

妮可代数结构答案

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1 集合

1.1

- (1) 不相等.
- (2) 相等.
- (3) 相等.

1.2

证明.

$$\left\{ \begin{array}{l} A \subseteq B \Rightarrow \forall x \in A, x \in B. \\ B \subset C \Rightarrow \left\{ \begin{array}{l} \forall x \in B, x \in C \\ \exists x \in C, x \notin B \end{array} \right. \end{array} \right. \Rightarrow \left\{ \begin{array}{l} \forall x \in A, x \in C \\ \exists x \in C, x \notin A \end{array} \right. \Rightarrow A \subset C.$$

□

1.3

- (1) 不成立.
- (2) 不成立.
- (3) 不成立.
- (4) 成立.
- (5) 成立.
- (6) 不成立.

1.4

- (1) 不成立.
- (2) 成立.
- (3) 成立.

1.5

证明.

(1)

$$A \cap (\overline{A} \cup B) = (A \cap \overline{A}) \cup (A \cap B) = \emptyset \cup (A \cap B) = A \cap B.$$

(2)

$$A \cup (A \cap B) = (A \cup A) \cap (A \cup B) = A \cap (A \cup B).$$

$$\begin{cases} A \subseteq A \cup (A \cap B) \\ A \supseteq A \cap (A \cup B) \end{cases} \Rightarrow A \cup (A \cap B) = A.$$

(3) (a)

$$\begin{aligned} \forall x \in \overline{\bigcap_i A_i} &\Rightarrow x \notin \bigcap_i A_i & \forall x \in \bigcup_i \overline{A_i} &\Rightarrow \exists 1 \leq k \leq n, x \in \overline{A_k} \\ &\Rightarrow \exists 1 \leq k \leq n, x \notin A_k & &\Rightarrow \exists 1 \leq k \leq n, x \notin A_k \\ &\Rightarrow \exists 1 \leq k \leq n, x \in \overline{A_k} & &\Rightarrow x \notin \bigcap_i A_i \\ &\Rightarrow x \in \bigcup_i \overline{A_i} & &\Rightarrow x \in \overline{\bigcap_i A_i} \\ &\Rightarrow \overline{\bigcap_i A_i} \subseteq \bigcup_i \overline{A_i} & &\Rightarrow \bigcup_i \overline{A_i} \subseteq \overline{\bigcap_i A_i} \end{aligned}$$

即证 $\overline{\bigcap_i A_i} = \bigcup_i \overline{A_i}$.

(b)

$$\begin{aligned} \forall x \in \overline{\bigcup_i A_i} &\Rightarrow x \notin \bigcup_i A_i & \forall x \in \bigcap_i \overline{A_i} &\Rightarrow \forall 1 \leq k \leq n, x \in \overline{A_k} \\ &\Rightarrow \forall 1 \leq k \leq n, x \notin A_k & &\Rightarrow \forall 1 \leq k \leq n, x \notin A_k \\ &\Rightarrow \forall 1 \leq k \leq n, x \in \overline{A_k} & &\Rightarrow x \notin \bigcup_i A_i \\ &\Rightarrow x \in \bigcap_i \overline{A_i} & &\Rightarrow x \in \overline{\bigcup_i A_i} \\ &\Rightarrow \overline{\bigcup_i A_i} \subseteq \bigcap_i \overline{A_i} & &\Rightarrow \bigcap_i \overline{A_i} \subseteq \overline{\bigcup_i A_i} \end{aligned}$$

即证 $\overline{\bigcup_i A_i} = \bigcap_i \overline{A_i}$.

□

1.6

证明.

$$(1) B \subseteq C \Rightarrow \forall x \in B, x \in C.$$

$$\forall x \in (A \cap B), x \in A \text{ 且 } x \in B \Rightarrow x \in A \text{ 且 } x \in C \Rightarrow x \in (A \cap C)$$

$$(2)$$

$$\begin{aligned} A \subseteq C, B \subseteq C &\Leftrightarrow A \cup C = C, B \cup C = C \\ &\Leftrightarrow (A \cup B) \cup C = A \cup (B \cup C) = A \cup C = C \\ &\Leftrightarrow (A \cup B) \subseteq C. \end{aligned}$$

$$(3) \text{ 若 } |A \cup B| > |A| + |B|, \text{ 则 } \exists x \in (A \cup B), \text{ 且 } x \notin A, x \notin B, \text{ 矛盾.}$$

$$|A \cup B| = |A| + |B| - |A \cap B|, |A \cup B| = |A| + |B| \text{ 当且仅当 } A \cap B = \phi \text{ 时.}$$

□

1.7

$$(1) \text{ 设所求集合为 } E.$$

1. (基础语句) 令 $D = \{0, 1, 2, 3, 4, 5, 6, 7, 8, 9\}$, 若 $x \in D$, 则 $x \in E$.
2. (归纳语句) 若 $x, y \in E$, 则 x 与 y 的连接 $\overline{xy} \in E$.
3. (终结语句) $x \in E$, 当且仅当 x 是由有限次 1, 2 得到的.

$$(2) \text{ 设所求集合为 } E.$$

1. (基础语句) 令 $D = \{0, 1, 2, 3, 4, 5, 6, 7, 8, 9\}$, 若 $x \in D$, 则 $x \in E, .x \in E$.
2. (归纳语句) 若 $x = a.b, y = c.d \in E$, 则 $\overline{ac}. \overline{bd} \in E$.
3. (终结语句) $x \in E$, 当且仅当 x 是由有限次 1, 2 得到的.

$$(3) \text{ 设所求集合为 } E. \text{ 先定义集合 } A$$

1. (基础语句) $1 \in A$.
2. (归纳语句) 若 $x \in A$, 则 $\overline{x0}, \overline{x1} \in A$.
3. (终结语句) $x \in A$, 当且仅当 x 是由有限次 1, 2 得到的.

再定义所求集合 E

1. (基础语句) $0 \in E$.
2. (归纳语句) 若 $x \in A$, 则 $\overline{x0} \in E$.
3. (终结语句) $x \in E$, 当且仅当 x 是由有限次 1, 2 得到的.

2 数论初步

2.1

证明.

(1)

$$\forall x|a, x|b \begin{cases} x > 0 & \xrightarrow{a>0, x|a} x \leq a \\ x < 0 & \xrightarrow{a>0} x < a \end{cases} \Rightarrow x < a \xrightarrow{a|a, a|b} (a, b) = a.$$

(2)

$$\left\{ \begin{array}{l} (a, b)|(a, b), (a, b)|b \\ \forall x|(a, b), x|b, \text{ 有 } x \leq (a, b). \text{ (证明同(1))} \end{array} \right. \Rightarrow ((a, b), b) = (a, b).$$

□

2.2

证明.

(1) 不妨假设 $\exists n > 0, (n, n+1) = d > 1$

$$\begin{aligned} (n, n+1) = d &\Rightarrow \exists x, y \in \mathbb{Z}, n = xd, n+1 = yd \\ &\Rightarrow 1 = (n+1) - n = (y-x)d > 0 \\ &\Rightarrow y > x, (y-x)d \geq d > 1 \\ &\Rightarrow \text{矛盾, 假设不成立.} \end{aligned}$$

(2) 可取 (n, k) , 证明如下

由推论 2.3, 取 $x = 1, a = n, b = k$, 有 $(n, k) = (n, n+k)$.

□

2.3

(1) $(314, 159) = 1$, 有解。由辗转相除法

$$314 = 159 \cdot 1 + 155$$

$$159 = 155 \cdot 1 + 4$$

$$155 = 4 \cdot 38 + 3$$

$$4 = 3 \cdot 1 + 1$$

即

$$1 = 4 - 3 \cdot 1$$

$$= 4 - (155 - 4 \cdot 38) \cdot 1$$

$$= (159 - 155 \cdot 1) \cdot 39 - 155$$

$$= 159 \cdot 39 - 155 \cdot 40$$

$$= 159 \cdot 39 - (314 - 159 \cdot 1) \cdot 40$$

$$= 159 \cdot 79 - 314 \cdot 40.$$

即 $x = -40, y = 79$.

(2) $(3141, 1592) = 1$, 有解。由辗转相除法

$$3141 = 1592 \cdot 1 + 1549$$

$$1592 = 1549 \cdot 1 + 43$$

$$1549 = 43 \cdot 36 + 1$$

即

$$1 = 1549 - 43 \cdot 36$$

$$= 1549 - (1592 - 1549 \cdot 1) \cdot 36$$

$$= 1549 \cdot 37 - 1592 \cdot 36$$

$$= (3141 - 1592 \cdot 1) \cdot 37 - 1592 \cdot 36$$

$$= 3141 \cdot 37 - 1592 \cdot 73.$$

即 $x = 37, y = -73$.

