

Zombie number of the Cartesian product of graphs

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Abstract

Zombies and Survivor is a variant of the pursuit-evasion game *Cops and Robber(s)*, with the difference that zombies must always move closer to the survivor. The game is played on a simple graph by two players. The goal of the zombies is to catch the survivor while the survivor's objective is to avoid being captured. The *zombie number* of G , denoted as $z(G)$, is the minimum number of zombies required to capture a single survivor on G , no matter what moves the survivor makes. In this paper, we prove a conjecture by Fitzpatrick et al.[1] about the zombie number of the *Cartesian product* of two graphs. This result provides a new proof for $z(Q_n) = \lceil \frac{2n}{3} \rceil$. We also introduce a new problem regarding *capture time* in the Cartesian product of two graphs. At last, we study computational complexity of finding the zombie number of a graph G , with and without a limited *capture time*.

Keywords: Cartesian Product of Graphs, Zombie Number, NP-Hard

1. Introduction

The *Zombies and Survivor* game is played on a simple graph by two players (we only discuss connected graphs, proofs can be easily modified for disconnected graphs). The deterministic version of this game [1] is played as follows. Initially, the zombie player has z zombies and places them on the graph's vertices. This initial arrangement that zombie player chooses is essential for him to win. Then the survivor player chooses one single vertex which is the survivor's initial position. Starting with the zombie player, on each player's turn, the zombie player must move each zombie to one of its adjacent vertices so that they get closer to the survivor, while the survivor player either moves to an adjacent vertex or stays at his current location. Here lies the difference between *Zombies and Survivor* and *Cops and Robber(s)* games, as in *Cops and Robber(s)* cops need not necessarily get closer to the robber(s). They can either hold their current position, get closer, or further away from the robber(s). Although zombies are not as intelligent as

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cops, they can still choose their path intelligently between the shortest paths. If any zombie and the survivor ever occupy the same vertex, the survivor is captured and the zombie player wins. The zombie number of a graph G , denoted as $z(G)$, is the minimum number of zombies required so that the zombie player can always capture the survivor, no matter how survivor moves.

The Cartesian product $G \square H$ of two graphs G and H , is a graph with vertex set of $V(G) \times V(H)$, where vertices (u_1, u_2) and (v_1, v_2) are adjacent if and only if $u_1 = v_1$ and $\{u_2, v_2\} \in E_H$, or $u_2 = v_2$ and $\{u_1, v_1\} \in E_G$ [3]. Figure 1 shows an example of the Cartesian product of two graphs.

Capture time of a game [5], noted as $\text{capt}(G, z)$, represents the maximum number of moves that survivor can avoid being caught on a graph G , while the zombie player tries to catch survivor as quickly as possible using z zombies. If a survivor-win play exist, $\text{capt}(G, z)$ goes to infinity.

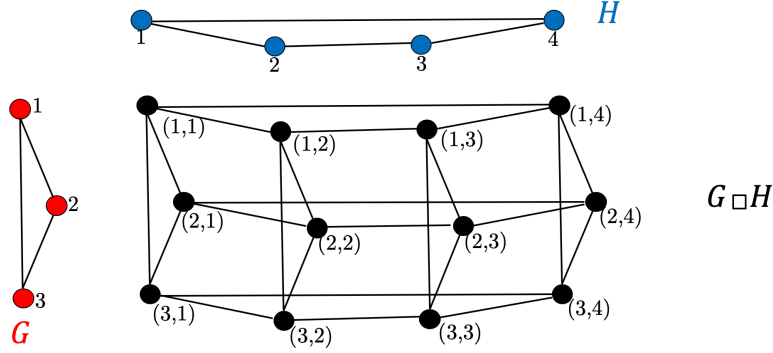


Figure 1: $C_3 \square C_4$ an example of the Cartesian product

Our contributions can be summarized as follows:

- 1) In [1], Fitzpatrick et al. conjectured that $z(G \square H) \leq z(G) + z(H)$. In section 2, we prove this conjecture and use it to show that $z(Q_n) = \lceil \frac{2n}{3} \rceil$.
- 2) In section 3, we provide a new bound on *capture time of zombies and survivor* game played on the Cartesian product of two graphs.
- 3) In section 4, we introduce a variation of *zombies and survivor* game, in which the zombie player is restricted to win in a limited number of moves, and prove it belongs to *NP-Hard* class of problems.
- 4) In section 5, we prove that the original *zombies and survivor* game belongs to *NP-Hard* class of problems.

