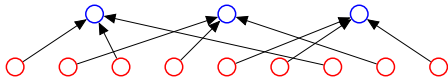


## Today.

More Counting.

## Ordered to unordered.

**Second Rule of Counting:** If order doesn't matter count ordered objects and then divide by number of orderings.



How many red nodes (ordered objects)? 9.

How many red nodes mapped to one blue node? 3.

How many blue nodes (unordered objects)?  $\frac{9}{3} = 3$ .

How many poker deals?  $52 \cdot 51 \cdot 50 \cdot 49 \cdot 48$ .

How many poker deals per hand?

Map each deal to ordered deal:  $5!$

How many poker hands?  $\frac{52 \cdot 51 \cdot 50 \cdot 49 \cdot 48}{5!}$

Questions?

## The first rule..

**Objects made by choosing from  $n_1$ , then  $n_2$ , ..., then  $n_k$**   
**the number of objects is  $n_1 \times n_2 \cdots \times n_k$ .**

How many outcomes possible for  $k$  coin tosses?

2 ways for first choice, 2 ways for second choice, ...

$$2 \times 2 \cdots \times 2 = 2^k$$

How many 10 digit numbers?

10 ways for first choice, 10 ways for second choice, ...

$$10 \times 10 \cdots \times 10 = 10^k$$

How many  $n$  digit base  $m$  numbers?

$m$  ways for first,  $m$  ways for second, ...

$$m^n$$

## ..order doesn't matter.

Choose 2 out of  $n$ ?

$$\frac{n \times (n-1)}{2} = \frac{n!}{(n-2)! \times 2}$$

Choose 3 out of  $n$ ?

$$\frac{n \times (n-1) \times (n-2)}{3!} = \frac{n!}{(n-3)! \times 3!}$$

Choose  $k$  out of  $n$ ?

$$\frac{n!}{(n-k)! \times k!}$$

**Notation:**  $\binom{n}{k}$  and pronounced " $n$  choose  $k$ ."

Familiar? Questions?

## Counting sets..when order doesn't matter.

How many poker hands?

$$52 \times 51 \times 50 \times 49 \times 48 \text{ ???}$$

Are A, K, Q, 10, J of spades

and 10, J, Q, K, A of spades the same?

**Second Rule of Counting:** If order doesn't matter count ordered objects and then divide by number of orderings.<sup>1</sup>

Number of orderings for a poker hand: " $5!$ "

(The "!" means factorial, not Exclamation.)

$$\frac{52 \times 51 \times 50 \times 49 \times 48}{5!}$$

Can write as...

$$\frac{52!}{5! \times 47!}$$

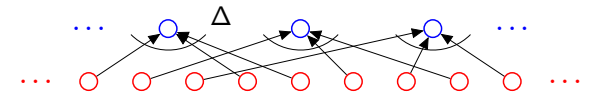
Generic: ways to choose 5 out of 52 possibilities.

<sup>1</sup>When each unordered object corresponds equal numbers of ordered objects.

## Example: Anagram

**First rule:**  $n_1 \times n_2 \cdots \times n_3$ . **Product Rule.**

**Second rule: when order doesn't matter divide...**



Orderings of ANAGRAM?

Ordered Set:  $7!$  First rule.

A's are the same!

What is  $\Delta$ ?

**ANAGRAM**

$A_1NA_2GRA_3M, A_2NA_1GRA_3M, \dots$

$\Delta = 3 \times 2 \times 1 = 3!$  First rule!

$\Rightarrow \frac{7!}{3!}$  Second rule!

## Some Practice.

How many orderings of letters of CAT?

3 ways to choose first letter, 2 ways for second, 1 for last.

$$\implies 3 \times 2 \times 1 = 3! \text{ orderings}$$

How many orderings of the letters in ANAGRAM?

Ordered, except for A!

total orderings of 7 letters.  $7!$

total "extra counts" or orderings of three A's?  $3!$

Total orderings?  $\frac{7!}{3!}$

How many orderings of MISSISSIPPI?

