Theoretical Guide
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Victor Manuel, Maxwell Oliveira & Pablo Arruda

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1 Notes

- number of digits in $n!$

$$\log_b n! = \log_b(1 \times 2 \times 3 \times ... \times n) = \log_b 1 + \log_b 2 + \log_b 3 + ... + \log_b n$$

2 C++

```
template<class T> using min_priority_queue = priority_queue<T, vector<T>, greater<T>>;
```

```
string(1, 'a')
```

2.1 Pragma optimize

```
#pragma GCC optimize("Ofast")
#pragma GCC target("avx,avx2,fma")
```

2.2 Ordered set and multiset

```
typedef tree<pair<ll, ll>, null_type, less<pair<ll, ll>>, rb_tree_tag, tree_order_statistics_node_update> ordered_set;
```

To change to multiset switch equal to less_equal.

2.3 Optimized unordered map

```
mp.reserve(8192);
mp.max_load_factor(0.25);
```

2.4 Interactive Problems

```
freopen("input.txt", "r", stdin);
freopen("output.txt", "w", stdout);
```

3 Bitwise

Turn on bit i x & (1 << i)
Turn off bit i x & ~(1 << i)

3.1 XOR from 1 to N

$$f(n) = \begin{cases} n & n \equiv 0 \pmod 4 \\ 1 & n \equiv 1 \pmod 4 \\ n+1 & n \equiv 2 \pmod 4 \\ 0 & n \equiv 3 \pmod 4 \end{cases}$$

4 Math

$\wedge$ = and = conjunction $\vee$ = or = disjunction

4.1 Trigonometry

4.2 Logarithm

$$\log_b mn = \log_b m + \log_b n \qquad log_b \frac{m}{n} = \log_b m - \log_n n \qquad \log_b n^p = p \log_b n$$

$$\log_b \sqrt[q]{n} = \frac{1}{q} \log_b n \qquad \log_b n = \log_a n \log_b a \qquad b^{\log_b k} = k$$

$$\log_b a = \frac{\log_c a}{\log_c b} \qquad \log_b a = \frac{1}{\log_a b} \qquad \log_b a \ \log_a c = \log_b c$$

$$\log_b 1 = 0 \qquad \log_b b = 1$$

4.3 Truth Tables

a	b	$a \Rightarrow b$
0	0	1
0	1	1
1	0	0
1	1	1

a	b	$a \oplus b$
0	0	0
0	1	1
1	0	1
1	1	0

4.4 De Morgan

$$\neg(p \land q) \iff \neg p \lor \neg q$$

$$\neg(p \lor q) \iff \neg p \land \neg q$$

4.5 2-SAT

Check and finds solution for boolean formulas of the form:

$$(a \lor b) \land (\neg a \lor c) \land (a \lor \neg b)$$

As $a \lor b \iff \neg a \Rightarrow b \land \neg b \Rightarrow a$, we construct a directed graph of these implications. It's possible to construct any truth table of 1 or 2 variables with only and's from pairs of or's.

$(a \lor b)$ turn of only the case $a = 0, b = 0$
$(a \lor \neg b)$ turn of only the case $a = 0, b = 1$
$(\neg a \lor b)$ turn of only the case $a = 1, b = 0$
$(\neg a \lor \neg b)$ turn of only the case $a = 1, b = 1$

Examples:
$a \oplus b = (a \lor b) \land (\neg a \lor \neg b)$
$a \land b = (a \lor b) \land (\neg a \lor b) \land (a \lor \neg b)$

5 Number Theory

$$(a + b) \bmod m = (a \bmod m + b \bmod m) \bmod m$$

$$(a - b) \bmod m = (a \bmod m - b \bmod m) \bmod m$$

$$(a \times b) \bmod m = ((a \bmod m) \times (b \bmod m)) \bmod m$$

$$a^b \bmod m = (a \bmod m)^b \bmod m$$

$$a \equiv b \pmod m \iff (b - a) | m$$

$$\gcd(a_1, a_2, a_3, a_4) = \gcd(a_1, \gcd(a_2, \gcd(a_3, a_4)))$$

$$\mathrm{lcm}(a, b) \times \gcd(a, b) = a \times b$$

$$\mathrm{lcm}(a, b) = \frac{a \times b}{\gcd(a, b)} = \frac{a}{\gcd(a, b)} \times b$$

