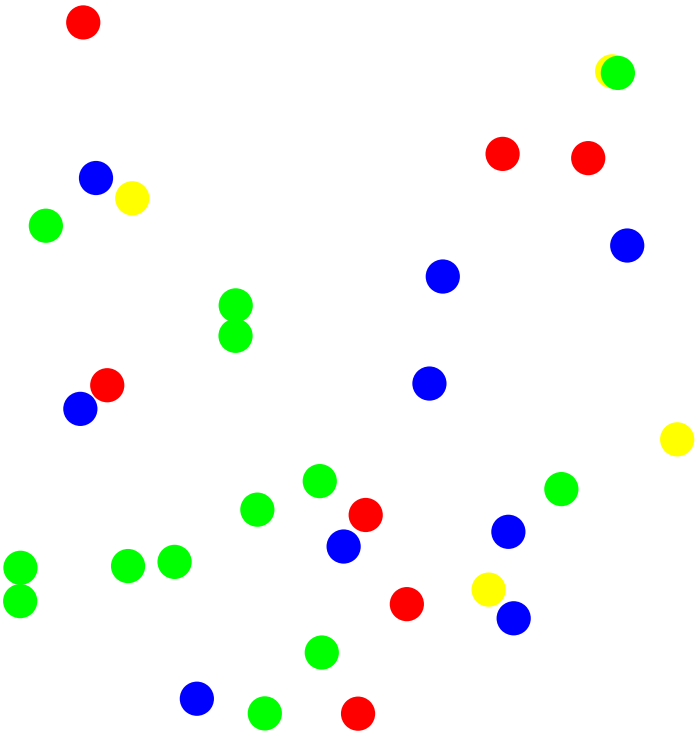
Partitions

Definition

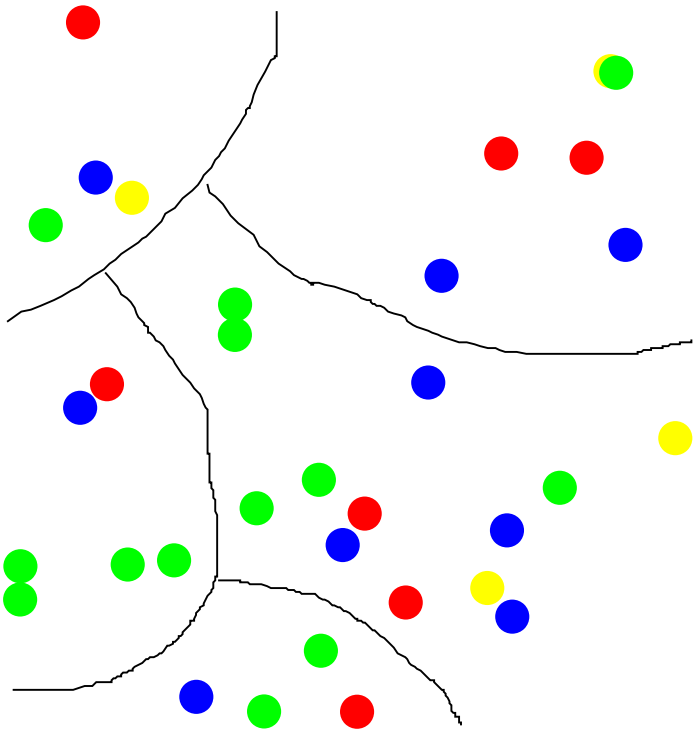
A partition $\mathcal{P}$ of a set A is a set of nonempty, mutually disjoint subsets of A whose union is A.

Examples

- If A is the set of students in this a class, a partition might be the groups who worked on HW4 together (solutions to be posted on Classes, by the way).
- If A is a set of colored points, a partition could be found just by grouping them by color.



or just by designating regions.



Big Idea

Partitions and equivalence relations are the same thing.

Proposition. Let A be a set with equivalence relation R. Then, its equivalence classes $\{[a] : a \in A\}$ form a partition of A.

