MATH103 Combinatorics Notes

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Contents

A Recurrence Relations

A1 Intro

Remark. Let there be a set $\{1, 2, \ldots, n\}$. The number of subsets of it is 2^n since for each number, we could say "include" or "exclude".

Example 1. Now consider the number of subsets with no two adjacent elements. Call them *good* subsets, and the count be $f(n)$.

(Scratch work begins)

First consider $n = 0$. Then the only *good* subset is $\varnothing$.

Now consider $n = 1$, both $\varnothing, \{1\}$ are good.

Now consider $n = 2$. We have subsets: $\varnothing, 1, 2, 12$. The set 12 is not good.

← notation simplified for fast typing

Similarly, we have $f(3) = 5$, $f(5) = 8$.

(Scratch ends here)

We have $f(n) = f(n-1) + f(n-2)$ for all $n \geq 2$. Hence, $f(n)$ is the sequence that satisfies the recurrence relation and the initial conditions $f(0) = 1$, $f(1) = 2$.

A2 Fibonacci sequence

$$0, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144, 233, 377, \ldots$$

Remark. Two notation conventions:

- $F_0 = 1, F_1 = 1, F_n = F_{n-1} + F_{n-2} \quad \forall n \geq 2$, and ← Textbook
- $f_0 = 0, f_1 = 1, f_n = f_{n-1} + f_{n-2} \quad \forall n \geq 2$. ← Preferred!

Example 2. Prof Rad is climbing 47 steps. Energized by coffee, she sometimes climbds one step per stride, sometimes two steps per stride. In how many ways can she do this?

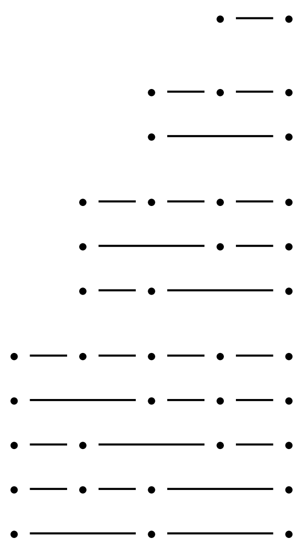
← It is the same recurrence as A1 but with init conditions shifted: $f(n) = F_{n+1} = f_{n+2}$.

Table 1: Table of the sequence in two notations

n	0	1	2	3	4	5	6	7	8
F_n	1	1	2	3	5	8	13	21	34
f_n	0	1	1	2	3	5	8	13	21

(Scratch work begins) Let $S(n)$ be the number of ways climbing n steps.

- $S(1) = 1$
- $S(2) = 2$
- $S(3) = 3$
- $S(4) = 5$



Conjecture: maybe Fibonacci?

(Scratch ends here)

Proof. Consider the set of ways she can cover n steps. We have two cases:

1. Her first stride is 1 step. Then, the number of ways is the number of ways to cover the remaining $n-1$ steps. Thus, this gives us $S(n-1)$ ways.
2. Her first stride is 2 steps. Then the number of ways is the number of ways to cover the remaining $n-2$ steps. Thus, this gives us $S(n-2)$ ways.

Therefore, we conclude that $S(n) = S(n-1) + S(n-2)$. We account the initial conditions and conclude the closed form:

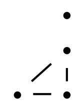
$$S(n) = F_n = f_{n+1}$$

for all n. Since Prof Rad climbs 47 steps, we get $\boxed{S(47) = 4807526976}$. $\square$

A3 Simplex numbers

Definition 1. *Two-dimensional* triangular numbers: $T_2(n) = 1 + 2 + 3 + \cdots + n$

- $T_2(1) = 1$
- $T_2(2) = 1 + 2 = 3$
- …



$$1, 3, 6, 10, 15, 21, 28, 36, 45, 55, \ldots$$

Theorem 1. $T_2(n) = 1 + 2 + \cdots + n = \frac{n(n+1)}{2}$

First proof. We prove by induction.

← Not as good of a proof: we must know what we are proving in the first place!

Base case $n = 1$: $T_2(1) = 1$, formula gives $\frac{1(1+1)}{2} = 1$.
Inductive hypothesis: Suppose proved formula for up to $n = k$.
Inductive step: Consider $n = k + 1$.

$$\begin{aligned} T_2(k+1) &= 1 + \cdots + k + (k+1) \\ &= T_2(k) + k + 1 \\ &= \frac{k(k+1)}{2} + k + 1 \\ &= \frac{k^2 + k + 2(k+1)}{2} \\ &= \frac{k^2 + 3k + 2}{2} \\ &= \frac{(k+1)(k+2)}{2} \\ &= \frac{(k+1)\left((k+1)+1\right)}{2} \end{aligned}$$

□

Proof by Gauss. Observe:

← Better proof: concluding the formula without knowing it first!

$$\begin{aligned} T_2(n) &= 1 + 2 + \cdots + (n-1) + n \\ &= n + (n-1) + \cdots + 2 + 1 \end{aligned}$$

Therefore, we **add** the two rows:

$$\begin{aligned} 2T_2(n) &= \underbrace{(n+1) + (n+1) + \cdots + (n+1)}_{n} \\ &= n(n+1) \\ \therefore \quad T_2(n) &= \frac{1}{2}n(n+1) \end{aligned}$$

□

Definition 2. Tetrahedral numbers: $T_3(n) = T_2(1) + T_2(2) + \cdots + T_2(n)$

- $T_3(5) = 1 + 3 + 6 + 10 + 15 = 35$

Definition 3. Simplex numbers: $T_{k+1}(n) = T_k(1) + \cdots + T_k(n)$

Some examples of simplex numbers $T_d(n)$:

$d\backslash n$	1	2	3	4	5	6	7
1	1	2	3	4	5	6	7
2	1	3	6	10	15	21	28
3	1	4	10	20	35	56	84
4	1	5	15	35	70	126	210
5	1	6	21	56	126	252	462

B Ramsey Theory

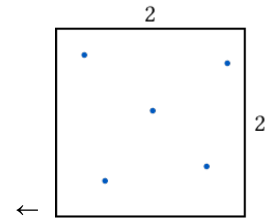
Invented by Frank Ramsey in 1930. We would need:

- Graph Theory
- Pigeonhole Principle
- Quantifiers
- Counterexamples

B1 Pigeonhole principle

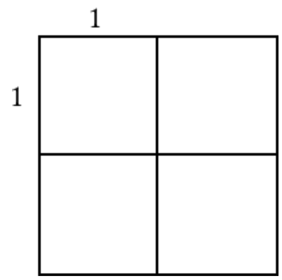
Theorem 2 (Dirichlet's Pigeonhole Principle)**.** If you put $n+1$ pigeons in n pigeonholes, then (at least) one pigeonhole will contain (at least) two pigeons.

Proof omitted. □



Example 3. Given 5 points in a square of side length 2, show that there must exist two points whose mutual distance is $\leq \sqrt{2}$.

Proof. Divide square into 4 smaller squares. We now have 4 pigeonholes and 5 dots:



These two points in the same pigeonhole have distance $\leq \sqrt{1^2 + 1^2} = \sqrt{2}$. ☐

Example 4. There exists two people in NYC who have exactly the same number of hairs on their head.

Example 5. There are 30 people at a party talking with each other. Afterwards, there will be two people who talked with the same number of people.

Proof. If we put a person who talked to i people into box i, we get 30 boxes; however, we cannot have someone who talked to 0 people and someone who talked at 29 people at the same time! Hence, we combine the box 0 and box 29, and only one of which could be the case.

Now we have 29 boxes and 30 people. By pigeonhole principle, there must be two people who talked with the same amount of people. ☐

Theorem 3 **(Strong Pigeonhole Principle).** Given pigeonholes $1, 2, \dots, n$ with capacities $c_1, c_2, \dots, c_n$ where $c_i \geq 0$; if we have at least $c_1 + c_2 + \cdots + c_n + 1$ pigeons in these pigeonholes, then at least one pigeonhole overflows.

Proof. Suppose BWOC that no pigeonhole overflows. Then for all $i = 1, 2, \dots, n$, we have the number of pigeons in $i \leq c_i$.

We add up and get inequalities:

$$\text{total \# pigeons} \leq c_1 + c_2 + \cdots + c_n$$

Contradiction! ☐

Example 6. There are five people supporting two teams. Then at least one team is supported by 3 people.

Proof. Assume BWOC that the two teams only have two supporters. Let $c_1 = c_2 = 2$. However, by SPP, $5 \geq 2 + 2 + 1$, hence one pigeonhole overflows. Therefore, one team must have > 2 supporters. □

B2 First Ramsey Theorem

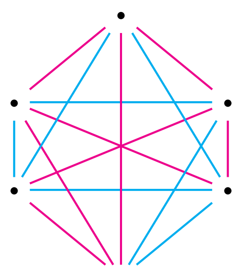
There are 6 people taking a class. Then:

either there exists 3 people such that each pair of them have previously taken a class together,

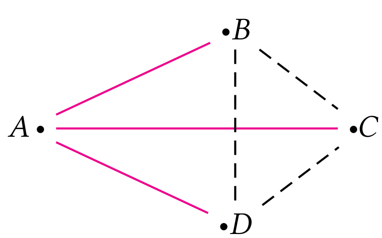
or (inclusive) there exists 3 people such that no two have taken a class together.

Theorem 4. If we have 6 vertices and we draw all edges between them (a K_6 graph), then for every possible way of coloring the edges red and blue, there must exist a **monochromatic** triangle.

← K_6 stands for *complete graph on 6 vertices.* It has 15 edges.



Proof. Pick any vertex and call it A. It has 5 edges colored red and blue. By the SPP, there exists at least 3 edges of the same color. WLOG let these three edges be red and call the other three vertices B, C, D.

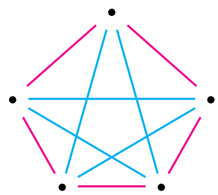


- If BC is red, then ABC is a red triangle.
- If CD is red, then ACD is a red triangle.
- If BD is red, then ABD is a red triangle.
- If none of the above has happened, then BC, CD, BD are all blue, meaning that BCD is a blue triangle!

□

Theorem 5. If there are 5 instead of 6 vertices, then the above coloring prediction cannot be made with certainty.

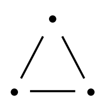
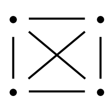
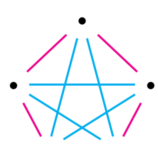
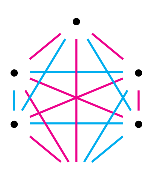
Counterexample.



□

B3 $K_p \to K_q,\ K_r$

In graphy theory, K_n is the **complete** graph on n vertices.

K_1		1 vertex	0 edges
K_2		2 vertices	1 edge
K_3		3 vertices	3 edges
K_4		4 vertices	6 edges
K_5		5 vertices	10 edges
K_6		6 vertices	15 edges

Remark. Note that K_n has $1 + 2 + 3 + \cdots + (n-1) = \frac{n(n-1)}{2}$ edges, hence is the $n-1$-th triangular number.

Ramsey Theory uses the following language convention: the expression

$$K_p \to K_q,\ K_r$$

represents a statement with the following meaning:

Definition 4. If the edges of K_p are colored red/blue, then it necessarily follows that either the K_p contains a red K_q, or K_p contains a blue K_r (or possibly both).

We want to know whether this statement is true for a given triple of (p, q, r).

Example 7. We proved in B2 that $K_6 \to K_3, K_3$.

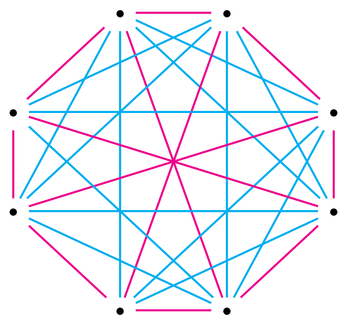
Non-example 8. We also showed that $K_5 \to K_3, K_3$ is false by exhibiting a coloring of K_5 that does not have a red or blue triangle (counterexample).

← write $K_5 \not\to K_3, K_3$

Example 9. It is known that $K_{18} \to K_4, K_4$ and $K_{17} \not\to K_4, K_4$.

Example 10. Also, $K_9 \to K_3, K_4$ and $K_8 \not\to K_3, K_4$.

← Here we have to decide in advance which color goes with the K_3 and which goes with the K_4 due to asymmetry.



This K_8 has no red triangle and no blue K_4.

Theorem 6 (Ramsey)**.** Let q, r be positive integers. Then there always exists a positive integer p such that

$$K_p \to K_q, K_r$$

is true.

We would see the following tabel giving us values of p that work.

Define a function $N(q, r)$ recursively:

← $q, r \in \mathbb{Z}^+$

- Base case: $N(1, r) = N(q, 1) = 1$
- Recurrence: $N(q, r) = N(q-1, r) + N(q, r-1)$ if $q, r \geq 2$.

We compute the value of $N(q, r)$ for:

← They do look like simplex numbers!

$q \backslash r$	1	2	3	4	5	6
1	1	1	1	1	1	1
2	1	2	3	4	5	6
3	1	3	6	10	15	21
4	1	4	10	20	35	56
5	1	5	15	35	70	126
6	1	6	21	56	126	252

We would want to prove that $K_{N(q,r)} \to K_q, K_r$ for all $q, r \geq 1$.

Proof. By induction.

Base case: If $q = r = 1$, then $N = 1$, we need to show that
$$K_1 \to K_1, K-r \quad \text{and} \quad K_1 \to K_q, K_1$$
for all q, r.
That is, suppose K_1 has its edges colored red/blue, then there exists a red K_1 or a blue K_r, and *vice versa.*
Since there are no edges, this is vacuously true.

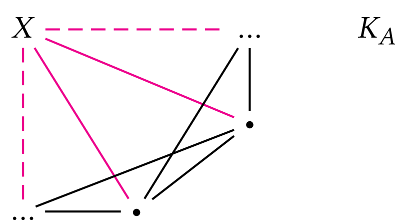
Inductive step: We will show that if we are given that A, B are numbers such that

← This works because as we fill out the table above, each new number we write in will work because it's the sum of the left and above numbers and they both work.

$$K_A \to K_{q-1}, K_r$$
$$\text{and } K_B \to K_q, K_{r-1}$$

are true, then $K_{A+B} \to K_q, K_r$.
Consider K_{A+B} colored red and blue. We will show that it has a red K_q or a blue K_r.
Pick a vertex and call it X. It would have $A + B - 1$ edges in total. We claim that X either has at least A red edges, or at least B blue edges. This is indeed true, because if not, the number of red edges would be $\leq A - 1$ and the number of blue edges would be $\leq B - 1$ and so the total number of edges would be $\leq A + B - 2 < A + B - 1$, which is a contradiction.
Now, if X has a red claw of size A:

← The neighbouring vertices connected by black edges form K_A, yet to be colored.



From our inductive hypothesis $K_A \to K_{q-1}, K_r$, we must have
either red K_{q-1}, in which case we combine with the vertex X and the red claw to get at least one red K_q.
or blue K_r, in which case we are done.
Similarly, if X has a blue claw of size B, then we make the same argument.

Hence, we know that $K_{A+B} \to K_q, K_r$ is true whenever $K_A \to K_{q-1}, K_r$ and $K_B \to K_q, K_{r-1}$.

□

B4 Ramsey numbers

Recall: Let m, n be positive integers. We know that there are numbers $p \in \mathbb{N}$ such that $K_p \to K_m, K_n$.

Remark. If p works, then so does any $q \geq p$ as K_q would contain copies of K_p.

So the question becomes, if we have $K_p \to K_m, K_n$, is p the **smallest** such number?

Definition 5. The **Ramsey number** $r(m, n)$ is the smallest such number.

Example 11. We know $K_6 \to K_3, K_3$ but $K_5 \not\to K_3, K_3$, so $r(3,3) = 6$.

Example 12. Mathematicians have proved that

$$K_{48} \to K_5, K_5$$
$$K_{42} \not\to K_5, K_5$$

so we have $43 \leq r(5,5) \leq 48$.

Remark. In general,

$$\begin{aligned} K_N \to K_m, K_n &\iff r(m,n) \leq N \\ K_{N-1} \not\to K_m, K_n &\iff r(m,n) \geq N \end{aligned}$$

Need both to get the precise value of $r(m, n)$.

Proposition 7. Properties of Ramsey numbers:

(a) $r(3,3) = 6$ ← proven in B2

(b) $r(m,n) = r(n,m)$ ← symmetry

(c) $r(1,n) = 1$ ← $K_1 \to K_1, K_n$, $K_0 \not\to K_1, K_n$

(d) $r(2,n) = n$

(e) $r(m,n) \leq r(m-1,n) + r(m,n-1)$ for all $m, n \geq 2$

Proof for (d). Claim: $K_2 \to K_2, K_n$, $K_{n-1} \not\to K_2, K_n$.

Color K_n. If all edges are blue then we have a blue K_n. Else we have some red edges, so we have some red K_2.

Now color K_{n-1} all blue: we realize that we don't have any red K_2, but we don't have a blue K_n either! □

Proof for (e). Let $A = r(m-1,n)$, $B = r(m,n-1)$. We have shown that if $K_A \to K_{m-1}, K_n$ and $K_B \to K_m, K_{n-1}$, then $K_{A+B} \to K_m, K_n$. Hence $r(m,n) \leq A + B$. □

Known facts:

$$\begin{aligned} r(2,2) &= 2 \\ r(3,3) &= 6 \\ r(4,4) &= 18 \\ 43 \leq r(5,5) &\leq 48 \\ 102 \leq r(6,6) &\leq 165 \end{aligned}$$

B5 A lower bound for $r(m, n)$

Our table of $N(m, n)$ gave us upper bonds for $r(m, n)$. Specifically,

$$r(m,n) \leq N(m,n) = \frac{(n+m-2)!}{(n-1)!(m-1)!} = \binom{m+n-2}{m-1}$$

What about lower bound?

Theorem 8.

$$r(m,n) \geq (m-1)(n-1)+1$$

if and only if $K_{(m-1)(n-1)} \not\to K_m, K_n$

Proof. We prove this by exhibiting a coloring of $K_{(m-1)(n-1)}$ that has no red K_m, no blue K_n.

Place vertices in grid:

$$\begin{array}{cc} & \begin{array}{cccc} \bullet & \bullet & \cdots & \bullet \\ \bullet & \bullet & \cdots & \bullet \\ \vdots & \vdots & \ddots & \vdots \\ \bullet & \bullet & \cdots & \bullet \end{array} \\ m{-}1 \text{ rows} & \\ & n{-}1 \text{ columns} \end{array}$$

Coloring rule of edges: If two vertices are in the same row, color the edges blue. If two vertices are in the same column, color the edges red. Every other edge arbitrary.

Claim: there exists no red K_m.

Consider the m vertices of such a K_m. There are $m-1$ rows. Pigeonhole principle ensures that some vertices must be in the same row. But that edge must be blue! So this is not a red K_m. Similarly, there are no blue K_n. □

Thus, we get: $(m-1)(n-1)+1 \le r(m,n) \le \dfrac{(n+m-2)!}{(n-1)!(m-1)!} = \binom{m+n-2}{m-1}$.

Observe there is still a huge gap between the bounds. Could we get better?

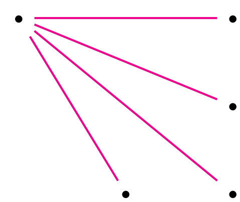
B6 The "parity" improvement

Our methods have shown that $K_{10} \to K_3, K_4$. But it is actually true that $K_9 \to K_3, K_4$. Why?

Proof. Given K_9 colored red or blue. We seek a red K_3 or a blue K_4.

That is to say that if we ever see a red 4-claw, then we are done!

← See this argument.



In addition, if we ever see a blue 6-claw, then we are also done because $K_6 \to K_3, K_3$ and we either have a red K_3 or a blue K_3, which would have to combine with the other vertex to get a blue K_4.

Now suppose we neither have a red 4-claw nor a blue 6-claw. This implies that each vertex has ≤ 3 red edges, and ≤ 5 blue edges. However, in a K_9, each vertex only has 8 edges, so they must exactly each have 3 red edges and 5 blue edges. Does this exist? We realize that to make this happen, we have:

- 9 vertices
- Each vertex has 3 red edges
- Every edge belongs to two vertices

Hence, we need to have exactly $\frac{3\times 9}{2} = 13.5$ red edges, but this cannot happen because we need a whole number of edges! Thus, it is not possible that we neither have a red 4-claw nor a blue 6-claw. □

Lemma 9 (Ramsey inductive step improved by parity)**.** Suppose

← Also seen here.

$$\begin{aligned} K_A &\to K_{q-1}, K_r \\ \text{and } K_B &\to K_q, K_{r-1} \end{aligned}$$

are true, then $K_{A+B} \to K_q, K_r$.