5.1 Sum of digits of N written in base b

$$f(n, b) = \begin{cases} n & n < b \\ f\left(n, \left\lfloor \frac{n}{b} \right\rfloor + (n \mod b)\right) & n \geq b \end{cases}$$

5.2 Some Primes

999999937 1000000007 1000000009 1000000021 1000000033 $10^{18} - 11$ $10^{18} + 3$ $2305843009213693951 = 2^{61} - 1$ $998244353 = 119 \times 2^{23} + 1$ $10^6 + 3$

5.3 Prime counting function - $\pi(x)$

Expected to have $\frac{x}{\log x}$ primes within $[1, x]$. The prime counting function is asymptotic to $\frac{x}{\log x}$, by the prime number theorem.

x	10	10^2	10^3	10^4	10^5	10^6	10^7	10^8
$\pi(x)$	4	25	168	1 229	9 592	78 498	664 579	5 761 455

5.4 Number of Divisors

The number of divisors of n is about $\sqrt[3]{n}$.

n	6	60	360	5040	55440	720720	4324320	21621600
$d(n)$	4	12	24	60	120	240	384	576

5.5 Large Prime Gaps

For numbers until 10^9 the largest gap is 400.
For numbers until 10^{18} the largest gap is 1500.

5.6 Fermat's Theorems

Let P be a prime number and a an integer, then:

$$a^p \equiv a \pmod p$$

$$a^{p-1} \equiv 1 \pmod p$$

Lemma: Let p be a prime number and a and b integers, then:

$$(a+b)^p \equiv a^p + b^p \pmod p$$

Lemma: Let p be a prime number and a an integer. The inverse of a modulo p is a^{p-2}:

$$a^{-1} \equiv a^{p-2} \pmod p$$

5.7 Divisibility Criteria

5.7.1 Other bases

Claim 1:

The divisibility rule for a number a to be divided by n is as follows. Express the number a in base $n+1$. Let s denote the sum of digits of a expressed in base $n+1$. Now $n|a \iff n|s$. More generally, $a \equiv s \pmod n$.

Example:

2	The last digit is even
3	The sum of the digits is divisible by 3
4	The last 2 digits are divisible by 4
5	The last digit is 0 or 5
7	Double the last digit and subtract it from a number made by the other digits. The res
8	The last three digits are divisible by 8
9	The sum of the digits is divisible by 9
11	Add and subtract digits in an alternating pattern (add digit, subtract next digit, add n
13	Multiply the last digit of N with 4 and add it to the rest truncate of the number. If th

Before setting to prove this, we will see an example of this. Say we want to check if 13|611. Express 611 in base 14.

$$611 = 3 \times 14^2 + 1 \times 14^1 + 9 \times 14^0 = (319)_{14}$$

where $(319)_{14}$ denotes that the decimal number 611 expressed in base 14. The sum of the digits $s = 3 + 1 + 9 = 13$. Clearly, $13|13$. Hence, $13|611$, which is indeed true since $611 = 13 \times 47$.

