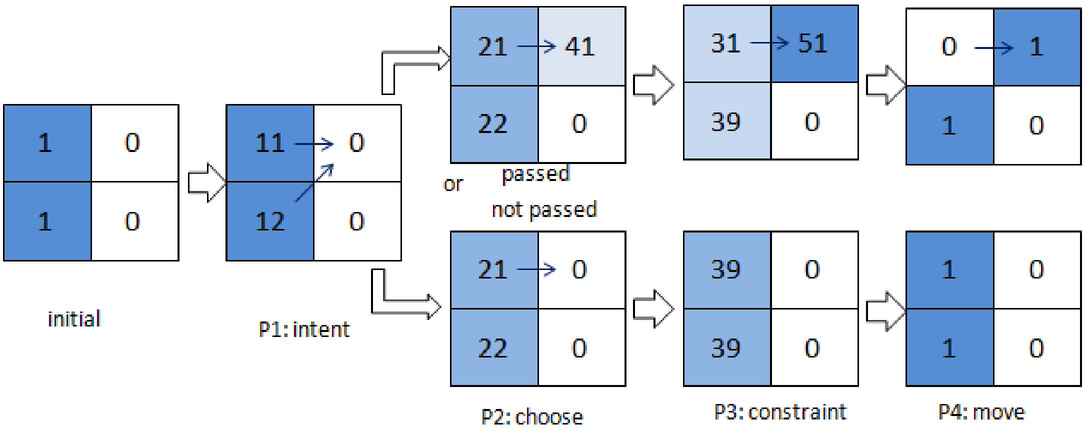

Figure 7. Movement Phases example

Pathogen Transmission

All macaques have the ability to carry pathogens and can transmit pathogens when they are moving. As mentioned before, Pathogen has four important states (Susceptible-1, Latent Infection-2, Symptomatic Infection-3, and Acquired Immunity-4). Susceptible refers to the macaque is vulnerable and can be infected. Latent Infection refers to how long a macaque takes to become symptomatic after becoming infected by neighbor macaques that is in state of infection or immunity. Symptomatic infection refers to the duration macaque suffering the disease. Acquired Immunity refers to the amount of time a macaque is clear of a pathogen.

Figure 8 gives an example, after each movement, state of each pathogen (not Susceptible) would change to next state, e.g., a) -> b), c) ->d) or e) -> f). If current sate is Susceptible, and there is at less one neighbor is during these states (Latent Infection, Symptomatic Infection, or Acquired Immunity), then it would be infected immediately (change to Latent Infection); this case can be seen from b) -> c) or d) -> e).