2. Zombie number of the Cartesian product of two graphs

To prove $z(G \square H) \leq z(G) + z(H)$, we show that $z(G) + z(H)$ zombies are enough for the zombie player to capture the survivor on $G \square H$.

To explain the proof we first need to define some notation. Assume H and G have m and n vertices, respectively.

For $1 \leq i \leq m$, define G_i to be the subgraph induced by vertices $(u, v = i)$. Similarly, for $1 \leq j \leq n$, define H_j to be the subgraph induced by vertices $(u = j, v)$.

In the Cartesian product of G and H , each G_i ($1 \leq i \leq m$) is isomorphic to G , and each H_j ($1 \leq j \leq n$) is isomorphic to H . Also the common vertex between G_i and H_j is (j, i) , and (x, y) is the vertex where the survivor is located. Figure 2 illustrates these definitions.

A G -edge is an edge in one of the G_i s and an H -edge is an edge in one of the H_j s. A G -move is a move made on a G -edge. Similarly, an H -move is a move made on an H -edge. If the survivor decides to remain in its current vertex, this move is considered both a G -move and an H -move.

Define $dist_I(j, k)$ to be the distance between vertices j and k on a graph I . Define the length of a path P to be $len(P)$.

For vertex (u, v) , define its G -equivalent vertex to be vertex $u \in G$, and its H -equivalent vertex, to be vertex $v \in H$. G -equivalent graph is a graph where each zombie and the survivor is put on its G -equivalent vertex. H -equivalent graph is defined in the same way.

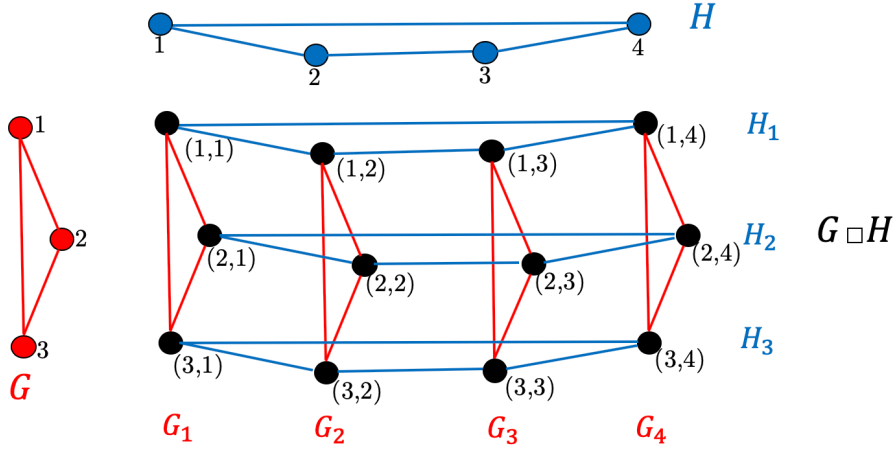


Figure 2: $G \square H$, G_i s, and H_i s.

Lemma 1. $dist_{G \square H}((x, y), (u, v)) = dist_G(x, u) + dist_H(y, v)$.