Proof. We have seen previously that equivalence classes are mutually disjoint. We need only show

$$\bigcup_{a \in A} [a] = A.$$

Since for all a, $[a] \subseteq A$ by definition, we automatically get $\cup_{a \in A} [a] \subseteq A$. But for all $x \in A$, $x \in [x] \subseteq \cup_{a \in A} [a]$. And so they are equivalent. ∎

Proposition. Given a partition $\mathcal{P}$, the relation $\overset{\mathcal{P}}{\equiv} = \{(x, y) : \exists P \in \mathcal{P},\ x, y \in P\}$ is an equivalence relation.

Proof. (reflexive) By definition, every element of A must be in some element of $\mathcal{P}$, so $x \overset{\mathcal{P}}{\equiv} x$.
(symmetric) If $x \overset{\mathcal{P}}{\equiv} y$, then there exists a set P containing x and y so it contains y and x, and thus $y \overset{\mathcal{P}}{\equiv} x$.
(transitive) Exercise. (Which part of the definition of partition is essential here?) ∎

Theorem. Let R be an equivalence relation on a finite set A and suppose all equivalence classes of R have cardinality m. Then the number of equivalence classes is $\frac{|A|}{m}$.

Proof. Really? ∎

I know, but this theorem can actually be useful for various counting problems.

Permutations of lists with repeated factors (anagrams)

Here are the anagrams (including nonsense words) of “ketchup”:

ketchup	ketchpu	ketcuhp	ketcuph	ketcphu	ketcpuh	kethcup	kethcpu	kethucp	kethupc	kethpcu	kethpuc
ketuchp	ketucph	ketuhcp	ketuhpc	ketupch	ketuphc	ketpchu	ketpcuh	ketphcu	ketphuc	ketpuch	ketpuhc
kecthup	kecthpu	kectuhp	kectuph	kectphu	kectpuh	kechtup	kechtpu	kechutp	kechupt	kechptu	kechput
kecuthp	kecutph	kecuhtp	kecuhpt	kecupth	kecupht	kecpthu	kecptuh	kecphtu	kecphut	kecputh	kecpuht
kehtcup	kehtcpu	kehtucp	kehtupc	kehtpcu	kehtpuc	kehctup	kehctpu	kehcutp	kehcupt	kehcptu	kehcput
kehutcp	kehutpc	kehuctp	kehucpt	kehuptc	kehupct	kehptcu	kehptuc	kehpctu	kehpcut	kehputc	kehpuct
keutchp	keutcph	keuthcp	keuthpc	keutpch	keutphc	keucthp	keuctph	keuchtp	keuchpt	keucpth	keucpht
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keptchu	keptcuh	kepthcu	kepthuc	keptuch	keptuhc	kepcthu	kepctuh	kepchtu	kepchut	kepcuth	kepcuht
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pethkcu	pethkuc	pethcku	pethcuk	pethukc	pethuck	petukch	petukhc	petuckh	petuchk	petuhkc	petuhck
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pehcktu	pehckut	pehctku	pehctuk	pehcukt	pehcutk	pehuktc	pehukct	pehutkc	pehutck	pehuckt	pehuctk
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pueckth	pueckht	puectkh	puecthk	puechkt	puechtk	puehktc	puehkct	puehtkc	puehtck	puehckt	puehctk
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pucketh	puckeht	puckteh	puckthe	puckhet	puckhte	pucekth	pucekht	pucetkh	pucethk	pucehkt	pucehtk
puctkeh	puctkhe	puctekh	puctehk	pucthke	puchtek	puchket	puchkte	puchekt	puchetk	puchtke	puchtek
puhketc	puhkect	puhktec	puhktce	puhkcet	puhkcte	puhektc	puhekct	puhetkc	puhetck	puheckt	puhectk
puhtkec	puhtkce	puhtekc	puhteck	puhtcke	puhtcek	puhcket	puhckte	puhcekt	puhcetk	puhctke	puhctek

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Length[Permutations[{"k", "e", "t", "c", "h", "u", "p"}]]
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5040

