

## $\mathbb{R}^n$ Bonus Problem #3

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### §1 Problem

~~Settlers of Catan~~ A board game is played on a hexagonal grid of 19 tiles. A 'traveler' token starts on the center tile. Each turn a die is rolled to determine what neighboring tile the traveler moves to (all six directions equally likely). The turn that the traveler leaves the board, the game ends. What is the expected number of turns of the game?

### §2 Diagram



### §3 Solution

We wish to find the expected value of the number of turns in the game, which we denote  $N$ .

$$\mathbb{E}(N) = \sum N \mathbb{P}(N)$$

The dice is truly random, so there is no upper bound on  $N$ . We note that this game is really akin to a Markov chain, in that it doesn't matter what the past states are.

Let  $X_i \in [0, 36]$  be the current state, or position of the traveler. The traveler always starts at position  $X_0 = 0$ . The final state must be  $X_N \in [19, 36]$ .

### §3.2 Transition Matrix

Now that we've defined some notation, we can write the transition matrix  $P$ . Because a  $37 \times 37$  matrix is cumbersome, we combine the states  $[19, 36]$  into a

$$P = \begin{pmatrix} p_{0,0} = 0 & p_{0,1} = \frac{1}{6} & p_{0,2} = \frac{1}{6} & p_{0,3} = \frac{1}{6} & p_{0,4} = \frac{1}{6} & p_{0,5} = \frac{1}{6} & p_{0,6} = \frac{1}{6} & p_{0,7} = 0 & p_{0,8} = 0 & p_{0,9} = 0 & p_{0,10} = 0 & p_{0,11} = 0 & p_{0,12} = 0 & p_{0,13} = 0 & p_{0,14} = 0 & p_{0,15} = 0 & p_{0,16} = 0 & p_{0,17} = 0 & p_{0,18} = 0 & p_{0,19} = 0 \\ p_{1,0} = \frac{1}{6} & p_{1,1} = 0 & p_{1,2} = \frac{1}{6} & p_{1,3} = 0 & p_{1,4} = 0 & p_{1,5} = 0 & p_{1,6} = \frac{1}{6} & p_{1,7} = \frac{1}{6} & p_{1,8} = \frac{1}{6} & p_{1,9} = \frac{1}{6} & p_{1,10} = 0 & p_{1,11} = 0 & p_{1,12} = 0 & p_{1,13} = 0 & p_{1,14} = 0 & p_{1,15} = 0 & p_{1,16} = 0 & p_{1,17} = 0 & p_{1,18} = 0 & p_{1,19} = 0 \\ p_{2,0} = 0 & p_{2,1} = \frac{1}{6} & p_{2,2} = 0 & p_{2,3} = \frac{1}{6} & p_{2,4} = 0 & p_{2,5} = 0 & p_{2,6} = 0 & p_{2,7} = 0 & p_{2,8} = 0 & p_{2,9} = \frac{1}{6} & p_{2,10} = \frac{1}{6} & p_{2,11} = \frac{1}{6} & p_{2,12} = 0 & p_{2,13} = 0 & p_{2,14} = 0 & p_{2,15} = 0 & p_{2,16} = 0 & p_{2,17} = 0 & p_{2,18} = 0 & p_{2,19} = 0 \\ p_{3,0} = \frac{1}{6} & p_{3,1} = 0 & p_{3,2} = \frac{1}{6} & p_{3,3} = 0 & p_{3,4} = \frac{1}{6} & p_{3,5} = 0 & p_{3,6} = 0 & p_{3,7} = 0 & p_{3,8} = 0 & p_{3,9} = 0 & p_{3,10} = 0 & p_{3,11} = \frac{1}{6} & p_{3,12} = \frac{1}{6} & p_{3,13} = \frac{1}{6} & p_{3,14} = 0 & p_{3,15} = 0 & p_{3,16} = 0 & p_{3,17} = 0 & p_{3,18} = 0 & p_{3,19} = 0 \\ p_{4,0} = 0 & p_{4,1} = 0 & p_{4,2} = 0 & p_{4,3} = \frac{1}{6} & p_{4,4} = 0 & p_{4,5} = \frac{1}{6} & p_{4,6} = 0 & p_{4,7} = 0 & p_{4,8} = 0 & p_{4,9} = 0 & p_{4,10} = 0 & p_{4,11} = 0 & p_{4,12} = 0 & p_{4,13} = \frac{1}{6} & p_{4,14} = \frac{1}{6} & p_{4,15} = \frac{1}{6} & p_{4,16} = 0 & p_{4,17} = 0 & p_{4,18} = 0 & p_{4,19} = 0 \\ p_{5,0} = \frac{1}{6} & p_{5,1} = 0 & p_{5,2} = 0 & p_{5,3} = 0 & p_{5,4} = \frac{1}{6} & p_{5,5} = 0 & p_{5,6} = \frac{1}{6} & p_{5,7} = 0 & p_{5,8} = 0 & p_{5,9} = 0 & p_{5,10} = 0 & p_{5,11} = 0 & p_{5,12} = 0 & p_{5,13} = 0 & p_{5,14} = 0 & p_{5,15} = \frac{1}{6} & p_{5,16} = \frac{1}{6} & p_{5,17} = \frac{1}{6} & p_{5,18} = 0 & p_{5,19} = 0 \\ p_{6,0} = \frac{1}{6} & p_{6,1} = \frac{1}{6} & p_{6,2} = 0 & p_{6,3} = 0 & p_{6,4} = 0 & p_{6,5} = \frac{1}{6} & p_{6,6} = 0 & p_{6,7} = 0 & p_{6,8} = 0 & p_{6,9} = 0 & p_{6,10} = 0 & p_{6,11} = 0 & p_{6,12} = 0 & p_{6,13} = 0 & p_{6,14} = 0 & p_{6,15} = 0 & p_{6,16} = 0 & p_{6,17} = \frac{1}{6} & p_{6,18} = \frac{1}{6} & p_{6,19} = 0 \\ p_{7,0} = 0 & p_{7,1} = 0 & p_{7,2} = 0 & p_{7,3} = 0 & p_{7,4} = 0 & p_{7,5} = 0 & p_{7,6} = \frac{1}{6} & p_{7,7} = 0 & p_{7,8} = \frac{1}{6} & p_{7,9} = 0 & p_{7,10} = 0 & p_{7,11} = 0 & p_{7,12} = 0 & p_{7,13} = 0 & p_{7,14} = 0 & p_{7,15} = 0 & p_{7,16} = 0 & p_{7,17} = 0 & p_{7,18} = \frac{1}{6} & p_{7,19} = \frac{1}{6} \\ p_{8,0} = 0 & p_{8,1} = \frac{1}{6} & p_{8,2} = 0 & p_{8,3} = 0 & p_{8,4} = 0 & p_{8,5} = 0 & p_{8,6} = 0 & p_{8,7} = \frac{1}{6} & p_{8,8} = 0 & p_{8,9} = \frac{1}{6} & p_{8,10} = 0 & p_{8,11} = 0 & p_{8,12} = 0 & p_{8,13} = 0 & p_{8,14} = 0 & p_{8,15} = 0 & p_{8,16} = 0 & p_{8,17} = 0 & p_{8,18} = 0 & p_{8,19} = 0 \\ p_{9,0} = 0 & p_{9,1} = 0 & p_{9,2} = \frac{1}{6} & p_{9,3} = 0 & p_{9,4} = 0 & p_{9,5} = 0 & p_{9,6} = 0 & p_{9,7} = 0 & p_{9,8} = \frac{1}{6} & p_{9,9} = 0 & p_{9,10} = \frac{1}{6} & p_{9,11} = 0 & p_{9,12} = 0 & p_{9,13} = 0 & p_{9,14} = 0 & p_{9,15} = 0 & p_{9,16} = 0 & p_{9,17} = 0 & p_{9,18} = 0 & p_{9,19} = 0 \\ p_{10,0} = 0 & p_{10,1} = 0 & p_{10,2} = \frac{1}{6} & p_{10,3} = 0 & p_{10,4} = 0 & p_{10,5} = 0 & p_{10,6} = 0 & p_{10,7} = 0 & p_{10,8} = 0 & p_{10,9} = \frac{1}{6} & p_{10,10} = \frac{1}{6} & p_{10,11} = \frac{1}{6} & p_{10,12} = 0 & p_{10,13} = 0 & p_{10,14} = 0 & p_{10,15} = 0 & p_{10,16} = 0 & p_{10,17} = 0 & p_{10,18} = 0 & p_{10,19} = 0 \\ p_{11,0} = 0 & p_{11,1} = 0 & p_{11,2} = \frac{1}{6} & p_{11,3} = \frac{1}{6} & p_{11,4} = 0 & p_{11,5} = 0 & p_{11,6} = 0 & p_{11,7} = 0 & p_{11,8} = 0 & p_{11,9} = 0 & p_{11,10} = 0 & p_{11,11} = 0 & p_{11,12} = 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0 & p_{14,11} = 0 & p_{14,12} = 0 & p_{14,13} = \frac{1}{6} & p_{14,14} = 0 &$$

