Mathematical Formulae
A Book of High School and Engineering Common Core Mathematical Formulae

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Contents

Part I
Algebra

Chapter 1
Logarithm

1.1 Basic Formulae

For $a^x = b$:

$$\log_a x, \forall x \leq 0 \text{ is undefined} \tag{1.1}$$
$$\log_a b = x, bax \neq 1, a \neq 1 \tag{1.2}$$
$$\log_b a^m = m \log_b a, \text{ for } a^m = b \tag{1.3}$$
$$a^{\log_a x} = x \tag{1.4}$$
$$a^{\log_b c} = c^{\log_b a} \tag{1.5}$$
$$\frac{1}{\log_a b} = \log_b a \tag{1.6}$$
$$\log_c(ab) = \log_c a + \log_c b \tag{1.7}$$
$$\log_c \left(\frac{a}{b}\right) = \log_c a - \log_c b \tag{1.8}$$
$$|\log_a x| = \begin{cases} -\log_a x, \text{ if } 0 < x < 1 \\ \log_a x, \text{ if } 1 \leq x < \infty \end{cases} \tag{1.9}$$

1.2 Series

$$e^x = 1 + \frac{x}{1!} + \frac{x^2}{2!} + \frac{x^3}{3!} + \cdots \infty = \lim_{n \to \infty} \sum_{i=0}^{n} \frac{x^i}{i!} \tag{1.10}$$
$$\log(1+x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4} + \cdots \infty = \lim_{n \to \infty} \sum_{i=1}^{n} (-1)^{(i-1)} \frac{x^i}{i} \tag{1.11}$$

Chapter 2
Complex Numbers

2.1 Basic Formulae

For $z = x + iy$,

$$|z| = \sqrt{x^2 + y^2} \tag{2.1}$$

$$\tan\theta = \frac{y}{x} \tag{2.2}$$

$$\bar{z} = x - iy \tag{2.3}$$

2.2 Arithmetic Operation of Complex Number

For two complex numbers $z_1 = x_1 + iy_1$ and $z_2 = x_2 + iy_2$:

$$z_1 + z_2 = (x_1 + x_2) + i(y_1 + y_2) \tag{2.4}$$

$$z_1 z_2 = (x_1 x_2 - y_1 y_2) + i(x_1 y_2 + x_2 y_1) \tag{2.5}$$

$$|z_1 z_2| = |z_1| \cdot |z_2| \tag{2.6}$$

$$\frac{z_1}{z_2} = \frac{(x_1 x_2 + y_1 y_2) + i(x_2 y_1 - x_1 y_2)}{{a_2}^2 + {b_2}^2} \tag{2.7}$$

$$\left|\frac{z_1}{z_2}\right| = \frac{|z_1|}{|z_2|} \tag{2.8}$$

2.3 Euler's Formula

$$z = re^{i\theta}, \text{ where} \tag{2.9}$$

$$r = |z| \tag{2.10}$$

$$e^{i\theta} = \cos\theta + i\sin\theta \tag{2.11}$$

$$\theta = \arctan\left(\frac{y}{x}\right) \tag{2.12}$$

2.4 Trigonometric Ratios in Complex Form

$$e^{i\theta} + e^{-i\theta} = 2\cos\theta \tag{2.13}$$

$$\Rightarrow \cos\theta = \frac{e^{i\theta} + e^{-i\theta}}{2} \tag{2.14}$$

$$e^{i\theta} - e^{-i\theta} = 2\sin\theta \tag{2.15}$$

$$\Rightarrow \sin\theta = \frac{e^{i\theta} - e^{-i\theta}}{2} \tag{2.16}$$

2.5 De Moivre's Formula

According to DeMoivre's Formula:

$$(\cos\theta + i\sin\theta)^n = \cos(n\theta) + i\sin(n\theta) \tag{2.17}$$

Proof

$$\begin{aligned} \cos\theta + i\sin\theta &= e^{i\theta} \\ \Rightarrow (\cos\theta + i\sin\theta)^n &= e^{n(i\theta)} \\ &= \cos(n\theta) + i\sin(n\theta) \\ &\text{Q.E.D.} \end{aligned}$$

