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 nonnnegative 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*

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

Then

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

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 c.*

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

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*
$$\begin{cases} x \equiv a_1 \pmod{m_1} \\ x \equiv a_2 \pmod{m_2} \\ \quad \vdots \qquad \quad \vdots \\ x \equiv a_k \pmod{m_k} \end{cases}$$
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 $\gcd(a, n)$.*

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*

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

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 $\mathbb{Z}_p$.* $\qquad\square$

Lemma 38. *If G is a group, $g \in G$, and n a positive integer such that $g^n = 1$, then the order of g divides n.*

Definition 39. *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 40. *Let p be a prime number. Then there exists a primitive root in $\mathbb{Z}_p^\times$.*

Definition 41. *If $[a]$ is a primitive root in $\mathbb{Z}_p$, the function*

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

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

Lemma 42. *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 43. *Let n be a positive integer. Then $\sum_{d \mid n} \varphi(d) = n$.*

Theorem 44. *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.*

<center>WORKSHEET #6</center>

Definition 45. *We say that an element $x \in \mathbb{Z}_n$ is a **square** or a **quadratic residue** if there is some $y \in \mathbb{Z}_n$ such that $y^2 = x$, and in this case, we call y a **square root** of x.*

Definition 46. *Let p be an odd prime. For $r \in \mathbb{Z}$ not a multiple of p we define the **Legendre symbol** of r with respect to p as*
$$\left(\frac{r}{p}\right) = \begin{cases} 1 & \text{if } [r] \text{ is a square in } \mathbb{Z}_p, \\ -1 & \text{if } [r] \text{ is a not square in } \mathbb{Z}_p. \end{cases}$$

Theorem 47 (Euler's Criterion). *For p an odd prime and $r \in \mathbb{Z}$ not a multiple of p, we have*
$$\left(\frac{r}{p}\right) \equiv r^{(p-1)/2} \pmod{p}.$$

Theorem 48 (Quadratic Reciprocity part -1). *If p is odd, then*
$$\left(\frac{-1}{p}\right) = \begin{cases} 1 & \text{if } p \equiv 1 \pmod{4} \\ -1 & \text{if } p \equiv 3 \pmod{4} \end{cases}.$$

Proposition 49. *Let p be an odd prime and a, b integers not divisible by p. Then*

(1) $a \equiv b \pmod{p}$ implies that $\left(\dfrac{a}{p}\right) = \left(\dfrac{b}{p}\right)$.

(2) $\left(\dfrac{ab}{p}\right) = \left(\dfrac{a}{p}\right)\left(\dfrac{b}{p}\right)$.

(3) $\left(\dfrac{a^2}{p}\right) = 1$.

<center>PROBLEM SET #3</center>

Theorem 50. *If p is an odd prime and $n > 0$, then $\mathbb{Z}_{p^n}$ has a primitive root.*

<center>WORKSHEET #7</center>

Theorem 51 (Quadratic Reciprocity). *Let p and q be distinct odd primes. Then*
$$\left(\frac{p}{q}\right) = \left(\frac{q}{p}\right) \qquad \text{if either } p \equiv 1 \pmod{4} \text{ or } q \equiv 1 \pmod{4},$$
$$\left(\frac{p}{q}\right) = -\left(\frac{q}{p}\right) \qquad \text{if both } p \equiv 3 \pmod{4} \text{ and } q \equiv 3 \pmod{4}.$$

Theorem 52 (Quadratic Reciprocity part 2). *Let p be an odd prime. Then*
$$\left(\frac{2}{p}\right) = 1 \qquad \text{if } p \equiv \pm 1 \pmod{8},$$
$$\left(\frac{2}{p}\right) = -1 \qquad \text{if } p \equiv \pm 3 \pmod{8}.$$

Lemma 53 (Gauss' Lemma)**.** *Let p be an odd prime and set $p' = \frac{p-1}{2}$. Note that every integer coprime to p is congruent modulo p to a unique integer in the set $S = \{\pm 1, \pm 2, \cdots, \pm p'\}$.*

Let a be an integer coprime to p. Consider the sequence

$$a, 2a, 3a, \ldots, p'a$$

and replace each element in the sequence with element of S that is congruent with modulo p to get a list L of p'-many elements of S.

