

mmooRREE COUNTING!

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 - ▶ Do the objects all look the same?

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 - ▶ Do the boxes all look the same?

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Answer: It depends.

- ▶ What do the objects look like?
 - ▶ Do the objects all look the same?
- ▶ What do the boxes look like?
 - ▶ Do the boxes all look the same?
- ▶ Are there any restrictions?
 - ▶ Is there a size limit?
 - ▶ Must there be an object in each box?

Counting distributions

Definition: A **distribution** is an assignment of objects to recipients.

Certain counting problems can be revisited in this framework:

$\left\{ \begin{array}{l} \text{Five-letter passwords} \\ \text{on } \{A, B, C, D, E, F, G\} \end{array} \right\}$ correspond to $\left\{ \begin{array}{l} \text{Distributions of} \\ \text{--- distinct objects} \\ \text{into --- distinct boxes} \end{array} \right\}$

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- What are candidates for objects, boxes?

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$\left\{ \begin{array}{l} \text{Five-letter passwords} \\ \text{on } \{A, B, C, D, E, F, G\} \\ \text{w/no repeated letters} \end{array} \right\}$ correspond to $\left\{ \begin{array}{l} \text{Distributions of} \\ \text{___ distinct objects} \\ \text{into ___ distinct boxes} \\ \text{satisfying _____} \end{array} \right\}$

- ▶ What are candidates for objects, boxes?
- ▶ View as a function
- ▶ View as a distribution
- ▶ Find the restriction

THE CHART

Question: In how many ways can we place k objects in n boxes?

Distributions of		Restrictions on # objects received			
k objects	n boxes	none	≤ 1	≥ 1	$= 1$
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identical	distinct				
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- ▶ $(n)_k$: Objects distinct, Boxes distinct, ≤ 1 object per box.
- ▶ $n!$: Permutations. What about when $n \neq k$?
- ▶ $\binom{n}{k}$: Objects _____, Boxes _____, _____.
- ▶ $\binom{n+k-1}{k}$: Objects _____, Boxes _____, _____.

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We can also fill in these answers:

- ▶ Objects identical, Boxes distinct, ≥ 1 object per box:

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We can also fill in these answers:

- ▶ Objects identical, Boxes distinct, ≥ 1 object per box:
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Distinct objects in indistinguishable boxes

When placing k distinguishable objects into n indistinguishable boxes, what matters? _____

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- ▶ Each object needs to be in some box.
- ▶ No object is in two boxes.

We have rediscovered _____.

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- ▶ No object is in two boxes.

We have rediscovered _____.

So ask “How many set partitions are there of a set with k objects?”

Or even, “How many set partitions are there of k objects into n parts?”

Stirling numbers

The **Stirling number of the second kind** counts the number of ways to partition a set of k elements into i **non-empty** subsets.

Notation: $S(k, i)$ or $\left\{ \begin{matrix} k \\ i \end{matrix} \right\}$. ← **Careful about this order!**

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k	$\left\{ \begin{matrix} k \\ 0 \end{matrix} \right\}$	$\left\{ \begin{matrix} k \\ 1 \end{matrix} \right\}$	$\left\{ \begin{matrix} k \\ 2 \end{matrix} \right\}$	$\left\{ \begin{matrix} k \\ 3 \end{matrix} \right\}$	$\left\{ \begin{matrix} k \\ 4 \end{matrix} \right\}$	$\left\{ \begin{matrix} k \\ 5 \end{matrix} \right\}$	$\left\{ \begin{matrix} k \\ 6 \end{matrix} \right\}$	$\left\{ \begin{matrix} k \\ 7 \end{matrix} \right\}$
0	1							
1		1						
2		1	1					
3		1	3	1				
4		1	7	6	1			
5		1	15	25	10	1		
6		1	31	90	65	15	1	
7		1						1

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In Stirling's triangle:

$$S(k, 1) = S(k, k) = 1.$$

$$S(k, 2) = 2^{k-1} - 1.$$

$$S(k, k-1) = \binom{k}{2}.$$

Later: Formula for $S(k, i)$.

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Later: Formula for $S(k, i)$.

To fill in the table, find a recurrence for $S(k, i)$:

Ask: In how many ways can we place k objects into i boxes?

We'll condition on the placement of element $\#i$:

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$S(k, n)$ counts ways to place k distinct obj. into n identical boxes.

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What if we then label the boxes?

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How many ways to distribute distinct objects into identical boxes:

- If there is exactly one item in each box?

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What if we then label the boxes?

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How many ways to distribute distinct objects into identical boxes:

- ▶ If there is exactly one item in each box?
- ▶ If there is at most one item in each box?

