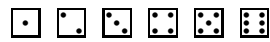


A Collection of Dice Problems

with solutions and useful appendices

(a work continually in progress)

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Chapter 1

Introduction and Notes

This is a (slowly) growing collection of dice-related mathematical problems, with accompanying solutions. Some are simple exercises suitable for beginners, while others require more sophisticated techniques.

Many dice problems have an advantage over some other problems of probability in that they can be investigated experimentally. This gives these types of problems a certain helpful down-to-earth feel.

Please feel free to comment, criticize, or contribute additional problems.

1.0.1 What are dice?

In the real world, dice (the plural of *die*) are polyhedra made of plastic, wood, ivory, or other hard material. Each face of the die is numbered, or marked in some way, so that when the die is cast onto a smooth, flat surface and allowed to come to rest, a particular number is specified.

Mathematically, we can consider a die to be a random variable that takes on only finitely many distinct values.

1.0.2 Terminology

A *fair* die is one for which each face appears with equal likelihood. A non-fair die is called *fixed*. The phrase *standard die* will refer to a fair, six-sided die, whose faces are numbered one through six. If not otherwise specified, the term *die* will refer to a standard die.

Chapter 2

Problems

2.1 Standard Dice

1. On average, how many times must a 6-sided die be rolled until a 6 turns up?
2. On average, how many times must a 6-sided die be rolled until all sides appear at least once? What about for an n -sided die?
3. Suppose we roll n dice and keep the highest one. What is the distribution of values?
4. How many dice must be rolled to have at least a 95% chance of rolling a six?
5. How many dice must be rolled to have at least a 95% chance of rolling a one and a two? What about a one, a two, and a three? What about a one, a two, a three, a four, a five and a six?
6. How many dice should be rolled to maximize the probability of rolling exactly one six? two sixes? n sixes?
7. What is the most probable: rolling at least one six with six dice, at least two sixes with twelve dice, or at least three sixes with eighteen dice? (This is an old problem, frequently connected with Isaac Newton.)
8. Suppose we roll n dice, remove all the dice that come up 1, and roll the rest again. If we repeat this process, eventually all the dice will be eliminated. How many rolls, on average, will we make? Show, for instance, that on average fewer than $O(\log n)$ throws occur.

2.2 Dice Sums

9. Show that the probability of rolling 14 is the same whether we throw 3 dice or 5 dice. Are there other examples of this phenomenon?
10. Suppose we roll n dice and sum the highest 3. What is the probability that the sum is 18?
11. A die is rolled once; call the result N . Then N dice are rolled once and summed. What is the distribution of the sum? What is the expected value of the sum? What is the most likely value?

12. A die is rolled and summed repeatedly. What is the probability that the sum will ever be a given value x ?
13. A die is rolled once. Call the result N . Then, the die is rolled N times, and those rolls which are equal to or greater than N are summed (other rolls are not summed). What is the distribution of the resulting sum? What is the expected value of the sum?

2.3 Non-Standard Dice

14. Show that the probability of rolling doubles with a non-fair (“fixed”) die is greater than with a fair die.
15. Find a pair of 6-sided dice, labelled with positive integers differently from the standard dice, so that the sum probabilities are the same as for a pair of standard dice.
16. Is it possible to have two non-fair n -sided dice, with sides numbered 1 through n , with the property that their sum probabilities are the same as for two fair n -sided dice?
17. Is it possible to have two non-fair 6-sided dice, with sides numbered 1 through 6, with a uniform sum probability? What about n -sided dice?
18. Suppose that we renumber four fair 6-sided dice (A, B, C, D) as follows: $A = \{0, 0, 4, 4, 4, 4\}, B = \{1, 1, 1, 5, 5, 5\}, C = \{2, 2, 2, 2, 6, 6\}, D = \{3, 3, 3, 3, 3, 3\}$.
 - (a) Find the probability that die A beats die D ; die D beats die C ; die C beats die B ; and die B beats die A .
 - (b) Discuss.
19. Find every six-sided die with sides numbered from the set $\{1, 2, 3, 4, 5, 6\}$ such that rolling the die twice and summing the values yields all values between 2 and 12 (inclusive). For instance, the die numbered 1, 2, 4, 5, 6, 6 is one such die. Consider the sum probabilities of these dice. Do any of them give sum probabilities that are “more uniform” than the sum probabilities for a standard die? What if we renumber two dice differently - can we get a uniform (or more uniform than standard) sum probability?

2.4 Games with Dice

20. **Craps** The game of craps is perhaps the most famous of all dice games. The player begins by throwing two standard dice. If the sum of these dice is 7 or 11, the player wins. If the sum is 2, 3 or 12, the player loses. Otherwise, the sum becomes the player’s *point*. The player continues to roll until either the point comes up again, in which case the player wins, or the player throws 7, in which case they lose. The natural question is: what is a player’s probability of winning?
21. **Non-Standard Craps** We can generalize the games of craps to allow dice with other than six sides. Suppose we use two (fair) n -sided dice. Then we can define a game analogous to craps in the following way. The player rolls two n -sided dice. If the sum of these dice is $n + 1$ or $2n - 1$, the player wins. If the sum of these dice is 2, 3 or $2n$, then the player loses. Otherwise the sum becomes the player’s point, and they win if they roll that sum again before rolling $n + 1$. We may again ask: what is the player’s probability of winning?

22. **Yahtzee** There are many probability questions we may ask with regard to the game of Yahtzee. For starters, what is the probability of rolling, in a single roll,
- (a) Yahtzee
 - (b) Four of a kind (but not Yahtzee)
 - (c) Three of a kind (but not four of a kind or Yahtzee)
 - (d) A full house
 - (e) A long straight
 - (f) A small straight

23. **More Yahtzee** What is the probability of getting Yahtzee, assuming that we are trying just to get Yahtzee, we make reasonable choices about which dice to re-roll, and we have three rolls? That is, assume we're in the situation where all we have left to get in a game of Yahtzee *is* Yahtzee, so that all other outcomes are irrelevant.

24. **Drop Dead** In the game of Drop Dead, the player starts by rolling five standard dice. If there are no 2's or 5's among the five dice, then the dice are summed and this is the player's score. If there are 2's or 5's, these dice become "dead" and the player gets no score. In either case, the player continues by rolling all non-dead dice, adding points onto the score, until all dice are dead.

For example, the player might roll $\{1, 3, 3, 4, 6\}$ and score 17. Then they roll all the dice again and get $\{1, 1, 2, 3, 5\}$ which results in no points and two of the dice dying. Rolling the three remaining dice, they might get $\{2, 3, 6\}$ for again no score, and one more dead die. Rolling the remaining two they might get $\{4, 6\}$ which gives them 10 points, bringing the score to 27. They roll the two dice again, and get $\{2, 3\}$ which gives no points and another dead die. Rolling the remaining die, they might get $\{3\}$ which brings the score to 30. Rolling again, they get $\{5\}$ which brings this player's round to an end with 30 points.

Some natural questions to ask are:

- (a) What is the expected value of a player's score?
 - (b) What is the probability of getting a score of 0? 1? 20? etc.
25. Suppose we play a game with a die where we roll and sum our rolls as long as we keep rolling larger values. For instance, we might roll a sequence like 1-3-4 and then roll a 2, so our sum would be 8. If we roll a 6 first, then we're through and our sum is 6. Three questions about this game:
- (a) What is the expected value of the sum?
 - (b) What is the expected value of the number of rolls?
 - (c) If the game is played with an n -sided die, what happens to the expected number of rolls as n approaches infinity?
26. Suppose we play a game with a die in which we use two rolls of the die to create a two digit number. The player rolls the die once and decides which of the two digits they want that roll to represent. Then, the player rolls a second time and this determines the other digit. For instance, the player might roll a 5, and decide this should be the "tens" digit, and then roll a 6, so their resulting number is 56.
- What strategy should be used to create the largest number on average? What about the three digit version of the game?

Chapter 3

Discussion, Hints, and Solutions

3.1 Single Die Problems

1. *On average, how many times must a 6-sided die be rolled until a 6 turns up?*

This problem is asking for the *expected* number of rolls until a 6 appears. Let X be the random variable representing the number of rolls until a 6 appears. Then the probability that $X = 1$ is $1/6$; the probability that $X = 2$ is $(5/6)(1/6) = 5/36$. In general, the probability that $X = k$ is

$$\left(\frac{5}{6}\right)^{k-1} \frac{1}{6} \quad (3.1)$$

since, in order for X to be k , there must be $k - 1$ rolls which can be any of the numbers 1 through 5, and then a 6, which appears with probability $1/6$.

We seek the expectation of X . This is defined to be

$$E = \sum_{n=1}^{\infty} nP(X = n) \quad (3.2)$$

where $P(X = n)$ is the probability that X takes on the value n . Thus,

$$E = \sum_{n=1}^{\infty} n \left(\frac{5}{6}\right)^{n-1} \frac{1}{6} = \frac{6}{5} \cdot \frac{1}{6} \sum_{n=1}^{\infty} n \left(\frac{5}{6}\right)^n \quad (3.3)$$

Using Equation B.3 from Appendix B, we can conclude that

$$E = \frac{6}{5} \cdot \frac{1}{6} \frac{5/6}{(1 - (5/6))^2} = 6. \quad (3.4)$$

Thus, on average, it takes 6 throws of a die before a 6 appears.

Here's another, quite different way to solve this problem. When rolling a die, there is a $1/6$ chance that a 6 will appear. If a 6 doesn't appear, then we're in essence starting over. That is to say, the number of times we expect to throw the dice before a 6 shows up is the same as the number of additional times we expect to throw the die after throwing a non-6. So we have a $1/6$ chance of rolling a 6 (and stopping), and a $5/6$ chance of not rolling a six, after which the number of rolls we expect to throw is the same as when we started. We can formulate this as

$$E = \frac{1}{6} + \frac{5}{6}(E + 1). \quad (3.5)$$

Solving for E , we find $E = 6$. Note that Equation 3.5 implicitly assumes that E is a finite number, which is something that, *a priori*, we do not necessarily know.

2. *On average, how many times must a 6-sided die be rolled until all sides appear at least once? What about for an n -sided die?*

To roll until every side of the die appears, we begin by rolling once. We then roll until a different side appears. Since there are 5 sides, this takes, on average, $\frac{1}{5/6} = 6/5$ rolls. Then we roll until a side different from the two already rolled appears. This requires, on average, $\frac{1}{4/6} = 6/4 = 3/2$ rolls. Continuing this process, and using the additive nature of expectation, we see that, on average,

$$1 + \frac{6}{5} + \frac{6}{4} + \frac{6}{3} + \frac{6}{2} + \frac{6}{1} = \frac{147}{10} = 14.7$$

rolls are needed until all 6 sides appear at least once. For an n -sided die, the number of rolls needed, on average, is

$$1 + \frac{n}{n-1} + \frac{n}{n-2} + \cdots + \frac{n}{1} = \sum_{i=1}^n \frac{n}{i} = n \sum_{i=1}^n \frac{1}{i}.$$

For large n , this is approximately $n \log n$.