2.6 Application of Euler's and De Moivre's Formula

For $z_1 = |r_1|\, e^{i\theta_1}$ and $z_2 = |r_2|\, e^{i\theta_2}$

$$z_1 z_2 = (r_1 r_2)\, e^{i(\theta_1+\theta_2)} \tag{2.18}$$

$$\frac{z_1}{z_2} = \left(\frac{r_1}{r_2}\right) e^{i(\theta_1-\theta_2)} \tag{2.19}$$

2.7 Roots of Unity

$$\sqrt[n]{1} = e^{i\frac{2k\pi}{n}}, \text{ where } k \in [0, n-1] \tag{2.20}$$

2.8 Important Relations of Complex Numbers

$$|z_1 + z_2| \leq |z_1| + |z_2| \tag{2.21}$$

$$|z_1 - z_2| \leq |z_1| + |z_2| \tag{2.22}$$

$$|z_1 - z_2| \geq |z_1| - |z_2| \tag{2.23}$$

$$|z_1 + z_2| \geq ||z_1| - |z_2|| \tag{2.24}$$

$$|z_1 + z_2|^2 = 2\left(|z_1|^2 + |z_2|^2\right) \tag{2.25}$$

Chapter 3
Progression

3.1 Arithmetic Progression (A.P.)

An arithmetic sequence is $a, a+n, a+2n, ...\infty$ or $t_n = a + (n-1)d$, where a is the first term, d is the common difference, and n is the n^{th}-term.
An arithmetic series is $a + (a+d) + (a+2d) + ...\infty$.

3.1.1 Sum of A.P. Series

$$\begin{aligned} S_n = a + (a+d) + ... + (a + \overline{n-2}d) + (a + \overline{n-1}d) \\ S_n = (a + \overline{n-1}d) + (a + \overline{n-2}d + ... + (a+d) + a \\ \Rightarrow 2S_n = n(2a + \overline{n-1}d) \\ \Rightarrow S_n = \frac{n}{2}(2a + \overline{n-1}d) \end{aligned} \tag{3.1}$$

3.1.2 Important Relation

If the three terms a, b, c are in A.P., then

$$2b = a + c \tag{3.2}$$

3.2 Geometric Progression (G.P.)

An geometric sequence is $a, ar, ar^2, ...\infty$ or $t_n = ar^{n-1}$, where a is the first term, r is the common ratio, and n is the n^{th}-term. An geometric series is $a + ar + ar^2 + ...\infty$.

3.2.1 The Value of 'r'

$$r = \frac{t_2}{t_1} = \frac{t_3}{t_2} = ... = \frac{t_n}{t_{n-1}} \tag{3.3}$$

3.2.2 Sum of a G.P. Series

For a definite G.P. series, where there are n terms in the series, the sum of the series is:

$$S_n = \frac{a|r^n - 1|}{|r-1|} \tag{3.4}$$

For an infite G.P. series the sum of the series is defined for $r < 1$. Sum of such a series is:

$$S_\infty = \frac{a}{1-r} \tag{3.5}$$

3.2.3 Important relations

If the three terms a, b, c are in G.P., then:

$$b^2 = ac \tag{3.6}$$

3.3 Harmonic Progression (H.P.)

If a, b, c are terms of an H.P. then $\frac{1}{a}, \frac{1}{b}, \frac{1}{c}$ are in A.P.

$$\frac{2}{b} = \frac{1}{a} + \frac{1}{c} \tag{3.7}$$

$$\Rightarrow b = \frac{2ac}{a+c} \tag{3.8}$$

3.4 Arithmetico-Geometric Progression (A.G.P.)

Sequence $a, (a+d)r, (a+2d)r^2, ..., (a+\overline{n-1}d)r^{n-1}$, where a $\rightarrow$first term of A.G.P., d $\rightarrow$common difference, and r $\rightarrow$common ratio.