We also write the matrix  $Q$ , which doesn't have any absorbing states.

$$\begin{aligned} Q = & \left( \begin{array}{ccccccccc|cccccccccccccccc|cccccccccccccccc|cccccccccccccccc|cccccccccccccccc} P_{0,0}=0 & P_{0,1}=\frac{1}{6} & P_{0,2}=-\frac{1}{6} & P_{0,3}=\frac{1}{6} & P_{0,4}=-\frac{1}{6} & P_{0,5}=\frac{1}{6} & P_{0,6}=-\frac{1}{6} & P_{0,7}=0 & P_{0,8}=0 & P_{0,9}=0 & P_{0,10}=0 & P_{0,11}=0 & P_{0,12}=0 & P_{0,13}=0 & P_{0,14}=0 & P_{0,15}=0 & P_{0,16}=0 & P_{0,17}=0 & P_{0,18}=0 \\ P_{1,0}=\frac{1}{6} & P_{1,1}=0 & P_{1,2}=\frac{1}{6} & P_{1,3}=0 & P_{1,4}=0 & P_{1,5}=0 & P_{1,6}=\frac{1}{6} & P_{1,7}=\frac{1}{6} & P_{1,8}=\frac{1}{6} & P_{1,9}=\frac{1}{6} & P_{1,10}=0 & P_{1,11}=0 & P_{1,12}=0 & P_{1,13}=0 & P_{1,14}=0 & P_{1,15}=0 & P_{1,16}=0 & P_{1,17}=0 & P_{1,18}=0 \\ P_{2,0}=\frac{1}{6} & P_{2,1}=\frac{1}{6} & P_{2,2}=0 & P_{2,3}=\frac{1}{6} & P_{2,4}=0 & P_{2,5}=0 & P_{2,6}=0 & P_{2,7}=0 & P_{2,8}=0 & P_{2,9}=\frac{1}{6} & P_{2,10}=\frac{1}{6} & P_{2,11}=\frac{1}{6} & P_{2,12}=0 & P_{2,13}=0 & P_{2,14}=0 & P_{2,15}=0 & P_{2,16}=0 & 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P_{9,16}=0 > P_{9,17}=0 > P_{9,18}=0 \\ P_{10,0}=0 > P_{10,1}=0 > P_{10,2}=0 > P_{10,3}=0 > P_{10,4}=0 > P_{10,5}=0 > P_{10,6}=0 > P_{10,7}=0 > P_{10,8}=0 > P_{10,9}=\frac{1}{6} > P_{10,10}=\frac{1}{6} > P_{10,11}=\frac{1}{6} > P_{10,12}=0 > P_{10,13}=0 > P_{10,14}=0 > P_{10,15}=0 > P_{10,16}=0 > P_{10,17}=0 > P_{10,18}=0 \\ P_{11,0}=0 > P_{11,1}=0 > P_{11,2}=\frac{1}{6} > P_{11,3}=\frac{1}{6} > P_{11,4}=0 > P_{11,5}=0 > P_{11,6}=0 > P_{11,7}=0 > P_{11,8}=0 > P_{11,9}=0 > P_{11,10}=\frac{1}{6} > P_{11,11}=0 > P_{11,12}=\frac{1}{6} > P_{11,13}=0 > P_{11,14}=0 > P_{11,15}=0 > P_{11,16}=0 > P_{11,17}=0 > P_{11,18}=0 \\ P_{12,0}=0 > P_{12,1}=0 > P_{12,2}=0 > P_{12,3}=\frac{1}{6} > P_{12,4}=0 > P_{12,5}=0 > P_{12,6}=0 > P_{12,7}=0 > P_{12,8}=0 > P_{12,9}=0 > P_{12,10}=0 > P_{12,11}=\frac{1}{6} > P_{12,12}=0 > P_{12,13}=\frac{1}{6} > P_{12,14}=0 > P_{12,15}=0 > P_{12,16}=0 > P_{12,17}=0 > P_{12,18}=0 \\ P_{13,0}=0 > P_{13,1}=0 > P_{13,2}=0 > P_{13,3}=\frac{1}{6} > P_{13,4}=\frac{1}{6} > P_{13,5}=0 > P_{13,6}=0 > P_{13,7}=0 > P_{13,8}=0 > P_{13,9}=0 > P_{13,10}=0 > P_{13,11}=\frac{1}{6} > P_{13,12}=\frac{1}{6} > P_{13,13}=0 > P_{13,14}=\frac{1}{6} > P_{13,15}=0 > P_{13,16}=0 > P_{13,17}=0 > P_{13,18}=0 \\ P_{14,0}=0 > P_{14,1}=0 > P_{14,2}=0 > P_{14,3}=0 > P_{14,4}=\frac{1}{6} > P_{14,5}=\frac{1}{6} > P_{14,6}=0 > P_{14,7}=0 > P_{14,8}=0 > P_{14,9}=0 > P_{14,10}=0 > P_{14,11}=0 > P_{14,12}=\frac{1}{6} > P_{14,13}=\frac{1}{6} > P_{14,14}=\frac{1}{6} > P_{14,15}=\frac{1}{6} > P_{14,16}=0 > P_{14,17}=0 > P_{14,18}=0 \\ P_{15,0}=0 > P_{15,1}=0 > P_{15,2}=0 > P_{15,3}=0 > P_{15,4}=\frac{1}{6} > P_{15,5}=\frac{1}{6} > P_{15,6}=0 > P_{15,7}=0 > P_{15,8}=0 > P_{15,9}=0 > P_{15,10}=0 > P_{15,11}=0 > P_{15,12}=0 > P_{15,13}=0 > P_{15,14}=\frac{1}{6} > P_{15,15}=\frac{1}{6} > P_{15,16}=\frac{1}{6} > P_{15,17}=0 > P_{15,18}=0 \\ P_{16,0}=0 > P_{16,1}=0 > P_{16,2}=0 > P_{16,3}=0 > P_{16,4}=0 > P_{16,5}=\frac{1}{6} > P_{16,6}=0 > P_{16,7}=0 > P_{16,8}=0 > P_{16,9}=0 > P_{16,10}=0 > P_{16,11}=0 > P_{16,12}=0 > P_{16,13}=0 > P_{16,14}=0 > P_{16,15}=\frac{1}{6} > P_{16,16}=\frac{1}{6} > P_{16,17}=\frac{1}{6} > P_{16,18}=0 \\ P_{17,0}=0 > P_{17,1}=0 > P_{17,2}=0 > P_{17,3}=0 &gt$$

$N = (I - Q)^{-1}$  is known as the fundamental matrix of  $P$ .