3. *Suppose we roll n dice and keep the highest one. What is the distribution of values?*

Let's find the probability that the highest number rolled is k . Among the n dice rolled, they must all show k or less. The probability of this occurring is

$$\frac{k^n}{6^n}.$$

However, some of these rolls don't actually have any k 's. That is, they are made up of only the numbers 1 through $k-1$. The probability of this occurring is

$$\frac{(k-1)^n}{6^n}$$

so the probability that the highest number rolled is k is

$$\frac{k^n - (k-1)^n}{6^n}.$$

So, for instance, the probability that, if 7 dice are rolled, the highest number to turn up will be 3 is

$$\frac{3^7 - 2^7}{6^7} = \frac{2059}{6^7} \approx 0.007355.$$

4. *How many dice must be rolled to have at least a 95% chance of rolling a six? 99%? 99.9%?*

Suppose we roll n dice. The probability that none of them turn up six is

$$\left(\frac{5}{6}\right)^n$$

and so the probability that at least one is a six is

$$1 - \left(\frac{5}{6}\right)^n.$$

To have a 95% chance of rolling a six, we need

$$1 - \left(\frac{5}{6}\right)^n \geq 0.95$$

which yields

$$n \geq \frac{\log 0.05}{\log(5/6)} = 16.43 \dots > 16.$$

Hence, $n \geq 17$ will give at least a 95% chance of rolling at least one six. Since $\log(0.01)/\log(5/6) = 25.2585 \dots$, 26 dice are needed to have a 99% chance of rolling at least one six. Similarly, since $\log(0.001)/\log(5/6) = 37.8877 \dots$, 38 dice are needed for a 99.9% chance.

5. *How many dice must be rolled to have at least a 95% chance of rolling a one and a two? What about a one, a two, and a three? What about a one, a two, a three, a four, a five and a six?*

Solving this problem requires the use of the inclusion-exclusion principal. Of the 6^n possible rolls of n dice, 5^n have no one's, and 5^n have no two's. The number that have neither one's nor two's is *not* $5^n + 5^n$ since this would count some rolls more than once: of those 5^n rolls with no one's, some have no two's either. The number that have neither one's nor two's is 4^n , so the number of rolls that don't have at least one one, and at least one two is

$$5^n + 5^n - 4^n = 2 \cdot 5^n - 4^n$$

and so the probability of rolling a one and a two with n dice is

$$1 - \frac{2 \cdot 5^n - 4^n}{6^n}.$$

This is an increasing function of n , and by direct calculation we can show that it's greater than 0.95 for $n \geq 21$. That is, if we roll at least 21 dice, there is at least a 95% chance that there will be a one and a two among the faces that turn up.

To include three's, we need to extend the method. Of the 6^n possible rolls, there are 5^n rolls that have no one's, 5^n that have no two's, and 5^n that have no three's. There are 4^n that have neither one's nor two's, 4^n that have neither one's nor three's, and 4^n that have neither two's nor three's. In addition, there are 3^n that have no one's, two's, or three's. So, the number of rolls that don't have a one, a two, and a three is

$$5^n + 5^n + 5^n - 4^n - 4^n - 4^n + 3^n = 3 \cdot 5^n - 3 \cdot 4^n + 3^n.$$

Hence, the probability of rolling at least one one, one two, and one three is

$$1 - \frac{3 \cdot 5^n - 3 \cdot 4^n + 3^n}{6^n}.$$

This is again an increasing function of n , and it is greater than 0.95 when $n \geq 23$.

Finally, to determine the probability of rolling at least one one, two, three, four, five and six, we extend the method even further. The result is that the probability $p(n)$ of rolling at least one of every possible face is

$$p(n) = 1 - \sum_{j=1}^5 (-1)^{(j+1)} \binom{6}{j} \left(\frac{6-j}{6}\right)^n = 1 - 6 \left(\frac{1}{6}\right)^n + 15 \left(\frac{1}{3}\right)^n - 20 \left(\frac{1}{2}\right)^n + 15 \left(\frac{2}{3}\right)^n - 6 \left(\frac{5}{6}\right)^n.$$

This exceeds 0.95 when $n \geq 27$. Below is a table showing some of the probabilities for various n .

n	$p(n)$
6	0.0154...
7	0.0540...
8	0.1140...
9	0.1890...
10	0.2718...
11	0.3562...
12	0.4378...
13	0.5138...
14	0.5828...
15	0.6442...
16	0.6980...
17	0.7446...
18	0.7847...
19	0.8189...
20	0.8479...
21	0.8725...
22	0.8933...
23	0.9107...
24	0.9254...
25	0.9376...
26	0.9479...
27	0.9565...
30	0.9748...
35	0.9898...
40	0.9959...

6. How many dice should be rolled to maximize the probability of rolling exactly one six? two sixes? n sixes?

Suppose we roll n dice. The probability that exactly one is a six is

$$\frac{\binom{n}{1}5^{n-1}}{6^n} = \frac{n5^{n-1}}{6^n}.$$

The question is: for what value of n is this maximal? If $n > 6$ then $\frac{(n+1)5^n}{6^{n+1}} < \frac{n5^{n-1}}{6^n}$, so the maximum must occur for some $n \leq 6$. Here's a table that gives the probabilities:

n	$\frac{n5^{n-1}}{6^n}$
1	$1/6 = 0.1666\dots$
2	$5/18 = 0.2777\dots$
3	$25/72 = 0.3472\dots$
4	$125/324 = 0.3858\dots$
5	$3125/7776 = 0.4018\dots$
6	$3125/7776 = 0.4018\dots$

This shows that the maximum probability is $\frac{3125}{7776}$, and it occurs for both $n = 5$ and $n = 6$.

For two sixes, the calculation is similar. The probability of exactly two sixes when rolling n dice is

$$\frac{\binom{n}{2}5^{n-2}}{6^n} = \frac{n(n-1)5^{n-2}}{2 \cdot 6^n}$$

A quick calculation shows that this is maximal for $n = 12$ or $n = 11$.

It seems that for n sixes, the maximal probability occurs with $6n$ and $6n - 1$ dice. I'll let you prove that.

7. What is the most probable: rolling at least one six with six dice, at least two sixes with twelve dice, or at least three sixes with eighteen dice? (This is an old problem, frequently connected with Isaac Newton.)

One way to solve this is to simply calculate the probability of each. The probability of rolling exactly m sixes when rolling r six-sided dice is

$$\binom{r}{m} \frac{5^{r-m}}{6^r}$$

so the probability of rolling at least m sixes when rolling r six-sided dice is

$$p(m, r) = \sum_{i=m}^r \binom{r}{i} \frac{5^{r-i}}{6^r}.$$

Grinding through the calculations yields

$$p(1, 6) = \frac{31031}{46656} \approx 0.66510202331961591221$$

$$p(2, 12) = \frac{1346704211}{2176782336} \approx 0.61866737373230871348$$

$$p(3, 18) = \frac{15166600495229}{25389989167104} \approx 0.59734568594772319497$$

so that we see that the six dice case is the clear winner.

8. *Suppose we roll n dice, remove all the dice that come up 1, and roll the rest again. If we repeat this process, eventually all the dice will be eliminated. How many rolls, on average, will we make? Show, for instance, that on average fewer than $O(\log n)$ throws occur.*

We expect that, on average, $5/6$ of the dice will be left after each throw. So, after k throws, we expect to have $n \left(\frac{5}{6}\right)^k$ dice left. When this is less than 2, we have, on average less than 6 throws left, so the number of throws should be, on average, something less than a constant time $\log n$.

Let M_n be the expected number of throws until all dice are eliminated. Then, thinking in terms of a Markov chain, we have the recurrence formula

$$M_n = \frac{1}{6^n} + \frac{5^n}{6^n} + \left(\frac{5}{6}\right)^n M_n + \sum_{j=1}^{n-1} (1 + M_j) \binom{n}{n-j} \frac{5^j}{6^n}$$

which allows us to solve for M_n :

$$M_n = \frac{1 + 5^n + \sum_{j=1}^{n-1} (1 + M_j) \binom{n}{n-j} 5^j}{6^n - 5^n}$$

Here are a few values of M_n .

n	M_n
1	6
2	8.72727272727273
3	10.5554445554446
4	11.9266962545651
5	13.0236615075553
6	13.9377966973204
7	14.7213415962620
8	15.4069434778816
9	16.0163673664838
10	16.5648488612594
15	18.6998719821123
20	20.2329362496041
30	22.4117651317294
40	23.9670168145374
50	25.1773086926527

We see that M_n increases quite slowly, another suggestion that $M_n = O(\log n)$. To show this, suppose $M_j < C \log j$ for all $2 \leq j < n$. Then we have

$$M_n < \frac{1 + 5^n + \max\{1 + 6, 1 + C \log(n-1)\} \sum_{j=1}^{n-1} \binom{n}{n-j} 5^j}{6^n - 5^n}$$

$$= \frac{1 + 5^n + C \log(n-1)(6^n - 5^n - 1)}{6^n - 5^n} = C \left(1 - \frac{1}{6^n - 5^n}\right) \log(n-1) + \frac{1 + 5^n}{6^n - 5^n} < C \log n$$

if and only if

$$\left(1 - \frac{1}{6^n - 5^n}\right) \frac{\log(n-1)}{\log n} + \frac{1 + 5^n}{C \log n (6^n - 5^n)} < 1$$

Since $M_2 / \log 2 < 13$, we may suppose $C = 13$. It is not hard to show the above inequality holds for all n , and hence $M_n < 13 \log n$ for all $n \geq 2$.

3.2 Dice Sums

9. Show that the probability of rolling 14 is the same whether we throw 3 dice or 5 dice.

This seems like a tedious calculation, and it is. To save some trouble, we can use a computer algebra system to determine the coefficient of x^{14} in the polynomials $(x + x^2 + x^3 + x^4 + x^5 + x^6)^3$ and $(x + x^2 + x^3 + x^4 + x^5 + x^6)^5$ (see Appendix C for an explanation of this method). They are 15 and 540, respectively, and so the probability in question is $\frac{15}{6^3} = \frac{540}{6^5} = \frac{5}{72}$.

Are there other examples of this phenomenon?

