

PMATH 340: Elementary Number Theory

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Contents

1	Pythagorean Triplets	1
1.1	Integral Pythagorean Triplets	1
2	Euler's Formula	4
2.1	Fermat's Little Theorem	4
2.2	Euler's Totient Function	5
3	Congruence Relations	9
3.1	Successive Squaring algorithm	9
3.2	Bases in Congruence Relations	10
3.3	Sums of Divisors with Phi	12
3.4	Primitive Roots Modulo p	13

Abstract

Number Theory is quite simply the study of integers. This course analyzes some interesting relationships between integers, and the implications of these relationships. You are expected to be familiar with what was taught in MATH 135, including but not limited to, *linear Diophantine equations*, *euclidean algorithm*, *congruence* and the *Chinese remainder theorem*.

Chapter 1

Pythagorean Triplets

1.1 Integral Pythagorean Triplets

Question: Find all integral Pythagorean triples.

In other words, find all integer triples a, b, c , such that a, b, c satisfy the Pythagorean formula, $c^2 = a^2 + b^2$. We may assume that $a, b > 0$ since if $a = 0$ or $b = 0$ then the solutions are known.

Find all triplets a, b, c such that $a, b, c \in \mathbb{N}$ and $c^2 = a^2 + b^2$

Examples:

$$\begin{aligned}5^2 &= 3^2 + 4^2 \\13^2 &= 5^2 + 12^2 \\17^2 &= 8^2 + 15^2 \\25^2 &= 7^2 + 24^2\end{aligned}$$

Note that, given a Pythagorean triple a, b, c , and an integer d , then da, db, dc form another Pythagorean triplet.

Definition 1.1.0.1

A Primitive Pythagorean triplet, or *PPT*, is a triple of natural numbers a, b, c so that $c^2 = a^2 + b^2$ and $\gcd(a, b, c) = 1$ since otherwise, you can divide by a common factor and find a smaller triplet.

We can now rewrite the question into a simpler question, which reduces the question into the essential component of it: Find all primitive Pythagorean triples.

Proposition 1.1.0.1

If (a, b, c) form a *PPT* so that $c^2 = a^2 + b^2$, then c is odd.

Proof

Suppose c is even. Then $c = 2k$ for $k \in \mathbb{N}$

Case 1: both a and b are even.

Then $\gcd(a, b, c) = 2 \neq 1$ thus a, b, c are not *PPT*

Case 2: both a and b are odd.

Then there exists $x, y \in \mathbb{Z}$ such that $a = 2x + 1$ and $b = 2y + 1$, and since $c^2 = a^2 + b^2$, we have that:

$$\begin{aligned} c^2 &= (2x + 1)^2 + (2y + 1)^2 \\ 4z^2 &= 4(x^2 + xy^2 + y) + 2 \\ 4(z^2 - x^2 - x - y^2 - y) &= 2 \\ 2(z^2 - x^2 - x - y^2 - y) &= 1 \end{aligned}$$

This is a contradiction, and thus, our first assumption is invalid. Therefore c must be an odd integer. ■

So far, we know that if a, b, c is a *PPT*, then c is odd and without loss of generality, we may assume that a is even and b is odd.

By rearranging the Pythagorean formula, we get:

$$a = \sqrt{(c - b)(c + b)}$$

Proposition 1.1.0.2

If a is odd, then $(c - b)$ and $(c + b)$ are squares.

Proof

Let p be a prime divisor of a . Then,

$$\begin{aligned} p^2 &\mid a^2 \\ p^2 &\mid (c + b)(c - b) \end{aligned}$$

Suppose p divides one of $(c + b)$ and $(c - b)$ but not both, then $(c + b)$ and $(c - b)$ are squares by the *Unique Factorization Theorem*.

Therefore it is enough to show that $\gcd(c + b, c - b) = 1$.

Let $d = \gcd(c + b, c - b)$, then we have the following:

$$\begin{aligned} d &\mid c + b \\ d &\mid c - b \\ \implies d &\mid (c + b) + (c - b) = 2c \\ \implies d &\mid (c + b) - (c - b) = 2b \end{aligned}$$

Proof (Cont.)

