WORKSHEET #1

Definition 1. *A triple (a, b, c) of natural numbers is a* ***Pythagoran triple*** *if they form the side lengths of a right triangle, where c is the length of the hypotenuse.*

Theorem 2 (Fundamental Theorem of Arithmetic)**.** *Every natural number $n \geq 1$ can be written as a product of prime numbers:*

$$n = p_1^{e_1} p_2^{e_2} \cdots p_k^{e_k}.$$

This expression is unique up to reordering. □

Definition 3. *We call the number e_i the* ***multiplicity*** *of the prime p_i in the prime factorization of*

$$n = p_1^{e_1} p_2^{e_2} \cdots p_k^{e_k}.$$

Definition 4. *Let m, n be integers and $K \geq 1$ be a natural number. We say that m* ***is congruent to*** *n* ***modulo*** *K, written as $m \equiv n \pmod{K}$, if $m - n$ is a multiple of K.*

Theorem 5. *Let n be an integer and $K \geq 1$ a natural number. Then n is congruent to exactly one nonnegative integer between 0 and $K - 1$: this number is the "remainder" when you divide n by K.* □

Proposition 6. *Let m, m', n, n' and K be natural numbers. Suppose that*

$$m \equiv m' \pmod{K} \quad \textit{and} \quad n \equiv n' \pmod{K}.$$

Then

$$m + n \equiv m' + n' \pmod{K} \quad \textit{and} \quad mn \equiv m'n' \pmod{K}.$$ □

Definition 7. *A triple (a, b, c) of natural numbers is a* ***primitive Pythagoran triple (PPT)*** *if $a^2 + b^2 = c^2$, and there is no common factor of a, b, c greater than 1; equivalently, a, b, c have no common prime factor.*

Theorem 8. *The set of primitive Pythagorean triples (a, b, c) with a odd is given by the formula*

$$a = st, \quad b = \frac{s^2 - t^2}{2}, \quad c = \frac{s^2 + t^2}{2},$$

where $s > t \geq 1$ are odd integers with no common factors.

Theorem 9. *The set of points on the unit circle $x^2 + y^2 = 1$ with positive rational coordinates is given by the formula*

$$(x, y) = \left(\frac{2v}{v^2 + 1}, \frac{v^2 - 1}{v^2 + 1} \right)$$

where v ranges through rational numbers greater than one.

WORKSHEET #2

Definition 10. *The* ***greatest common divisor*** *of two integers a and b, denoted $\gcd(a, b)$, is the largest integer that divides a and b.*

Definition 11. *Two integers a and b are* ***coprime*** *if $\gcd(a, b) = 1$.*

Theorem 12. *The Euclidean algorithm terminates and outputs the correct value of $\gcd(a, b)$.*

Definition 13. *An expression of the form $ra + sb$ with $r, s \in \mathbb{Z}$ is a* ***linear combination*** *of a and b.*

Corollary 14. *If a, b are integers, then $\gcd(a, b)$ can be realized as a linear combination of a and b. Concretely, we can use the Euclidean algorithm to do this.*

Theorem 15. *Let a, b, c be integers. The equation*

$$ax + by = c$$

has an integer solution if and only if c is divisible by $d := \gcd(a, b)$. If this is the case, there are infinitely many solutions. If (x_0, y_0) is a one particular solution, then the general solution is of the form

$$x = x_0 - (b/d)n, \quad y = y_0 + (a/d)n$$

as n ranges through all integers.

PROBLEM SET #1

Lemma 16. *Lat a, b, c be integers. If a and b are coprime, and a divides bc, then a divides bc.*

WORKSHEET #3

Definition 17. *A* ***congruence class*** *modulo K is a set of the form*

$$[a] := \{n \in \mathbb{Z} \mid n \equiv a \pmod{K}\}$$

for some $a \in \mathbb{Z}$.

Definition 18. *A* ***representative*** *for a congruence class is an element of the congruence class.*

Proposition 19. *Given $K > 0$, the set of integers $\mathbb{Z}$ is the disjoint union of K congruence classes:*

$$\mathbb{Z} = [0] \sqcup [1] \sqcup \cdots \sqcup [K-1].$$

Definition 20. *The ring $\mathbb{Z}_K$ is the set of congruence classes modulo K:*

$$\{[0], [1], \ldots, [K-1]\}$$

equipped with the operations

$$[a] + [b] = [a+b] \quad \textit{and} \quad [a][b] = [ab].$$

Definition 21. *We say that a number a is a* ***unit modulo*** *K if there is an integer solution x to $ax \equiv 1 \pmod{K}$, and we say that such a number x is an* ***inverse modulo*** *K to a.*

Definition 22. *We say that a congruence class $[a]$ is a* ***unit in*** *$\mathbb{Z}_K$ if there is a congruence class $x \in \mathbb{Z}_K$ such that $[a]x = [1]$, and we say that such a class x is an* ***inverse*** *to $[a]$ in $\mathbb{Z}_K$.*

Theorem 23. *Let a and n be integers, with n positive. Then a is a unit modulo n if and only if a and n are coprime.*

Theorem 24 (Chinese Remainder Theorem)**.** *Given $m_1, \ldots, m_k > 0$ integers such that m_i and m_j are coprime for each $i \neq j$, and $a_1, \ldots, a_k \in \mathbb{Z}$, the system of congruences*

$$\begin{cases} x \equiv a_1 \pmod{m_1} \\ x \equiv a_2 \pmod{m_2} \\ \quad \vdots \qquad\qquad \vdots \\ x \equiv a_k \pmod{m_k} \end{cases}$$

has a solution $x \in \mathbb{Z}$. Moreover, the set of solutions forms a unique congruence class modulo $m_1 m_2 \cdots m_k$.