2.4

证明.

$$(0) \quad n = 1, n^3 - n = 0, \text{ 有 } 0 = 6 \cdot 0, 6|(n^3 - n).$$

$$(1) \quad n = 2, n^3 - n = 0, \text{ 有 } 6 = 6 \cdot 1, 6|(n^3 - n).$$

$$(2) \quad \text{假设 } n = k, k \in \mathbb{N} \text{ 时, 有 } 6|(k^3 - k), \text{ 则 } n = k + 1 \text{ 时有}$$

$$\begin{aligned} (k+1)^3 - (k+1) &= k^3 + 3k^2 + 2k \\ &= (k^3 - k) + 3k(k+1) \end{aligned}$$

显然有 $6|(k^3 - k)$, 下证 $6|3k(k+1)$

$$1^\circ \quad k = 1, 3k(k+1) = 6, \text{ 有 } 6 = 6 \cdot 1, 6|3k(k+1)$$

$$2^\circ \quad \text{若 } 6|3k(k+1), \text{ 则}$$

$$3(k+1)(k+2) = 3k(k+1) + 6(k+1) \Rightarrow 6|3(k+1)(k+2)$$

即证

$$\forall k \in \mathbb{N} \quad 6|3k(k+1) \Rightarrow 6|(k+1)^3 - (k+1)$$

综上, 即证

$$\forall n > 0, \quad 6|(n^3 - n).$$

□

2.5

证明.

$$\left\{ \begin{array}{ll} 3^4 \equiv 1(\text{mod } 10) & \Rightarrow 3^{4n} \equiv 1(\text{mod } 10) \\ & \Rightarrow 3^{m+4n} \equiv (-1)(\text{mod } 10). \\ 10|(3^m + 1) & \Rightarrow 3^m \equiv (-1)(\text{mod } 10) \end{array} \right.$$

即证

$$10|(3^{m+4n} + 1)$$

□

2.6

(1)

$$2345 = 5 \cdot 7 \cdot 67$$

(2)

$$3456 = 2 \cdot 2 \cdot 2 \cdot 2 \cdot 2 \cdot 2 \cdot 2 \cdot 3 \cdot 3 \cdot 3$$

2.7

证明. 不妨假设 $\exists n > 0$, 使得 $n(n+1) = d^2$ 为平方数, 则有

$$n^2 < n(n+1) = d^2 < (n+1)^2 \Rightarrow n < d < n+1$$

不存在相邻整数间的整数, d 不存在, 假设不成立, 即证. □

2.8

证明. $n = 5! + 1 = 2 \cdot 3 \cdot 4 \cdot 5 + 1$.

(1)

$$n+1 = 2 \cdot 3 \cdot 4 \cdot 5 + 2 = 2 \cdot (3 \cdot 4 \cdot 5 + 1)$$

(2)

$$n+2 = 2 \cdot 3 \cdot 4 \cdot 5 + 3 = 3 \cdot (2 \cdot 4 \cdot 5 + 1)$$

(3)

$$n+3 = 2 \cdot 3 \cdot 4 \cdot 5 + 4 = 4 \cdot (2 \cdot 3 \cdot 5 + 1)$$

(4)

$$n+4 = 2 \cdot 3 \cdot 4 \cdot 5 + 5 = 5 \cdot (2 \cdot 3 \cdot 4 + 1)$$

□

2.9

(1) $(1, 1) = 1|2$, 方程有解, $x_0 = 0, y_0 = 2$ 为一组特解, 故通解为

$$\begin{cases} x = t & (t \in \mathbb{Z}) \\ y = 2 - t \end{cases}$$

(2) $(2, 1) = 1|2$, 方程有解, $x_0 = 0, y_0 = 2$ 为一组特解, 故通解为

$$\begin{cases} x = t & (t \in \mathbb{Z}) \\ y = 2 - 2t \end{cases}$$

(3) $(15, 16) = 1|17$, 方程有解, $x_0 = -17, y_0 = 17$ 为一组特解, 故通解为

$$\begin{cases} x = 16t - 17 & (t \in \mathbb{Z}) \\ y = 17 - 15t \end{cases}$$

2.10

(1) $(6, -15) = 3|51$, 方程有解, $x_0 = 11, y_0 = 1$ 为一组特解, 故通解为

$$\begin{cases} x = 11 - 5t & (t \in \mathbb{Z}) \\ y = 1 - 2t \end{cases}$$

又要求负整数解, 故 $x, y < 0, t \geq 3$, 即所以负整数解为

$$\begin{cases} x = 11 - 5t & (t \in \mathbb{Z}, t \geq 3) \\ y = 1 - 2t \end{cases}$$

(2) $(6, 15) = 3|51$, 方程有解, $x_0 = 6, y_0 = 1$ 为一组特解, 故通解为

$$\begin{cases} x = 6 + 5t & (t \in \mathbb{Z}) \\ y = 1 - 2t \end{cases}$$

又要求负整数解, 故 $x, y < 0, t$ 无解, 即无负整数解.

2.11

必须要用 30 张

设需要 x 张 5 分, y 张 1 角, $z = (30 - x - y)$ 张 2 角五分. 有

$$\begin{aligned} 0.05x + 0.1y + 0.25(30 - x - y) &= 5 \Leftrightarrow x + 2y + 5(30 - x - y) = 100 \\ &\Leftrightarrow 4x + 3y = 50 \end{aligned}$$

$(4, 3) = 1|50$, 方程有解, $x_0 = 2, y_0 = 14$ 为一组特解, 故通解为

$$\begin{cases} x = 2 + 3t & (t \in \mathbb{Z}) \\ y = 14 - 4t \end{cases}$$

又 $x, y, z \in \mathbb{N}$, 即

$$\begin{cases} 2 + 3t \geq 0 \\ 14 - 4t \geq 0 \\ 14 + t \geq 0 \end{cases} \xrightarrow{t \in \mathbb{Z}} t = 0, 1, 2, 3.$$

即有 4 种方案, 记 x 张 5 分, y 张 1 角, z 张 2 角五分, 则方案为

$$\begin{cases} x = 2 \\ y = 14 \\ z = 14 \end{cases} \quad \begin{cases} x = 5 \\ y = 10 \\ z = 15 \end{cases} \quad \begin{cases} x = 8 \\ y = 6 \\ z = 16 \end{cases} \quad \begin{cases} x = 11 \\ y = 2 \\ z = 17 \end{cases}$$

不多于 30 张

即求 $a, b, c \in \mathbb{N}, 0.05a + 0.1b + 0.25c = 5$, 且 $a + b + c \leq 30$. 即解

$$\begin{cases} a + 2b + 5c = 100 \\ (a + b + c) \leq 30 \\ a, b, c \in \mathbb{N} \end{cases}$$

(1) $c \leq 13$

$$a + 2b + 5c < 2 \cdot (30 - c) + 5c = 3c + 60 \leq 99 < 100, \text{无解.}$$

(2) $c > 20$

$$a + 2b + 5c > 5c > 100, \text{无解.}$$

(3) 由 (1)(2) 可知 $14 \leq c \leq 20$

$$a + 2b = 100 - 5c, (1, 2) = 1|100 - 5c \Rightarrow \text{方程存在解.}$$

又 $a = 100 - 5c, b = 0$ 为一组特解, 故通解为

$$\begin{cases} a = 100 - 5c - 2t; \\ b = t. \end{cases} (t \in \mathbb{N})$$

$$\begin{cases} a+b+c=100-4k-t & \leq 30 \\ a=100-5c-2t & \geq 0 \end{cases} \Rightarrow \begin{cases} t \geq 70-4k \\ t \leq \left\lfloor \frac{100-5k}{2} \right\rfloor \end{cases}$$

即解的组数为

$$\begin{cases} \left\lfloor \frac{100-5k}{2} \right\rfloor - (70-4k) + 1; & (70-4k \geq 0) \\ \left\lfloor \frac{100-5k}{2} \right\rfloor + 1. & (70-4k < 0) \end{cases}$$

$$(a) \ (c=14) \text{ 解的组数为 } \left\lfloor \frac{100-5 \times 14}{2} \right\rfloor - (70-4 \times 14) + 1 = 2$$

$$(b) \ (c=15) \text{ 解的组数为 } \left\lfloor \frac{100-5 \times 15}{2} \right\rfloor - (70-4 \times 15) + 1 = 3$$

$$(c) \ (c=16) \text{ 解的组数为 } \left\lfloor \frac{100-5 \times 16}{2} \right\rfloor - (70-4 \times 16) + 1 = 5$$

$$(d) \ (c=17) \text{ 解的组数为 } \left\lfloor \frac{100-5 \times 17}{2} \right\rfloor - (70-4 \times 17) + 1 = 6$$

$$(e) \ (c=18) \text{ 解的组数为 } \left\lfloor \frac{100-5 \times 18}{2} \right\rfloor + 1 = 6$$

$$(f) \ (c=19) \text{ 解的组数为 } \left\lfloor \frac{100-5 \times 19}{2} \right\rfloor + 1 = 3$$

$$(g) \ (c=20) \text{ 解的组数为 } \left\lfloor \frac{100-5 \times 20}{2} \right\rfloor + 1 = 1$$

即共有 $2+3+5+6+6+3+1=26$ 种兑换方法.