Here are those for “ukelele”:

ukelele	ukeleel	ukellee	ukeelle	ukeelel	ukeeell	ukleele	ukleeel	uklelee	uklleee	ueklele	uekleel
uekllee	uekelle	uekelel	uekeell	uelkele	uelkeel	uelklee	uelekle	uelekel	uelelke	uelelek	ueleekl
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ueelelk	ueeekll	ueeelkl	ueeellk	ulkeele	ulkeeel	ulkelee	ulkleee	ulekele	ulekeel	uleklee	uleekle
uleekel	uleelke	uleelek	uleeekl	uleeelk	ulelkee	uleleke	uleleek	ullkeee	ullekee	ulleeke	ulleeek
kuelele	kueleel	kuellee	kueelle	kueelel	kueeell	kuleele	kuleeel	kulelee	kulleee	keulele	keuleel
keullee	keuelle	keuelel	keueell	keluele	kelueel	kelulee	keleule	keleuel	kelelue	keleleu	keleeul
keleelu	kelluee	kelleue	kelleeu	keeulle	keeulel	keeuell	keelule	keeluel	keellue	keelleu	keeleul
keelelu	keeeull	keeelul	keeellu	klueele	klueeel	kluelee	kluleee	kleuele	kleueel	kleulee	kleeule
kleeuel	kleelue	kleeleu	kleeeul	kleeelu	kleluee	kleleue	kleleeu	kllueee	klleuee	klleeue	klleeeu
euklele	eukleel	eukllee	eukelle	eukelel	eukeell	eulkele	eulkeel	eulklee	eulekle	eulekel	eulelke
eulelek	euleekl	euleelk	eullkee	eulleke	eulleek	eueklle	eueklel	euekell	euelkle	euelkel	euellke
euellek	euelekl	euelelk	eueekll	eueelkl	eueellk	ekulele	ekuleel	ekullee	ekuelle	ekuelel	ekueell
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elkuele	elkueel	elkulee	elkeule	elkeuel	elkelue	elkeleu	elkeeul	elkeelu	elkluee	elkleue	elkleeu
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eleluke	eleluek	elelkue	elelkeu	eleleuk	eleleku	eleeukl	eleeulk	eleekul	eleeklu	eleeluk	eleelku
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leeklue	leekleu	leekeul	leekelu	leeluke	leeluek	leelkue	leelkeu	leeleuk	leeleku	leeeukl	leeeulk
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Length[Permutations[{"u", "k", "e", "l", "e", "l", "e"}]]
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420

