

Chapter 13

Number Theory

Number theory is the study of the integers. *Why* anyone would want to study the integers is not immediately obvious. First of all, what's to know? There's 0, there's 1, 2, 3, and so on, and, oh yeah, -1, -2, Which one don't you understand? Second, what practical value is there in it? The mathematician G. H. Hardy expressed pleasure in its impracticality when he wrote:

[Number theorists] may be justified in rejoicing that there is one science, at any rate, and that their own, whose very remoteness from ordinary human activities should keep it gentle and clean.

Hardy was specially concerned that number theory not be used in warfare; he was a pacifist. You may applaud his sentiments, but he got it wrong: Number Theory underlies modern cryptography, which is what makes secure online communication possible. Secure communication is of course crucial in war—which may leave poor Hardy spinning in his grave. It's also central to online commerce. You're reaping the benefits of Number Theory every time you type a system password.

13.1 Divisibility

Since we'll be focussing on properties of the integers, we'll adopt the default convention in this chapter that variables range over integers.

The nature of number theory emerges as soon as we consider the *divides* relation

$$a \text{ divides } b \quad \text{iff} \quad ak = b \text{ for some } k.$$

The notation, $a \mid b$, is an abbreviation for “ a divides b .” If $a \mid b$, then we also say that b is a *multiple* of a . As we've seen, a consequence of this definition is that every number divides zero.

This seems simple enough, but let's play with this definition. The Pythagoreans, an ancient sect of mathematical mystics, said that a number is *perfect* if it equals

the sum of its positive integral divisors, excluding itself. For example, $6 = 1 + 2 + 3$ and $28 = 1 + 2 + 4 + 7 + 14$ are perfect numbers. On the other hand, 10 is not perfect because $1 + 2 + 5 = 8$, and 12 is not perfect because $1 + 2 + 3 + 4 + 6 = 16$. Euclid characterized all the *even* perfect numbers around 300 BC. But is there an *odd* perfect number? More than two thousand years later, we still don't know! All numbers up to about 10^{300} have been ruled out, but no one has proved that there isn't an odd perfect number waiting just over the horizon.

So a half-page into number theory, we've strayed past the outer limits of human knowledge! This is pretty typical; number theory is full of questions that are easy to pose, but incredibly difficult to answer. Interestingly, computer scientists have found ways to turn these difficulties to their advantage. Every time you buy a book from Amazon, check your grades on WebSIS, or use a PayPal account, you are relying on number theoretic algorithms.

Don't Panic —we're going to stick to some relatively benign parts of number theory. We rarely put any of these super-hard unsolved problems on exams :-)

13.1.1 Facts About Divisibility

The lemma below states some basic facts about divisibility that are *not* difficult to prove:

Lemma 13.1.1. *The following statements about divisibility hold.*

1. If $a \mid b$, then $a \mid bc$ for all c .
2. If $a \mid b$ and $b \mid c$, then $a \mid c$.
3. If $a \mid b$ and $a \mid c$, then $a \mid sb + tc$ for all s and t .
4. For all $c \neq 0$, $a \mid b$ if and only if $ca \mid cb$.

Proof. We'll prove only part 2.; the other proofs are similar.

Proof of 2.: Since $a \mid b$, there exists an integer k_1 such that $ak_1 = b$. Since $b \mid c$, there exists an integer k_2 such that $bk_2 = c$. Substituting ak_1 for b in the second equation gives $ak_1k_2 = c$, which implies that $a \mid c$. □

A number $p > 1$ with no positive divisors other than 1 and itself is called a *prime*. Every other number greater than 1 is called *composite*. For example, 2, 3, 5, 7, 11, and 13 are all prime, but 4, 6, 8, and 9 are composite. The number 1 is considered neither prime nor composite. This is just a matter of definition, but reflects the fact that 1 does not behave like a prime in many contexts, such as the Fundamental Theorem of Arithmetic, which we'll come to shortly.

13.1.2 When Divisibility Goes Bad

As you learned in elementary school, if one number does *not* evenly divide another, then there is a "remainder" left over. More precisely, if you divide n by d , then you get a quotient q and a remainder r :

Famous Problems in Number Theory

Fermat's Last Theorem Do there exist positive integers x , y , and z such that

$$x^n + y^n = z^n$$

for some integer $n > 2$? In a book he was reading around 1630, Fermat claimed to have a proof, but not enough space in the margin to write it down. Wiles finally gave a proof of the theorem in 1994, after seven years of working in secrecy and isolation in his attic. His proof did not fit in any margin.

Goldbach Conjecture Is every even integer greater than or equal to 4 the sum of two primes? For example, $4 = 2 + 2$, $6 = 3 + 3$, $8 = 3 + 5$, etc. The conjecture holds for all numbers up to 10^{16} . In 1939 Schnirelman proved that every even number can be written as the sum of not more than 300,000 primes, which was a start. Today, we know that every even number is the sum of at most 6 primes.

Twin Prime Conjecture Are there infinitely many primes p such that $p + 2$ is also a prime? In 1966 Chen showed that there are infinitely many primes p such that $p + 2$ is the product of at most two primes. So the conjecture is known to be *almost* true!

Primality Testing Is there an efficient way to determine whether n is prime? A naive search for factors of n takes a number of steps exponential in $\log n$, which is the size of n in bits. All known procedures for prime checking blew up like this on various inputs. Finally in 2002, an amazingly simple, new method was discovered by Agrawal, Kayal, and Saxena, which showed that prime testing only required a polynomial number of steps. Their paper began with a quote from Gauss emphasizing the importance and antiquity of the problem even in his time—two centuries ago. So prime testing is definitely not in the category of infeasible problems requiring an exponentially growing number of steps in bad cases.

Factoring Given the product of two large primes $n = pq$, is there an efficient way to recover the primes p and q ? The best known algorithm is the “number field sieve”, which runs in time proportional to:

$$e^{1.9(\ln n)^{1/3}(\ln \ln n)^{2/3}}$$

This is infeasible when n has 300 digits or more.

Theorem 13.1.2 (Division Theorem). *Let n and d be integers such that $d > 0$. Then there exists a unique pair of integers q and r such that $n = qd + r$ and $0 \leq r < d$.¹*

As an example, suppose that $n = 2716$ and $d = 10$. Then the quotient is $q = 271$ and the remainder is $r = 6$, since $2716 = 271 \cdot 10 + 6$.

The remainder r in the Division Theorem is denoted $\text{rem}(n, d)$. In other words, $\text{rem}(n, d)$ is the remainder when n is divided by d . For example, $\text{rem}(32, 5)$ is the remainder when 32 is divided by 5, which is 2. Similarly, $\text{rem}(-11, 7) = 3$, since $-11 = (-2) \cdot 7 + 3$. There is a remainder operator built into many programming languages. For example, the expression “32 % 5” evaluates to 2 in Java, C, and C++. However, all these languages treat negative numbers strangely.

We’ll take this familiar Division Theorem for granted without proof, but there is an important feature that you should notice. The theorem asserts that the quotient q and remainder r exist and also that these values are *unique*. Thus, the Division Theorem is one example of an “existence and uniqueness” theorem; there are many others. Not surprisingly, the proof of such a theorem always has two parts:

- A proof that something exists, such as the quotient q and remainder r .
- A proof that nothing else fits the bill; that is, there is no other quotient q' and remainder r' .

13.1.3 Die Hard

We’ve previously looked at the Die Hard water jug problem with jugs of sizes 3 and 5, and 3 and 9. It would be nice if we could solve all these silly water jug questions at once. In particular, how can one form g gallons using jugs with capacities a and b ? Here’s where number theory comes in handy.

Finding an Invariant Property

Suppose that we have water jugs with capacities a and b . The state of the system is described below with a pair of numbers (x, y) , where x is the amount of water in the jug with capacity a and y is the amount in the jug with capacity b . Let’s carry

¹This theorem is often called the “Division Algorithm,” even though it is not an algorithm in the modern sense.

out sample operations and see what happens, assuming the b -jug is big enough:

$(0, 0) \rightarrow (a, 0)$	fill first jug
$\rightarrow (0, a)$	pour first into second
$\rightarrow (a, a)$	fill first jug
$\rightarrow (2a - b, b)$	pour first into second (assuming $2a \geq b$)
$\rightarrow (2a - b, 0)$	empty second jug
$\rightarrow (0, 2a - b)$	pour first into second
$\rightarrow (a, 2a - b)$	fill first
$\rightarrow (3a - 2b, b)$	pour first into second (assuming $3a \geq 2b$)

What leaps out is that at every step, the amount of water in each jug is of the form

$$s \cdot a + t \cdot b \tag{13.1}$$

for some integers s and t . An expression of the form (13.1) is called an *integer linear combination* of a and b , but in this chapter we'll just call it a *linear combination*, since we're only talking integers. So we're suggesting:

Lemma 13.1.3. *Suppose that we have water jugs with capacities a and b . Then the amount of water in each jug is always a linear combination of a and b .*

Lemma 13.1.3 is easy to prove by induction on the number of pourings.

Proof. We use induction. Let $P(n)$ be the proposition that after n steps, the amount of water in each jug is a linear combination of a and b .

Base case: ($n = 0$) $P(0)$ is true, because both jugs are initially empty, and $0 \cdot a + 0 \cdot b = 0$.