2.12

设买了 x 个苹果, $12-x$ 个橘子, 每个苹果 y 分钱, 每个橘子 $y-3$ 分钱, 则有

$$\begin{cases} 0 \leq 12-x < x \\ xy + (12-x)(y-3) = 99 \end{cases} \Leftrightarrow \begin{cases} 6 < x \leq 12 \\ x+4y = 45 \end{cases}$$

$(1, 4) = 1|45$, 方程有解, $x_0 = 9, y_0 = 9$ 为一组特解, 故通解为

$$\begin{cases} x = 9 + 4t \\ y = 9 - t \end{cases} \quad (t \in \mathbb{Z})$$

又 $6 < x \leq 12$, 即 $t = 0, x = 9, 12-x = 3$, 买了 9 个苹果和 3 个橘子.

2.13

$$6k + 5 \equiv 6k + 1 \pmod{4}$$

又 $6k \equiv 6 \pmod{4}$, 有

$$\begin{aligned} 6k + 5 &\equiv 7 \pmod{4} \\ &\equiv 3 \pmod{4} \end{aligned}$$

2.14

证明.

(1) 分情况讨论 $6k, 6k + 2, 6k + 3, 6k + 4$ ($k \geq 1$) 即可, 不再赘述.

(2) 记素数为 $p, p > 3$.

(a) $p < 6$, 则 $p = 5$, 成立.

(b) $p > 6$, 有 $(6, p) = 1$, 故 p 属于 6 的缩系, 故 p 模 6 或与 1 或 5 同余.

□

2.15

证明.

不妨设这两个连续的立方数为 k^3 与 $(k + 1)^3$.

$$\begin{aligned} (k + 1)^3 - k^3 &\equiv 3k^2 + 3k + 1 \pmod{3} \\ &\equiv 1 \pmod{3} \end{aligned}$$

□

2.16

证明.

设该数为 $A = \overline{a_n a_{n-1} \dots a_1 a_0}$, 则

$$A = \sum_{i=0}^{i=n} a_i \cdot 10^i, \quad \sum_{i=0}^{i=n} a_i \equiv 0 \pmod{3}$$

又 $\forall k \in \mathbb{N}, 10^i \equiv 1(\text{mod}3)$, 故

$$\begin{aligned} A &\equiv \sum_{i=0}^{i=n} a_i \cdot 10^i (\text{mod}3) \\ &\equiv \sum_{i=0}^{i=n} a_i (\text{mod}3) \\ &\equiv 0 (\text{mod}3) \end{aligned}$$

□

2.17

证明.

(1)

$$10 \equiv -1(\text{mod}11) \Rightarrow 10^k \equiv (-1)^k(\text{mod}11)$$

(2) 设数为 $A = \overline{a_n a_{n-1} \dots a_1 a_0}$, 则

$$A \equiv 0(\text{mod}11) \Leftrightarrow \sum_{i=0}^n (-1)^i \cdot a_i \equiv 0(\text{mod}11)$$

即偶数位之和与奇数位之和的差能被 11 整除等价于该数也能被 11 整除.

□

2.18

(1)

$$\begin{aligned} 2x &\equiv 1(\text{mod}17) \\ &\xrightarrow{(2,17)=1} x \equiv 9(\text{mod}17) \\ &\equiv 18(\text{mod}17) \end{aligned}$$

(2) $(3, 18) = 3|6$, 故有 3 组解由 $x \equiv 2(\text{mod}6)$ 得原方程解为

$$x \equiv 2 + 6t(\text{mod}18) \quad (0 \leq t \leq 2).$$

即

$$x \equiv 2, 8, 14(\text{mod}18).$$

(3) $(4, 18) = 2|6$, 故有 2 组解解 $2x \equiv 3(\text{mod}9)$

$$\begin{aligned} 2x &\equiv 3(\text{mod}9) \\ &\equiv 12(\text{mod}9) \end{aligned} \xrightarrow{(2,9)=1} x \equiv 6(\text{mod}9).$$

即原方程解为

$$x \equiv 6 + 9t(\text{mod}18) \quad (t = 0, 1) \Rightarrow x \equiv 6, 15(\text{mod}18).$$

(4)

$$\begin{aligned} 3x &\equiv 1(\text{mod}17) \\ &\equiv 18(\text{mod}17) \end{aligned} \xrightarrow{(3,17)=1} x \equiv 6(\text{mod}17).$$

2.19

(1) $(2, 3) = 1$, 有解。本题中

$$M = 2 \cdot 3 = 6, M_1 = 3, M_2 = 2.$$

由

$$\begin{cases} 3b_1 &\equiv 1(\text{mod}2) \\ 2b_2 &\equiv 1(\text{mod}3) \end{cases} \Rightarrow \begin{cases} b_1 &= 1 \\ b_2 &= 2 \end{cases}$$

从而

$$\begin{aligned} y &= 3 \cdot 1 \cdot 1 + 2 \cdot 1 \cdot 2 \\ &= 7 \end{aligned} \Rightarrow y \equiv 1(\text{mod}6).$$

(2) $(41, 26) = 1$, 有解。原式等价于

$$\begin{cases} x \equiv 31(\text{mod}41) \\ x \equiv 7(\text{mod}26) \end{cases}$$

本题中

$$M = 41 \cdot 26, M_1 = 26, M_2 = 41.$$

由

$$\begin{cases} 26b_1 &\equiv 1(\text{mod}41) \\ 41b_2 &\equiv 1(\text{mod}26) \end{cases} \Rightarrow \begin{cases} b_1 &= 30 \\ b_2 &= 7 \end{cases}$$

从而

$$\begin{aligned} y &= 26 \cdot 31 \cdot 30 + 41 \cdot 7 \cdot 7 \\ &= 26819 \end{aligned} \Rightarrow y \equiv 605 \pmod{1066}.$$

(3) $(2, 3) = (2, 7) = (3, 7) = 1$, 有解。本题中

$$M = 2 \cdot 3 \cdot 7 = 42, M_1 = 21, M_2 = 14, M_3 = 6.$$

由

$$\begin{cases} 21b_1 \equiv 1 \pmod{2} \\ 14b_2 \equiv 1 \pmod{3} \\ 6b_3 \equiv 1 \pmod{7} \end{cases} \Rightarrow \begin{cases} b_1 = 1 \\ b_2 = 2 \\ b_3 = 6 \end{cases}$$

从而

$$\begin{aligned} y &= 21 \cdot 1 \cdot 1 + 14 \cdot 1 \cdot 2 + 6 \cdot 6 \cdot 6 \\ &= 265. \end{aligned} \Rightarrow y \equiv 13 \pmod{42}.$$

(4) 原式等价于

$$\begin{cases} x \equiv 3 \pmod{5} \\ x \equiv 3 \pmod{7} \\ x \equiv 3 \pmod{11} \end{cases}$$

$(5, 7) = (5, 11) = (7, 11) = 1$, 有解。本题中

$$M = 5 \cdot 7 \cdot 11 = 385, M_1 = 77, M_2 = 55, M_3 = 35$$

由

$$\begin{cases} 77b_1 \equiv 1 \pmod{5} \\ 55b_2 \equiv 1 \pmod{7} \\ 35b_3 \equiv 1 \pmod{11} \end{cases} \Rightarrow \begin{cases} b_1 = 3 \\ b_2 = 6 \\ b_3 = 6 \end{cases}$$

从而

$$\begin{aligned} y &= 77 \cdot 3 \cdot 3 + 55 \cdot 3 \cdot 6 + 35 \cdot 3 \cdot 6 \\ &= 2313. \end{aligned} \Rightarrow y \equiv 3 \pmod{385}.$$

2.20

设

$$\begin{cases} 3x \equiv m-1 & (\text{mod } 20) \\ 5y \equiv m & (\text{mod } 20) \\ 7z \equiv m+1 & (\text{mod } 20). \end{cases} \quad (1 \leq m \leq 18)$$

则

$$\begin{cases} 3x = 20(m-1) + (m-1) \\ 5y = 20m + m \\ 7z = 20(m+1) + (m+1). \end{cases} \Rightarrow \begin{cases} x = 7m-7 \\ y = \frac{21m}{5} \\ z = 3m+3. \end{cases} \Rightarrow 5|m, m \in \{5, 10, 15\}$$

即

$$\begin{cases} x = 28 \\ y = 21 \\ z = 18; \end{cases} \quad \begin{cases} x = 63 \\ y = 42 \\ z = 33; \end{cases} \quad \begin{cases} x = 98 \\ y = 63 \\ z = 48. \end{cases}$$

2.21

由题意有

$$\begin{cases} n \equiv 0 & (\text{mod } 2) \\ n+1 \equiv 0 & (\text{mod } 3) \\ n+2 \equiv 0 & (\text{mod } 4) \\ n+3 \equiv 0 & (\text{mod } 5) \\ n+4 \equiv 0 & (\text{mod } 6) \end{cases} \Leftrightarrow \begin{cases} n \equiv 0 & (\text{mod } 2) \\ n \equiv 2 & (\text{mod } 3) \\ n \equiv 2 & (\text{mod } 4) \\ n \equiv 2 & (\text{mod } 5) \\ n \equiv 2 & (\text{mod } 6) \end{cases}$$

