

CHAPTER 4

Exercise (14). If $n \in \mathbb{Z}$, then $5n^2 + 3n + 7$ is odd. (Try cases.)

Proof. Suppose $n \in \mathbb{Z}$. Then n must be either an even or odd integer.

Case 1: Lets suppose that n is an even integer. Then by the definition of an even integer, n can be expressed as $n = 2k$, where $k \in \mathbb{Z}$. Therefore $5n^2 + 3n + 7 = 5(2k)^2 + 3(2k) + 7 = 20k^2 + 6k + 7 = 2(10k^2 + 3k + 3) + 1 = 2m + 1$, where $m = 10k^2 + 3k + 3$. Note that m is an integer because of the closure properties of the integers. Since $5n^2 + 3n + 7 = 2m + 1$, then $5n^2 + 3n + 7$ is an odd integer by the definition of odd. Thus when n is even, then $5n^2 + 3n + 7$ is odd.

Case 2: Suppose that n is an odd integer. Then by the definition of an odd integer, n can be expressed as $n = 2k + 1$, where $k \in \mathbb{Z}$. Therefore $5n^2 + 3n + 7 = 5(2k + 1)^2 + 3(2k + 1) + 7 = 5(4k^2 + 4k + 1) + 6k + 3 + 7 = 20k^2 + 20k + 5 + 6k + 3 + 7 = 20k^2 + 26k + 15 = 2(10k^2 + 13k + 7) + 1 = 2m + 1$, where $m = 10k^2 + 13k + 7$ and likewise $m \in \mathbb{Z}$. Since $5n^2 + 3n + 7 = 2m + 1$, then $5n^2 + 3n + 7$ is odd by definition. Thus when n is odd, then $5n^2 + 3n + 7$ is odd.

In each case $5n^2 + 3n + 7$ is odd, satisfying all possible integer values for n . □

Exercise (16). If two integers have the same parity, then their sum is even. (Try cases.)

Proof. Suppose we have $x, y \in \mathbb{Z}$ such that they share the same parity, that is to say either x and y are both even or x and y are both odd.

Case 1: Suppose x is even and y is even, then they can be expressed as $x = 2p$ and $y = 2q$ for some $p, q \in \mathbb{Z}$. Therefore $x + y = (2p) + (2q) = 2p + 2q = 2(p + q) = 2n$, where $n = p + q$ and $n \in \mathbb{Z}$ because of the closure properties of addition under the integers. Because $x + y = 2n$, that makes $x + y$ even by definition whenever x and y are even.

Case 2: Suppose x is odd and y is odd, then $x = 2p + 1$ and $y = 2q + 1$ for some $p, q \in \mathbb{Z}$. Therefore $x + y = (2p + 1) + (2q + 1) = 2p + 1 + 2q + 1 = 2p + 2q + 2 = 2(p + q + 1) = 2n$, where $n = p + q + 1$ and $n \in \mathbb{Z}$ because of the closure properties of addition under the integers. Because $x + y = 2n$, our sum $x + y$ is even by definition.

Thus for all cases in which two integers have the same parity, where either both integers are odd or both integers are even, we observe that their sum is even. \square

Exercise (18). Suppose x and y are positive real numbers. If $x < y$, then $x^2 < y^2$.

Proof. Suppose $x, y \in \mathbb{R}^+$ and that $x < y$. Multiplying both sides of the inequality by x will reveal that $x^2 < yx$. Likewise when we multiply both sides of the inequality by y , we reveal that $xy < y^2$. Note that $xy = yx$ because of the commutative properties of multiplication. Combining our inequality results in $x^2 < xy < y^2$. Hence by the transitivity property under inequalities in the real numbers, $x^2 < y^2$. Thus for all positive real numbers, if $x < y$ then $x^2 < y^2$. \square

Exercise (20). If a is an integer and $a^2 \mid a$, then $a \in \{-1, 0, 1\}$.

Proof. Suppose that $a \in \mathbb{Z}$ such that $a^2 \mid a$. Then by definition of divisibility, there exists a $b \in \mathbb{Z}$ such that $a = a^2b$. In order to show that a is in the set of $\{-1, 0, 1\}$, it suffices to show that there exists such a b for each value of a such that $a = a^2b$ is true.

Case 1: Suppose $a = -1$, then via substitution $a = a^2b$ gives us $-1 = (-1)^2b = 1b$, or $-1 = 1b$. If we let $b = -1$ then we find that $a^2 \mid a$ and that $a \in \{-1, 0, 1\}$.