Yes. Let $p_d(t, n)$ be the probability of rolling a sum of t with n d -sided dice. Then:

- $p_3(5, 2) = p_3(5, 3) = \frac{2}{9}$
- $p_3(10, 4) = p_3(10, 6) = \frac{10}{81}$
- $p_4(9, 3) = p_4(9, 4) = \frac{5}{32}$

- $p_6(14, 3) = p_6(14, 5) = \frac{5}{72}$
- $p_9(15, 2) = p_9(15, 4) = \frac{4}{81}$
- $p_{20}(27, 2) = p_{20}(27, 3) = \frac{7}{200}$

Questions: Are there others? Can we find *all* of them?

10. Suppose we roll n dice and sum the highest 3. What is the probability that the sum is 18?

In order for the sum to be 18, there must be at least three 6's among the n dice. So, we could calculate probability that there are 3, 4, 5, ..., n 6's among the n dice. The sum of these probabilities would be the probability of rolling 18. Since n could be much greater than 3, an easier way to solve this problem is to calculate the probability that the sum is *not* 18, and then subtract this probability from 1. To get a sum that is not 18, there must be 0, 1 or 2 6's among the n dice. We calculate the probability of each occurrence:

$$\begin{aligned} \text{zero 6's: the probability is } & \frac{5^n}{6^n} \\ \text{one 6: the probability is } & \frac{n5^{n-1}}{6^n} \\ \text{two 6's: the probability is } & \frac{\binom{n}{2}5^{n-2}}{6^n} \end{aligned}$$

Hence, the probability of rolling a sum of 18 is

$$1 - \left(\frac{5^n}{6^n} + \frac{n5^{n-1}}{6^n} + \frac{\binom{n}{2}5^{n-2}}{6^n} \right) = 1 - \left(\frac{5}{6} \right)^n \left(1 + \frac{9}{50}n + \frac{1}{50}n^2 \right) = p(n) \quad (3.6)$$

say. Then, for example, $p(1) = p(2) = 0$, $p(3) = 1/216$, $p(4) = 7/432$, and $p(5) = 23/648$.

11. A die is rolled once; call the result N . Then N dice are rolled once and summed. What is the distribution of the sum? What is the expected value of the sum? What is the most likely value?

Since each of the possible values $\{1, 2, 3, 4, 5, 6\}$ of N are equally likely, we can calculate the distribution by summing the individual distributions of the sum of 1, 2, 3, 4, 5, and 6 dice, each weighted by $\frac{1}{6}$. We can do this using polynomials. Let

$$p = \frac{1}{6}(x + x^2 + x^3 + x^4 + x^5 + x^6).$$

Then the distribution of the sum is given by the coefficients of the polynomial

$$\begin{aligned} D &= \sum_{i=1}^6 \frac{1}{6} p^i \\ &= \frac{1}{279936} x^{36} + \frac{1}{46656} x^{35} + \frac{7}{93312} x^{34} + \frac{7}{34992} x^{33} + \frac{7}{15552} x^{32} + \frac{7}{7776} x^{31} + \frac{77}{46656} x^{30} + \\ &\quad \frac{131}{46656} x^{29} + \frac{139}{31104} x^{28} + \frac{469}{69984} x^{27} + \frac{889}{93312} x^{26} + \frac{301}{23328} x^{25} + \frac{4697}{279936} x^{24} + \frac{245}{11664} x^{23} + \\ &\quad \frac{263}{10368} x^{22} + \frac{691}{23328} x^{21} + \frac{1043}{31104} x^{20} + \frac{287}{7776} x^{19} + \frac{11207}{279936} x^{18} + \frac{497}{11664} x^{17} + \frac{4151}{93312} x^{16} + \end{aligned}$$

$$\frac{3193}{69984}x^{15} + \frac{1433}{31104}x^{14} + \frac{119}{2592}x^{13} + \frac{749}{15552}x^{12} + \frac{2275}{46656}x^{11} + \frac{749}{15552}x^{10} + \frac{3269}{69984}x^9 + \frac{4169}{93312}x^8 + \frac{493}{11664}x^7 + \frac{16807}{279936}x^6 + \frac{2401}{46656}x^5 + \frac{343}{7776}x^4 + \frac{49}{1296}x^3 + \frac{7}{216}x^2 + \frac{1}{36}x.$$

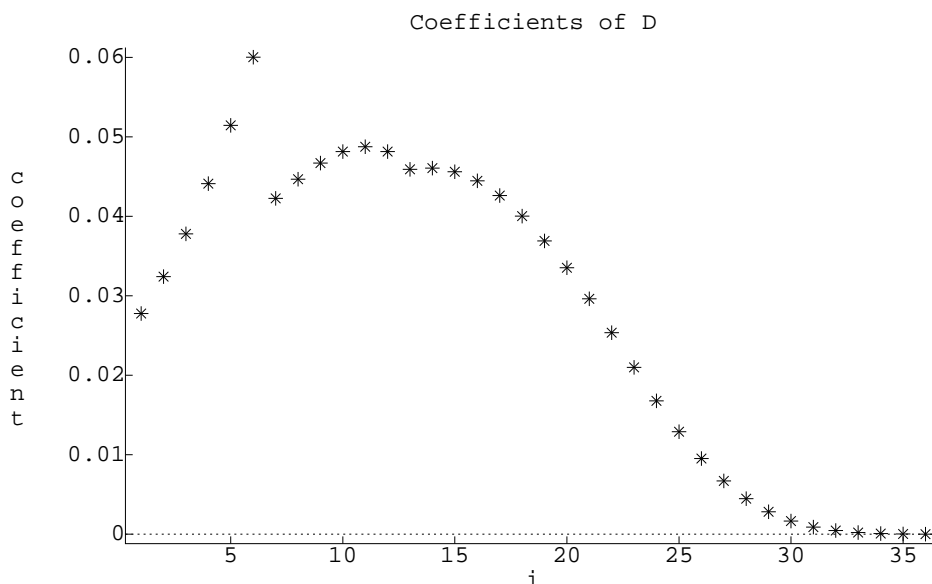
To get the expected value E , we must calculate

$$E = \sum_{i=1}^{36} id_i$$

where $D = \sum_{i=1}^{36} d_i x^i$. This works out to $E = \frac{49}{4} = 12.25$.

More simply, one can calculate the expected value of the sum as follows, using the fact that the expected value of a single roll is 3.5:

$$E = \frac{1}{6} (3.5 + 2 \times 3.5 + 3 \times 3.5 + \cdots + 6 \times 3.5) = 12.25.$$



You can see from the plot of the coefficients of D that 6 is the most likely value. It is perhaps a bit surprising that there are three “local maxima” in the plot, at $i = 6, 11,$ and 14 .

12. A die is rolled and summed repeatedly. What is the probability that the sum will ever be a given value x ?

Let’s start by considering 2-sided dice, with sides numbered 1 and 2. Let $p(x)$ be the probability that the sum will ever be x . Then $p(1) = 1/2$ since the only way to ever have a sum of 1 is to roll 1 on the first roll. We then have $p(2) = 1/2 + 1/2p(1) = 3/4$, since there are two mutually exclusive ways to get a sum of 2: roll 2 on the first roll, or roll a 1 followed by a 1 on the second roll. Now, extending this idea, we have, for $x > 2$,

$$p(x) = \frac{1}{2}p(x-1) + \frac{1}{2}p(x-2). \tag{3.7}$$

This equation could be used to calculate $p(x)$ for any given value of x . However, this would require calculating p for all lower values. Can we get an *explicit* expression for $p(x)$?

Equation 3.7 is an example of a *linear recurrence relation*. One way to get a solution, or explicit formula, for such a relation is by examining the *auxiliary* equation for equation 3.7:

$$x^2 = \frac{1}{2}x + \frac{1}{2}$$

or

$$x^2 - \frac{1}{2}x - \frac{1}{2} = 0$$

The roots of this equation are

$$\alpha = 1 \text{ and } \beta = -\frac{1}{2}$$

A powerful theorem (see Appendix E) says that

$$p(n) = A\alpha^n + B\beta^n = A + B\left(-\frac{1}{2}\right)^n$$

for constants A and B . Since $p(1) = 1/2$ and $p(2) = 3/4$ we can solve for A and B to find that

$$p(n) = \frac{2}{3} + \frac{1}{3}\left(-\frac{1}{2}\right)^n.$$

For 3-sided dice, we have

$$p(1) = \frac{1}{3}, p(2) = \frac{4}{9}, \text{ and } p(3) = \frac{16}{27}$$

with, for $n > 3$,

$$p(n) = \frac{1}{3}(p(n-1) + p(n-2) + p(n-3)) = \frac{1}{3}\sum_{i=1}^3 p(n-i).$$

The characteristic equation for this recurrence equation can be written

$$3x^3 - x^2 - x - 1 = 0$$

which has roots

$$\alpha = 1, \beta = -\frac{1}{3} - \frac{\sqrt{2}}{3}i, \text{ and } \gamma = -\frac{1}{3} + \frac{\sqrt{2}}{3}i.$$

Using these, and the fact that

$$p(1) = \frac{1}{3}, p(2) = \frac{4}{9}, \text{ and } p(3) = \frac{16}{27},$$

we find

$$p(n) = \frac{1}{2} + \frac{1}{4}\beta^n + \frac{1}{4}\gamma^n.$$

Since β and γ are complex conjugates, and, in any case, $p(n)$ is always real, we might prefer to write $p(n)$ like this:

$$p(n) = \frac{1}{2} + \frac{1}{2}\left(\frac{1}{\sqrt{3}}\right)^n \cos\left(n\left(\frac{\pi}{2} + \tan^{-1}\frac{1}{\sqrt{2}}\right)\right)$$

Using this formula to generate a table, we see that while $p(n)$ is asymptotic to the value $1/2$, it wobbles quite a bit:

x	$p(x)$	$p(x) - p(x - 1)$
1	0.33333333333333333333333333333333	
2	0.44444444444444444444444444444444	0.11111111111111111111111111111111
3	0.5925925925925925925925925925925	0.1481481481481481481481481481481
4	0.4567901234567901234567901234	-0.1358024691358024691358024691
5	0.4979423868312757201646090534	0.04115226337448559670781893002
6	0.5157750342935528120713305898	0.01783264746227709190672153636
7	0.4901691815272062185642432556	-0.02560585276634659350708733424
8	0.5012955342173449169333942996	0.01112635269013869836915104404
9	0.5024132500127013158563227150	0.001117715795356398922928415384
10	0.4979593219190841504513200901	-0.004453928093617165405002624938
11	0.5005560353830434610803457015	0.002596713463959310629025611496
12	0.5003095357716096424626628355	-0.0002464996114338186176828660183
13	0.4996082976912457513314428757	-0.0007012380803638911312199598200
14	0.5001579562819662849581504709	0.0005496585907205336267075952194
15	0.5000252632482738929174187274	-0.0001326930336923920407317435396
16	0.4999305057404953097356706913	-0.00009475750777858318174803604667
17	0.5000379084235784958704132966	0.0001074026830831861347426052109
18	0.4999978924707825661745009051	-0.00004001595279592969591239145842
19	0.4999887688782854572601949643	-0.000009123592497108914305940764722
20	0.5000081899242155064350363887	0.00001942104593004917484142432929