由 $n=2$ 为一个特解, 有模 $[2, 3, 4, 5, 6] = 60$ 唯一解

$$n \equiv 2 \pmod{60}$$

故所求最小整数 $n(n > 2)$ 为

$$n = 62.$$

2.22

(1)

$$\phi(42) = \phi(2 \cdot 3 \cdot 7) = \phi(2) \cdot \phi(3) \cdot \phi(7) = 1 \cdot 2 \cdot 6 = 12.$$

(2)

$$\phi(420) = \phi(2^2 \cdot 3 \cdot 5 \cdot 7) = \phi(2^2) \cdot \phi(3) \cdot \phi(5) \cdot \phi(7) = 2 \cdot 2 \cdot 4 \cdot 6 = 96.$$

(3)

$$\phi(4200) = \phi(2^3 \cdot 3 \cdot 5^2 \cdot 7) = \phi(2^3) \cdot \phi(3) \cdot \phi(5^2) \cdot \phi(7) = 4 \cdot 2 \cdot 20 \cdot 6 = 960.$$

2.23

(1) 小于 18 且与 18 互素的正整数有

$$1, 5, 7, 11, 13, 17$$

(2)

$$1 \cdot 5 \equiv 5(\text{mod } 18)$$

$$5 \cdot 5 \equiv 25(\text{mod } 18)$$

$$\equiv 7(\text{mod } 18)$$

$$7 \cdot 5 \equiv 35(\text{mod } 18)$$

$$11 \cdot 5 \equiv 55(\text{mod } 18)$$

$$\equiv 17(\text{mod } 18)$$

$$\equiv 1(\text{mod } 18)$$

$$13 \cdot 5 \equiv 65(\text{mod } 18)$$

$$17 \cdot 5 \equiv 85(\text{mod } 18)$$

$$\equiv 11(\text{mod } 18)$$

$$\equiv 13(\text{mod } 18)$$

仍为缩系，引理 2.1 成立.

2.24

设 m, n 有素数分解

$$m = m_1^{k_1} m_2^{k_2} \cdots m_x^{k_x} \cdot p^M, \quad n = n_1^{l_1} n_2^{l_2} \cdots n_y^{l_y} \cdot p^N$$

且

$$\forall 1 \leq i \leq x, 1 \leq j \leq y, \text{ 有 } m_i \neq n_j. \quad (m_i, n_j \text{ 均为素数})$$

$$\begin{aligned}
\phi(mn) &= \phi\left(p^{M+N} \cdot \prod_{i=1}^x m_i^{k_i} \cdot \prod_{j=1}^y n_j^{l_j}\right) \\
&= \phi(p^{M+N}) \cdot \prod_{i=1}^x \phi(m_i^{k_i}) \cdot \prod_{j=1}^y \phi(n_j^{l_j}) \\
&= p^{M+N} \cdot \left(1 - \frac{1}{p}\right) \cdot \prod_{i=1}^x m_i^{k_i} \left(1 - \frac{1}{m_i}\right) \cdot \prod_{j=1}^y n_j^{l_j} \left(1 - \frac{1}{n_j}\right) \\
&= mn \cdot \left(1 - \frac{1}{p}\right) \cdot \prod_{i=1}^x \left(1 - \frac{1}{m_i}\right) \cdot \prod_{j=1}^y \left(1 - \frac{1}{n_j}\right)
\end{aligned}$$

$$\begin{aligned}
\phi(m)\phi(n) &= \phi\left(p^M \cdot \prod_{i=1}^x m_i^{k_i}\right) \cdot \phi\left(p^N \cdot \prod_{j=1}^y n_j^{l_j}\right) \\
&= \phi(p^M) \cdot \phi(p^N) \cdot \prod_{i=1}^x \phi(m_i^{k_i}) \cdot \prod_{j=1}^y \phi(n_j^{l_j}) \\
&= p^M \cdot \left(1 - \frac{1}{p}\right) \cdot p^N \cdot \left(1 - \frac{1}{p}\right) \cdot \prod_{i=1}^x m_i^{k_i} \left(1 - \frac{1}{m_i}\right) \cdot \prod_{j=1}^y n_j^{l_j} \left(1 - \frac{1}{n_j}\right) \\
&= mn \cdot \left(1 - \frac{1}{p}\right)^2 \cdot \prod_{i=1}^x \left(1 - \frac{1}{m_i}\right) \cdot \prod_{j=1}^y \left(1 - \frac{1}{n_j}\right)
\end{aligned}$$

即

$$\phi(m)\phi(n) = \left(1 - \frac{1}{p}\right) \cdot \phi(mn)$$

2.25

证明.

显然有 $n \geq 0$, 否则 $\phi(n) \geq 0 > n$, 问题无意义.

(1) $6|n$ 即 $2|n, 3|n$, 不妨记 n 有素数分解

$$n = 2^p \cdot 3^q \cdot n_1^{k_1} n_2^{k_2} \cdots n_N^{k_N}. \quad (p, q \geq 1)$$

则

$$\begin{aligned}
 \phi(n) &= \phi(2^p \cdot 3^q \cdot n_1^{k_1} n_2^{k_2} \cdots n_N^{k_N}) \\
 &= \phi(2^p) \cdot \phi(3^q) \cdot \prod_{i=1}^N \phi(n_i^{k_i}) \\
 &= n \cdot \left(1 - \frac{1}{2}\right) \cdot \left(1 - \frac{1}{3}\right) \cdot \prod_{i=1}^N \left(1 - \frac{1}{n_i}\right) \\
 &= \frac{n}{3} \cdot \prod_{i=1}^N \left(1 - \frac{1}{n_i}\right) \\
 &\leq \frac{n}{3}
 \end{aligned}$$

即证, 且当且仅当 $N = 0$ 时等号成立.

(2) 由 T14 可知

$$n - 1 \equiv 5 \pmod{6}; \quad n + 1 \equiv 1 \pmod{6}; \quad n \equiv 0 \pmod{6}$$

即 $6|n$, 由 (1) 即证.

□

2.26

(1)

$$\begin{aligned}
 \frac{3}{2}\phi(3) &= \frac{3}{2} \cdot 2 = 3 = 1 + 2. & \frac{4}{2}\phi(4) &= \frac{4}{2} \cdot 2 = 4 = 1 + 3. \\
 \frac{5}{2}\phi(5) &= \frac{5}{2} \cdot 4 = 10 = 1 + 2 + 3 + 4. & \frac{6}{2}\phi(6) &= \frac{6}{2} \cdot 2 = 6 = 1 + 5. \\
 \frac{7}{2}\phi(7) &= \frac{7}{2} \cdot 6 = 21 = 1 + 2 + 3 + 4 + 5 + 6. & \frac{8}{2}\phi(8) &= \frac{8}{2} \cdot 4 = 16 = 1 + 3 + 5 + 7.
 \end{aligned}$$

(2) 对于整数 $n \geq 3$, 缩系中所有数的和等于 $\frac{1}{2}n \cdot \phi(n)$. 即

$$\sum_{\substack{(d,n)=1 \\ 1 \leq d \leq n-1}} d = \frac{1}{2}\phi(n) \cdot n.$$

(3) 证明.

$\forall 1 \leq d \leq n-1, (d, n) = 1$, 有 $(n-d, n) = 1$, 且 $d \neq n/2$, 故

$$\sum_{\substack{(d,n)=1 \\ 1 \leq d \leq n-1}} d = \sum_{\substack{(d,n)=1 \\ 1 \leq d < n/2}} d + (n-d) = \frac{1}{2}n \cdot \phi(n)$$

□

2.27

$$\begin{aligned} 314^{159} &\equiv (7 \cdot 45 - 1)^{159} \pmod{7} \\ &\equiv (-1)^{159} \pmod{7} \\ &\equiv (-1) \pmod{7} \\ &\equiv 6 \pmod{7} \end{aligned}$$

2.28

(1) 求末位即求模 10 余数

$$\begin{aligned} 7^{355} &\equiv (7^4)^{88} \cdot 7^3 \pmod{10} \\ &\equiv (2400 + 1)^{88} \cdot (340 + 3) \pmod{10} \\ &\equiv 3 \pmod{10} \end{aligned}$$

即末位为 3. 用欧拉定理 $7^{\phi(10)} \equiv 1 \pmod{10}$ 亦可.

(2) 求末两位即求模 100 余数

$$\begin{aligned} 7^{355} &\equiv (7^4)^{88} \cdot 7^3 \pmod{100} \\ &\equiv (2400 + 1)^{88} \cdot (300 + 43) \pmod{100} \\ &\equiv 43 \pmod{100} \end{aligned}$$

即末两位为 43. 用欧拉定理 $7^{\phi(100)} \equiv 1 \pmod{100}$ 亦可.

2.29

证明.