Inductive step. We assume by induction hypothesis that after n steps the amount of water in each jug is a linear combination of a and b . There are two cases:

- If we fill a jug from the fountain or empty a jug into the fountain, then that jug is empty or full. The amount in the other jug remains a linear combination of a and b . So $P(n + 1)$ holds.
- Otherwise, we pour water from one jug to another until one is empty or the other is full. By our assumption, the amount in each jug is a linear combination of a and b before we begin pouring:

$$\begin{aligned} j_1 &= s_1 \cdot a + t_1 \cdot b \\ j_2 &= s_2 \cdot a + t_2 \cdot b \end{aligned}$$

After pouring, one jug is either empty (contains 0 gallons) or full (contains a or b gallons). Thus, the other jug contains either $j_1 + j_2$ gallons, $j_1 + j_2 - a$, or $j_1 + j_2 - b$ gallons, all of which are linear combinations of a and b . So $P(n + 1)$ holds in this case as well.

So in any case, $P(n + 1)$ follows, completing the proof by induction. \square

This theorem has an important corollary:

Corollary 13.1.4. *Bruce dies.*

Proof. In Die Hard 6, Bruce has water jugs with capacities 3 and 6 and must form 4 gallons of water. However, the amount in each jug is always of the form $3s + 6t$ by Lemma 13.1.3. This is always a multiple of 3 by part (3) of Lemma 13.1.1, so he can not measure out 4 gallons. \square

But Lemma 13.1.3 isn't very satisfying. We've just managed to recast a pretty understandable question about water jugs into a complicated question about linear combinations. This might not seem like progress. Fortunately, linear combinations are closely related to something more familiar and that will help us solve the water jug problem.

13.2 The Greatest Common Divisor

We've already examined the Euclidean Algorithm for computing $\gcd(a, b)$, the greatest common divisor of a and b . This quantity turns out to be a very valuable piece of information about the relationship between a and b . We'll be making arguments about greatest common divisors all the time.

13.2.1 Linear Combinations and the GCD

The theorem below relates the greatest common divisor to linear combinations. This theorem is *very* useful; take the time to understand it and then remember it!

Theorem 13.2.1. *The greatest common divisor of a and b is equal to the smallest positive linear combination of a and b .*

For example, the greatest common divisor of 52 and 44 is 4. And, sure enough, 4 is a linear combination of 52 and 44:

$$6 \cdot 52 + (-7) \cdot 44 = 4$$

Furthermore, no linear combination of 52 and 44 is equal to a smaller positive integer.

Proof. By the well-ordering principle, there is a smallest positive linear combination of a and b ; call it m . We'll prove that $m = \gcd(a, b)$ by showing both $\gcd(a, b) \leq m$ and $m \leq \gcd(a, b)$.

First, we show that $\gcd(a, b) \leq m$. Now any common divisor of a and b , that is, any c such that $c \mid a$ and $c \mid b$ will divide both sa and tb , and therefore also divides $sa + tb$. The $\gcd(a, b)$ is by definition a common divisor of a and b , so

$$\gcd(a, b) \mid sa + tb$$

every s and t . In particular, $\gcd(a, b) \mid m$, which implies that $\gcd(a, b) \leq m$.

Now, we show that $m \leq \gcd(a, b)$. We do this by showing that $m \mid a$. A symmetric argument shows that $m \mid b$, which means that m is a common divisor of a and b . Thus, m must be less than or equal to the *greatest* common divisor of a and b .

All that remains is to show that $m \mid a$. By the Division Algorithm, there exists a quotient q and remainder r such that:

$$a = q \cdot m + r \quad (\text{where } 0 \leq r < m)$$

Recall that $m = sa + tb$ for some integers s and t . Substituting in for m and rearranging terms gives:

$$\begin{aligned} a &= q \cdot (sa + tb) + r \\ r &= (1 - qs)a + (-qt)b \end{aligned}$$

We've just expressed r as a linear combination of a and b . However, m is the *smallest* positive linear combination and $0 \leq r < m$. The only possibility is that the remainder r is not positive; that is, $r = 0$. This implies $m \mid a$. \square

The proof notes that every linear combination of a and b is a multiple of $\gcd(a, b)$. Conversely, since $\gcd(a, b)$ is a linear combination of a and b , every multiple of $\gcd(a, b)$ is as well. This establishes a corollary:

Corollary 13.2.2. *Every linear combination of a and b is a multiple of $\gcd(a, b)$ and vice versa.*

Now we can restate the water jugs lemma in terms of the greatest common divisor:

Corollary 13.2.3. *Suppose that we have water jugs with capacities a and b . Then the amount of water in each jug is always a multiple of $\gcd(a, b)$.*

For example, there is no way to form 2 gallons using 1247 and 899 gallon jugs, because 2 is not a multiple of $\gcd(1247, 899) = 29$.

13.2.2 Properties of the Greatest Common Divisor

We'll often make use of some basic gcd facts:

Lemma 13.2.4. *The following statements about the greatest common divisor hold:*

1. *Every common divisor of a and b divides $\gcd(a, b)$.*
2. *$\gcd(ka, kb) = k \cdot \gcd(a, b)$ for all $k > 0$.*
3. *If $\gcd(a, b) = 1$ and $\gcd(a, c) = 1$, then $\gcd(a, bc) = 1$.*
4. *If $a \mid bc$ and $\gcd(a, b) = 1$, then $a \mid c$.*

$$5. \gcd(a, b) = \gcd(b, \text{rem}(a, b)).$$

Here's the trick to proving these statements: translate the gcd world to the linear combination world using Theorem 13.2.1, argue about linear combinations, and then translate back using Theorem 13.2.1 again.

Proof. We prove only parts 3 and 4.

Proof of 3.: The assumptions together with Theorem 13.2.1 imply that there exist integers $s, t, u,$ and v such that:

$$\begin{aligned} sa + tb &= 1 \\ ua + vc &= 1 \end{aligned}$$

Multiplying these two equations gives:

$$(sa + tb)(ua + vc) = 1$$

The left side can be rewritten as $a \cdot (asu + btu + csv) + bc(tv)$. This is a linear combination of a and bc that is equal to 1, so $\gcd(a, bc) = 1$ by Theorem 13.2.1.

Proof of 4: Theorem 13.2.1 says that $\gcd(ac, bc)$ is equal to a linear combination of ac and bc . Now $a \mid ac$ trivially and $a \mid bc$ by assumption. Therefore, a divides every linear combination of ac and bc . In particular, a divides $\gcd(ac, bc) = c \cdot \gcd(a, b) = c \cdot 1 = c$. The first equality uses part 2. of this lemma, and the second uses the assumption that $\gcd(a, b) = 1$. \square

Lemma 13.2.4.5 is the preserved invariant from Lemma 8.1.7 that we used to prove partial correctness of the Euclidean Algorithm.

Now let's see if it's possible to make 3 gallons using 21 and 26-gallon jugs. Using Euclid's algorithm:

$$\gcd(26, 21) = \gcd(21, 5) = \gcd(5, 1) = 1.$$

Now 3 is a multiple of 1, so we can't *rule out* the possibility that 3 gallons can be formed. On the other hand, we don't know it can be done.

13.2.3 One Solution for All Water Jug Problems

Can Bruce form 3 gallons using 21 and 26-gallon jugs? This question is not so easy to answer without some number theory.

Corollary 13.2.2 says that 3 can be written as a linear combination of 21 and 26, since 3 is a multiple of $\gcd(21, 26) = 1$. In other words, there exist integers s and t such that:

$$3 = s \cdot 21 + t \cdot 26$$

We don't know what the coefficients s and t are, but we do know that they exist.

Now the coefficient s could be either positive or negative. However, we can readily transform this linear combination into an equivalent linear combination

$$3 = s' \cdot 21 + t' \cdot 26$$

the solution that approach gives:

(0, 0)	$\xrightarrow{\text{fill 21}}$	(21, 0)	$\xrightarrow{\text{pour 21 into 26}}$	(0, 21)					
	$\xrightarrow{\text{fill 21}}$	(21, 21)	$\xrightarrow{\text{pour 21 into 26}}$	(16, 26)	$\xrightarrow{\text{empty 26}}$	(16, 0)	$\xrightarrow{\text{pour 21 into 26}}$	(0, 16)	
	$\xrightarrow{\text{fill 21}}$	(21, 16)	$\xrightarrow{\text{pour 21 into 26}}$	(11, 26)	$\xrightarrow{\text{empty 26}}$	(11, 0)	$\xrightarrow{\text{pour 21 into 26}}$	(0, 11)	
	$\xrightarrow{\text{fill 21}}$	(21, 11)	$\xrightarrow{\text{pour 21 into 26}}$	(6, 26)	$\xrightarrow{\text{empty 26}}$	(6, 0)	$\xrightarrow{\text{pour 21 into 26}}$	(0, 6)	
	$\xrightarrow{\text{fill 21}}$	(21, 6)	$\xrightarrow{\text{pour 21 into 26}}$	(1, 26)	$\xrightarrow{\text{empty 26}}$	(1, 0)	$\xrightarrow{\text{pour 21 into 26}}$	(0, 1)	
	$\xrightarrow{\text{fill 21}}$	(21, 1)	$\xrightarrow{\text{pour 21 into 26}}$	(0, 22)					
	$\xrightarrow{\text{fill 21}}$	(21, 22)	$\xrightarrow{\text{pour 21 into 26}}$	(17, 26)	$\xrightarrow{\text{empty 26}}$	(17, 0)	$\xrightarrow{\text{pour 21 into 26}}$	(0, 17)	
	$\xrightarrow{\text{fill 21}}$	(21, 17)	$\xrightarrow{\text{pour 21 into 26}}$	(12, 26)	$\xrightarrow{\text{empty 26}}$	(12, 0)	$\xrightarrow{\text{pour 21 into 26}}$	(0, 12)	
	$\xrightarrow{\text{fill 21}}$	(21, 12)	$\xrightarrow{\text{pour 21 into 26}}$	(7, 26)	$\xrightarrow{\text{empty 26}}$	(7, 0)	$\xrightarrow{\text{pour 21 into 26}}$	(0, 7)	
	$\xrightarrow{\text{fill 21}}$	(21, 7)	$\xrightarrow{\text{pour 21 into 26}}$	(2, 26)	$\xrightarrow{\text{empty 26}}$	(2, 0)	$\xrightarrow{\text{pour 21 into 26}}$	(0, 2)	
	$\xrightarrow{\text{fill 21}}$	(21, 2)	$\xrightarrow{\text{pour 21 into 26}}$	(0, 23)					
	$\xrightarrow{\text{fill 21}}$	(21, 23)	$\xrightarrow{\text{pour 21 into 26}}$	(18, 26)	$\xrightarrow{\text{empty 26}}$	(18, 0)	$\xrightarrow{\text{pour 21 into 26}}$	(0, 18)	
	$\xrightarrow{\text{fill 21}}$	(21, 18)	$\xrightarrow{\text{pour 21 into 26}}$	(13, 26)	$\xrightarrow{\text{empty 26}}$	(13, 0)	$\xrightarrow{\text{pour 21 into 26}}$	(0, 13)	
	$\xrightarrow{\text{fill 21}}$	(21, 13)	$\xrightarrow{\text{pour 21 into 26}}$	(8, 26)	$\xrightarrow{\text{empty 26}}$	(8, 0)	$\xrightarrow{\text{pour 21 into 26}}$	(0, 8)	
	$\xrightarrow{\text{fill 21}}$	(21, 8)	$\xrightarrow{\text{pour 21 into 26}}$	(3, 26)	$\xrightarrow{\text{empty 26}}$	(3, 0)	$\xrightarrow{\text{pour 21 into 26}}$	(0, 3)	

The same approach works regardless of the jug capacities and even regardless the amount we're trying to produce! Simply repeat these two steps until the desired amount of water is obtained:

1. Fill the smaller jug.
2. Pour all the water in the smaller jug into the larger jug. Whenever the larger jug becomes full, empty it out.

By the same reasoning as before, this method eventually generates every multiple of the greatest common divisor of the jug capacities —all the quantities we can possibly produce. No ingenuity is needed at all!

13.2.4 The Pulverizer

We saw that no matter which pair of integers a and b we are given, there is always a pair of integer coefficients s and t such that

$$\gcd(a, b) = sa + tb.$$

The previous subsection gives a roundabout and not very efficient method of finding such coefficients s and t . In Chapter 8.1.4 we defined and verified the “Extended Euclidean GCD algorithm,” which is a much more efficient way to find these coefficients. In this section we give a more straightforward description of

this procedure for finding s and t that dates to sixth-century India, where it was called *kuttak*, which means “The Pulverizer.”

Suppose we use Euclid’s Algorithm to compute the GCD of 259 and 70, for example:

$$\begin{aligned}
 \gcd(259, 70) &= \gcd(70, 49) && \text{since } \text{rem}(259, 70) = 49 \\
 &= \gcd(49, 21) && \text{since } \text{rem}(70, 49) = 21 \\
 &= \gcd(21, 7) && \text{since } \text{rem}(49, 21) = 7 \\
 &= \gcd(7, 0) && \text{since } \text{rem}(21, 7) = 0 \\
 &= 7.
 \end{aligned}$$

The Pulverizer goes through the same steps, but requires some extra bookkeeping along the way: as we compute $\gcd(a, b)$, we keep track of how to write each of the remainders (49, 21, and 7, in the example) as a linear combination of a and b (this is worthwhile, because our objective is to write the last nonzero remainder, which is the GCD, as such a linear combination). For our example, here is this extra bookkeeping:

x	y	$(\text{rem}(x, y))$	$=$	$x - q \cdot y$
259	70	49	$=$	$259 - 3 \cdot 70$
70	49	21	$=$	$70 - 1 \cdot 49$
			$=$	$70 - 1 \cdot (259 - 3 \cdot 70)$
			$=$	$-1 \cdot 259 + 4 \cdot 70$
49	21	7	$=$	$49 - 2 \cdot 21$
			$=$	$(259 - 3 \cdot 70) - 2 \cdot (-1 \cdot 259 + 4 \cdot 70)$
			$=$	$3 \cdot 259 - 11 \cdot 70$
21	7	0		

We began by initializing two variables, $x = a$ and $y = b$. In the first two columns above, we carried out Euclid’s algorithm. At each step, we computed $\text{rem}(x, y)$, which can be written in the form $x - q \cdot y$. (Remember that the Division Algorithm says $x = q \cdot y + r$, where r is the remainder. We get $r = x - q \cdot y$ by rearranging terms.) Then we replaced x and y in this equation with equivalent linear combinations of a and b , which we already had computed. After simplifying, we were left with a linear combination of a and b that was equal to the remainder as desired. The final solution is boxed.

13.2.5 Problems

Class Problems

Problem 13.1.

A number is *perfect* if it is equal to the sum of its positive divisors, other than itself. For example, 6 is perfect, because $6 = 1 + 2 + 3$. Similarly, 28 is perfect, because $28 = 1 + 2 + 4 + 7 + 14$. Explain why $2^{k-1}(2^k - 1)$ is perfect if $2^k - 1$ is prime.

Euclid knew this, and also was able to show that all *even* perfect numbers are of exactly this form. To this day, no one knows if there are any odd perfect numbers!

Problem 13.2. (a) Use the Pulverizer to find integers x, y such that

$$x50 + y21 = \gcd(50, 21).$$

(b) Now find integers x', y' with $y' > 0$ such that

$$x'50 + y'21 = \gcd(50, 21)$$

Problem 13.3.

For nonzero integers, a, b , prove the following properties of divisibility and gcd's. (You may use the fact that $\gcd(a, b)$ is an integer linear combination of a and b . You may not appeal to uniqueness of prime factorization because the properties below are needed to *prove* unique factorization.)

(a) Every common divisor of a and b divides $\gcd(a, b)$.

(b) If $a \mid bc$ and $\gcd(a, b) = 1$, then $a \mid c$.

(c) If $p \mid ab$ for some prime, p , then $p \mid a$ or $p \mid b$.

(d) Let m be the smallest integer linear combination of a and b that is positive. Show that $m = \gcd(a, b)$.

13.3 The Fundamental Theorem of Arithmetic

We now have almost enough tools to prove something that you probably already know.

Theorem 13.3.1 (Fundamental Theorem of Arithmetic). *Every positive integer n can be written in a unique way as a product of primes:*

$$n = p_1 \cdot p_2 \cdots p_j \qquad (p_1 \leq p_2 \leq \cdots \leq p_j)$$

Notice that the theorem would be false if 1 were considered a prime; for example, 15 could be written as $3 \cdot 5$ or $1 \cdot 3 \cdot 5$ or $1^2 \cdot 3 \cdot 5$. Also, we're relying on a standard convention: the product of an empty set of numbers is defined to be 1, much as the sum of an empty set of numbers is defined to be 0. Without this convention, the theorem would be false for $n = 1$.

There is a certain wonder in the Fundamental Theorem, even if you've known it since you were in a crib. Primes show up erratically in the sequence of integers. In fact, their distribution seems almost random:

$$2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41, 43, \dots$$

Basic questions about this sequence have stumped humanity for centuries. And yet we know that every natural number can be built up from primes in *exactly one way*. These quirky numbers are the building blocks for the integers. The Fundamental Theorem is not hard to prove, but we'll need a couple of preliminary facts.

The Prime Number Theorem

Let $\pi(x)$ denote the number of primes less than or equal to x . For example, $\pi(10) = 4$ because 2, 3, 5, and 7 are the primes less than or equal to 10. Primes are very irregularly distributed, so the growth of π is similarly erratic. However, the Prime Number Theorem gives an approximate answer:

$$\lim_{x \rightarrow \infty} \frac{\pi(x)}{x / \ln x} = 1$$

Thus, primes gradually taper off. As a rule of thumb, about 1 integer out of every $\ln x$ in the vicinity of x is a prime.

The Prime Number Theorem was conjectured by Legendre in 1798 and proved a century later by de la Vallee Poussin and Hadamard in 1896. However, after his death, a notebook of Gauss was found to contain the same conjecture, which he apparently made in 1791 at age 15. (You sort of have to feel sorry for all the otherwise “great” mathematicians who had the misfortune of being contemporaries of Gauss.)

In late 2004 a billboard appeared in various locations around the country:

$$\left\{ \begin{array}{l} \text{first 10-digit prime found} \\ \text{in consecutive digits of } e \end{array} \right\} . \text{com}$$

Substituting the correct number for the expression in curly-braces produced the URL for a Google employment page. The idea was that Google was interested in hiring the sort of people that could and would solve such a problem.