Case 2: Suppose $a = 0$, then $a = a^2b$ holds for any value of b . Note that although the statement holds, the notion that $a^2 \mid a$ for $a = 0$ is undefined.

Case 3: Suppose $a = 1$, then $a = a^2b$ via substitution is $1 = (1)^2b = 1b$. This holds when we

let $b = 1$.

Thus if a is an integer and $a^2 \mid a$, then a is in the set $\{-1, 0, 1\}$. \square

Exercise (26). Every odd integer is a difference of two squares.

Proof. Suppose x is an odd integer, then by definition of odd $x = 2k + 1$ for some $k \in \mathbb{Z}$.

Hence $x = 2k + 1 = k^2 + 2k + 1 - k^2 = (2k + 1)^2 - k^2 = l^2 - k^2$, where $l = 2k + 1$ and $l \in \mathbb{Z}$ due to the closure properties of the integers. Note that $l^2 - k^2$ is the difference of two squares.

Thus every odd integer is a difference of two squares. \square

Exercise (28). Let $a, b, c \in \mathbb{Z}$. Suppose a and b are not both zero, and $c \neq 0$. Prove that $c \gcd(a, b) \leq \gcd(ca, cb)$.

Proof. Suppose $a, b, c \in \mathbb{Z}$. Let $d = \gcd(a, b)$, then by definition $d \mid a$ and $d \mid b$. That means $a = dn$ and $b = dm$ for some $n, m \in \mathbb{Z}$. Multiplying both equations by c we observe that $ca = cdn$ and $cb = cdm$. Thus $cd \mid ca$ and $cd \mid cb$ where $cd \in \mathbb{Z}$. Since $\gcd(ca, cb)$ is the greatest common divisor, $cd \leq \gcd(ca, cb)$. Thus $c * \gcd(a, b) \leq \gcd(ca, cb)$. Note that the inequality holds irrespective of whether $c < 0$ or $c > 0$. \square

CHAPTER 5

Exercise (4). Suppose $a, b, c \in \mathbb{Z}$. If a does not divide bc , then a does not divide b .

Proof. (By Contraposition) Suppose $a, b, c \in \mathbb{Z}$ such that a divides b . So $b = an$ for some $n \in \mathbb{Z}$. Multiplying both sides by c , $bc = anc = a(ac) = am$, Let $m = ac$. Note that by the closure properties of the integers, $m \in \mathbb{Z}$. Since $bc = am$, by definition of divisibility $a \mid bc$. Therefore by contraposition if a does not divide bc , then a does not divide b . \square

Exercise (5). Suppose $x \in \mathbb{R}$. If $x^2 + 5x < 0$ then $x < 0$.

Proof. (By Contraposition) Assume $x \in \mathbb{R}$ such that $x \geq 0$. Multiplying both sides by $(x+5)$:
 $x(x+5) = x^2 + 5x \geq 0(x+5) = 0$. Since $x^2 + 5x \geq 0$ if $x \geq 0$. Then by contraposition it must be the case that if $x^2 + 5x < 0$ then $x < 0$. \square

Exercise (6). Suppose $x \in \mathbb{R}$. If $x^3 - x > 0$ then $x > -1$.

Proof. (By Contraposition) Let $x \in \mathbb{R}$ such that $x \geq -1$. When we add 1 to both sides, $x + 1 \geq 0$. Further more when we multiply $(x^2 - x)$ to both sides, $(x^2 - x)(x + 1) = x^3 - x^2 + x^2 - x = x^3 - x \geq 0(x^2 - x) = 0$. Thus $x^3 - x \geq 0$ if $x \geq -1$. Hence by contraposition it must be the case that if $x^3 - x > 0$ then $x > -1$. \square

Exercise (7). Suppose $a, b \in \mathbb{Z}$. If both ab and $a + b$ are even, then both a and b are even.

Proof. (By Contraposition) Suppose $a, b \in \mathbb{Z}$ such that either a is odd or b is odd. Then there are three distinct possibilities, a is odd and b is even, b is odd and a is even, or a and b are both odd.

Case 1: Suppose a is odd and b is even, then by definition of even and odd $a = 2n + 1$ and $b = 2m$ respectively where $n, m \in \mathbb{Z}$. Hence $ab = (2n + 1)(2m) = 4mn + 2m = 2(2mn + m)$ which is even, and $a + b = 2n + 1 + 2m = 2(n + m) + 1$ which is odd. Thus both ab and $a + b$ being even is false.