In addition, if A, B are **both even numbers**, then $K_{A+B-1} \to K_q, K_r$.

B7 Variations

More colors!

For example:

$$K_p \to K_a, K_b, K_c$$

(given K_p colored red, blue, green, it must contain a red K_a, or a blue K_b, or a green K_c.)

Example 13. It is known that $K_{17} \to K_3, K_3, K_3$.

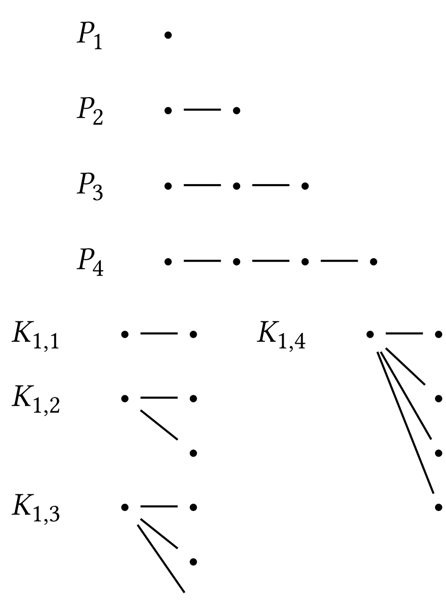
Proof sketch. Pick a vertex which has 16 edges. We observe $16 \div 3 = 5\frac{1}{3} \implies$ at least one color occurs 6 times (i.e. we can see a red/blue/green 6-claws). $\square$

Remark. $r(a, b, c)$ is the smallest number that works for the above.

Other graphs

Paths:

Claws:



Example 14. Show that $r(K_{1,3}, K_{1,3}) = 6$.

Proof. We know $K_6 \to K_3, K_3$. Pick a vertex that has 5 neighbors. By the strong pigeonhole principle, we must have three edges of the same color $\implies$ either red or blue $K_{1,3}$. $\square$

C Counting

C1 Three principles

Addition principle

← aka. counting by cases

Definition 6. If a set S is *partitioned* into subsets $S_1, S_2, \ldots S_n$, then the cardinality of S is

$$|S| = |S_1| + \cdots + |S_n|.$$

← that is, $S = \bigcup S_i$ and $S_i \cap S_j = \emptyset$ whenever $i \neq j$

The art lies in:

- making each S_i easy to count, and
- not having too many S_i if there is no formula for $|S_i|$.

Remark (Variations)**.** If the S_i cover S but they overlap, then we have the inequality $|S| < \sum_{i=1}^{n} |S_i|$ because the overlap implies that we are *overcounting*.

← The inclusion/exclusion principle handles overlaps precisely

Example 15. Let S be the set of *good* subsets of $[5] = \{1, 2, 3, 4, 5\}$. We could first try:

← *good* meaning no adjacent elements

- S_1 contains the subsets that contain 5
- S_2 contains the subsets that don't contain 5

We have previously shown that $|S_1|$ = number of *good* subsets of [3] and $|S_2|$ = number of *good* subsets of [4].

Alternatively, we could also let T_i be the *good* subsets of [5] with cardinality i. Then

S is partitioned into $T_0 \cup T_1 \cup T_2 \cup T_3$. We count:

$$\left.\begin{array}{lccc} T_0 & : & \varnothing & |T_0| = 1 \\ T_1 & : & 1, 2, 3, 4, 5 & |T_1| = 5 \\ T_2 & : & 13, 14, 15, 24, 25, 35 & |T_2| = 6 \\ T_3 & : & 135 & |T_3| = 1 \end{array}\right) |S|=13$$

Subtraction principle

Definition 7. Let $A \subseteq S$ and A^c be its complement in S. Then A, A^c partition S and $|S| = |A| + |A^c|$. This means that

$$|A| = |S| - |A^c|.$$

Example 16. How many 2-digit numbers have distinct nonzero digits?

Let S be the set of all 2-digit numbers $\{10, 11, \dots, 99\}$ and let A be the subset of those with nonzero distinct digits. We count:

$$\begin{array}{rl} A^c : 11, 22, \dots, 99 & \text{(distinct fails)} \\ 10, 20, \dots, 90 & \text{(nonzero fails)} \end{array}$$

Hence $|A| = |S| - |A^c| = 90 - 18 = 72$.

Multiplication principle

Definition 8. Suppose we have to do two tasks in sequence. We suppose:

← Note: sometimes the 2nd task could depend on the 1st one

- Task 1 has m outcomes
- Task 2 has n outcomes, regardless of how Task 1 was carried out.

Then there are mn ways of carrying out both tasks.

← Similarly for 3 or more tasks in sequence

Example 17. How many 2-digit numbers have distinct nonzero digits?

Let $\boxed{a}\,\boxed{b}$ be the two digits in these numbers. Let Task 1 be selecting digit $\boxed{a}$ and Task 2 be selecting digit $\boxed{b}$.

- Task 1: 9 ways (1,2,...,9)
- Task 2: 8 ways (1,2...,9 but not same as a)

Hence there are $9 \times 8 = 72$ such numbers.

Tricky example 18. How many **odd** numbers in the range 1000-9999 have distinct digits?

Attempt 1: Let a b c d be the 4 digits in these numbers and assign them Tasks 1-4. We have:
- Task 1: 9 ways (1-9)
- Task 2: 9 ways (0-9 except a)
- Task 3: 8 ways (0-9 except a , b)
- Task 4: Could be 2 or 3 or 4 or 5 (depending on how many odd digits had already been used)

Hence, the best we can say here is that the answer is between $9 \times 9 \times 8 \times 2$ and $9 \times 9 \times 8 \times 5$.

← BAD! This is a large range!

Attempt 2: Let a b c d be the 4 digits in these numbers and try the order d a b c for Tasks 1-4. We have:
- Task 1: 5 ways $(1, 3, 5, 7, 9)$
- Task 2: 8 ways (1-9 except d)
- Task 3: 8 ways (0-9 except a , d)
- Task 4: 7 ways (0-9 except a , d , b)

Therefore, the number of ways is $5 \times 8 \times 8 \times 7 = 2240$.

Example 19. How many numebrs $0, 1, \ldots 99999$ have exactly one digit 6?

We can assign tasks:

- Task 1: choose a location for 6, giving us 5 ways
- Task 2: assign the remaining digits from left to right, giving us 9^4 ways

Hence there are $5 \times 9^4 = 32805$ such numbers.

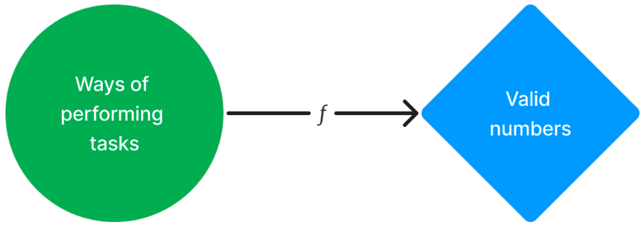
Non-example 20. How many integers $0, 1, \ldots 99999$ have *at least* one digit 6?

Attempt: We can assign tasks:

- Task 1: choose a location for 6, giving us 5 ways
- Task 2: assign the remaining digits from left to right, giving us 10^4 ways

But the answer of 50000 is **wrong**! But why?

The counting process for this problem is corresponding the ways of performing tasks to valid 5-digit numbers:



We have correctly counting the green set. However, for this to count the blue set, we need f to be **bijective**. That is, every valid number must be obtained in exactly one way. However, in this case, our f is surjective but not injective. For instance, 62516 will be counted *twice*:

- 6____ then 62516; or
- ____6 then 62516.

Hence, 50000 > correct answer!

Correct way: Using the subtract principle to deduct numbers that don't have 6: $10^5 - 9^5 = 40951 < 50000$.

C2 Probability

Definition 9.

$$\text{Probability} = \frac{\text{number of favourable cases}}{\text{number of total cases}}$$

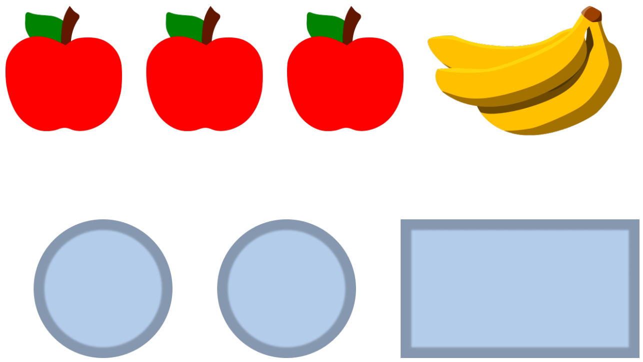
Example 21. Probability of 3 dice rolling the same number: $P = \frac{6}{6^3} = \frac{1}{36}$.

C3 The counting framework

Here is a very general problem:

"How many distinguishable ways to map a multiset S to a multiset T satisfying given constraints?"

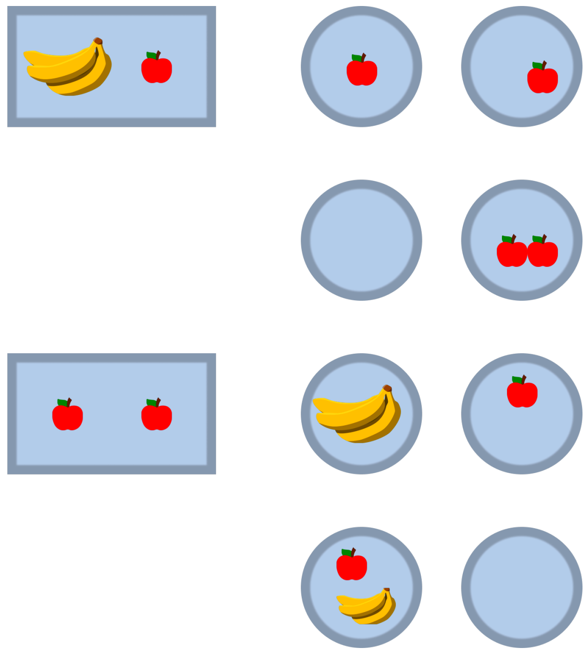
Example 22. There are fruits and plates. Let $S = \{3 \cdot \text{apple}, 1 \cdot \text{banana}\}$ and $T = \{2 \cdot \text{circle}, 1 \cdot \text{rectangle}\}$. How many ways are there to serve fruit on plates such that the rectangular plate has an even number of fruit?



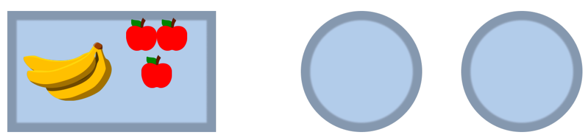
Ans: Organize by number of fruit on rectangle.

0

2



4



Hence there are 9 ways.

The general counting problem

Let there be multisets

$$
\begin{aligned}
S &= \{a_1 \cdot 1, a_2 \cdot 2, \dots, a_s \cdot s\} && \text{object types } 1, 2, \dots, s \\
T &= \{b_1 \cdot U_1, b_2 \cdot U_2, \dots, b_t \cdot U_t\} && \text{box types } U_1, \dots, U_t
\end{aligned}
$$

How many distinguishable maps $f : S \to T$ are there, subject to restrictions on the numbers $u_i = \left|f^{-1}(U_i)\right|$?

← The number of items mapped to boxes of type U_i

Remark (Special cases)**.** To recognize which situation applies to the problem:

- By objects:
  - Distinct: $S = \{1, 2, \dots, s\}$
  - Identical: $S = \{s \cdot 1\}$
- By boxes:

  - Distinct: $T = \{U_1, \dots, U_t\}$
  - Identical: $T = \{t \cdot U_1\}$
- For each case above, we can apply constraints:
  - $0 \le u_i \le 1$
  - $0 \le u_i < \infty$ no constraint
  - $1 \le u_i < \infty$ nonempty
  - $0 \le u_i \le n_i$ for some $n_i \in \mathbb{N}_0$ max. capacity
  - $u_i \in N_i \subseteq \mathbb{N}$

3.3 A Framework for Counting Questions: The Counting Table 95

Table 3.1 Balls and boxes counting problems.

Number of Ways to Put Balls into Boxes $S = S_1 = \{1, 2, \dots, s\}$, or $S = S_2 = \{s \cdot 1\}$, a multiset of balls $T = T_1 = \{U_1, U_2, \dots, U_t\}$, or $T = T_2 = \{t \cdot U_1\}$, a multiset of boxes Box U_i contains u_i balls				
Conditions on S and $T \rightarrow$ on $u_i \downarrow$	$T = T_1$ distinct $S = S_1$ distinct	$T = T_1$ distinct $S = S_2$ identical	$T = T_2$ identical $S = S_1$ distinct	$T = T_2$ identical $S = S_2$ identical
$0 \le u_i \le 1$ Assume $t \ge s$	1	2	3	4
$u_i \ge 0$	5	6	7	8
$u_i \ge 1$	9	10	11	12
for $i = 1, \dots, t$, $0 \le u_i \le n_i$, $n_i \in \mathbb{Z}^{>0}$	13	14		
$u_i \in N_i \subset \mathbb{Z}^{\ge 0}$ for $i = 1, \dots, t$	15	16		

Example 23. We have 10 distinct books to be shared between 2 children. Each child needs 2 books to avoid a crisis. ← Table entry 15

- Distinct objects $\{1, 2, \dots, 10\}$
- Distinct boxes $\{U_1, U_2\}$
- Constraints: $u_i \in [2, \infty[$

Example 24 (Attempt 1)**.** 10 distinct books, 5 of them to be arranged on shelf (order matters) ← Table entry 15

- $S = \{1, 2, \dots, 10\}$
- $T = \{U_1, U_2, \dots, U_5, U_6\}$ (positions on shelf + extra for unshelved books)
- $u_1 = \cdots = u_5 = 1, u_6 = 5$

Example 25 (Attempt 2)**.** 10 distinct books, 5 of them to be arranged on shelf (order matters) ← Table entry 1, easier!

- $S = \{1, 2, \dots, 5\}$ (numbered stickers to arrange books)
- $T = \{U_1, U_2, \dots, U_{10}\}$ (10 books)
- $0 \leq u_1 \leq 1$ (each book can get 0 or 1 sticker)

Example 26. I have 10 books and will take 5 on holiday.

- Take 1: ← Table entry 15
  - $S = \{1, 2, \dots, 10\}$
  - $T = \{U_1, U_2\}$
  - $u_1 = u_2 = 5$
- Take 2: ← Table entry 2
  - $S = \{5 \cdot 1\}$ (identical 'stickers' marking on-holiday)
  - $T = \{U_1, U_2 \ \dots, U_{10}\}$
  - $0 \leq u_1 \leq 1$ (each book can get 0 or 1 sticker)

C4 Permutations of a set

Remark. Recall $[n] = \{1, 2, \dots, n\}$.

Definition 10. Let $0 \leq s \leq t$.

- An s-**permutation** of $[t]$ is an ordered list of s distinct elements of $[t]$.
- A t-**permutation** of $[t]$ is just a **permutation** of $[t]$.

Example 27. 10 books, arrange 5 on shelf: 5-perm of [10]

Example 28. 20 athletes, Gold, Silver and Bronze awarded: 3-perm of [20]

Theorem 10. The number of s-perms of $[t]$ is

$$\underbrace{t(t-1)\dots(t-s+1)}_{s \text{ terms}}$$

Proof. Select elements of the list one-by-one. We have t ways to pick the first, $t-1$ ways of picking the second, etc. □

Definition 11 (s-th falling-factorial function)**.** This inspires the following notation

$$(x)_s = x(x-1)\dots(x-s+1) = \frac{t!}{(t-s)!}$$

← There is also a rising $(x)^s = x(x+1)\dots(x+s-1)$

Remark. $(x)_0 = 1, (n)_n = n!$

Example 29. Number of ways to shelve 5 books out of 10 is

$$(10)_5 = 10 \times 9 \times 8 \times 7 \times 6 = 30240$$

C5 Circular permutations

A circular 5-perm of $[n]$ is an arrangement of s distinct elements of $[n]$ around a round table. The difference from a non-circular perm is that the orientation of the table does not matter! How many ways to do so?

If there is a head of the table and positions are marked clockwise, then it would be the same as the s-perm $(n)_s$.

However, we consider all ways of marking the 'head' of the tablen to be equivalent, so we divide s upon that. Hence, we get the answer $\frac{1}{s}(n)_s = \frac{n!}{s(n-s)!}$.

C6 Table entries 3,4,5

- 3 : s distinct objects, t identical boxes, 0 or 1 per box.

$$\# \text{ ways} = \begin{cases} 1 & s \le t \\ 0 & \text{otherwise} \end{cases}$$

- $\boxed{4}$: s identical objects, t identical boxes, 0 or 1 per box.

$$\# \text{ ways} = \begin{cases} 1 & s \leq t \\ 0 & \text{otherwise} \end{cases}$$

- $\boxed{5}$: s distinct objects, t distinct boxes, no restrictions.

$$\# \text{ ways} = \underbrace{t \times t \times \cdots \times t}_{s \text{ times}} = t^s$$

Remark. $0^0 = 1$ in combinatorics. ← NOT in analysis!!

3.3 A Framework for Counting Questions: The Counting Table 95

Table 3.1 Balls and boxes counting problems.

Number of Ways to Put Balls into Boxes

$S = S_1 = \{1, 2, \ldots, s\}$, or $S = S_2 = \{s \cdot 1\}$, a multiset of balls

$T = T_1 = \{U_1, U_2, \ldots, U_t\}$, or $T = T_2 = \{t \cdot U_1\}$, a multiset of boxes

Box U_i contains u_i balls

Conditions on S and T → on u_i ↓	$T = T_1$ distinct $S = S_1$ distinct	$T = T_1$ distinct $S = S_2$ identical	$T = T_2$ identical $S = S_1$ distinct	$T = T_2$ identical $S = S_2$ identical
$0 \leq u_i \leq 1$ Assume $t \geq s$	$\boxed{1}$	$\boxed{2}$	$\boxed{3}$	$\boxed{4}$
$u_i \geq 0$	$\boxed{5}$	$\boxed{6}$	$\boxed{7}$	$\boxed{8}$
$u_i \geq 1$	$\boxed{9}$	$\boxed{10}$	$\boxed{11}$	$\boxed{12}$
for $i = 1, \ldots, t$, $0 \leq u_i \leq n_i$, $n_i \in \mathbb{Z}^{>0}$	$\boxed{13}$	$\boxed{14}$		
$u_i \in N_i \subset \mathbb{Z}^{\geq 0}$ for $i = 1, \ldots, t$	$\boxed{15}$	$\boxed{16}$		

C7 Combinations of sets: table entries 2,6,10

If we let $0 \le s \le t$, then an s-**combination of** $[t]$ is a subset of size s of $[t]$.

Definition 12. The binomial coefficient $\binom{t}{s}$ is defined (combinatorially) to be the number of s-combinations of $[t]$.

Theorem 11.

$$\binom{t}{s} = \frac{(t)_s}{s!} = \frac{t!}{(t-s)!s!}$$

Proof. Consider the number of s-perms of $[t]$.

We can count it directly: $(t)_s$.

Alternatively, make task 1 'selecting a subset of size s', which gives us $\binom{t}{s}$ ways. Make task 2 the ways of ordering a subset, which give $s!$ ways. By multiplication principle, the number of s-perms of $[t]$ is $\binom{t}{s}s!$.

We have $(t)_s = \binom{t}{s}s!$, giving us the formula above. □

Example 30. All of the following are equivalent and satisfy table entry 2 : ← $0 \le u_i \le 1$

- Select s books out of t distinct books;
- Place s stickers on t books, at most one sticker per book;
- Put s identical objects into t distinct boxes, each box can only have at most 1 object.

Example 31. These equivalent problems satisfy table entry 6 : ← $0 \le u_i < \infty$

- Solutions to $x_1 + x_2 + x_3 + x_4 + x_5 = 12$ where $x_i \ge 0$ are integers.
- Packing a box of 12 bagels of 5 different types of bagels with unlimited supply.
- Number of permutations of 12 objects and 4 'drawer dividers':

$$\bullet\bullet \mid \bullet\bullet\bullet \mid \bullet\bullet \mid \bullet\bullet\bullet\bullet \mid \bullet$$

Remark. In general, when we count the number of anagrams s •s and $t-1$ |s, there are $s+t-1$ total symbols. We must select s of the $s+t-1$ positions to be •. Hence, the number of ways would be

← LHS is choose •, RHS is choose |.

$$\binom{s+t-1}{s} = \binom{s+t-1}{t-1}$$

Example 32. Entry 10 is the same as 6 except that each box must be nonempty:

- Solutions to $x_1 + \cdots + x_s = t$ where $x_i \geq 1$ integers.
- Select s bagels from t types, with each type chosen at least once.
  This reduces to the prev problem: select one of each type of bagel first; then, we choose $s - t$ bagels of t types.
- Anagrams with s •s and $t-1$ |: must avoid || and | at beginning or end. Then we could think about placing $t-1$ dividers in the $s-1$ spaces between •s, giving us $\binom{s-1}{t-1}$ ways.