|       |                           |                            |                            |                            |                            |                            |                            |                            |                            |                            |                            |                            |                            |                            |                            |                            |                            |                          |                          |
|-------|---------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|--------------------------|--------------------------|
| $N =$ | $P_{0,0} = \frac{45}{16}$ | $P_{1,0} = \frac{15}{16}$  | $P_{2,0} = \frac{15}{16}$  | $P_{3,0} = \frac{15}{16}$  | $P_{4,0} = \frac{15}{16}$  | $P_{5,0} = \frac{15}{16}$  | $P_{6,0} = \frac{15}{16}$  | $P_{7,0} = \frac{7}{2}$    | $P_{8,0} = \frac{5}{4}$    | $P_{9,0} = \frac{7}{2}$    | $P_{10,0} = \frac{15}{16}$ | $P_{11,0} = \frac{7}{2}$   | $P_{12,0} = \frac{5}{4}$   | $P_{13,0} = \frac{7}{2}$   | $P_{14,0} = \frac{5}{4}$   | $P_{15,0} = \frac{7}{2}$   | $P_{16,0} = \frac{15}{16}$ | $P_{17,0} = \frac{7}{2}$ | $P_{18,0} = \frac{5}{4}$ |
|       | $P_{1,1} = \frac{15}{16}$ | $P_{2,1} = \frac{15}{16}$  | $P_{3,1} = \frac{15}{16}$  | $P_{4,1} = \frac{15}{16}$  | $P_{5,1} = \frac{15}{16}$  | $P_{6,1} = \frac{15}{16}$  | $P_{7,1} = \frac{7}{2}$    | $P_{8,1} = \frac{5}{4}$    | $P_{9,1} = \frac{7}{2}$    | $P_{10,1} = \frac{15}{16}$ | $P_{11,1} = \frac{7}{2}$   | $P_{12,1} = \frac{5}{4}$   | $P_{13,1} = \frac{7}{2}$   | $P_{14,1} = \frac{5}{4}$   | $P_{15,1} = \frac{7}{2}$   | $P_{16,1} = \frac{15}{16}$ | $P_{17,1} = \frac{7}{2}$   | $P_{18,1} = \frac{5}{4}$ |                          |
|       | $P_{2,2} = \frac{15}{16}$ | $P_{3,2} = \frac{15}{16}$  | $P_{4,2} = \frac{15}{16}$  | $P_{5,2} = \frac{15}{16}$  | $P_{6,2} = \frac{15}{16}$  | $P_{7,2} = \frac{7}{2}$    | $P_{8,2} = \frac{5}{4}$    | $P_{9,2} = \frac{7}{2}$    | $P_{10,2} = \frac{15}{16}$ | $P_{11,2} = \frac{7}{2}$   | $P_{12,2} = \frac{5}{4}$   | $P_{13,2} = \frac{7}{2}$   | $P_{14,2} = \frac{5}{4}$   | $P_{15,2} = \frac{7}{2}$   | $P_{16,2} = \frac{15}{16}$ | $P_{17,2} = \frac{7}{2}$   | $P_{18,2} = \frac{5}{4}$   |                          |                          |
|       | $P_{3,3} = \frac{15}{16}$ | $P_{4,3} = \frac{15}{16}$  | $P_{5,3} = \frac{15}{16}$  | $P_{6,3} = \frac{15}{16}$  | $P_{7,3} = \frac{7}{2}$    | $P_{8,3} = \frac{5}{4}$    | $P_{9,3} = \frac{7}{2}$    | $P_{10,3} = \frac{15}{16}$ | $P_{11,3} = \frac{7}{2}$   | $P_{12,3} = \frac{5}{4}$   | $P_{13,3} = \frac{7}{2}$   | $P_{14,3} = \frac{5}{4}$   | $P_{15,3} = \frac{7}{2}$   | $P_{16,3} = \frac{15}{16}$ | $P_{17,3} = \frac{7}{2}$   | $P_{18,3} = \frac{5}{4}$   |                            |                          |                          |