5.8 Diophantine Equations

6 Constants

```
LLINF = 0x3f3f3f3f3f3f3f3fLL
```

```
MOD = 998'244'353
```

```
PI = acos(-1)
```

INT_MIN INT_MAX INT64_MIN INT64_MAX

6.1 Some Powers of Two

$2^0 \approx 10^0$	$2^1 \approx 10^0$	$2^2 \approx 10^0$	$2^3 \approx 10^0$	$2^4 \approx 10^1$	$2^5 \approx 10^1$
$2^6 \approx 10^1$	$2^7 \approx 10^2$	$2^8 \approx 10^2$	$2^9 \approx 10^2$	$2^{10} \approx 10^3$	$2^{11} \approx 10^3$
$2^{12} \approx 10^3$	$2^{13} \approx 10^3$	$2^{14} \approx 10^4$	$2^{15} \approx 10^4$	$2^{16} \approx 10^4$	$2^{17} \approx 10^5$
$2^{18} \approx 10^5$	$2^{19} \approx 10^5$	$2^{20} \approx 10^6$	$2^{21} \approx 10^6$	$2^{22} \approx 10^6$	$2^{23} \approx 10^6$
$2^{24} \approx 10^7$	$2^{25} \approx 10^7$	$2^{26} \approx 10^7$	$2^{27} \approx 10^8$	$2^{28} \approx 10^8$	$2^{29} \approx 10^8$
$2^{30} \approx 10^9$	$2^{31} \approx 10^9$	$2^{32} \approx 10^9$	$2^{33} \approx 10^9$	$2^{34} \approx 10^{10}$	$2^{35} \approx 10^{10}$
$2^{36} \approx 10^{10}$	$2^{37} \approx 10^{11}$	$2^{38} \approx 10^{11}$	$2^{39} \approx 10^{11}$	$2^{40} \approx 10^{12}$	$2^{41} \approx 10^{12}$
$2^{42} \approx 10^{12}$	$2^{43} \approx 10^{12}$	$2^{44} \approx 10^{13}$	$2^{45} \approx 10^{13}$	$2^{46} \approx 10^{13}$	$2^{47} \approx 10^{14}$
$2^{48} \approx 10^{14}$	$2^{49} \approx 10^{14}$	$2^{50} \approx 10^{15}$	$2^{51} \approx 10^{15}$	$2^{52} \approx 10^{15}$	$2^{53} \approx 10^{15}$
$2^{54} \approx 10^{16}$	$2^{55} \approx 10^{16}$	$2^{56} \approx 10^{16}$	$2^{57} \approx 10^{17}$	$2^{58} \approx 10^{17}$	$2^{59} \approx 10^{17}$
$2^{60} \approx 10^{18}$	$2^{61} \approx 10^{18}$	$2^{62} \approx 10^{18}$	$2^{63} \approx 10^{18}$	$2^{64} \approx 10^{19}$	$2^{65} \approx 10^{19}$
$2^{66} \approx 10^{19}$	$2^{67} \approx 10^{20}$	$2^{68} \approx 10^{20}$	$2^{69} \approx 10^{20}$	$2^{70} \approx 10^{21}$	$2^{71} \approx 10^{21}$

6.2 Some Factorials

$6! \approx 10^2$	$7! \approx 10^3$	$8! \approx 10^4$	$9! \approx 10^5$	$10! \approx 10^6$	$11! \approx 10^7$
$12! \approx 10^8$	$13! \approx 10^9$	$14! \approx 10^{10}$	$15! \approx 10^{12}$	$16! \approx 10^{13}$	$17! \approx 10^{14}$
$18! \approx 10^{15}$	$19! \approx 10^{17}$	$20! \approx 10^{18}$	$21! \approx 10^{19}$	$22! \approx 10^{21}$	$23! \approx 10^{22}$

7 Progressions

7.1 Geometric Progression

General Term: $a_1 q^{n-1}$

Sum: $\dfrac{a_1(q^n - 1)}{q - 1}$

Infinite Sum:

$$-1 < q < 1$$
$$\frac{a_1}{1 - q}$$

7.2 Arithmetic Progression

General Term: $a_1 + (n-1)r$

Sum: $\dfrac{(a_1 + a_n)n}{2}$

7.2.1 Sum of Second Order Arithmetic Progression

Where a_1 is the first element of the original progression, b_1 is the first element of the derived progression, n is the number of elements of the original progression and r is the ratio of the derived progression

$$a_1 n + \frac{(b_1 n(n-1)}{2} + \frac{rn(n-1)(n-2)}{6}$$

8 Counting Problems

8.1 Burnside's Lemma

Let G be a group that acts on a set X. The Burnside Lemma states that the number of distinct orbits is equal to the average number of points fixed by an element of G.

$$T = \frac{1}{|G|} \sum_{g \in G} |\texttt{fix}(g)|$$

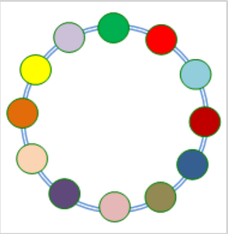
Where a orbit $\texttt{orb}(x)$ is defined as

$$\texttt{orb}(x) = \{y \in X : \exists g \in G \; gx = y\}$$

and $\texttt{fix}(g)$ is the set of elements in X fixed by g

$$\texttt{fix}(g) = \{x \in X : gx = x\}$$

Example: With k distinct types of beads how many distinct necklaces of size n can be made? Considering that two necklaces are equal if the rotation of one gives the other.