C8 Anagrams

Example 33. Find the number of anagrams of the word

COMBINATORIALISTICALLY

First, suppose all 22 letters were distinct. We put subscripts:

$$\mathrm{C_1O_1MBI_1NA_1T_1O_2RI_2A_2L_1I_3ST_2I_4C_2A_3L_2L_3Y}$$

Now we have this multiset:

$$\{2\mathrm{C}, 2\mathrm{O}, \mathrm{M}, \mathrm{B}, 4\mathrm{I}, \mathrm{N}, 3\mathrm{A}, 2\mathrm{T}, \mathrm{R}, 3\mathrm{L}, \mathrm{S}, \mathrm{Y}\}$$

We want to find the ways of arranging this!

- Assuming everything is distinct: 22! ways.
- Same assumption but with two tasks in multiplication:
  - Task 1: Arrange without subscripts (what we want)
  - Task 2: Add subscripts: the number of ways to add them is

$$2! \times 2! \times 1! \times 1! \times 4! \times 1! \times 3! \times 2! \times 1! \times 3! \times 1! \times 1!$$

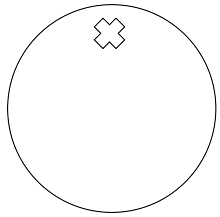
Therefore, our answer would be (in multinomial coefficient) ← DO NOT LEAVE OUT 1s

$$\frac{22!}{2! \times 2! \times 1! \times 1! \times 4! \times 1! \times 3! \times 2! \times 1! \times 3! \times 1! \times 1!} = \binom{22}{2, 2, 1, 1, 4, 1, 3, 2, 1, 3, 1, 1}$$

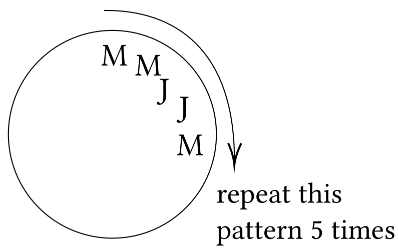
C9 More circular tables

Example 34. An alien conference has 9 Martian hare delegates and 16 Jovian hare delegates, with each type of hare identical. How many distinguishable ways are there to seat them at a circular table?

Method: first consider the ways of arrangement at a marked table.



- We seat 9 Martian hares and fill out the rest with Jovian ones: $\binom{25}{9}$.
- We place all hares (the answer we want) and then mark the table. In the end we should get the same answer of $\binom{25}{9}$.
  - How do we mark the table? There are 25 places that can be marked, but not all of them are distinct! For instance:



then the table only has 5 distinct markings due to rotational symmetry.

Theorem 12. Consider an arrangement on a circular table with n spots. Let R_k be the action of rotating this table by k places. Define:

← F is the *stabilizer* of the group action

$$F = \{k \in \mathbb{Z} \mid R_k \text{ leaves the arrangement unchanged}\}$$

Then we have:

1. F is the set of multiples of some $d|n$.
2. A length d pattern would be repeated $\frac{n}{d}$ times (so there are only $\frac{n}{d}$ distinct markings)

Proof. Let d be the smallest positive integer such that $R_d \in F$. Suppose BWOC $k \in F$ but $d \nmid k$. Then let $k = md + r$ with $r \leq d$, and rotation by r would be: $R_k R_{-md}$. Since $k \in F$, this also fixes the arrangement. However, $r < d$ contradicts the fact that d is the smallest positive integer such that $R_d \in F$. □

← Review Abstract Alg. 1

Back to Example 34: $F = d\mathbb{Z}$ where $d = 1, 5, 25$.

- If $d = 1$, 25 ways of marking the table.

- $d = 5$, 5 ways of marking.
- $d = 25$, 1 way of marking.

Definition 13 (Multichoose notation)**.** Define the ways to select a bag of k items from n different types of item to be $\left(\binom{n}{k}\right) = \binom{k+n-1}{k} = \binom{k+n-1}{n-1}$.

D Binomial Coefficients

We know that $\binom{n}{k}$ is the number of k-subsets of $[n]$, which is $\frac{n!}{k!(n-k)!}$.

D1 Binomial identities

Proposition 13.

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

That is, the number of ways to get k-subsets in $[n]$ is the same as that of $n-k$-subsets.

Proposition 14.

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

This is because the RHS counts **all** subsets of $[n]$, while each summand on the LHS counts the number of k-subsets thereof.

Proposition 15. For $n \geq 1$,

$$\binom{n}{0} + \binom{n}{2} + \cdots + \binom{n}{2\lfloor \frac{n}{2} \rfloor} = 2^{n-1}$$

This is because the RHS chooses any subset of $[n-1]$, then makes the subset **even** by putting or not putting the n into it (the n doesn't get to choose).

← $\lfloor a \rfloor$ is the largest integer $\leq a$

Proposition 16 (Binomial recurrence)**.**

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

This is because the LHS chooses k-subsets of $[n]$, and the RHS splits the case into 1) the subset contains n, which gives us $\binom{n-1}{k-1}$ ways to choose the rest, and 2) the subset doesn't contain n, which gives us $\binom{n-1}{k}$.

This allows us to construct the table:

$n\backslash k$	0	1	2	3	4
0	1	0	0	0	0
1	1	1	0	0	0
2	1	2	1	0	0
3	1	3	3	1	0
4	1	4	6	4	1

Proposition 17.

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

Say there are $2n$ students: n in class G and n in class S. We need to choose n students.

- Method 1: choose n students: $\binom{2n}{n}$
- Method 2: let $k = 0, 1, \ldots, n$. Select k S to go and select k G to NOT go. Then we have $\binom{n}{k}$ for each of the process. Hence, the total number of ways is $\sum_{k=0}^{n} \binom{n}{k}^2$.

D2 Binomial theorem

Theorem 18. Let $n \geq 0$ be an integer. Then:

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

← This gives a relationship between the Karaji/Pascal triangle and polynomial algebra.

Proof.

$$(x + y)^n = (x + y)(x + y) \ldots (x + y)$$

A typical term looks like n terms x, y multiplied together, in some amount: $x^{n-k}y^k$.

We get that term by selecting k partentheses to take the y from, and we take x from the rest. This gives $\binom{n}{k}$ ways. □

Example 35.

$$\begin{aligned}
(x+y)^0 &= 1,\\
(x+y)^1 &= x+y,\\
(x+y)^2 &= x^2+2xy+y^2,\\
(x+y)^3 &= x^3+3x^2y+3xy^2+y^3,\\
(x+y)^4 &= x^4+4x^3y+6x^2y^2+4xy^3+y^4,\\
(x+y)^5 &= x^5+5x^4y+10x^3y^2+10x^2y^3+5xy^4+y^5,\\
(x+y)^6 &= x^6+6x^5y+15x^4y^2+20x^3y^3+15x^2y^4+6xy^5+y^6,\\
(x+y)^7 &= x^7+7x^6y+21x^5y^2+35x^4y^3+35x^3y^4+21x^2y^5+7xy^6+y^7,\\
&\ldots
\end{aligned}$$

Example 36.

$$\begin{aligned}
1.01^5 &= \sum_{k=0}^{5}\binom{5}{k}0.01^k\\
&= 1.010510100501
\end{aligned}$$

Table 2: Jia-Karaji triangle up to $n = 20$.

1																				
1	1																			
1	2	1																		
1	3	3	1																	
1	4	6	4	1																
1	5	10	10	5	1															
1	6	15	20	15	6	1														
1	7	21	35	35	21	7	1													
1	8	28	56	70	56	28	8	1												
1	9	36	84	126	126	84	36	9	1											
1	10	45	120	210	252	210	120	45	10	1										
1	11	55	165	330	462	462	330	165	55	11	1									
1	12	66	220	495	792	924	792	495	220	66	12	1								
1	13	78	286	715	1287	1716	1716	1287	715	286	78	13	1							
1	14	91	364	1001	2002	3003	3432	3003	2002	1001	364	91	14	1						
1	15	105	455	1365	3003	5005	6435	6435	5005	3003	1365	455	105	15	1					
1	16	120	560	1820	4368	8008	11440	12870	11440	8008	4368	1820	560	120	16	1				
1	17	136	680	2380	6188	12376	19448	24310	24310	19448	12376	6188	2380	680	136	17	1			
1	18	153	816	3060	8568	18564	31824	43758	48620	43758	31824	18564	8568	3060	816	153	18	1		
1	19	171	969	3876	11628	27132	50388	75582	92378	92378	75582	50388	27132	11628	3876	969	171	19	1	
1	20	190	1140	4845	15504	38760	77520	125970	167960	184756	167960	125970	77520	38760	15504	4845	1140	190	20	1

D3 Further binomial identities

Immediate consequences from the binomial theorem:

Corollary 19. $(1+x)^n = \sum_{k=1}^{n} \binom{n}{k} x^k$

And therefore,

Corollary 20. $2^n = \sum_{k=0}^{n} \binom{n}{k}$, $0^n = \sum_{k=0}^{n} (-1)^k \binom{n}{k}$

← take $x = 1$ or $x = -1$

Theorem 21. Observe:

(a)

$$\sum_{k=1}^{n} k\binom{n}{k} = 1\binom{n}{1} + 2\binom{n}{2} + \cdots + n\binom{n}{n} = n \cdot 2^{n-1}$$

(b)

$$\sum_{k=1}^{n} k\binom{n}{k} = 1\binom{n}{1} + 2\binom{n}{2} + \cdots + n\binom{n}{n} = (n+1)n2^{n-2}$$

(Scratch work begins)

(a)

$$\begin{array}{llllll}
0 \cdot 1 & & & & & \\
0 \cdot 1 & 1 \cdot 1 & & & & = 1 = 1 \times 1 \\
0 \cdot 1 & 1 \cdot 2 & 2 \cdot 1 & & & = 4 = 2 \times 2 \\
0 \cdot 1 & 1 \cdot 3 & 2 \cdot 3 & 3 \cdot 1 & & = 12 = 3 \times 4 \\
0 \cdot 1 & 1 \cdot 4 & 2 \cdot 6 & 3 \cdot 4 & 4 \cdot 1 & = 32 = 4 \times 8
\end{array}$$

(b)

$$\begin{array}{llllll}
0 \cdot 1 & & & & & \\
0 \cdot 1 & 1 \cdot 1 & & & & = 1 = 1 \times 1 \\
0 \cdot 1 & 1 \cdot 2 & 4 \cdot 1 & & & = 6 = 3 \times 2 \\
0 \cdot 1 & 1 \cdot 3 & 4 \cdot 3 & 9 \cdot 1 & & = 24 = 6 \times 4 \\
0 \cdot 1 & 1 \cdot 4 & 4 \cdot 6 & 9 \cdot 4 & 16 \cdot 1 & = 80 = 10 \times 8
\end{array}$$

(Scratch ends here)

Proof (a), method 1. We know $\sum_{k=0}^{n}\binom{n}{k}x^k \equiv (1+x)^n$. Hence, we can take the derivative of both sides:

$$\sum_{k=1}^{n} k\binom{n}{k}x^{k-1} \equiv n(1+x)^{n-1}$$

Now let $x = 1$ and obtain $\sum_{k=1}^{n} k\binom{n}{k} = n \cdot 2^{n-1}$. □

Proof (b), method 1. Similar to proof (a) but we first multiply both sides of the differentiated equation in (a) by x: $\sum_{k=1}^{n} k\binom{n}{k}x^k \equiv xn(1+x)^{n-1}$. Then we differentiate it again and plug in $x = 1$. □ ← check this!

Proof (a), method 2. We let there be n people, with k of them selected to join the elite squad™. One of the people in elite squad™ is given a secret microfiche. In how many ways can this be done?

Way 1: Choose k be the size of the elite squad™, so k could be anything from 1 to n. We need to choose k people among n, giving us $\binom{n}{k}$ ways. Then, we choose one person among the k to give a microfiche. The total number of ways is $\sum_{k=1}^{n}\binom{n}{k}k$.

Way 2: Assign a microfiche, which can be done in n ways. Decide who else is in the squad: it is either 'yes' (in the elite squad™) or 'no'. Hence, we make a binary decision for $n-1$ people, which gives us 2^{n-1} ways. The total number of ways is $n \cdot 2^{n-1}$.

Both methods give the same answer. □

Proof (b), method 2. We let there be n people, with k of them selected to jointhe elite squad™. One of the person in elite squad™ is given a homework problem. One of the person (could be the same) in elite squad™ is given an investigation problem. In how many ways can this be done?

Way 1: Choose k be the size of the elite squad™, so k could be anything from 1 to n. We need to choose k people among n, giving us $\binom{n}{k}$ ways. Then, we choose one person among the k to give homework, and choose again to give an investigation. The total number of ways is $\sum_{k=1}^{n}\binom{n}{k}k^2$.

Way 2: We first consider the case where the homework and investigation go to the same person. Assign them, which can be done in n ways. Decide who else is in the squad: it is either 'yes' (in the elite squad™) or 'no'. Hence, we make a binary decision for $n-1$ people, which gives us 2^{n-1} ways. The total number of ways is $n \cdot 2^{n-1}$.

Next, we consider the case where the homework and investigation go to different people. Assign homework, which can be done in n ways. Then, assign investigation, which can be given to the rest $n-1$ people. We then decide who else is in the squad, giving us 2^{n-2} ways.
Hence, we have $n \cdot 2^{n-1} + n(n-1) \cdot 2^{n-2} = n(n+1)2^{n-2}$ ways.

Both methods give the same answer. □

D4 Newton's Binomial Theorem

Theorem 22 (Newton)**.** If $x, y \in \mathbb{R}$ and $|\frac{y}{x}| < 1$, let $\alpha > 0$ be real. Then ← not only integers!

$$(x+y)^\alpha = \sum_{k=0}^{\infty} \binom{\alpha}{k} x^{\alpha-k} y^k = x^\alpha \sum_{k=0}^{\infty} \binom{\alpha}{k} \left(\frac{y}{x}\right)^k$$

where $\binom{\alpha}{k} = \frac{(\alpha)_k}{k!}$ and $(\alpha)_k = \alpha(\alpha-1)\dots(\alpha-k+1)$ is the falling factorial.

Proof. Let $f(z) = (1+z)^\alpha$. Then $f^{(k)}(z) = (\alpha)_k(1+z)^{\alpha-k}$ and so $f^{(k)}(0) = (\alpha)_k$. By the Taylor series of $f(z)$, we get $f(z) = \sum_{k=0}^{\infty} \frac{(\alpha)_k}{k!} z^k$ for all $|z| < 1$. □

Example 37. What is the $\frac{1}{2}$th row of the Karaji triangle?

k	0	1	2	3	4	5	...
$\left(\frac{1}{2}\right)_k$	1	$\frac{1}{2}$	$\frac{-1}{4}$	$\frac{3}{8}$	$\frac{-15}{16}$	$\frac{105}{32}$	
$\binom{\frac{1}{2}}{k}$	1	$\frac{1}{2}$	$\frac{-1}{8}$	$\frac{1}{16}$	$\frac{-5}{128}$	$\frac{7}{256}$	

Example 38.

$$\begin{aligned}\sqrt{103} &= \sqrt{100+3} \\ &= 10 \sum_{k=0}^{\infty} \binom{\frac{1}{2}}{k} \left(\frac{3}{100}\right)^k \\ &= 10 \cdot \left(1 + \frac{15}{1000} - \frac{1125}{10^7} + \dots\right) \\ &\simeq 10.148875\end{aligned}$$

Actual answer: 10.14889...

D5 Simplex numbers

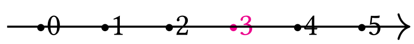
Recall the simplex numbers $T_d(n)$:

$d \backslash n$	1	2	3	4	5	6	7
1	1	2	3	4	5	6	7
2	1	3	6	10	15	21	28
3	1	4	10	20	35	56	84
4	1	5	15	35	70	126	210
5	1	6	21	56	126	252	462

Observe that these are the same as binomial coefficients and just organised differently!

Consider teh nonnegative integer lattice in $d+1$ dimensions: $\mathbb{N}^{d+1} \subseteq \mathbb{R}^{d+1}$. What are the points $(a_0, a_1, \dots, a_d)$ such that $a_0 + a_1 + \cdots + a_d = k$ for a given $k \geq 0$? How many are there?

Example 39. When $k = 3$ and $d = 0$:



In general, the number of points on the plane satisfying $x_0 + x_1 + \cdots + x_d = k - 1$ is equal to $T_d(k)$. From our multichoose argument, this is $T_d(k) = \binom{d+k-1}{d} = \left(\!\binom{k}{d}\!\right)$.

E Catalan numbers

E1 Examples

Example 40. How many sequecnes $a_1, a_2, \dots, a_n$ are there, where n of the terms are $+1$ and n are -1, such that the partial sums are all nonnegative? That is, $a_1 + a_2 + \cdots + a_k \geq 0$ for all k?

The problem concerns a multiset: n objects of type 1 and n of type 2. We want to count the number of permutations such that the number of type 1 occuring in the first k letters is $\geq$ the number of type 2 occuring in the first k letters for all $k = 0, 1, \dots, 2n$.

Definition 14. Let C_n be the number of permutations as above. This is the n-th **Catalan number**.

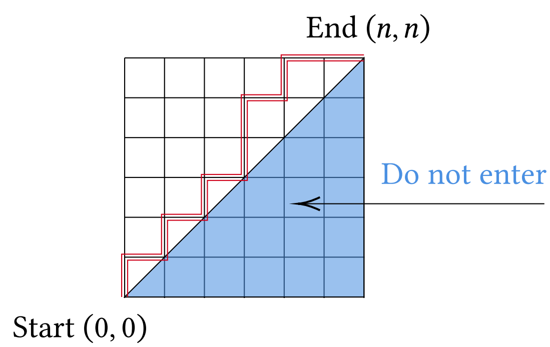
We can calculate a few:

n	C_n	$\binom{2n}{n}$	$C_n/\binom{2n}{n}$
0	1	1	1
1	1	2	1/2
2	2	6	1/3
3	5	20	1/4
4	14	70	1/5

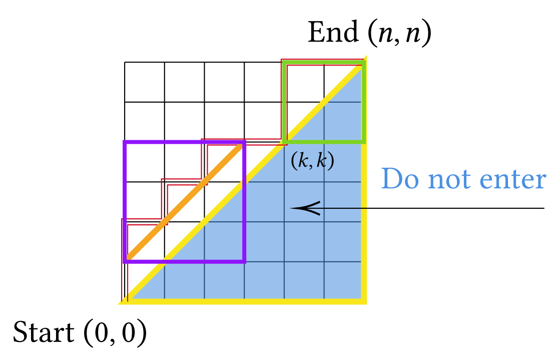
Example 41. C_n is also the number of anagrams of $\underbrace{NN\ldots N}_{n}\underbrace{EE\ldots E}_{n}$ such that every initial segment has more N than E.

Conjecture: $C_n = \frac{1}{n+1}\binom{2n}{n}$

E2 First attempt



Question: when is the **first time** we return to the diagonal? That is, what is the smallest $k \in \{1, 2, \ldots, n\}$ such that we get (k, k)?



Steps:

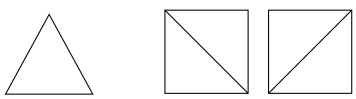
1. $(0,0) \to (0,1)$ — 1 way
2. $(0,1) \to (k-1,k)$ w/o crossing orange line — C_{k-1} ways ← in the purple square
3. $(k-1,k) \to (k,k)$ — 1 way
4. $(0,1) \to (k-1,k)$ w/o crossing yellow line — C_{n-k} ways ← in the green square

Hence ← the Catalan recurrence

$$C_n = \sum_{k=1}^{n} C_{k-1}C_{n-k}$$

And so $C_n = C_0C_{n-1} + \cdots + C_{n-1}C_0$.

Example 42. How many ways to triangulate a convex 47-sided polygon by drawing diagonals? ANS: D_{47}!



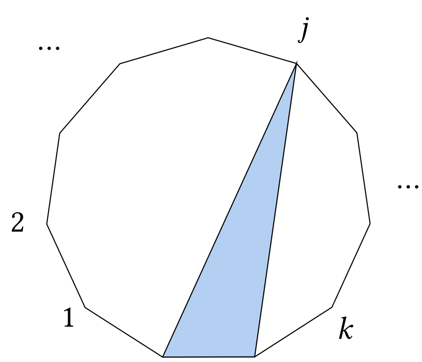
Examples: $D_3 = 1$ $\quad$ $D_4 = 2$ $\quad \ldots$

Conjecture: $D_n = C_{n-2}$

Induction proof. Base case is done as shown above.

