

Rajeev Atla

~~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 diagram of a hexagonal lattice with 37 cells. The central cell is labeled 0 and has a red dot. Cells 1 through 14 are labeled with black numbers and have red dots. Cells 15 through 36 are labeled with black numbers and have green dots. The lattice is surrounded by 21 green dots labeled 19 through 36, 38 through 40, and 42 through 44.

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

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  $X_N \in [19, 36]$ .

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} & 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Page 2 of 4

$$N^{-1} = \begin{pmatrix} p_{0,0} = 1 & 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} = 1 & p_{1,2} = \frac{1}{6} & p_{1,3} = \frac{1}{6} & 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} = \frac{1}{6} & 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} = \frac{1}{6} & p_{2,1} = \frac{1}{6} & p_{2,2} = 1 & 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} = \frac{1}{6} & p_{3,2} = \frac{1}{6} & p_{3,3} = 1 & p_{3,4} = \frac{1}{6} & p_{3,5} = \frac{1}{6} & p_{3,6} = \frac{1}{6} & 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} = 1 & 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} = 1 & 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} = 0 & 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} = \frac{1}{6} & p_{6,3} = 0 & p_{6,4} = 0 & p_{6,5} = \frac{1}{6} & p_{6,6} = 1 & p_{6,7} = \frac{1}{6} & p_{6,8} = \frac{1}{6} & 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} = \frac{1}{6} & p_{7,6} = \frac{1}{6} & p_{7,7} = 1 & 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} = 1 & 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} = \frac{1}{6} & p_{9,8} = \frac{1}{6} & p_{9,9} = 1 & 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} = 1 & p_{10,11} = 0 & 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} = 0 & 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} = 1 & 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} = 1 & 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} = 1 & 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} = \frac{1}{6} & 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_{1$$