How hard is this problem? Would you have to look through thousands or millions or billions of digits of e to find a 10-digit prime? The rule of thumb derived from the Prime Number Theorem says that among 10-digit numbers, about 1 in

$$\ln 10^{10} \approx 23$$

is prime. This suggests that the problem isn't really so hard! Sure enough, the first 10-digit prime in consecutive digits of e appears quite early:

$e = 2.718281828459045235360287471352662497757247093699959574966$
 $96762772407663035354759457138217852516642\mathbf{7427466391}9320030$
 $599218174135966290435729003342952605956307381323286279434 \dots$

Lemma 13.3.2. *If p is a prime and $p \mid ab$, then $p \mid a$ or $p \mid b$.*

Proof. The greatest common divisor of a and p must be either 1 or p , since these are the only positive divisors of p . If $\gcd(a, p) = p$, then the claim holds, because a is a multiple of p . Otherwise, $\gcd(a, p) = 1$ and so $p \mid b$ by part (4) of Lemma 13.2.4. \square

A routine induction argument extends this statement to:

Lemma 13.3.3. *Let p be a prime. If $p \mid a_1 a_2 \cdots a_n$, then p divides some a_i .*

Now we're ready to prove the Fundamental Theorem of Arithmetic.

Proof. We proved earlier using the well-ordering principle that every positive integer can be expressed as a product of primes. So we just have to prove this expression is unique. We will use the well-ordering principle to prove this too.

The proof is by contradiction: assume, contrary to the claim, that there exist positive integers that can be written as products of primes in more than one way. By the well-ordering principle, there is a smallest integer with this property. Call this integer n , and let

$$\begin{aligned} n &= p_1 \cdot p_2 \cdots p_j \\ &= q_1 \cdot q_2 \cdots q_k \end{aligned}$$

be two of the (possibly many) ways to write n as a product of primes. Then $p_1 \mid n$ and so $p_1 \mid q_1 q_2 \cdots q_k$. Lemma 13.3.3 implies that p_1 divides one of the primes q_i . But since q_i is a prime, it must be that $p_1 = q_i$. Deleting p_1 from the first product and q_i from the second, we find that n/p_1 is a positive integer *smaller* than n that can also be written as a product of primes in two distinct ways. But this contradicts the definition of n as the smallest such positive integer. \square

13.3.1 Problems

Class Problems

Problem 13.4. (a) Let $m = 2^9 5^{24} 11^7 17^{12}$ and $n = 2^3 7^{22} 11^{21} 13^{11} 17^9 19^2$. What is the $\gcd(m, n)$? What is the *least common multiple*, $\text{lcm}(m, n)$, of m and n ? Verify that

$$\gcd(m, n) \cdot \text{lcm}(m, n) = mn. \quad (13.2)$$

(b) Describe in general how to find the $\gcd(m, n)$ and $\text{lcm}(m, n)$ from the prime factorizations of m and n . Conclude that equation (13.2) holds for all positive integers m, n .

13.4 Alan Turing



The man pictured above is Alan Turing, the most important figure in the history of computer science. For decades, his fascinating life story was shrouded by government secrecy, societal taboo, and even his own deceptions.

At 24 Turing wrote a paper entitled *On Computable Numbers, with an Application to the Entscheidungsproblem*. The crux of the paper was an elegant way to model a computer in mathematical terms. This was a breakthrough, because it allowed the tools of mathematics to be brought to bear on questions of computation. For example, with his model in hand, Turing immediately proved that there exist problems that no computer can solve—no matter how ingenious the programmer. Turing’s paper is all the more remarkable because he wrote it in 1936, a full decade before any electronic computer actually existed.

The word “Entscheidungsproblem” in the title refers to one of the 28 mathematical problems posed by David Hilbert in 1900 as challenges to mathematicians of the 20th century. Turing knocked that one off in the same paper. And perhaps you’ve heard of the “Church-Turing thesis”? Same paper. So Turing was obviously a brilliant guy who generated lots of amazing ideas. But this lecture is about one of Turing’s less-amazing ideas. It involved codes. It involved number theory. And it was sort of stupid.

Let’s look back to the fall of 1937. Nazi Germany was rearming under Adolf Hitler, world-shattering war looked imminent, and—like us—Alan Turing was pondering the usefulness of number theory. He foresaw that preserving military secrets would be vital in the coming conflict and proposed a way *to encrypt communications using number theory*. This is an idea that has ricocheted up to our own time. Today, number theory is the basis for numerous public-key cryptosystems, digital signature schemes, cryptographic hash functions, and digital cash systems. Every

time you buy a book from Amazon, check your grades on WebSIS, or use a PayPal account, you are relying on number theoretic algorithms. Furthermore, military funding agencies are among the biggest investors in cryptographic research. Sorry Hardy!

Soon after devising his code, Turing disappeared from public view, and half a century would pass before the world learned the full story of where he'd gone and what he did there. We'll come back to Turing's life in a little while; for now, let's investigate the code Turing left behind. The details are uncertain, since he never formally published the idea, so we'll consider a couple of possibilities.

13.4.1 Turing's Code (Version 1.0)

The first challenge is to translate a text message into an integer so we can perform mathematical operations on it. This step is not intended to make a message harder to read, so the details are not too important. Here is one approach: replace each letter of the message with two digits ($A = 01$, $B = 02$, $C = 03$, etc.) and string all the digits together to form one huge number. For example, the message "victory" could be translated this way:

$$\begin{array}{cccccccc} \text{"v} & \text{i} & \text{c} & \text{t} & \text{o} & \text{r} & \text{y"} \\ \rightarrow & 22 & 09 & 03 & 20 & 15 & 18 & 25 \end{array}$$

Turing's code requires the message to be a prime number, so we may need to pad the result with a few more digits to make a prime. In this case, appending the digits 13 gives the number 2209032015182513, which is prime.

Now here is how the encryption process works. In the description below, m is the unencoded message (which we want to keep secret), m^* is the encrypted message (which the Nazis may intercept), and k is the key.

Beforehand The sender and receiver agree on a secret key, which is a large prime k .

Encryption The sender encrypts the message m by computing:

$$m^* = m \cdot k$$

Decryption The receiver decrypts m^* by computing:

$$\frac{m^*}{k} = \frac{m \cdot k}{k} = m$$

For example, suppose that the secret key is the prime number $k = 22801763489$ and the message m is "victory". Then the encrypted message is:

$$\begin{aligned} m^* &= m \cdot k \\ &= 2209032015182513 \cdot 22801763489 \\ &= 50369825549820718594667857 \end{aligned}$$

There are a couple of questions that one might naturally ask about Turing's code.

1. How can the sender and receiver ensure that m and k are prime numbers, as required?

The general problem of determining whether a large number is prime or composite has been studied for centuries, and reasonably good primality tests were known even in Turing's time. In 2002, Manindra Agrawal, Neeraj Kayal, and Nitin Saxena announced a primality test that is guaranteed to work on a number n in about $(\log n)^{12}$ steps, that is, a number of steps bounded by a twelfth degree polynomial in the length (in bits) of the input, n . This definitively places primality testing way below the problems of exponential difficulty. Amazingly, the description of their breakthrough algorithm was only thirteen lines long!

Of course, a twelfth degree polynomial grows pretty fast, so the Agrawal, *et al.* procedure is of no practical use. Still, good ideas have a way of breeding more good ideas, so there's certainly hope further improvements will lead to a procedure that is useful in practice. But the truth is, there's no practical need to improve it, since very efficient *probabilistic* procedures for primetesting have been known since the early 1970's. These procedures have some probability of giving a wrong answer, but their probability of being wrong is so tiny that betting on their answers is the best bet you'll ever make.

2. Is Turing's code secure?

The Nazis see only the encrypted message $m^* = m \cdot k$, so recovering the original message m requires factoring m^* . Despite immense efforts, no really efficient factoring algorithm has ever been found. It appears to be a fundamentally difficult problem, though a breakthrough someday is not impossible. In effect, Turing's code puts to practical use his discovery that there are limits to the power of computation. Thus, provided m and k are sufficiently large, the Nazis seem to be out of luck!

This all sounds promising, but there is a major flaw in Turing's code.

13.4.2 Breaking Turing's Code

Let's consider what happens when the sender transmits a *second* message using Turing's code and the same key. This gives the Nazis two encrypted messages to look at:

$$m_1^* = m_1 \cdot k \qquad \text{and} \qquad m_2^* = m_2 \cdot k$$

The greatest common divisor of the two encrypted messages, m_1^* and m_2^* , is the secret key k . And, as we've seen, the gcd of two numbers can be computed very efficiently. So after the second message is sent, the Nazis can recover the secret key and read *every* message!

It is difficult to believe a mathematician as brilliant as Turing could overlook such a glaring problem. One possible explanation is that he had a slightly different system in mind, one based on *modular* arithmetic.