Let's skip over 4- and 5-sided dice to deal with 6-sided dice. Let $p(x)$ be the probability that the sum will ever be x . We know that:

$$p(1) = \frac{1}{6}$$

$$p(2) = \frac{1}{6} + \frac{1}{6}p(1) = \frac{7}{36}$$

$$p(3) = \frac{1}{6} + \frac{1}{6}p(2) + \frac{1}{6}p(1) = \frac{49}{216}$$

$$p(4) = \frac{1}{6} + \frac{1}{6}p(3) + \frac{1}{6}p(2) + \frac{1}{6}p(1) = \frac{343}{1296}$$

$$p(5) = \frac{1}{6} + \frac{1}{6}p(4) + \frac{1}{6}p(3) + \frac{1}{6}p(2) + \frac{1}{6}p(1) = \frac{2401}{7776}$$

$$p(6) = \frac{1}{6} + \frac{1}{6}p(5) + \frac{1}{6}p(4) + \frac{1}{6}p(3) + \frac{1}{6}p(2) + \frac{1}{6}p(1) = \frac{16807}{46656}$$

and for $x > 6$,

$$p(x) = \frac{1}{6} \sum_{i=1}^6 p(x - i).$$

Here's a table of the values of $p(x)$ and $p(x) - p(x - 1)$ for $x \leq 20$:

So, we can consider M to be a transition matrix of a regular Markov system. Hence M^∞ is a matrix with all identical rows given by the vector w where the sum of the entries of w equals 1, and

$$wM = w.$$

A little simple algebra shows that

$$w = \left\langle \frac{2}{7}, \frac{5}{21}, \frac{4}{21}, \frac{1}{7}, \frac{2}{21}, \frac{1}{21} \right\rangle$$

Hence, $v(\infty)$ is a vector of six identical probabilities equal to

$$w \cdot v(6) = \frac{2}{7}$$

Thus, $\lim_{i \rightarrow \infty} = \frac{2}{7}$.

More questions:

- (a) Notice that while $p(x)$ is settling down on $\frac{2}{7}$, it does so quite non-monotonically: $p(x)$ increases to its maximum at $x = 6$, and then wobbles around quite a bit. Is the sequence $p(i)$ eventually monotonic, or does it always wobble?
13. A die is rolled once. Call the result N . Then, the die is rolled N times, and those rolls which are equal to or greater than N are summed (other rolls are not summed). What is the distribution of the resulting sum? What is the expected value of the sum?

This is a perfect problem for the application of the polynomial representation of the distribution of sums.

The probability of a sum of k is the coefficient on x^k in the polynomial

$$\begin{aligned} & \frac{1}{6} \left(\frac{1}{6} (x + x^2 + x^3 + x^4 + x^5 + x^6) \right) + \frac{1}{6} \left(\frac{1}{6} (1 + x^2 + x^3 + x^4 + x^5 + x^6) \right)^2 + \\ & \frac{1}{6} \left(\frac{1}{6} (2 + x^3 + x^4 + x^5 + x^6) \right)^3 + \frac{1}{6} \left(\frac{1}{6} (3 + x^4 + x^5 + x^6) \right)^4 + \\ & \frac{1}{6} \left(\frac{1}{6} (4 + x^5 + x^6) \right)^5 + \frac{1}{6} \left(\frac{1}{6} (5 + x^6) \right)^6 \\ = & \frac{1}{279936}x^{36} + \frac{1}{7776}x^{30} + \frac{5}{46656}x^{29} + \frac{5}{23328}x^{28} + \frac{5}{23328}x^{27} + \frac{5}{46656}x^{26} + \frac{1}{46656}x^{25} + \\ & \frac{59}{31104}x^{24} + \frac{13}{5832}x^{23} + \frac{5}{1296}x^{22} + \frac{11}{2916}x^{21} + \frac{67}{23328}x^{20} + \frac{1}{486}x^{19} + \\ & \frac{1117}{69984}x^{18} + \frac{23}{1296}x^{17} + \frac{7}{288}x^{16} + \frac{16}{729}x^{15} + \frac{1}{54}x^{14} + \frac{1}{72}x^{13} + \\ & \frac{6781}{93312}x^{12} + \frac{47}{729}x^{11} + \frac{377}{5832}x^{10} + \frac{67}{1296}x^9 + \frac{19}{432}x^8 + \frac{1}{36}x^7 + \\ & \frac{8077}{46656}x^6 + \frac{565}{5832}x^5 + \frac{7}{108}x^4 + \frac{5}{108}x^3 + \frac{1}{27}x^2 + \frac{1}{36}x + \frac{27709}{279936} \end{aligned}$$

So, that's the distribution.

The expected value is simply the sum of i times the coefficient on x^i in the distribution polynomial. The result is $\frac{133}{18} = 7.38888\dots$

3.3 Non-Standard Dice

14. Show that the probability of rolling doubles with a non-fair (“fixed”) die is greater than with a fair die.

For a fair, n -sided die, the probability of rolling doubles with it is $n \times \frac{1}{n^2} = \frac{1}{n}$. Suppose we have a “fixed” n -sided die, with probabilities p_1, \dots, p_n of rolling sides 1 through n respectively. The probability of rolling doubles with this die is

$$p_1^2 + \dots + p_n^2.$$

We want to show that this is greater than $\frac{1}{n}$. A nice trick is to let

$$\epsilon_i = p_i - \frac{1}{n} \text{ for } i = 1, \dots, n.$$

Then

$$p_1^2 + \dots + p_n^2 = \left(\epsilon_1 + \frac{1}{n}\right)^2 + \dots + \left(\epsilon_n + \frac{1}{n}\right)^2 = \epsilon_1^2 + \dots + \epsilon_n^2 + \frac{2}{n}(\epsilon_1 + \dots + \epsilon_n) + \frac{1}{n}.$$

Now, since $p_1 + \dots + p_n = 1$, we can conclude that $\epsilon_1 + \dots + \epsilon_n = 0$. Hence,

$$p_1^2 + \dots + p_n^2 = \epsilon_1^2 + \dots + \epsilon_n^2 + \frac{1}{n} > \frac{1}{n}$$

precisely when not all the ϵ_i 's are zero, i.e. when the die is “fixed”.

15. Find a pair of 6-sided dice, labelled with positive integers differently from the standard dice, so that the sum probabilities are the same as for a pair of standard dice.

Number one die with sides 1,2,2,3,3,4 and one with 1,3,4,5,6,8. Rolling these two dice gives the same sum probabilities as two normal six-sided dice.

A natural question is: how can we find such dice? One way is to consider the polynomial

$$(x + x^2 + x^3 + x^4 + x^5 + x^6)^2.$$

This factors as

$$x^2(1+x)^2(1+x+x^2)^2(1-x+x^2)^2.$$

We can group this factorization as

$$\begin{aligned} & \left(x(1+x)(1+x+x^2)\right) \left(x(1+x)(1+x+x^2)(1-x+x^2)^2\right) \\ & = (x + 2x^2 + 2x^3 + x^4)(x + x^3 + x^4 + x^5 + x^6 + x^8). \end{aligned}$$

This yields the “weird” dice (1,2,2,3,3,4) and (1,3,4,5,6,8). See Appendix C for more about this method.

See [1] for more on renumbering dice.

16. *Is it possible to have two non-fair n -sided dice, with sides numbered 1 through n , with the property that their sum probabilities are the same as for two fair n -sided dice?*

Another way of asking the question is: suppose you are given two n -sided dice that exhibit the property that when rolled, the resulting sum, as a random variable, has the same probability distribution as for two fair n -sided dice; can you then conclude that the two given dice are fair? This question was asked by Lewis Robertson, Rae Michael Shortt and Stephen Landry in [2]. Their answer is surprising: you *can* sometimes, depending on the value of n . Specifically, if n is 1,2,3,4,5,6,7,8,9,11 or 13, then two n -sided dice whose sum “acts fair” are, in fact, fair. If n is any other value, then there exist pairs of n -sided dice which are not fair, yet have “fair” sums.

The smallest example, with $n = 10$, gives dice with the approximate probabilities (see [Rob 2] for the exact values)

$$(0.07236, 0.14472, 0.1, 0.055279, 0.127639, 0.127639, 0.055279, 0.1, 0.14472, 0.07236)$$

and

$$(0.13847, 0, 0.2241, 0, 0.13847, 0.13847, 0, 0.2241, 0, 0.13847).$$

It’s clear that these dice are not fair, yet the sum probabilities for them are the same as for two fair 10-sided dice.

17. *Is it possible to have two non-fair 6-sided dice, with sides numbered 1 through 6, with a uniform sum probability? What about n -sided dice?*

No. Let p_1, p_2, p_3, p_4, p_5 and p_6 be the probabilities for one 6-sided die, and q_1, q_2, q_3, q_4, q_5 and q_6 be the probabilities for another. Suppose that these dice together yield sums with uniform probabilities. That is, suppose $P(\text{sum} = k) = \frac{1}{11}$ for $k = 2, \dots, 12$. Then

$$p_1q_1 = \frac{1}{11} \text{ and } p_6q_6 = \frac{1}{11}.$$

Also,

$$\frac{1}{11} = P(\text{sum} = 7) \geq p_1q_6 + p_6q_1$$

so

$$p_1 \frac{1}{11p_6} + p_6 \frac{1}{11p_1} \leq \frac{1}{11}$$

i.e.,

$$\frac{p_1}{p_6} + \frac{p_6}{p_1} \leq 1.$$

Now, if we let $x = \frac{p_1}{p_6}$, then we have

$$x + \frac{1}{x} \leq 1$$

which is impossible, since for positive real x , $x + \frac{1}{x} \geq 2$. Thus, no such dice are possible.

An identical proof shows that this is an impossibility regardless of the number of sides of the dice.

18. *Suppose that we renumber four fair 6-sided dice (A, B, C, D) as follows: $A = \{0, 0, 4, 4, 4, 4\}, B = \{1, 1, 1, 5, 5, 5\}, C = \{2, 2, 2, 2, 6, 6\}, D = \{3, 3, 3, 3, 3, 3\}$.*

(a) *Find the probability that die A beats die D ; die D beats die C ; die C beats die B ; and die B beats die A .*

(b) Discuss.