3.4.1 Sum of A.G.P.:

For an infinite A.G.P. series, the sum is defined for $r < 1$:

$$S_\infty = \frac{a}{1-r} + \frac{dr}{(1-r)^2} \tag{3.9}$$

3.5 Special Series

For $n \in \mathbb{N}$

$$1 + 2 + 3 + ... + (n-1) + n = \frac{n(n-1)}{2} \tag{3.10}$$

$$1^2 + 2^2 + 3^2 + ... + (n-1)^2 + n^2 = \frac{n(n+1)(2n+1)}{6} \tag{3.11}$$

$$1^3 + 2^3 + 3^3 + ... + (n-1)^3 + n^3 = [\frac{n(n-1)}{2}]^2 \tag{3.12}$$

3.5.1 Riemann Zeta Function

$$\zeta(s) = \sum_{n=1}^{\infty} \frac{1}{n^s} \tag{3.13}$$

3.5.2 Riemann's Infinite Series as an Integration

$$\lim_{n\to\infty} \frac{1}{n} \sum_{i=r_1}^{r_2} f(\frac{i}{n}) = \int_{\frac{r_1}{n}}^{\frac{r_2}{n}} f(x)dx \tag{3.14}$$

Chapter 4

Test of Convergence of Infinite Series

If $a_1, a_2, a_3, ..., a_n$ is a sequence by a_n and their sum of series is S_n, then the following apply.

4.1 Definition

If

$$\lim_{n\to\infty} S_n = l$$

where l is a finite value, the series S_n is said to converge. A non-convergent series is called a divergent series.

4.2 Tests of Convergence

4.2.1 Comparison Test

If u_n and v_n are two positive series, then:

1. (a) v_n converges
   (b) $u_n \leq v_n \forall n$ Then u_n converges.
2. (a) v_n diverges
   (b) $u_n \geq v_n \forall n$ Then u_n diverges.

4.2.2 Limit Form

If

$$\lim_{x\to\infty} \frac{u_n}{v_n} = l$$

where l is a finite quantity $\neq 0$, then u_n and v_n converge and diverge together.

4.2.3 Integral Test or Maclaurin-Cauchy Test

For a series

$$\sum_{i=N}^{\infty} f(x), \text{ where } N \in \mathbb{Z} \tag{4.1}$$

will only converge if the improper integral

$$\int_N^\infty f(x)dx \tag{4.2}$$

is finite.

If the improper integral is finite, the upper and lower limit of the infinite series is given by:

$$\int_N^\infty f(x)dx \leq \sum_{i=N}^\infty f(x) \leq f(N) + \int_N^\infty f(x)dx \tag{4.3}$$

4.2.4 Ratio Test

If, for two series $\sum u_n$ and $\sum v_n$:

1. (a) $\sum v_n$ converges
   (b) from or after a particular term $\frac{u_n}{u_{n+1}} > \frac{v_n}{v_{n+1}}$, then u_n converges.
2. (a) $\sum v_n$ diverges
   (b) from or after a particular term $\frac{u_n}{u_{n+1}} < \frac{v_n}{v_{n+1}}$, then u_n diverges.

4.2.5 D'Alembert's Ratio Test

$$\lim_{n\to\infty} \frac{u_n}{u_{n+1}} = \lambda \tag{4.4}$$

- series converges if $\lambda < 1$
- series diverges if $\lambda > 1$
- fails if $\lambda = 1$

4.2.6 Rabbe's Test

$$\lim_{n\to\infty} n\left[\frac{u_n}{u_{n+1}} - 1\right] = \kappa \tag{4.5}$$

- series converges if $\kappa < 1$
- series diverges if $\kappa > 1$
- fails if $\kappa = 1$

4.2.7 Cauchy's Root Test

$$\lim_{n\to\infty} |u_n| = \lambda \tag{4.6}$$

- series converges for $\lambda < 1$
- series diverges for $\lambda > 1$
- test fails for $\lambda = 1$

4.2.8 Logarithmic Test

$$\lim_{n\to\infty} n\log\left(\frac{u_n}{u_{n+1}}\right) = \kappa \tag{4.7}$$

- series converges for $\kappa < 1$
- series diverges for $\kappa > 1$
- test fails for $\kappa = 1$