Inductive step: suppose it works for $n = 2, 3, \ldots, k+1$. Now we want to show $D_{k+2} = C_k$.

Case j: we pick a side that has a triangle that goes to the vertex j.



On the left, we have a $j+1$ sided polygon and so the number of ways of triangulation is $D_{j+1} = C_{j-1}$.

On the right, we have a $k-j+2$ sided polygon and so the number of ways of triangulation is $D_{k-j+2} = C_{k-j}$.

Hence, the number of ways in total is $C_{j-1} \cdot C_{k-j}$. We conclude that

$$D_{k+2} = \sum_{j=1}^{k} C_{j-1} C_{k-j} = C_k$$

by the Catalan recurrence. □

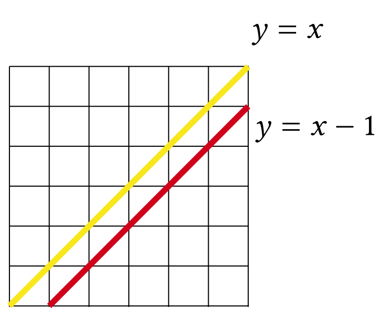
E3 The Catalan bijection

Suppose a path $(0,0) \to (n,n)$ is **good** if it does not cross the diagonal $y = x$. We claim that the count of good paths is $\frac{1}{n+1}\binom{2n}{n}$.

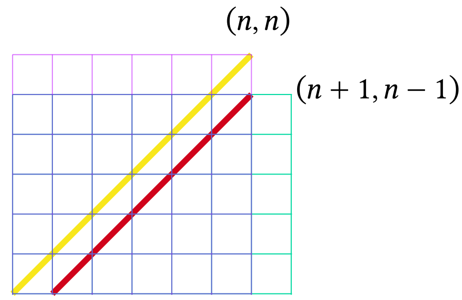
Alternatively, we could show that the number of **bad** paths is # all paths $- \frac{1}{n+1}\binom{2n}{n}$, which means we want to show:

$$\begin{aligned} \#\ \textbf{bad}\ \text{paths} &= \binom{2n}{n} - \frac{1}{n+1}\binom{2n}{n} \\ &= \frac{n}{n+1}\binom{2n}{n} \\ &= \frac{n}{n+1} \frac{(2n)!}{n!n!} \\ &= \frac{(2n)!}{(n-1)!(n+1)!} \\ &= \binom{2n}{n+1} \end{aligned}$$

A **bad** path is one that crosses the diagonal $y = x$, but that is equivalent to touching the subdiagonal $y = x - 1$.



Claim: the number of paths $(0,0) \to (n,n)$ that touch the red line is the same as the number of paths $(0,0) \to (n+1, n-1)$.



The latter quantity is just $\binom{2n}{n+1}$.

We use the following bijection:

$$\begin{array}{c} \text{Bad path to } (n,n) \\ \Big\updownarrow \; \begin{array}{l} \text{Keep path the same up} \\ \text{to the first time it hits the} \\ \text{red subdiagonal. After that,} \\ \text{swap } N \leftrightarrow E \text{ (reflect path} \\ \text{across the red line)} \end{array} \\ \text{(Bad) path to } (n+1, n-1) \end{array}$$

$\leftarrow$ all paths are bad to $(n+1, n-1)$!

F Stirling numbers

F1 Table entries 11, 9, 7

3.3 A Framework for Counting Questions: The Counting Table 95

Table 3.1 Balls and boxes counting problems.

Number of Ways to Put Balls into Boxes $S = S_1 = \{1, 2, \ldots, s\}$, or $S = S_2 = \{s \cdot 1\}$, a multiset of balls $T = T_1 = \{U_1, U_2, \ldots, U_t\}$, or $T = T_2 = \{t \cdot U_1\}$, a multiset of boxes Box U_i contains u_i balls				
Conditions on S and $T \rightarrow$ on $u_i \downarrow$	$T = T_1$ distinct $S = S_1$ distinct	$T = T_1$ distinct $S = S_2$ identical	$T = T_2$ identical $S = S_1$ distinct	$T = T_2$ identical $S = S_2$ identical
$0 \leq u_i \leq 1$ Assume $t \geq s$	1	2	3	4
$u_i \geq 0$	5	6	7	8
$u_i \geq 1$	9	10	11	12
for $i = 1, \ldots, t$, $0 \leq u_i \leq n_i$, $n_i \in \mathbb{Z}^{>0}$	13	14		
$u_i \in N_i \subset \mathbb{Z}^{\geq 0}$ for $i = 1, \ldots, t$	15	16		

11 : How many ways to place s distinct objects into t **unmarked** boxes such that none of the boxes are empty?
$\Leftrightarrow$ organizing s distinct people into t nonempty teams.
We don't know the (closed-form) answer yet, so we temporarily call it $\left\{ s \atop t \right\}$.

$\leftarrow$ Distinct objects, identical boxes, $u_i \geq 1$

Example 43. We have 4 people: A,B,C and D, and we group them into 3 teams. This is the situation $s = 4, t = 3$. We group:

- AB|C|D
- AC|B|D
- AD|B|C
- BC|A|D
- BD|A|C
- CD|A|B

Therefore, $\left\{ {4 \atop 3} \right\} = 6$.

9 : How many ways to place s distinct objects into t **named** boxes such that none of the boxes are empty?
$\Leftrightarrow$ organizing s distinct people into t nonempty teams with different team names.
Compared with 11 , this gives $t!$ more ways due to the labelling. Therefore, the answer is $t!\left\{ {s \atop t} \right\}$.

← Distinct objects, distinct boxes, $u_i \geq 1$

Remark. This is the same as counting the number of *surjective* functions

$$\{1, 2, \dots, s\} \to \{1, 2, \dots, t\}$$

we expect some relationship with the quantity t^s, which counts all functions.

7 : How many ways to place s distinct objects into t **unmarked** boxes?

Answer: $\displaystyle\sum_{k=0}^{t} \left\{ {s \atop k} \right\}$ where k is the # of nonempty boxes.

← Distinct objects, identical boxes, $u_i \geq 0$. i.e. 11 but boxes can be empty

Remark. Observe:

$u_i \geq 0$	5 t^s	7 $\sum_{k=0}^{t} \left\{ {s \atop k} \right\}$
$u_i \geq 1$	9 $t!\left\{ {s \atop t} \right\}$	11 $\left\{ {s \atop t} \right\}$

We can get 9 by multiplying 11 by $t!$, but we cannot get 5 from 7 in the same way due to the empty boxes!

The ways to label boxes in 5 is only $(t)_k$ ways for each # of nonempty boxes k.

Conclusion:

$$t^s = \sum_{k=0}^{t} (t)_k \left\{ {s \atop k} \right\}$$

It follows that the quantities $0^s, 1^s, \dots, s^s$ are *linearly* related to $\left\{ {s \atop 0} \right\}, \left\{ {s \atop 1} \right\}, \dots, \left\{ {s \atop s} \right\}$.

Example 44. Let $s = 3$.

$$\begin{bmatrix} 0 \\ 1 \\ 8 \\ 27 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 2 & 2 & 0 \\ 1 & 3 & 6 & 6 \end{bmatrix} \cdot \begin{bmatrix} \left\{ {3 \atop 0} \right\} \\ \left\{ {3 \atop 1} \right\} \\ \left\{ {3 \atop 2} \right\} \\ \left\{ {3 \atop 3} \right\} \end{bmatrix}$$

where every entry (i, j) of the matrix is $(i)_j$.

We can invert the matrix to find what $\left\{ {s \atop t} \right\}$ is, but it's computationally quite terrible!

F2 Stirling numbers of the second kind

Definition 15 (Stirling numbers of the second kind)**.**

$$\left\{ {s \atop t} \right\} = \text{\# of ways to place } s \text{ distinct objects into } t \text{ identical empty boxes}$$

Proposition 23.

1. $\left\{ {s \atop t} \right\} = 0$ if $t > s$ — too many boxes
2. $\left\{ {s \atop s} \right\} = 1$ — must have object in its own box
3. $\left\{ {s \atop 1} \right\} = 1$ for $s \geq 1$ — everything in 1 box
4. $\left\{ {s \atop s-1} \right\} = \binom{s}{2}$ — which 2 ppl in the team of 2, rest solo
5. $\left\{ {s \atop 2} \right\} = 2^{s-1} - 1$

   Ways:
   (a) Ask who else among the $s - 1$ people are my team, count the possibilities. Subtract the case when everyone is in my team for the other team to be nonempty.
   (b) Categorize s people into two *distinct* boxes, which gives us 2^s ways. Then, subtract the 2 ways where everyone is in the same box. Finally, since the boxes aren't distinct after all, we divide the result by 2!.
6. $\left\{ {s \atop 0} \right\} = \begin{cases} 1 & \text{if } s = 0 \\ 0 & \text{if } s \geq 1 \end{cases}$

$s \backslash t$	0	1	2	3	4	5	6	Row sum
0	1	0	0	0	0	0	0	1
1	0	1	0	0	0	0	0	1
2	0	1	1	0	0	0	0	2
3	0	1	3	1	0	0	0	5
4	0	1	7	6	1	0	0	15
5	0	1	15	25	10	1	0	522
6	0	1	31	90	65	15	1	203

← The row sums are Bell numbers!

Theorem 24.

$$\left\{ {s \atop t} \right\} = t \left\{ {s-1 \atop t} \right\} + \left\{ {s-1 \atop t-1} \right\}$$

Understand this as placing people $1, 2, \ldots, s$ into teams $T_1, \ldots, T_t$.

From perspective of person s:

Case 1: Person s is alone, so $\left\{ {s-1 \atop t-1} \right\}$ ways to organize the rest.

Case 2: Person s is not alone.

- Organize the rest into t teams, which is $\left\{ {s-1 \atop t} \right\}$ ways.
- Join one of the teams, which is t ways.

Add the two cases.

F3 Stirling numbers of the first kind

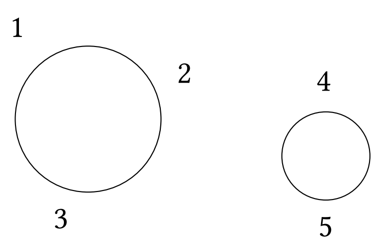
Definition 16 (Stirling numbers of the first kind)**.**

$\left[{n \atop k} \right]$ = # of ways of seating n people at k circular tables (no empty table)

In general, $\left[{n \atop k} \right] \geq \left\{ {n \atop k} \right\}$ (usually a lot bigger) because of the extra choices needed to seat the k teams at tables.

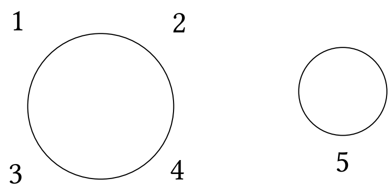
Example 45. We let $n = 5, k = 2$.

Case 1: split into 3+2



- Choose two people to sit at the table for two: $\binom{5}{2}$=10
- Place around the circular tables: $(3-1)! \times (2-1)! = 2$

Case 2: split into 4+1



- Choose 1 person to sit alone: 5
- Place around circular table: $(4-1)! = 6$

Hence, the total ways is $\left[{5 \atop 2}\right] = 20 + 30 = 50$.

Remark. The first task of each case gives us $\left\{{5 \atop 2}\right\} = 10 + 5 = 15$. We can get crude bounds:

$$2\left\{{5 \atop 2}\right\} < \left[{5 \atop 2}\right] < 6\left\{{5 \atop 2}\right\}$$

Proposition 25.

1. $\left[{n \atop k}\right] = 0$ if $k > n$: too many tables
2. $\left[{n \atop 0}\right] = 0$ if $n \geq 1$: not enough tables
3. $\left[{n \atop n}\right] = 1$: one person per table
4. $\left[{n \atop 1}\right] = (n-1)!$ for $n \geq 1$: simple circular permutation
5. $\left[{n \atop n-1}\right] = \binom{n}{2}$: which 2 sit at the table for 2

Table of values of $\left[{n \atop k}\right]$

$s \backslash t$	0	1	2	3	4	5	6	Row sum	Alternating sum
0	1	0	0	0	0	0	0	1	1
1	0	1	0	0	0	0	0	1	-1
2	0	1	1	0	0	0	0	2	0
3	0	2	3	1	0	0	0	6	0
4	0	6	11	6	1	0	0	24	0
5	0	24	50	35	10	1	0	120	0
6	0	120	274	225	85	15	1	720	0

Theorem 26.

$$\left[{n \atop k}\right] = (n-1)\left[{n-1 \atop k}\right] + \left[{n-1 \atop k-1}\right]$$

Proof. Consider from the perspective of yourself. We seat n people at k table.

- You sit alone:
  - You seat the rest of the people at $k-1$ tables: $\begin{bmatrix} n-1 \\ k-1 \end{bmatrix}$ ways
  - Claim the last table by yourself
- You don't sit alone:
  - Seat the rest of the people at k tables: $\begin{bmatrix} n-1 \\ k \end{bmatrix}$ ways
  - You sit to the left of somebody: $n-1$ ways

□

Theorem 27.

$$\sum_{k=0}^{n} \begin{bmatrix} n \\ k \end{bmatrix} = n!$$

Proof outline. We claim:

$$\begin{aligned} \text{LHS} &= \text{\# ways to seat } n \text{ people at circular tables} \\ \text{RHS} &= \text{\# permutations of } [n] = \{1, 2, \dots, n\} \end{aligned}$$

and there is a bijections between ways to seat n people at circular tables and permutations of $[n]$. □

← Consider the elements of S_n.

Theorem 28.

$$\sum_{k=0}^{n} (-1)^k \begin{bmatrix} n \\ k \end{bmatrix} = \begin{cases} 1 & n = 0 \\ -1 & n = 1 \\ 0 & n \geq 2 \end{cases}$$

Sketch. We are effectively counting the permutations with ± sign according to whether the number of cycles is even or odd.

It turns out:

$$(-1)^{\text{\# cycles}} = (-1)^n \cdot (\text{sign of permutation})$$

and follows that

$$LHS = (-1)^n \cdot \det \begin{bmatrix} 1 & 1 & \dots & 1 \\ 1 & 1 & \dots & 1 \\ \vdots & \vdots & \ddots & \vdots \\ 1 & 1 & \dots & 1 \end{bmatrix}$$

Since $\det[] = 1$, $\det[1] = 1$ and $\det = 0$ otherwise, we are done. □

Theorem 29.

$$1 + \frac{1}{2} + \frac{1}{3} + \cdots + \frac{1}{n} = \frac{\begin{bmatrix} n+1 \\ 2 \end{bmatrix}}{n!}$$

Proof by induction. True for:

$$\begin{aligned}1 &= \frac{1}{1}\\ 1+\frac{1}{2} &= \frac{3}{2!}\\ 1+\frac{1}{2}+\frac{1}{3} &= \frac{11}{3!}\end{aligned}$$

Then, suppose true for $n = k-1$. Then

$$\begin{aligned}1+\frac{1}{2}+\cdots+\frac{1}{k-1}+\frac{1}{n} &= \frac{\begin{bmatrix}k\\2\end{bmatrix}}{(k-1)!}+\frac{1}{k}\\ &= \frac{k\begin{bmatrix}k\\2\end{bmatrix}+(k-1)!}{k!}\\ &= \frac{k\begin{bmatrix}k\\2\end{bmatrix}+\begin{bmatrix}k\\1\end{bmatrix}}{k!}\\ &= \frac{\begin{bmatrix}k+1\\2\end{bmatrix}}{k!}\end{aligned}$$

□

G The inclusion-exclusion (IE) principle

Sometimes AND is easy, but OR is difficult. This is when IE can help.

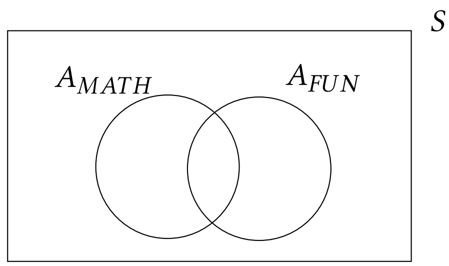
It is really about handling Venn diagrams or indicator functions.

G1 Introduction

Example 46. How many anagrams of MATHFUN have **neither** of the substrings MATH or FUN?

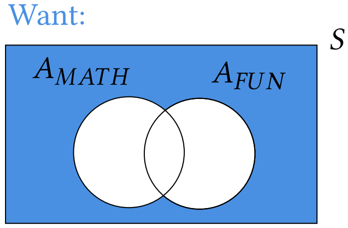
Let S = {anagrams of MATHFUN}, A_{MATH} = {anagrams of MATH} and A_{FUN} =

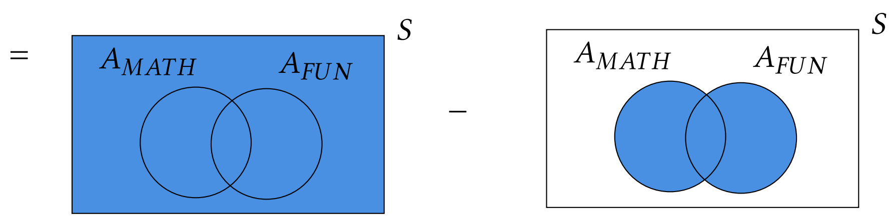
{anagrams of FUN}. We can draw the following Venn diagram:



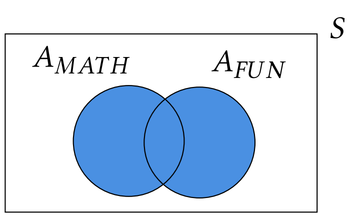
Where:

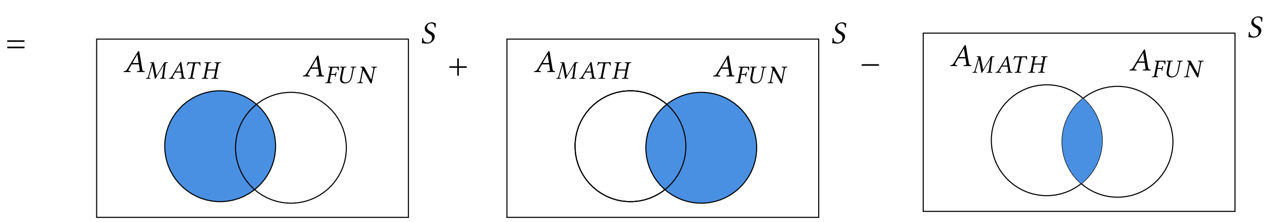
Want:





Note that





4! 5! 2!

And hence, the answer is $7! - (4! + 5! - 2!) = 4898$.

Indicator functions

These are $\{0, 1\}$-valued functions on S.