PROBLEM SET #2

Lemma 25. *Lat a, b, c be integers. If a and b are coprime, a divides c, and b divides c, then a divides bc.*

Definition 26. *Given integers $a_1, \ldots, a_m$, the* ***greatest common divisor*** *of $a_1, \ldots, a_m$ is the largest integer that divides all of them.*

Theorem 27. *Let a, b, n be integers, with $n > 0$. Then $[a]x = [b]$ has a solution x in $\mathbb{Z}_n$ if and only if $\gcd(a, n)$ divides b. In this case, the number of distinct solutions is exactly $\gcd(a, n)$.*

Worksheet #4

Definition 28. *A **group** is a set G equipped with a product operation*

$$G \times G \to G \qquad (g,h) \mapsto gh$$

*and an **identity** element $1 \in G$ such that*

- *the product is associative: $(gh)k = g(hk)$ for all $g, h, k \in G$,*
- *$g1 = 1g = g$ for all $g \in G$, and*
- *for every $g \in G$, there is an inverse element $g^{-1} \in G$ such that $gg^{-1} = g^{-1}g = 1$.*

Definition 29. *A group is **abelian** if the product is commutative: $gh = hg$ for all $g, h \in G$.*

Definition 30. *A **finite group** is a group G that is a finite set.*

Definition 31. *Let G be a group and $g \in G$. The **order** of g is the smallest positive integer n such that $g^n = e$, if some such n exists, and ∞ if no such integer exists.*

Theorem 32 (Lagrange's Theorem)**.** *Let G be a finite group and $g \in G$. Then the order of g is finite and divides the cardinality of the group G.*

Theorem 33 (Fermat's Little Theorem)**.** *Let p be a prime number and a an integer. If p does not divide a, then*

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

Definition 34. *Let n be a positive integer. We define $\varphi(n)$ to be the number of elements of $\mathbb{Z}_n^\times$. We call this **Euler's phi function**.*

Proposition 35. *Euler's phi function satisfies the following properties.*

1. *If p is a prime and n is a positive integer, then $\varphi(p^n) = p^{n-1}(p-1)$.*
2. *If m, n are coprime positive integers, then $\varphi(mn) = \varphi(m)\varphi(n)$.*

Theorem 36 (Euler's Theorem)**.** *Let a, n be coprime integers, with n positive. Then*

$$a^{\varphi(n)} \equiv 1 \pmod{n}.$$

Worksheet #5

Proposition 37. *Let p be a prime. Let $p(x)$ be a polynomial of degree d with coefficients in $\mathbb{Z}_p$. Then $p(x)$ has at most d roots in $\mathbb{Z}_p$.* $\square$

Definition 38. *Let n be a positive integer. An element $x \in \mathbb{Z}_n^\times$ is a **primitive root** if the order of x in $\mathbb{Z}_n^\times$ equals $\phi(n)$ (the cardinality of $\mathbb{Z}_n^\times$).*

Theorem 39. *Let p be a prime number. Then there exists a primitive root in $\mathbb{Z}_p^\times$.*

Definition 40. *If $[a]$ is a primitive root in $\mathbb{Z}_p$, then every nonzero element of $\mathbb{Z}_p$ can be written as $[a]^m$ for a unique nonnegative integer $m < p-1$. We call the function*

$$\mathbb{Z}_p^\times \to \mathbb{Z}_{p-1} \quad [b] \mapsto [m] \text{ such that } [b] = [a]^m$$

*the **discrete logarithm** or **index** of $\mathbb{Z}_p^\times$ with base $[a]$.*

Lemma 41. *Let p be a prime and $[a]$ a primitive root in $\mathbb{Z}_p$. The corresponding discrete logarithm function $I : \mathbb{Z}_p^\times \to \mathbb{Z}_{p-1}$ satisfies the property*

$$I(xy) = I(x) + I(y) \quad \text{and} \quad I(x^n) = [n]I(x)$$

for $x, y \in \mathbb{Z}_p^\times$ and $n \in \mathbb{N}$.

Proposition 42. *Let n be a positive integer. Then $\displaystyle\sum_{d \mid n} \varphi(d) = n$.*

Theorem 43. *Let p be a prime. Suppose that there are n distinct solutions to $x^n = 1$ in $\mathbb{Z}_p$. Then $\mathbb{Z}_p^\times$ has exactly $\varphi(n)$ elements of order n.*