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~~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?

A hexagonal grid of 19 cells, numbered 0 to 18. Cell 0 is the central cell. Cells 1 through 6 form a ring around cell 0. Cells 7 through 12 form the next ring. Cells 13 through 18 form the outermost ring. Each cell has a red dot in the center. The grid is surrounded by green dots and numbers 19 through 36, which are not part of the grid itself.

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} = \frac{1}{6} & 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} = 0 & 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} = \frac{1}{6} & 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} = \frac{1}{6} & 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} = \frac{1}{6} & 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} = 1 \\ 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} = 0 & 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} = \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_{11,19} = 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_{12,19} = 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} = 0 & p_{13,12} = \frac{1}{6} & p_{13,13} = \frac{1}{6} & p_{13,14} = \frac{1}{6} & p_{13,15} = 0 & p_{13,16} = 0 & p_{13,17} = 0 & p_{13,18} = 0 & p_{13,19} = 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} = 0 & 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} = 0 & p_{14,13} = \frac{1}{6} &amp$$

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

$$Q = \begin{matrix} & \begin{matrix} P_{0,0} = 0 \\ P_{1,0} = \frac{1}{6} \\ P_{2,0} = \frac{1}{6} \\ P_{3,0} = \frac{1}{6} \\ P_{4,0} = \frac{1}{6} \\ P_{5,0} = \frac{1}{6} \\ P_{6,0} = \frac{1}{6} \\ P_{7,0} = 0 \\ P_{8,0} = 0 \\ P_{9,0} = 0 \end{matrix} & \begin{matrix} P_{0,1} = \frac{1}{6} \\ P_{1,1} = 0 \\ P_{2,1} = \frac{1}{6} \\ P_{3,1} = 0 \\ P_{4,1} = 0 \\ P_{5,1} = 0 \\ P_{6,1} = \frac{1}{6} \\ P_{7,1} = \frac{1}{6} \\ P_{8,1} = 0 \\ P_{9,1} = \frac{1}{6} \end{matrix} & \begin{matrix} P_{0,2} = \frac{1}{6} \\ P_{1,2} = 0 \\ P_{2,2} = 0 \\ P_{3,2} = \frac{1}{6} \\ P_{4,2} = 0 \\ P_{5,2} = 0 \\ P_{6,2} = 0 \\ P_{7,2} = 0 \\ P_{8,2} = 0 \\ P_{9,2} = \frac{1}{6} \end{matrix} & \begin{matrix} P_{0,3} = \frac{1}{6} \\ P_{1,3} = 0 \\ P_{2,3} = \frac{1}{6} \\ P_{3,3} = 0 \\ P_{4,3} = 0 \\ P_{5,3} = 0 \\ P_{6,3} = 0 \\ P_{7,3} = 0 \\ P_{8,3} = 0 \\ P_{9,3} = \frac{1}{6} \end{matrix} & \begin{matrix} P_{0,4} = \frac{1}{6} \\ P_{1,4} = 0 \\ P_{2,4} = 0 \\ P_{3,4} = \frac{1}{6} \\ P_{4,4} = 0 \\ P_{5,4} = 0 \\ P_{6,4} = 0 \\ P_{7,4} = 0 \\ P_{8,4} = 0 \\ P_{9,4} = \frac{1}{6} \end{matrix} & \begin{matrix} P_{0,5} = \frac{1}{6} \\ P_{1,5} = 0 \\ P_{2,5} = 0 \\ P_{3,5} = 0 \\ P_{4,5} = \frac{1}{6} \\ P_{5,5} = 0 \\ P_{6,5} = \frac{1}{6} \\ P_{7,5} = 0 \\ P_{8,5} = 0 \\ P_{9,5} = \frac{1}{6} \end{matrix} & \begin{matrix} P_{0,6} = \frac{1}{6} \\ P_{1,6} = 