13.5 Modular Arithmetic

On page 1 of his masterpiece on number theory, *Disquisitiones Arithmeticae*, Gauss introduced the notion of “congruence”. Now, Gauss is another guy who managed to cough up a half-decent idea every now and then, so let’s take a look at this one. Gauss said that a is *congruent to b modulo n* iff $n \mid (a - b)$. This is denoted $a \equiv b \pmod{n}$. For example:

$$29 \equiv 15 \pmod{7} \quad \text{because } 7 \mid (29 - 15).$$

There is a close connection between congruences and remainders:

Lemma 13.5.1 (Congruences and Remainders).

$$a \equiv b \pmod{n} \quad \text{iff} \quad \text{rem}(a, n) = \text{rem}(b, n).$$

Proof. By the Division Theorem, there exist unique pairs of integers q_1, r_1 and q_2, r_2 such that:

$$\begin{array}{ll} a = q_1n + r_1 & \text{where } 0 \leq r_1 < n, \\ b = q_2n + r_2 & \text{where } 0 \leq r_2 < n. \end{array}$$

In these terms, $\text{rem}(a, n) = r_1$ and $\text{rem}(b, n) = r_2$. Subtracting the second equation from the first gives:

$$a - b = (q_1 - q_2)n + (r_1 - r_2) \quad \text{where } -n < r_1 - r_2 < n.$$

Now $a \equiv b \pmod{n}$ if and only if n divides the left side. This is true if and only if n divides the right side, which holds if and only if $r_1 - r_2$ is a multiple of n . Given the bounds on $r_1 - r_2$, this happens precisely when $r_1 = r_2$, which is equivalent to $\text{rem}(a, n) = \text{rem}(b, n)$. \square

So we can also see that

$$29 \equiv 15 \pmod{7} \quad \text{because } \text{rem}(29, 7) = 1 = \text{rem}(15, 7).$$

This formulation explains why the congruence relation has properties like an equality relation. Notice that even though $\pmod{7}$ appears over on the right side the \equiv symbol, it is in no sense more strongly associated with the 15 than the 29. It would really be clearer to write $29 \equiv_{\text{mod } 7} 15$ for example, but the notation with the modulus at the end is firmly entrenched and we’ll stick to it.

We’ll make frequent use of the following immediate Corollary of Lemma 13.5.1:

Corollary 13.5.2.

$$a \equiv \text{rem}(a, n) \pmod{n}$$

Still another way to think about congruence modulo n is that it *defines a partition of the integers into n sets so that congruent numbers are all in the same set*. For example, suppose that we're working modulo 3. Then we can partition the integers into 3 sets as follows:

$$\begin{aligned} & \{ \dots, -6, -3, 0, 3, 6, 9, \dots \} \\ & \{ \dots, -5, -2, 1, 4, 7, 10, \dots \} \\ & \{ \dots, -4, -1, 2, 5, 8, 11, \dots \} \end{aligned}$$

according to whether their remainders on division by 3 are 0, 1, or 2. The upshot is that when arithmetic is done modulo n there are really only n different kinds of numbers to worry about, because there are only n possible remainders. In this sense, modular arithmetic is a simplification of ordinary arithmetic and thus is a good reasoning tool.

There are many useful facts about congruences, some of which are listed in the lemma below. The overall theme is that *congruences work a lot like equations*, though there are a couple of exceptions.

Lemma 13.5.3 (Facts About Congruences). *The following hold for $n \geq 1$:*

1. $a \equiv a \pmod{n}$
2. $a \equiv b \pmod{n}$ *implies* $b \equiv a \pmod{n}$
3. $a \equiv b \pmod{n}$ *and* $b \equiv c \pmod{n}$ *implies* $a \equiv c \pmod{n}$
4. $a \equiv b \pmod{n}$ *implies* $a + c \equiv b + c \pmod{n}$
5. $a \equiv b \pmod{n}$ *implies* $ac \equiv bc \pmod{n}$
6. $a \equiv b \pmod{n}$ *and* $c \equiv d \pmod{n}$ *imply* $a + c \equiv b + d \pmod{n}$
7. $a \equiv b \pmod{n}$ *and* $c \equiv d \pmod{n}$ *imply* $ac \equiv bd \pmod{n}$

Proof. Parts 1.–3. follow immediately from Lemma 13.5.1. Part 4. follows immediately from the definition that $a \equiv b \pmod{n}$ iff $n \mid (a - b)$. Likewise, part 5. follows because if $n \mid (a - b)$ then it divides $(a - b)c = ac - bc$. To prove part 6., assume

$$a \equiv b \pmod{n} \tag{13.3}$$

and

$$c \equiv d \pmod{n}. \tag{13.4}$$

Then

$$\begin{aligned} a + c &\equiv b + c \pmod{n} && \text{(by part 4. and (13.3)),} \\ c + b &\equiv d + b \pmod{n} && \text{(by part 4. and (13.4)), so} \\ b + c &\equiv b + d \pmod{n} && \text{and therefore} \\ a + c &\equiv b + d \pmod{n} && \text{(by part 3.)} \end{aligned}$$

Part 7. has a similar proof. □

13.5.1 Turing's Code (Version 2.0)

In 1940 France had fallen before Hitler's army, and Britain alone stood against the Nazis in western Europe. British resistance depended on a steady flow of supplies brought across the north Atlantic from the United States by convoys of ships. These convoys were engaged in a cat-and-mouse game with German "U-boats" — submarines — which prowled the Atlantic, trying to sink supply ships and starve Britain into submission. The outcome of this struggle pivoted on a balance of information: could the Germans locate convoys better than the Allies could locate U-boats or vice versa?

Germany lost.

But a critical reason behind Germany's loss was made public only in 1974: the British had broken Germany's naval code, Enigma. Through much of the war, the Allies were able to route convoys around German submarines by listening into German communications. The British government didn't explain *how* Enigma was broken until 1996. When the analysis was finally released (by the US), the author was none other than Alan Turing. In 1939 he had joined the secret British code-breaking effort at Bletchley Park. There, he played a central role in cracking the German's Enigma code and thus in preventing Britain from falling into Hitler's hands.

Governments are always tight-lipped about cryptography, but the half-century of official silence about Turing's role in breaking Enigma and saving Britain may be related to some disturbing events after the war.

Let's consider an alternative interpretation of Turing's code. Perhaps we had the basic idea right (multiply the message by the key), but erred in using *conventional* arithmetic instead of *modular* arithmetic. Maybe this is what Turing meant:

Beforehand The sender and receiver agree on a large prime p , which may be made public. (This will be the modulus for all our arithmetic.) They also agree on a secret key $k \in \{1, 2, \dots, p - 1\}$.

Encryption The message m can be any integer in the set $\{0, 1, 2, \dots, p - 1\}$; in particular, the message is no longer required to be a prime. The sender encrypts the message m to produce m^* by computing:

$$m^* = \text{rem}(mk, p) \tag{13.5}$$

Decryption (Uh-oh.)

The decryption step is a problem. We might hope to decrypt in the same way as before: by dividing the encrypted message m^* by the key k . The difficulty is that m^* is the *remainder* when mk is divided by p . So dividing m^* by k might not even give us an integer!

This decoding difficulty can be overcome with a better understanding of arithmetic modulo a prime.

13.5.2 Problems

Class Problems

Problem 13.5.

The following properties of equivalence mod n follow directly from its definition and simple properties of divisibility. See if you can prove them without looking up the proofs in the notes.

- (a) If $a \equiv b \pmod{n}$, then $ac \equiv bc \pmod{n}$.
- (b) If $a \equiv b \pmod{n}$ and $b \equiv c \pmod{n}$, then $a \equiv c \pmod{n}$.
- (c) If $a \equiv b \pmod{n}$ and $c \equiv d \pmod{n}$, then $ac \equiv bd \pmod{n}$.
- (d) $\text{rem}(a, n) \equiv a \pmod{n}$.

Problem 13.6. (a) Why is a number written in decimal evenly divisible by 9 if and only if the sum of its digits is a multiple of 9? *Hint:* $10 \equiv 1 \pmod{9}$.

(b) Take a big number, such as 37273761261. Sum the digits, where every other one is negated:

$$3 + (-7) + 2 + (-7) + 3 + (-7) + 6 + (-1) + 2 + (-6) + 1 = -11$$

Explain why the original number is a multiple of 11 if and only if this sum is a multiple of 11.

Problem 13.7.

At one time, the Guinness Book of World Records reported that the “greatest human calculator” was a guy who could compute 13th roots of 100-digit numbers that were powers of 13. What a curious choice of tasks . . .

(a) Prove that

$$d^{13} \equiv d \pmod{10} \tag{13.6}$$

for $0 \leq d < 10$.

(b) Now prove that

$$n^{13} \equiv n \pmod{10} \tag{13.7}$$

for all n .

13.6 Arithmetic with a Prime Modulus

13.6.1 Multiplicative Inverses

The *multiplicative inverse* of a number x is another number x^{-1} such that:

$$x \cdot x^{-1} = 1$$

Generally, multiplicative inverses exist over the real numbers. For example, the multiplicative inverse of 3 is $1/3$ since:

$$3 \cdot \frac{1}{3} = 1$$

The sole exception is that 0 does not have an inverse.

On the other hand, inverses generally do not exist over the integers. For example, 7 can not be multiplied by another integer to give 1.

Surprisingly, multiplicative inverses do exist when we're working *modulo a prime number*. For example, if we're working modulo 5, then 3 is a multiplicative inverse of 7, since:

$$7 \cdot 3 \equiv 1 \pmod{5}$$

(All numbers congruent to 3 modulo 5 are also multiplicative inverses of 7; for example, $7 \cdot 8 \equiv 1 \pmod{5}$ as well.) The only exception is that numbers congruent to 0 modulo 5 (that is, the multiples of 5) do not have inverses, much as 0 does not have an inverse over the real numbers. Let's prove this.