Chapter 5
Determinants

5.1 Definition

For a determinant:

$$\Delta = \begin{vmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ a_3 & b_3 & c_3 \end{vmatrix} = a_1 \begin{vmatrix} b_2 & c_2 \\ b_3 & c_3 \end{vmatrix} - b_1 \begin{vmatrix} a_2 & c_2 \\ a_3 & c_3 \end{vmatrix} + c_1 \begin{vmatrix} a_2 & b_2 \\ a_3 & b_3 \end{vmatrix} \tag{5.1}$$

5.1.1 Minor and Cofactor

For a third order determinant

$$\begin{vmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ a_3 & b_3 & c_3 \end{vmatrix}$$

Minor

$$M(a_{11}) = M_{11} = \begin{vmatrix} b_2 & c_2 \\ b_3 & c_3 \end{vmatrix} \tag{5.2}$$

i.e., all the terms of determinant expect those in the same row and columns as the one of which the minor is being calculated.

Cofactor

$$C_{ij} = (-1)^{i+j} M_{ij} \tag{5.3}$$

5.2 Properties of Determinants

1. Transposing a determinant does not alter its value.

$$\Delta = \Delta^T \tag{5.4}$$

2. If rows and columns are interchanges m times, the value of the new determinant is

$$\Delta' = (-1)^m \Delta \tag{5.5}$$

3. If two parallel lines are equal, then $\Delta = 0$

4. For $\Delta = \begin{vmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ a_3 & b_3 & c_3 \end{vmatrix}$ and $\Delta_1 = \begin{vmatrix} ka_1 & kb_1 & kc_1 \\ a_2 & b_2 & c_2 \\ a_3 & b_3 & c_3 \end{vmatrix}$, then $\Delta_1 = k\Delta$

5. For $\Delta = \begin{vmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ a_3 & b_3 & c_3 \end{vmatrix}$ and $\Delta_1 = \begin{vmatrix} ka_1 & b_1 & c_1 \\ ka_2 & b_2 & c_2 \\ ka_3 & b_3 & c_3 \end{vmatrix}$, then $\Delta_1 = k\Delta$

6. For $C_n \to k_1C_l + k_2C_m + k_3C_n$ or $R_n \to k_1R_l + k_2R_m + k_3R_n$, $\Delta' = \Delta$

5.3 Cramer's Rule

For a system of equations:

$$\begin{aligned} a_1x + b_1y + c_1z &= d_1 \\ a_2x + b_2y + c_2z &= d_2 \\ a_3x + b_3y + c_3z &= d_3 \end{aligned}$$

the following determinants are defined:

$$\begin{aligned} D &= \begin{vmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ a_3 & b_3 & c_3 \end{vmatrix} \\ D_x &= \begin{vmatrix} d_1 & b_1 & c_1 \\ d_2 & b_2 & c_2 \\ d_3 & b_3 & c_3 \end{vmatrix} \\ D_y &= \begin{vmatrix} a_1 & d_1 & c_1 \\ a_2 & d_2 & c_2 \\ a_3 & d_3 & c_3 \end{vmatrix} \\ D_z &= \begin{vmatrix} a_1 & b_1 & d_1 \\ a_2 & b_2 & d_2 \\ a_3 & b_3 & d_3 \end{vmatrix} \end{aligned}$$

The solution for the system of equations is:

$$x = \frac{D_x}{D} \tag{5.6}$$

$$y = \frac{D_y}{D} \tag{5.7}$$

$$z = \frac{D_z}{D} \tag{5.8}$$

5.3.1 Consistency Test

1. If $D \neq 0$, the system is consistent and has unique solutions.
2. If $D = D_x = D_y = D_z = 0$, the system may or may not be consisten and it will have infinite solutions and the system will be dependent.
3. If $D = 0$ and at least one of D_x, D_y, D_z is non zero, the system is inconsistent

Chapter 6
Matrices

For a matrix,

$$A_{m\times n} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix}$$

and where I_p is an identity matrix of the p^{th} order, the following relations are applicable.