Example 47. Let:

$$\mathbb{1}_s(x) = 1 \quad \text{for all anagrams of } x$$
$$\mathbb{1}_{MATH}(x) = \begin{cases} 1 & \text{if } x \text{ contains MATH} \\ 0 & \text{otherwise} \end{cases}$$
$$\mathbb{1}_{FUN}(x) = \begin{cases} 1 & \text{if } x \text{ contains FUN} \\ 0 & \text{otherwise} \end{cases}$$

Proposition 30. Key facts about indicator functions:

AND:

$$\mathbb{1}_{A \cap B} = \mathbb{1}_A \mathbb{1}_B$$

COMPLEMENT:

$$\mathbb{1}_A^c = 1 - \mathbb{1}_A$$

OR:

$$\begin{aligned} \mathbb{1}_{A \cup B} &= 1 - \mathbb{1}_{A^c \cap B^c} \\ &= 1 - \mathbb{1}_{A^c} \mathbb{1}_{B^c} \\ &= 1 - (1 - \mathbb{1}_A)(1 - \mathbb{1}_B) \\ &= \mathbb{1}_A + \mathbb{1}_B - \mathbb{1}_{A \cap B} \end{aligned}$$

So we get the same formula for the previous example:

$$\mathbb{1}_{\text{MATH or FUN}} = \mathbb{1}_{MATH} + \mathbb{1}_{FUN} - \mathbb{1}_{\text{MATH and FUN}} \qquad (*)$$

Definition 17. For any function $f : S \to \mathbb{R}$, we can define

$$\int f = \sum_{x \in S} f(x)$$

For indicator functions,

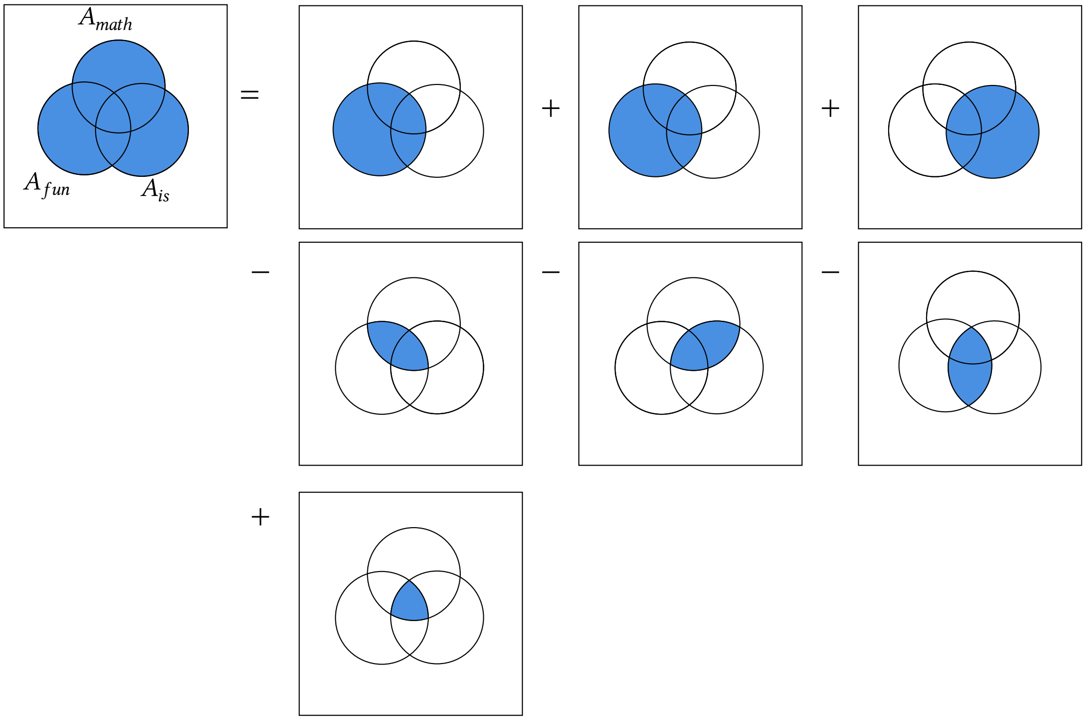
$$\int \mathbb{1}_A = \sum_{x \in S} \begin{cases} 1 & x \in A \\ 0 & x \notin A \end{cases} = \sum_{x \in A} 1 = |A|$$

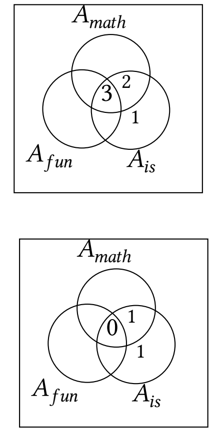
we get the cardinality of A.

Therefore, we integrate both sides of $(*)$ and get the cardinality of $A_{MATH} \cup A_{FUN}$.

Example 48. How many anagrams of MATHISFUN do contain at least one of MATH, IS or FUN?

Method 1:





Hence:

$$\begin{aligned} ANS =& 6! + 8! + 7! \\ & - 5! - 6! - 4! \\ & + 3! \\ =& 45222 \end{aligned}$$

Method 2: Let $\mathbb{1}_M, \mathbb{1}_I, \mathbb{1}_F$ be the indicator functions. Then:

$$\begin{aligned} \mathbb{1}_{M\vee I\vee F} &= 1 - \mathbb{1}_{M^c\wedge I^c\wedge F^c} \\ &= 1 - (1 - \mathbb{1}_M)(1 - \mathbb{1}_I)(1 - \mathbb{1}_F) \end{aligned}$$

and the formula is the same as method 1.

G2 The IE formula

Let S be a set of objects (e.g. anagrams). Let $P_1, \ldots, P_n$ be properties these objects could satisfy (e.g. “contains MATH”). Then sets $A_i = \{x \in S \mid P(x) \text{ true}\}$.

Theorem 31.

0.
$$|S| = |S|$$

1.
$$\left|A_1^c\right| = |S| - |A_1|$$

2.
$$\left|A_1^c \cap A_2^c\right| = |S| - |A_1| - |A_2| + |A_1 \cap A_2|$$

3.
$$\begin{aligned}\left|A_1^c \cap A_2^c \cap A_3^c\right| =& |S| \\ & - |A_1| - |A_2| - |A_3| \\ & + |A_1 \cap A_2| + |A_2 \cap A_3| + |A_3 \cap A_1| \\ & - |A_1 \cap A_2 \cap A_3|\end{aligned}$$

$\vdots$

n.
$$\begin{aligned}\left|A_1^c \cap \cdots \cap A_n^c\right| &= \sum_{I \subseteq [n]} (-1)^{|I|} \left|\bigcap_{i \in I} A_i\right| \\ &= |S| - (|A_1| + \cdots + |A_n|) + (\cdots + |A_i \cap A_j| + \dots) - \cdots + (-1)^n |A_1 \cap \cdots \cap A_n|\end{aligned}$$

Proof by indicator function. We observe:

$$\begin{aligned}\mathbb{1}_{A_1^c \cap \cdots \cap A_n^c} &= \mathbb{1}_{A_1^c} \cdot \cdots \cdot \mathbb{1}_{A_n^c} \\ &= \sum_{I \subseteq [n]} \prod_{i=1}^{n} \begin{cases} -\mathbb{1}_{A_i} & \text{if } c \in I \\ 1 & \text{if } c \notin I \end{cases} \\ &= \sum_{I \subseteq [n]} \prod_{i \in I} (-\mathbb{1}_{A_i}) \\ &= \sum_{I \subseteq [n]} (-1)^{|I|} \mathbb{1}_{\bigcap_{i \in I} A_i}\end{aligned}$$

Now integrate both sides and get the result. □

Example 49. How many integers in $S = \{1, 2, \dots, 1000\}$ are not divisible by 5 or 6 or 8?

Let $A_i = \{x \in S \mid x \text{ divisible by } i\}$. We want $\left|A_2^c \cap A_5^c \cap A_8^c\right|$.

We know that we need to subtract from 1000:

$$|A_5| = \frac{1000}{5} = 200$$

$$|A_6| = \lfloor \frac{1000}{6} \rfloor = 166$$
$$|A_8| = \frac{1000}{8} = 125$$

The least common multiple (lcm) helps with the rest to add back:

$$\begin{aligned}
|A_5 \cap A_6| = |A_{30}| &= \lfloor \frac{1000}{30} \rfloor = 33 \\
|A_6 \cap A_8| = |A_{24}| &= \lfloor \frac{1000}{24} \rfloor = 41 \\
|A_8 \cap A_5| = |A_{40}| &= \frac{1000}{40} = 25 \\
-|A_5 \cap A_6 \cap A_8| = -|A_{120}| &= -\lfloor \frac{1000}{120} \rfloor = -8
\end{aligned}$$

Therefore, ANS = 600.

Example 50. How many anagrams of HAPPYMATH contain neither HAPPY nor MATH?

$$\begin{aligned}
S &= \{\text{all anagrams}\} & |S| &= \frac{9!}{2!2!2!} \\
A_1 &= \{\text{Anagrams with HAPPY}\} & |A_1| &= 5! \quad \boxed{\text{HAPPY}}\ \text{MATH} \\
A_2 &= \{\text{Anagrams with MATH}\} & |A_2| &= \frac{6!}{2!} \quad \text{HAPPY}\boxed{\text{MATH}} \\
A_1 \cap A_2 &= \{\text{Anagrams with MATH and HAPPY}\}
\end{aligned}$$

Case 1: $\boxed{\text{HAPPY}}\boxed{\text{MATH}}$ 2!

Case 2: $\boxed{\text{MATHAPPY}}$ H 2!

So $|A_1 \cap A_2| = 4$. Hence, ANS is

$$|S| - |A_1| - |A_2| + |A_1 \cap A_2| = 45360 - 120 - 360 + 4 = 44884$$

G3 Combinations of a multiset

- How many ways to take 7 scrabble tiles from a bag?
- How many ways to get a bag of 12 bagels from limited supply of different bags?
- How many ways to place r identical pigeons in k pigeonholes without exceeding capacities $n_1, n_2, \dots, n_k$.

In general, let $X = \{n_1 \cdot a_1, n_2 \cdot a_2, \dots, n_k \cdot a_k\}$ be a multiset. How many r-combinations of X are there? (i.e. objects of types $a_1, \dots, a_k$ of maximum quantities $n_1, n_2, \dots, n_k$.)

Special cases:

1. If $n_1 = \cdots = n_k = 1$: $\binom{k}{r}$
2. If $n_1 = n_2 = \cdots = n_k = \infty$: $\left(\binom{k}{r}\right) = \binom{r+k-1}{r}$
3. If $n_1, n_2, \ldots, n_k \geq r$: $\left(\binom{k}{r}\right) = \binom{r+k-1}{r}$
4. If $r > n_1 + n_2 + \cdots + n_k$: 0

← by Strong Pigeonhole

Example 51. How many ways to select 10 jewels from a bag of 3 Amethyst, 4 Beryl and 5 Citrine?

Method 1: Easy answer by complement: choose which 2 to stay in the bag: AA, AB, AC, BB, BC, CC $\boxed{\text{6 ways}}$

Method 2: Integer solutions to $a + b + c = 10$ such that

$$\begin{aligned} 0 \leq a \leq 3 \\ 0 \leq b \leq 4 \\ 0 \leq c \leq 5 \end{aligned}$$

We first pretend there are infinite supply of jewels and call the set of ways S. Let the sets S_A, S_B, S_C be the ways with too many A ($a \geq 4$), B ($b \geq 5$) and C ($c \geq 6$) respectively. Then:

$$\begin{aligned}
|S| &= \left(\binom{3}{10}\right) = \binom{12}{10} = 66 \\
|S_A| &= \left(\binom{3}{6}\right) = \binom{8}{6} = 28 \\
|S_B| &= \left(\binom{3}{5}\right) = \binom{7}{5} = 21 \\
|S_C| &= \left(\binom{3}{4}\right) = \binom{6}{4} = 15 \\
|S_A \cap S_B| &= \left(\binom{3}{1}\right) = \binom{3}{1} = 3 \\
|S_A \cap S_C| &= \left(\binom{3}{0}\right) = 1 \\
|S_B \cap S_C| &= 0 \\
|S_A \cap S_B \cap S_C| &= 0
\end{aligned}$$

Hence, the answer would be, by IE, $66 - (28 + 21 + 15) + (3 + 1 + 0) - 0 = 6$.

G4 Symmetric IE

Remark. The previous example is not symmetric since the three jewels have different constraints.

Now suppose $|A_{i_1} \cap A_{i_2} \cap \cdots \cap A_{i_h}|$ depends only on the number of distinct indices chosen and not on which indices are chosen.

Then set

$$\begin{aligned}
\alpha_0 &= |S| \\
\alpha_1 &= |A_1| = \cdots = |A_n| \\
\alpha_2 &= |A_1 \cap A_2| = \cdots = |A_i \cap A_j| = \ldots \\
&\vdots \\
\alpha_n &= |A_1 \cap A_2 \cap \cdots \cap A_n|
\end{aligned}$$

Then the 2^n terms of the IE formula collapse to $n+1$ terms:

$$\begin{aligned}
|A_1^c \cap \cdots \cap A_n^c| &= \alpha_0 - n\alpha_1 + \cdots + (-1)^i \binom{n}{i} \alpha_i + \cdots + (-1)^n \alpha_n \\
&= \sum_{k=0}^{n} (-1)^k \binom{n}{k} \alpha_k
\end{aligned}$$

Example 52. How many integers $0, 1, \ldots, 99999$ contain each of $2, 5, 8$ in their digits?

We know $(5)_3 \cdot 7^2 < ANS < (5)_3 \cdot 10^2$. Using symmetric IE, let A_i be the set of numbers without digit i. Then:

$$\begin{aligned}
\alpha_0 &= |S| = 10^5 \\
\alpha_1 &= |A_2| = |A_5| = |A_8| = 9^5 \\
\alpha_2 &= |A_2 \cap A_5| = \cdots = |A_5 \cap A_8| = 8^5 \\
\alpha_3 &= |A_2 \cap A_5 \cap A_8| = 7^5
\end{aligned}$$

Hence,

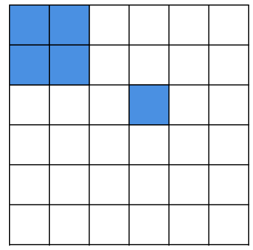
$$ANS = 10^5 - \binom{3}{1} 9^5 + \binom{3}{2} 8^5 - \binom{3}{3} 7^5 = 4350$$

G5 Rook problems

Example 53. How many ways to place 6 identical rooks on 6×6 board such that

1. no two in the same row or column

2. no rook on blue squares:

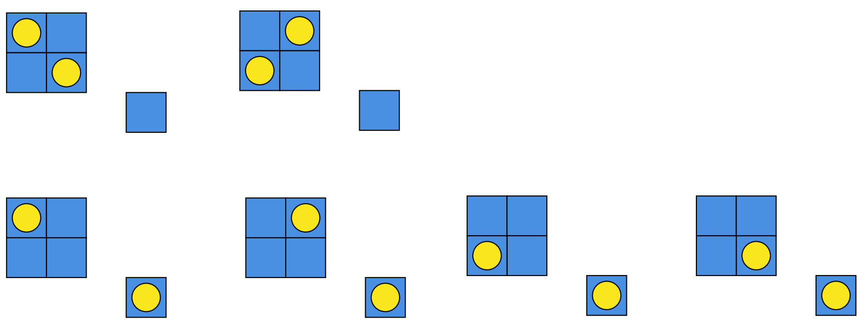


Solution: We'll solve the problem for distinct rooks labelled $1, 2, \ldots, 6$ and then divide by $6!$. Let $S =$ all arrangements ignoring blue squares and $A_i =$ arrangements where rook i is on a blue square.

We use symmetric IE:

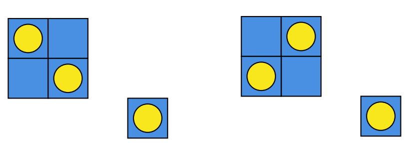
← choose rows and choose columns

$$\begin{aligned}\alpha_0 &= |S| = 6! \times 6! \\ \alpha_1 &= |A_1| = 5 \times (5!)^2 \\ \alpha_2 &= |A_1 \cap A_2| = 6 \cdot 2! \cdot (4!)^2\end{aligned}$$



(And then label the two rooks)

$$\alpha_3 = |A_1 \cap A_2 \cap A_3| = 2 \cdot 3! \cdot (3!)^2$$



(And then label the 3 rooks)

$$\alpha_4 = \alpha_5 = \alpha_6 = 0$$

Hence, by symmetric IE, the answer for labelled rooks would be:

$$(6!)^2 - \binom{6}{1} \cdot 5 \cdot 1! \cdot (5!)^2 + \binom{6}{2} \cdot 6 \cdot 2! \cdot (4!)^2 - \binom{6}{3} \cdot 2 \cdot 3! \cdot (3!)^2$$

$$=6!6! - \frac{6!}{1!5!} \cdot 5 \cdot 1 \cdot 5!5! + \frac{6!}{2!4!} \cdot 6 \cdot 2! \cdot 4!4! - \frac{6!}{3!3!} \cdot 2 \cdot 3!3!3!$$
$$=6!(6! - 5 \cdot 5! + 6 \cdot 4! - 2 \cdot 3!)$$

Therefore, the **unlabelled** rooks have an answer of $6! - 5 \cdot 5! + 6 \cdot 4! - 2 \cdot 3! = 252$.

General rook formula

The number of ways to place n rooks on a $n \times n$ board such that

1. no two in the same row or column
2. no rook on blue squares

is

$$n! - r_1(n-1)! + \cdots + (-1)^n r_n 0!$$

where r_k is the number of ways to place k identical rooks on blue squares satisfying rule 1.

H Power series

H1 Geometric series

Let

$$\begin{aligned} S &= 1 + x + x^2 + \cdots + x^n \\ xS &= x + x^2 + \cdots + x^n + x^{n+1} \end{aligned}$$

Hence, $1 + x + \cdots + x^n = \frac{1-x^{n+1}}{1-x}$ whenever $x \neq 1$. If $x = 1$, then the sum is simply $n + 1$.

← Works in any division ring!

Remark. A variation:

Do notes from 3/25 and 3/27

Theorem 32. It is impossible to tile a 10×10 square using 1×4 tiles.

H3 9899^{-1}

Mystery:

$$\frac{1}{9899} = 0.00\ 01\ 01\ 02\ 03\ 05 \ldots$$

Explanation: If we have $f_0 = 0, f_1 = 1$ and $f_n = f_{n-1} + f_{n-2}$, then the RHS looks like

$$\sum_{k=0}^{\infty} \frac{f_k}{100^{k+1}} = \frac{1}{100} \sum_{k=0}^{\infty} f_k \left(\frac{1}{100}\right)^k$$

Consider $F(x) = \sum_{k=0}^{\infty} f_k x^k$. The series converges for $|x| < \frac{1}{2}$ because we can easily bound it above through $f_k \leq 2^k$ by induction. Hence, we observe:

← There exists a better bound, but this is sufficient.

$$\begin{array}{rlll} F & = 0 + x + & x^2 + & 2x^3 + \cdots + f_n x^n + \ldots \\ xF & = & x^2 + & x^3 + \cdots + f_{n-1} x^n + \ldots \\ x^2 F & = & & x^3 + \cdots + f_{n-2} x^n + \ldots \\ \hline F - xF - x^2 F & = 0 + x + & 0x^2 + & \ldots \end{array}$$

Therefore, we have a closed form for f_n:

$$\sum f_n x^n = \frac{x}{1 - x - x^2}$$

Therefore, the RHS could be written as:

$$\begin{aligned} 0.0001010203\ldots &= \frac{1}{100} \sum f_n \left(\frac{1}{100}\right)^n \\ &= \frac{1}{100} \cdot \frac{\frac{1}{100}}{1 - \frac{1}{100} - \frac{1}{100^2}} \\ &= \frac{1}{9899} \\ &= LHS \end{aligned}$$

□

More on the closed form of f_n

Write $1 - x - x^2 = (x - \alpha)(x - \beta)$. Therefore, $\alpha, \beta = -\frac{1 \pm \sqrt{5}}{2}$. We then use partial fractions to get

$$\begin{aligned} \sum f_n x^n &= \frac{x}{1 - x - x^2} \\ &= \frac{-\alpha}{\alpha - \beta} \cdot \frac{1}{x - \alpha} + \frac{\beta}{\alpha - \beta} \cdot \frac{1}{x - \beta} \\ &= \frac{-1}{\alpha - \beta} \left(\frac{1}{\frac{x}{\alpha} - 1} - \frac{1}{\frac{x}{\beta} - 1} \right) \\ &= \frac{1}{\alpha - \beta} \left(\frac{1}{1 - \frac{x}{\alpha}} - \frac{1}{1 - \frac{x}{\beta}} \right) \qquad \text{by geometric series formula,} \end{aligned}$$

$$= \frac{1}{\alpha - \beta}\left(\sum_{i=0}^{\infty}\left(\frac{x}{\alpha}\right)^i - \sum_{i=0}^{\infty}\left(\frac{x}{\beta}\right)^i\right)$$

Hence, we get the constant term of the n-th derivative:

$$\begin{aligned}\frac{f^{(n)}(0)}{n!} &= \frac{1}{\alpha - \beta} \cdot \left(n!\frac{1}{\alpha^n} - n!\frac{1}{\beta^n}\right) \cdot \frac{1}{n!} \\ &= \frac{1}{\alpha - \beta} \cdot \left(\frac{1}{\alpha^n} - \frac{1}{\beta^n}\right) \\ &= \frac{1}{\sqrt{5}}\left(\frac{1}{\beta^n} - \frac{1}{\alpha^n}\right)\end{aligned}$$

Since $\alpha = \frac{-(1+\sqrt{5})}{2}, \beta = \frac{-(1-\sqrt{5})}{2}$, we observe that $\frac{1}{\alpha} = \frac{1-\sqrt{5}}{2}$ and $\frac{1}{\beta} = \frac{1+\sqrt{5}}{2}$. Thus, we substitute them back in:

$$\begin{aligned}\frac{f^{(n)}(0)}{n!} &= \frac{1}{\sqrt{5}}\left(\frac{1}{\beta^n} - \frac{1}{\alpha^n}\right) \\ &= \frac{1}{\sqrt{5}}\left(\left(\frac{1+\sqrt{5}}{2}\right)^n - \left(\frac{1-\sqrt{5}}{2}\right)^n\right)\end{aligned}$$

which is Binet's formula.