Proof. Since there is a path from (x, y) to (x, v) with length $dist_H(y, v)$ and a path from

(x, v) to (u, v) of length $\text{dist}_G(x, u)$, we only need to prove there can be no path with length less than $\text{dist}_G(x, u) + \text{dist}_H(y, v)$. Suppose not, this path uses some G -edges and some H -edges. If a G -edge is followed by an H -edge (or vice-versa), then we can swap these edges and still end up in the same vertex. For example, path $(u_1, v_1) \rightarrow (u_2, v_1) \rightarrow (u_2, v_2)$ ends up in the same vertex as path $(u_1, v_1) \rightarrow (u_1, v_2) \rightarrow (u_2, v_2)$. Since we can swap each two edges of different type, there is a path with G -edges before H -edges with the same length that has all G -edges in G_y and all H -edges in H_u . Since this path has a length less than $\text{dist}_G(x, u) + \text{dist}_H(y, v)$, there must be an x, u -path in G , with length less than $\text{dist}_G(x, u)$, or a y, v -path in H , with length less than $\text{dist}_H(y, v)$, which is a contradiction. Thus the statement holds. \square

Theorem 2. $z(G \square H) \leq z(G) + z(H)$.

Proof. We provide a winning strategy for the Cartesian product of G and H using $z(G) + z(H)$ zombies. First, we place $z(G)$ zombies, that have a winning strategy on a single G , $G_{a=1}$ and call them G -zombies. We do the same for $H_{b=1}$ and call them H -zombies.

Consider one of the shortest paths between vertices a (the index of G -subgraph shared by G -zombies) and y in H and call it p_H . We also define p_G in the same manner between b and x .

On each zombie turn, if $a \neq y$, each G -zombie will move along the p_H path in its corresponding H subgraph. According to lemma 1, since zombies' and survivor's equivalents on H are getting closer, thus their actual vertices on $G \square H$ are getting closer as well and this move is possible. Since they are all moving along similar paths (in their corresponding H -subgraphs) they will still share the same G -subgraph. Now consider when $a = y$, G -zombies will play their winning strategy (that they had on a single G) in this case. This move is also possible since in G 's strategy, zombies would get closer to the survivor on each turn. If $a = y$ and the survivor makes an H -move, G -zombies will maintain their positioning by mimicking the exact same move on their corresponding H . This means for those turns that $a = y$ holds, if we consider the G -equivalent graph between G -zombies and the survivor, it is just like a simple game played on a single G . H -zombies will follow the same strategy but in their corresponding environment.

Suppose using this strategy the survivor wins, then the survivor must either do infinite G -moves or infinite H -moves. Without loss of generality, suppose the survivor makes infinite H -moves, we prove that this is not possible. After $\text{len}(p_G)$ number of H -moves, H -zombies will get to H_x . Now for each G -move made by survivor and having zombies mimicking it, nothing changes in their H -equivalent graph. Since the survivor can do infinite H -moves and prevent being caught, it means that the survivor could also avoid being caught on a single H which contradicts our assumption. \square

An example for further understanding can be found at Appendix A.

Corollary 3. $z(Q_n) \leq \lceil \frac{2n}{3} \rceil$

Proof. We prove this by using both induction and Theorem 2. First note that the Cartesian product of hypercube graphs Q_m and Q_n is equal to Q_{m+n} . It is easy to see

$z(Q_3) = 2$, $z(Q_2) = 2$, and $z(Q_1) = 1$. For $n > 3$, we consider Q_n as the Cartesian product of Q_3 and Q_{n-3} . Using the induction base, we know that $z(Q_{n-3}) \leq \lceil \frac{2n-6}{3} \rceil$. According to Theorem 2, $z(Q_n) \leq z(Q_{n-3}) + z(Q_3)$ and $z(Q_{n-3}) \leq \lceil \frac{2n-6}{3} \rceil = \lceil \frac{2n}{3} \rceil - 2$, we can see that $z(Q_n) \leq \lceil \frac{2n}{3} \rceil$. \square

It is already proved that at least $\lceil \frac{2n}{3} \rceil$ zombies are needed to capture one survivor on graph Q_n (Theorem 16 of [1]):

Theorem 4. For each integer $n \geq 1$, $z(Q_n) \geq \lceil \frac{2n}{3} \rceil$.

Combining Corollary 3 and Theorem 4 we can conclude that $z(Q_n) = \lceil \frac{2n}{3} \rceil$. This proves Conjecture 18 from [1] which is already proved in [2] with a different method.

3. Capture time in Cartesian product of graphs

Let $rad(G)$ represent the length of G 's radius.