19. Find every six-sided die with sides numbered from the set $\{1,2,3,4,5,6\}$ such that rolling the die twice and summing the values yields all values between 2 and 12 (inclusive). For instance, the die numbered 1,2,4,5,6,6 is one such die. Consider the sum probabilities of these dice. Do any of them give sum probabilities that are "more uniform" than the sum probabilities for a standard die? What if we renumber two dice differently - can we get a uniform (or more uniform than standard) sum probability?

The numbers 1, 2, 5 and 6 must always be among the numbers on the die, else sums of 2, 3, 11 and 12 would not be possible. In order to get a sum of 5, either 3 or 4 must be on the die also. The last place on the die can be any value in $\{1,2,3,4,5,6\}$. Hence there are 11 dice with the required property. Listed with their corresponding error, they are:

1,2,4,5,6,6	0.0232884399551066
1,2,4,5,5,6	0.0325476992143659
1,2,4,4,5,6	0.0294612794612795
1,2,3,5,6,6	0.0232884399551066
1,2,3,5,5,6	0.026374859708193
1,2,3,4,5,6	0.0217452300785634
1,2,3,3,5,6	0.0294612794612795
1,2,2,4,5,6	0.026374859708193
1,2,2,3,5,6	0.0325476992143659
1,1,2,4,5,6	0.0232884399551066
1,1,2,3,5,6	0.0232884399551066

The error here is the sum of the square of the difference between the actual probability of rolling each of the sums 2 through 12 and $1/11$ (the probability we would have for each sum if we had a uniform distribution). That is, if p_i is the probability of rolling a sum of i with this die, then the error is

$$\sum_{i=2}^{12} (p_i - \frac{1}{11})^2.$$

Note that the standard die gives the smallest error (i.e., the closest to uniform sum).

If we renumber two dice differently, many more cases are possible. One pair of dice are 1,3,4,5,6,6 and 1,2,2,5,6,6. These two dice give all sum values between 2 and 12, with an error (as above) of 0.018658810325477, more uniform than the standard dice. The best dice for near-uniformity are 1,2,3,4,5,6 and 1,1,1,6,6,6 which yield all the sums from 2 to 12 with near equal probability: the probability of rolling 7 is $1/6$ and all other sums are $1/12$. The error is $5/792$, or about 0.00631.

3.4 Games with Dice

20. **Craps** What is the probability of winning a round of the game Craps?

The probability of winning a round of craps can be expressed as

$$P(\text{rolling 7 or 11}) + \sum_{b \in \{4,5,6,8,9,10\}} P(\text{rolling } b)P(\text{rolling } b \text{ again before rolling 7}).$$

We now evaluate each probability. The probability of rolling 7 is $\frac{6}{36} = \frac{1}{6}$, and the probability of rolling 11 is $\frac{2}{36} = \frac{1}{18}$. Hence,

$$P(\text{rolling 7 or 11}) = \frac{6}{36} + \frac{2}{36} = \frac{2}{9}.$$

The following table gives the probability of rolling b , for $b \in \{4, 5, 6, 8, 9, 10\}$. (This is the probability of b becoming the “point”.)

4	$3/36 = 1/12$
5	$4/36 = 1/9$
6	$5/36$
8	$5/36$
9	$4/36 = 1/9$
10	$3/36 = 1/12$

Finally, we need to determine the probability of rolling b before rolling 7. Let p be the probability of rolling b on any single roll. Rolling b before rolling 7 involves rolling some number of rolls, perhaps zero, which are not b or 7, followed by a roll of b . The probability of rolling k rolls which are not b or 7, followed by a roll of b is

$$\left(1 - p - \frac{1}{6}\right)^k p = \left(\frac{5}{6} - p\right)^k p.$$

Since k may be any non-negative integer value, we have

$$P(\text{rolling } b \text{ before rolling } 7) = \sum_{k=0}^{\infty} \left(\frac{5}{6} - p\right)^k p = \frac{p}{\frac{1}{6} + p}.$$

See Appendix B for some formulas for simplifying series such as the one above. Another way of looking at this is that the probability of rolling b before rolling a 7 is the conditional probability of rolling b , given that either b or 7 was rolled.

We can calculate the following table:

b	$P(\text{rolling } b)$	$P(\text{rolling } b \text{ again before rolling } 7)$	$P(\text{rolling } b)P(\text{rolling } b \text{ again before rolling } 7)$
4	$1/12$	$1/3$	$1/36$
5	$1/9$	$2/5$	$2/45$
6	$5/36$	$5/11$	$25/396$
8	$5/36$	$5/11$	$25/396$
9	$1/9$	$2/5$	$2/45$
10	$1/12$	$1/3$	$1/36$

Thus, the probability of winning a round of craps is

$$\frac{2}{9} + \frac{1}{36} + \frac{2}{45} + \frac{25}{396} + \frac{25}{396} + \frac{2}{45} + \frac{1}{36} = \frac{244}{495} = 0.4929.$$

Since $\frac{244}{495} = \frac{1}{2} - \frac{7}{990}$, the odds are just slightly against the player.

21. **Non-Standard Craps** We can generalize the games of craps to allow dice with other than six sides. Suppose we use two (fair) n -sided dice. Then we can define a game analagous to craps in the following way. The player rolls two n -sided dice. If the sum of these dice is $n + 1$ or $2n - 1$, the player wins. If the sum of these dice is 2, 3 or $2n$ the player loses. Otherwise the sum becomes the player’s point, and they win if they roll that sum again before rolling $n + 1$. We may again ask: what is the player’s probability of winning?

22. **Yahtzee** There are many probability questions we may ask with regard to the game of Yahtzee. For starters, what is the probability of rolling, in a single roll,

- a) Yahtzee
- b) Four of a kind (but not Yahtzee)
- c) A full house
- d) Three of a kind (but not Yahtzee, four of a kind or full house)
- e) A long straight
- f) A small straight

These questions aren't *too* tricky, so I'll just give the probabilities here:

(a) Yahtzee: $\frac{6}{6^5} = \frac{1}{1296} \approx 0.07716\%$

(b) Four of a kind (but not Yahtzee): $\frac{\binom{5}{4} \cdot 6 \cdot 5}{6^5} = \frac{25}{1296} \approx 1.929\%$

(c) A full house: $\frac{\binom{5}{3} \cdot 6 \cdot 5}{6^5} = \frac{25}{648} \approx 3.858\%$

(d) Three of a kind (but not Yahtzee, four of a kind or full house) :

$$\frac{\binom{5}{3} \cdot 6 \cdot 5 \cdot 4}{6^5} = \frac{25}{162} \approx 15.432\% \quad (3.8)$$

(e) A long straight: $\frac{2 \cdot 5!}{6^5} = \frac{5}{162} \approx 3.086\%$

(f) A small straight (but not a long straight):

$$\frac{2(4! \cdot (6-1) \cdot 5) + 4! \cdot (6-2) \cdot 5}{6^5} = \frac{1680}{6^5} = \frac{35}{162} \approx 21.60\%. \quad (3.9)$$

23. **More Yahtzee** What is the probability of getting Yahtzee, assuming that we are trying just to get Yahtzee, we make reasonable choices about which dice to re-roll, and we have three rolls? That is, if we're in the situation where all we have left to get in a game of Yahtzee is Yahtzee, so all other outcomes are irrelevant.

This is quite a bit trickier than the previous questions on Yahtzee. The difficulty here lies in the large number of ways that one can reach Yahtzee: roll it on the first roll; roll four of a kind on the first roll and then roll the correct face on the remaining die, etc. One way to calculate the probability is to treat the game as a *Markov chain* (see Appendix D for general information on Markov chains).

We consider ourselves in one of five *states* after each of the three rolls. We will say that we are in state b if we have b common dice among the five. For example, if a roll yields 12456, we'll be in state 1; if a roll yields 11125, we'll be in state 3. Now, the goal in Yahtzee is to try to get to state 5 in three rolls (or fewer). Each roll gives us a chance to change from our initial state to a better, or equal, state. We can determine the probabilities of changing from state i to state j . Denote this probability by $P_{i,j}$. Let the 0 state refer to the initial state before rolling. Then we have the following probability matrix:

$$P = (P_{i,j}) = \begin{pmatrix} 0 & \frac{120}{1296} & \frac{900}{1296} & \frac{250}{1296} & \frac{25}{1296} & \frac{1}{1296} \\ 0 & \frac{120}{1296} & \frac{900}{1296} & \frac{250}{1296} & \frac{25}{1296} & \frac{1}{1296} \\ 0 & 0 & \frac{120}{216} & \frac{80}{216} & \frac{15}{216} & \frac{1}{216} \\ 0 & 0 & 0 & \frac{25}{36} & \frac{10}{36} & \frac{1}{36} \\ 0 & 0 & 0 & 0 & \frac{5}{6} & \frac{1}{6} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (3.10)$$

The one representing $P_{5,5}$ indicates that if we reach yahtzee, state 5, before the third roll, we simply stay in that state. Now, the probability of being in state 5 after 3 rolls is given by

$$\sum P_{0,i_1} P_{i_1,i_2} P_{i_2,5} = (M^3)_{1,5}$$

where the sum is over all triples (i_1, i_2, i_3) with $0 \leq i_j \leq 5$. Calculating M^3 gives us the probability

$$\frac{2783176}{6^{10}} = \frac{347897}{7558272} \approx 0.04603.$$

Since $\frac{347897}{7558272} = \frac{1}{21} - \frac{347897}{7558272}$, a player will get Yahtzee about once out of every twenty-one attempts.

24. Drop Dead

- (a) What is the expected value of a player's score?
 (b) What is the probability of getting a score of 0? 1? 10? 20? etc.

(a) The player begins with five dice, and throws them repeatedly, until no dice are left. The key factor in calculating the expected score is the fact that the number of dice being thrown changes. When throwing n dice, a certain number may "die" (i.e. come up 2 or 5), and leave j non-dead dice. The probability of this occurring is

$$P_{n,j} = \binom{n}{n-j} \frac{2^{n-j} 4^j}{6^n}.$$

The following table gives $P_{n,j}$ for n and j between 0 and 5.