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eλ3lukϵ	eλ3luϵk	eλ3lkuϵ	eλ3lkϵu	eλ3lϵuk	eλ3lϵku	eλ3ϵukl	eλ3ϵulk	eλ3ϵkul	eλ3ϵklu	eλ3ϵluk	eλ3ϵlku
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ϵkuelλ3	ϵkuel3λ	ϵkueλl3	ϵkueλ3l	ϵkue3lλ	ϵkue3λl	ϵkuleλ3	ϵkule3λ	ϵkulλe3	ϵkulλ3e	ϵkul3eλ	ϵkul3λe
ϵkuλel3	ϵkuλe3l	ϵkuλle3	ϵkuλl3e	ϵkuλ3el	ϵkuλ3le	ϵku3elλ	ϵku3eλl	ϵku3leλ	ϵku3lλe	ϵku3λel	ϵku3λle
ϵkeulλ3	ϵkeul3λ	ϵkeuλl3	ϵkeuλ3l	ϵkeu3lλ	ϵkeu3λl	ϵkeluλ3	ϵkelu3λ	ϵkelλu3	ϵkelλ3u	ϵkel3uλ	ϵkel3λu
ϵkeλul3	ϵkeλu3l	ϵkeλlu3	ϵkeλl3u	ϵkeλ3ul	ϵkeλ3lu	ϵke3ulλ	ϵke3uλl	ϵke3luλ	ϵke3lλu	ϵke3λul	ϵke3λlu
ϵklueλ3	ϵklue3λ	ϵkluλe3	ϵkluλ3e	ϵklu3eλ	ϵklu3λe	ϵkleuλ3	ϵkleu3λ	ϵkleλu3	ϵkleλ3u	ϵkle3uλ	ϵkle3λu
ϵklλue3	ϵklλu3e	ϵklλeu3	ϵklλe3u	ϵklλ3ue	ϵklλ3eu	ϵkl3ueλ	ϵkl3uλe	ϵkl3euλ	ϵkl3eλu	ϵkl3λue	ϵkl3λeu
ϵkλuel3	ϵkλue3l	ϵkλule3	ϵkλul3e	ϵkλu3el	ϵkλu3le	ϵkλeul3	ϵkλeu3l	ϵkλelu3	ϵkλel3u	ϵkλe3ul	ϵkλe3lu
ϵkλlue3	ϵkλlu3e	ϵkλleu3	ϵkλle3u	ϵkλl3ue	ϵkλl3eu	ϵkλ3uel	ϵkλ3ule	ϵkλ3eul	ϵkλ3elu	ϵkλ3lue	ϵkλ3leu
ϵk3uelλ	ϵk3ueλl	ϵk3uleλ	ϵk3ulλe	ϵk3uλel	ϵk3uλle	ϵk3eulλ	ϵk3euλl	ϵk3eluλ	ϵk3elλu	ϵk3eλul	ϵk3eλlu
ϵk3lueλ	ϵk3luλe	ϵk3leuλ	ϵk3leλu	ϵk3lλue	ϵk3lλeu	ϵk3λuel	ϵk3λule	ϵk3λeul	ϵk3λelu	ϵk3λlue	ϵk3λleu
ϵeuklλ3	ϵeukl3λ	ϵeukλl3	ϵeukλ3l	ϵeuk3lλ	ϵeuk3λl	ϵeulkλ3	ϵeulk3λ	ϵeulλk3	ϵeulλ3k	ϵeul3kλ	ϵeul3λk
ϵeuλkl3	ϵeuλk3l	ϵeuλlk3	ϵeuλl3k	ϵeuλ3kl	ϵeuλ3lk	ϵeu3klλ	ϵeu3kλl	ϵeu3lkλ	ϵeu3lλk	ϵeu3λkl	ϵeu3λlk