Thus, we have that,

$$\begin{aligned} d &\mid \gcd(2b, 2c) \\ d &\mid 2\gcd(b, c) \\ d &= 1 \text{ or } d = 2 \end{aligned}$$

Suppose $d = 2$, we know that,

$$\begin{aligned} d &\mid (c - b) \text{ and } d \mid (c - b)(c + b) = a^2 \\ &\implies 2 \mid a^2 \\ &\implies 2 \mid a \\ &\implies a \text{ is even} \end{aligned}$$

But we assumed that a was odd, so d must be equal to 1. Since $d = \gcd(c+b, c-b)$ and $d = 1$, $(c - b)$ and $(c + b)$ are coprime, and so are squares by the *Unique Factorization Theorem*. ■

Since we have that $(c - b)$ and $(c + b)$ are coprime and squares, we also have that $\exists s, t \in \mathbb{N}$ where $\gcd(s, t) = 1$ and $c - b = t^2$ and $c + b = s^2$

$$\begin{aligned} &\implies c = \frac{s^2 + t^2}{2} \\ &\quad b = \frac{s^2 - t^2}{2} \\ a^2 &= c^2 - b^2 = s^2 \cdot t^2 \\ &\implies a = s \cdot t \end{aligned}$$

Theorem 1.1.0.3 (Pythagorean Triple Theorem)

Every primitive Pythagorean triple (a, b, c) , where a, c are odd, b is even, can be obtained

by $a = s \cdot t$, $b = \frac{s^2 - t^2}{2}$, $c = \frac{s^2 + t^2}{2}$, where $s, t \in \mathbb{N}$, $s > t$, and s, t are odd and coprime ($\gcd(s, t) = 1$).

Example: $s = 3$, $t = 1$

$$\begin{aligned} b &= \frac{3^2 - 1^2}{2} = 4 \\ c &= \frac{3^2 + 1^2}{2} = 5 \\ a &= 3 \cdot 1 = 3 \\ \text{A } PPT &\text{ is } (3, 4, 5) \end{aligned}$$

It's Important to note that this does not guarantee the result to be a *PPT* for any s and t satisfying the conditions, however, every *PPT* will have an s and t decomposition.

Chapter 2

Euler's Formula

2.1 Fermat's Little Theorem

Definition 2.1.0.1 (Congruence)

Let $a, b, m \in \mathbb{Z}, m \in \mathbb{N}$. We say that a is *congruent* to b modulo m , if $m \mid (b - a)$. We use the following notation:

$$a \equiv b \pmod{m}$$

Theorem 2.1.0.1

If $a, b, c \in \mathbb{Z}, m \in \mathbb{N}$ and $\gcd(c, m) = 1$, then,

$$\begin{aligned} a \cdot c &\equiv b \cdot c \pmod{m} \\ \implies a &\equiv b \pmod{m} \end{aligned}$$

Question: Given $a \in \mathbb{Z}, m \in \mathbb{N}$, find an integer $\gamma \in \mathbb{N}$, such that $a^\gamma \equiv 1 \pmod{m}$

Theorem 2.1.0.2 (Fermat's Little Theorem (FLT))

$\forall a, p \in \mathbb{Z}$, prime p , $\gcd(a, p) = 1$ then,

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

So part of the question is trivial with *FLT*, namely, when m is prime then we can simply let γ be $m - 1$ and we've found a solution to the problem.

Finding an integer γ satisfying the equation for any integer m however, is much more difficult.

Definition 2.1.0.2 (Reduced Residue Class Set)

Let $m \in \mathbb{N}$, we define the reduced residue class set as:

$$R_m = \{b \in \mathbb{Z}: 1 \leq b \leq m, \gcd(b, m) = 1\}$$

Example:

The residue class set R_p for a prime number p is the following:

$$R_p = \{1, 2, 3, 4, \dots, p-1\}$$

Recall that the key step for proving *FLT* is to see that:

$$\{1, 2, 3, \dots, p-1\} \equiv \{a, 2a, 3a, \dots, (p-1)a\} \pmod{p} \text{ for } p \nmid a.$$

Example: $a = 3, p = 5$

$$R_5 = \{1, 2, 3, 4\}$$

if we abuse notation,

$$3 \cdot R_5 = \{3, 6, 9, 12\}$$

notice that when we take the mod 5 of each element we get,

$$3 \cdot R_5 \pmod{5} \equiv \{3, 1, 4, 2\}$$

which is exactly R_5 in a different order

2.2 Euler's Totient Function

Definition 2.2.0.1 (Euler's Phi/Totient Function)