(1)

$$\begin{aligned}(k+1)^p - k^p &\equiv 1 \pmod{p} \Leftrightarrow p \mid (k+1)^p - k^p - 1 \\ &\Leftrightarrow p \mid \sum_{i=1}^{p-1} C_p^i \cdot k^{p-i}\end{aligned}$$

有

$$C_p^i = \frac{p(p-1)\dots(p-i+1)}{i!} \in \mathbb{N}, \Rightarrow i! \mid p(p-1)\dots(p-i+1). \quad (1 \leq i \leq p-1)$$

又 $\forall 1 \leq i \leq p-1, (p, i) = 1$, 故 $(p, i!) = 1$, 即

$$i! \mid (p-1)\dots(p-i+1) \Rightarrow \frac{(p-1)\dots(p-i+1)}{i!} \in \mathbb{N}, \quad p \mid C_p^i.$$

故有

$$p \mid C_p^i \Rightarrow p \mid \sum_{i=1}^{p-1} C_p^i \cdot k^{p-i} \Rightarrow (k+1)^p - k^p \equiv 1 \pmod{p}.$$

(2) 对于任意素数 p 有 $p \nmid a$, 则

$$\begin{aligned}a^p &\equiv \sum_{k=0}^{a-1} ((k+1)^p - k^p) \pmod{p} \\ &\equiv \sum_{k=0}^{a-1} 1 \pmod{p} \\ &\equiv a \pmod{p}\end{aligned}$$

又 $(a^p, a) = a, (p, a) = 1$, 故有

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

□

2.30

证明.

(1)

$$\forall 1 \leq k \leq p-1, (k, p) = 1 \text{ 且 } p \nmid k \Rightarrow k^{p-1} \equiv 1 \pmod{p}$$

故

$$\begin{aligned}\sum_{i=1}^{p-1} i^{p-1} &\equiv \sum_{i=1}^{p-1} 1 \pmod{p} \\ &\equiv p-1 \pmod{p} \\ &\equiv -1 \pmod{p}.\end{aligned}$$

(2)

$$\begin{aligned}\forall 1 \leq k \leq p-1, (k, p) = 1 \text{ 且 } p \mid k &\Rightarrow k^{p-1} \equiv 1 \pmod{p} \\ &\Rightarrow k^p \equiv k \pmod{p}\end{aligned}$$

故

$$\begin{aligned}\sum_{i=1}^{p-1} i^{p-1} &\equiv \sum_{i=1}^{p-1} i \pmod{p} \\ &\equiv \frac{p(p-1)}{2} \pmod{p} \\ &\equiv 0 \pmod{p}. \quad (2 \mid p-1)\end{aligned}$$

□

2.31

$$\begin{array}{lll}d(42) = d(2 \cdot 3 \cdot 7) & d(420) = d(2^2 \cdot 3 \cdot 5 \cdot 7) & d(4200) = d(2^3 \cdot 3 \cdot 5^2 \cdot 7) \\ = 2^3 & = 3 \cdot 2^3 & = 4 \cdot 3 \cdot 2^2 \\ = 8. & = 24. & = 48.\end{array}$$

$$\sigma(42) = \sigma(2 \cdot 3 \cdot 7)$$

$$= \frac{2^2 - 1}{2 - 1} \cdot \frac{3^2 - 1}{3 - 1} \cdot \frac{7^2 - 1}{7 - 1}$$

$$= 96.$$

$$\sigma(420) = \sigma(2^2 \cdot 3 \cdot 5 \cdot 7)$$

$$= \frac{2^3 - 1}{2 - 1} \cdot \frac{3^2 - 1}{3 - 1} \cdot \frac{5^2 - 1}{5 - 1} \cdot \frac{7^2 - 1}{7 - 1}$$

$$= 1344.$$

$$\sigma(4200) = \sigma(2^3 \cdot 3 \cdot 5^2 \cdot 7)$$

$$= \frac{2^4 - 1}{2 - 1} \cdot \frac{3^2 - 1}{3 - 1} \cdot \frac{5^3 - 1}{5 - 1} \cdot \frac{7^2 - 1}{7 - 1}$$

$$= 14880.$$

2.32

不妨设 n 有素数分解

$$n = n_1^{k_1} n_2^{k_2} \cdots n_x^{k_x} \Rightarrow \sigma(n) = (k_1 + 1)(k_2 + 1) \cdots (k_x + 1) = 60$$

又

$$\lceil \log_2(10^4) \rceil = 13 \Rightarrow k_1 + k_2 + \cdots + k_x \leq 13$$

$$n = 2^4 \cdot 3^2 \cdot 5 \cdot 7 = 5040 \quad \text{或} \quad n = 2^4 \cdot 5^2 \cdot 3 \cdot 7 = 8400$$

2.33

证明.

设 d_1, d_2, \dots, d_k 为 n 的全部因子 (相同因子算两遍), 则

$$\forall 1 \leq i \leq k, \exists! 1 \leq j \leq k, d_j = n/d_i$$

不妨取一个排列使得 $i + j = k + 1$.

$$\begin{aligned} \sum_{d|n} \frac{1}{d} &= \frac{1}{n} \sum_{i=1}^k \frac{n}{d_i} \\ &= \frac{1}{n} \sum_{i=1}^k d_{k+1-i} \\ &= \frac{1}{n} \sum_{i=1}^k d_i \\ &= \frac{1}{n} \sigma(n). \end{aligned}$$

□

2.34

证明.

不妨记偶完全数为

$$n = 2^{p-1} \cdot (2^p - 1) \quad (p, 2^p - 1 \text{ 均为素数})$$

由题意可得

$$2^{p-1} \cdot (2^p - 1) \equiv 6 \pmod{10} \quad \text{或} \quad 2^{p-1} \cdot (2^p - 1) \equiv 8 \pmod{10}$$

等价于

$$2^{p-2} \cdot (2^p - 1) \equiv 3 \pmod{5} \quad \text{或} \quad 2^{p-2} \cdot (2^p - 1) \equiv 4 \pmod{5}$$

$$\begin{cases} (2^{p-2}, 5) = 1 \\ (2^p - 1, 5) = 1 \end{cases} \Rightarrow \begin{cases} 2^{p-2} \equiv a \pmod{5} & (a \in \{1, 2, 3, 4\}) \\ 2^p - 1 \equiv b \pmod{5} & (b \in \{1, 2, 3, 4\}) \end{cases}$$

$$(1) \quad 2^{p-2} \equiv 1 \pmod{5}$$

$$\begin{aligned} 2^p - 1 &\equiv 2^2 \cdot 1 - 1 \pmod{5} \\ &\equiv 3 \pmod{5} \end{aligned} \Rightarrow \begin{aligned} 2^{p-2} \cdot (2^p - 1) &\equiv 3 \cdot 1 \pmod{5} \\ &\equiv 3 \pmod{5} \end{aligned}$$

$$(2) \quad 2^{p-2} \equiv 2 \pmod{5}$$

$$\begin{aligned} 2^p - 1 &\equiv 2^2 \cdot 2 - 1 \pmod{5} \\ &\equiv 2 \pmod{5} \end{aligned} \Rightarrow \begin{aligned} 2^{p-2} \cdot (2^p - 1) &\equiv 2 \cdot 2 \pmod{5} \\ &\equiv 4 \pmod{5} \end{aligned}$$

$$(3) \quad 2^{p-2} \equiv 3 \pmod{5}$$

$$\begin{aligned} 2^p - 1 &\equiv 2^2 \cdot 3 - 1 \pmod{5} \\ &\equiv 1 \pmod{5} \end{aligned} \Rightarrow \begin{aligned} 2^{p-2} \cdot (2^p - 1) &\equiv 3 \cdot 1 \pmod{5} \\ &\equiv 3 \pmod{5} \end{aligned}$$

$$(4) 2^{p-2} \equiv 4 \pmod{5}$$

$$\begin{aligned} 2^p - 1 &\equiv 2^2 \cdot 4 - 1 \pmod{5} \\ &\equiv 0 \pmod{5} \end{aligned} \Rightarrow 0 \notin \{1, 2, 3, 4\}, \text{该情况不存在.}$$

综上, 即证

$$2^{p-1} \cdot (2^p - 1) \equiv 6 \pmod{10} \quad \text{或} \quad 2^{p-1} \cdot (2^p - 1) \equiv 8 \pmod{10}$$

□

2.35

证明.