$n \setminus j$	0	1	2	3	4	5
1	1/3	2/3	0	0	0	0
2	1/9	4/9	4/9	0	0	0
3	1/27	6/27	12/27	8/27	0	0
4	1/81	8/81	24/81	32/81	16/81	0
5	1/243	10/243	40/243	80/243	80/243	32/243

When throwing n dice, the expected sum is $3.5n$, if none of the dice come up 2 or 5. Let $E(n)$ represent the expected score starting with n dice (so we're ultimately concerned with $E(5)$). Consider $E(1)$. Rolling a single die, the expected score is

$$E(1) = 3.5P_{1,1} + E(1)P_{1,1}.$$

That is, in one roll, we pick up 3.5 points, on average, if we don't "drop dead" (so we get $3.5P_{1,1}$ expected points), and then we're in the same position as when we started (so we pick up $E(1)P_{1,1}$ expected points). We can solve this equation to get

$$E(1) = 3 \cdot \left(\frac{2}{3}\right) \left(\frac{7}{2}\right) = 7.$$

Now, suppose we start with 2 dice. The expected score is

$$E(2) = (2 \cdot 3.5 + E(2)) P_{2,2} + E(1)P_{2,1}.$$

That is, on a single roll, we pick up $2 \cdot 3.5$ points on average if none of the dice “die”, in which case we’re back where we started from (and then expect to pick up $E(2)$ points), *or* exactly one of the dice “die”, and so we expect to pick up $E(1)$ points with the remaining die. This equation yields

$$E(2) = \frac{1}{1 - P_{2,2}} (7P_{2,2} + E(1)P_{2,1}) = \frac{56}{5}.$$

Continuing in this way, we have the general equation

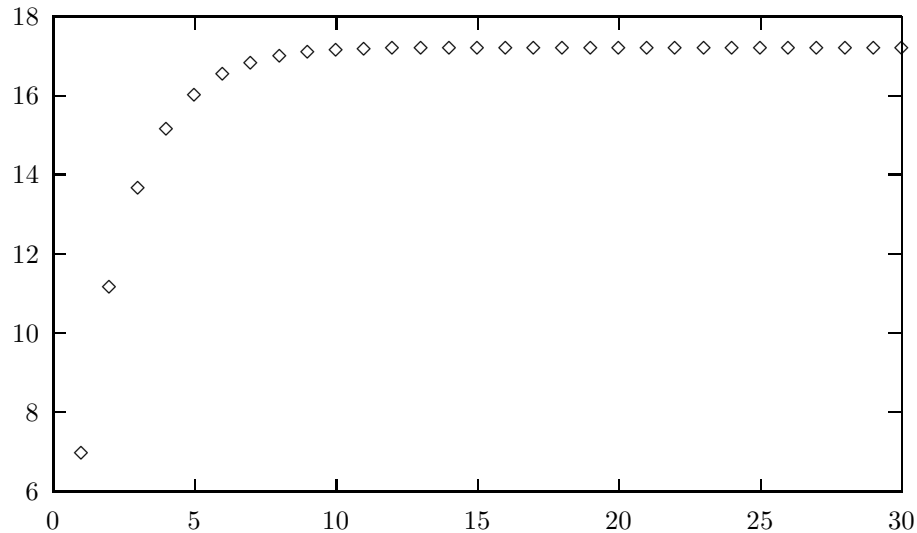
$$E(n) = 3.5 \cdot n \cdot P_{n,n} + \sum_{j=1}^n E(j)P_{n,j}$$

which we can rewrite as

$$E(n) = \frac{1}{1 - P_{n,n}} \left(3.5 \cdot n \cdot P_{n,n} + \sum_{j=1}^{n-1} E(j)P_{n,j} \right)$$

With this formula, we can calculate $E(n)$ for whatever value of n we want. Here is a table of $E(n)$:

n	$E(n)$
1	7
2	$\frac{56}{5} = 11.2$
3	$\frac{1302}{95} \approx 13.70526$
4	$\frac{3752}{247} \approx 15.19028$
5	$\frac{837242}{52117} \approx 16.06466$
6	$\frac{4319412}{260585} \approx 16.57583$
10	$\frac{9932935945754444}{577645434482545} \approx 17.19556$
20	≈ 17.26399
30	$\approx 17.26412371400800701809841213$
100	$\approx 17.26412423601867057324993502$
250	$\approx 17.26412422187783220247082379$



So we see that a game of Drop Dead, using 5 dice, will have, on average, a score of about 16.06.

Further questions: Notice that if we play the game with more than 5 dice, the expected score does not increase very much. In fact, it appears as if there is an *upper bound* on the expected score; that is, it seems that there is some B so that $E(n) < B$ for all n . What is the smallest possible value for B ? Also, we expect $E(n)$ to always increase as n increases. Can we prove this is so?

(b) Calculating the exact probabilities of scores seems to be a bit of a pain. The easiest score to work out is zero. To get zero, the player must roll at least one 2 or 5 on every roll. If we define a Markov process, with states 0, F, 5, 4, 3, 2, 1 (in that order), where 0 means a score of zero has been achieved, F means a score greater than 0 has been achieved, and 5 through 1 are the current number of dice being rolled, we have the following transition matrix:

$$P_0 = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{243} & \frac{32}{243} & 0 & \frac{80}{243} & \frac{80}{243} & \frac{40}{243} & \frac{10}{243} \\ \frac{1}{81} & \frac{16}{81} & 0 & 0 & \frac{32}{81} & \frac{8}{27} & \frac{8}{81} \\ \frac{1}{27} & \frac{2}{27} & 0 & 0 & 0 & \frac{4}{9} & \frac{2}{9} \\ \frac{1}{9} & \frac{1}{9} & 0 & 0 & 0 & 0 & \frac{4}{9} \\ \frac{1}{3} & \frac{2}{3} & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

Since the game takes at most five rolls, the fifth power of this matrix tells us what we want to know:

$$P_0^5 = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ \frac{978853}{4782969} & \frac{3804116}{4782969} & 0 & 0 & 0 & 0 & 0 \\ \frac{4163}{19683} & \frac{15520}{19683} & 0 & 0 & 0 & 0 & 0 \\ \frac{55}{243} & \frac{188}{243} & 0 & 0 & 0 & 0 & 0 \\ \frac{7}{27} & \frac{20}{27} & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{3} & \frac{2}{3} & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

Thus we see that the probability of achieving a score of zero is $\frac{978853}{4782969} = \frac{978853}{3^{14}}$, which is about 0.2046538457598....

The probability of achieving a score of 1 is calculatable in a similar way. Our transition matrix is

$$P_1 = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{11}{81} & 0 & \frac{80}{243} & \frac{80}{243} & \frac{40}{243} & \frac{10}{243} \\ 0 & \frac{17}{81} & 0 & 0 & \frac{32}{81} & \frac{8}{27} & \frac{8}{81} \\ 0 & \frac{1}{3} & 0 & 0 & 0 & \frac{4}{9} & \frac{2}{9} \\ 0 & \frac{5}{9} & 0 & 0 & 0 & 0 & \frac{4}{9} \\ \frac{1}{18} & \frac{17}{18} & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

A note on this lower-left most entry: once the player has only one die left, they have a 1/6 chance of rolling a one; but then, the die must die, which occurs with probability 1/3. Hence the 1/18 probability of getting a score of 1 after the state of one die is attained.

Raising this matrix to the fifth power yields

$$P_1^5 = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ \frac{305285}{14348907} & \frac{4477684}{4782969} & 0 & 0 & 0 & 0 & 0 \\ \frac{1300}{59049} & \frac{18383}{19683} & 0 & 0 & 0 & 0 & 0 \\ \frac{17}{729} & \frac{226}{243} & 0 & 0 & 0 & 0 & 0 \\ \frac{2}{81} & \frac{25}{27} & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{18} & \frac{17}{18} & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

and thus the probability of a score of 1 in this game is $305285/14348907 = 0.0212758365497804118\dots$

Scores higher than 1 are more difficult, since it will not be necessary to reach a single die. On the other hand, to achieve a score of n , there can be at most $n + 4$ rolls, so the problem is finite. Appendix F has experimental data for comparison to any exact calculations you might attempt.

25. Suppose we play a game with a die where we roll and sum our rolls as long as we keep rolling larger values. For instance, we might roll a sequence like 1-3-4 and then roll a 2, so our sum would be 8. If we roll a 6 first, then we're through and our sum is 6. Three questions about this game:

- (a) What is the expected value of the sum?
- (b) What is the expected value of the number of rolls?
- (c) If the game is played with an n -sided die, what happens to the expected number of rolls as n approaches infinity?

We can consider this game as a Markov chain with an absorbing state. If we consider the state to be the value of the latest roll, or 0 if the latest roll is not larger than the previous one, then we have the following transition matrix:

$$P = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1/6 & 0 & 1/6 & 1/6 & 1/6 & 1/6 & 1/6 \\ 2/6 & 0 & 0 & 1/6 & 1/6 & 1/6 & 1/6 \\ 3/6 & 0 & 0 & 0 & 1/6 & 1/6 & 1/6 \\ 4/6 & 0 & 0 & 0 & 0 & 1/6 & 1/6 \\ 5/6 & 0 & 0 & 0 & 0 & 0 & 1/6 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad (3.11)$$

Using the notation of Appendix D, we have

$$Q = \begin{pmatrix} 0 & 1/6 & 1/6 & 1/6 & 1/6 & 1/6 \\ 0 & 0 & 1/6 & 1/6 & 1/6 & 1/6 \\ 0 & 0 & 0 & 1/6 & 1/6 & 1/6 \\ 0 & 0 & 0 & 0 & 1/6 & 1/6 \\ 0 & 0 & 0 & 0 & 0 & 1/6 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

so that $N = (I - Q)^{-1}$ is

$$N = \begin{pmatrix} 1 & 1/6 & 7/36 & 49/216 & 343/1296 & 2401/7776 \\ 0 & 1 & 1/6 & 7/36 & 49/216 & 343/1296 \\ 0 & 0 & 1 & 1/6 & 7/36 & 49/216 \\ 0 & 0 & 0 & 1 & 1/6 & 7/36 \\ 0 & 0 & 0 & 0 & 1 & 1/6 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

The row sum of N is

$$\begin{pmatrix} 16807/7776 \\ 2401/1296 \\ 343/216 \\ 49/36 \\ 7/6 \\ 1 \end{pmatrix}$$

and so the expected number of rolls before absorption (i.e., the number of rolls that count in the sum) is

$$(1/6)(16807/7776 + 2401/1296 + 343/216 + 49/36 + 7/6 + 1) = 70993/7776 \approx 1.521626.$$

We use N to calculate the expected sum as well. If the first roll is a 1, the expected sum will be

$$1 + 2 \cdot \frac{1}{6} + 3 \cdot \frac{7}{36} + 4 \cdot \frac{49}{216} + 5 \cdot \frac{343}{1296} + 6 \cdot \frac{2401}{7776} = 6.$$

In fact, for any first roll, the expected sum is 6. Hence, the expected sum is 6.