4 S's, 4 I's, 2 P's.

11 letters total.

$11!$  ordered objects.

$4! \times 4! \times 2!$  ordered objects per "unordered object"

$$\implies \frac{11!}{4!4!2!}$$

## Splitting 5 dollars..

How many ways can Alice, Bob, and Eve split 5 dollars.

Alice gets 3, Bob gets 1, Eve gets 1: (A,A,A,B,E).

Separate Alice's dollars from Bob's and then Bob's from Eve's.

Five dollars are five stars: \*\*\*\*\*.

Alice: 2, Bob: 1, Eve: 2.

Stars and Bars: \*\*|\*|\*\*.

Alice: 0, Bob: 1, Eve: 4.

Stars and Bars: |\*|\*\*\*\*.

Each split "is" a sequence of stars and bars.

Each sequence of stars and bars "is" a split.

**Counting Rule: if there is a one-to-one mapping between two sets they have the same size!**

## Sampling...

Sample  $k$  items out of  $n$

Without replacement:

Order matters:  $n \times n-1 \times n-2 \dots \times n-k+1 = \frac{n!}{(n-k)!}$

Order does not matter:

Second Rule: divide by number of orders - " $k!$ "

$$\implies \frac{n!}{(n-k)!k!}$$

" $n$  choose  $k$ "

With Replacement.

Order matters:  $n \times n \times \dots \times n = n^k$

Order does not matter: Second rule ???

Problem: depends on how many of each item we chose!

Different number of unordered elts map to each unordered elt.

Unordered elt: 1, 2, 3     3! ordered elts map to it.

Unordered elt: 1, 2, 2      $\frac{3!}{2!}$  ordered elts map to it.

How do we deal with this mess??

## Splitting up some money....

How many ways can Bob and Alice split 5 dollars?

For each of 5 dollars pick Bob or Alice ( $2^5$ ), divide out order ???

5 dollars for Bob and 0 for Alice:

one ordered set: (B, B, B, B, B).

4 for Bob and 1 for Alice:

5 ordered sets: (A, B, B, B, B); (B, A, B, B, B); ...

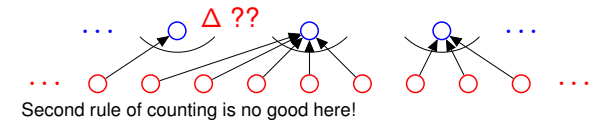
"Sorted" way to specify, first Alice's dollars, then Bob's.

(B, B, B, B, B): 1: (B, B, B, B, B)

(A, B, B, B, B): 5: (A, B, B, B, B), (B, A, B, B, B), (B, B, A, B, B), ...

(A, A, B, B, B):  $\binom{5}{2}$ ; (A, A, B, B, B), (A, B, A, B, B), (A, B, B, A, B), ...

and so on.



## Splitting 5 dollars..

## Stars and Bars.

How many different 5 star and 2 bar diagrams?

| \* | \* \* \* \*

7 positions in which to place the 2 bars.

-----

Alice: 0; Bob 1; Eve: 4

| \* | \* \* \* \*

Bars in first and third position.

Alice: 1; Bob 4; Eve: 0

\* | \* \* \* \* |

Bars in second and seventh position.

$\binom{7}{2}$  ways to do so and

$\binom{7}{2}$  ways to split 5 dollars among 3 people.

## Stars and Bars.

Ways to add up  $n$  numbers to sum to  $k$ ? or

" $k$  from  $n$  with replacement where order doesn't matter."

In general,  $k$  stars  $n-1$  bars.

\*\*|\*|...|\*\*.

$n+k-1$  positions from which to choose  $n-1$  bar positions.

$$\binom{n+k-1}{n-1}$$

Or:  $k$  unordered choices from set of  $n$  possibilities with replacement.  
**Sample with replacement where order doesn't matter.**

## Quick review of the basics.

**First rule:**  $n_1 \times n_2 \cdots \times n_3$ .

$k$  Samples with replacement from  $n$  items:  $n^k$ .

