

# Chapter 1

## The computation of my life

### 1.1 A very special Rolling

We want to say something about dice rolling. Consider the roll of a  $N$ -sided dice that we roll **with explosion**. This means that on a roll of  $N$ , we roll again and add the result to the previous roll. This differ from a standard roll from the fact that the potential result is theoretically unbounded (although the probability decreases as the result increases). We denote this roll as  $dN^*$ .

If we then look at the probability of rolling  $n$  on such a dice, we get

$$\mathbb{P}_N(n) = \mathbb{P}(\text{a roll of } dN^* \text{ gives } n) = \quad (1.1)$$

$$= \begin{cases} 0 & \text{if } n \text{ is a multiple of } N \\ \frac{1}{N} & \text{if } 1 \leq n \leq N - 1 \\ \frac{1}{N^2} & \text{if } N + 1 \leq n < 2N - 1 \\ \vdots & \\ \frac{1}{N^{k+1}} & \text{if } kN + 1 \leq n < (k + 1)N - 1 \\ \vdots & \end{cases} \quad (1.2)$$

$$= \sum_{k=0}^{+\infty} \frac{1}{N^{k+1}} \chi_{[kN+1, (k+1)N-1]}(n). \quad (1.3)$$

We want to understand what is the expected value as well as the variance for  $\mathbb{P}_N$ . To do that we need to remind ourselves of other computations.

### 1.1.1 Geometric series

Consider a real number  $|x| < 1$ , and the following sum:

$$S_R(x) = 1 + x + x^2 + \dots + x^R. \quad (1.4)$$

If  $x \neq 1$  (ensured by the fact that  $|x| < 1$ ), we have that

$$S_R(x) = \frac{1 - x^{R+1}}{1 - x}. \quad (1.5)$$

Using that  $|x| < 1$ , this means that as  $R$  grows,  $|x|^{R+1}$  goes to zero. So, if we perform the limit to  $R$  to infinity we get

$$\sum_{\ell=0}^{+\infty} x^\ell = \lim_{R \rightarrow +\infty} S_R(x) = \lim_{R \rightarrow +\infty} \frac{1 - x^{R+1}}{1 - x} = \frac{1}{1 - x}. \quad (1.6)$$

We want to apply this to  $X := x^{-1}$ . In this case the condition becomes  $|X| > 1$ , and in this case we get the formula:

$$\sum_{\ell=0}^{+\infty} \frac{1}{X^{\ell+1}} = \frac{1}{X - 1}. \quad (1.7)$$

We can also consider the sum starting from 1 and get

$$\sum_{\ell=1}^{+\infty} \frac{1}{X^\ell} = \frac{1}{X - 1}. \quad (1.8)$$

### 1.1.2 First and second moments of the geometric series

To compute the first two moments of the geometric series (1.8), we differentiate respect to  $X$  both sides. Differentiating the left side we get

$$\partial_X \left( \sum_{\ell=1}^{+\infty} \frac{1}{X^\ell} \right) = \sum_{\ell=1}^{+\infty} \frac{-\ell}{X^{\ell+1}} = - \sum_{\ell=2}^{+\infty} \frac{\ell-1}{X^\ell} = - \sum_{\ell=1}^{+\infty} \frac{\ell-1}{X^\ell} \quad (1.9)$$

$$= - \sum_{\ell=1}^{+\infty} \frac{\ell}{X^\ell} + \sum_{\ell=1}^{+\infty} \frac{1}{X^\ell} = - \sum_{\ell=1}^{+\infty} \frac{\ell}{X^\ell} + \frac{1}{X-1}. \quad (1.10)$$

We substitute now the definition in (1.8) to get

$$\sum_{\ell=1}^{+\infty} \frac{\ell}{X^\ell} = -\partial_X \left( \frac{1}{X-1} \right) + \frac{1}{X-1} \quad (1.11)$$

$$= \frac{1}{(X-1)^2} + \frac{1}{X-1} = \frac{X}{(X-1)^2} \quad (1.12)$$

If we differentiate again, the left term of (1.12) gives us

$$\partial_X \left( \sum_{\ell=1}^{+\infty} \frac{\ell}{X^\ell} \right) = \sum_{\ell=1}^{+\infty} \frac{-\ell^2}{X^{\ell+1}} = -\sum_{\ell=2}^{+\infty} \frac{(\ell-1)^2}{X^\ell} = -\sum_{\ell=1}^{+\infty} \frac{(\ell-1)^2}{X^\ell} \quad (1.13)$$

$$= -\sum_{\ell=1}^{+\infty} \frac{\ell^2}{X^\ell} + 2\sum_{\ell=1}^{+\infty} \frac{\ell}{X^\ell} - \sum_{\ell=1}^{+\infty} \frac{1}{X^\ell} \quad (1.14)$$

$$= -\sum_{\ell=1}^{+\infty} \frac{\ell^2}{X^\ell} + 2 \left( \frac{1}{(X-1)^2} + \frac{1}{X-1} \right) - \frac{1}{X-1} \quad (1.15)$$

$$= -\sum_{\ell=1}^{+\infty} \frac{\ell^2}{X^\ell} + \frac{2}{(X-1)^2} + \frac{1}{X-1} \quad (1.16)$$