ϵekulλ3	ϵekul3λ	ϵekuλl3	ϵekuλ3l	ϵeku3lλ	ϵeku3λl	ϵekluλ3	ϵeklu3λ	ϵeklλu3	ϵeklλ3u	ϵekl3uλ	ϵekl3λu
ϵekλul3	ϵekλu3l	ϵekλlu3	ϵekλl3u	ϵekλ3ul	ϵekλ3lu	ϵek3ulλ	ϵek3uλl	ϵek3luλ	ϵek3lλu	ϵek3λul	ϵek3λlu
ϵelukλ3	ϵeluk3λ	ϵeluλk3	ϵeluλ3k	ϵelu3kλ	ϵelu3λk	ϵelkuλ3	ϵelku3λ	ϵelkλu3	ϵelkλ3u	ϵelk3uλ	ϵelk3λu
ϵelλuk3	ϵelλu3k	ϵelλku3	ϵelλk3u	ϵelλ3uk	ϵelλ3ku	ϵel3ukλ	ϵel3uλk	ϵel3kuλ	ϵel3kλu	ϵel3λuk	ϵel3λku
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ϵe3uklλ	ϵe3ukλl	ϵe3ulkλ	ϵe3ulλk	ϵe3uλkl	ϵe3uλlk	ϵe3kulλ	ϵe3kuλl	ϵe3kluλ	ϵe3klλu	ϵe3kλul	ϵe3kλlu
ϵe3lukλ	ϵe3luλk	ϵe3lkuλ	ϵe3lkλu	ϵe3lλuk	ϵe3lλku	ϵe3λukl	ϵe3λulk	ϵe3λkul	ϵe3λklu	ϵe3λluk	ϵe3λlku
ϵlukeλ3	ϵluke3λ	ϵlukλe3	ϵlukλ3e	ϵluk3eλ	ϵluk3λe	ϵluekλ3	ϵluek3λ	ϵlueλk3	ϵlueλ3k	ϵlue3kλ	ϵlue3λk
ϵluλke3	ϵluλk3e	ϵluλek3	ϵluλe3k	ϵluλ3ke	ϵluλ3ek	ϵlu3keλ	ϵlu3kλe	ϵlu3ekλ	ϵlu3eλk	ϵlu3λke	ϵlu3λek
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ϵlkλue3	ϵlkλu3e	ϵlkλeu3	ϵlkλe3u	ϵlkλ3ue	ϵlkλ3eu	ϵlk3ueλ	ϵlk3uλe	ϵlk3euλ	ϵlk3eλu	ϵlk3λue	ϵlk3λeu
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λl3ukeϵ	λl3ukϵe	λl3uekϵ	λl3ueϵk	λl3uϵke	λl3uϵek	λl3kueϵ	λl3kuϵe	λl3keuϵ	λl3keϵu	λl3kϵue	λl3kϵeu
λl3eukϵ	λl3euϵk	λl3ekuϵ	λl3ekϵu	λl3eϵuk	λl3eϵku	λl3ϵuke	λl3ϵuek	λl3ϵkue	λl3ϵkeu	λl3ϵeuk	λl3ϵeku
λϵukel3	λϵuke3l	λϵukle3	λϵukl3e	λϵuk3el	λϵuk3le	λϵuekl3	λϵuek3l	λϵuelk3	λϵuel3k	λϵue3kl	λϵue3lk
λϵulke3	λϵulk3e	λϵulek3	λϵule3k	λϵul3ke	λϵul3ek	λϵu3kel	λϵu3kle	λϵu3ekl	λϵu3elk	λϵu3lke	λϵu3lek