Sample without replacement:  $\frac{n!}{(n-k)!}$

**Second rule: when order doesn't matter divide..when possible.**

Sample without replacement and order doesn't matter:  $\binom{n}{k} = \frac{n!}{(n-k)!k!}$ .  
 "n choose k"

**One-to-one rule: equal in number if one-to-one correspondence.**

Sample with replacement and order doesn't matter:  $\binom{k+n-1}{n-1}$ .

## Combinatorial Proofs.

**Theorem:**  $\binom{n}{k} = \binom{n}{n-k}$

**Proof:** How many subsets of size  $k$ ?  $\binom{n}{k}$

How many subsets of size  $k$ ?

Choose a subset of size  $n-k$

and what's left out is a subset of size  $k$ .

Choosing a subset of size  $k$  is same

as choosing  $n-k$  elements to not take.

$\Rightarrow \binom{n}{n-k}$  subsets of size  $k$ . □

## Balls in bins.

" $k$  Balls in  $n$  bins"  $\equiv$  " $k$  samples from  $n$  possibilities."

"indistinguishable balls"  $\equiv$  "order doesn't matter"

"only one ball in each bin"  $\equiv$  "without replacement"

5 balls into 10 bins

5 samples from 10 possibilities with replacement

Example: 5 digit numbers.

5 indistinguishable balls into 52 bins only one ball in each bin

5 samples from 52 possibilities without replacement

Example: Poker hands.

5 indistinguishable balls into 3 bins

5 samples from 3 possibilities with replacement and no order

Dividing 5 dollars among Alice, Bob and Eve.

## Pascal's Triangle

$$\begin{array}{ccccccc}
 & & & & 0 & & & & \\
 & & & & 1 & & 1 & & \\
 & & & 1 & 2 & & 1 & & \\
 & & 1 & 3 & 3 & & 1 & & \\
 & 1 & 4 & 6 & 4 & & 1 & & 
 \end{array}$$

Row  $n$ : coefficients of  $(1+x)^n = (1+x)(1+x)\cdots(1+x)$ .

Foil (4 terms) on steroids:

$2^n$  terms: choose 1 or  $x$  from each factor of  $(1+x)$ .

Simplify: collect all terms corresponding to  $x^k$ .

Coefficient of  $x^k$  is  $\binom{n}{k}$ : choose  $k$  factors where  $x$  is in product.

$$\begin{array}{cccc}
 & & \binom{0}{0} & \\
 & & \binom{1}{0} & \binom{1}{1} \\
 & \binom{2}{0} & \binom{2}{1} & \binom{2}{2} \\
 \binom{3}{0} & \binom{3}{1} & \binom{3}{2} & \binom{3}{3}
 \end{array}$$

Pascal's rule  $\Rightarrow \binom{n+1}{k} = \binom{n}{k} + \binom{n}{k-1}$ .

## Sum Rule

Two indistinguishable jokers in 54 card deck.

How many 5 card poker hands?

**Sum rule: Can sum over disjoint sets.**

No jokers "exclusive" or One Joker "exclusive" or Two Jokers

$$\binom{52}{5} + \binom{52}{4} + \binom{52}{3}$$

Two distinguishable jokers in 54 card deck.

How many 5 card poker hands? Choose 4 cards plus one of 2 jokers!

$$\binom{52}{5} + 2 * \binom{52}{4} + \binom{52}{3}$$

Wait a minute! Same as choosing 5 cards from 54 or

$$\binom{54}{5}$$

**Theorem:**  $\binom{54}{5} = \binom{52}{5} + 2 * \binom{52}{4} + \binom{52}{3}$ .

**Algebraic Proof:** Why? Just why? Especially on Monday!

Above is combinatorial proof. □

## Combinatorial Proofs.

**Theorem:**  $\binom{n+1}{k} = \binom{n}{k} + \binom{n}{k-1}$ .

**Proof:** How many size  $k$  subsets of  $n+1$ ?  $\binom{n+1}{k}$ .

How many size  $k$  subsets of  $n+1$ ?