0 \\ P_{2,6} = 0 \\ P_{3,6} = 0 \\ P_{4,6} = 0 \\ P_{5,6} = \frac{1}{6} \\ P_{6,6} = 0 \\ P_{7,6} = 0 \\ P_{8,6} = \frac{1}{6} \\ P_{9,6} = \frac{1}{6} \end{matrix} & \begin{matrix} P_{0,7} = 0 \\ P_{1,7} = \frac{1}{6} \\ P_{2,7} = 0 \\ P_{3,7} = 0 \\ P_{4,7} = 0 \\ P_{5,7} = 0 \\ P_{6,7} = \frac{1}{6} \\ P_{7,7} = 0 \\ P_{8,7} = \frac{1}{6} \\ P_{9,7} = \frac{1}{6} \end{matrix} & \begin{matrix} P_{0,8} = 0 \\ P_{1,8} = \frac{1}{6} \\ P_{2,8} = 0 \\ P_{3,8} = 0 \\ P_{4,8} = 0 \\ P_{5,8} = 0 \\ P_{6,8} = 0 \\ P_{7,8} = \frac{1}{6} \\ P_{8,8} = 0 \\ P_{9,8} = \frac{1}{6} \end{matrix} & \begin{matrix} P_{0,9} = 0 \\ P_{1,9} = \frac{1}{6} \\ P_{2,9} = \frac{1}{6} \\ P_{3,9} = 0 \\ P_{4,9} = 0 \\ P_{5,9} = 0 \\ P_{6,9} = 0 \\ P_{7,9} = 0 \\ P_{8,9} = \frac{1}{6} \\ P_{9,9} = \frac{1}{6} \end{matrix} & \begin{matrix} P_{0,10} = 0 \\ P_{1,10} = \frac{1}{6} \\ P_{2,10} = \frac{1}{6} \\ P_{3,10} = 0 \\ P_{4,10} = 0 \\ P_{5,10} = 0 \\ P_{6,10} = 0 \\ P_{7,10} = 0 \\ P_{8,10} = 0 \\ P_{9,10} = \frac{1}{6} \end{matrix} & \begin{matrix} P_{0,11} = 0 \\ P_{1,11} = 0 \\ P_{2,11} = \frac{1}{6} \\ P_{3,11} = \frac{1}{6} \\ P_{4,11} = 0 \\ P_{5,11} = 0 \\ P_{6,11} = 0 \\ P_{7,11} = 0 \\ P_{8,11} = 0 \\ P_{9,11} = \frac{1}{6} \end{matrix} & \begin{matrix} P_{0,12} = 0 \\ P_{1,12} = 0 \\ P_{2,12} = 0 \\ P_{3,12} = \frac{1}{6} \\ P_{4,12} = \frac{1}{6} \\ P_{5,12} = 0 \\ P_{6,12} = 0 \\ P_{7,12} = 0 \\ P_{8,12} = 0 \\ P_{9,12} = \frac{1}{6} \end{matrix} & \begin{matrix} P_{0,13} = 0 \\ P_{1,13} = 0 \\ P_{2,13} = 0 \\ P_{3,13} = \frac{1}{6} \\ P_{4,13} = \frac{1}{6} \\ P_{5,13} = 0 \\ P_{6,13} = 0 \\ P_{7,13} = 0 \\ P_{8,13} = 0 \\ P_{9,13} = \frac{1}{6} \end{matrix} & \begin{matrix} P_{0,14} = 0 \\ P_{1,14} = 0 \\ P_{2,14} = 0 \\ P_{3,14} = 0 \\ P_{4,14} = \frac{1}{6} \\ P_{5,14} = 0 \\ P_{6,14} = 0 \\ P_{7,14} = 0 \\ P_{8,14} = 0 \\ P_{9,14} = \frac{1}{6} \end{matrix} & \begin{matrix} P_{0,15} = 0 \\ P_{1,15} = 0 \\ P_{2,15} = 0 \\ P_{3,15} = 0 \\ P_{4,15} = \frac{1}{6} \\ P_{5,15} = \frac{1}{6} \\ P_{6,15} = 0 \\ P_{7,15} = 0 \\ P_{8,15} = 0 \\ P_{9,15} = \frac{1}{6} \end{matrix} & \begin{matrix} P_{0,16} = 0 \\ P_{1,16} = 0 \\ P_{2,16} = 0 \\ P_{3,16} = 0 \\ P_{4,16} = 0 \\ P_{5,16} = \frac{1}{6} \\ P_{6,16} = 0 \\ P_{7,16} = 0 \\ P_{8,16} = 0 \\ P_{9,16} = \frac{1}{6} \end{matrix} & \begin{matrix} P_{0,17} = 0 \\ P_{1,17} = 0 \\ P_{2,17} = 0 \\ P_{3,17} = 0 \\ P_{4,17} = 0 \\ P_{5,17} = \frac{1}{6} \\ P_{6,17} = 0 \\ P_{7,17} = 0 \\ P_{8,17} = 0 \\ P_{9,17} = \frac{1}{6} \end{matrix} & \begin{matrix} P_{0,18} = 0 \\ P_{1,18} = 0 \\ P_{2,18} = 0 \\ P_{3,18} = 0 \\ P_{4,18} = 0 \\ P_{5,18} = \frac{1}{6} \\ P_{6,18} = 0 \\ P_{7,18} = 0 \\ P_{8,18} = 0 \\ P_{9,18} = \frac{1}{6} \end{matrix} \end{matrix}$$

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

[illegible]

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

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