Lemma 13.6.1. *If p is prime and k is not a multiple of p , then k has a multiplicative inverse.*

Proof. Since p is prime, it has only two divisors: 1 and p . And since k is not a multiple of p , we must have $\gcd(p, k) = 1$. Therefore, there is a linear combination of p and k equal to 1:

$$sp + tk = 1$$

Rearranging terms gives:

$$sp = 1 - tk$$

This implies that $p \mid (1 - tk)$ by the definition of divisibility, and therefore $tk \equiv 1 \pmod{p}$ by the definition of congruence. Thus, t is a multiplicative inverse of k . \square

Multiplicative inverses are the key to decryption in Turing's code. Specifically, we can recover the original message by multiplying the encoded message by the *inverse* of the key:

$$\begin{aligned} m^* \cdot k^{-1} &= \text{rem}(mk, p) \cdot k^{-1} && \text{(def. (13.5) of } m^*) \\ &\equiv (mk)k^{-1} \pmod{p} && \text{(by Cor. 13.5.2)} \\ &\equiv m \pmod{p}. \end{aligned}$$

This shows that m^*k^{-1} is congruent to the original message m . Since m was in the range $0, 1, \dots, p-1$, we can recover it exactly by taking a remainder:

$$m = \text{rem}(m^*k^{-1}, p)$$

So now we can decrypt!

13.6.2 Cancellation

Another sense in which real numbers are nice is that one can cancel multiplicative terms. In other words, if we know that $m_1k = m_2k$, then we can cancel the k 's and conclude that $m_1 = m_2$, provided $k \neq 0$. In general, cancellation is *not* valid in modular arithmetic. For example, this congruence is correct:

$$2 \cdot 3 \equiv 4 \cdot 3 \pmod{6}$$

But if we cancel the 3's, we reach a false conclusion:

$$2 \equiv 4 \pmod{6}$$

The fact that multiplicative terms can not be cancelled is the most significant sense in which congruences differ from ordinary equations. However, this difference goes away if we're working modulo a *prime*; then cancellation is valid.

Lemma 13.6.2. *Suppose p is a prime and k is not a multiple of p . Then*

$$ak \equiv bk \pmod{p} \quad \text{implies} \quad a \equiv b \pmod{p}$$

Proof. Multiply both sides of the congruence by k^{-1} . □

We can use this lemma to get a bit more insight into how Turing's code works. In particular, the encryption operation in Turing's code *permutes the set of possible messages*. This is stated more precisely in the following corollary.

Corollary 13.6.3. *Suppose p is a prime and k is not a multiple of p . Then the sequence:*

$$\text{rem}((0 \cdot k), p), \quad \text{rem}((1 \cdot k), p), \quad \text{rem}((2 \cdot k), p), \quad \dots, \quad \text{rem}(((p-1) \cdot k), p)$$

is a permutation² of the sequence:

$$0, \quad 1, \quad 2, \quad \dots, \quad (p-1)$$

This remains true if the first term is deleted from each sequence.

²A *permutation* of a sequence of elements is a sequence with the same elements (including repeats) possibly in a different order. More formally, if

$$\vec{e} ::= e_1, e_2, \dots, e_n$$

is a length n sequence, and $\pi : \{1, \dots, n\} \rightarrow \{1, \dots, n\}$ is a bijection, then

$$e_{\pi(1)}, e_{\pi(2)}, \dots, e_{\pi(n)},$$

is a *permutation* of \vec{e} .

Proof. The first sequence contains p numbers, which are all in the range 0 to $p - 1$ by the definition of remainder. Furthermore, the numbers in the first sequence are all different; by Lemma 13.6.2, $ik \equiv jk \pmod{p}$ if and only if $i \equiv j \pmod{p}$, and no two numbers in the range 0, 1, ..., $p - 1$ are congruent modulo p . Thus, the first sequence must contain *all* of the numbers from 0 to $p - 1$ in some order. The claim remains true if the first terms are deleted, because both sequences begin with 0. \square

For example, suppose $p = 5$ and $k = 3$. Then the sequence:

$$\underbrace{\text{rem}((0 \cdot 3), 5)}_{=0}, \quad \underbrace{\text{rem}((1 \cdot 3), 5)}_{=3}, \quad \underbrace{\text{rem}((2 \cdot 3), 5)}_{=1}, \quad \underbrace{\text{rem}((3 \cdot 3), 5)}_{=4}, \quad \underbrace{\text{rem}((4 \cdot 3), 5)}_{=2}$$

is a permutation of 0, 1, 2, 3, 4 and the last four terms are a permutation of 1, 2, 3, 4. As long as the Nazis don't know the secret key k , they don't know how the set of possible messages are permuted by the process of encryption and thus can't read encoded messages.

13.6.3 Fermat's Theorem

A remaining challenge in using Turing's code is that decryption requires the inverse of the secret key k . An effective way to calculate k^{-1} follows from the proof of Lemma 13.6.1: $k^{-1} = \text{rem}(t, p)$ where s, t are coefficients such that $sp + tk = 1$. Notice that t is easy to find using the Pulverizer.

An alternative approach, about equally efficient and probably more memorable, is to rely on Fermat's Theorem, which is much easier than his famous Last Theorem—and more useful.

Theorem 13.6.4 (Fermat's Theorem). *Suppose p is a prime and k is not a multiple of p . Then:*

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

Proof. We reason as follows:

$$\begin{aligned} 1 \cdot 2 \cdots (p-1) &= \text{rem}(k, p) \cdot \text{rem}(2k, p) \cdots \text{rem}((p-1)k, p) && \text{(by Cor 13.6.3)} \\ &\equiv k \cdot 2k \cdots (p-1)k \pmod{p} && \text{(by Cor 13.5.2)} \\ &\equiv (p-1)! \cdot k^{p-1} \pmod{p} && \text{(rearranging terms)} \end{aligned}$$

Now $(p-1)!$ can not be a multiple of p , because the prime factorizations of $1, 2, \dots, (p-1)$ contain only primes smaller than p . Therefore, we can cancel $(p-1)!$ from the first expression and the last by Lemma 13.6.2, which proves the claim. \square

Here is how we can find inverses using Fermat's Theorem. Suppose p is a prime and k is not a multiple of p . Then, by Fermat's Theorem, we know that:

$$k^{p-2} \cdot k \equiv 1 \pmod{p}$$

Therefore, k^{p-2} must be a multiplicative inverse of k . For example, suppose that we want the multiplicative inverse of 6 modulo 17. Then we need to compute $\text{rem}(6^{15}, 17)$, which we can do by successive squaring. All the congruences below hold modulo 17.

$$\begin{aligned} 6^2 &\equiv 36 \equiv 2 \\ 6^4 &\equiv (6^2)^2 \equiv 2^2 \equiv 4 \\ 6^8 &\equiv (6^4)^2 \equiv 4^2 \equiv 16 \\ 6^{15} &\equiv 6^8 \cdot 6^4 \cdot 6^2 \cdot 6 \equiv 16 \cdot 4 \cdot 2 \cdot 6 \equiv 3 \end{aligned}$$

Therefore, $\text{rem}(6^{15}, 17) = 3$. Sure enough, 3 is the multiplicative inverse of 6 modulo 17, since:

$$3 \cdot 6 \equiv 1 \pmod{17}$$

In general, if we were working modulo a prime p , finding a multiplicative inverse by trying every value between 1 and $p-1$ would require about p operations. However, the approach above requires only about $\log p$ operations, which is far better when p is large.

13.6.4 Breaking Turing's Code —Again

The Germans didn't bother to encrypt their weather reports with the highly-secure Enigma system. After all, so what if the Allies learned that there was rain off the south coast of Iceland? But, amazingly, this practice provided the British with a critical edge in the Atlantic naval battle during 1941.

The problem was that some of those weather reports had originally been transmitted from U-boats out in the Atlantic. Thus, the British obtained both unencrypted reports and the same reports encrypted with Enigma. By comparing the two, the British were able to determine which key the Germans were using that day and could read all other Enigma-encoded traffic. Today, this would be called a *known-plaintext attack*.

Let's see how a known-plaintext attack would work against Turing's code. Suppose that the Nazis know both m and m^* where:

$$m^* \equiv mk \pmod{p}$$

Now they can compute:

$$\begin{aligned} m^{p-2} \cdot m^* &= m^{p-2} \cdot \text{rem}(mk, p) && \text{(def. (13.5) of } m^*) \\ &\equiv m^{p-2} \cdot mk \pmod{p} && \text{(by Cor 13.5.2)} \\ &\equiv m^{p-1} \cdot k \pmod{p} \\ &\equiv k \pmod{p} && \text{(Fermat's Theorem)} \end{aligned}$$

Now the Nazis have the secret key k and can decrypt any message!

This is a huge vulnerability, so Turing's code has no practical value. Fortunately, Turing got better at cryptography after devising this code; his subsequent cracking of Enigma surely saved thousands of lives, if not the whole of Britain.

13.6.5 Turing Postscript

A few years after the war, Turing's home was robbed. Detectives soon determined that a former homosexual lover of Turing's had conspired in the robbery. So they arrested him—that is, they arrested Alan Turing—because homosexuality was a British crime punishable by up to two years in prison at that time. Turing was sentenced to a humiliating hormonal “treatment” for his homosexuality: he was given estrogen injections. He began to develop breasts.