As a consequence, the second to last term in (1.12) we get

$$\sum_{\ell=1}^{+\infty} \frac{\ell^2}{X^\ell} = -\partial_X \left( \frac{1}{(X-1)^2} + \frac{1}{X-1} \right) + \frac{2}{(X-1)^2} + \frac{1}{X-1} \quad (1.17)$$

$$= - \left( -\frac{2}{(X-1)^3} - \frac{1}{(X-1)^2} \right) + \frac{2}{(X-1)^2} + \frac{1}{X-1} \quad (1.18)$$

$$= \frac{2}{(X-1)^3} + \frac{3}{(X-1)^2} + \frac{1}{X-1} = \frac{X(X+1)}{(X-1)^3}. \quad (1.19)$$

### 1.1.3 Finite sums

One can easily find also that the following two finite sums are true (which will be useful later):

$$\sum_{\ell=1}^R 1 = R, \quad (1.20)$$

$$\sum_{\ell=1}^R \ell = \frac{R(R+1)}{2}, \quad (1.21)$$

$$\sum_{\ell=1}^R \ell^2 = \frac{R(R+1)(2R+1)}{6}. \quad (1.22)$$

## 1.2 Expected value

To calculate the expected value, we proceed with an explicit calculation:

$$\mathbb{E}_N = \sum_{n=1}^{+\infty} n \mathbb{P}_N(n) = \sum_{n=1}^{+\infty} \sum_{k=0}^{+\infty} \frac{n}{N^{k+1}} \chi_{[kN+1, (k+1)N-1]}(n) \quad (1.23)$$

$$= \sum_{m=0}^{+\infty} \sum_{j=1}^{N-1} \sum_{k=0}^{+\infty} \frac{mN+j}{N^{k+1}} \chi_{[kN+1, (k+1)N-1]}(mN+j). \quad (1.24)$$

Given that  $j$  is between 1 and  $N-1$ ,  $\chi_{[kN+1, (k+1)N-1]}(mN+j)$  is 0 if and only if  $m = k$ , otherwise is 1. As a consequence we get:

$$\mathbb{E}_N = \sum_{j=1}^{N-1} \sum_{k=0}^{+\infty} \frac{kN+j}{N^{k+1}} = \sum_{j=1}^{N-1} \left( \sum_{k=0}^{+\infty} \frac{kN}{N^{k+1}} + \sum_{k=0}^{+\infty} \frac{j}{N^{k+1}} \right) \quad (1.25)$$

$$= \sum_{j=1}^{N-1} \left( \sum_{k=1}^{+\infty} \frac{k}{N^k} + j \sum_{k=1}^{+\infty} \frac{1}{N^k} \right) = \sum_{j=1}^{N-1} \left( \frac{N}{(N-1)^2} + \frac{j}{N-1} \right) \quad (1.26)$$

$$= \frac{N}{N-1} + \frac{N}{2} = \frac{N(N+1)}{2(N-1)}. \quad (1.27)$$

For example, we get that the expected value for an exploding  $d6^*$  is  $21/5 = 4,2$ , slightly more than the one of a normal  $d6$  (which is  $3,5$ ).

## 1.3 A very special Die

Consider now this configuration: we roll a  $d6$ ; if it rolls more than 3, it counts as a 0, if it rolls a 3, we roll again and add the new result to the value of the dice, potentially rolling again or summing a 0. This new probability is

as follows:

$$\mathbb{P}_N^0(n) = \begin{cases} \frac{1}{2} & \text{if } n = 0 \\ \frac{1}{6} & \text{if } n = 1, 2 \\ \frac{1}{12} & \text{if } n = 3 \\ \frac{1}{36} & \text{if } n = 4, 5 \\ \vdots & \\ \frac{1}{2 \times 6^k} & \text{if } n = 3k \\ \frac{1}{6^{k+1}} & \text{if } n = 3k + 1, 3k + 2 \\ \vdots & \end{cases} \quad (1.28)$$

$$= \frac{1}{2} \sum_{k=0}^{+\infty} \frac{1}{6^k} \chi_{3k}(n) + \sum_{k=0}^{+\infty} \frac{1}{6^{k+1}} [\chi_{3k+1}(n) + \chi_{3k+2}(n)]. \quad (1.29)$$

We can now compute the expected value and we get

$$\mathbb{E}_N^0 = \sum_{n=0}^{+\infty} n \left[ \frac{1}{2} \sum_{k=0}^{+\infty} \frac{1}{6^k} \chi_{3k}(n) + \sum_{k=0}^{+\infty} \frac{1}{6^{k+1}} [\chi_{3k+1}(n) + \chi_{3k+2}(n)] \right] \quad (1.30)$$

$$= \frac{1}{2} \sum_{k=0}^{+\infty} \frac{3k}{6^k} + \sum_{k=0}^{+\infty} \frac{6k+3}{6^{k+1}} = \frac{3}{2} \sum_{k=0}^{+\infty} \frac{k}{6^k} + \sum_{k=0}^{+\infty} \frac{k}{6^k} + 3 \sum_{k=0}^{+\infty} \frac{1}{6^{k+1}} \quad (1.31)$$

$$= \frac{5}{2} \sum_{k=1}^{+\infty} \frac{k}{6^k} + 3 \sum_{k=1}^{+\infty} \frac{1}{6^k} = \frac{5}{2} \times \frac{6}{25} + 3 \times \frac{1}{5} = \frac{6}{5}. \quad (1.32)$$