λϵulke3	λϵulk3e	λϵulek3	λϵule3k	λϵul3ke	λϵul3ek	λϵu3kel	λϵu3kle	λϵu3ekl	λϵu3elk	λϵu3lke	λϵu3lek
λϵkuel3	λϵkue3l	λϵkule3	λϵkul3e	λϵku3el	λϵku3le	λϵkeul3	λϵkeu3l	λϵkelu3	λϵkel3u	λϵke3ul	λϵke3lu
λϵklue3	λϵklu3e	λϵkleu3	λϵkle3u	λϵkl3ue	λϵkl3eu	λϵk3uel	λϵk3ule	λϵk3eul	λϵk3elu	λϵk3lue	λϵk3leu
λϵeukl3	λϵeuk3l	λϵeulk3	λϵeul3k	λϵeu3kl	λϵeu3lk	λϵekul3	λϵeku3l	λϵeklu3	λϵekl3u	λϵek3ul	λϵek3lu
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λϵluke3	λϵluk3e	λϵluek3	λϵlue3k	λϵlu3ke	λϵlu3ek	λϵlkue3	λϵlku3e	λϵlkeu3	λϵlke3u	λϵlk3ue	λϵlk3eu
λϵleuk3	λϵleu3k	λϵleku3	λϵlek3u	λϵle3uk	λϵle3ku	λϵl3uke	λϵl3uek	λϵl3kue	λϵl3keu	λϵl3euk	λϵl3eku
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λ3elukϵ	λ3eluϵk	λ3elkuϵ	λ3elkϵu	λ3elϵuk	λ3elϵku	λ3eϵukl	λ3eϵulk	λ3eϵkul	λ3eϵklu	λ3eϵluk	λ3eϵlku
λ3lukeϵ	λ3lukϵe	λ3luekϵ	λ3lueϵk	λ3luϵke	λ3luϵek	λ3lkueϵ	λ3lkuϵe	λ3lkeuϵ	λ3lkeϵu	λ3lkϵue	λ3lkϵeu
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3lϵukeλ	3lϵukλe	3lϵuekλ	3lϵueλk	3lϵuλke	3lϵuλek	3lϵkueλ	3lϵkuλe	3lϵkeuλ	3lϵkeλu	3lϵkλue	3lϵkλeu
3lϵeukλ	3lϵeuλk	3lϵekuλ	3lϵekλu	3lϵeλuk	3lϵeλku	3lϵλuke	3lϵλuek	3lϵλkue	3lϵλkeu	3lϵλeuk	3lϵλeku
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3λulkeϵ	3λulkϵe	3λulekϵ	3λuleϵk	3λulϵke	3λulϵek	3λuϵkel	3λuϵkle	3λuϵekl	3λuϵelk	3λuϵlke	3λuϵlek
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```
Length[Permutations[{"u", "k", "e", "l", "ϵ", "λ", "3"}]]
```

5040

What we are really doing is taking the set of all lists (w/o repeats) of length 7 from 7 elements (above).

Then we impose an equivalence relation on them, namely two such permutations are equivalent if the l's occupy the same set of positions, and the e's occupy the same set of positions.

$$\text{ukel}\epsilon\lambda 3 \equiv \text{ukel}3\lambda\epsilon \equiv \text{uk}\epsilon\text{le}\lambda 3 \equiv \text{uk}\epsilon\text{l}3\lambda\text{e} \equiv \text{uk}3\text{le}\lambda\epsilon \equiv \text{uk}3\text{l}\epsilon\lambda\text{e}$$

$$\equiv \text{uke}\lambda\epsilon\text{l}3 \equiv \text{uke}\lambda 3\text{l}\epsilon \equiv \text{uk}\epsilon\lambda\text{el}3 \equiv \text{uk}\epsilon\lambda 3\text{le} \equiv \text{uk}3\lambda\text{el}\epsilon \equiv \text{uk}3\lambda\epsilon\text{le}$$

or if x and y are such permutation

$$x \equiv y \Longleftrightarrow \{i : x_i \text{ is "ell"}\} = \{i : y_i \text{ is "ell"}\} \bigwedge \{i : x_i \text{ is "ee"}\} = \{i : y_i \text{ is "ee"}\}$$