Case 2: Suppose a is even and b is odd. Then $a = 2n$ and $b = 2m + 1$ for some $n, m \in \mathbb{Z}$. Thus $ab = (2n)(2m + 1) = 4mn + 2n = 2(2mn + n)$ which is even and $a + b = 2n + 2m + 1 = 2(n + m) + 1$ which is odd. It is not the case that ab and $a + b$ are both even.

Case 3: Suppose a is odd and b is odd. Then $a = 2n + 1$ and $b = 2m + 1$ for some $n, m \in \mathbb{Z}$. Thus $ab = (2n + 1)(2m + 1) = 4nm + 2n + 2m + 1 = 2(2nm + n + m) + 1$ which is odd, and

$a + b = 2n + 1 + 2m + 1 = 2n + 2m + 2 = 2(n + m + 1)$ which is even. Thus both ab and $a + b$ being even is false.

Therefore if a or b is odd, then ab or $a + b$ is odd. It follows by contraposition that if ab and $a + b$ are even then a and b are even. \square

Exercise (9). Suppose $n \in \mathbb{Z}$. If $3 \nmid n^2$, then $3 \nmid n$.

Proof. (By Contraposition) Suppose $n \in \mathbb{Z}$ such that $3 \mid n$. Then by definition of divisibility n can be expressed as $n = 3k$ for some $k \in \mathbb{Z}$. It follows that $n^2 = (3k)^2 = 9k^2 = 3(3k^2) = 3b$, where $b = 3k^2$. Thus $3 \mid n^2$ if $3 \mid n$. By contraposition it follows that if $3 \nmid n^2$ then $3 \nmid n$. \square

Exercise (10). Suppose $x, y, z \in \mathbb{Z}$ and $x \neq 0$. If $x \nmid yz$, then $x \nmid y$ and $x \nmid z$.

Proof. (By Contraposition) Let $x, y, z \in \mathbb{Z}$ and $x \neq 0$ such that $x \mid y$ or $x \mid z$. Then $x \mid y$ can be expressed as $y = xa$ for some $a \in \mathbb{Z}$. It follows that $yz = xaz = x(az)$ noting that $az \in \mathbb{Z}$ because of the closure properties of the integers. By definition $x \mid yz$. Similarly if $x \mid z$ then $z = xb$ for some $b \in \mathbb{Z}$ and $yz = xbz = x(bz)$ where $bz \in \mathbb{Z}$. Thus when $x \mid z$ or $x \mid y$ then $x \mid yz$, it follows by contraposition that if $x \nmid yz$ then $x \nmid y$ and $x \nmid z$. \square

Exercise (16). Suppose $x, y \in \mathbb{Z}$. If $x + y$ is even, then x and y have the same parity.

Proof. (By Contraposition) Lets suppose that $x, y \in \mathbb{Z}$ and x and y do not share the same parity, i.e. x is odd and y is even or y is odd and x is even.

Case 1: Suppose x is even and y is odd, then $x = 2n$ and $y = 2k + 1$ for some $n, k \in \mathbb{Z}$. It follows that $x + y = (2n) + (2k + 1) = 2n + 2k + 1 = 2(n + k) + 1$. Thus $x + y$ is odd by definition.

Case 2: Suppose x is odd and y is even, then $x = 2n + 1$ and $y = 2k$ for some $n, k \in \mathbb{Z}$. It follows that $x + y = (2n + 1) + (2k) = 2n + 2k + 1 = 2(n + k) + 1$. Thus $x + y$ is odd by

definition in this case as well.

Therefore when x and y do not have the same parity, $x + y$ is odd. It follows that by contraposition if $x + y$ is even then x and y must share the same parity. \square

Exercise (18). If $a, b \in \mathbb{Z}$, then $(a + b)^3 \equiv a^3 + b^3 \pmod{3}$.

Proof. Suppose $a, b \in \mathbb{Z}$. Observe that $(a + b)^3 - (a^3 + b^3) = a^3 + 3a^2b + 3ab^2 + b^3 - a^3 - b^3 = 3(a^2b + ab^2)$. Note that $a^2b + ab^2$ is an integer by closure the closure properties of the integers. Thus $3 \mid [(a + b)^3 - (a^3 + b^3)]$, in other words $(a + b)^3 \equiv a^3 + b^3 \pmod{3}$. \square

Exercise (19). Let $a, b, c \in \mathbb{Z}$ and $n \in \mathbb{N}$. If $a \equiv b \pmod{n}$ and $a \equiv c \pmod{n}$, then $c \equiv b \pmod{n}$.