由题意可得

$$n = 2^{p-1} \cdot (2^p - 1) \quad (p, 2^p - 1 \text{ 均为素数})$$

又 $n > 6$, 故 $p > 2$, $2|p-1$, 不妨记 $p-1 = 2k$ ($k \in \mathbb{Z}^*$), 有

$$n = 2^{2k} \cdot (2^{2k+1} - 1) = 4^k \cdot (2 \cdot 4^k - 1)$$

又

$$\forall k \geq 1, 4^k \equiv m \pmod{9}, \text{ 有 } m \in \{4, 7, 1\}$$

$$(1) 4^k \equiv 4 \pmod{9}$$

$$\begin{aligned} 2 \cdot 4^k - 1 &\equiv 2 \cdot 4 - 1 \pmod{9} \\ &\equiv 7 \pmod{9} \end{aligned} \Rightarrow \begin{aligned} 4^k \cdot (2 \cdot 4^k - 1) &\equiv 4 \cdot 7 \pmod{9} \\ &\equiv 1 \pmod{9} \end{aligned}$$

$$(2) 4^k \equiv 7 \pmod{9}$$

$$\begin{aligned} 2 \cdot 4^k - 1 &\equiv 2 \cdot 7 - 1 \pmod{9} \\ &\equiv 4 \pmod{9} \end{aligned} \Rightarrow \begin{aligned} 4^k \cdot (2 \cdot 4^k - 1) &\equiv 7 \cdot 4 \pmod{9} \\ &\equiv 1 \pmod{9} \end{aligned}$$

$$(3) 4^k \equiv 1 \pmod{9}$$

$$\begin{aligned} 2 \cdot 4^k - 1 &\equiv 2 \cdot 1 - 1 \pmod{9} \\ &\equiv 1 \pmod{9} \end{aligned} \Rightarrow \begin{aligned} 4^k \cdot (2 \cdot 4^k - 1) &\equiv 1 \cdot 1 \pmod{9} \\ &\equiv 1 \pmod{9} \end{aligned}$$

综上, 即证

$$n \equiv 1 \pmod{9}.$$

□

2.36

证明. $\forall p, \sigma(p) = p + 1, \phi(p) = p - 1, d(p) = 2$, 有

$$\sigma(p) = \phi(p) + d(p) \Rightarrow \sum_{p \leq x} \sigma(p) = \sum_{p \leq x} \phi(p) + \sum_{p \leq x} d(p).$$

□

2.37

$$2^1 \equiv 2 \pmod{15}$$

$$2^2 \equiv 4 \pmod{15}$$

$$2^3 \equiv 8 \pmod{15}$$

$$2^4 \equiv 1 \pmod{15}$$

因此, 2模15的阶为4.

$$7^1 \equiv 7 \pmod{15}$$

$$7^2 \equiv 4 \pmod{15}$$

$$7^3 \equiv 13 \pmod{15}$$

$$7^4 \equiv 1 \pmod{15}$$

因此, 7模15的阶为4.

$$8^1 \equiv 8 \pmod{15}$$

$$8^2 \equiv 4 \pmod{15}$$

$$8^3 \equiv 2 \pmod{15}$$

$$8^4 \equiv 1 \pmod{15}$$

因此, 8模15的阶为4.

$$4^1 \equiv 4 \pmod{15}$$

$$4^2 \equiv 1 \pmod{15}$$

因此, 4模15的阶为2.

$$11^1 \equiv 11 \pmod{15}$$

$$11^2 \equiv 1 \pmod{15}$$

因此, 11模15的阶为2.

$$14^1 \equiv 14 \pmod{15}$$

$$14^2 \equiv 1 \pmod{15}$$

因此, 14模15的阶为2.

$$13^1 \equiv 13 \pmod{15}$$

$$13^2 \equiv 4 \pmod{15}$$

$$13^3 \equiv 7 \pmod{15}$$

$$13^4 \equiv 1 \pmod{15}$$

因此, 13模15的阶为4.

2.38

(1) 2 为 29 的原根.

$$n = \text{ind}_2 k \Leftrightarrow 2^n \equiv k \pmod{29}$$

k	1	2	3	4	5	6	7	8	9	10	11	12	13	14
n	0	1	5	2	22	6	12	3	10	23	25	7	18	13
k	15	16	17	18	19	20	21	22	23	24	25	26	27	28
n	27	4	21	11	9	24	17	26	20	8	16	19	15	14

(2) 由 2 为 29 的原根可知

$$\text{ind}_2 9 + \text{ind}_2 x = \text{ind}_2 2 \pmod{28}$$

又由 (1) 得 $\text{ind}_2 9 = 10$, $\text{ind}_2 2 = 1$, 有

$$\text{ind}_2 x = -9 \equiv 19 \pmod{28} \Rightarrow x \equiv 2^{19} \equiv 26 \pmod{29}.$$

(3) 由 2 为 29 的原根可知

$$9 \cdot \text{ind}_2 x = \text{ind}_2 2 \pmod{28}$$

又由 (1) 得 $\text{ind}_2 2 = 1$, 有

$$\begin{aligned} 9 \cdot \text{ind}_2 x &\equiv 1 \pmod{28} \Rightarrow \text{ind}_2 x \equiv 25 \pmod{28} \\ &\Rightarrow x \equiv 11 \pmod{29}. \end{aligned}$$

2.39

证明.

不对, 证明如下:

$$457^{911} \equiv 1 \pmod{10021} \Leftrightarrow \begin{cases} 457^{911} \equiv 1 \pmod{11} \\ 457^{911} \equiv 1 \pmod{911} \end{cases}$$

又

$$\begin{cases} 457^{10} \equiv 1 \pmod{11} \\ 457^{910} \equiv 1 \pmod{911} \end{cases} \Rightarrow \begin{cases} 457^{911} \equiv 6 \pmod{11} \\ 457^{911} \equiv 1457 \pmod{911} \end{cases}$$

故不对.

□

2.40

$\phi(\phi(37)) = 12$, 即 37 有 12 个原根.

又 $2^{36} \equiv 1 \pmod{37}$, 且

$$\begin{cases} 2^1 \equiv 2 \pmod{37}; & 2^2 \equiv 4 \pmod{37}; \\ 2^3 \equiv 8 \pmod{37}; & 2^4 \equiv 16 \pmod{37}; \\ 2^6 \equiv 27 \pmod{37}; & 2^9 \equiv 31 \pmod{37}; \\ 2^{12} \equiv 26 \pmod{37}; & 2^{18} \equiv 36 \pmod{37}; \end{cases} \Rightarrow 2 \text{ 为 } 37 \text{ 最小原根.}$$

由推论 2.7, 对于 $a = 2^i$ ($(i, 36) = 1$), a 模 37 的阶为 36. 即原根集合为

$$\{x \mid 1 \leq x \leq 36, x \equiv 2^i \pmod{37}\}, \text{ 且 } i \in \{1, 5, 7, 11, 13, 17, 19, 23, 25, 29, 31, 35\}$$

经计算

$$\begin{aligned} 2^1 &\equiv 2 \pmod{37}, 2^5 \equiv 32 \pmod{37}, 2^7 \equiv 17 \pmod{37}, 2^{11} \equiv 13 \pmod{37}, \\ 2^{13} &\equiv 15 \pmod{37}, 2^{17} \equiv 18 \pmod{37}, 2^{19} \equiv 35 \pmod{37}, 2^{23} \equiv 5 \pmod{37}, \\ 2^{25} &\equiv 20 \pmod{37}, 2^{29} \equiv 24 \pmod{37}, 2^{31} \equiv 22 \pmod{37}, 2^{35} \equiv 19 \pmod{37}, \end{aligned}$$

即 37 的原根集合为

$$\{2, 5, 13, 15, 17, 18, 19, 20, 22, 24, 32, 35\}$$

2.41

证明.

设 $(-a)$ 模 q 的阶为 d .

$$\begin{aligned} q \mid (a^p + 1) &\Rightarrow a^p \equiv -1 \pmod{q} \\ &\Rightarrow -a^p \equiv 1 \pmod{q} \quad \Rightarrow d \mid p, d = 1 \text{ 或 } p. \\ &\Rightarrow (-a)^p \equiv 1 \pmod{q} \end{aligned}$$

(1) $d = 1$

$$\begin{aligned} -a \equiv 1 \pmod{q} &\Rightarrow a + 1 \equiv 0 \pmod{q} \\ &\Rightarrow q \mid (a + 1). \end{aligned}$$

(2) $d = p$

$$\begin{aligned} (-a)^p \equiv 1 \pmod{q} &\Rightarrow p \mid \phi(q), p \mid (q - 1) \\ &\Rightarrow 2p \mid (q - 1) \\ &\Rightarrow \exists k \in \mathbb{Z}, 2kp = q - 1, q \mid (2kp + 1) \end{aligned}$$

即证

$$q \mid (a + 1) \text{ 或 } q \mid (2kp + 1) \quad (k \text{ 为某个整数}).$$

□

2.42

证明.

6 的正因子为 1, 2, 3, 6, 则 $(a + 1)$ 模 p 的阶为 6 等价于

$$\begin{cases} (a + 1) \not\equiv 1 \pmod{p} & (a + 1)^2 \not\equiv 1 \pmod{p} \\ (a + 1)^3 \not\equiv 1 \pmod{p} & (a + 1)^6 \equiv 1 \pmod{p} \end{cases}$$

(1)

$$(a, p) = 1 \Rightarrow (a + 1) \not\equiv 1 \pmod{p} \Rightarrow p \nmid (a - 1).$$

(2) 由 $a^3 \equiv 1 \pmod{p}, a \not\equiv 1 \pmod{p}, a^2 \not\equiv 1 \pmod{p}$, 得

$$a^3 - 1 = (a - 1)(a^2 + a + 1) \equiv 0 \pmod{p} \Rightarrow p \mid (a^2 + a + 1)$$

$$(a + 1)^2 = a^2 + 2a + 1 \equiv a \not\equiv 1 \pmod{p}.$$

(3)

$$(a + 1)^3 \equiv a(a + 1) \equiv -a^3 \equiv -1 \pmod{p}.$$

(4)

$$(a + 1)^6 \equiv 1 \pmod{p}.$$

即证 $(a+1)$ 模 p 的阶为 6.