Then $\left(\dfrac{a}{p}\right) = (-1)^\nu$, where ν is the number of negative integers in L.

Lemma 54. *Let p and q be two coprime odd positive integers. Then*

$$\sum_{k=1}^{\frac{p-1}{2}} \left\lfloor \frac{kq}{p} \right\rfloor + \sum_{\ell=1}^{\frac{q-1}{2}} \left\lfloor \frac{\ell p}{q} \right\rfloor = \frac{p-1}{2} \cdot \frac{q-1}{2}.$$

WORKSHEET #8

Theorem 55 (Euclid)**.** *There are infinitely many primes.*

Proposition 56. *For each of the following conditions, there are infinitely many primes p:*

- $p \equiv 1 \pmod 3$
- $p \equiv 2 \pmod 3$
- $p \equiv 1 \pmod 4$
- $p \equiv 3 \pmod 4$

WORKSHEET #9

Theorem 57. *An odd prime is a sum of two squares if and only if it is congruent to 1 modulo 4.*

Theorem 58 (Sums of Two Squares Theorem)**.** *A positive integer n is a sum of two squares if and only if: for every prime p such that $p \equiv 3 \pmod 4$ and p divides n, the multiplicity of p in the prime factorization of n is even.*

WORKSHEET #10

Definition 59. *A **finite continued fraction** is an expression of the form*

$$a_0 + \cfrac{1}{a_1 + \cfrac{1}{a_2 + \cfrac{1}{\ddots + \frac{1}{a_n}}}}$$

for some integers $a_0 \in \mathbb{Z}, a_1, \ldots, a_n \in \mathbb{Z}_{>0}$. We write $[a_0; a_1, \ldots, a_n]$ as shorthand for this.

*An **infinite continued fraction** is an expression of the form*

$$a_0 + \cfrac{1}{a_1 + \cfrac{1}{a_2 + \cfrac{1}{a_3 + \cfrac{1}{\ddots}}}}$$

for some integers $a_0 \in \mathbb{Z}, a_1, a_2, a_3, \ldots \in \mathbb{Z}_{>0}$.
We write $[a_0; a_1, a_2, \ldots]$ as shorthand for this.

*By a **continued fraction** we mean either an infinite or finite continued fraction. We call the numbers a_i the **partial quotients** in the continued fraction.*

Definition 60. *Given an infinite continued fraction $[a_0; a_1, a_2, \ldots]$, the k-th **convergent** of the continued fraction is the value C_k of the finite continued fraction $[a_0; a_1, \ldots, a_k]$.*

Theorem 61. *Every infinite continued fraction converges to a real number; i.e., for any $[a_0; a_1, a_2, a_3, \dots]$ with $a_0 \in \mathbb{Z}$ and $a_1, a_2, \dots \in \mathbb{Z}_{>0}$, the sequence of convergents $C_1, C_2, C_3, \dots$ converges. We call this limit the value of the infinite continued fraction.*

Algorithm 62 (Continued Fraction Algorithm)**.** *Given a real number r,*

  (I) Start with $\beta_0 := r$ and $n := 0$.
  (II) Set $a_n := \lfloor \beta_n \rfloor$.
  (III) If $a_n = \beta_n$, STOP; the continued fraction is $[a_0; a_1, \dots, a_n]$.
    Else, set $\beta_{n+1} := (\beta_n - a_n)^{-1}$, and return to Step (??).
If the algorithm does not terminate, the continued fraction is $[a_0; a_1, a_2, \dots]$.