Theorem 33 (Binet's formula). $f_n = \frac{1}{\sqrt{5}}\left(\left(\frac{1+\sqrt{5}}{2}\right)^n - \left(\frac{1-\sqrt{5}}{2}\right)^n\right)$

Corollary 34. $f_n \to \frac{1}{\sqrt{5}}\left(\frac{1+\sqrt{5}}{2}\right)^n$ as $n \to \infty$.

Type the σ example

H4 Polynomial power series

We were able to obtain a formula for the Fibonacci numbers

$$0, 1, 1, 2, 3, 5, 8, \dots$$

by converting the sequence into a function

$$F(x) = \sum_{n=0}^{\infty} f_n x^n$$

We showed that

$$F(x) = \frac{x}{1 - x - x^2} = \frac{A}{1 - \alpha x} + \frac{B}{1 - \beta x}$$

and we used the geometric series

$$\frac{1}{1-\alpha x} = \sum_{n=0}^{\infty} (\alpha x)^n$$

to get

$$f_n = A\alpha^n + B\beta^n$$

In general, partial fractions will involve terms of the form

$$\frac{1}{1-\alpha x}, \frac{1}{(1-\alpha x)^2}, \frac{1}{(1-\alpha x)^3}, \cdots$$

Theorem 35.

$$\frac{1}{(1-x)^k} = \sum_{n=0}^{\infty} \left(\!\binom{k}{n}\!\right) x^n$$

valid when $|x| < 1$. It follows that: $\leftarrow \left(\!\binom{k}{n}\!\right) = \binom{k+n-1}{n}$

$$\frac{1}{(1-\alpha x)^k} = \sum_{n=0}^{\infty} \left(\!\binom{k}{n}\!\right) \alpha^n x^n$$

when $|x| < \left|\frac{1}{\alpha}\right|$.

Proof. We observe that when the geometric sequence converges absolutely:

$$\begin{aligned} LHS &= (1 + x + x^2 + \dots)^k \\ &= \underbrace{(1 + x + x^2 + \dots) \cdot (1 + x + x^2 + \dots) \cdot \dots \cdot (1 + x + x^2 + \dots)}_{k} \end{aligned}$$

To get the coefficient for x^n, we want to select terms from each bracket

$$x^{a_1}, x^{a_2}, \dots, x^{a_k}$$

such that $a_1 + a_2 + \dots + a_k = n$. This is equivalent to the problem of choosing a bag of n bagels of k different types. □

Last time, we found a formula

$$\sum_{n=0}^{\infty} n^2 x^n = \frac{x + x^2}{(1-x)^3}$$

using derivatives.

We now have an alternative approach:

$$\left(\!\binom{1}{n}\!\right) = \binom{n+0}{0} = 1$$
$$\left(\!\binom{2}{n}\!\right) = \binom{n+1}{1} = n+1$$
$$\left(\!\binom{3}{n}\!\right) = \binom{n+2}{2} = \frac{(n+2)(n+1)}{2}$$

Write n^2 as a linear combination of them:

$$n^2 = 2 \cdot \frac{(n+2)(n+1)}{2} - 3(n+1) + 1 \cdot 1$$

And so

$$\begin{aligned}\sum_{n=0}^{\infty} n^2 x^n &= \sum_{n=0}^{\infty} \left(2 \cdot \frac{(n+2)(n+1)}{2} - 3(n+1) + 1 \cdot 1\right) x^n \\ &= \frac{2}{(1-x)^3} + \frac{-3}{(1-x)^2} + \frac{1}{1-x} \\ &= \frac{x^2 + x}{(1-x)^3}\end{aligned}$$

Remark. We have two natural bases for the vector space of polynomials in n:

$$\begin{matrix} 1, & n, & n^2, & n^3, \dots \\ \left(\!\binom{1}{n}\!\right), & \left(\!\binom{2}{n}\!\right), & \left(\!\binom{3}{n}\!\right), & \left(\!\binom{4}{n}\!\right), \dots \end{matrix}$$

H5 Linear recurrence relations

We can apply our analysis of the Fibonacci series $f_0 = 0, f_1 = 1, f_n = f_{n-1} + f_{n-2}$ to more general recursively-defined sequences.

Homogeneous order-k linear recurrence

$$g_n = c_1 g_{n-1} + c_2 g_{n-2} + \cdots + c_k g_{n-k}$$

with $n \geq k$ and initial conditions $g_0 = a_0, g_1 = a_1, \dots, g_{k-1} = a_{k-1}$.

Example 54. Order 2 with distinct roots:

$$\begin{cases} g_n = 2g_{n-1} + 3g_{n-2} \\ g_0 = 3, g_1 = 5 \end{cases}$$

And so $(g_n) = (3, 5, 19, 53, 163, \dots)$.

Let $G(x) = \sum_{n=0}^{\infty} g_n x^n$.

$$\begin{array}{rlll} G & = 3+ & 5x+ & 19x^2 + \cdots + g_n x^n + \dots \\ xG & = & 3x+ & 5x^2 + \cdots + g_{n-1} x^n + \dots \\ x^2 G & = & & 3x^2 + \cdots + g_{n-2} x^n + \dots \\ \hline G - 2xG - 3x^2 G & = 3- & x+ & 0x^2 + \dots \end{array}$$

And hence $(1 - 2x - 3x^2)G = 3 - x$. Therefore,

$$\begin{aligned} G = \frac{3-x}{1-2x-3x^2} &= \frac{3-x}{(1-3x)(1+x)} \\ &= \frac{2}{1-3x} + \frac{1}{1+x} \\ &= \sum_{n=0}^{\infty} (2 \cdot 3^n + 1 \cdot (-1)^n) x^n \end{aligned}$$

And so $g_n = 2 \cdot 3^n + (-1)^n$.

Example 55. Order 2 with repeated roots:

$$\begin{cases} g_n = 4g_{n-1} + 4g_{n-2} \\ g_0 = 1, g_1 = 6 \end{cases}$$

Thus, the sequence is $(g_n) = (1, 6, 20, 56, 144 \dots)$.

Let $G(x) = \sum_{n=0}^{\infty} g_n x^n$.

$$\begin{array}{rlll} G & = 1+ & 6x+ & 20x^2 + \cdots + g_n x^n + \dots \\ xG & = & x+ & 6x^2 + \cdots + g_{n-1} x^n + \dots \\ x^2 G & = & & x^2 + \cdots + g_{n-2} x^n + \dots \\ \hline G - 4xG - 4x^2 G & = 1+ & 2x+ & 0x^2 + \dots \end{array}$$

And hence $(1 - 4x - 4x^2)G = 1 + 2x$. Therefore,

$$\begin{aligned} G = \frac{1+2x}{1-4x-4x^2} &= \frac{1+2x}{(1-2x)^2} \\ &= \frac{2}{(1-2x)^2} + \frac{-1}{1-2x} \\ &= \sum_{n=0}^{\infty} \left(2 \cdot \left(\!\binom{2}{n}\!\right) 2^n + (-1) 2^n\right) x^n \end{aligned}$$

We observe $\left(\!\binom{2}{n}\!\right) = n + 1$, so $g_n = 2^n(2n + 1)$.

Inhomogeneous recurrence

Inhomogeneous: there are some other known sequences added.

Example 56. Inhomogeneous, order 1:

$$\begin{cases} g_n = -g_{n-1} + 2^n \\ g_0 = 1 \end{cases}$$

Then $(g_n) = (1, 1, 3, 5, 11, \dots)$.

Let $G = \sum_{n=0}^{\infty} g_n x^n$ and observe that $H = \sum_{n=0}^{\infty} 2^n x^n = \frac{1}{1-2x}$.

$$\begin{array}{rlll} G & = 1+ & x+ & 3x^2 + \cdots + g_n x^n + \dots \\ xG & = & x+ & x^2 + \cdots + g_{n-1} x^n + \dots \\ H & = 1+ & 2x & 4x^2 + \cdots + g_{n-2} x^n + \dots \\ \hline G + xG - H & = 1+ & 2x+ & 4x^2 + 0 + \dots \end{array}$$

Thus, $G = \frac{1}{(1+x)(1-2x)} = \frac{2/3}{1-2x} + \frac{1/3}{1+x} = \sum_{n=0}^{\infty} (\frac{2}{3} \cdot 2^n + \frac{1}{3}(-1)^n)$. Hence, $g_n = \frac{2^{n+1} + (-1)^n}{3}$.

H6 Nickels and dimes

Example 57. How many ways are there to make \$1.03 out of nickels (5¢) and pennies (1¢)?

Answer: that would be the number of solutions to $5a + b = 103$ with $a, b \in \mathbb{N}$. We can have:

$$(a, b) = (0, 103), (1, 98), \dots, (20, 3)$$

More generally, the number of solutions to $5a + b = n$ is $\lfloor \frac{n}{5} \rfloor + 1$ since the number of nickels have to be $a = 0, 1, \dots, \lfloor \frac{n}{5} \rfloor$.

Example 58. How many ways are there to make \$1.03 out of dimes (10¢), nickels (5¢) and pennies (1¢)?

We use the previous solution:

- 0 dimes: $\lfloor \frac{103}{5} \rfloor + 1 = 21$
- 1 dimes: $\lfloor \frac{93}{5} \rfloor + 1 = 19$
- …
- 10 dimes: $\lfloor \frac{3}{5} \rfloor + 1 = 1$

Then we sum them up. Since they are consecutive odd numbers,

$$21 + 19 + 17 + \cdots + 1 = 11^2 = 121$$

Another method

Revisit Example 57.

Consider the rational function

$$\frac{1}{1-x} \cdot \frac{1}{1-x^5} = (1 + x + x^2 + x^3 + \dots)(1 + x^5 + x^{10} + x^{15} + \dots)$$

we want to know what the coefficient for x^{103} is. Note this is equivalent to the previous example since we are choosing x^p terms from the first part and x^{5q} terms from the second part, and we are looking for ways to get $5q + p = 103$.

To get the coefficient of x^{103}, consider

$$1 + x + x^2 + x^3 + x^4 = \frac{1-x^5}{1-x}$$

And hence $\frac{1}{1-x} = \frac{1+x+x^2+x^3+x^4}{1-x^5}$. Furthermore, we see that

$$\frac{1}{(1-x^5)^2} = \sum_{n\geq 0} \left(\!\binom{2}{n}\!\right) (x^5)^n$$

We observe that the LHS becomes:

$$\begin{aligned} \frac{1}{1-x} \cdot \frac{1}{1-x^5} &= \frac{1 + x + x^2 + x^3 + x^4}{1-x^5} \cdot \frac{1}{1-x^5} \\ &= (1 + x + x^2 + x^3 + x^4) \cdot \sum_{n\geq 0} \left(\!\binom{2}{n}\!\right) (x^5)^n \end{aligned}$$

To get x^{103}, we want $x^p \cdot x^{5q} = x^{103}$ such that $0 \leq p \leq 4$ and $q \geq 0$. The only solution is $(p, q) = (3, 20)$. The coefficient is therefore

$$1 \cdot \left(\!\binom{2}{20}\!\right) = 21$$

Now revisit Example 58 Similarly, consider

$$\frac{1}{1-x} \cdot \frac{1}{1-x^5} \cdot \frac{1}{1-x^{10}} = (1+x+x^2+x^3+\dots)(1+x^5+x^{10}+x^{15}+\dots)(1+x^{10}+x^{20}+\dots)$$

We now want to get the coefficient of x^{103}, which are from choosing terms x^a, x^{5b}, and x^{10c} from the parts above such that $a + 5b + 10c = 103$.

Also, we prepare that

$$\frac{1}{1-x} = \frac{1 + x + x^2 + x^3 + \cdots + x^9}{1 - x^{10}}$$

and

$$\frac{1}{1-x^5} = \frac{1 + x^5}{1 - x^{10}}$$

We observe that the LHS becomes:

$$\begin{aligned}
&\frac{1}{1-x} \cdot \frac{1}{1-x^5} \cdot \frac{1}{1-x^{10}} \\
=&\frac{1 + x + x^2 + x^3 + \cdots + x^9}{1-x^{10}} \cdot \frac{1+x^5}{1-x^{10}} + \frac{1}{1-x^{10}} \\
=&(1 + x + \cdots + x^4 + 2(x^5 + \cdots + x^9) + x^{10} + \cdots + x^{14}) \cdot \sum_{n \geq 0} \left(\!\binom{3}{n}\!\right) x^{10}
\end{aligned}$$

We pick an x^p term from the first part and a x^{10q} term from the 2nd part such that $p + 10q = 103$, $0 \leq p \leq 14$ and $q \geq 0$.

There are two solutions: $(p, q) = (3, 10)$ or $(13, 9)$. The coefficient of x^{103} is

$$1 \cdot \left(\!\binom{3}{10}\!\right) + 1 \cdot \left(\!\binom{3}{9}\!\right) = 66 + 55 = 121$$

H7 Characteristic ops and egf

Example 57 and Example 58 are equivalent to asking *How many ways to get a bag of 103 bagels*:

1. of 2 types, plain + garlic such that we can get any number of plain but garlic must be a multiple of 5?
2. of 3 types, plain + garlic + onion, where can get any number of plain, but garlic must be a multiple of 5 and onion has to be a multiple of 10?

These are combinations with constraints. That is, we want to put 103 "balls" in buckets

$$U_p, U_g, U_o$$

with capacities

$$U_p \in \{0, 1, 2, \dots\} = N_p$$

$$U_g \in \{0, 5, 10, \dots\} = N_g$$
$$U_o \in \{0, 10, 20, \dots\} = N_0$$

Effectively, we convert each set to a power series. There are two ways to convert a subset $N \subseteq \mathbb{N}$ into a power series.

- Step 1: Convert N into a 0-1 sequence:

$$a = (a_n) \text{ where } a_n = \begin{cases} 1 & \text{if } n \in N \\ 0 & \text{otherwise} \end{cases}$$

- Step 2:
  - Characteristic OPS (ordinary power series) X_N of N:

$$(a_n) \mapsto \sum_{n \geq 0} a_n x^n$$

  - Characteristic EGF (exponential generating function) $\mathfrak{X}_n$ of N:

$$(a_n) \mapsto \sum_{n \geq 0} \frac{a_n}{n!} x^n$$

Example 59. $N = \{0, 1, 2, \dots\}$ (no constraint)

$$a^N = 1, 1, 1, \dots$$
$$X_N = 1 + x + x^2 + \cdots = \frac{1}{1-x}$$
$$\mathfrak{X}_N = 1 + x + \frac{x^2}{2!} + \cdots = e^x$$

Example 60. $N = \{1, 2, 3, \dots\}$ (at least 1 object)

$$a^N = 0, 1, 1, \dots$$
$$X_N = x + x^2 + \cdots = \frac{x}{1-x}$$
$$\mathfrak{X}_N = x + \frac{x^2}{2!} + \cdots = e^x - 1$$

Example 61. $N = \{0, 1\}$ (at most 1 object)

$$a^N = 1, 1, 0, 0, \dots$$
$$X_N = 1 + x$$
$$\mathfrak{X}_N = 1 + x$$

Example 62. $N = \{0, 2, 4, 6, \dots\}$ (even numbers of object)

$$a^N = 1, 0, 1, 0, \dots$$
$$X_N = 1 + x^2 + x^4 + \cdots = \frac{x}{1-x^2}$$
$$\mathfrak{X}_N = 1 + \frac{x^2}{2!} + \frac{x^4}{4!} + \cdots = \cosh x = \frac{e^x + e^{-x}}{2}$$

Example 63. $N = \{1, 3, 5, 7, \dots\}$ (odd numbers of object)

$$\begin{aligned} a^N &= 0, 1, 0, 1, \dots \\ X_N &= x + x^3 + x^5 + \cdots = \frac{x}{1 - x^2} \\ \mathfrak{X}_N &= x + \frac{x^3}{3!} + \frac{x^5}{5!} + \cdots = \sinh x = \frac{e^x - e^{-x}}{2} \end{aligned}$$

Example 64. $N = \{0, 5, 10, 15, \dots\}$ (multiples of 5 numbers of object)

$$\begin{aligned} a^N &= 1, 0, 0, 0, 0, 1, 0, \dots \\ X_N &= 1 + x^5 + x^10 + \cdots = \frac{1}{1 - x^5} \\ \mathfrak{X}_N &= 1 + \frac{x^5}{5!} + \frac{x^{10}}{10!} + \cdots = \frac{1}{5} \sum_{k=0}^{4} e^{\omega^k x} \end{aligned}$$

where $\omega = e^{2\pi i/5}$ is a primitive 5th root of unity.

I Generating functions

I1 OPS and EGF

Suppose a combiatorial problem has an answer a_n for each $n \geq 0$. We will encode an entire sequence (a_n) as a function and try to find the function.

Definition 18 (Ordinary power series)**.**

$$g(x) = \sum_n a_n x^n$$

Definition 19 (Exponential generating function)**.**

$$G(x) = \sum_n \frac{a_n}{n!} x^n$$

Remark. Special case mentioned here: if (a_n) is a sequence of 0s and 1s where $a_n = \begin{cases} 1 & n \in N \\ 0 & n \notin N \end{cases}$ for some set $N \subseteq \mathbb{N}$, then $g = X_n$ and $G = \mathfrak{X}_n$.

Example 65. Sequence: $1, 1, 1, 1, \dots$

- OPS: $1 + x + x^2 + \cdots = \frac{1}{1-x}$ $\leftarrow |x| < 1$
- EGF: $1 + x + \frac{x^2}{2!} + \cdots = e^x$

Example 66. Sequence: $1, \alpha, \alpha^2, \dots$

- OPS: $1 + \alpha x + \alpha x^2 + \cdots = \frac{1}{1-\alpha x}$ ← $|x| < 1/|\alpha|$
- EGF: $1 + \alpha x + \frac{\alpha^2 x^2}{2!} + \cdots = e^{\alpha}$

Example 67. Sequence: $a_n = \binom{m}{n}$

$$\binom{m}{0}, \binom{m}{1}, \dots, \binom{m}{m}, 0, 0, 0, \dots$$

- OPS: $\binom{m}{0} + \binom{m}{1}x + \cdots + \binom{m}{m}x^m = (1+x)^m$
- EGF: $\binom{m}{0} + \binom{m}{1}x + \binom{m}{2}\frac{x^2}{2!} + \cdots + \binom{m}{m}\frac{x^m}{m!} = ??$ ← We don't know how to solve this yet!

Example 68. Sequence: $a_n = (m)_n$

$$(m)_0, (m)_1, \dots, (m)_m, 0, 0, 0, \dots$$

- OPS: $(m)_0 + (m)_1 x + \cdots + (m)_m x^m = ??$ ← We don't know how to solve this yet!
- EGF: $(m)_0 + (m)_1 x + \frac{(m)_2}{2!}x^2 + \cdots + \frac{(m)_m}{m!}x^m = (1+x)^m$ ← Since $\frac{(m)_k}{k!} = \binom{m}{k}$

Remark. Two skills needed:

1. Recognizing OPS/EGF as a function
2. Given OPS/EGF, finding sequence (a_n).

Definition 20. Notation: Write $[x^n : g] = x^n$ coefficient of the Taylor series of function g.

Remark. If $(a_n) \xrightarrow{ops} g(x)$, then $a_n = [x^n : g]$. Similarly, if $(a_n) \xrightarrow{egf} G(x)$, then $a_n = n![x^n : G]$.

I2 The multiplication rule

Proposition 36. Suppose

$$(a_n) \xrightarrow{ops} f$$
$$(b_n) \xrightarrow{ops} g$$

Let $f \circ g \xleftarrow{ops} (c_n)$. Then

$$c_n = \sum_{k=0}^{n} a_k b_{n-k}$$

Proof. Make a multiplication table.