Three years later, Alan Turing, the founder of computer science, was dead. His mother explained what happened in a biography of her own son. Despite her repeated warnings, Turing carried out chemistry experiments in his own home. Apparently, her worst fear was realized: by working with potassium cyanide while eating an apple, he poisoned himself.

However, Turing remained a puzzle to the very end. His mother was a devoutly religious woman who considered suicide a sin. And, other biographers have pointed out, Turing had previously discussed committing suicide by eating a poisoned apple. Evidently, Alan Turing, who founded computer science and saved his country, took his own life in the end, and in just such a way that his mother could believe it was an accident.

Turing's last project before he disappeared from public view in 1939 involved the construction of an elaborate mechanical device to test a mathematical conjecture called the Riemann Hypothesis. This conjecture first appeared in a sketchy paper by Bernhard Riemann in 1859 and is now one of the most famous unsolved problems in mathematics.

13.6.6 Problems

Class Problems

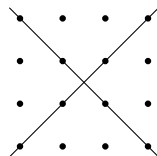
Problem 13.8.

Two nonparallel lines in the real plane intersect at a point. Algebraically, this means that the equations

$$y = m_1x + b_1$$

$$y = m_2x + b_2$$

have a unique solution (x, y) , provided $m_1 \neq m_2$. This statement would be false if we restricted x and y to the integers, since the two lines could cross at a noninteger point:



The Riemann Hypothesis

The formula for the sum of an infinite geometric series says:

$$1 + x + x^2 + x^3 + \cdots = \frac{1}{1 - x}$$

Substituting $x = \frac{1}{2^s}$, $x = \frac{1}{3^s}$, $x = \frac{1}{5^s}$, and so on for each prime number gives a sequence of equations:

$$\begin{aligned} 1 + \frac{1}{2^s} + \frac{1}{2^{2s}} + \frac{1}{2^{3s}} + \cdots &= \frac{1}{1 - 1/2^s} \\ 1 + \frac{1}{3^s} + \frac{1}{3^{2s}} + \frac{1}{3^{3s}} + \cdots &= \frac{1}{1 - 1/3^s} \\ 1 + \frac{1}{5^s} + \frac{1}{5^{2s}} + \frac{1}{5^{3s}} + \cdots &= \frac{1}{1 - 1/5^s} \\ &\text{etc.} \end{aligned}$$

Multiplying together all the left sides and all the right sides gives:

$$\sum_{n=1}^{\infty} \frac{1}{n^s} = \prod_{p \in \text{primes}} \left(\frac{1}{1 - 1/p^s} \right)$$

The sum on the left is obtained by multiplying out all the infinite series and applying the Fundamental Theorem of Arithmetic. For example, the term $1/300^s$ in the sum is obtained by multiplying $1/2^{2s}$ from the first equation by $1/3^s$ in the second and $1/5^{2s}$ in the third. Riemann noted that every prime appears in the expression on the right. So he proposed to learn about the primes by studying the equivalent, but simpler expression on the left. In particular, he regarded s as a complex number and the left side as a function, $\zeta(s)$. Riemann found that the distribution of primes is related to values of s for which $\zeta(s) = 0$, which led to his famous conjecture:

The Riemann Hypothesis: Every nontrivial zero of the zeta function $\zeta(s)$ lies on the line $s = 1/2 + ci$ in the complex plane.

Researchers continue to work intensely to settle this conjecture, as they have for over a century. A proof would immediately imply, among other things, a strong form of the Prime Number Theorem—and earn the prover a \$1 million prize! (We're not sure what the cash would be for a counter-example, but the discoverer would be wildly applauded by mathematicians everywhere.)

However, an analogous statement holds if we work over the integers *modulo a prime, p* . Find a solution to the congruences

$$y \equiv m_1x + b_1 \pmod{p}$$

$$y \equiv m_2x + b_2 \pmod{p}$$

when $m_1 \not\equiv m_2 \pmod{p}$. Express your solution in the form $x \equiv? \pmod{p}$ and $y \equiv? \pmod{p}$ where the ?'s denote expressions involving $m_1, m_2, b_1,$ and b_2 . You may find it helpful to solve the original equations over the reals first.

Problem 13.9.

Let $S_k = 1^k + 2^k + \dots + (p-1)^k$, where p is an odd prime and k is a positive multiple of $p-1$. Use Fermat's theorem to prove that $S_k \equiv -1 \pmod{p}$.

Homework Problems

Problem 13.10. (a) Use the Pulverizer to find the inverse of 13 modulo 23 in the range $\{1, \dots, 22\}$.

(b) Use Fermat's theorem to find the inverse of 13 modulo 23 in the range $\{1, \dots, 22\}$.

13.7 Arithmetic with an Arbitrary Modulus

Turing's code did not work as he hoped. However, his essential idea— using number theory as the basis for cryptography— succeeded spectacularly in the decades after his death.

In 1977, Ronald Rivest, Adi Shamir, and Leonard Adleman at MIT proposed a highly secure cryptosystem (called **RSA**) based on number theory. Despite decades of attack, no significant weakness has been found. Moreover, RSA has a major advantage over traditional codes: the sender and receiver of an encrypted message need not meet beforehand to agree on a secret key. Rather, the receiver has both a *secret key*, which she guards closely, and a *public key*, which she distributes as widely as possible. To send her a message, one encrypts using her widely-distributed public key. Then she decrypts the message using her closely-held private key. The use of such a *public key cryptography* system allows you and Amazon, for example, to engage in a secure transaction without meeting up beforehand in a dark alley to exchange a key.

Interestingly, RSA does not operate modulo a prime, as Turing's scheme may have, but rather modulo the product of *two* large primes. Thus, we'll need to know a bit about how arithmetic works modulo a composite number in order to understand RSA. Arithmetic modulo an arbitrary positive integer is really only a little more painful than working modulo a prime, in the same sense that a doctor says "This is only going to hurt a little" before he jams a big needle in your arm.

13.7.1 Relative Primality and Phi

First, we need a new definition. Integers a and b are *relatively prime* iff $\gcd(a, b) = 1$. For example, 8 and 15 are relatively prime, since $\gcd(8, 15) = 1$. Note that every integer is relatively prime to a genuine prime number p , except for multiples of p .

We'll also need a certain function that is defined using relative primality. Let n be a positive integer. Then $\phi(n)$ denotes the number of integers in $\{1, 2, \dots, n-1\}$ that are relatively prime to n . For example, $\phi(7) = 6$, since 1, 2, 3, 4, 5, and 6 are all relatively prime to 7. Similarly, $\phi(12) = 4$, since only 1, 5, 7, and 11 are relatively prime to 12. If you know the prime factorization of n , then computing $\phi(n)$ is a piece of cake, thanks to the following theorem. The function ϕ is known as *Euler's phi function*; it's also called Euler's *totient* function.

Theorem 13.7.1. *The function ϕ obeys the following relationships:*

- (a) *If a and b are relatively prime, then $\phi(ab) = \phi(a)\phi(b)$.*
- (b) *If p is a prime, then $\phi(p^k) = p^k - p^{k-1}$ for $k \geq 1$.*

Here's an example of using Theorem 13.7.1 to compute $\phi(300)$:

$$\begin{aligned}\phi(300) &= \phi(2^2 \cdot 3 \cdot 5^2) \\ &= \phi(2^2) \cdot \phi(3) \cdot \phi(5^2) && \text{(by Theorem 13.7.1.(a))} \\ &= (2^2 - 2^1)(3^1 - 3^0)(5^2 - 5^1) && \text{(by Theorem 13.7.1.(b))} \\ &= 80.\end{aligned}$$

The proof of Theorem 13.7.1.(a) requires a few more properties of modular arithmetic worked out in the next section (see Problem 13.16). We'll also give another a proof in a few weeks based on rules for counting things.

To prove Theorem 13.7.1.(b), notice that the numbers in the interval from 0 to $p^k - 1$ that are divisible by p are all those of the form mp . For mp to be in the interval, m can take any value from 0 to $p^{k-1} - 1$ and no others, so there are exactly p^{k-1} numbers in the interval that are divisible by p . Now $\phi(p^k)$ equals the number of remaining elements in the interval, namely, $p^k - p^{k-1}$.

13.7.2 Generalizing to an Arbitrary Modulus

Let's generalize what we know about arithmetic modulo a prime. Now, instead of working modulo a prime p , we'll work modulo an arbitrary positive integer n . The basic theme is that arithmetic modulo n may be complicated, but the integers *relatively prime* to n remain fairly well-behaved. For example, the proof of Lemma 13.6.1 of an inverse for k modulo p extends to an inverse for k relatively prime to n :

Lemma 13.7.2. *Let n be a positive integer. If k is relatively prime to n , then there exists an integer k^{-1} such that:*

$$k \cdot k^{-1} \equiv 1 \pmod{n}$$

As a consequence of this lemma, we can cancel a multiplicative term from both sides of a congruence if that term is relatively prime to the modulus:

Corollary 13.7.3. *Suppose n is a positive integer and k is relatively prime to n . If*

$$ak \equiv bk \pmod{n}$$

then

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

This holds because we can multiply both sides of the first congruence by k^{-1} and simplify to obtain the second.