Let $m \in \mathbb{N}$. Define $\phi(m) := \#$ elements in R_m

$$\phi(m) = \# \text{ elements in } \{b \in \mathbb{Z}: 1 \leq b \leq m, \gcd(b, m) = 1\}$$

Example 1: $\phi(p) = p - 1$

Since $R_p = \{1, 2, 3, \dots, p-1\}$, there are $p-1$ elements in R_p

Example 2: $\phi(p^k) = p^k - p^{k-1}$

Constructing R_{p^k} , it's clear that there would be p^k elements in the set if we were to include the values of b which don't satisfy the condition that $\gcd(b, p^k) = 1$. The question now is how many values of b are there which don't satisfy the condition? The only time $\gcd(b, p^k) \neq 1$ is when $b \mid p^k$. Since p is prime, this is also when b is a multiple of p . There are exactly p^{k-1} multiples of p , and so the value of Euler's Phi Function is $p^k - p^{k-1}$.

Theorem 2.2.0.1 (Euler's Formula)

Let $a \in \mathbb{Z}, m \in \mathbb{N}, \gcd(a, m) = 1$. Then,

$$a^{\phi(m)} \equiv 1 \pmod{m}.$$

Remark: By Euler's formula, we can see that when $m = p$ is prime then $a^{p-1} \equiv 1 \pmod{p}$, so *FLT* is just a special case of Euler's formula.

Lemma 2.2.0.2

If $\gcd(a, m) = 1$, then the following sets are congruent in $\text{mod } m$

$$\begin{aligned} a \cdot R_m &= ab_1, ab_2, \dots, ab_{\phi(m)} \\ R_m &= b_1, b_2, \dots, b_{\phi(m)} \end{aligned}$$

In other words, $R_m \equiv a \cdot R_m \pmod{m}$

Proof (Lemma 1.2.0.4)

It suffices to prove that any two numbers ab_i, ab_j are congruent to m if and only iff $i = j$, since this will show that $ab_1, \dots, ab_{\phi(m)}$ all have a different module m .

Suppose $ab_i = ab_j \pmod{m}$. Since $\gcd(a, m) = 1$, we can cancel out a , so $b_i \equiv b_j \pmod{m}$. But since $1 \leq b_i, b_j \leq m$, this implies that $i = j$.

Thus, we have that $R_m \equiv a \cdot R_m \pmod{m}$. ■

Proof (Euler's Formula)

By Lemma 1.2.0.4, we have that,

$$\begin{aligned} R_m &\equiv a \cdot R_m \pmod{m} \\ \text{Suppose we have that,} \\ R_m &= \{b \in \mathbb{Z}: 1 \leq b \leq m, \gcd(b, m) = 1\} \\ a \cdot R_m &= \{a \cdot b \in \mathbb{Z}: 1 \leq a \cdot b \leq m, \gcd(b, m) = 1\} \end{aligned}$$

Now consider what we get if we take the product of all terms in these sets. Notice that,

$$\prod_{b \in R_m} b \equiv \prod_{b \in R_m} a \cdot b \pmod{m}$$

Thus we have that,

$$\prod_{b \in R_m} b \equiv a^{\phi(m)} \cdot \prod_{b \in R_m} b \pmod{m}$$

and since $\forall b \in R_m, \gcd(b, m) = 1$, we're able to cancel out the cartesian products and are left with the following:

$$1 \equiv a^{\phi(m)} \pmod{m}$$
■

Example: Compute the remainder of 5^{10000} divided by 9

$\gcd(5, 9) = 1$, so we use Euler's formula.

Notice that $\phi(9) = 6$

So, by Euler, $5^6 \equiv 1 \pmod{9}$

Notice that $5^{10000} = (5^6)^{1666} \cdot 5^4$
 $5^{10000} \equiv 1^{1666} \cdot 625 \pmod{9}$
 $5^{10000} \equiv 4 \pmod{9}$
 So the remainder is 4.

To give some motivation for the next theorem, notice how in order to use Euler's formula, we need to determine $\phi(m)$, which of course becomes very difficult when m gets large. So we need a trick to determining $\phi(m)$ for large m .