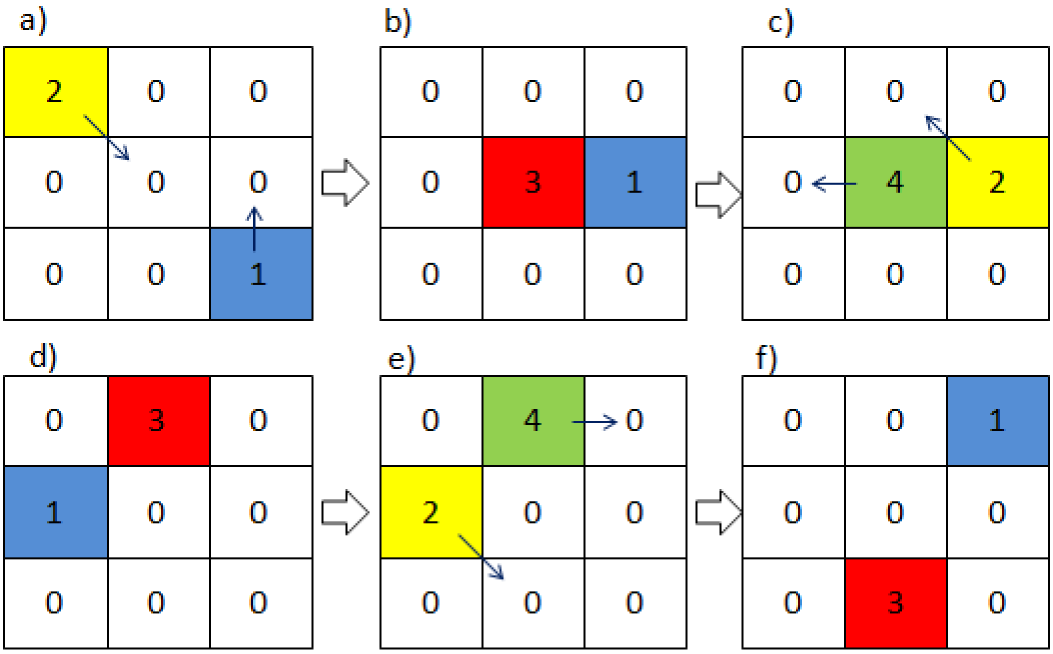

Figure 8. Pathogen Transmission Example

Implementation of Rules

Each layer has specific rules (in Cell-DEVS, it is called zone). For each cell, it would follow the rules of its layer. Firstly, it would check preconditions of each rule from top to down, if it meets any preconditions, the cell state would change to post condition after certain delay time specified in this rule.

Layer Zoos definition:

```
localtransition : nothing
zone : pathogen-trans { (0,0,4)..(9,9,4) }
zone : monkey-gender { (0,0,3)..(9,9,3) }
zone : monkey-movement { (0,0,2)..(9,9,2) }
zone : temple { (0,0,1)..(9,9,1) }
zone : landscape { (0,0,0)..(9,9,0) }
```

Default rules of “nothing” and “landscape” and “temple” are normal, just change default value and pass the current state.

```
[nothing]
rule : {(0,0,0)} 100 { t }

[landscape]
rule : {7} 0 { (0,0,0)=-1 }
rule : {(0,0,0)} 100 { t }

[temple]
rule : {0} 0 { (0,0,0)=-1 }
rule : {(0,0,0)} 100 { t }
```

Movement initiation: get MonkeyOccupation from macro file, and check if it is not out of the coast (0,0,-2)!=5, then set monkey with distribution possibility of MonkeyOccupation percentage.

```
[monkey-movement]
%initial
rule : {if(uniform(0,1)<= #Macro(MonkeyOccupation), 1, 0)} 0 { (0,0,0)=-1 and (0,0,-2)!=5 }
rule : {0} 0 { (0,0,0)=-1 }
```

Movement phase 1: randomly change current occupied state to 11-18, with eight intent directions.

```
[monkey-movement]
%phase 1: intent
rule : {randInt(7) + 11} 100 { (0,0,0)=1 }
```

