

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?

The diagram shows a hexagonal lattice structure. The central cell is labeled 0. It is surrounded by six cells labeled 1 through 6. This central cluster is further surrounded by a ring of cells labeled 7 through 18. The vertices of the lattice are marked with green dots and labeled with numbers 1 through 19. The labels are arranged such that the central cell (0) is surrounded by vertices 1 through 6, and the outer ring of cells (7-18) is surrounded by vertices 7 through 18. The vertices 19 through 30 are located at the outermost points of the lattice.

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

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

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$$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} = \frac{1}{6} & 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} = \frac{1}{6} & 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} = 0 & p_{3,3} = \frac{1}{6} & p_{3,4} = \frac{1}{6} & p_{3,5} = \frac{1}{6} & 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} = 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} = 0 & p_{5,1} = 0 & p_{5,2} = 0 & p_{5,3} = 0 & p_{5,4} = \frac{1}{6} & p_{5,5} = \frac{1}{6} & 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} = 0 & p_{6,1} = \frac{1}{6} & p_{6,2} = 0 & p_{6,3} = 0 & p_{6,4} = 0 & p_{6,5} = 0 & p_{6,6} = 1 & 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} = 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} = 0 & 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} = 0 & 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} = 0 & 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} = 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} & p$$

$N =$	$P_{0,0} = \frac{45}{79}$	$P_{0,1} = \frac{16}{79}$	$P_{0,2} = \frac{16}{79}$	$P_{0,3} = \frac{16}{79}$	$P_{0,4} = \frac{16}{79}$	$P_{0,5} = \frac{16}{79}$	$P_{0,6} = \frac{16}{79}$	$P_{0,7} = \frac{7}{79}$	$P_{0,8} = \frac{5}{79}$	$P_{0,9} = \frac{7}{79}$	$P_{0,10} = \frac{7}{79}$	$P_{0,11} = \frac{7}{79}$	$P_{0,12} = \frac{5}{79}$	$P_{0,13} = \frac{7}{79}$	$P_{0,14} = \frac{5}{79}$	$P_{0,15} = \frac{7}{79}$	$P_{0,16} = \frac{5}{79}$	$P_{0,17} = \frac{7}{79}$	$P_{0,18} = \frac{5}{79}$
	$P_{1,0} = \frac{92566}{191222}$	$P_{1,1} = \frac{34888}{191222}$	$P_{1,2} = \frac{34888}{191222}$	$P_{1,3} = \frac{19722}{191222}$	$P_{1,4} = \frac{16771}{191222}$	$P_{1,5} = \frac{19722}{191222}$	$P_{1,6} = \frac{34888}{191222}$	$P_{1,7} = \frac{6783}{191222}$	$P_{1,8} = \frac{8776}{191222}$	$P_{1,9} = \frac{6783}{191222}$	$P_{1,10} = \frac{16771}{191222}$	$P_{1,11} = \frac{173}{191222}$	$P_{1,12} = \frac{2772}{191222}$	$P_{1,13} = \frac{16771}{191222}$	$P_{1,14} = \frac{5878}{191222}$	$P_{1,15} = \frac{16771}{191222}$	$P_{1,16} = \frac{2772}{191222}$	$P_{1,17} = \frac{173}{191222}$	$P_{1,18} = \frac{16771}{191222}$
	$P_{2,0} = \frac{92566}{191222}$	$P_{2,1} = \frac{92566}{191222}$	$P_{2,2} = \frac{92566}{191222}$	$P_{2,3} = \frac{92566}{191222}$	$P_{2,4} = \frac{92566}{191222}$	$P_{2,5} = \frac{92566}{191222}$	$P_{2,6} = \frac{92566}{191222}$	$P_{2,7} = \frac{173}{191222}$	$P_{2,8} = \frac{7406}{191222}$	$P_{2,9} = \frac{173}{191222}$	$P_{2,10} = \frac{92566}{191222}$	$P_{2,11} = \frac{92566}{191222}$	$P_{2,12} = \frac{92566}{191222}$	$P_{2,13} = \frac{92566}{191222}$	$P_{2,14} = \frac{92566}{191222}$	$P_{2,15} = \frac{92566}{191222}$	$P_{2,16} = \frac{92566}{191222}$	$P_{2,17} = \frac{92566}{191222}$	$P_{2,18} = \frac{92566}{191222}$