Theorem 5. $capt(G \square H, z_G + z_H) < rad(G) + rad(H) + capt(G, z_G) + capt(H, z_H)$

Proof. By using z_G zombies as G -zombies and z_H zombies as H -zombies, and having them follow the same set of moves provided in Theorem 2, with the difference that initially a and b are centers of graphs H and G . We show that survivor's G -moves cannot exceed $rad(H) + capt(G, z_G)$. With the same conclusion, it can be shown that H -moves cannot exceed $rad(G) + capt(H, z_H)$ as well.

According to the definition of the radius of a graph, after at most first $radius(H)$ G -moves that survivor makes, $a = y$ holds. Now since for each G -move made from now on by survivor, G -zombies can follow their strategy on a G graph, and after at most $capt(G, z_G)$ G -moves, survivor will be captured.

Since each of survivor's moves is either a G -move or an H -move or both, after less than $rad(G) + rad(H) + capt(G, z_G) + capt(H, z_H)$ moves the survivor will be captured. \square

4. Limited capture time zombie number problem is NP-Hard

A well known example of an NP-hard problem is the *dominating-set* problem in graph theory[4]. A *dominating-set* for a graph G is a subset D of $V(G)$ such that every vertex not in D is adjacent to at least one member of D . The domination number $\gamma(G)$ is the number of vertices in the smallest dominating-set for G .

We define $Lcz(G, k)$ (*limited capture time zombie number*) as the minimum number of zombies needed so that zombie player is able to capture the survivor in at most k moves on graph G .

Let $N_G[u]$ represent the closed neighborhood of u in graph G .

The LCZ_k problem is defined as below:

INSTANCE: A simple undirected graph $G = (V, E)$ and a positive integer z .

QUESTION: Is $Lcz(G, k) \leq z$?

The dominating-set problem is defined below:

INSTANCE: A simple undirected graph $G = (V, E)$ and a positive integer d .

QUESTION: Is $\gamma(G) \leq d$?

Theorem 6. $LCZ_k \in NP\text{-}Hard$

Proof. We prove this by reducing the dominating-set problem to LCZ_k in polynomial time.

Consider k to be an arbitrary positive integer. We construct a new graph G'_k from G . Suppose G has n vertices. For each $v \in V(G)$, we add $k - 1$ new vertices $(v, 1 \leq i < k)$ making a new path, $(v, (v, 1), (v, 2), \dots, (v, k - 1))$ (as shown in figure 3). Creating G'_k can be done in polynomial time.

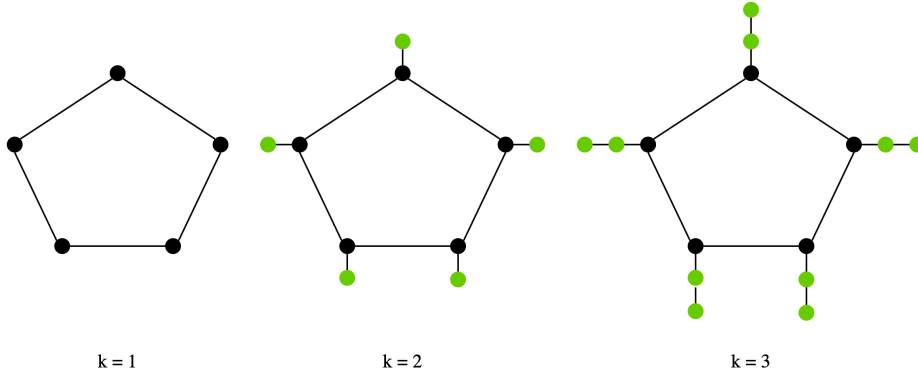


Figure 3: G'_k obtained from $G = C_5$ where for $k = 1, 2, 3$

We prove this theorem by showing $Lcz(G'_k, k) = \gamma(G)$. Consider set S' as zombies' initial vertices on G'_k , so that zombies are able to capture the survivor within k moves. Let S be the set of vertices $v \in V(G)$ such that $v \in S'$ or $(v, i) \in S'$. If there is a vertex $u \in V(G)$ not dominated by S , then there is no vertex v such that $v \in S'$ and $v \in N_{G'_k}[u] \cup \{(u, 1 \leq i < k)\}$. By having the survivor in vertex $(u, k - 1)$, there is no zombie at distance k or less from him, which means he will not be captured. Thus $\gamma(G) \leq Lcz(G'_k, k)$ holds.

