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1 What is number theory?

To put it succinctly, number theory is the study of the set of natural numbers: the positive integers $1, 2, 3, 4, \ldots$. This may sound overly simplistic. How could an entire subject be built on such a simple premise as the numbers that we all learned about in elementary school? However, it turns out that many deep and fascinating problems arise very quickly from just asking questions about the natural numbers. In this chapter, our goal is just to demonstrate this by showing a few such questions, and give a little bit of the flavor of some of the techniques and concepts that arise in number theory.

1.1 Prime numbers: The atoms of the natural number universe

One concept that very quickly arises in number theory is that of prime numbers. As you probably know, a natural number $n$, other than 1, is called prime if its only factors are 1 and itself\(^1\). What is the significance of prime numbers? The simple answer is that they are the building blocks of the natural numbers, in the following sense: every natural number can be written as a product of prime numbers, and this can be done in one and only one way. For example, $12 = 2 \cdot 2 \cdot 3$, and other than reordering these factors, there is no other way to write 12 as a product of prime numbers. Similarly, $75 = 3 \cdot 5 \cdot 5$, $79 = 79$ (itself prime), and $82 = 2 \cdot 41$. By analogy with the physical world, prime numbers are like the atoms of the natural numbers. Just as every molecule in the universe is made up of atoms, and different arrangements of atoms give rise to different types of molecules, similarly every natural number is made up of prime numbers multiplied together, and different collections of prime numbers will always have different products.

To briefly deal with the number 1, first consider this: if 1 were allowed as a prime number, this would violate the uniqueness part of the statement we made above. This is because we can write 6 as $2 \cdot 3$, or $1 \cdot 2 \cdot 3$, or $1 \cdot 1 \cdot 1 \cdot 1 \cdot 1 \cdot 2 \cdot 3$. If 1 were considered prime, all of these would be different ways of writing 6 as a product of prime numbers. You might also ask how we can write 1 as

\(^1\)You might be asking why 1 is explicitly excluded from this definition. Read on for the answer.
a product of prime numbers. Note that an empty product of numbers is 1. This is because, in a sense, 1 is the starting point for forming a product: to multiply 3 numbers, start with 1, then multiply it by the first number, then multiply the result by the second number, then multiply that result by the third number. Try doing this for 2 numbers, then for 1 number. When you get down to a product of 0 numbers, all you have is the starting point, which is 1. So the natural number 1 can also be written uniquely as a product of prime numbers, namely, the product of no prime numbers at all.

1.2 “Simple” questions about prime numbers

If prime numbers are important, one question we can ask immediately is how many prime numbers there are. Are there a fixed number of them, or are there infinitely many? Your intuition probably says that there are infinitely many, and that’s correct. This is not hard to prove, and we will do so fairly soon.

Another question that, knowing that there are infinitely many prime numbers, one might ask, is how often they occur within the natural numbers. Looking at the lowest natural numbers, we see primes occurring fairly often:

\[1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, \ldots\]

However, if we go further out into the natural numbers, they seem to occur much more rarely:

\[\ldots, 5001, 5002, 5003, 5004, 5005, 5006, 5007, 5008, 5009, 5010, 5011, 5012, 5013, 5014, 5015, 5016, 5017, 5018, 5019, \ldots\]

So what can be said about the distribution of the prime numbers within the sequence of natural numbers? There are many, many answers to this question. Indeed, this is a story that has been developing for a few hundred years, and is still far from being completely answered.

One thing that you might notice from the above lists is that pairs of numbers that are two apart sometimes occur as primes\(^2\). This occurs frequently in the lower numbers: 3 and 5, 5 and 7, 11 and 13, 17 and 19. However, even in the second list, there is still a pair like this: 5009 and 5011.

\(^2\)Note that pairs of consecutive numbers, other than 2 and 3, can never both be prime. This is because with two consecutive numbers, one must be even and the other odd, and an even number larger than 2 can never be prime.
Pairs of prime numbers such as these, separated by a distance of 2, are called twin primes. Here are some even larger pairs of twin primes: 9857 and 9859, 71,261 and 71,263, 104,681 and 104,683. As far out as mankind has been able to look into the prime numbers, we have always found more pairs of twin primes. So it is natural to ask, are there infinitely many pairs of twin primes? The answer is believed to be yes. But remarkably, even with all the sophistication of modern mathematics, no one has yet been able to prove this simple-sounding statement.