Now, suppose the game is played with an n -sided die. Let E be the expected number of rolls. Let $E(j)$ be the expected number of rolls if the first roll is j . Then,

$$E(j) = 1 + \frac{1}{n}E(j+1) + \frac{1}{n}E(j+2) + \cdots + \frac{1}{n}E(n)$$

and so

$$E(j+1) = 1 + \frac{1}{n}E(j+2) + \frac{1}{n}E(j+3) + \cdots + \frac{1}{n}E(n)$$

from which we can conclude

$$E(j) = \left(1 + \frac{1}{n}\right) E(j+1).$$

Since $E(n) = 1$, we have

$$E(j) = \left(1 + \frac{1}{n}\right)^{n-j}.$$

Thus,

$$\begin{aligned} E &= \frac{1}{n} \sum_{j=1}^n E(j) = \frac{1}{n} \sum_{j=1}^n \left(1 + \frac{1}{n}\right)^{n-j} = \frac{1}{n} \left(\frac{n+1}{n}\right)^n \sum_{j=1}^n \left(\frac{n}{n+1}\right)^j \\ &= \left(\frac{n+1}{n}\right)^n \left(1 - \left(\frac{n}{n+1}\right)^n\right) = \left(\frac{n+1}{n}\right)^n - 1. \end{aligned}$$

And so we see that

$$\lim_{n \rightarrow \infty} E = e - 1 = 1.718281828459\dots$$

26. Suppose we play a game with a die in which we use two rolls of the die to create a two digit number. The player rolls the die once and decides which of the two digits they want that roll to represent. Then, the player rolls a second time and this determines the other digit. For instance, the player might roll a 5, and decide this should be the "tens" digit, and then roll a 6, so their resulting number is 56.

What strategy should be used to create the largest number on average? What about the three digit version of the game?

A strategy in this game is merely a rule for deciding whether the first roll should be the "tens" digit or the "ones" digit. If the first roll is a 6, then it must go in the "tens" digit, and if it's a 1, then it must go in the "ones" digit. This leaves us with what to do with 2,3,4 and 5. If the first roll is b , then using it as the "ones" digit results in an expected number of $\frac{7}{2} \cdot 10 + b$. Using it as the "tens" digit results in an expected number of $10b + \frac{7}{2}$. So, when is $10b + \frac{7}{2} > \frac{7}{2} \cdot 10 + b$? When $b \geq 4$. Thus, if the first roll is 4, 5 or 6, the player should use it for the "tens" digit. With this strategy, the expected value of the number is

$$\frac{1}{6}(63.5 + 53.5 + 43.5 + 38 + 37 + 36) = 45.25.$$

In the three-digit version of the game, once we have decided what to do with the first roll, we'll be done, since we will then be in the two-digit case which we solved above. Note this is obviously true if we place the first roll in the "hundreds" digit. If we place the first roll in the "ones" digit, then the strategy to maximize the resulting number is the same as the two-digit case, simply multiplied by a factor of ten. If we place the first roll in the "tens" digit, then our strategy is to put the next roll b in the "hundreds" digit if

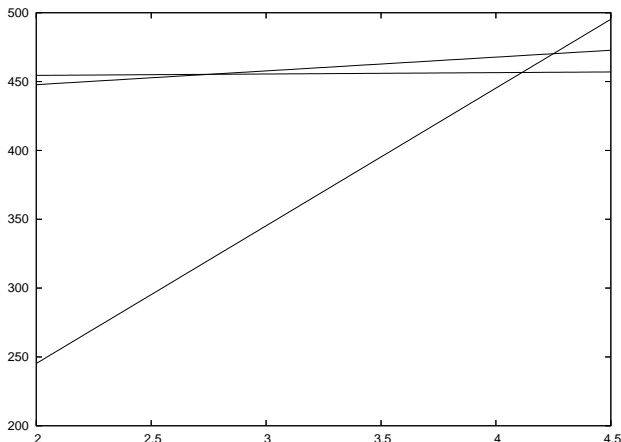
$$100b + 3.5 > 350 + b$$

i.e., if $b \geq 4$. Thus we have the same strategy in all three cases: put the second roll in the largest digit if it is at least 4.

Now, if the first roll, b , is placed in the "hundreds" digit, then the expected value will be $100b + 45.25$. If the first roll is placed in the "ones" digit, then the expected value will be $452.5 + b$. If the first roll is placed in the "tens" digit, then the expected value will be

$$10b + (351 + 352 + 353 + 403.5 + 503.5 + 603.5)/6 = 427.75 + 10b.$$

Our strategy thus comes down to maximizing the quantities $100b + 45.25$, $427.75 + 10b$, and $452.5 + b$. From the graph below, we see that $100b + 45.25$ is the largest when $b \geq 5$; $427.75 + 10b$ is largest when $3 \leq b \leq 4$, and $452.5 + b$ is largest when $b < 3$. Thus our strategy for the first roll is this: if it is at least 5, put it in the "hundreds" digit; if it is 3 or 4, put it in the "tens" digit; otherwise, put it in the ones digit. If the second roll is 4, 5, or 6, place it in the largest available digit.



The expected value using this strategy is thus

$$(645.25 + 545.25 + (40 + 427.75) + (30 + 427.75) + (452.5 + 2) + (452.5 + 1))/6 = 504.$$

Chapter 4

Problems for the future

Here are some problems that I intend to add to this collection some time in the future, as soon as I get around to writing decent solutions.

1. the game of Threes (see wikipedia). Best strategy for minimal score?
2. more drop dead: probability of getting zero? probability of any particular value?
3. If a die is rolled 100 times (say), what is the probability that all six sides have appeared at least one?
If a die is rolled 100 times (say), what is the probability that there is a run of 6 that has all six possible faces? What about a run of 10 with all six faces at least once?
4. A die is rolled repeatedly and summed. What is the expected number of rolls until the sum is:
 - (a) a prime? Experimentally it appears to be around 2.432211 (one million trials).
 - (b) a power of 2? Hmmmm...
 - (c) a multiple of n ? The answer appears to be n .
5. For every composite n , there appear to pairs of "weird" dice with n sides (i.e. a pair of dice not numbered in the usual way with sum probabilities equal to the standard dice). Prove this. For many n , there are many such pairs. Give useful bounds on the number of such pairs in terms of n .

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Appendix A

Dice sum probabilities

Sums of 2, 6-Sided Dice

Sum	Probability
2	$1/36$
3	$2/36 = 1/18$
4	$3/36 = 1/12$
5	$4/36 = 1/9$
6	$5/36$
7	$6/36 = 1/6$
8	$5/36$
9	$4/36 = 1/9$
10	$3/36 = 1/12$
11	$2/36 = 1/18$
12	$1/36$

Sums of 3, 6-Sided Dice

Sum	Probability
3	$1/216$
4	$3/216 = 1/72$
5	$6/216 = 1/36$
6	$10/216 = 5/108$
7	$15/216 = 5/72$
8	$21/216 = 7/72$
9	$25/216$
10	$27/216 = 1/8$
11	$27/216 = 1/8$
12	$25/216$
13	$21/216 = 7/72$
14	$15/216 = 5/72$
15	$10/216 = 5/108$
16	$6/216 = 1/36$
17	$3/216 = 1/72$
18	$1/216 = 1/216$

Appendix B

Handy Series Formulae

For $|r| < 1$,

$$\sum_{n=0}^{\infty} ar^n = \frac{a}{1-r} \quad (\text{B.1})$$

For $|r| < 1$,

$$\sum_{n=0}^N ar^n = \frac{a(1-r^{N+1})}{1-r} \quad (\text{B.2})$$

For $|r| < 1$

$$\sum_{n=1}^{\infty} nr^n = \frac{r}{(1-r)^2} \quad (\text{B.3})$$

For $|r| < 1$

$$\sum_{n=1}^N nr^n = \frac{r(1-r^N(1+N-Nr))}{(1-r)^2} \quad (\text{B.4})$$

Appendix C

Dice Sums and Polynomials

Very often in mathematics a good choice of notation can take you a long way. An example of this is the following method for representing sums of dice. Suppose we have an n -sided die, with sides $1, 2, \dots, n$ that appear with probability p_1, p_2, \dots, p_n , respectively. Then, if we roll the die twice and add the two rolls, the probability that the sum is k is given by

$$\sum_{j=1}^n p_j p_{k-j} = \sum_{j=k-1}^{n-k} p_j p_{k-j} \quad (\text{C.1})$$

if we say $p_i = 0$ if $i < 1$ or $i > n$.

Now consider the following polynomial:

$$P = p_1 x + p_2 x^2 + \dots + p_n x^n \quad (\text{C.2})$$

If we square P , we get

$$P^2 = a_2 x^2 + a_3 x^3 + \dots + a_{2n} x^{2n} \quad (\text{C.3})$$

where a_k , for $k=2, 3, \dots, 2n$, is given by

$$a_k = \sum_{j=k-1}^{n-k} p_j p_{k-j}. \quad (\text{C.4})$$

In other words, the probability of rolling the sum of k is the same as the coefficient of x^k in the polynomial given by squaring the polynomial P .

Here's an example. Suppose we consider a standard 6-sided die. Then

$$P = \frac{1}{6}x + \frac{1}{6}x^2 + \frac{1}{6}x^3 + \frac{1}{6}x^4 + \frac{1}{6}x^5 + \frac{1}{6}x^6 \quad (\text{C.5})$$

and so

$$P^2 = \frac{x^2}{36} + \frac{2x^3}{36} + \frac{3x^4}{36} + \frac{4x^5}{36} + \frac{5x^6}{36} + \frac{6x^7}{36} + \frac{5x^8}{36} + \frac{4x^9}{36} + \frac{3x^{10}}{36} + \frac{2x^{11}}{36} + \frac{x^{12}}{36} \quad (\text{C.6})$$

$$= \frac{x^2}{36} + \frac{x^3}{18} + \frac{x^4}{12} + \frac{x^5}{9} + \frac{5x^6}{36} + \frac{x^7}{6} + \frac{5x^8}{36} + \frac{x^9}{9} + \frac{x^{10}}{12} + \frac{x^{11}}{18} + \frac{x^{12}}{36} \quad (\text{C.7})$$

And so, we see that the probability of rolling a sum of 9, for instance, is $1/9$.