The size of each equivalence class is thus the number of permutations of the “ee” positions (3!) and the “ell” positions (2!) multiplied.

$$\frac{7!}{3!\ \ 2!}$$

420

Example

6 tennis players in a club want to play singles (one-on-one) matches. How many ways can matchups be made?

Example

6 tennis players in a club want to play singles (one-on-one) matches. How many ways can this be done?

Start with arrangements of the 6 players. There are 6! possibilities. Assume that for any given list $(x_1, x_2, x_3, x_4, x_5, x_6)$, x_1 will play x_2, x_3 will play x_4 and x_5 will play x_6.

We form an equivalence relation by noting the matchups are the same if we make any number of switches in the individual matchups (2 choices for each of 3 pairs $= 2^3$) or any permutations of the pairings themselves ($(3)_3 = 3!$ arrangements of pairs). Thus each equivalence class has $2^3 \cdot 3! = 48$ elements. Thus the total number of possibilities is

$$\frac{6!}{48}$$

Combinations

We define

$$n^k = \text{the number of lists of length } k \text{ from } n \text{ elements.}$$

$$(n)_k = \text{the number of lists of length } k \text{ from } n \text{ elements without repeats.}$$

$$\binom{n}{k} = \text{the number of subsets of size } k \text{ from a set of n elements.}$$

Formula

Notice that sets could be considered equivalence classes of lists with distinct elements where the relation is “is a rearrangement of”.
Since k elements can be arranged $k!$ ways, we have

$$\binom{n}{k} = \frac{(n)_k}{k!} = \frac{n!}{(n-k)!\,k!}$$

Corollary

$$\binom{n}{k} = \binom{n}{n-k}$$

Binomial Theorem

$$(x+y)^n = \sum_{k=0}^{n} \binom{n}{k} x^k y^{n-k}$$

Examples

1. What is the coefficient of x^3 in $(2x+1)^6$?

2.

$$\binom{n}{0}+\binom{n}{1}+\binom{n}{2}+\cdots+\binom{n}{n}=$$

Example

Show that

$$\binom{n}{0}-\binom{n}{1}+\binom{n}{2}-\binom{n}{3}+\cdots\pm\binom{n}{n}=0.$$

This means by rearrangement,

$$\binom{n}{0}+\binom{n}{2}+\binom{n}{4}+\cdots=\binom{n}{1}+\binom{n}{3}+\binom{n}{5}+\cdots$$

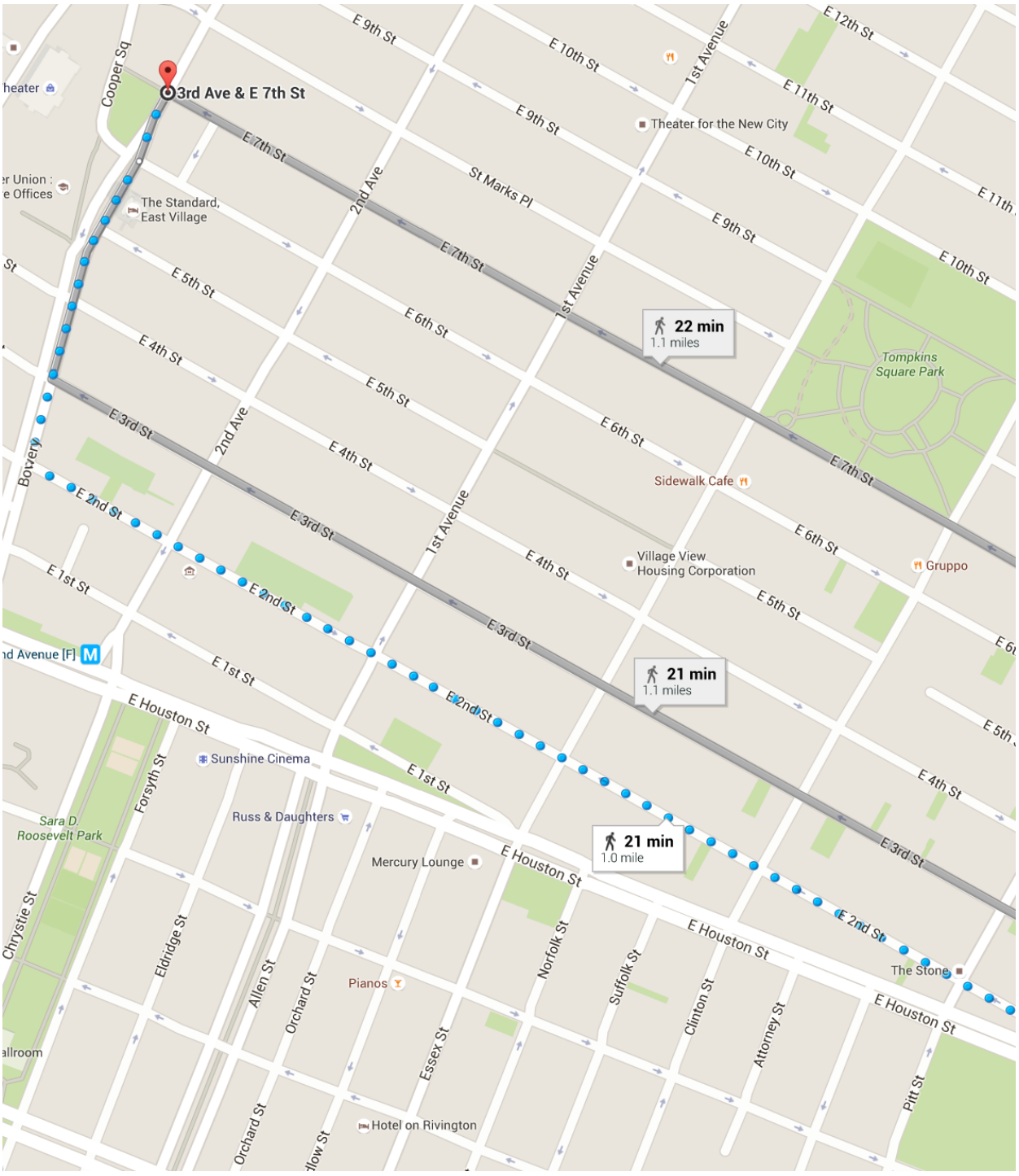
Is there a combinatorial proof of this?

Pascal's Identity

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

Exercise

How many (sane) ways can one walk from Houston and Ave D to 3rd Ave and 7th St?



Total ways of traversing a 6×5 grid:

$\binom{11}{5}$

462

If we exclude 5th between Ave C and Ave B (There is a school blocking the through-street), we get

$\binom{11}{5} - \binom{4}{1}\binom{6}{2}$

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