□

Proposition 37. Suppose

$$(a_n) \xrightarrow{egf} F$$

$$(b_n) \xrightarrow{egf} G$$

Let $F \circ G \xleftarrow{egf} (c_n)$. Then

$$c_n = \sum_{k=0}^{n} \binom{n}{k} a_k b_{n-k}$$

Proof. We observe

$$(a_n) \xrightarrow{egf} F \xleftarrow{ops} \left(\frac{a_n}{n!}\right)$$

$$(b_n) \xrightarrow{egf} G \xleftarrow{ops} \left(\frac{b_n}{n!}\right)$$

$$(c_n) \xrightarrow{egf} F \circ G \xleftarrow{ops} \left(\frac{c_n}{n!}\right)$$

By Proposition 36, we get

$$\frac{c_n}{n!} = \sum_{k=0}^{n} \left(\frac{a_k}{k!}\right)\left(\frac{b_{n-k}}{(n-k)!}\right)$$

Therefore, $c_n = \sum_{k=0}^{n} \binom{n}{k} a_k b_{n-k}$. □

Proposition 38 (Generalization)**.** Sequences

$$\begin{array}{c} (a_n^1), (a_n^2), \dots, (a_n^t) \\ \Big\downarrow {\scriptstyle ops} \\ f_1, f_2, \dots, f_t \end{array}$$

Then $f_1 \circ f_2 \circ \dots \circ f_t =: f \xleftarrow{ops} (c_n)$ where

$$c_n = \sum_{\substack{k_1, k_2, \dots, k_t \geq 0 \\ k_1 + \dots + k_t = n}} a_n^1 a_n^2 \dots a_n^t$$

Similarly, if

$$\begin{array}{c}(a_n^1), (a_n^2), \dots, (a_n^t) \\ \Big\downarrow{\scriptstyle egf} \\ F_1, F_2, \dots, F_t\end{array}$$

Then $F_1 \circ F_2 \circ \dots \circ F_t =: F \xleftarrow{egf} (d_n)$ where

$$d_n = \sum_{\substack{k_1, k_2, \dots, k_t \geq 0 \\ k_1 + \dots + k_t = n}} \binom{n}{k_1, k_2, \dots, k_t} a_n^1 a_n^2 \dots a_n^t$$

Example 69 (Use of OPS)**.** Let $a_n = \binom{p}{n}, b_n = \binom{q}{n}$. Hence

$$(a_n) \xrightarrow{ops} (1+x)^p = f(x)$$

$$(b_n) \xrightarrow{ops} (1+x)^q = g(x)$$

then

$$f(x) \circ g(x) = (1+x)^p (1+x)^q = (1+x)^{p+q} \xleftarrow{ops} (c_n)$$

where $c_n = \binom{p+q}{n}$. The multiplication rule also gives

$$c_n = \sum_{k=0}^{n} a_n b_n$$

which means

$$\binom{p+q}{n} = \sum_{k=0}^{n} a_n b_n$$

← can also prove by combinatorics: think of Hogwarts!

Similarly, we can use the general version to get

$$\binom{p_1 + \dots + p_t}{n} = \sum_{\substack{k_i \geq 0 \\ k_1 + \dots + k_t = n}} \binom{p_1}{k_1}\binom{p_2}{k_2} \dots \binom{p_t}{k_t}$$

Example 70 (Use of EGF)**.** Say

$$(\alpha^n) \xrightarrow{egf} e^{\alpha x}$$

$$(\beta^n) \xrightarrow{egf} e^{\beta x}$$

Then

$$e^{(\alpha+\beta)x} \xleftarrow{egf} (\alpha+\beta)^n$$

The multiplication rule gives us

$$(\alpha+\beta)^n = \sum_{k=0}^{n} \binom{n}{k} \alpha^n \beta^n$$

We just reproved the binomial theorem!

I3 Combinations with constraints

We now tackle (16) in the table.

3.3 A Framework for Counting Questions: The Counting Table 95

Table 3.1 Balls and boxes counting problems.

Number of Ways to Put Balls into Boxes $S = S_1 = \{1, 2, \ldots, s\}$, or $S = S_2 = \{s \cdot 1\}$, a multiset of balls $T = T_1 = \{U_1, U_2, \ldots, U_t\}$, or $T = T_2 = \{t \cdot U_1\}$, a multiset of boxes Box U_i contains u_i balls				
Conditions on S and T → on u_i ↓	$T = T_1$ distinct $S = S_1$ distinct	$T = T_1$ distinct $S = S_2$ identical	$T = T_2$ identical $S = S_1$ distinct	$T = T_2$ identical $S = S_2$ identical
$0 \le u_i \le 1$ Assume $t \ge s$	1	2	3	4
$u_i \ge 0$	5	6	7	8
$u_i \ge 1$	9	10	11	12
for $i = 1, \ldots, t$, $0 \le u_i \le n_i$, $n_i \in \mathbb{Z}^{>0}$	13	14		
$u_i \in N_i \subset \mathbb{Z}^{\ge 0}$ for $i = 1, \ldots, t$	15	16		

Theorem 39. Let $N_1, N_2, \ldots, N_t$ be subsets of $\mathbb{N}$. Let c_s be the # of solutions to

$$x_1 + x_2 + \cdots + x_t = s$$

such that $x_i \in N_i$ for all i.

This is equivalent to # of ways to place s identical objects in t distinct boxes s.t. # of objects u_i in box i is in N_i for all i.

Also equivalent to # ways to select bag of s bagels from t types, s.t. # of bagels of type $i \in N_i$ for all i.

Let $(c_n) \xrightarrow{ops} f$. Then

$$f = \underbrace{X_{N_1} \cdot X_{N_2} \dots X_{N_t}}_{\text{prod. of characteristic ops}}$$

Proof omitted. Similar reasoning to Example 58. □

Example 71. How many ways to pick 10 marbles from $\{3R, 4G, 5B\}$?

Answer:

$$\begin{aligned}
N_R &= \{0,1,2,3\} && \xrightarrow{ops} \frac{1-x^4}{1-x} = X_R \\
N_G &= \{0,1,2,3,4\} && \xrightarrow{ops} \frac{1-x^5}{1-x} = X_G \\
N_B &= \{0,1,2,3,4,5\} && \xrightarrow{ops} \frac{1-x^6}{1-x} = X_B
\end{aligned}$$

We want to know c_{10}. Theorem above tells us $(c_n) \xleftarrow{ops} X_R X_G X_B$ and so we want the x^10 coeff. of

$$\begin{aligned}
&\frac{1-x^4}{1-x} \cdot \frac{1-x^5}{1-x} \cdot \frac{1-x^6}{1-x} \\
=&(1 - x^4 - x^5 - x^6 + x^9 + x^{10} + x^{11} - x^{15}) \cdot \frac{1}{(1-x)^3} \\
=&(1 - x^4 - x^5 - x^6 + x^9 + x^{10} + x^{11} - x^{15}) \cdot \sum_{n \geq 0} \left(\!\binom{3}{n}\!\right) x^n
\end{aligned}$$

Hence we select x^a and select x^b from the two product factors. We table the possibilities:

$$\begin{aligned}
(a,b) = (0,10) \quad & \text{coefficient: } 1 \cdot \left(\!\binom{3}{10}\!\right) = 66 \\
(4,6) \quad & -1 \cdot \left(\!\binom{3}{6}\!\right) = -28 \\
(5,5) \quad & -1 \cdot \left(\!\binom{3}{5}\!\right) = -21 \\
(6,4) \quad & -1 \cdot \left(\!\binom{3}{4}\!\right) = -15 \\
(9,1) \quad & 1 \cdot \left(\!\binom{3}{1}\!\right) = 3 \\
(10,0) \quad & 1 \cdot \left(\!\binom{3}{0}\!\right) = 1 \\
\hline
& \text{total} = 6
\end{aligned}$$

Example 72. How many ways to select a bag of 47 fruits of 4 types, namely:

- # apples is even
- # bananas is a multiple of 5
- # cherries is ≤ 4
- # dragon fruit is ≤ 1

Combinatorial way: we let $k = \#$ of bananas and cherries.

For each $k = 0, 1, \ldots, 47$:

- Choose k bananas + cherries

$$\text{1 way}\begin{cases}\#B = \lfloor \frac{k}{5} \rfloor \cdot 5 & \text{largest mult. of 5} \\ \#C = k - \lfloor \frac{k}{5} \rfloor \cdot 5 & \text{remainder}\end{cases}$$

- Choose $47 - k$ apples and dragon fruit

$$\text{1 way}\begin{cases}\#A = \lfloor \frac{47-k}{2} \rfloor \cdot 2 & \text{largest mult. of 2} \\ \#D = (47-k) - \lfloor \frac{47-k}{2} \rfloor \cdot 2 & \text{remainder}\end{cases}$$

Hence the only choices made are through choosing k, which gives us 48 ways.

Generating function: Consider this as a combinations with constraints problem. Let c_n be the number of ways to choose n fruit with the aforementioned conditions. Then

$$f(x) = \sum_n c_n x^n$$

satisfies

$$f = X_A X_B X_c X_D$$

Now since

$$\begin{aligned} N_A &= \{0, 2, 4, \ldots\} \\ N_B &= \{0, 5, 10, \ldots\} \\ N_C &= \{0, 1, 2, 3, 4\} \\ N_D &= \{0, 1\} \end{aligned}$$

We could write their OPS:

$$\begin{aligned} X_A &= 1 + x^2 + x^4 + \ldots = \frac{1}{1-x^2} \\ X_B &= 1 + x^5 + x^{10} + \ldots = \frac{1}{1-x^5} \\ X_c &= 1 + x + x^2 + x^3 + x^4 = \frac{1-x^5}{1-x} \end{aligned}$$

$$X_D = 1 + x$$

Thus,

$$\begin{aligned} f(x) &= \frac{1}{1-x^2} \cdot \frac{1}{1-x^5} \cdot \frac{1-x^5}{1-x} \cdot (1+x) \\ &= \frac{1+x}{(1+x)(1-x)(1-x)} \\ &= \frac{1}{(1-x)^2} \\ &= \sum_{n=0} \left(\!\binom{2}{n}\!\right) x^n \\ &= \sum_{n \geq 0} (n+1) x^n \\ \Rightarrow c_n &= n+1 \end{aligned}$$

Therefore, $c_{47} = 47 + 1 = 48$.

I4 Permutations with constraints

Example 73. We have R, G, B marbles. We want to place 7 of them in a row such that

- #R is odd
- #G is a multiple of 3
- #B is anything

Combinatorial way: split into cases by first selecting combinations of (R, G, B):

$$(1,0,6), (1,3,3), (1,6,0), (3,0,4), (3,3,1), (5,0,2), (7,0,0)$$

And then we solve each anagram problem:

$$\binom{7}{1,0,6}, \binom{7}{1,3,3}, \binom{7}{1,6,0}, \binom{7}{3,0,4}, \binom{7}{3,3,1}, \binom{7}{5,0,2}, \binom{7}{7,0,0}$$

Sum them up and we get 351 ways.

Generating function: Consider

$$\begin{aligned} \mathfrak{X}_R - &= x + \frac{x^3}{3!} + \cdots = \sinh x = \frac{e^x - e^{-x}}{2} \\ \mathfrak{X}_G &= 1 + \frac{x^3}{3!} + \frac{x^6}{6!} + \cdots = \frac{e^x + e^{\zeta_3 x} + e^{\zeta_3^2 x}}{3} \end{aligned}$$

$$\mathfrak{X}_B = 1 + x + \frac{x^2}{2!} + \cdots = e^x$$

Let $F = \mathfrak{X}_R\mathfrak{X}_G\mathfrak{X}_B$. What is $[x^7 : F]$? ← the coeff. of F on x^7 term

We need to pick powers x^r in $\mathfrak{X}_R$, x^g in $\mathfrak{X}_G$, x^b in $\mathfrak{X}_B$ such that $r + g + b = 7$. The solutions (r, g, b) are the same ones as before:

$$(1,0,6),(1,3,3),(1,6,0),(3,0,4),(3,3,1),(5,0,2),(7,0,0)$$

We want the coefficients for each such case. For instance,

$$(r,g,b) = (1,3,3) \qquad \rightarrow \qquad x\frac{x^3}{3!}\frac{x^3}{3!} \qquad \text{coefficient is } \frac{1}{1!3!3!} = \frac{1}{7!}\binom{7}{1,3,3}$$

and similar for other cases.

Thus, the answer is $7![x^7 : F]$.

In general, if p_n is the number of ways to line up n marbles with the aforementioned constraints, then $p_n = n![x^n : \mathfrak{X}_R\mathfrak{X}_G\mathfrak{X}_B]$. That is,

$$(p_n) \xrightarrow{egf} \mathfrak{X}_R\mathfrak{X}_G\mathfrak{X}_B$$

General formula for $F = \mathfrak{X}_R\mathfrak{X}_G\mathfrak{X}_B$: ← (Optional content)

$$\begin{aligned} F &= \frac{1}{6}\left(e^x - e^{-x}\right)\left(e^x + e^{\zeta_3 x} + e^{\zeta_3^2 x}\right)e^x \\ &= \frac{1}{6}\left(e^{3x} - e^x + e^{(2+\zeta_3)x} + e^{\zeta_3 x} + e^{(2+\zeta_3^2)x} - e^{\zeta_3^2 x}\right) \end{aligned}$$

Thus

$$ANS = \frac{1}{6}\left(3^n - (-1)^n + (z+\zeta_3)^n - \zeta_3^n + \left(z+\zeta_3^2\right)^n - \zeta_3^{2n}\right)$$

Theorem 40. Let constraints $N_1, N_2, \ldots, N_t \subseteq \mathbb{N}$. Let $p_s = \#\, s$-permutations of $\{\infty\cdot 1, \infty\cdot 2, \ldots, \infty\cdot t\}$ such that # of type k is in the set N_k. Let $(p_G) \xrightarrow{egf} F$. Then

$$F = \mathfrak{X}_{N_1}\mathfrak{X}_{N_2}\ldots\mathfrak{X}_{N_t}$$

where $\mathfrak{X}_{N_i}$ is the characteristic EGF of N_i.

Example 74. How many 47-digit numbers have at least 2 digits equal to 1? ← allowing leading 0s

This is a question about permutations with constraints: $\mathfrak{X}_0 = \mathfrak{X}_2 = \cdots = \mathfrak{X}_9 = e^x$, and $\mathfrak{X}_1 = \frac{x^2}{2!} + \frac{x^3}{3!} + \cdots = e^x - 1 - x$. Let a_n be the number of the n-digit numbers with the aforementioned constraints. Then

$$(a_n) \xrightarrow{egf} \mathfrak{X}_0\mathfrak{X}_1\ldots\mathfrak{X}_9 = (e^x)^9(e^x - 1 - x)$$

meaning $F = e^{10x} - e^{9x} - xe^{9x}$. We want to find $47![x^{47} : F]$. We observe that since

$$\begin{aligned} e^{10x} &\xleftarrow{egf} (10^n) \\ e^{9x} &\xleftarrow{egf} (9^n) \\ xe^{9x} &\xleftarrow{egf} (n9^{n-1}) \end{aligned}$$

Therefore, $F \xleftarrow{egf} (10^n - 9^n - n9^{n-1})$. Hence

$$\begin{aligned} xe^{9x} &= \sum_{n=0}^{\infty} x\frac{9^n x^n}{n!} \\ &= \sum_{m=1}^{\infty} 9^{m-1} \cdot m \cdot \frac{x^m}{m!} && m = n+1 \end{aligned}$$

When $n = 47$, we have $10^{47} - 9^{47} - 47 \cdot 9^{46}$ ways.

Lemma 41.

$$x^k e^{\alpha x} \xleftarrow{egf} \left((n)_k \alpha^{n0k}\right)$$

Proof. For $n < k$, coefficient of LHS is 0 and RHS is also 0.

For $n \geq k$, coefficient of LHS is

$$x^k \frac{(\alpha x)^{n-k}}{(n-k)!} = \frac{\alpha^{n-k} x^n}{(n-k)!} = (n)_k \alpha^{n-k} \frac{x^n}{n!}$$

□

Example 75. How many n-digit numbers have an odd number of digits of each prime 2,3,5,7? We have

$$\begin{aligned} \mathfrak{X}_2 = \mathfrak{X}_3 = \mathfrak{X}_5 = \mathfrak{X}_7 &= \sinh x = \frac{e^x - e^{-x}}{2} \\ \mathfrak{X}_0 = \mathfrak{X}_1 = \mathfrak{X}_4 = \cdots = \mathfrak{X}_9 &= e^x \end{aligned}$$

$$\begin{aligned} F &= \left(\frac{e^x - e^{-x}}{2}\right)^4 e^{6x} \\ &= \frac{1}{16}\left(e^{10x} - 4e^{8x} + 6e^{6x} - 4e^{4x} + e^{2x}\right) \end{aligned}$$

Therefore, the answer is

$$\frac{1}{16}\left(10^n - 4 \cdot 8^n + 6 \cdot 6^n - 4 \cdot 4^n + 2^n\right)$$

I5 Return of the counting table

Now we re-calculate these entries using generating functions:

$u_i \le 1$	1 $(t)_s$	2 $\binom{t}{s}$	$N = \{0, 1\}$
$u_i \ge 0$	5 t^s	6 $\left(\!\binom{t}{s}\!\right)$	$N = \{0, 1, 2, \dots\}$
$u_i \ge 1$	9 $t!\left\{ {s \atop t} \right\}$	10 $\left(\!\binom{t}{s-t}\!\right) = \binom{s-1}{t-1}$	$N = \{1, 2, 3, \dots\}$

We use OPS for **combinations**.

2 We observe

$$N = \{0, 1\} \xrightarrow[ops]{char} 1 + x$$

since there are t distinct boxes, we need to do this for each box, so we have $(1+x)^t$. Let

$$F \xleftarrow{ops} (1+x)^t = \sum_{s=0}^{t} \binom{t}{s} x^s$$

and we have $[x^s : F] = \binom{t}{s}$.

6 We observe

$$N = \{0, 1, 2, \dots\} \xrightarrow[ops]{char} 1 + x + x^2 + \dots \overset{geom}{=} \frac{1}{1-x}$$

we do that for all t distinct boxes, so we have $\left(\frac{1}{1-x}\right)^t$. Let

$$F \xleftarrow{ops} \left(\frac{1}{1-x}\right)^t = \sum_{s=0}^{\infty} \left(\!\binom{t}{s}\!\right) x^s$$

and we have $[x^s : F] = \left(\!\binom{t}{s}\!\right)$.

10 We observe

$$N = \{1, 2, \dots\} \xrightarrow[ops]{char} x + x^2 + \dots \overset{geom}{=} \frac{x}{1-x}$$

we do that for all t distinct boxes, so we have $\left(\frac{x}{1-x}\right)^t$. Let

$$F \xleftarrow{ops} \left(\frac{x}{1-x}\right)^t = \sum_{s=0}^{\infty} x^t \left(\!\binom{t}{s}\!\right) x^s = \sum_{r=t}^{\infty} \left(\!\binom{t}{r-t}\!\right) x^r$$

and we have $[x^s : F] = \left(\!\binom{t}{s-t}\!\right) = \binom{s-1}{t-1}$.

Now we have to use EGF for the **permutations**.

1 We observe

$$N = \{0,1\} \xrightarrow[egf]{char} 1 + x$$

since there are t distinct boxes, we need to do this for each box, so we have $(1+x)^t$. Let

$$F \xleftarrow{egf} (1+x)^t = \sum_{s=0}^{t} \binom{t}{s} x^s$$

and we have $s![x^s : F] = s!\binom{t}{s} = (t)_s$.

5 We observe

$$N = \{0,1,2,\dots\} \xrightarrow[egf]{char} 1 + x + \frac{1}{2!}x^2 + \dots \overset{taylor}{=} e^x$$

we do that for all t distinct boxes, so we have e^{tx}. Let

$$F \xleftarrow{egf} e^{tx} = \sum_{s=0}^{\infty} \frac{t^s}{s!} x^s$$

and we have $s![x^s : F] = t^s$.

9 We observe

$$N = \{1,2,\dots\} \xrightarrow[egf]{char} x + \frac{1}{2!}x^2 + \dots \overset{taylor}{=} e^x - 1$$

we do that for all t distinct boxes, so we have $(e^x-1)^t$. Let

$$\begin{aligned} F \xleftarrow{egf} (e^x-1)^t &= \sum_{s=0}^{t} \binom{t}{k} (e^x)^{t-k} (-1)^k && \text{binomial thm.} \\ &= \sum_{k=0}^{t} (-1)^k \binom{t}{k} \frac{1}{s!} (t-k)^s x^s \\ &= \sum_{s=0}^{\infty} \sum_{k=0}^{t} (-1)^k \binom{t}{k} (t-k)^s \frac{x^s}{s!} \end{aligned}$$

and we have $s![x^s : F] = \sum_{k=0}^{t} (-1)^k \binom{t}{k} (t-k)^s$.

Surprise: we got a formula for Stirling numbers of the second kind!

Proposition 42.

$$t! \left\{ {s \atop t} \right\} = \sum_{k=0}^{t} (-1)^k \binom{t}{k} (t-k)^s$$

Alternate proof (counting argument). Use symmetric IE. The LHS means placing s people into t named groups.

Let $S =$ all ways to place s people into t **possibly empty** named groups. We let A_i be the ways where team i is empty. Then $\alpha_k = \left|A_{i_1} \cap A_{i_2} \cap \cdots \cap A_{i_k}\right| = (t-k)^s$. We use the formula for symmetric IE. $\square$

← But we want nonempty groups!

J Partitions

We tackle table entries $\boxed{8}$ and $\boxed{12}$.

J1 Integer partitions

$\boxed{12}$: How many ways to put s identical objects into t identical boxes with **no empty boxes**?

i.e. ways to write $s = x_1 + \cdots + x_t$ where x_i are positive integer and the *order doesn't matter.* WLOG let $x_1 \geq x_2 \geq \cdots \geq x_t \geq 1$.