For two different dice the method is the same. For instance, if we roll a 4-sided die, and a 6-sided die, and sum them, the probability that the sum is equal to k is given by the coefficient on x^k in the polynomial

$$\left(\frac{x}{4} + \frac{x^2}{4} + \frac{x^3}{4} + \frac{x^4}{4} \right) \left(\frac{x}{6} + \frac{x^2}{6} + \frac{x^3}{6} + \frac{x^4}{6} + \frac{x^5}{6} + \frac{x^6}{6} \right) \quad (\text{C.8})$$

which, when expanded, is

$$\frac{x^2}{24} + \frac{x^3}{12} + \frac{x^4}{8} + \frac{x^5}{6} + \frac{x^6}{6} + \frac{x^7}{6} + \frac{x^8}{8} + \frac{x^9}{12} + \frac{x^{10}}{24}. \quad (\text{C.9})$$

Notice that this can be written as

$$\frac{1}{24} (x^2 + 2x^3 + 3x^4 + 4x^5 + 4x^6 + 4x^7 + 3x^8 + 2x^9 + x^{10}) \quad (\text{C.10})$$

In general, a fair n -sided die can be represented by the polynomial

$$\frac{1}{n} (x + x^2 + x^3 + \cdots + x^n) \quad (\text{C.11})$$

With this notation, many questions about dice sums can be transformed into equivalent questions about polynomials. For instance, asking whether or not there exist other pairs of dice that give the same sum probabilities as a pair of standard dice is the same as asking: in what ways can the polynomial

$$(x + x^2 + x^3 + x^4 + \dots + x^n)^2 \quad (\text{C.12})$$

be factored into two polynomials (with certain conditions on the degrees and coefficients of those polynomials)?

Appendix D

Markov Chain Facts

A *Markov chain* is a mathematical model for describing a process that moves in a sequence of steps through a set of states. A finite Markov chain has a finite number of states, $\{s_1, s_2, \dots, s_n\}$. When the process is in state s_i , there is a probability p_{ij} that the process will next be in state s_j . The matrix $P = (p_{ij})$ is called the *transition matrix* for the Markov chain. Note that the rows of the matrix sum to 1.

The ij -th entry of P^k (i.e. the k -th power of the matrix P) gives the probability of the process moving from state i to state j in exactly k steps.

An *absorbing state* is one which the process can never leave once it is entered. An *absorbing chain* is a chain which has at least one absorbing state, and starting in any state of the chain, it is possible to move to an absorbing state. In an absorbing chain, the process will eventually end up in an absorbing state.

Let P be the transition matrix of an absorbing chain. By renumbering the states, we can always rearrange P into *canonical form*:

$$P = \left(\begin{array}{c|c} J & O \\ \hline R & Q \end{array} \right)$$

where J is an identity matrix (with 1's on the diagonal and 0's elsewhere) and O is a matrix of all zeros. Q and R are non-negative matrices that arise from the transition probabilities between non-absorbing states.

The series $N = I + Q + Q^2 + Q^3 + \dots$ converges, and $N = (I - Q)^{-1}$. The matrix N gives us important information about the chain, as the following theorem shows.

Theorem 1 Let P be the transition matrix for an absorbing chain in canonical form. Let $N = (I - Q)^{-1}$. Then:

- The ij -th entry of N is the expected number of times that the chain will be in state j after starting in state i .
- The sum of the i -th row of N gives the mean number of steps until absorption when the chain is started in state i .
- The ij -th entry of the matrix $B = NR$ is the probability that, after starting in non-absorbing state i , the process will end up in absorbing state j .

An *ergodic chain* is one in which it is possible to move from any state to any other state (though not necessarily in a single step).

A *regular chain* is one for which some power of its transition matrix has no zero entries. A regular chain is therefore ergodic, though not all ergodic chains are regular.

Theorem 2 Suppose P is the transition matrix of an ergodic chain. Then there exists a matrix A such that

$$\lim_{k \rightarrow \infty} \frac{P + P^2 + P^3 + \dots + P^k}{k} = A$$

For regular chains,

$$\lim_{k \rightarrow \infty} P^k = A.$$

The matrix A has each row the same vector $\mathbf{a} = (a_1, a_2, \dots, a_n)$. One way to interpret this is to say that the long-term probability of finding the process in state i does not depend on the initial state of the process.

The components a_1, a_2, \dots, a_n are all positive. The vector \mathbf{a} is the unique vector such that

$$a_1 + a_2 + \dots + a_n = 1$$

and

$$\mathbf{a}P = \mathbf{a}$$

For this reason, \mathbf{a} is sometimes called the *fixed point probability vector*.

The following theorem is sometimes called the *Mean First Passage Theorem*.

Theorem 3 Suppose we have a regular Markov chain, with transition matrix P . Let $E = (e_{ij})$ be a matrix where, for $i \neq j$, e_{ij} is the expected number of steps before the process enters state j for the first time after starting in state i , and e_{ii} is the expected number of steps before the chain re-enters state i . Then

$$E = (I - Z + JZ')D$$

where $Z = (I - P - A)^{-1}$, $A = \lim_{k \rightarrow \infty} P^k$, Z' is the diagonal matrix whose diagonal entries are the same as Z , J is the matrix of all 1's, and D is a diagonal matrix with $D_{ii} = 1/A_{ii}$.

Appendix E

Linear Recurrence Relations

Here's a useful theorem:

Theorem 1 Consider the linear recurrence relation

$$x_n = a_1x_{n-1} + a_2x_{n-2} + \cdots + a_k = 0 \quad (\text{E.1})$$

If the polynomial equation

$$x^n - a_1x^{n-1} - a_2x^{n-2} - \cdots - a_k = 0 \quad (\text{E.2})$$

has k distinct roots r_1, \dots, r_k , then the recurrence relation E.1 has as a general solution

$$x_n = c_1r_1^n + c_2r_2^n + \cdots + c_kr_k^n. \quad (\text{E.3})$$

Proof: We can prove this with a bit of linear algebra, but we'll do that some other time.

Example: May as well do the old classic. The Fibonacci numbers are defined by

$$f_0 = 1, f_1 = 1, \text{ and } f_n = f_{n-1} + f_{n-2} \text{ for } n > 1.$$

The characteristic equation is

$$x^2 - x - 1 = 0$$

which has roots

$$r_1 = \frac{1 + \sqrt{5}}{2} \text{ and } r_2 = \frac{1 - \sqrt{5}}{2}.$$

So

$$f_n = A \left(\frac{1 + \sqrt{5}}{2} \right)^n + B \left(\frac{1 - \sqrt{5}}{2} \right)^n$$

for constants A and B . Since

$$f_0 = 1 = A + B$$

and

$$f_1 = 1 = A + B + \frac{\sqrt{5}}{2}(A - B)$$

we conclude that

$$A = \frac{1 + \sqrt{5}}{2\sqrt{5}} \text{ and } B = \frac{-1 + \sqrt{5}}{2\sqrt{5}}$$

so that

$$f_n = \frac{(1 + \sqrt{5})^{n+1} - (1 - \sqrt{5})^{n+1}}{2^{n+1}\sqrt{5}}.$$

Appendix F

Drop Dead Simulation Data

In 10^7 simulated games of Drop Dead, the following frequencies of scores were achieved.

score (n)	number of games with score n	number of games with score $\leq n$
0	2044719	2044719
1	212885	2257604
2	69266	2326870
3	226785	2553655
4	353402	2907057
5	180453	3087510
6	338023	3425533
7	335320	3760853
8	220094	3980947
9	258632	4239579
10	321143	4560722
11	233060	4793782
12	259303	5053085
13	257301	5310386
14	240123	5550509
15	225187	5775696
16	241364	6017060
17	223916	6240976
18	211570	6452546
19	208928	6661474
20	199351	6860825
21	184160	7044985
22	179823	7224808
23	170278	7395086
24	158398	7553484
25	150177	7703661
26	144061	7847722
27	133669	7981391
28	126951	8108342
29	120721	8229063
30	112686	8341749
31	107082	8448831
32	101481	8550312
33	95625	8645937
34	90543	8736480
35	85022	8821502

36	80163	8901665
37	74323	8975988
38	70833	9046821
39	66156	9112977
40	61407	9174384
41	57766	9232150
42	53754	9285904
43	50170	9336074
44	47367	9383441
45	44263	9427704
46	41087	9468791
47	38652	9507443
48	35709	9543152
49	32950	9576102
50	31230	9607332
51	28709	9636041
52	26898	9662939
53	25022	9687961
54	23160	9711121
55	21400	9732521
56	19890	9752411
57	18385	9770796
58	17360	9788156
59	16018	9804174
60	14872	9819046
61	13627	9832673
62	12830	9845503
63	11798	9857301
64	10968	9868269
65	10345	9878614
66	9332	9887946
67	8584	9896530
68	8028	9904558
69	7478	9912036
70	6846	9918882
71	6220	9925102
72	5928	9931030
73	5411	9936441
74	5091	9941532
75	4660	9946192
76	4263	9950455
77	3796	9954251
78	3750	9958001
79	3401	9961402
80	3077	9964479
81	2940	9967419
82	2674	9970093
83	2455	9972548
84	2174	9974722
85	2087	9976809
86	2019	9978828
87	1701	9980529
88	1650	9982179
89	1504	9983683

90	1334
91	1234
92	1149
93	1056
94	975
95	845
96	817
97	772
98	676
99	615
100	583
101	539
102	501
103	460
104	395
105	354
106	326
107	318
108	285
109	247
110	223
111	225
112	194
113	160
114	175
115	148
116	140
117	119
118	138
119	105
120	99
121	96
122	105
123	64
124	75
125	54
126	54
127	65
128	52
129	48
130	45
131	28
132	32
133	33
134	37
135	27
136	27
137	34
138	12
139	23
140	21
141	12
142	17
143	12

9985017
9986251
9987400
9988456
9989431
9990276
9991093
9991865
9992541
9993156
9993739
9994278
9994779
9995239
9995634
9995988
9996314
9996632
9996917
9997164
9997387
9997612
9997806
9997966
9998141
9998289
9998429
9998548
9998686
9998791
9998890
9998986
9999091
9999155
9999230
9999284
9999338
9999403
9999455
9999503
9999548
9999576
9999608
9999641
9999678
9999705
9999732
9999766
9999778
9999801
9999822
9999834
9999851
9999863

144	13	9999876
145	14	9999890
146	15	9999905
147	5	9999910
148	13	9999923
149	6	9999929
150	5	9999934
151	7	9999941
152	5	9999946
153	8	9999954
154	3	9999957
155	2	9999959
156	7	9999966
157	1	9999967
158	2	9999969
159	1	9999970
160	2	9999972
161	1	9999973
162	2	9999975
163	3	9999978
164	3	9999981
165	2	9999983
166	4	9999987
167	2	9999989
170	2	9999991
172	1	9999992
174	2	9999994
175	1	9999995
177	2	9999997
178	1	9999998
181	1	9999999
192	1	1000000