	$P_{3,0} = \frac{191222}{191222}$	$P_{3,1} = \frac{34888}{191222}$	$P_{3,2} = \frac{34888}{191222}$	$P_{3,3} = \frac{92566}{191222}$	$P_{3,4} = \frac{92566}{191222}$	$P_{3,5} = \frac{92566}{191222}$	$P_{3,6} = \frac{92566}{191222}$	$P_{3,7} = \frac{191222}{191222}$	$P_{3,8} = \frac{191222}{191222}$	$P_{3,9} = \frac{191222}{191222}$	$P_{3,10} = \frac{92566}{191222}$	$P_{3,11} = \frac{92566}{191222}$	$P_{3,12} = \frac{92566}{191222}$	$P_{3,13} = \frac{92566}{191222}$	$P_{3,14} = \frac{92566}{191222}$	$P_{3,15} = \frac{92566}{191222}$	$P_{3,16} = \frac{92566}{191222}$	$P_{3,17} = \frac{92566}{191222}$	$P_{3,18} = \frac{92566}{191222}$
	$P_{4,0} = \frac{16771}{191222}$	$P_{4,1} = \frac{191222}{191222}$	$P_{4,2} = \frac{191222}{191222}$	$P_{4,3} = \frac{92566}{191222}$	$P_{4,4} = \frac{92566}{191222}$	$P_{4,5} = \frac{92566}{191222}$	$P_{4,6} = \frac{92566}{191222}$	$P_{4,7} = \frac{92566}{191222}$	$P_{4,8} = \frac{92566}{191222}$	$P_{4,9} = \frac{92566}{191222}$	$P_{4,10} = \frac{92566}{191222}$	$P_{4,11} = \frac{92566}{191222}$	$P_{4,12} = \frac{92566}{191222}$	$P_{4,13} = \frac{92566}{191222}$	$P_{4,14} = \frac{92566}{191222}$	$P_{4,15} = \frac{92566}{191222}$	$P_{4,16} = \frac{92566}{191222}$	$P_{4,17} = \frac{92566}{191222}$	$P_{4,18} = \frac{92566}{191222}$
	$P_{5,0} = \frac{191222}{191222}$	$P_{5,1} = \frac{92566}{191222}$	$P_{5,2} = \frac{92566}{191222}$	$P_{5,3} = \frac{92566}{191222}$	$P_{5,4} = \frac{92566}{191222}$	$P_{5,5} = \frac{92566}{191222}$	$P_{5,6} = \frac{92566}{191222}$	$P_{5,7} = \frac{92566}{191222}$	$P_{5,8} = \frac{92566}{191222}$	$P_{5,9} = \frac{92566}{191222}$	$P_{5,10} = \frac{92566}{191222}$	$P_{5,11} = \frac{92566}{191222}$	$P_{5,12} = \frac{92566}{191222}$	$P_{5,13} = \frac{92566}{191222}$	$P_{5,14} = \frac{92566}{191222}$	$P_{5,15} = \frac{92566}{191222}$	$P_{5,16} = \frac{92566}{191222}$	$P_{5,17} = \frac{92566}{191222}$	$P_{5,18} = \frac{92566}{191222}$
	$P_{6,0} = \frac{34888}{191222}$	$P_{6,1} = \frac{191222}{191222}$	$P_{6,2} = \frac{191222}{191222}$	$P_{6,3} = \frac{92566}{191222}$	$P_{6,4} = \frac{92566}{191222}$	$P_{6,5} = \frac{92566}{191222}$	$P_{6,6} = \frac{92566}{191222}$	$P_{6,7} = \frac{92566}{191222}$	$P_{6,8} = \frac{92566}{191222}$	$P_{6,9} = \frac{92566}{191222}$	$P_{6,10} = \frac{92566}{191222}$	$P_{6,11} = \frac{92566}{191222}$	$P_{6,12} = \frac{92566}{191222}$	$P_{6,13} = \frac{92566}{191222}$	$P_{6,14} = \frac{92566}{191222}$	$P_{6,15} = \frac{92566}{191222}$	$P_{6,16} = \frac{92566}{191222}$	$P_{6,17} = \frac{92566}{191222}$	$P_{6,18} = \frac{92566}{191222}$
	$P_{7,0} = \frac{6783}{191222}$	$P_{7,1} = \frac{$																	

$$t = N\mathbf{1}$$
$$t = \left( \begin{array}{c} \frac{213}{\frac{20}{184}} \\ \frac{20}{184} \\ \frac{20}{184} \\ \frac{20}{184} \\ \frac{20}{184} \\ \frac{20}{184} \\ \frac{20}{174} \\ \frac{20}{101} \\ \frac{20}{124} \\ \frac{20}{101} \\ \frac{20}{124} \\ \frac{20}{101} \\ \frac{20}{124} \\ \frac{20}{101} \\ \frac{20}{124} \\ \frac{20}{101} \\ \frac{20}{124} \\ \frac{20}{101} \end{array} \right)$$

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