Theorem 2.2.0.3 (Phi Function Theorem)

If $m, n \in \mathbb{Z}$ and $\gcd(m, n) = 1$, then we have that $\phi(m \cdot n) = \phi(m) \cdot \phi(n)$

Using this theorem in conjunction with what we know about $\phi(p)$ and $\phi(p^k)$ for prime numbers p , we can calculate $\phi(m)$ for large m values much faster by first putting m in its prime factorized form, and then calculating ϕ for each base number in m , and then multiplying the values together.

Example: Compute $\phi(1000)$

$$\begin{aligned}\phi(1000) &= \phi(2^3 \cdot 5^3) \\ &= \phi(2^3) \cdot \phi(5^3) \\ &= (2^3 - 2^2) \cdot (5^3 - 5^2) \\ &= 400\end{aligned}$$

Proof (Phi Function Theorem)

We need to show that $\phi(m \cdot n) = \phi(m) \cdot \phi(n)$ when $n, m \in \mathbb{Z}$ and $\gcd(m, n) = 1$. Recall that $\phi(m)$ is just the number of elements in the reduced residue set R_m . The proof is easier if we compare R_{mn} to $R_m \times R_n$.

$$\begin{aligned}R_{mn} &= \{b \in \mathbb{Z} : 1 \leq b \leq m \cdot n, \gcd(b, m \cdot n) = 1\} \\ R_m &= \{c \in \mathbb{Z} : 1 \leq c \leq m, \gcd(c, m) = 1\} \\ R_n &= \{d \in \mathbb{Z} : 1 \leq d \leq n, \gcd(d, n) = 1\} \\ R_m \times R_n &= \{(c, d) : c, d \in \mathbb{Z}, 1 \leq c \leq m, 1 \leq d \leq n, \gcd(c, m) = 1, \gcd(d, n) = 1\}\end{aligned}$$

We need to show that the size of R_{mn} is equal to the size of $R_m \times R_n$. If we can construct a bijection between these two sets, then that would imply that they are of equal size as required.

Define a map:

$$\begin{aligned}f : R_{mn} &\rightarrow R_m \times R_n \\ b &\mapsto (c, d) \\ c &\equiv b \pmod{m} \\ d &\equiv b \pmod{n}\end{aligned}$$

Proof (Phi Function Theorem cont.)

Since b is coprime to $m \cdot n$, b is coprime to both m and n , thus the mapping is well defined. The bijection is followed by the *Chinese Remainder Theorem (CRT)*.

Since *CRT* says that any

$$\begin{cases} x \equiv c \pmod{m} \\ x \equiv d \pmod{n} \end{cases}$$

has a *unique* solution $x \equiv x_0 \pmod{m \cdot n}$, then,

$$\begin{cases} x_0 \equiv c \pmod{m} \\ x_0 \equiv d \pmod{n} \end{cases}$$

So a bijection between the two sets exists, and thus we have they are equal in size, as required. ■

Corollary 2.2.0.3.1

$$\phi(m) = m \cdot \prod_{i=1}^t \left(1 - \frac{1}{p_i}\right)$$

Example: Compute $\phi(1000)$

$$\begin{aligned} 1000 &= 2^3 \cdot 5^3 \\ \phi(1000) &= 1000 \left(1 - \frac{1}{2}\right) \left(1 - \frac{1}{5}\right) \\ &= 400 \end{aligned}$$

Proof (Corollary)

This result is found by dividing by the common factor of p^k for each base number in the prime factorized form of m , since

$$\phi(m) = \prod_{i=1}^t (p^{k_i} - p^{k_i-1})$$

Where i is the index of the current prime number in the prime factorized form of m . Simply rearranging this formula will give you the result of the corollary. ■

Chapter 3

Congruence Relations

3.1 Successive Squaring algorithm

Question: Compute the remainder r of when 9^{53} is divided by 67. In other words, solve for r in $9^{53} \equiv r \pmod{67}$.

Motivation: Using theorems we know, such as the *congruence power theorem* from MATH135, we are required to use 53 as an exponent, which is far too large for us to compute. Thus, a better method is needed for computing these remainder problems for large exponents.

Theorem 3.1.0.1 (Method of Successive Squaring To Compute $a^k \pmod{m}$)

Step 1: Write k as a sum of powers of 2

Step 2: Make a table of the powers of a modulo m using successive squaring

Then,

$$a^k \equiv \prod_{i=1}^t (A_i)^{u_i} \pmod{m}$$

Now that we have the resources to answer the question, let's go through the question.