Movement phase 2: Each empty cell (not occupied) can only choose one neighbor who wants to come in, and change its state from 0 to 41-48. If more than one neighbor wants to come in, it would follow certain priority. Here, we would change the choosing cell (41-48) to 0 if any violation of following conditions. For the case of forest and male, we check whether there is a cell in the reverse direction has corresponding intent value. For the case of forest and female, we check current cell is not the border of temple. For the case of river and male, we use probability of macro value *RiverCrossRatio* to set 41-48 (cross) or 0 (not cross). For the case of river and female, we use probability of macro value *RiverCrossRatio* and make sure that current cell is not the border of temple. In order to keep coherence, the cells with intent direction (11-18) would change to 21-28.

```
[monkey-movement]
%phase 2: choose //forest & female
rule : {41} 100 { (0,0,0)=0 and (0,-1,0)=11 and (0,0,-2)=7 and (0,-1,1)=2 and (0,0,-1)!=8}
rule : {42} 100 { (0,0,0)=0 and (1,-1,0)=12 and (0,0,-2)=7 and (1,-1,1)=2 and (0,0,-1)!=8 }
rule : {43} 100 { (0,0,0)=0 and (1,0,0)=13 and (0,0,-2)=7 and (1,0,1)=2 and (0,0,-1)!=8 }
rule : {44} 100 { (0,0,0)=0 and (1,1,0)=14 and (0,0,-2)=7 and (1,1,1)=2 and (0,0,-1)!=8 }
rule : {45} 100 { (0,0,0)=0 and (0,1,0)=15 and (0,0,-2)=7 and (0,1,1)=2 and (0,0,-1)!=8 }
rule : {46} 100 { (0,0,0)=0 and (-1,1,0)=16 and (0,0,-2)=7 and (-1,1,1)=2 and (0,0,-1)!=8 }
rule : {47} 100 { (0,0,0)=0 and (-1,0,0)=17 and (0,0,-2)=7 and (-1,0,1)=2 and (0,0,-1)!=8 }
rule : {48} 100 { (0,0,0)=0 and (-1,-1,0)=18 and (0,0,-2)=7 and (-1,-1,1)=2 and (0,0,-1)!=8 }

%phase 2: choose //forest & male
rule : {41} 100 { (0,0,0)=0 and (0,-1,0)=11 and (0,0,-2)=7 and (0,-1,1)=1} …
rule : {48} 100 { (0,0,0)=0 and (-1,-1,0)=18 and (0,0,-2)=7 and (-1,-1,1)=1}

%phase 2: choose //river & female
rule : {if(uniform(0,1)>#Macro(RiverCrossRatio), 0, 41)} 100 { (0,0,0)=0 and (0,-1,0)=11 and (0,0,-2)=6 and (0,-1,1)=2 and (0,0,-1)!=8 } …
rule : {if(uniform(0,1)>#Macro(RiverCrossRatio), 0, 48)} 100 { (0,0,0)=0 and (-1,-1,0)=18 and (0,0,-2)=6 and (-1,-1,1)=2 and (0,0,-1)!=8 }

%phase 2: choose //river & male
rule : {if(uniform(0,1)>#Macro(RiverCrossRatio), 0, 41)} 100 { (0,0,0)=0 and (0,-1,0)=11 and (0,0,-2)=6 and (0,-1,1)=1} …
rule : {if(uniform(0,1)>#Macro(RiverCrossRatio), 0, 48)} 100 { (0,0,0)=0 and (-1,-1,0)=18 and (0,0,-2)=6 and (-1,-1,1)=1}
rule : {(0,0,0)+10} 100 { (0,0,0)=11 or (0,0,0)=12 or (0,0,0)=13 or (0,0,0)=14 or (0,0,0)=15 or (0,0,0)=16 or (0,0,0)=17 or (0,0,0)=18 }
```

Movement phase 3: We use this phase to authorize the movement after choosing phase, we change the intent cell (21-28) to (31-38) if the target cell state has coherent state (41-48); otherwise (means collision ant target not available), change to 39 to deprive the right of moving. In order to keep coherence, for choosing cell (41-48), after this phase, we turn it to corresponding (51-58).

```
[monkey-movement]
%phase 3: constraint // if intent doesn't choose, turn 39 and stay
rule : {31} 100 { (0,0,0)=21 and (0,1,0)=41 } …
rule : {38} 100 { (0,0,0)=28 and (1,1,0)=48 }
rule : {39} 100 { (0,0,0)=21 or (0,0,0)=22 or (0,0,0)=23 or (0,0,0)=24 or (0,0,0)=25 or (0,0,0)=26 or (0,0,0)=27 or (0,0,0)=28 }
rule : {(0,0,0)+10} 100 { (0,0,0)>=41 and (0,0,0)<=48 }
```

Movement phase 4: now monkey can move. Every intended cell are 31-38 (approved) or 39 (deprived), we empty the approved cell (0) and remain value (1) for the deprived cell. For target cell, the cells in (51-58) all are valid to move people into, so change to 1.

```
[monkey-movement]
%phase 4: move from
rule : {0} 100 { (0,0,0)>=31 and (0,0,0)<=38 }
%phase 4: cannot move from, remain 1
rule : {1} 100 { (0,0,0)=39 }
%phase 4: move to
rule : {1} 100 { (0,0,0)>=51 and (0,0,0)<=58 }
rule : {(0,0,0)} 100 { t }
```