Now for each vertex v in one of G 's smallest dominating-sets, place a zombie on vertex v of G'_k . These zombies can capture the survivor in at most k moves. To show this, consider survivor's initial vertex, if it is not a newly added vertex, he can be captured in one move. Now suppose survivor is initially on (u, i) . Since u is dominated by a zombie, after zombies' first move, survivor will be trapped inside the u 's path, and would be captured in at most k moves. Therefore, $Lcz(G'_k, k) \leq \gamma(G)$.

By combining these results, $Lcz(G'_k, k) = \gamma(G)$. Therefore the dominating-set problem is reduced to LCZ_k .

□

5. Zombie Number Problem is NP-Hard

Now define zombie number (Z) problem:

INSTANCE: A simple undirected graph $G = (V, E)$ and a positive integer z .

QUESTION: Is $z(G) \leq z$?

Theorem 7. $Z \in NP\text{-Hard class}$.

Proof. We reduce dominating-set problem to Z .

To do this, we add n copies of $K_{n,n}$ to G . We call the newly obtained graph H , and call the G -subgraph simply as G , and the i -th ($1 \leq i \leq n$) bipartite subgraph as B_i . (i, j, b) represents the j -th vertex in B_i 's part b ($b = 1, 2$). For each vertex (i, j, b) we connect it to vertices in $N_G[j]$ (See figure 4). Since we are adding $2n^2$ new vertices, building H can be done in polynomial time.

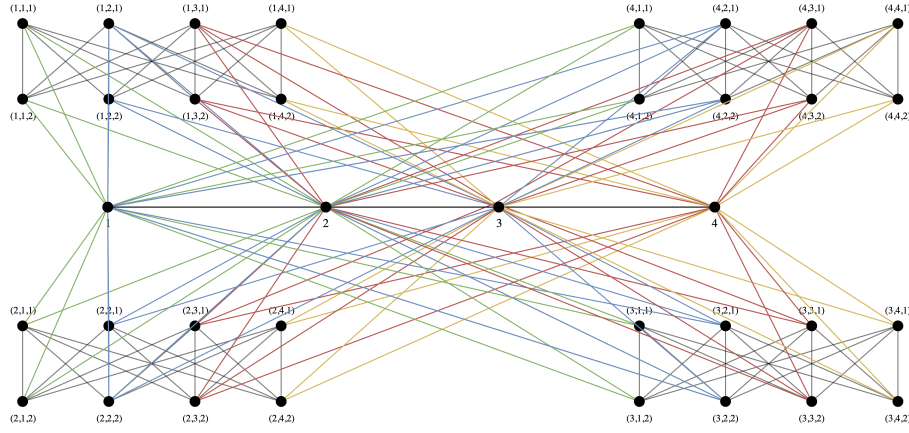


Figure 4: H obtained from P_4 , zombie player needs at least $\gamma(P_4) = 2$ zombies to win

By having zombies on each vertex of G 's dominating-set, survivor will be captured on the first move and zombie player wins. Thus, $z(H) \leq \gamma(G)$. Now suppose we have zombies less than the domination number of graph: $z < \gamma(G)$. We prove survivor can avoid being captured.

Since there are n bipartite subgraphs, one of them is initially free of zombies. Further, since zombies are not dominating G , there will be a vertex $w \in V(G)$ with no zombies as its neighbors. Thus the survivor can safely start at vertex $(k, v = w, b = 1)$ (let (k, v, b) denote the survivor's vertex).