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- ▶ What about with no restrictions?

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How many ways to distribute distinct objects into identical boxes:

- ▶ If there is exactly one item in each box?
- ▶ If there is at most one item in each box?
- ▶ What about with no restrictions? $(n \geq k \rightsquigarrow \text{Bell number } B_k)$

Bell numbers

Definition: The **Bell number** B_k is the number of partitions of a set with k elements, into any number of non-empty parts.

We have $B_k = S(k, 0) + S(k, 1) + S(k, 2) + \cdots + S(k, k)$.

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B_0	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9
1	1	2	5	15	52	203	877	4140	21147

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Theorem 2.3.3. The Bell numbers satisfy a recurrence:

$$B_k = \binom{k-1}{0} B_0 + \binom{k-1}{1} B_1 + \cdots + \binom{k-1}{k-1} B_{k-1}.$$

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Proof: How many partitions of $\{1, \dots, k\}$ are there?

LHS: B_k , obviously.

RHS:

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Proof: How many partitions of $\{1, \dots, k\}$ are there?

LHS: B_k , obviously.

RHS: Condition on the box containing the last element k :
How many partitions of $[k]$ contain i elements in the box with k ?

Indistinguishable objects in indistinguishable boxes

When placing k indistinguishable objects into n indistinguishable boxes, what matters? _____

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- ▶ We are partitioning the **integer** k instead of the **set** $[k]$.

Example. What are the partitions of 6?

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Example. What are the partitions of 6?

Definition: $P(k, i)$ is the number of partitions of k into i parts.

Example. We saw $P(6, 1) = 1$, $P(6, 2) = 3$, $P(6, 3) = 3$,
 $P(6, 4) = 2$, $P(6, 5) = 1$, and $P(6, 6) = 1$.

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Definition: $P(k)$ is the number of partitions of k into **any number** of parts.

Example. $P(6) = 1 + 3 + 3 + 2 + 1 + 1 = 11$.

THE CHART, COMPLETED

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distinct	identical	$\sum S(k, i)$	1 or 0	$S(k, n)$	1 or 0
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$P(k, n)$ counts ways to place k identical obj. into n identical boxes.

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distinct	distinct	n^k	$(n)_k$	$n!S(k, n)$	$n!$ or 0
identical	distinct	$\binom{n}{k}$	$\binom{n}{k}$	$\binom{n}{k-n}$	1 or 0
distinct	identical	$\sum S(k, i)$	1 or 0	$S(k, n)$	1 or 0
identical	identical			$P(k, n)$	

$P(k, n)$ counts ways to place k identical obj. into n identical boxes.

How many ways to distribute identical objects into identical boxes:

- If there is exactly one item in each box?

THE CHART, COMPLETED

Question: In how many ways can we place k objects in n boxes?

Distributions of		Restrictions on # objects received			
k objects	n boxes	none	≤ 1	≥ 1	$= 1$
distinct	distinct	n^k	$(n)_k$	$n!S(k, n)$	$n!$ or 0
identical	distinct	$\binom{n}{k}$	$\binom{n}{k}$	$\binom{n}{k-n}$	1 or 0
distinct	identical	$\sum S(k, i)$	1 or 0	$S(k, n)$	1 or 0
identical	identical			$P(k, n)$	1 or 0

$P(k, n)$ counts ways to place k identical obj. into n identical boxes.

How many ways to distribute identical objects into identical boxes:

- ▶ If there is exactly one item in each box?
- ▶ If there is at most one item in each box?

THE CHART, COMPLETED

Question: In how many ways can we place k objects in n boxes?

Distributions of		Restrictions on # objects received			
k objects	n boxes	none	≤ 1	≥ 1	$= 1$
distinct	distinct	n^k	$\binom{n}{k}$	$n!S(k, n)$	$n!$ or 0
identical	distinct	$\binom{n}{k}$	$\binom{n}{k}$	$\binom{n}{k-n}$	1 or 0
distinct	identical	$\sum S(k, i)$	1 or 0	$S(k, n)$	1 or 0
identical	identical		1 or 0	$P(k, n)$	1 or 0

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- ▶ If there is exactly one item in each box?
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- ▶ What about with no restrictions?

THE CHART, COMPLETED

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distinct	identical	$\sum S(k, i)$	1 or 0	$S(k, n)$	1 or 0
identical	identical	$\sum P(k, i)$	1 or 0	$P(k, n)$	1 or 0

$P(k, n)$ counts ways to place k identical obj. into n identical boxes.

How many ways to distribute identical objects into identical boxes:

- ▶ If there is exactly one item in each box?
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- ▶ What about with no restrictions?

(This is the # of integer partitions of k into at most n parts.)