Monkey-gender: first, initiate the gender of monkey, with male of distribution possibility of MaleRatio percentage from the macro file and female of 100-MaleRatio percentage. Whenever there is 31-38 in movement layer, this gender cell would change to 0. Similarly, whenever there is 51-58 in movement layer, it would change to the gender of corresponding cell where would move into.

```
[monkey-gender]
%initial
rule : {if(uniform(0,1)<=#Macro(MaleRatio), 1, 2)} 100 { (0,0,-1)=1 and (0,0,0)!=1 and (0,0,0)!=2 }
rule : {0} 0 { (0,0,0)=-1 }

%move from
rule : {0} 100 { (0,0,-1)>=31 and (0,0,-1)<=38 }

%move to
rule : {1} 100 { ((0,0,-1)=51 and (0,-1,0)=1) or ((0,0,-1)=52 and (1,-1,0)=1) or ((0,0,-1)=53 and (1,0,0)=1) or ((0,0,-1)=54 and (1,1,0)=1) or ((0,0,-1)=55 and (0,1,0)=1) or ((0,0,-1)=56 and (-1,1,0)=1) or ((0,0,-1)=57 and (-1,0,0)=1) or ((0,0,-1)=58 and (-1,-1,0)=1)}
rule : {2} 100 { ((0,0,-1)=51 and (0,-1,0)=2) or ((0,0,-1)=52 and (1,-1,0)=2) or ((0,0,-1)=53 and (1,0,0)=2) or ((0,0,-1)=54 and (1,1,0)=2) or ((0,0,-1)=55 and (0,1,0)=2) or ((0,0,-1)=56 and (-1,1,0)=2) or ((0,0,-1)=57 and (-1,0,0)=2) or ((0,0,-1)=58 and (-1,-1,0)=2)}
rule : {(0,0,0)} 100 { t }
```

Pathogen-trans: This layer records all information of pathogen transmission according to the monkey movements. Initially, it would distribute the monkey with Susceptible-1 and Latent Infection-2 with the macro variable InitialInfectionRatio.

```
[pathogen-trans]
%initial
rule : {if(uniform(0,1)<=#Macro(InitialInfectionRatio), 2, 1)} 100 { (0,0,-2)=1 and (0,0,0)=0 }
rule : {0} 0 { (0,0,0)=-1 }
```

Move from: Whenever there is 31-38 in movement layer, this pathogen cell would change to 0. If the value is 39, and if it is not Susceptible, it means cannot more, but still we need change the next state following the pathogen life cycle.

```
[pathogen-trans]
%move from
rule : {0} 100 { (0,0,-2)>=31 and (0,0,-2)<=38 }
rule : {(0,0,0)+1} 100 { (0,0,-2)=39 and (0,0,0)>1 and (0,0,0)<4 }
rule : {1} 100 { (0,0,-2)=39 and (0,0,0)=4 }
```

Move to: Similarly, whenever there is 51-58 in movement layer, it would change to the pathogen state with the value of corresponding cell where would move into. Note that we need change the next state following the pathogen life cycle if it is not in susceptible.

```
[pathogen-trans]
%move to //1 susceptible; 2 latent infection; 3 sysmtomatic infection; 4 acquired immunity
rule : {1} 100 { (0,0,-2)=51 and (0,-1,0)=4 } ...
rule : {1} 100 { (0,0,-2)=58 and (-1,-1,0)=4 }
rule : {((0,-1,0)+1)} 100 { (0,0,-2)=51 and (0,-1,0)>1 } ...
rule : {((-1,-1,0)+1)} 100 { (0,0,-2)=58 and (-1,-1,0)>1 }
rule : {1} 100 { (0,0,-2)=51 and (0,-1,0)=1 } ...
rule : {1} 100 { (0,0,-2)=58 and (-1,-1,0)=1 }
```

Get infected: anytime if current cell is susceptible and has at least one neighbor with the state of not susceptible, than change the state to 2, means it get infected to latent infection.

```
[pathogen-trans]
%get infected
rule : {2} 100 { (0,0,0)=1 and ((0,1,0)>1 or (-1,1,0)>1 or (-1,0,0)>1 or (-1,-1,0)>1 or (0,-1,0)>1 or
(1,-1,0)>1 or (1,0,0)>1 or (1,1,0)>1 ) }
rule : {(0,0,0)} 100 { t }
```

Simulation Results

The following test is all based on a same landscape and temple setting. What we want to see is that based on different macro variables setting, how do the monkeys move and how long would the pathogen vanish?