Proof. Assume $a, b, c \in \mathbb{Z}$ and $n \in \mathbb{N}$ such that $a \equiv b \pmod{n}$ and $a \equiv c \pmod{n}$. Then there exists an n such that $n \mid (a - b)$ and $n \mid (a - c)$. Then by definition of divisibility, $(a - b) = nx$ and $(a - c) = ny$ for some $x, y \in \mathbb{Z}$. Observe that by subtracting the two equations, $(a - b) - (a - c) = c - b = nx - ny = n(x - y)$. Thus $c - b = n(x - y)$, so $n \mid (c - b)$ by definition of divisibility. Therefore $c \equiv b \pmod{n}$ by definition of congruence modulo n . \square

Exercise (22). Let $a \in \mathbb{Z}, n \in \mathbb{N}$. If a has remainder r when divided by n , then $a \equiv r \pmod{n}$.

Proof. Suppose $a \in \mathbb{Z}, n \in \mathbb{N}$ such that a has a remainder r when divided by n . By the division algorithm $a = nx + r$, where $x \in \mathbb{Z}$ and $r \in [0, n)$. Consider what happens when we subtract both sides of the equation by the remainder: $a - r = nx + r - r = nx$. So $n \mid (a - r)$ because $a - r = nx$. Therefore $a \equiv r \pmod{n}$ by definition of congruence modulo n . \square

Exercise (24). If $a \equiv b \pmod{n}$ and $c \equiv d \pmod{n}$, then $ac \equiv bd \pmod{n}$.

Proof. Suppose $a \equiv b \pmod{n}$ and $c \equiv d \pmod{n}$. Then there exists an $n \in \mathbb{Z}$ such that $a = b + nx$ and $c = d + ny$, where $x, y \in \mathbb{Z}$. It follows that $ac = (b + nx)(d + ny) = bd + bny + dnx + n^2xy = bd + n(by + dx + nxy)$, so $ac = bd + n(by + dx + nxy)$. Subtracting both sides by bd gives $ac - bd = n(by + dx + nxy)$. Therefore $ac \equiv bd \pmod{n}$ by definition of congruence modulo n . \square

Exercise (25). Let $n \in \mathbb{N}$. If $2^n - 1$ is prime, then n is prime.

Proof. (By Contraposition) Assume $n \in \mathbb{N}$ and n is not prime. Then n can be expressed as $n = ab$ for some $a, b \in \mathbb{Z}$ and $a, b > 1$. It follows that $2^n - 1 = 2^{ab} - 1 = (2^b - 1)(2^{ab-b} + 2^{ab-2b} + 2^{ab-3b} + \dots + 2^{ab-ab})$. Thus $2^n - 1$ is a composite number. Therefore by contraposition it must be the case that if $2^n - 1$ is prime, then n is prime. \square

Exercise (32). If $a \equiv b \pmod{n}$, then a and b have the same remainder when divided by n .

Proof. Assignment Homework 7: §6 and §7, due Wednesday, March 5, 2025 10:00 AM. Homework 7: §6 Suppose $a \equiv b \pmod{n}$. Then by definition $n \mid a - b$ which can be expressed in the form $a - b = xn$ for some $x \in \mathbb{Z}$. Subsequently $a = b + xn$ and $b = yn + r$ by the division algorithm. Thus $a = b + xn = (yn + r) + xn = yn + xn + r = n(y + x) + r$. So we have $a = n(y + x) + r$ and $b = yn + r$. When we divide both sides by n we see that both a and b share the same remainder. Thus when $a \equiv b \pmod{n}$, then a and b have the same remainder when divided by n . \square

Reflection:

Length of time: It might have taken me 3 minutes to maybe an hour or more on some problems. Getting stuck on some of the last problems in each chapter. A lot of time was

spent mulling and meandering about problems trying to get a foothold or an idea as to how to proceed, sometimes I'd struggle with one, think about it during work, fall asleep and somehow it would just click on waking. I probably should've leveraged more assistance since there are time constraints I need to consider.

Difficulty: Some of the problems were challenging to me, what I wrote for problem 28 in chapter 4 feels like it has gaps in it for example.

Challenges: Lot of the later proofs in the chapters required me to "align my thinking".

Comparison: I had to ape problem 25 in Chapter 5, thought about if it could be expressed better in summation notation. I tended to avoid the solutions in the back because its almost too spartan for my tastes and I encountered a typo early on in the book.