13.7.3 Euler's Theorem

RSA essentially relies on Euler's Theorem, a generalization of Fermat's Theorem to an arbitrary modulus. The proof is much like the proof of Fermat's Theorem, except that we focus on integers relatively prime to the modulus. Let's start with a lemma.

Lemma 13.7.4. *Suppose n is a positive integer and k is relatively prime to n . Let k_1, \dots, k_r denote all the integers relatively prime to n in the range $0 \leq k_i < n$. Then the sequence:*

$$\text{rem}(k_1 \cdot k, n), \quad \text{rem}(k_2 \cdot k, n), \quad \text{rem}(k_3 \cdot k, n), \quad \dots, \quad \text{rem}(k_r \cdot k, n)$$

is a permutation of the sequence:

$$k_1, \quad k_2, \quad \dots, \quad k_r.$$

Proof. We will show that the numbers in the first sequence are all distinct and all appear in the second sequence. Since the two sequences have the same length, the first must be a permutation of the second.

First, we show that the numbers in the first sequence are all distinct. Suppose that $\text{rem}(k_i k, n) = \text{rem}(k_j k, n)$. This is equivalent to $k_i k \equiv k_j k \pmod{n}$, which implies $k_i \equiv k_j \pmod{n}$ by Corollary 13.7.3. This, in turn, means that $k_i = k_j$ since both are between 1 and $n - 1$. Thus, a term in the first sequence is not equal to any other term.

Next, we show that each number in the first sequence appears in the second. By assumption, $\text{gcd}(k_i, n) = 1$ and $\text{gcd}(k, n) = 1$, which means that

$$\begin{aligned} \text{gcd}(n, \text{rem}(k_i k, n)) &= \text{gcd}(k_i k, n) && \text{(by Lemma 13.2.4.5)} \\ &= 1 && \text{(by Lemma 13.2.4.3).} \end{aligned}$$

So $\text{rem}(k_i k, n)$ is relatively prime to n and is in the range from 0 to $n - 1$ by the definition of remainder. The second sequence is defined to consist of all such integers. \square

We can now prove Euler's Theorem:

Theorem 13.7.5 (Euler's Theorem). *Suppose n is a positive integer and k is relatively prime to n . Then*

$$k^{\phi(n)} \equiv 1 \pmod{n}$$

Proof. Let k_1, \dots, k_r denote all integers relatively prime to n such that $0 \leq k_i < n$. Then $r = \phi(n)$, by the definition of the function ϕ . Now we can reason as follows:

$$\begin{aligned} k_1 \cdot k_2 \cdots k_r &= \text{rem}(k_1 \cdot k, n) \cdot \text{rem}(k_2 \cdot k, n) \cdots \text{rem}(k_r \cdot k, n) && \text{(by Lemma 13.7.4)} \\ &\equiv (k_1 \cdot k) \cdot (k_2 \cdot k) \cdots (k_r \cdot k) \pmod{n} && \text{(by Cor 13.5.2)} \\ &\equiv (k_1 \cdot k_2 \cdots k_r) \cdot k^r \pmod{n} && \text{(rearranging terms)} \end{aligned}$$

Lemma 13.2.4.3. implies that $k_1 \cdot k_2 \cdots k_r$ is prime relative to n . Therefore, we can cancel this product from the first expression and the last by Corollary 13.7.3. This proves the claim. \square

We can find multiplicative inverses using Euler's theorem as we did with Fermat's theorem: if k is relatively prime to n , then $k^{\phi(n)-1}$ is a multiplicative inverse of k modulo n . However, this approach requires computing $\phi(n)$. Our best method for doing so requires factoring n , which can be quite difficult in general. Fortunately, when we know how to factor n , we can use Theorem 13.7.1 to compute $\phi(n)$ efficiently!

13.7.4 RSA

Finally, we are ready to see how the *RSA public key encryption scheme* works:

Beforehand The receiver creates a public key and a secret key as follows.

1. Generate two distinct primes, p and q .
2. Let $n = pq$.
3. Select an integer e such that $\gcd(e, (p-1)(q-1)) = 1$.
The *public key* is the pair (e, n) . This should be distributed widely.
4. Compute d such that $de \equiv 1 \pmod{(p-1)(q-1)}$.
The *secret key* is the pair (d, n) . This should be kept hidden!

Encoding The sender encrypts message m to produce m' using the public key:

$$m' = \text{rem}(m^e, n).$$

Decoding The receiver decrypts message m' back to message m using the secret key:

$$m = \text{rem}((m')^d, n).$$

13.7.5 Problems

Exam Problems

Problem 13.11. (a) Use the Pulverizer to find integers s, t such that

$$40s + 7t = \gcd(40, 7).$$

Show your work.

4in

(b) Adjust your answer to part **(a)** to find an inverse modulo 40 of 7 in the range $\{1, \dots, 39\}$.

2in

Class Problems

Problem 13.12.

Let's try out RSA! There is a complete description of the algorithm at the bottom of the page. You'll probably need extra paper. **Check your work carefully!**

(a) As a team, go through the **beforehand** steps.

- Choose primes p and q to be relatively small, say in the range 10-40. In practice, p and q might contain several hundred digits, but small numbers are easier to handle with pencil and paper.

- Try $e = 3, 5, 7, \dots$ until you find something that works. Use Euclid's algorithm to compute the gcd.
- Find d (using the Pulverizer —see appendix for a reminder on how the Pulverizer works —or Euler's Theorem).

When you're done, put your public key on the board. This lets another team send you a message.

(b) Now send an encrypted message to another team using their public key. Select your message m from the codebook below:

- 2 = Greetings and salutations!
- 3 = Yo, wassup?
- 4 = You guys are slow!
- 5 = All your base are belong to us.
- 6 = Someone on *our* team thinks someone on *your* team is kinda cute.
- 7 = You *are* the weakest link. Goodbye.

(c) Decrypt the message sent to you and verify that you received what the other team sent!

RSA Public Key Encryption

Beforehand The receiver creates a public key and a secret key as follows.

1. Generate two distinct primes, p and q .
2. Let $n = pq$.
3. Select an integer e such that $\gcd(e, (p-1)(q-1)) = 1$.
The *public key* is the pair (e, n) . This should be distributed widely.
4. Compute d such that $de \equiv 1 \pmod{(p-1)(q-1)}$.
The *secret key* is the pair (d, n) . This should be kept hidden!

Encoding The sender encrypts message m , where $0 \leq m < n$, to produce m' using the public key:

$$m' = \text{rem}(m^e, n).$$

Decoding The receiver decrypts message m' back to message m using the secret key:

$$m = \text{rem}((m')^d, n).$$

Problem 13.13.

A critical fact about RSA is, of course, that decrypting an encrypted message always gives back the original message! That is, that $\text{rem}((m^d)^e, pq) = m$. This will follow from something slightly more general:

Lemma 13.7.6. *Let n be a product of distinct primes and $a \equiv 1 \pmod{\phi(n)}$ for some nonnegative integer, a . Then*

$$m^a \equiv m \pmod{n}. \quad (13.8)$$

(a) Explain why Lemma 13.7.6 implies that k and k^5 have the same last digit. For example:

$$\underline{2}^5 = 3\underline{2} \qquad \underline{79}^5 = 307705639\underline{9}$$

Hint: What is $\phi(10)$?

(b) Explain why Lemma 13.7.6 implies that the original message, m , equals $\text{rem}((m^e)^d, pq)$.

(c) Prove that if p is prime, then

$$m^a \equiv m \pmod{p} \quad (13.9)$$

for all nonnegative integers $a \equiv 1 \pmod{p-1}$.

(d) Prove that if n is a product of distinct primes, and $a \equiv b \pmod{p}$ for all prime factors, p , of n , then $a \equiv b \pmod{n}$.

(e) Combine the previous parts to complete the proof of Lemma 13.7.6.

Homework Problems

Problem 13.14. (a) Use the Pulverizer to find the inverse of 13 modulo 23 in the range $\{1, \dots, 22\}$.

(b) Use Fermat's theorem to find the inverse of 13 modulo 23 in the range $\{1, \dots, 22\}$.

n

Problem 13.15.

Find the remainder of $26^{1818181}$ divided by 297. *Hint:* $1818181 = (180 \cdot 10101) + 1$; Euler's theorem

Problem 13.16.

Suppose m, n are relatively prime. In the problem you will prove the key property of Euler's function that $\phi(mn) = \phi(m)\phi(n)$.

(a) Prove that for any a, b , there is an x such that

$$x \equiv a \pmod{m}, \quad (13.10)$$

$$x \equiv b \pmod{n}. \quad (13.11)$$

Hint: Congruence (13.10) holds iff

$$x = jm + a. \quad (13.12)$$

for some j . So there is such an x only if

$$jm + a \equiv b \pmod{n}. \quad (13.13)$$

Solve (13.13) for j .

(b) Prove that there is an x satisfying the congruences (13.10) and (13.11) such that $0 \leq x < mn$.

(c) Prove that the x satisfying part (b) is unique.

(d) For an integer k , let k^* be the integers between 1 and $k - 1$ that are relatively prime to k . Conclude from part (c) that the function

$$f : (mn)^* \rightarrow m^* \times n^*$$

defined by

$$f(x) ::= (\text{rem}(x, m), \text{rem}(x, n))$$

is a bijection.

(e) Conclude from the preceding parts of this problem that

$$\phi(mn) = \phi(m)\phi(n).$$

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