□

3 映射

3.1

- (1) 不能构成映射, 如 $x_1 = 0$, 则 $x_2 = 0, 1, \dots, 9$ 均满足.
- (2) 能构成映射, $\forall y_1 \in \mathbb{R}, \exists! y_2 = y_1^2$.
- (3) 不能构成映射, 如 $y_1 = 1$, 则 $y_2 = \pm 1$ 均满足.

3.2

(1)

$$R_f = \{2, -2, 0\}$$

(2)

$$\begin{cases} |A| = 9 \\ |R_f| = 3 \end{cases} \Rightarrow n = 3^9.$$

3.3

(1) 满射

$$\forall y \in \mathbb{Z}^+, \exists x = \pm(y-1) \in \mathbb{Z}, f(x) = y.$$

(2) 既不是单射, 又不是满射. 值域为 $\{0, 1, 2\} \subseteq \mathbb{Z} \cup \{0\}$

$$\forall y \in \mathbb{Z} \cup \{0\} \begin{cases} y \in \{0, 1, 2\}, \exists x = 3k + y (k \in \mathbb{Z}), f(x) = y. \\ y \notin \{0, 1, 2\}, \forall x \in \mathbb{Z}, f(x) \neq y. \end{cases}$$

(3) f, g 均是双射.

$$\begin{cases} \forall y \in \mathbb{Z}, \exists! x = y - 1 \in \mathbb{Z}, f(x) = y. \\ \forall y \in \mathbb{Z}, \exists! x = y + 1 \in \mathbb{Z}, g(x) = y. \end{cases}$$

(4) 满射.

$$\forall y \in \{0, 1\}, \exists x = 2k + y + 1 (k \in \mathbb{Z}), f(x) = y.$$

(5) 既不是单射, 又不是满射.

$$\begin{cases} \forall y \in \mathbb{Z}, y < -16, \forall x \in \mathbb{Z}, f(x) > y. \\ \exists y = -15, f(0) = f(-2) = y. \end{cases}$$

3.4

证明.

$$\begin{cases} f: A \times B \rightarrow B \times A, (a, b) \mapsto (b, a) \\ g: B \times A \rightarrow A \times B, (b, a) \mapsto (a, b) \end{cases}$$

则

$$f \circ g = I_{A \times B}, \quad g \circ f = I_{B \times A}, \quad g = f^{-1}.$$

即 f 为双射, 即证 $|A \times B| = |B \times A|$. □

3.5

证明.

(1)

$$\forall f(x) = \sum_{i=0}^n a_i \cdot x^i, \exists! g(x) = \sum_{i=1}^n i \cdot a_i \cdot x^{i-1}, \frac{d}{dx} f(x) = g(x). (a_i \in \mathbb{R})$$

值域为 $R[x]$, 是满射不是双射.

$$\forall g(x) = \sum_{i=0}^n a_i \cdot x^i, \exists f(x) = a + \sum_{i=0}^n \frac{a_i}{i+1} \cdot x^{i+1}, \frac{d}{dx} f(x) = g(x). (a, a_i \in \mathbb{R})$$

(2)

$$\forall f(x) = \sum_{i=0}^n a_i \cdot x^i, \exists! g(x) = \sum_{i=0}^n \frac{a_i}{i+1} \cdot x^{i+1}, I(f(x)) = g(x). (a_i \in \mathbb{R})$$

值域为常数项为 0 的实系数多项式, 既不是满射, 也不是双射.

$$\forall g(x) = a (0 \neq a \in \mathbb{R}), \text{ 若 } \exists f(x) \in R[x], \text{ 满足 } I(f(x)) = g(x) = a \quad I(f(x)) = g(x).$$

则

$$a = g(x) = \int_0^x f(t) dt \xrightarrow{x=0} g(0) = \int_0^0 f(t) dt = 0 \neq a.$$

矛盾. □

3.6

证明. $\forall (b_{i1}, b_{i2}, \dots, b_{in}) \in S(B),$

$$\exists! f \in F, f: A \rightarrow B, a_j \mapsto b_{ij}. \text{满足 } g(f) = (b_{i1}, b_{i2}, \dots, b_{in}).$$

即证 g 即是单射, 又是满射, 即 g 是从 F 到 $S(B)$ 的双射.

$$|F| = |S(B)| = |B|^n = m^n.$$

□

3.7

证明.

$$(1) f(A \cup B) = f(A) \cup f(B)$$

$$(a) \forall y \in f(A \cup B), \exists x \in A \cup B, f(x) = y.$$

$$\begin{cases} x \in A, y = f(x) \in f(A) \\ x \in B, y = f(x) \in f(B) \end{cases} \Rightarrow y \in f(A) \cup f(B) \Rightarrow f(A \cup B) \subseteq f(A) \cup f(B).$$

$$(b) \forall y \in f(A) \cup f(B), y \in f(A) \text{ 或 } y \in f(B).$$

$$\begin{cases} y \in f(A), \exists x \in A, f(x) = y \\ y \in f(B), \exists x \in B, f(x) = y \end{cases} \Rightarrow y \in f(A \cup B) \Rightarrow f(A) \cup f(B) \subseteq f(A \cup B).$$

综上, 即证

$$f(A \cup B) = f(A) \cup f(B).$$

$$(2) f(A \cap B) \subseteq f(A) \cap f(B)$$

$$\forall y \in f(A \cap B), \exists x \in A \cap B, f(x) = y.$$

由 $x \in A \cap B$ 有 $x \in A, x \in B$, 即

$$\begin{cases} x \in A, y = f(x) \in f(A) \\ x \in B, y = f(x) \in f(B) \end{cases} \Rightarrow y \in f(A) \cap f(B) \Rightarrow f(A \cap B) \subseteq f(A) \cap f(B).$$

(3)

$$S = \mathbb{Z}, T = \{1\}, A = \{2k + 1 | k \in \mathbb{Z}\}, B = \{2k | k \in \mathbb{Z}\}$$

取 $f : S \rightarrow T, n \mapsto 1$, 则

$$\begin{cases} f(A \cap B) = f(\phi) = \phi. \\ f(A) \cap f(B) = \{1\} \end{cases} \Rightarrow f(A \cap B) \neq f(A) \cap f(B).$$

□

3.8

(1) f 为单射: $f(\tilde{A}) \subseteq \widetilde{f(A)}$.

$$\forall y \in f(\tilde{A}) \subseteq S, \exists! x \in \tilde{A} \text{ 且 } x \in \tilde{A}, f(x) = y.$$

有

$$\forall x \in A, f(x) \neq y, y \notin f(A) \Rightarrow y \in \widetilde{f(A)}.$$

即

$$\forall y \in f(\tilde{A}) \subseteq S, y \in \widetilde{f(A)} \Rightarrow f(\tilde{A}) \subseteq \widetilde{f(A)}.$$

(2) f 为满射: $\widetilde{f(A)} \subseteq f(\tilde{A})$.

$$\forall y \in \widetilde{f(A)}, \exists x \in S, f(x) = y.$$

若 $x \in A, y = f(x) \in f(A)$, 矛盾. 故 $x \in \tilde{A}$.

$$y = f(x) \in f(\tilde{A}) \Rightarrow \widetilde{f(A)} \subseteq f(\tilde{A}).$$

3.9

(1)

$$f \circ g = 3(3x + 1) = 9x + 3.$$

(2)

$$f \circ g = 3$$

(3)

$$g \circ f = 3(3x) + 1 = 9x + 1.$$

(4)

$$g \circ h = 3(3x + 2) + 1 = 9x + 7.$$

(5)

$$f \circ g \circ h = 3(3(3x + 2) + 1) = 27x + 21.$$

3.10

证明.

先证 $g \circ f$ 是从 A 到 C 的映射.

$$\forall x \in A, \exists! y = f(x) \in B, \exists! z = g(y) \in C.$$

假设 $g \circ f$ 不是从 A 到 C 的单射, 则等价于

$$\exists c \in C, \exists a_1, a_2 \in A, a_1 \neq a_2, g \circ f(a_1) = g \circ f(a_2) = c.$$

即

$$g(f(a_1)) = g(f(a_2)) = c \in C \xrightarrow{g} \exists! b \in B, g(b) = c, f(a_1) = f(a_2) = b \in B.$$

又

$$f \text{ 为单射} \Rightarrow \exists a \in A, f(a) = b.$$

即 $a_1 = a_2 = a$, 矛盾, 即证 $g \circ f$ 是从 A 到 C 的单射.

□

3.11

会发生矛盾.

(1) 先证 g 为满射若 $\exists y \in S, \forall x \in S, g(x) \neq y$, 则 $f(y) \in S$, 且 $f(y) \notin f \circ g(S)$, 矛盾.(2) 再证 g 为单射若 $\exists a, b \in S, a \neq b$, 且 $g(a) = g(b)$, 则 $f(g(a)) = f(g(b))$.又 $f \circ g(a) = a, f \circ g(b) = b, a \neq b$, 矛盾.

综上, 即证 g 为双射. 故

$$\forall x \in S, f(g(x)) = f(f^{-1}(x)) = x, \Rightarrow \forall x \in S, g(x) = f^{-1}(x), g \circ f = I_S.$$

故矛盾.