Zombies in G (e.g. at vertex u) are at distance 2 from survivor ($u \rightarrow (k, u, 3 - b) \rightarrow (k, v, b)$), which means after their move all of them should be at one of (k, v, b) 's neighbors, that is, $N_G[v]$ or, $(k, 1 \leq i \leq n, 3 - b)$. Therefore, each zombie joining B_k does not share the same partition as survivor's, since it has to be on one of its neighbors.

On each survivor turn, assume that the survivor is at (k, v, b) and zombies are either in G , or in $B_{(i \neq k)}$, or in B_k at a vertex of the form $(k, j, 3 - b)$ (not in the same partition as survivor). Since there is a vertex $w \in G$ not being dominated by zombies, survivor

should move to vertex $(k, w, 3 - b)$. Since the survivor is now sharing the same partition as all zombies in B_k , and $N_G[w]$ is empty of zombies, none of his neighbors is occupied by a zombie and survivor will be safe by following this strategy indefinitely.

It is now proved that $z(H) = \gamma(G)$, thus the dominating-set problem is reduced to Z .

□

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Appendix A. An example for zombie number of Cartesian product of two graphs

Example 8. $z(P_3 \square P_4) = 2$

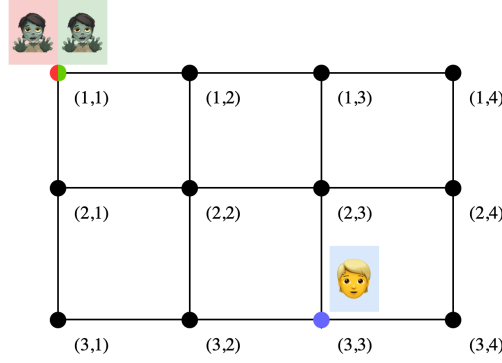


Figure A.5: $P_3 \square P_4$ and initial vertices

It is easy to show that $z(P_3) = z(P_4) = 1$. On each of these path graphs, zombie's initial position could be any vertex of the graph. For this example, we put the G -zombie and H -zombie ($G = P_3$ and $H = P_4$) both on vertex $(1,1)$. We show the survivor with blue color, H -zombie with red, and G -zombie with green. G -zombie will try to get to the same G_i as survivor's which is G_3 using an H -edge. H -zombie will try to get to H_3 (See figure A.6).

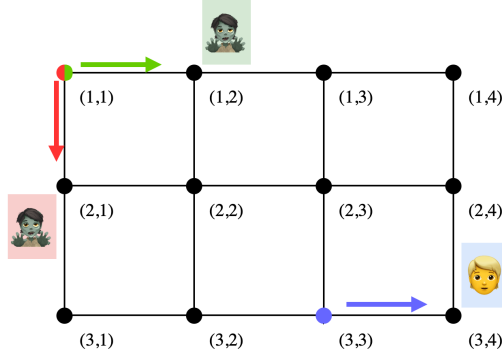


Figure A.6: First move of players

After zombies' move the survivor must move. No matter what move he makes, either G -zombie has made itself closer to H_x or H -zombie has made itself closer to G_y . In this case, H -zombie got closer to H_x . Since neither H or G -zombies share H_x or G_y with the survivor, they will still try to achieve that (See figure A.7).

Now H -zombie shares the same copy of H as survivor and it is survivor's turn. If survivor moves to another H_i , H -zombie will mimic the move. If survivor makes an H -move, H -zombie will do whatever it did on a single H for capturing the survivor. This

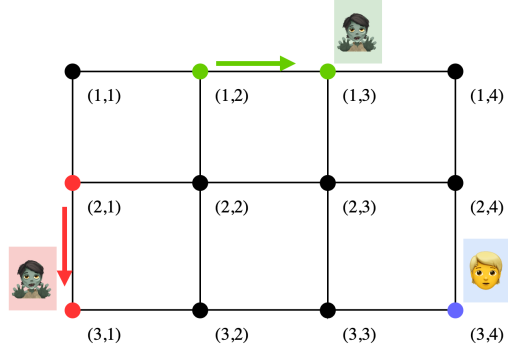
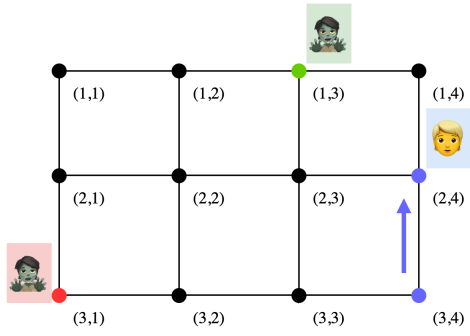