Question: Compute the remainder r of when 9^{53} is divided by 67. In other words, solve for r in $9^{53} \equiv r \pmod{67}$.

Answer

Step 1: (Write the exponent as a sum of powers of 2)

$$\begin{aligned}53 &= 2^5 + 21 \\53 &= 2^5 + 2^4 + 2^2 + 2^0\end{aligned}$$

The largest exponent is 5 in the rewritten number, and so for the next step, we will go up to $9^{2^5} = 9^{32}$

Step 2: (Create a table of the powers of 9 modulo 67)

$$\begin{array}{llll}9^1 \equiv & 9 & \equiv 9(mod\ 67) \\9^2 \equiv & 81 & \equiv 14(mod\ 67) \\9^4 \equiv & (14^2) \equiv & 196 & \equiv 62(mod\ 67) \\9^8 \equiv & (62^2) \equiv & 3844 & \equiv 25(mod\ 67) \\9^{16} \equiv & (25^2) \equiv & 625 & \equiv 22(mod\ 67) \\9^{32} \equiv & (22^2) \equiv & 484 & \equiv 15(mod\ 67)\end{array}$$

Notice that,

$$\begin{aligned}9^{53} &\equiv 9^{32} \cdot 9^{16} \cdot 9^4 \cdot 9^1 \pmod{67} \\9^{53} &\equiv 15 \cdot 22 \cdot 62 \cdot 9 \pmod{67} \\9^{53} &\equiv 24 \pmod{67}\end{aligned}$$

Thus we have that the remainder when 9^{53} is divided by 67, is 24. ■

3.2 Bases in Congruence Relations

Question: Let $k, m \in \mathbb{N}$, $b \in \mathbb{Z}$. Solve the congruence relation for x :

$$x^k \equiv b \pmod{m}$$

Note that so far we know how to solve for k if we are given x, b and m , but now we are looking to solve for x when given k, b and m .

We can very easily solve it if $k = 1$, so let's suppose $k > 1$.

Theorem 3.2.0.1 (Solving For x in Congruence Relations)

Let $b, k, m \in \mathbb{Z}$, $k \geq 1$, $m \geq 1$ such that we have that $\gcd(b, m) = 1$ and $\gcd(k, \phi(m)) = 1$. Then, the following steps will give a solution to

$$x^k \equiv b \pmod{m}$$

Step 1: Compute $\phi(m)$

Step 2: Find positive integers $u, v \in \mathbb{N}$ that satisfy $k \cdot u - \phi(m) \cdot v = 1$. Note: this step is from the linear diophantine equation theorem, which states that $a \cdot x + b \cdot y = c$ has a solution if $\gcd(a, b) \mid c$. We can find solutions to this using the *Euclidean Algorithm*

Step 3: $x = b^u \pmod{m}$ is a solution to the relation

Proof

It's enough to show that $x = b^u$ is a solution.

$$(b^u)^k = b^{ku} = b^{1+\phi(m)v} = (b^{\phi(m)})^v b$$

By Euler's formula, $b^{\phi(m)} \equiv 1 \pmod{m}$, so,

$$(b^u)^k \equiv 1^v b \equiv b \pmod{m}$$

So, $x = b^u$ is a solution to the equation. ■

Remark: This theorem gives us a way to find the k^{th} root of b modulus m .

Example: Solve $x^{25} \equiv 7 \pmod{135}$.

Answer

Notice that $\gcd(7, 135) = 1$ and $\gcd(25, \phi(135)) = 1$

The conditions for our theorem are met, so we may use it.

We have the following linear diophantine equation:

$$25 \cdot u + 72 \cdot v = 1$$

Solved by *E.Z.K.*, gives $u = 49, v = 17$.

By our theorem, we have that $x = 7^{49}$ is a solution. We can perform $7^{49} \pmod{135}$ to find a smaller solution to our equation using successive squaring. Since an example of successive squaring is given on the previous page, this will be skipped. The answer after successive squaring is 52 (this is different than the answer given in class (88), but this is the correct answer), and so we know that $52^{25} \equiv 7 \pmod{135}$, as required.

Example: Solve $x^4 \equiv 7 \pmod{15}$

Answer

Notice that $\gcd(7, 15) = 1$ and $\gcd(4, \phi(15)) = 4 \neq 1$, so we cannot use our theorem.