In a fascinating development to this story, some significant progress has been made on this problem very recently. In 2013, a mathematician named Yitang Zhang became the first to prove that there are infinitely many pairs of consecutive prime numbers separated by at most a certain finite distance. Specifically, if we let $p_n$ denote the $n^{th}$ prime number, Zhang proved that there are infinitely many pairs of consecutive primes $(p_n, p_{n+1})$ for which

$$p_{n+1} - p_n \leq 70,000,000.$$  

While that number 70,000,000 seems rather huge, this was the first time in history that anyone had been able to prove that there was any fixed bound for which such a statement is true. (Note that the twin prime conjecture is exactly this statement, with the number 70,000,000 replaced with the number 2.)

Immediately after Zhang announced his proof, mathematicians from around the world set out to whittle away at that number 70,000,000, and see if this bound could be made smaller. Before long, a worldwide, internet-organized project called Polymath was established to see how small the bound could be made. The project was organized and led largely by famed UCLA mathematician Terence Tao, but with contributions from literally hundreds of people all over the world. Over a period of months, they managed to bring the bound down from 70,000,000 all the way to 246. That is, the following is now a theorem; its proof is credited to an entire community of mathematicians:

**Theorem.** There are infinitely many pairs of consecutive primes $(p_n, p_{n+1})$ for which

$$p_{n+1} - p_n \leq 246.$$  

---

3To hear more about this story, from Tao himself, see https://www.youtube.com/watch?v=pp06oGD4m00
Another simple-sounding question that we can ask about the distribution of the prime numbers is how many primes there are in any particular interval of numbers. For this, we start by defining the **prime-counting function**:

\[ \pi(x) = \text{the number of prime numbers less than or equal to } x \]

Note that with this function, the number of primes in any half-open interval of real numbers \((x_1, x_2]\) is just \(\pi(x_2) - \pi(x_1)\).

Using a list of all the prime numbers up to 200 (on the left), or up to 10,000 (on the right), we can graph the function \(\pi(x)\):

![Graph of \(\pi(x)\) for x values 50 to 150 and 4,000 to 8,000]

Obviously, the value of \(\pi(x)\) should “jump” by 1 exactly when \(x\) is a prime number, so it makes sense that the graph of this function has a stair-step shape, as the graph on the left shows. However, if we zoom out far enough on this picture, as we have done with the right graph, it starts to look like a smooth curve. One might be tempted to ask: is there a formula for a curve that closely approximates that graph?

Around the turn of the nineteenth century, Adrien-Marie Legendre conjectured that this curve is approximated by the function

\[ L(x) = \frac{x}{\log(x)} \]

where \(\log\) denotes the natural log function. Almost exactly 100 years later, in 1896, this was finally proved by two mathematicians, independently: Jacques Hadamard and Charles Jean de la Vallée-Poussin. More specifically, they proved that the function \(\pi(x)\) asymptotically approaches \(L(x)\), in the sense
that the relative error (percent error) between the two functions tends to 0 as \( x \) goes to infinity:

\[
\lim_{x \to \infty} \frac{\pi(x) - L(x)}{x} = 0
\]

Finding good bounds on the error term, \( |\pi(x) - L(x)| \), is an active area of research today. Indeed, perhaps the most famous unsolved problem in all of mathematics, known as the \textit{Riemann Hypothesis}, is known to be equivalent to a certain bound on this type of error in approximations to the prime-counting function.

### 1.3 Natural number solutions to equations

Another type of problem studied in number theory is to find solutions to algebraic equations using only natural numbers. These are often referred to as \textit{Diophantine problems}. For example, you are no doubt familiar with the formula

\[
a^2 + b^2 = c^2
\]

that occurs in the Pythagorean Theorem. In that theorem from geometry, \( a, b, \) and \( c \) represent the lengths of the sides of a right triangle, so we usually think of them as being any positive real numbers. But are there solutions to this equation where \( a, b, \) and \( c \) are all natural numbers?

You probably have seen some such solutions before. Probably the most well known is \( 3^2 + 4^2 = 5^2 \), which gives the so-called “3-4-5 triangle”. Another well-known example is \( 5^2 + 12^2 = 13^2 \). Let’s make a quick definition to make it easier to discuss these:

\textbf{Definition.} A triple of three natural numbers \( (a, b, c) \) that satisfies \( a^2 + b^2 = c^2 \) is called a \textit{Pythagorean triple}.