How many contain the first element?

Chose first element, need to choose  $k-1$  more from remaining  $n$  elements.

$$\Rightarrow \binom{n}{k-1}$$

How many don't contain the first element ?

Need to choose  $k$  elements from remaining  $n$  elts.

$$\Rightarrow \binom{n}{k}$$

So,  $\binom{n}{k-1} + \binom{n}{k} = \binom{n+1}{k}$ . □

## Combinatorial Proof.

**Theorem:**  $\binom{n}{k} = \binom{n-1}{k-1} + \dots + \binom{n-1}{k}$ .

**Proof:** Consider size  $k$  subset where  $i$  is the first element chosen.

$$\{1, \dots, \underline{i}, \dots, n\}$$

Must choose  $k-1$  elements from  $n-i$  remaining elements.

$\Rightarrow \binom{n-i}{k-1}$  such subsets.

Add them up to get the total number of subsets of size  $k$  which is also  $\binom{n+1}{k}$ . □

## Binomial Theorem: $x = 1$

**Theorem:**  $2^n = \binom{n}{n} + \binom{n}{n-1} + \dots + \binom{n}{0}$

**Proof:** How many subsets of  $\{1, \dots, n\}$ ?

Construct a subset with sequence of  $n$  choices:  
element  $i$  is in or is not in the subset: 2 poss.

First rule of counting:  $2 \times 2 \dots \times 2 = 2^n$  subsets.

How many subsets of  $\{1, \dots, n\}$ ?

$\binom{n}{i}$  ways to choose  $i$  elts of  $\{1, \dots, n\}$ .

Sum over  $i$  to get total number of subsets..which is also  $2^n$ . □

## Simple Inclusion/Exclusion

**Sum Rule: For disjoint sets  $S$  and  $T$ ,**  $|S \cup T| = |S| + |T|$

Used to reason about all subsets

by adding number of subsets of size 1, 2, 3, ...

Also reasoned about subsets that contained or didn't contain an element. (E.g., first element, first  $i$  elements.)

**Inclusion/Exclusion Rule: For any  $S$  and  $T$ ,**

$|S \cup T| = |S| + |T| - |S \cap T|$ .

**Example:** How many 10-digit phone numbers have 7 as their first or second digit?

$S$  = phone numbers with 7 as first digit.  $|S| = 10^9$

$T$  = phone numbers with 7 as second digit.  $|T| = 10^9$ .

$S \cap T$  = phone numbers with 7 as first and second digit.  $|S \cap T| = 10^8$ .

Answer:  $|S| + |T| - |S \cap T| = 10^9 + 10^9 - 10^8$ .

## Summary.

First Rule of counting: Objects from a sequence of choices:

$n_i$  possibilities for  $i$ th choice.

$n_1 \times n_2 \times \dots \times n_k$  objects.

Second Rule of counting: If order does not matter.

Count with order. Divide by number of orderings/sorted object.

Typically:  $\binom{n}{k}$ .

Stars and Bars: Sample  $k$  objects with replacement from  $n$ .

Order doesn't matter.

Typically:  $\binom{n+k-1}{k}$  or  $\binom{n+k-1}{n-1}$ .

Inclusion/Exclusion: two sets of objects.

Add number of each subtract intersection of sets.

Sum Rule: If disjoint just add.

Combinatorial Proofs: Identity from counting same in two ways.

Pascal's Triangle Example:  $\binom{n+1}{k} = \binom{n}{k-1} + \binom{n}{k}$ .

RHS: Number of subsets of  $n+1$  items size  $k$ .

LHS:  $\binom{n}{k-1}$  counts subsets of  $n+1$  items with first item.

$\binom{n}{k}$  counts subsets of  $n+1$  items without first item.

Disjoint – so add!