10x10 size per layer
delay : transport
defaultDelayTime : 100s
border : nowrapped
stopSimulationTime: 100,000s

First Case

MonkeyOccupation: 10%
RiverCrossRatio: 50%
MaleRatio: 50%
InitialInfectionRatio: 40%

As seen from Figure 9, there is one river in the landscape (in first part) and 3 temples (in second part). After initialization, 10% are occupied with monkey (blue cells in third part), 50% females (yellow ones in forth part), and 40% monkeys got infected initially (yellow ones in fifth part).

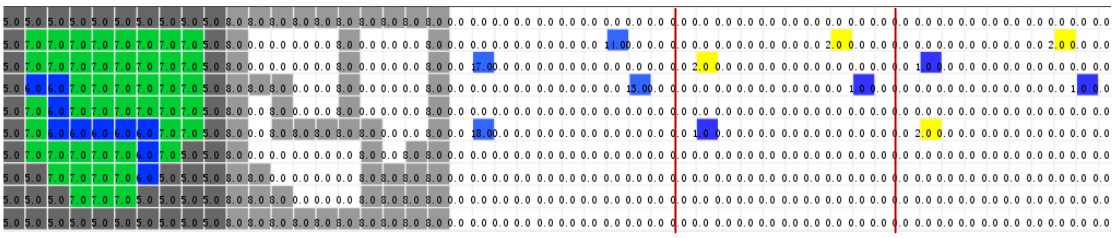

Figure 9. First Case, after initialization

Figure 10 shows how the monkey would move, each cell gets intent direction randomly. In the four monkeys, an interesting thing is that the left-top monkey wants to move outside the temple (intent is 17), but the monkey is female, so after the constraints phase, the state turns to 39 (stay, no move to anywhere). Another interesting thing are the right-top two cells, they want to move to a same empty cell, while this target cell only choose the cell below.

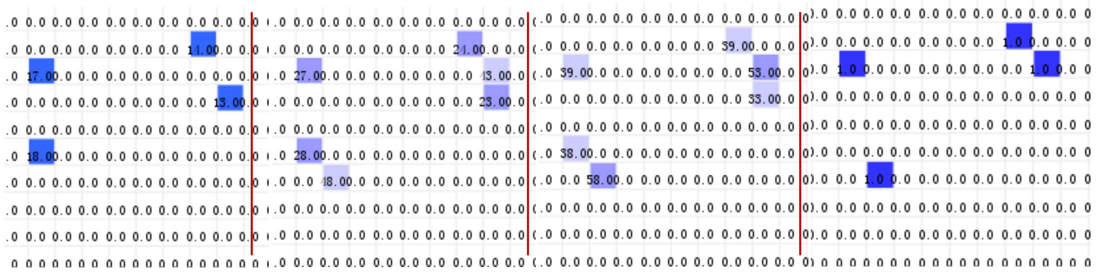

Figure 10. Monkey movement (P1-intent at 100s; P2-choose at 200s; P3-constraint at 300s; P4-move at 400s)

Pathogen transmission distributed exactly with the monkey movement, due to four monkeys, it only takes 1,800s for all pathogen vanishing. Figure 11 shows an example, initially two cells got infected, at each time, the state may change following pathogen life cycle. The interesting ones are right-top two cells in part 2. One cell is in symptomatic infection (red), and its one neighbor is susceptible (blue), so in part 3, this blue cell got infected to latent infection (yellow).

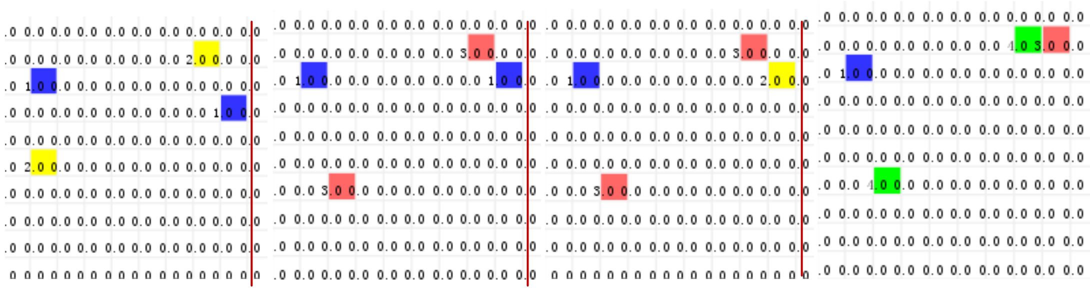

Figure 11. Pathogen transmission (p1 at 100s; p2 at 400s; p3 at 500s; p4 at 800)

Second Case

MonkeyOccupation: 20%
RiverCrossRatio: 50%
MaleRatio: 50%
InitialInfectionRatio: 40%

As seen from Figure 12, we only change the monkey occupation to 20%, this time there are more monkeys.