Here are a few Pythagorean triples:

\[
(3, 4, 5) \quad (5, 12, 13) \quad (6, 8, 10) \\
(8, 15, 17) \quad (15, 20, 25) \quad (28, 45, 53)
\]

Once again, after studying these for a little while, some natural questions arise: How many Pythagorean triples are there? Are there only finitely many, or infinitely many? Can we list them all in some way?

An easy way to see that there are infinitely many Pythagorean triples is to start with one, and scalar multiply the ordered triple by any number to
get another Pythagorean triple. This works because, if \( a^2 + b^2 = c^2 \) and \( d \) is any number, then

\[
(da)^2 + (db)^2 = d^2a^2 + d^2b^2 = d^2(a^2 + b^2) = d^2c^2 = (dc)^2.
\]

For example, starting with the Pythagorean triple \((3, 4, 5)\), doubling all three numbers gives the Pythagorean triple \((6, 8, 10)\). Multiplying by 3 gives \((9, 12, 15)\), which is another. Continuing in this way will obviously give infinitely many distinct Pythagorean triples.

But this also does not give all of them. As we can see from the above list, there are triples like \((5, 12, 13)\) and \((8, 15, 17)\) that are not scalar multiples of \((3, 4, 5)\). Starting with one of these other triples and scalar multiplying will give another infinite series of Pythagorean triples:

\[
(5, 12, 13) \text{ gives } (10, 24, 26), \ (15, 36, 39), \ (20, 48, 52), \ldots
\]
\[
(8, 15, 17) \text{ gives } (16, 30, 34), \ (24, 45, 51), \ (32, 60, 68), \ldots
\]

Since this is an obvious way of getting many infinite lists of Pythagorean triples, let’s try to focus on just the Pythagorean triples that are the “starting points” of these lists. The thing that distinguishes these starting triples from the ones that have been scalar multiplied by some number is that in the latter type of triple, all three numbers share a common factor. For example, in \((6, 8, 10)\), all three numbers are multiples of 2; in \((15, 36, 39)\), all three numbers are multiples of 3. So we are more interested in the Pythagorean triples that don’t have a common factor.

**Definition.** A Pythagorean triple \((a, b, c)\) is called **primitive** if \(a\), \(b\), and \(c\) have no common factor.

It is not hard to prove that if any two of the numbers in a Pythagorean triple share a common factor, then the third number will also be a multiple of that same factor. By contrapositive, this definition is equivalent to saying that no two of \(a\), \(b\), and \(c\) have a common factor. (The fancy math way of saying this is that \(a\), \(b\), and \(c\) are **pair-wise relatively prime.**)

To study the primitive Pythagorean triples in greater depth, we will employ a clever geometric trick. Notice that if \(a^2 + b^2 = c^2\), then dividing both sides of this equation by \(c^2\) yields

\[
\left(\frac{a}{c}\right)^2 + \left(\frac{b}{c}\right)^2 = 1.
\]
Thus, for any Pythagorean triple \((a, b, c)\), we can let \(X = \frac{a}{c}\) and \(Y = \frac{b}{c}\), and the pair \((X, Y)\) will be a pair of rational numbers (because \(a, b,\) and \(c\) are integers) that satisfy the equation

\[X^2 + Y^2 = 1.\]

As everyone knows, this is the equation for the unit circle in the \(XY\)-plane. We will call a point in the \(XY\)-plane with rational coordinates a rational point. Since \(a, b,\) and \(c\) are positive integers, \(X\) and \(Y\) will also be positive numbers. So what we have just said is that

Every Pythagorean triple \((a, b, c)\) yields a rational point \((X, Y)\) on the unit circle with \(X > 0, Y > 0\), via the map

\[(a, b, c) \mapsto (X, Y) = \left(\frac{a}{c}, \frac{b}{c}\right).\]

It is easy to see that two Pythagorean triples that are scalar multiples of one another give rise to the same rational point on the circle, so it again makes sense to restrict our attention to the primitive Pythagorean triples.