6.1 Sum of Two Matrices

$$A_{m\times n} + B_{m\times n} = \begin{bmatrix} a_{11}+b_{11} & a_{12}+b_{12} & \cdots & a_{1n}+b_{1n} \\ a_{21}+b_{21} & a_{22}+b_{21} & \cdots & a_{2n}+b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1}+b_{m1} & a_{m2}+b_{m2} & \cdots & a_{mn}+b_{mn} \end{bmatrix} \tag{6.1}$$

6.2 Multiplication of Two Matrices

If

$$C_{m\times p} = A_{m\times n} \cdot B_{n\times p} \tag{6.2}$$

then,

$$c_{ik} = \sum_{j=1}^{n} a_{ij} \cdot b_{jk} \tag{6.3}$$

6.2.1 Multiplicative Properties

1. Multiplication of matrices is associative, hence $(AB)C = A(BC)$.

2. $AI = A$

3. $A \cdot A^{-1} = I$
4. $A \cdot (adj A) = (adj A) \cdot A = |A|I$
5. $A^{-1} = \dfrac{1}{|A|}(adj A)^t$
6. $(AB)^t = B^t A^t$

6.3 Adjoint of a Matrix

$$adj A = \begin{bmatrix} M_{11} & M_{12} & \cdots & M_{1n} \\ M_{21} & M_{22} & \cdots & M_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ M_{m1} & M_{m2} & \cdots & M_{mn} \end{bmatrix}^t \text{, where } M_{ij} \text{ is the minor of } a_{ij} \tag{6.4}$$

6.4 Martin's Rule

For a system of equation,

$$\begin{gathered} a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n = b_1 \\ a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n = b_2 \\ \vdots \\ a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n = b_n \end{gathered}$$

The system can be written as:

$$\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_3 \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_n \end{bmatrix} \tag{6.5}$$

$$\Rightarrow AX = B \tag{6.6}$$

$$\Rightarrow X = A^{-1}B \tag{6.7}$$

Chapter 7

Binomial Theorem

For a binomial expansion $(a+b)^n$, there are $(n+1)$ terms and $(a+b+c)^n$ has $\frac{(n+1)(n+2)}{2}$ terms.

7.1 Expansion of a binomial expression

$$
\begin{aligned}
(a+b)^n &=^n C_0 a^n b^0 +^n C_1 a^{n-1} b^1 +^n C_2 a^{n-2} b^2 + \cdots +^n C_n a^0 b^n \\
&= \sum_{i=0}^{n} {}^n C_i a^{n-i} b^i \\
&\forall n \in \mathbb{N} \qquad (7.1) \\
(a+b)^n &= a^n b^0 + n a^{n-1} b + \frac{n(n-1)}{2!} a^{n-2} b^2 + \cdots + \frac{n(n-1)\cdots 3 \cdot 2 \cdot 1}{n!} a^0 b^n + \cdots \infty \\
&\forall n \in \mathbb{R} \qquad (7.2)
\end{aligned}
$$

7.2 Trinomial Expansion

For $(a+b+c)^n$:

$$
\begin{aligned}
(a+b+c+)^n &= \sum \frac{n!}{i!j!k!} a^i b^j c^k \\
&\forall (i+j+k) = n;\ i, j, k, n \in \mathbb{N} \qquad (7.3)
\end{aligned}
$$

7.3 Properties of Coefficients

$$\text{Sum of Co-efficients: } C_0 + C_1 + C_2 + \cdots + C_{n-1} + C_n = 2^n \qquad (7.4)$$

$$\text{Sum of Odd Co-efficients: } C_0 + C_2 + C_4 + \cdots + C_{2n-3} + C_{2n-1} = 2^{n-1} \qquad (7.5)$$

$$C_0 - C_1 + C_2 - \cdots + C_{2n-1} - C_{2n} = 0 \qquad (7.6)$$

7.4 Pascal's Rule

For $1 \leq k \leq n$ and $k, n \in \mathbb{N}$:

$$\binom{n}{k} + \binom{n}{k-1} = \binom{n+1}{k} \tag{7.7}$$

Chapter 8
Boolean Algebra

Let B be a set of a, b, c with operations sum $(+)$ and product $(\cdot)$.
Then B is said to belong to the Boolean Structure if the following conditions are satisfied:

Table 8.1: Properties of Boolean Algebraic Structure

Property	Name of Property
$a + b \in B$ $a \cdot b \in B$	Closure Property
$a + b = b + a$ $a \cdot b = b \cdot a$	Associative Law
$a(b + c) = ab + ac$ $a + bc = (a + b)(a + c)$	Commutative Law
$\{0, 1\} \in B$ $a + 0 = a$ $a + 1 = 1$ $a \cdot 0 = 0$ $a \cdot 1 = a$	Laws of 1 and 0
$a + ab = a$ $a(a + b) = a$	Absorption Law
$(a + b)' = (a'b')$	De'Morgan's Law

Chapter 9

Remainder Theorems

9.1 Remainder Theorem

If a function $f(x)$ is divided by a binomial $x - a$, then the remainder is provided by $f(a)$.

$$\frac{f(x)}{x-a} \equiv f(a) \mod (x-a) \tag{9.1}$$

Worked Example

Find the remainder when $f(x) = x^3 - 4x^2 - 7x + 10$ is divided by $(x - 2)$.
The remainder:

$$R = \left(x^3 - 4x^2 - 7x + 10\right) \mod (x-2)$$

is given by:

$$\begin{aligned} R = f(2) &= (2)^3 - 4(2)^2 - 7(2) + 10 \\ &= 8 - 16 - 14 + 10 = -12 \end{aligned}$$

9.2 Euler's Remainder Theorem

According to Euler's Remainder Theorem, if x and n are two co-prime numbers:

$$x^{\varphi(n)} \equiv 1 \mod n, x, n \in \mathbb{Z}^+ \tag{9.2}$$

where, $\varphi(n)$ is Euler's totient function.

9.2.1 Euler's Totient Function

For a number defined as:

$$n = \prod_{i=1}^{r} {a_r}^{b_r} \tag{9.3}$$

then Euler's totient function is defined as:

$$\begin{aligned}\varphi(n) &= n \cdot \left[\left(1-\frac{1}{a_1}\right)\cdot\left(1-\frac{1}{a_2}\right)\cdot\left(1-\frac{1}{a_3}\right)\cdots\right]\\ &= n\prod_{i=1}^{r}\left(1-\frac{1}{a_r}\right)\end{aligned} \tag{9.4}$$

Worked Example

Find the remainder if 3^{76} is divided by 35.

Since:

$$35 = 5^1 \times 7^1$$

Hence the totient quotient of 35 is:

$$\begin{aligned}\varphi(35) &= 35 \cdot \left(1-\frac{1}{5}\right)\cdot\left(1-\frac{1}{7}\right)\\ &= 35 \times \frac{4}{5} \times \frac{6}{7}\\ &= 24\end{aligned}$$

Hence Euler's Theorem yields:

$$\begin{aligned}3^{24} &\equiv 1 \mod 35\\ 3^{76} &\equiv 3^{24\times 3+4}\\ &\equiv \left(3^{24}\right)^3 \times 3^4 \mod 35\\ &\equiv (1)^3 \times 3^4 \mod 35\\ &\equiv 81 \mod 35\\ &\equiv 11 \mod 35\end{aligned}$$

The remainder when 3^{76} is divided by 35 is 11.

9.3 Wilson Theorem

According to Wilson Theorem:

$$(n-1)! \equiv -1 \mod n \tag{9.5}$$

Worked Example

Find the remainder when 28! is divided by 31.
By Wilson's Theorem:

$$\begin{aligned}
30! &\equiv -1 \mod 31\\
\Rightarrow 30 \cdot 29 \cdot 28! &\equiv -1 \mod 31\\
\text{Let } 28! \mod 31 &= x\\
\Rightarrow (-1) \cdot (-2) \cdot x &\equiv 30 \mod 31\\
\Rightarrow 2x &= 30\\
\Rightarrow x &= 15
\end{aligned}$$

The remainder when 28! is divided by 31 is 15.