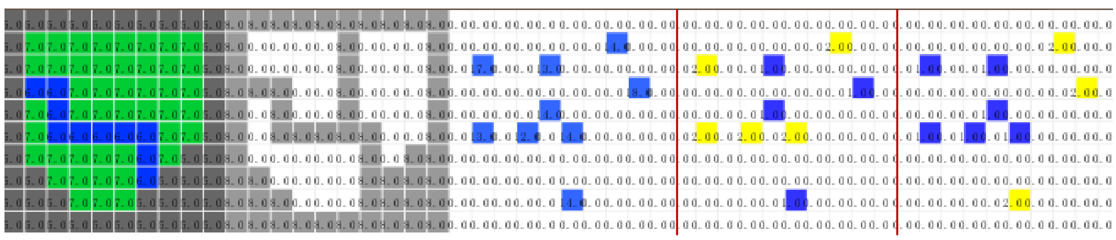

Figure 12. Second Case, after initialization

Figure 13 shows how the monkey would move (with gender layer view), an interesting thing is that the middle two cells in p3 and p4 remain unchanged. Some reasons: for the blue cell, it intended enter into river, which has low possibility and this time it does not make it; for the yellow cell (female), it is at the border of temple, so she definitely cannot move downward.

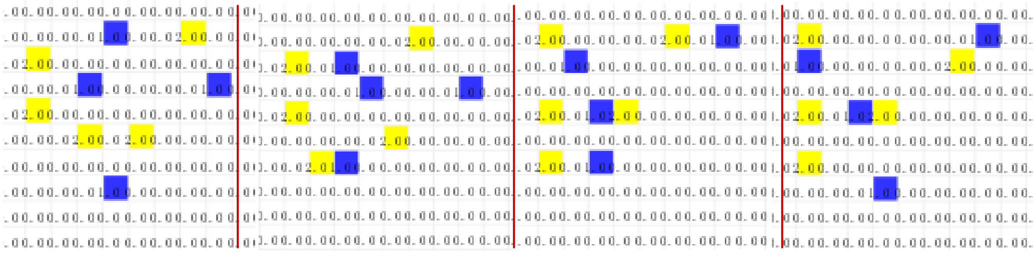

Figure 13. Gender movement (P1-intent at 500s; P2-choose at 1000s; P3-constraint at 1900s; P4-move at 2000s)

Pathogen transmission for this case cost 95,000s to vanish. Figure 14 shows some snapshots during this time.

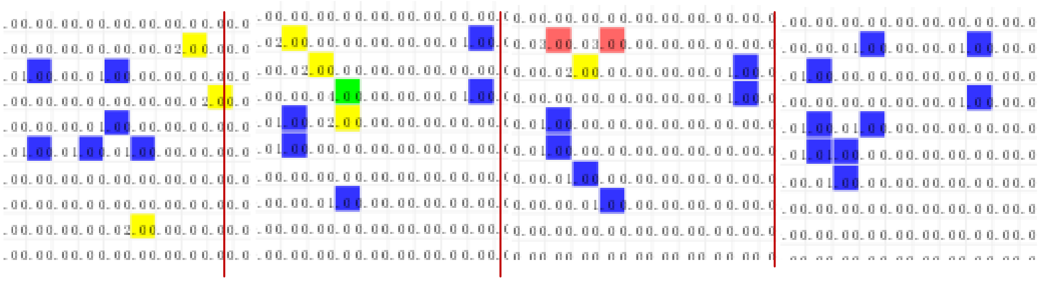

Figure 14. Pathogen transmission (p1 at 100s; p2 at 2600s; p3 at 6600s; p4 at 10000)

Third Case

MonkeyOccupation: 20%
RiverCrossRatio: 80%
MaleRatio: 20%
InitialInfectionRatio: 60%

As seen from Figure 15, with the same monkey occupation as the second case, we change other parameters: higher river cross ratio (80%), more females (80%), and higher initial infection ratio (60%).