|       | $P_{4,4} = \frac{15}{16}$ | $P_{5,4} = \frac{15}{16}$  | $P_{6,4} = \frac{15}{16}$  | $P_{7,4} = \frac{7}{2}$    | $P_{8,4} = \frac{5}{4}$    | $P_{9,4} = \frac{7}{2}$    | $P_{10,4} = \frac{15}{16}$ | $P_{11,4} = \frac{7}{2}$   | $P_{12,4} = \frac{5}{4}$   | $P_{13,4} = \frac{7}{2}$   | $P_{14,4} = \frac{5}{4}$   | $P_{15,4} = \frac{7}{2}$   | $P_{16,4} = \frac{15}{16}$ | $P_{17,4} = \frac{7}{2}$   | $P_{18,4} = \frac{5}{4}$   |                            |                            |                          |                          |
|       | $P_{5,5} = \frac{15}{16}$ | $P_{6,5} = \frac{15}{16}$  | $P_{7,5} = \frac{7}{2}$    | $P_{8,5} = \frac{5}{4}$    | $P_{9,5} = \frac{7}{2}$    | $P_{10,5} = \frac{15}{16}$ | $P_{11,5} = \frac{7}{2}$   | $P_{12,5} = \frac{5}{4}$   | $P_{13,5} = \frac{7}{2}$   | $P_{14,5} = \frac{5}{4}$   | $P_{15,5} = \frac{7}{2}$   | $P_{16,5} = \frac{15}{16}$ | $P_{17,5} = \frac{7}{2}$   | $P_{18,5} = \frac{5}{4}$   |                            |                            |                            |                          |                          |
|       | $P_{6,6} = \frac{15}{16}$ | $P_{7,6} = \frac{7}{2}$    | $P_{8,6} = \frac{5}{4}$    | $P_{9,6} = \frac{7}{2}$    | $P_{10,6} = \frac{15}{16}$ | $P_{11,6} = \frac{7}{2}$   | $P_{12,6} = \frac{5}{4}$   | $P_{13,6} = \frac{7}{2}$   | $P_{14,6} = \frac{5}{4}$   | $P_{15,6} = \frac{7}{2}$   | $P_{16,6} = \frac{15}{16}$ | $P_{17,6} = \frac{7}{2}$   | $P_{18,6} = \frac{5}{4}$   |                            |                            |                            |                            |                          |                          |
|       | $P_{7,7} = \frac{7}{2}$   | $P_{8,7} = \frac{5}{4}$    | $P_{9,7} = \frac{7}{2}$    | $P_{10,7} = \frac{15}{16}$ | $P_{11,7} = \frac{7}{2}$   | $P_{12,7} = \frac{5}{4}$   | $P_{13,7} = \frac{7}{2}$   | $P_{14,7} = \frac{5}{4}$   | $P_{15,7} = \frac{7}{2}$   | $P_{16,7} = \frac{15}{16}$ | $P_{17,7} = \frac{7}{2}$   | $P_{18,7} = \frac{5}{4}$   |                            |                            |                            |                            |                            |                          |                          |
|       | $P_{8,8} = \frac{5}{4}$   | $P_{9,8} = \frac{7}{2}$    | $P_{10,8} = \frac{15}{16}$ | $P_{11,8} = \frac{7}{2}$   | $P_{12,8} = \frac{5}{4}$   | $P_{13,8} = \frac{7}{2}$   | $P_{14,8} = \frac{5}{4}$   | $P_{15,8} = \frac{7}{2}$   | $P_{16,8} = \frac{15}{16}$ | $P_{17,8} = \frac{7}{2}$   | $P_{18,8} = \frac{5}{4}$   |                            |                            |                            |                            |                            |                            |                          |                          |
|       | $P_{9,9} = \frac{7}{2}$   | $P_{10,9} = \frac{15}{16}$ | $P_{11,9} = \frac{7}{2}$   | $P_{12,9} = \frac{5}{4}$   | $P_{13,9} = \frac{7}{2}$   | $P_{14,9} = \frac{5}{4}$   | $P_{15,9} = \frac{7}{2}$   | $P_{16,9} = \frac{15}{16}$ | $P_{17,9} = \frac{7}{2}$   | $P_{18,9} = \frac{5}{4}$   |                            |                            |                            |                            |                            |                            |                            |                          |                          |

$$t = N\mathbf{1}$$
[illegible]

Finally, we see that  $t_0 = \boxed{\frac{213}{29} \approx 7.345}$