3.12

(1)

$$\tau\sigma = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 \\ 1 & 2 & 3 & 6 & 5 & 4 \end{pmatrix} = (1)(2)(3)(4\ 6)(5).$$

(2)

$$\tau^2\sigma = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 \\ 2 & 4 & 1 & 5 & 6 & 3 \end{pmatrix} = (124563).$$

(3)

$$\sigma^2\tau = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 \\ 3 & 1 & 4 & 5 & 6 & 2 \end{pmatrix} \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 \\ 1 & 5 & 3 & 4 & 2 & 6 \end{pmatrix} = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 \\ 3 & 6 & 4 & 5 & 1 & 2 \end{pmatrix}.$$

(4)

$$\sigma^{-1}\tau\sigma = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 \\ 2 & 6 & 1 & 3 & 4 & 5 \end{pmatrix} \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 \\ 1 & 2 & 3 & 6 & 5 & 4 \end{pmatrix} = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 \\ 2 & 6 & 1 & 5 & 4 & 3 \end{pmatrix}.$$

3.13

(1)

$$(257)(78)(145) = \begin{pmatrix} 1 & 2 & 4 & 5 & 7 & 8 \\ 4 & 5 & 7 & 1 & 8 & 2 \end{pmatrix} = (147825).$$

(2)

$$(72815)(21)(476)(12) = \begin{pmatrix} 1 & 2 & 4 & 5 & 6 & 7 & 8 \\ 5 & 8 & 2 & 7 & 4 & 6 & 1 \end{pmatrix} = (1576428).$$

3.14

(1)

$$\begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\ 8 & 2 & 6 & 3 & 7 & 4 & 5 & 1 \end{pmatrix} = (18)(2)(364)(57).$$

(2)

$$\begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\ 3 & 6 & 4 & 1 & 8 & 2 & 5 & 7 \end{pmatrix} = (134)(26)(587).$$

(3)

$$\begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\ 3 & 1 & 4 & 7 & 2 & 5 & 8 & 6 \end{pmatrix} = (13478652).$$

3.15

(1)

$$(47)(261)(567)(1234) = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 & 7 \\ 6 & 3 & 7 & 2 & 1 & 4 & 5 \end{pmatrix} = (1642375).$$

故阶为 7.

(2)

$$(163)(1357)(67)(12345) = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 & 7 \\ 2 & 5 & 4 & 7 & 1 & 6 & 3 \end{pmatrix} = (125)(347)(6).$$

 $[3, 3, 1] = 3$, 故阶为 3.**3.16**

证明.

(1) 由定理 3.9, 任何 n 元置换都可以表示成若干不相交的轮换之乘积.

(2) 任意轮换可以表示成对换之积.

(3) 任意对换 $\sigma = (ij)$ ($j > i$), 有

$$(ij) = (i(i+1))((i+1)(i+2)) \dots ((j-1)j).$$

综上, 即证任意置换都可以表示成对换 $(12), \dots, ((n-1)n)$ 的乘积.

□

3.17

证明.

(1)

$$\begin{aligned}
 x_1x_2x_3 + x_1\bar{x}_2x_3 + x_1 + x_1\bar{x}_2\bar{x}_3 &= x_1(x_2x_3 + \bar{x}_2x_3) + x_1(x_2\bar{x}_3 + \bar{x}_2\bar{x}_3) \\
 &= x_1x_3(x_2 + \bar{x}_2) + x_1\bar{x}_3(x_2 + \bar{x}_2) \\
 &= x_1x_3 + x_1\bar{x}_3 \\
 &= x_1(x_3 + \bar{x}_3) \\
 &= x_1.
 \end{aligned}$$

(2)

$$\begin{aligned}
 x_1x_2 + x_2x_3 + \bar{x}_1x_3 &= x_1x_2 + (x_1 + \bar{x}_1)x_2x_3 + \bar{x}_1x_3 \\
 &= x_1x_2 + x_1x_2x_3 + \bar{x}_1x_2x_3 + \bar{x}_1x_3 \\
 &= x_1x_2(1 + x_3) + \bar{x}_1x_3(1 + x_2) \\
 &= x_1x_2 + \bar{x}_1x_3.
 \end{aligned}$$

□

3.18

证明. (1)

$$\begin{aligned}
 f \cdot g + \bar{f} &= f \cdot (f + g) + \bar{f} \\
 &= f \cdot f + f \cdot g + \bar{f} \\
 &= f + \bar{f} + f \cdot g \\
 &= 1 + f \cdot g \\
 &= 1
 \end{aligned}$$

(2)

$$\begin{aligned}
 \bar{f} + g &= \bar{f} + f + g \\
 &= 1 + g \\
 &= 1
 \end{aligned}$$

(3)

$$\begin{aligned} p \cdot \bar{q} &= \overline{\bar{p} + q} \\ &= \bar{1} \\ &= 0 \end{aligned}$$

□

3.19

(1)

$$f = x_1x_2 + x_1\bar{x}_2 + \bar{x}_1x_2 + \bar{x}_1\bar{x}_2.$$

(2)

$$g = x_1x_2 + \bar{x}_1\bar{x}_2.$$

4 二元关系

4.1

- (1) R_1 有对称性.
- (2) R_2 有对称性.
- (3) R_3 有传递性, 反自反性.
- (4) R_4 有自反性, 传递性, 反对称性.
- (5) R_5 有自反性, 对称性, 传递性.

4.2

- (1) aR_1b , 当且仅当 $ab \geq 0$, 有

$$\left\{ \begin{array}{l} \forall a \in \mathbb{Z}, aR_1a; \\ aR_1b \leftrightarrow ab \geq 0 \leftrightarrow bR_1a; \\ (-1)R_10, 0R_11, (-1)\not R_11. \end{array} \right.$$

- (2) aR_2b , 当且仅当 $a \geq b$, 有

$$\left\{ \begin{array}{l} \forall a \in \mathbb{Z}, aR_2a; \\ aR_2b, bR_2c \Rightarrow a \geq b \geq c \Rightarrow aR_2c; \\ 5R_21, 1\not R_25. \end{array} \right.$$

- (3) aR_3b , 当且仅当 $ab > 0$, 有

$$\left\{ \begin{array}{l} aR_3b \Rightarrow ab > 0 \Rightarrow bR_3a; \\ aR_3b, bR_3c \Rightarrow ab > 0, bc > 0, ac = abcd/b^2 > 0 \Rightarrow aR_3c; \\ 0 \in \mathbb{Z}, 0\not R_30. \end{array} \right.$$

4.3

- (1) $R_1 \circ R_2 = \{(c, d)\}$
- (2) $R_2 \circ R_1 = \{(a, d), (a, c)\}$
- (3) $R_1^2 = \{(a, a), (a, b), (a, d)\}$

$$(4) R_2^3 = \{(b, c), (b, d), (c, d)\}$$

4.4

证明.

$$\forall (a, c) \in R_1 \circ (R_2 \cap R_3), \text{ 则}$$

$$\exists (a, b) \in (R_2 \cap R_3), (b, c) \in R_1.$$

故

$$\begin{cases} (a, b) \in R_2 \\ (a, b) \in R_3 \end{cases} \Rightarrow \begin{cases} (a, c) \in R_1 \circ R_2 \\ (a, c) \in R_1 \circ R_3 \end{cases} \Rightarrow (a, c) \in ((R_1 \circ R_2) \cap (R_1 \circ R_3))$$

$$\text{即证 } R_1 \circ (R_2 \cap R_3) \subseteq (R_1 \circ R_2) \cap (R_1 \circ R_3).$$

□

4.5

证明.

$$(1) \forall x \in A, (x, x) \in I_A, \text{ 故 } (x, x) \in R', \text{ 即证 } R' \text{ 在 } A \text{ 上自反.}$$

$$(2) R \subseteq I_A \cup R \Rightarrow R \subseteq R'.$$

$$(3) \text{ 若有自反关系 } R'' \text{ 满足 } R \subseteq R'', \text{ 由自反性可得 } I_A \subseteq R'', \text{ 故}$$

$$R' = I_A \cup R \subseteq R''$$

即证 R' 为 R 的自反闭包.

□

4.6

(1) 证明. (a) 自反性:

$$\forall (a, b) \in \mathbb{N} \times \mathbb{N}, a + b = b + a \Rightarrow (a, b) \sim (a, b).$$

(b) 对称性:

$$\forall (a, b) \sim (c, d), \text{ 有 } a + d = b + c, c + b = a + d \Rightarrow (c, d) \sim (a, b).$$

(c) 传递性:

$$\forall (a, b) \sim (c, d), (c, d) \sim (e, f), \text{ 有 } a + d = b + c, c + f = d + e$$

故

$$a + f = (a + d) + (c + f) - d - c = (b + c) + (d + e) - d - c = b + e \Rightarrow (a, b) \sim (e, f).$$

□

(2)

4.7

证明.

(1)

(2c)

□

4.8

4.9

4.10

4.11

4.12

4.13

4.14

4.15

4.16

4.17

4.18

4.19

4.20

5 群论初步

6 商群

7 环和域

8 格和布尔代数