$$T = \frac{1}{n+1} \sum_{i=0}^{n} k^{gcd(i,n)} \qquad T = \frac{1}{n} \sum_{i=0}^{n-1} k^{gcd(i,n)}$$

9 Identities

$$\sum_{i=1}^{n} i = \frac{n(n+1)}{2} \qquad \sum_{i=1}^{n} i^2 = \frac{n(n+1)(2n+1)}{6} \qquad \sum_{i=1}^{n} i^3 = \left(\frac{n(n+1)}{2}\right)^2$$

$$\sum_{i=1}^{n} \frac{1}{i} \approx \log n \qquad \sum_{i=0}^{\infty} \frac{1}{2^i} = 2$$

10 Geometry

10.1 Trigonometry

10.1.1 Sines Rule

$$\frac{a}{sin(\alpha)} = \frac{b}{sin(\beta)} = \frac{c}{sin(\gamma)}$$

10.1.2 Cossines Rule

$$a^2 = b^2 + c^2 - 2bccos(\alpha)$$

10.2 Triangle Existence Condition

$$a + b \geq c$$

$$a + c \geq b$$

$$b + c \geq a$$

10.3 Shoelace Formula

$$A = \frac{1}{2}|\sum_{i=1}^{n-1}(p_i \times p_{i+1}) = \frac{1}{2}|\sum_{i=1}^{n-1}(x_i y_{i+1} - x_{i+1} y_i)|$$

Where the points $p_1, pn, \ldots$ are in adjecent order and the first and last vertex is the same, that is, $p_1 = pn$

10.4 Pick's Theorem

$$A = a + \frac{b}{2} + 1$$

where A is the area of the polygon, a is the number of integer points inside the polygon and b is the number of integer points in the boundary of the polygon

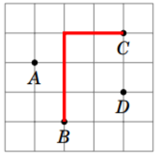
10.5 Distances

$$d(p,q) = \sqrt{(q.x - p.x)^2 + (q.y - p.y)^2}$$

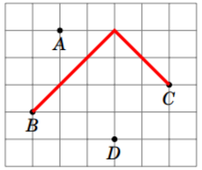
$$d(p,q)|p.x - q.x| + |p.y - q.y|$$

10.6 Maximum possible Manhattan distance between two points given n points

Given n points, for instance:



Rotate all coordinates 45^o do that (x,y) becomes $(x+y, y-x)$, so, p becomes p' and q becomes q'.



The maximum manhattan distance is obtaining by choosing the two points that maximize:

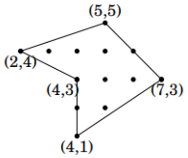
$$max(|p'.x - q'.x|, |p'.y - q'.y|)$$

10.7 Boundary points

The number of integer points in the boundary of a polygon is:

$$B = v + b$$

where v is the number of vertices (integer points as well) and b is the number of integer points situated between two vertices, like in the following figure:



b can be calculated for every line connecting two points (including the line between the last and the first point) as follows:

$$boundary\_points(p, q) = \begin{cases} |p.y - q.y| - 1 & \text{p.x = q.x} \\ |p.x - q.x| - 1 & \text{p.y = q.y} \\ gcd(|p.x - q.x|, |p.y - q.y|) - 1 \end{cases}$$

10.8 3D Shapes

Volume of Sphere: $\frac{4}{3}\pi r^3$

Prism: $V = bh$

Pyramid: $\frac{bh}{3}$

Cone: $\frac{\pi r^2 h}{3}$

10.9 2D Shapes

Perimeter of circle: $2\pi r$

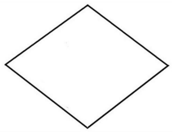
Area of circle: πr^2

Area of triangle: $\frac{b * h}{2}$

Square: l^2

Rectangle: hr

Rhombus:



D is the biggest diagonal and d is the smallest diagonal

$$A = \frac{1}{2} * D * d$$