

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 hexagonal grid of 19 cells, numbered 0 to 18, arranged in a honeycomb pattern. Each cell contains a red dot and a black number. The cells are surrounded by 21 green dots, numbered 19 to 39, arranged in a larger hexagonal pattern around the central cluster.

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 37×37 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} = \frac{1}{6} & 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 & 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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$$

$\rho_{0,0} = 45$	$\rho_{0,1} = 16$	$\rho_{0,2} = 16$	$\rho_{0,3} = 16$	$\rho_{0,4} = 16$	$\rho_{0,5} = 16$	$\rho_{0,6} = 16$	$\rho_{0,7} = 7$	$\rho_{0,8} = 5$	$\rho_{0,9} = 7$	$\rho_{0,10} = 5$	$\rho_{0,11} = 7$	$\rho_{0,12} = 5$	$\rho_{0,13} = 7$	$\rho_{0,14} = 5$	$\rho_{0,15} = 7$	$\rho_{0,16} = 5$	$\rho_{0,17} = 7$	$\rho_{0,18} = 5$
$\rho_{1,0} = 34566$	$\rho_{1,1} = 107714$	$\rho_{1,2} = 34566$	$\rho_{1,3} = 107714$	$\rho_{1,4} = 34566$	$\rho_{1,5} = 107714$	$\rho_{1,6} = 34566$	$\rho_{1,7} = 14325$	$\rho_{1,8} = 22485$	$\rho_{1,9} = 14325$	$\rho_{1,10} = 22485$	$\rho_{1,11} = 14325$	$\rho_{1,12} = 22485$	$\rho_{1,13} = 14325$	$\rho_{1,14} = 22485$	$\rho_{1,15} = 14325$	$\rho_{1,16} = 22485$	$\rho_{1,17} = 14325$	$\rho_{1,18} = 22485$
$\rho_{2,0} = 191995$	$\rho_{2,1} = 618085$	$\rho_{2,2} = 191995$	$\rho_{2,3} = 618085$	$\rho_{2,4} = 191995$	$\rho_{2,5} = 618085$	$\rho_{2,6} = 191995$	$\rho_{2,7} = 249915$	$\rho_{2,8} = 399915$	$\rho_{2,9} = 249915$	$\rho_{2,10} = 399915$	$\rho_{2,11} = 249915$	$\rho_{2,12} = 399915$	$\rho_{2,13} = 249915$	$\rho_{2,14} = 399915$	$\rho_{2,15} = 249915$	$\rho_{2,16} = 399915$	$\rho_{2,17} = 249915$	$\rho_{2,18} = 399915$
$\rho_{3,0} = 1099995$	$\rho_{3,1} = 3499995$	$\rho_{3,2} = 1099995$	$\rho_{3,3} = 3499995$	$\rho_{3,4} = 1099995$	$\rho_{3,5} = 3499995$	$\rho_{3,6} = 1099995$	$\rho_{3,7} = 4499995$	$\rho_{3,8} = 6999995$	$\rho_{3,9} = 4499995$	$\rho_{3,10} = 6999995$	$\rho_{3,11} = 4499995$	$\rho_{3,12} = 6999995$	$\rho_{3,13} = 4499995$	$\rho_{3,14} = 6999995$	$\rho_{3,15} = 4499995$	$\rho_{3,16} = 6999995$	$\rho_{3,17} = 4499995$	$\rho_{3,18} = 6999995$
$\rho_{4,0} = 6199995$	$\rho_{4,1} = 19199995$	$\rho_{4,2} = 6199995$	$\rho_{4,3} = 19199995$	$\rho_{4,4} = 6199995$	$\rho_{4,5} = 19199995$	$\rho_{4,6} = 6199995$	$\rho_{4,7} = 7799995$	$\rho_{4,8} = 11999995$	$\rho_{4,9} = 7799995$	$\rho_{4,10} = 11999995$	$\rho_{4,11} = 7799995$	$\rho_{4,12} = 11999995$	$\rho_{4,13} = 7799995$	$\rho_{4,14} = 11999995$	$\rho_{4,15} = 7799995$	$\rho_{4,16} = 11999995$	$\rho_{4,17} = 7799995$	$\rho_{4,18} = 11999995$
$\rho_{5,0} = 34999995$	$\rho_{5,1} = 107999995$	$\rho_{5,2} = 34999995$	$\rho_{5,3} = 107999995$	$\rho_{5,4} = 34999995$	$\rho_{5,5} = 107999995$	$\rho_{5,6} = 34999995$	$\rho_{5,7} = 139999995$	$\rho_{5,8} = 219999995$	$\rho_{5,9} = 139999995$	$\rho_{5,10} = 219999995$	$\rho_{5,11} = 139999995$	$\rho_{5,12} = 219999995$	$\rho_{5,13} = 139999995$	$\rho_{5,14} = 219999995$	$\rho_{5,15} = 139999995$	$\rho_{5,16} = 219999995$	$\rho_{5,17} = 139999995$	$\rho_{5,18} = 219999995$
$\rho_{6,0} = 199999995$	$\rho_{6,1} = 619999995$	$\rho_{6,2} = 199999995$	$\rho_{6,3} = 619999995$	$\rho_{6,4} = 199999995$	$\rho_{6,5} = 619999995$	$\rho_{6,6} = 199999995$	$\rho_{6,7} = 249999995$	$\rho_{6,8} = 399999995$	$\rho_{6,9} = 249999995$	$\rho_{6,10} = 399999995$	$\rho_{6,11} = 249999995$	$\rho_{6,12} = 399999995$	$\rho_{6,13} = 249999995$	$\rho_{6,14} = 399999995$	$\rho_{6,15} = 249999995$	$\rho_{6,16} = 399999995$	$\rho_{6,17} = 249999995$	$\rho_{6,18} = 399999995$
$\rho_{7,0} = 1099999995$	$\rho_{7,1} = 3499999995$	$\rho_{7,2} = 1099999995$	$\rho_{7,3} = 3499999995$	$\rho_{7,4} = 1099999995$	$\rho_{7,5} = 3499999995$	$\rho_{7,6} = 1099999995$	$\rho_{7,7} = 4499999995$	$\rho_{7,8} = 6999999995$	$\rho_{7,9} = 4499999995$	$\rho_{7,10} = 6999999995$	$\rho_{7,11} = 4499999995$	$\rho_{7,12} = 6999999995$	$\rho_{7,13} = 4499999995$	$\rho_{7,14} = 6999999995$	$\rho_{7,15} = 4499999995$	$\rho_{7,16} = 6999999995$	$\rho_{7,17} = 4499999995$	$\rho_{7,18} = 6999999995$
$\rho_{8,0} = 6199999995$	$\rho_{8,1} = 19199999995$	$\rho_{8,2} = 6199999995$	$\rho_{8,3} = 19199999995$	$\rho_{8,4} = 6199999995$	$\rho_{8,5} = 19199999995$	$\rho_{8,6} = 6199999995$	$\rho_{8,7} = 77999999995$	$\rho_{8,8} = 119999999995$	$\rho_{8,9} = 77999999995$	$\rho_{8,10} = 119999999995$	$\rho_{8,11}$							

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

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

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

[illegible]

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