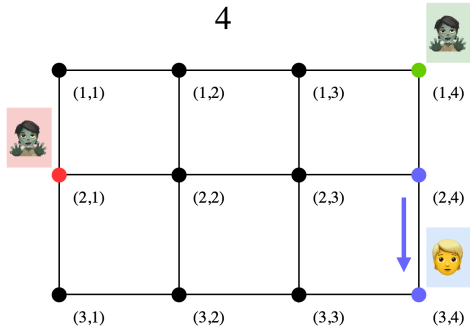
Figure A.7: Second move made by zombies, third in total

means survivor cannot do infinite *H-moves*. Thus for him being able to survive he has to do infinite *G-moves*, which again leads to *G-zombie* capturing him. For other moves, you can see figure A.8.

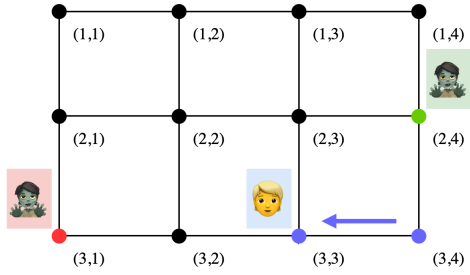
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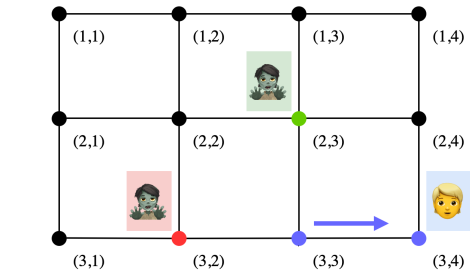
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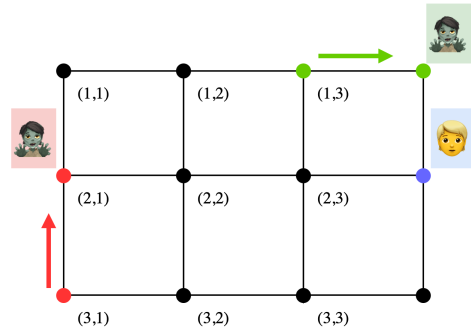


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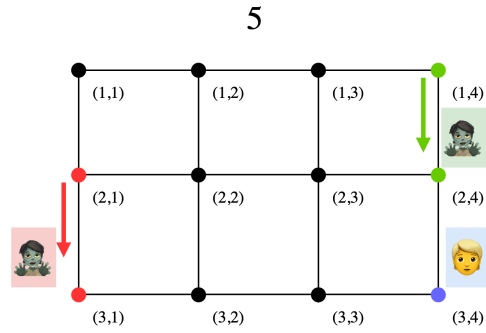


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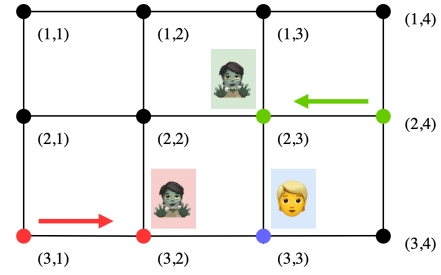
Zombies' Moves



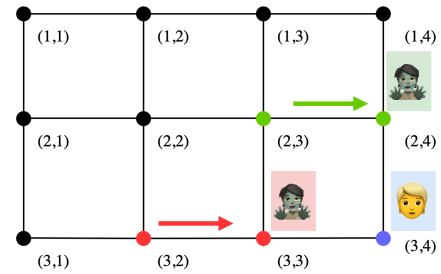
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Figure A.8: Other moves made by players