$P_{0,0} = 45$	$P_{0,1} = 16$	$P_{0,2} = 3456$	$P_{0,3} = 16$	$P_{0,4} = 106714$	$P_{0,5} = 16$	$P_{0,6} = 19722$	$P_{0,7} = 16$	$P_{0,8} = 7$	$P_{0,9} = 5$	$P_{0,10} = 7$	$P_{0,11} = 5$	$P_{0,12} = 7$	$P_{0,13} = 7$	$P_{0,14} = 5$	$P_{0,15} = 7$	$P_{0,16} = 5$	$P_{0,17} = 7$	$P_{0,18} = 5$
$P_{1,0} = 16$	$P_{1,1} = 16$	$P_{1,2} = 3456$	$P_{1,3} = 16$	$P_{1,4} = 106714$	$P_{1,5} = 16$	$P_{1,6} = 19722$	$P_{1,7} = 16$	$P_{1,8} = 7$	$P_{1,9} = 5$	$P_{1,10} = 7$	$P_{1,11} = 5$	$P_{1,12} = 7$	$P_{1,13} = 7$	$P_{1,14} = 5$	$P_{1,15} = 7$	$P_{1,16} = 5$	$P_{1,17} = 7$	$P_{1,18} = 5$
$P_{2,0} = 16$	$P_{2,1} = 16$	$P_{2,2} = 3456$	$P_{2,3} = 16$	$P_{2,4} = 106714$	$P_{2,5} = 16$	$P_{2,6} = 19722$	$P_{2,7} = 16$	$P_{2,8} = 7$	$P_{2,9} = 5$	$P_{2,10} = 7$	$P_{2,11} = 5$	$P_{2,12} = 7$	$P_{2,13} = 7$	$P_{2,14} = 5$	$P_{2,15} = 7$	$P_{2,16} = 5$	$P_{2,17} = 7$	$P_{2,18} = 5$
$P_{3,0} = 16$	$P_{3,1} = 16$	$P_{3,2} = 3456$	$P_{3,3} = 16$	$P_{3,4} = 106714$	$P_{3,5} = 16$	$P_{3,6} = 19722$	$P_{3,7} = 16$	$P_{3,8} = 7$	$P_{3,9} = 5$	$P_{3,10} = 7$	$P_{3,11} = 5$	$P_{3,12} = 7$	$P_{3,13} = 7$	$P_{3,14} = 5$	$P_{3,15} = 7$	$P_{3,16} = 5$	$P_{3,17} = 7$	$P_{3,18} = 5$
$P_{4,0} = 16$	$P_{4,1} = 16$	$P_{4,2} = 3456$	$P_{4,3} = 16$	$P_{4,4} = 106714$	$P_{4,5} = 16$	$P_{4,6} = 19722$	$P_{4,7} = 16$	$P_{4,8} = 7$	$P_{4,9} = 5$	$P_{4,10} = 7$	$P_{4,11} = 5$	$P_{4,12} = 7$	$P_{4,13} = 7$	$P_{4,14} = 5$	$P_{4,15} = 7$	$P_{4,16} = 5$	$P_{4,17} = 7$	$P_{4,18} = 5$
$P_{5,0} = 16$	$P_{5,1} = 16$	$P_{5,2} = 3456$	$P_{5,3} = 16$	$P_{5,4} = 106714$	$P_{5,5} = 16$	$P_{5,6} = 19722$	$P_{5,7} = 16$	$P_{5,8} = 7$	$P_{5,9} = 5$	$P_{5,10} = 7$	$P_{5,11} = 5$	$P_{5,12} = 7$	$P_{5,13} = 7$	$P_{5,14} = 5$	$P_{5,15} = 7$	$P_{5,16} = 5$	$P_{5,17} = 7$	$P_{5,18} = 5$
$P_{6,0} = 16$	$P_{6,1} = 16$	$P_{6,2} = 3456$	$P_{6,3} = 16$	$P_{6,4} = 106714$	$P_{6,5} = 16$	$P_{6,6} = 19722$	$P_{6,7} = 16$	$P_{6,8} = 7$	$P_{6,9} = 5$	$P_{6,10} = 7$	$P_{6,11} = 5$	$P_{6,12} = 7$	$P_{6,13} = 7$	$P_{6,14} = 5$	$P_{6,15} = 7$	$P_{6,16} = 5$	$P_{6,17} = 7$	$P_{6,18} = 5$
$P_{7,0} = 16$	$P_{7,1} = 16$	$P_{7,2} = 3456$	$P_{7,3} = 16$	$P_{7,4} = 106714$	$P_{7,5} = 16$	$P_{7,6} = 19722$	$P_{7,7} = 16$	$P_{7,8} = 7$	$P_{7,9} = 5$	$P_{7,10} = 7$	$P_{7,11} = 5$	$P_{7,12} = 7$	$P_{7,13} = 7$	$P_{7,14} = 5$	$P_{7,15} = 7$	$P_{7,16} = 5$	$P_{7,17} = 7$	$P_{7,18} = 5$
$P_{8,0} = 16$	$P_{8,1} = 16$	$P_{8,2} = 3456$	$P_{8,3} = 16$	$P_{8,4} = 106714$	$P_{8,5} = 16$	$P_{8,6} = 19722$	$P_{8,7} = 16$	$P_{8,8} = 7$	$P_{8,9} = 5$	$P_{8,10} = 7$	$P_{8,11} = 5$	$P_{8,12} = 7$	$P_{8,13} = 7$	$P_{8,14} = 5$	$P_{8,15} = 7$	$P_{8,16} = 5$	$P_{8,17} = 7$	$P_{8,18} = 5$
$P_{9,0} = 16$	$P_{9,1} = 16$	$P_{9,2} = 3456$	$P_{9,3} = 16$	$P_{9,4} = 106714$	$P_{9,5} = 16$	$P_{9,6} = 19722$	$P_{9,7} = 16$	$P_{9,8} = 7$	$P_{9,9} = 5$	$P_{9,10} = 7$	$P_{9,11} = 5$	$P_{9,12} = 7$	$P_{9,13} = 7$	$P_{9,14} = 5$	$P_{9,15} = 7$	$P_{9,16} = 5$	$P_{9,17} = 7$	$P_{9,18} = 5$
$P_{10,0} = 16$	$P_{10,1} = 16$	$P_{10,2} = 3456$	$P_{10,3} = 16$	$P_{10,4} = 106714$	$P_{10,5} = 16$	$P_{10,6} = 19722$	$P_{10,7} = 16$	$P_{10,8} = 7$	$P_{10,9} = 5$	$P_{10,10} = 7$	$P_{10,11} = 5$	$P_{10,12} = 7$	$P_{10,13} = 7$	$P_{10,14} = 5$	$P_{10,15} = 7$	$P_{10,16} = 5$	$P_{10,17} = 7$	$P_{10,18} = 5$
$P_{11,0} = 16$	$P_{11,1} = 16$	$P_{11,2} = 3456$	$P_{11,3} = 16$	$P_{11,4} = 106714$	$P_{11,5} = 16$	$P_{11,6} = 19722$												

In order to get the expected number of steps, we find  $t_0$ , where

$$t = N\mathbf{1}$$

Here,  $\mathbf{1}$  is a vector whose entries are all 1.

[illegible]

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