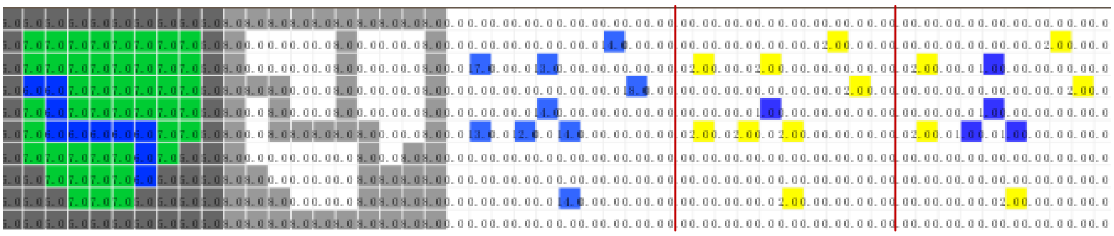

Figure 15. Third Case, after initialization

This time, Pathogen transmission for this case only cost 32,000s to vanish. Figure 16 shows some snapshots during this time. Compare with case two, it saved around 60%. The possible reason would be it has higher initial infection ratio, it gives more chance for the cells having similar pathogen states, which makes the cell change their pathogen state more coherent.

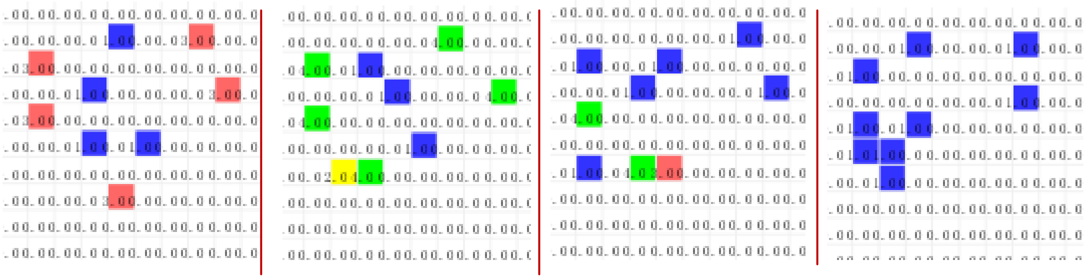

Figure 16. Pathogen transmission (p1 at 400s; p2 at 1100s; p3 at 2400s; p4 at 10000)

Conclusions

This paper focus on using pathogen transmission study amongst macaques, a Cell-DEVS model has designed. This model consists of five layers (landscape, temple, movement, gender, and pathogen) to store different state variables of macaques parameters. Random movement is realized by using different phases (intent, choose, constraint, move); and a simplified pathogen life cycle was considered. After different test cases using CD++ implementation, the behaviors or macaques are proved correctly and accurately. This kind of work can help us to understand better about pathogen transmission patterns, such as the vanishing duration, macaque occupation, and landscape influence related human interaction.

Future Considerations

This model can be easily modified and extended to future purpose. Here are some potential directions:

1) GIS information automatic gathering

The landscape information can be gathered intelligently from GIS tools, which can reflect some true geographical study area, like a island or a zoo. To do so, extract interested parameter information and convert it *.inc (coast, forest, river) and modify related parameters in *.ma (cell size). Of course, you can extend the model by adding new parameters.

2) Pathogen life cycle

Current life cycle is simply, in order to consider more complicated pathogen behaviors, other parameters would be added, and the life cycle state diagram would be expended. Besides, the duration between two states would be not the same, could be more precise. Also, the getting infected rule also can be very complicated, such as considering the distance, the number or states of infected neighbors.

Reference

Kennedy, R. C., Lane, K. E., Arifin, S. N., Fuentes, A., Hollocher, H., & Madey, G. R. (2009). A GIS aware agent-based model of pathogen transmission. *International Journal of Intelligent Control and Systems*, *14*(1), 51-61.