Going the other direction, suppose we are given a rational point \((X, Y)\) on the unit circle, in the first quadrant. Since \(X\) and \(Y\) are rational numbers, we can choose a common denominator for them, and thereby write \(X = \frac{a}{c}\) and \(Y = \frac{b}{c}\) for some natural numbers \(a, b,\) and \(c\). Then since

\[X^2 + Y^2 = \left(\frac{a}{c}\right)^2 + \left(\frac{b}{c}\right)^2 = 1,
\]

we can multiply both sides by \(c^2\) to get \(a^2 + b^2 = c^2\). That is, \((a, b, c)\) is a Pythagorean triple. Furthermore, dividing out any common factor among them, we can make this into primitive Pythagorean triple, and as we just pointed out, this primitive Pythagorean triple will correspond to the same \((X, Y)\) that we started with.

In other words, we have now established a one-to-one correspondence between two sets: the set of primitive Pythagorean triples, and the set of rational points on the unit circle in the first quadrant. We will now proceed to parametrize the latter, which will in turn give us a parametrization of the former.

To parametrize the rational points on the unit circle, we will use a classic method called stereographic projection. Let \((X, Y)\) be any point on the unit
circle other than \((-1, 0)\), and consider the line \(L\) through the point \((X, Y)\) and the point \((-1, 0)\), as in the following figure.

We will use the slope \(m\) of the line \(L\) to parametrize the points \((X, Y)\). It is easy to see from the figure that points on the unit circle in the first quadrant will correspond to slopes between 0 and 1. What we need now is to find equations for \(X\) and \(Y\) in terms of the slope \(m\).

From the point-slope formula, the equation for the line \(L\) is \(Y = m(X+1)\). So to find \(X\) and \(Y\), we need to solve simultaneously the system of equations

\[
\begin{align*}
X^2 + Y^2 &= 1 \\
Y &= m(X + 1)
\end{align*}
\]

Substituting the second equation into the first gives

\[
X^2 + m^2(X + 1)^2 = 1,
\]

which can be simplified to

\[
(1 + m^2)X^2 + 2m^2X + (m^2 - 1) = 0. \tag{1}
\]

We could try solving for \(X\) using the quadratic formula, but there is an easier way. Solving Equation (1) should give us both points of intersection between the line and the circle, and we already know that one of those points is \((-1, 0)\). So we already know that \(X = -1\) is a solution to this equation, which means that we can factor out \((X+1)\) from it. The other factor will give
us the other solution, which is the \(X\) value of the other point of intersection, the one we’re actually interested in.

Equation (1) factors as
\[
(X + 1)\left( (1 + m^2)X + (m^2 - 1) \right) = 0.
\]

So the solution we want is \(X = \frac{1 - m^2}{1 + m^2}\). Substituting this back into the equation for the line gives
\[
Y = m(X + 1) = m\left( \frac{1 - m^2}{1 + m^2} + 1 \right) = \frac{2m}{1 + m^2}.
\]

So the coordinates of the point on the circle, in terms of the slope \(m\), are
\[
(X, Y) = \left( \frac{1 - m^2}{1 + m^2}, \frac{2m}{1 + m^2} \right).
\]

Now, since the slope of the line is \(m = \frac{Y - 0}{X - (-1)} = \frac{Y}{X + 1}\), it is easy to see that when \(X\) and \(Y\) are rational numbers, \(m\) is also rational. And conversely, from Equation (2), it is easy to see that when \(m\) is rational, \(X\) and \(Y\) will be rational as well. Thus, Equation (2) establishes a one-to-one correspondence between the following two sets:

\[
\{\text{rational points } (X,Y) \text{ on the unit circle with } X > 0, Y > 0 \} \quad \text{and} \quad \{\text{rational numbers } m \text{ with } 0 < m < 1 \}
\]

Since we previously gave a one-to-one correspondence between the first of these sets and the set of primitive Pythagorean triples, we can now conclude the following:

**Theorem.** There are infinitely many primitive Pythagorean triples. To find all of them, let \(m\) be any rational number with \(0 < m < 1\), and compute \(X = \frac{1 - m^2}{1 + m^2}\) and \(Y = \frac{2m}{1 + m^2}\). Write \(X = \frac{a}{c}\) and \(Y = \frac{b}{c}\) for some natural numbers \(a\), \(b\), and \(c\), with no common factor among them. Then \((a,b,c)\) is a primitive Pythagorean triple, and this process gives all of them.