We can, however, use the *Splitting Module Theorem* from MATH 135.

By *SMT*, $x^4 \equiv 7 \pmod{15}$ if and only if $x^4 \equiv 7 \pmod{5}$ and $x^4 \equiv 7 \pmod{3}$.

Consider $x^4 \equiv 7 \pmod{5}$.

Notice that if x is a solution, it must be coprime to 5, since $\gcd(5, 7) = 1$. So, by *FLT*, we have that $x^4 \equiv 1 \pmod{5}$, however, $7 \equiv 2 \pmod{5}$, which is a contradiction, and so $x^4 \equiv 7 \pmod{5}$ has no solution.

Thus, $x^4 \equiv 7 \pmod{15}$ has no solution by *SMT*.

3.3 Sums of Divisors with Phi

Question: Let $n \in \mathbb{N}$, and d_1, d_2, \dots, d_k be all positive divisors of n . What is the sum of $\phi(d_1) + \phi(d_2) + \dots + \phi(d_k)$?

Answer

The sum is equal to n . This will be proven as a theorem, but for now let's consider the summation when n is prime.

Let $n = p$, where p is prime.

$d_1 = 1, d_2 = p$ are the only divisors by the properties of primes. Thus we have,

$$\phi(1) + \phi(p) = 1 + p - 1 = p = n$$

Let $n = p^k$, where p is prime.

$d_1 = 1, d_2 = p, d_3 = p^2, \dots, d_k = p^k$ are the only divisors of n .

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

Notice the cancellation,

$$= p^k = n$$

We've shown that when n is prime or has a prime base, the sum of Euler's phi function of the divisors of n is equal to n . This will be helpful since every integer can be expressed as a product of primes.

Theorem 3.3.0.1 (Euler's Phi Function Summation Formula)

For $n \in \mathbb{N}$ and $d \geq 1$,

$$\sum_{d|n} \phi(d) = n$$

Proof

Let $F = \sum_{d|n} \phi(d)$.

If we can show for $m, n \in \mathbb{N}$, if $\gcd(m, n) = 1$, then $F(m \cdot n) = F(m) \cdot F(n)$, then we are done, since we can express any number as a product of primes, and we know that $F(p^k) = p^k$ for any prime p .

Let $m = p_1^{d_1} p_2^{d_2} \dots p_k^{d_k}$, and let $n = \gamma_1^{t_1} \gamma_2^{t_2} \dots \gamma_j^{t_j}$

Notice how since $\gcd(m, n) = 1$, all p_k are different from γ_j . By the *Divisors From Prime Factorization Theorem*, any divisor d of $m \cdot n$ has the form of a subset of the product of primes multiplied together, i.e, if we let $e = p_1^{\omega_1} p_2^{\omega_2} \dots p_l^{\omega_l}$ and $f = \gamma_1^{i_1} \gamma_2^{i_2} \dots \gamma_w^{i_w}$, where $e \mid m$ and $f \mid n$, then $d = e \cdot f$.

Thus, any divisor d of $m \cdot n$ is a product of e (a positive divisor of m) and f (a positive divisor of n), where $\gcd(e, f) = 1$ since $\gcd(m, n) = 1$.

Proof (cont.)

The converse of this is also true. If e is a positive divisor of m , and f is a positive divisor of n , then $e \cdot f$ is a positive divisor of $m \cdot n$, with $\gcd(e, f) = 1$.

To sum up what we have so far, let $\{e_1, e_2, \dots, e_s\}$ be the set of all positive divisors of m , and let $\{f_1, f_2, \dots, f_u\}$ be the set of all positive divisors of n . Then, $\{e_i \cdot f_j : 1 \leq i \leq s, 1 \leq j \leq u\}$ is the set of all positive divisors of $m \cdot n$. Notice that all $\gcd(e_i, f_j)$ are coprime by definition.

$$\begin{aligned}
 F(m \cdot n) &= \sum_{i=1}^s \sum_{j=1}^u \phi(e_i \cdot f_j) \\
 &= \sum_{i=1}^s \sum_{j=1}^u \phi(e_i) \cdot \phi(f_j) \\
 &= \sum_{i=1}^s \phi(e_i) \cdot \sum_{j=1}^u \phi(f_j) \\
 &= F(m) \cdot F(n)
 \end{aligned}$$

■

3.4 Primitive Roots Modulo p

Question: Let $m \in \mathbb{N}$. For some $a \in \mathbb{Z}$, where $\gcd(a, m) = 1$, what is the smallest positive integer k such that $a^k \equiv 1 \pmod{m}$?