Theorem 63. *For any real number r, the continued fraction obtained from the Continued Fraction Algorithm with input r converges to r.*

Proposition 64. *Let r be a real number. The Continued Fraction Algorithm with input r terminates in finitely many steps if and only if r is rational.*

Theorem 65 (Dirichlet Approximation Theorem)**.** *Let $r = [a_0; a_1, a_2, a_3, \dots]$ be a real number. Then for every convergent $C_k = \dfrac{p_k}{q_k}$ (in lowest terms), we have $\left| r - \dfrac{p_k}{q_k} \right| < \dfrac{1}{q_k^2}$.*

  In particular, if r is irrational, there are infinitely many rational numbers $\dfrac{p}{q}$ such that $\left| r - \dfrac{p}{q} \right| < \dfrac{1}{q^2}$.

Proposition 66. *Let $[a_0; a_1, a_2, \dots]$ be a continued fraction. Set*

$$p_0 := a_0, \qquad p_1 := a_0 a_1 + 1, \qquad p_k := a_k p_{k-1} + p_{k-2}$$
$$q_0 := 1, \qquad q_1 := a_1, \qquad q_k := a_k q_{k-1} + q_{k-2}.$$

Then,

  (1) $C_k = \dfrac{p_k}{q_k}$ for all $k \geq 0$, and
  (2) $p_k q_{k-1} - p_{k-1} q_k = (-1)^{k-1}$ for all $k \geq 1$.

PROBLEM SET #5

Theorem 67. *Let r be a real number, $C_k = \dfrac{p_k}{q_k}$ be the k-th convergent of r, and $\dfrac{p}{q} \neq r$ be a rational number, with $q > 0$. If $q < q_k$, then $\left| r - \dfrac{p}{q} \right| > \left| r - \dfrac{p_k}{q_k} \right|$.*

WORKSHEET #11

Definition 68. *The equation $x^2 - Dy^2 = 1$ for some fixed positive integer D that is not a perfect square, where the variables x, y range through integers is called a **Pell's equation**. We say that a solution (x_0, y_0) is a **positive solution** if x_0, y_0 are both positive integers. We say that one positive solution (x_0, y_0) is **smaller** than another positive solution (x_1, y_1) if $x_0 < x_1$; equivalently, $y_0 < y_1$.*

Definition 69. *Let D be a positive integer that is not a perfect square. We define the **quadratic ring** of D to be*

$$\mathbb{Z}[\sqrt{D}] := \{a + b\sqrt{D} \mid a, b \in \mathbb{Z}\} \subseteq \mathbb{R}.$$

Definition 70. *For the quadratic ring $\mathbb{Z}[\sqrt{D}]$ we define the **norm** function*

$$N : \mathbb{Z}[\sqrt{D}] \to \mathbb{Z} \qquad N(a + b\sqrt{D}) = a^2 - b^2 D.$$

Note that $N(a + b\sqrt{D}) = (a + b\sqrt{D})(a - b\sqrt{D})$.

Lemma 71. *For the quadratic ring $\mathbb{Z}[\sqrt{D}]$ the norm function satisfies the multiplicative property $N(\alpha\beta) = N(\alpha)N(\beta)$.*

Theorem 72. *Let D be a positive integer that is not a perfect square. Consider the Pell's equation $x^2 - Dy^2 = 1$. Let (a, b) be the smallest positive solution (assuming that some positive solution exists). Then every positive solution (c, d) can be obtained by the rule*

$$c + d\sqrt{D} = (a + b\sqrt{D})^k$$

for some positive integer k.

WORKSHEET #12

Theorem 73. *Let D be a positive integer that is not a perfect square. Then the Pell's equation $x^2 - Dy^2 = 1$ has a positive solution.*

Theorem 74. *Let D be a positive integer that is not a perfect square. For every positive solution (a, b) to the Pell's equation $x^2 - Dy^2 = 1$, there is some $k \in \mathbb{Z}_{\geq 0}$ such that the ratio $\frac{a}{b}$ is a convergent C_k of the continued fraction of $\sqrt{D}$.*

Theorem 75. *Let r be an irrational real number. If p, q are integers with $q > 0$ such that $|r - \frac{p}{q}| < \frac{1}{2q^2}$, then there is some $k \in \mathbb{Z}_{\geq 0}$ such that $\frac{p}{q}$ is a convergent C_k of the continued fraction of r.*