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The hats of n individuals are jumbled and handed back to them at random.

- * What is the chance that no one gets back his own hat?
- * What is the chance that exactly k people recover their hats?



Individuals	1	2	•••	n
Hats	Π_1	Π_2	•••	Π_n

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Permutations $(\Pi_1, \Pi_2, \dots, \Pi_n)$ of $(1, 2, \dots, n)$

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= $\{(\Pi_1, \dots, \Pi_j, \dots, \Pi_n) : \Pi_j = j\}$

$$X_{j} = \begin{cases} 1 & \text{if } A_{j} \text{ occurs} \\ 0 & \text{otherwise} \end{cases}$$

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no one gets their own hat

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$$A_1^0\cap\cdots\cap A_n^0=\{X_1+\cdots+X_n=0\}\qquad \text{no one gets their own hat}$$

$$\{X_1+\cdots+X_n=k\}\qquad \text{k individuals get their hats}$$

$$A_1^c \cap \cdots \cap A_n^c = \{X_1 + \cdots + X_n = 0\} \qquad \{X_1 + \cdots + X_n = k\}$$

$$[X_1 + \cdots + X_n = k]$$

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The 1st term
$$P(A_1) = P\{(\Pi_1, \Pi_2, ..., \Pi_n) : \Pi_1 = 1\}$$

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$$P(A_1) = P\{(\Pi_1, \Pi_2, ..., \Pi_n) : \Pi_1 = 1\} = \frac{(n-1)!}{n!} = \frac{1}{n}$$

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The 2nd term
$$P(A_1 \cap A_2) = P\{(\Pi_1, \Pi_2, \dots, \Pi_n) : \Pi_1 = 1, \Pi_2 = 2\}$$

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$$P(A_1 \cap A_2 \cdots \cap A_{\mathfrak{j}}) = P\{ (\Pi_1, \Pi_2, \ldots, \Pi_n) : \Pi_1 = 1, \Pi_2 = 2, \ldots, \Pi_{\mathfrak{j}} = \mathfrak{j} \}$$

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The jth term

$$\mathbf{P}(A_1 \cap A_2 \dots \cap A_j) = \mathbf{P}\{(\Pi_1, \Pi_2, \dots, \Pi_n) : \Pi_1 = 1, \Pi_2 = 2, \dots, \Pi_j = j\} = \frac{(n-j)!}{n!} = \frac{1}{n!}$$

$$A_1^c \cap \cdots \cap A_n^c = \{X_1 + \cdots + X_n = 0\}$$

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$$\mathbf{P}(A_1 \cap A_2 \dots \cap A_j) = \mathbf{P}\{(\Pi_1, \Pi_2, \dots, \Pi_n) : \Pi_1 = 1, \Pi_2 = 2, \dots, \Pi_j = j\} = \frac{(n-j)!}{n!} = \frac{1}{n!}$$

$$S_{j} = {n \choose j} \mathbf{P}(A_{1} \cap A_{2} \cap \cdots \cap A_{j}) = \frac{n^{\underline{j}}}{\underline{j}!} \cdot \frac{1}{n^{\underline{j}}} = \frac{1}{\underline{j}!}$$

$$A_1^c \cap \dots \cap A_n^c = \{X_1 + \dots + X_n = 0\} \qquad \{X_1 + \dots + X_n = k\}$$

The inclusion–exclusion sums
$$S_{j} = \binom{n}{j} P(A_{1} \cap A_{2} \cap \cdots \cap A_{j}) = \frac{n^{\underline{j}}}{\underline{j}!} \cdot \frac{1}{n^{\underline{j}}} = \frac{1}{\underline{j}!}$$

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$$P(A_1^c \cap A_2^c \cap \cdots \cap A_n^c) = S_0 - S_1 + S_2 - \cdots + (-1)^n S_n$$

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$$\mathbf{P}\{X_1 + X_2 + \dots + X_n = k\} = S_k - \binom{k+1}{k} S_{k+1} + \binom{k+2}{k} S_{k+2} - \dots + (-1)^{n-k} \binom{n}{k} S_n$$

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$$\begin{aligned} \mathbf{P}\{X_1 + X_2 + \dots + X_n &= k\} = S_k - \binom{k+1}{k} S_{k+1} + \binom{k+2}{k} S_{k+2} - \dots + (-1)^{n-k} \binom{n}{k} S_n \\ &= \frac{1}{k!} - \frac{(k+1)!}{k!1!} \cdot \frac{1}{(k+1)!} + \frac{(k+2)!}{k!2!} \cdot \frac{1}{(k+2)!} - \dots + (-1)^{n-k} \frac{n!}{k!(n-k)!} \cdot \frac{1}{n!} \end{aligned}$$

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$$\begin{split} \textbf{P}\{X_1 + X_2 + \dots + X_n &= k\} = S_k - \binom{k+1}{k} S_{k+1} + \binom{k+2}{k} S_{k+2} - \dots + (-1)^{n-k} \binom{n}{k} S_n \\ &= \frac{1}{k!} - \frac{(k+1)!}{k!1!} \cdot \frac{1}{(k+1)!} + \frac{(k+2)!}{k!2!} \cdot \frac{1}{(k+2)!} - \dots + (-1)^{n-k} \frac{n!}{k!(n-k)!} \cdot \frac{1}{n!} \\ &= \frac{1}{k!} \left(1 - \frac{1}{1!} + \frac{1}{2!} - \dots + (-1)^{n-k} \frac{1}{(n-k)!} \right) \end{split}$$

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$$\begin{split} \textbf{P}\{X_1 + X_2 + \dots + X_n &= k\} = S_k - \binom{k+1}{k} S_{k+1} + \binom{k+2}{k} S_{k+2} - \dots + (-1)^{n-k} \binom{n}{k} S_n \\ &= \frac{1}{k!} - \frac{(k+1)!}{k!1!} \cdot \frac{1}{(k+1)!} + \frac{(k+2)!}{k!2!} \cdot \frac{1}{(k+2)!} - \dots + (-1)^{n-k} \frac{n!}{k!(n-k)!} \cdot \frac{1}{n!} \\ &= \frac{1}{k!} \left(1 - \frac{1}{1!} + \frac{1}{2!} - \dots + (-1)^{n-k} \frac{1}{(n-k)!} \right) \to \frac{e^{-1}}{k!} \end{split}$$

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The probability that at least one individual gets his own hat is approximately two-thirds and is almost independent of the number in the party.

$$\begin{aligned} \mathbf{P}\{X_1 + X_2 + \dots + X_n &= k\} = S_k - \binom{k+1}{k} S_{k+1} + \binom{k+2}{k} S_{k+2} - \dots + (-1)^{n-k} \binom{n}{k} S_n \\ &= \frac{1}{k!} - \frac{(k+1)!}{k!1!} \cdot \frac{1}{(k+1)!} + \frac{(k+2)!}{k!2!} \cdot \frac{1}{(k+2)!} - \dots + (-1)^{n-k} \frac{n!}{k!(n-k)!} \cdot \frac{1}{n!} \\ &= \frac{1}{k!} \left(1 - \frac{1}{1!} + \frac{1}{2!} - \dots + (-1)^{n-k} \frac{1}{(n-k)!} \right) \to \frac{e^{-1}}{k!} \end{aligned}$$

The number of individuals who retrieve their own hats is governed approximately by a Poisson distribution with mean 1.