We know by Euler that $k = \phi(m)$ is a solution to the equation, so we can say that the smallest integer k always exists, and $k \leq \phi(m)$.

Definition 3.4.0.1 (Exponent of a modulo m)

Let $a \in \mathbb{Z}$, $m \in \mathbb{N}$, where $\gcd(a, m) = 1$. The smallest exponent e such that $a^e \equiv 1 \pmod{m}$ is called the exponent of a modulo m , and is denoted by $e_m(a)$. Note that $e_m(a) \leq \phi(m)$.

Example: Compute $e_7(5)$. i.e., find the smallest integer e such that $5^e \equiv 1 \pmod{7}$.

Answer

First, compute $\phi(7) = 6$, so the possible values of $e_7(5)$ are between 1 and 6.

$$\begin{aligned}5^1 &\equiv 5 \not\equiv 1 \pmod{7} \\5^2 &\equiv 25 \equiv 4 \pmod{7} \\5^3 &\equiv 4 \cdot 5 \equiv 6 \pmod{7} \\5^4 &\equiv 6 \cdot 5 \equiv 2 \pmod{7} \\5^5 &\equiv 2 \cdot 5 \equiv 3 \pmod{7} \\5^6 &\equiv 3 \cdot 5 \equiv 1 \pmod{7}\end{aligned}$$

So, the smallest exponent e which solves the congruence relation $5^e \equiv 1 \pmod{7}$ is the maximum value it could have been, i.e, equal to $\phi(7) = 6$.

To give some motivation for the next proposition, notice how long it would take to calculate $e_m(a)$ for large values of $\phi(m)$. Surely, not all positive integers between 1 and $\phi(m)$ are possible values for e , so let's try to reduce the values from this range even further.

Proposition 3.4.0.1 (Exponent Divisibility Property)

Let $a, m \in \mathbb{Z}$, with $\gcd(a, m) = 1$, and suppose there is a solution to the equation $a^n \equiv 1 \pmod{m}$ for some $n \in \mathbb{N}$. Then, we have that

$$e_m(a) \mid n$$

In particular,

$$e_m(a) \mid \phi(m)$$

Remark: In our last example in which we calculated $e_7(5)$, we had to calculate the value of 5^n modulo 7 for all $1 \leq n \leq \phi(7)$. If we can prove this proposition, we would have only needed to calculate the value of 5^n modulo 7 for the divisors of $\phi(7)$, so 1, 2 and 3.

Proof (Exponent Divisibility Property)

By definition, $a^{e_m(a)} \equiv 1 \pmod{m}$. Let $d = \gcd(e_m(a), n) = e_m(a)$, since $e_m(a)$ is primitive.

By the *Linear Diophantine Equation Theorem*, there exists two positive integers u, v such that $e_m(a) \cdot u - n \cdot v = d$. Then, $a^{e_m(a) \cdot u} = (a^{e_m(a)})^u \equiv 1^u \equiv 1 \pmod{m}$

$$1 \equiv a^{e_m(a) \cdot u} = a^{n \cdot v + d} = (a^n)^v \cdot a^d \equiv 1^v \cdot a^d \equiv a^d \pmod{m}$$

But, by definition, $d = e_m(a)$, and so we have $e_m(a) \mid n$ as required. ■

Definition 3.4.0.2 (Primitive Roots mod m)

Let $m \in \mathbb{Z}$ and let there exist a positive integer e_m such that, for all $a \in \mathbb{Z}$ where $\gcd(a, m) = 1$, we have that $a^{e_m} \equiv 1 \pmod{m}$, and e_m is the smallest positive integer satisfying this property.

Then, a positive integer g such that $\gcd(g, m) = 1$ is called the primitive root mod m if $e_m(g) = e_m$

In particular, if $m = p$ for a prime p , $e_p = p - 1$. A primitive root g of p satisfies $e_p(g) = p - 1$.

Theorem 3.4.0.2

For any prime p , there exists a primitive root modulo p .