Let $p_t(s)$ denote the answer (the number of partitions of the integer s into t parts).

Example 76. $s = 8, t = 3$ could be partitioned into:

$$\begin{gathered} 6+1+1 \\ 5+2+1 \\ 4+3+1 \\ 4+2+2 \\ 3+3+2 \end{gathered}$$

Hence, $p_3(8) = 5$.

$\boxed{8}$: How many ways to put s identical objects into t identical boxes, possibly with some empty boxes?

Answer: $\displaystyle\sum_{k=0}^{t} p_k(s)$ where k is the number of nonempty parts.

Special cases for $\boxed{8}$:

$t \geq s$: define the **partition function**

$$p(s) := p_0(s) + p_1(s) + \cdots + p_s(s)$$

s	$p(s)$	
0	1	$0 =$ empty sum
1	1	1
2	2	$2 = 1 + 1$
3	3	$3 = 2 + 1 = 1 + 1 + 1$
4	5	$4 = 3 + 1 = 2 + 2 = 2 + 1 + 1 = 1 + 1 + 1 + 1$
5	7	$5 = 4 + 1 = 3 + 2 = 3 + 1 + 1 = 2 + 2 + 1 = 2 + 1 + 1 + 1 = 1 + 1 + 1 + 1 + 1$

Remark. *Not Fibonacci*!! But why does it start out like Fibonacci?
Answer: Let's consider the generating function

$$P(x) = \sum_{s=0}^{\infty} p(s)x^s$$

As an example, consider the partitioning of 4¢ of money out of coins of **all** integer values: 1¢, 2¢, 3¢, 4¢, ... The generating function for this is

$$P(x) = \underbrace{(1 + x + x^2 + \dots)}_{1¢}\underbrace{(1 + x^2 + x^4 \dots)}_{2¢}\underbrace{(1 + x^3 + x^6 + \dots)}_{3¢}\cdots = \prod_{k=1}^{\infty} \frac{1}{1 - x^k}$$

Euler showed that the denominator is

← Euler's pentagonal number formula

$$\prod_{k=1}^{\infty}(1 - x^k) = 1 - x - x^2 + x^5 + x^7 - x^{12} - x^{15} + \dots$$

Every term either has a 0, 1 or -1 coefficient.
We compare with the generating function for Fibonacci numbers:

$$(F_n) = 1, 1, 2, 3, 5, \dots \xrightarrow{ops} \frac{1}{1 - x - x^2}$$

while

$$(p(n)) \xrightarrow{ops} \frac{1}{1 - x - x^2 + x^5 + \dots}$$

should agree up to $n = 4$.

(Scratch work begins) In 1918, Hardy and Ramanujan showed that

$$p(n) \approx \frac{1}{4n\sqrt{3}} \exp\left(\pi\sqrt{\frac{2n}{3}}\right) \qquad \text{as } n \to \infty$$

(Scratch ends here)

J2 Properties of partition numbers

Recall that $p_k(n)$ is # of ways to group n **identical** robots into k nonempty teams, also number of positive integer solutions to

$$n = x_1 + x_2 + \cdots + x_k$$

where $x_1 \geq x_2 \geq \cdots \geq x_k \geq 1$.

← Note that if the robots are distinct, then we have Stirling numbers of the 2nd kind.

Table of partition numbers

$n \backslash k$	1	2	3	4	5	6	7	sum
1	1	0	0	0	0	0	0	1
2	1	1	0	0	0	0	0	2
3	1	1	1	0	0	0	0	3
4	1	2	1	1	0	0	0	5
5	1	2	2	1	1	0	0	7
6	1	3	3	2	1	1	0	11
7	1	3	4	3	2	1	1	15

Proposition 43. Properties of partition numbers:

1. $p_k(n) = 0$ if $k > n$ [too many parts]
2. $p_n(n) = 1$ [$1 + 1 + \cdots + 1$]
3. $p_1(n) = 1$ [just a team of n bots]
4. $p_k(0) = 0$ if $k \geq 1$ [obvious]
5. $p_2(s) = \lfloor \frac{s}{2} \rfloor$ [The smaller part is anything from $1, 2, \ldots, \lfloor \frac{s}{2} \rfloor$]
6. $p_{s-1}(s) = 1$ for $s \geq 2$ [$2 + 1 + \cdots + 1$ only option]
7. $p_{s-2}(s) = 2$ for $s \geq 4$ $\left[\begin{cases} 2 + 2 + 1 + \cdots + 1 \\ 3 + 1 + \cdots + 1 \end{cases} \text{only options}\right]$
8. **The recursive formula**:

$$p_k(n) = p_{k-1}(n-1) + p_k(n-k)$$

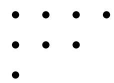
LHS: Group n bots into k teams

RHS: *First term*: there exists a solo robot. We place the $n-1$ robots into $k-1$ teams and add the solo robot to the rest.

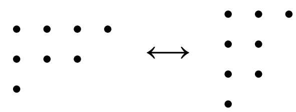
Second term: there are no solo robots, so each team has size ≥ 2. We place 1 robot into each team, and then pretend they don't exist. Then we place the leftover $n-k$ robots so that each team is 'nonempty'. Now we have ensured that each team has ≥ 2 robots.

J3 Ferros diagrams

A partition can be drawn as a configuration of dots.

Example 77. 8=4+3+1 

Proposition 44. For any n, there is an **involution** (self-inverse map) on the set of partitions of n: simply reflect the Ferros diagram along the diagonal:



This is called **conjugation**.

J4 Partition identities

Theorem 45. The number of partitions of n into k parts is equal to the number of partitions of n with largest part k

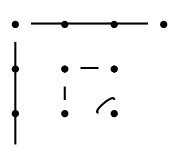
Proof. The number of Ferros diagrams with k rows is the same as the number of Ferros diagrams with k columns □

Theorem 46. The number of partitions of n is congruent to (≡) the number of partitions of n into distinct odd parts mod 2.

Proof. Consider the set of partitions of n. Conjugation split this set into conjugate **pairs** and self-conjugate elements. Hence, the # of partitions of n is ≡ # self-conjugate partitions of n mod 2.

← Pairs are even and don't change parities

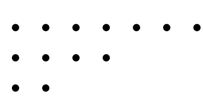
Claim: self-conjugate elements ⟷ odd distinct partitions. By example:



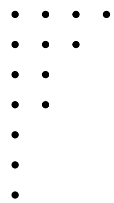
□

Theorem 47. # distinct parts ⟷ # no gaps ⟷ # odd parts

Proof of # = #. Distinct parts means F.D. has all rows different: e.g. 14 = 7+4+2+1



No gaps means F.D. has all columns different: $14 = 4 + 3 + 2 + 2 + 1 + 1 + 1$



Why? A gap means one row is 2 or more shorter than the previous one, implying equal columns.

By conjugation, # distinct parts $\longleftrightarrow$ # no gaps. $\square$

Proof of # = #. Define generating functions for # distinct parts and # odd parts:

$$C(x) = \sum c_n x^n, \qquad D(x) = \sum d_n x^n$$

We observe:

$$\begin{aligned} C(x) &= (1+x)(1+x^2)\cdots = \prod_{n=1}^{\infty}(1+x^n) \\ &= \left(\frac{1-x^2}{1-x}\right)\left(\frac{1-x^4}{1-x^2}\right)\left(\frac{1-x^6}{1-x^3}\right)\cdots \\ &= \frac{1}{1-x}\cdot\frac{1}{1-x^3}\cdot\cdots \\ &= \prod_{n\text{ odd}}\frac{1}{1-x^n} = D(x) \end{aligned}$$

$\square$

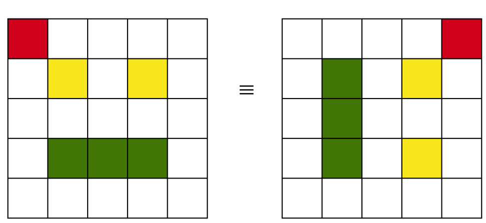
K Counting with symmetries

K1 Chessboard

How many colorings of a 5-by-5 chessboard in 4 colors do we have? ANS: 4^{25}

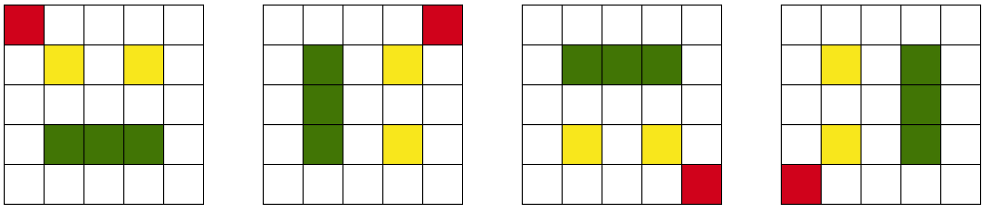
What if 2 colorings are considered the same if they are rotationally equivalent?

← In the example, white is also a color



Strategy: Let

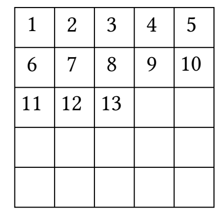
n_4 : number of patterns with 4 equivalent forms, e.g.

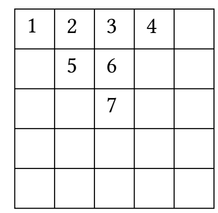


n_2 : number of patterns with 2 equivalent forms;

n_1 : number of patterns with 1 equivalent forms.

- Let A_4 be all patterns on a fixed board. Then $|A_4| = 4^{25}$ and $|A_4| = 4n_4 + 2n_2 + n_1$.
- Let A_2 be all patterns on a fixed board that are symmetric when rotated 180°. Then $|A_2| = 4^{13}$ and $|A_2| = 2n_2 + n_1$.
- Let A_2 be all patterns on a fixed board that are symmetric when rotated 90°. Then $|A_2| = 4^7$ and $|A_1| = n_1$.

← 

← 

Thus:

$$\begin{aligned} 4n_4 + 2n_2 + n_1 &= 4^{25} \\ 2n_2 + n_1 &= 4^{13} \\ n_1 &= 4^7 \end{aligned}$$

So we write

$$\begin{bmatrix} 4 & 2 & 1 \\ 0 & 2 & 1 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} n_4 \\ n_2 \\ n_1 \end{bmatrix} = \begin{bmatrix} 4^{25} \\ 4^{13} \\ 4^7 \end{bmatrix}$$

Notice that

$$\frac{1}{4}\begin{bmatrix} 1 & 1 & 2 \end{bmatrix}\begin{bmatrix} 4 & 2 & 1 \\ 0 & 2 & 1 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \end{bmatrix}$$

← note the RHS represents $n_1 + n_2 + n_4$

Solve for LHS and we are done.

Example 78. How many ways too place plates of a colors on a circular table with 6 places, up to rotational equivalece?

Let n_k be the number of such arrangements that have k vertices on a fixed table. Then $ANS = n_6 + n_3 + n_2 + n_1$. Now:

- $|A_6| = a^6 = 6n_6 + 3n_3 + 2n_2 + n_1$

- $|A_3| = a^3 = 3n_3 + n_1$
- $|A_2| = a^2 = 2n_2 + n_1$
- $|A_1| = a = n_1$

So we write

$$\begin{bmatrix} 6 & 3 & 2 & 1 \\ 0 & 3 & 0 & 1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} n_6 \\ n_3 \\ n_2 \\ n_1 \end{bmatrix} = \begin{bmatrix} a^6 \\ a^3 \\ a^2 \\ a \end{bmatrix}$$

Notice that

$$\frac{1}{6}\begin{bmatrix} 1 & 1 & 2 & 2 \end{bmatrix} \begin{bmatrix} 6 & 3 & 2 & 1 \\ 0 & 3 & 0 & 1 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \end{bmatrix}$$

← note the RHS represents $n_1 + n_2 + n_4$

Solve for LHS:

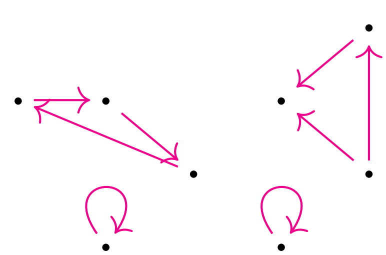
$$ANS = \frac{1}{6}\begin{bmatrix} 1 & 1 & 2 & 2 \end{bmatrix} \begin{bmatrix} a^6 \\ a^3 \\ a^2 \\ a \end{bmatrix} = \frac{a^6 + a^3 + 2a^2 + 2a}{6}$$

K2 Group actions on sets

Both of the problems above are about counting **orbits** of a group action. We look at actions of group G on a set X.

Example 79. $G = \mathbb{Z}/4\mathbb{Z}$ and X be the set of colorings/patterns in 4 colors of a 5×5 chessboard. We "relabel" the group elements as $\{R_0, R_{90}, R_{180}, R_{270}\}$ where R_k is rotation by k degrees. Then the group action $R_k \cdot x$ would just be taking a coloring $x \in X$ and rotate it by k°. The **orbits** are the equivalence classes under the group action.

Example 80. Visually, let $G = \{0, 1, 2\}$ be a cyclic group of order 3 under + and let X be the set:



← the actions corresponding to 2 are just those of 1 in reverse direction due to 2 being the inverse of 1

We observe that we have 4 **orbits**.

Theorem 48. Let $G = \mathbb{Z}/3\mathbb{Z}$ act on a **finite** set X. Then X is **partitioned** into orbits of size 3 and orbits of size 1. That is,

$$|X| \equiv \underbrace{|\text{orbits of size } 1|}_{|X^G|} \mod 3$$

where X^G is the set of **fixed points** of the action.

Proof. For each $x \in X$,

Either: $1 \cdot x = x$
Then $2x = 1(1x) = 1 \cdot x = x$ and so x is **completely** fixed by the group action. This means the orbit of x has size 1.

Or: $1 \cdot x = x' \neq x$
Then claim that $x'' = 2 \cdot x$ is distinct from x and x'. This is because if $2x = x$, then $1 \cdot 2x = 1 \cdot x = x$ resulting in a contradiction of $x = x'$. Similarly, if $2x = 1x$, then $2 \cdot 2x = 2 \cdot 1x$ resulting in a contradiction of $x' = x$.
Thus, orbit of this x must have size 3.

□

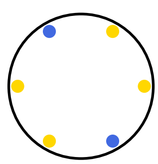
K3 Stabilizers

Definition 21 (Stabilizer of x)**.** For any $x \in X$, define

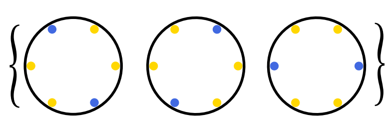
$$G_x = \operatorname{Stab}(x) = \{g \in G \mid g \cdot x = x\}$$

That is, all elements that would fix the particular x when acting on it.

Example 81. Let $G = \mathbb{Z}/6\mathbb{Z}$.

$X =$ 

$G_x = \{0, 3\}$

Orbit $(x) =$ 

Theorem 49. $\operatorname{Stab}(x)$ is a subgroup of G.

Theorem 50 (Orbit-stabilizer)**.** If G is a finite group acting on a set X, then

$$|\operatorname{Orbit}(x)||G_x| = |G|$$

for all $x \in X$.

Proof omitted, just see abstract alg. notes. □

K4 Fixed points

Let G act on X. For all $g \in G$, define

$$X^g = \{x \in X \mid g \cdot x = x\}$$

i.e. the set of the elements fixed by g.

Define

$$X^G = \bigcap_{g \in G} x^g$$

to be the fixed point set of the action, i.e. the set of elements that are fixed by any g.

Example 82. Let $G = \mathbb{Z}/6\mathbb{Z}$ and X be the set of patterns of plates on a table for 6. Let $g = 2$. Then

$$X^g = \{\text{tables in the form of } (ababab)\}$$

where a, b aren't necessarily distinct. Moreover,

$$X^G = \{\text{monochromatic tables}\}$$

Theorem 51.

$$\sum_{x \in X} |G^x| = \sum_{g \in G} |X^g|$$

Proof. Both are equal to

$$|\{(x, g) \mid g \cdot x = x\} \subseteq X \times G|$$

□

K5 Burnside's lemma

Lemma 52 (Burnside's)**.** Let G be a finite group acting on finite set X. Then the number of the orbits are the average number of fixed points of the elements of G:

← X/G is the set of orbits

$$\#\text{ Orbits} = |X/G| = \frac{1}{|G|} \sum_{g \in G} |X^g|$$

Proof. Let B denote orbits.

$$|X/G| = \sum_{B \in X/G} 1$$

$$
\begin{aligned}
&= \sum_{B \in X/G} \sum_{x \in B} \frac{1}{|B|} \\
&= \sum_{x \in X} \frac{1}{|\operatorname{orbit}(x)|} \\
&= \sum_{x \in X} \frac{|G_x|}{|G|} && \text{by O-S thm.} \\
&= \frac{1}{|G|} \sum_{x \in X} |G_x| \\
&= \frac{1}{|G|} \sum_{g \in G} |X^g| && \text{by Theorem 51}
\end{aligned}
$$

□

Example 83. Recall Investigation 7: *A dinner party host has unlimited numbers of plates in a different colours. How many distinguishable arrangements of coloured plates are there at a circular table with 6 equally-spaced seats?*

Let $G = \mathbb{Z}/6\mathbb{Z}$, X be the arrangements on a fixed table. We calculate:

$$
\begin{aligned}
|X/G| &= \frac{1}{|G|}\left(x^0 + x^1 + x^2 + x^3 + x^4 + x^5\right) \\
&= \frac{1}{6}(a^6 + a + a^2 + a^3 + a^2 + a) \\
&= \frac{a^6 + a^3 + 2a^2 + 2a}{6}
\end{aligned}
$$

K6 Circular tables

Example 84. We let a circular table be arranged with a colors of plates in n places. How many arrangements are there up to rotation?

Let X be the set of arrangements on a **fixed** table. Hence, $|X| = a^n$. Let $G = \mathbb{Z}/n\mathbb{Z}$. We want to calculate X^k for each group element k. ← set of fixed points

Remark. The cyclic group of order n has subgroups that are cyclic groups of order d for all $d|n$.

The subgroup generated by $k \in \mathbb{Z}/\mathrm{n}\mathbb{Z}$ is

$$\{0, \gcd(n,k), 2\gcd(n,k), \dots\}$$

For any k,

$$|X^k| = a^{\gcd(n,k)}$$

so

$$\frac{1}{n}\sum_{k=0}^{n-1} a^{\gcd(n,k)} = \frac{1}{n}\sum_{d|n} a^d \cdot \#\{k \mid \gcd(k,n) = d\}$$

Example 85. $n = 12$:

k	1	2	3	4	5	6	7	8	9	10	11	12
$\gcd(n,k)$	1	2	3	4	1	6	1	4	3	2	1	12

Example 86. How many k have $\gcd(18,k) = 2$? Ans: the same as the number of j s.t. $\gcd(9,j) = 1$.

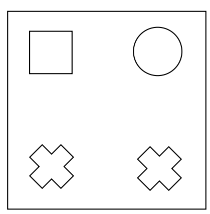
Theorem 53. Let $\phi(n) = \#\{0 \le k < n \mid \gcd(n,k) = 1\}$. Then

$$\phi(n) = n \prod_{\substack{p|n \\ p \text{ prime}}} \left(\frac{p-1}{p}\right)$$

Thus, the number of table arrangements is

$$\frac{1}{n}\sum \phi\left(\frac{n}{d}\right) a^d$$

Example 87 (Quadrum)**.** On a card with 3 symbol types on 4 corners:



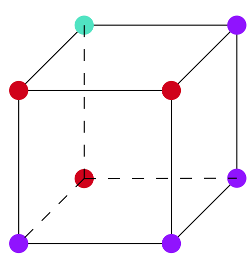
we have

$$\frac{1}{4}\sum_{d|4} 3^d \phi\left(\frac{4}{d}\right) = \frac{1}{4}(3 * 2 + 3^2 * 1 + 3^4 * 1) = 24$$

total number of cards.

K7 Octum

Now we have the game *Quadrum* but on a cube!



First, we need to get the rotational group G of the cube. This group is of size $|G| = 6 \times 4 = 24$.

← symmetric group of order 4

Now let's count the order of the elements of the group.

Element	$|X^g|$
• 1 identity element	a^8
• 6 90° rotation around face-face axis	a^2
• 3 180° rotation around face-face axis	a^4
• 8 120° rotation around vertex-vertex axis	a^4
•	
• 6 180° rotation around edge-edge axis	a^4

Hence, the number of cards is

$$\frac{1}{24}\left(a^8 + 6a^2 + 3a^4 + 8a^4 + 6a^4\right)$$