### 1.4 A few words about applications

At this point, you may be asking, “What good is any of this? How do whole-number solutions to equations, or even the fact that natural numbers can
all be written as products of prime numbers, relate to anything in the real
world?” One answer is that number theory is one of the branches of math-
ematics farthest from any application to science. To most mathematicians,
this makes it no less worthy of study. Artists create and study art, poets
write verses, and musicians make music, all because these pursuits give them
and others some sense of satisfaction, or because they find beauty in it. The
same is true of pure mathematics, the title given to mathematics that is not
directly concerned with applications to real world problems.

Number theory has often been called the purest branch of pure math,
precisely because of this lack of relevance to the real world. Some number
theorists may even take comfort in this lack of applicability. Indeed, the
famous twentieth century number theorist G. H. Hardy once wrote,

“No one has yet discovered any warlike purpose to be served by
the theory of numbers...and it seems unlikely that anyone will
do so for many years.”

However, Hardy’s prediction did turn out to be premature. Only a few
decades after he wrote this, number theory suddenly came to the forefront
of the blossoming subject of cryptography, a field which had been in its
infancy at the time of Hardy’s quote. Since the late 1970’s, number theory
has found extensive applications in cryptography. Moreover, since the late
1990’s, as the internet has proliferated into everyone’s homes, lifestyles, and
even pockets, certain aspects of computational number theory have become
an essential behind-the-scenes part of our everyday life. Indeed, today, when
you do almost anything on the internet, whether with your phone or tablet
or laptop, the privacy of that internet communication depends upon that
device doing some number theoretic calculations involving prime numbers.

We will learn all about this eventually. The number theory needed to
understand the basics of it is not all that advanced. But for now, we can
summarize the idea behind this as follows. Much of cryptography, the study
of secure communication, is based on the concept of mathematical functions
that can be computed easily, but whose inverse is extremely difficult to com-
pute without knowing some special piece of additional information. A classic
example of this is computing a product of two given numbers, versus the
inverse problem of factoring the resulting product back into the two original
numbers.

To be more specific, suppose that $p$ and $q$ are two prime numbers, and for
the sake of making this realistic, assume that they are both huge numbers,
perhaps 300 digits long each. It is not hard at all for a computer to multiply these two numbers and find the product $n = pq$. A modern computer can handle this in a fraction of a millisecond. However, if you give the computer the resulting number $n$, without giving it any extra information about the values of $p$ or $q$, then it is extremely difficult for the computer to find the original numbers $p$ and $q$ that are the unique prime factors of $n$. What do we mean by difficult? If all of the computers in the entire world worked together on the problem, all running the most sophisticated factoring algorithms currently known to mankind, it would still take them millions of years to find $p$ and $q$. 


2 Intro to proofs: Propositional logic

A proposition is a statement that has a well-defined truth value, either true or false. We will use capital letters $P, Q, R, \ldots$ to denote propositions.

Example 1.

$P = \text{It is raining.}$

$Q = \text{I brought an umbrella to school.}$

$R = \text{I ate cereal for breakfast today.}$

We can combine propositions with logical connectors, such as and, or, not, and implies (or “if-then”). This produces a propositional expression. The truth values of the propositions $P$ and $Q$ determine the truth value of a propositional expression such as $P$ or $Q$ in fairly obvious ways: $P$ or $Q$ is true if either $P$ is true, or $Q$ is true, or both, and is false otherwise (if both $P$ and $Q$ are false).

There are standard symbols for all of these logical connectors, as follows:

- $P \land Q$ means $P$ and $Q$
- $P \lor Q$ means $P$ or $Q$
- $\neg P$ means not $P$ (or equivalently, “$P$ is false”)
- $P \implies Q$ means $P$ implies $Q$ (or equivalently, “if $P$, then $Q$”)
- $P \iff Q$ means $P$ if and only if $Q$

Parentheses are often used in propositional expressions as well, such as in the expression 

$$(P \land Q) \lor (\neg P \land \neg Q)$$

A simple way to understand the meanings of these logical connectors is using truth tables. For example, here is the truth table for $P \lor Q$:

<table>
<thead>
<tr>
<th>$P$</th>
<th>$Q$</th>
<th>$P \lor Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F$</td>
<td>$F$</td>
<td>$F$</td>
</tr>
<tr>
<td>$F$</td>
<td>$T$</td>
<td>$T$</td>
</tr>
<tr>
<td>$T$</td>
<td>$F$</td>
<td>$T$</td>
</tr>
<tr>
<td>$T$</td>
<td>$T$</td>
<td>$T$</td>
</tr>
</tbody>
</table>

Here are the truth tables for the other logical connectors:
Perhaps the one of these which is the least obvious is the truth table for $P \rightarrow Q$. Certainly if $P$ is true and $Q$ is false, then $P \rightarrow Q$ must be false, and it makes sense that if both $P$ and $Q$ are true, then $P \rightarrow Q$ is true. But in the other cases, when $P$ is false, the statement $P \rightarrow Q$ says nothing about whether $Q$ should be true or false. So if $P$ is false, then no matter what truth value $Q$ has, we say that $P \rightarrow Q$ is true.

If that’s confusing, think about this with some actual statements in place of $P$ and $Q$, such as the statements from Example 1 above. Suppose I make a declaration that “if it is raining, then I bring an umbrella to school”. That is, let’s pretend that in my life, this statement is always true. What does this say about whether or not I bring an umbrella on days when it’s not raining? Perhaps I always bring an umbrella, regardless. Perhaps I never bring an umbrella when it’s not raining. Perhaps when it’s not raining, I flip a coin and decide whether or not to bring my trusty umbrella. In any of those cases, the statement “if it is raining, then I bring an umbrella to school” is still true. The one way it would be false is if there were a day when it did rain, and I did not bring an umbrella.

We say that two propositional expressions are equivalent (or logically equivalent) if they have the same truth value for all possible truth values of the propositional variables in each formula. For example, $P \leftrightarrow Q$ is logically equivalent to the formula

$$ (P \land Q) \lor (\neg P \land \neg Q) \quad (1) $$

mentioned earlier. We can see why by looking at the truth table for each formula. Here is a truth table for expression (1), built up step by step from left to right:
\[
\begin{array}{cccccc}
P & Q & P \land Q & \neg P & \neg Q & \neg P \land \neg Q \\
F & F & F & F & F & F \\
F & T & T & F & T & T \\
T & F & F & T & F & T \\
T & T & T & T & T & T \\
\end{array}
\]

To be completed by you!

Note that the last column is exactly the same as the column for \( P \leftrightarrow Q \) in the truth tables above. This shows that these two propositional expressions are logically equivalent.

**Theorem 2.1.** Each of the following is true:

(a) \( P \rightarrow Q \) is logically equivalent to \( \neg Q \rightarrow \neg P \).

(b) \( P \leftrightarrow Q \) is logically equivalent to \( (P \rightarrow Q) \land (Q \rightarrow P) \).

(c) \( \neg(P \lor Q) \) is logically equivalent to \( \neg P \land \neg Q \).

(d) \( \neg(P \land Q) \) is logically equivalent to \( \neg P \lor \neg Q \).

(e) \( \neg(\neg P) \) is logically equivalent to \( P \).

**Proof.** To be completed by you!

**Remark.**

- In part (1), the if-then statement \( \neg Q \rightarrow \neg P \) is called the *contrapositive* of the if-then statement \( P \rightarrow Q \). Part (1) shows that a statement and its contrapositive are always logically equivalent. This will be a useful proof technique in some situations: instead of proving \( P \rightarrow Q \) directly, you might instead prove \( \neg Q \rightarrow \neg P \).

- Part (2) shows that to prove an if-and-only-if statement \( P \leftrightarrow Q \), you can prove \( P \rightarrow Q \) and \( Q \rightarrow P \). Indeed, this is the standard strategy for proving an if-and-only-if statement.

- Parts (3) and (4) are called De Morgan’s Laws, named after the 19th-century British mathematician Augustus De Morgan. They give the standard way to negate a statement involving \( \land \) or \( \lor \).

- Part (5) is fairly obvious, but it says that a double negative \( \neg \neg \) can be removed from a propositional expression.
Exercise 1. Find a propositional expression using only $\wedge$, $\lor$, and $\neg$ that is equivalent to $P \rightarrow Q$. Use this (and perhaps the rules from the previous theorem) to find a simple expression, again using only $\wedge$, $\lor$, and $\neg$, that is logically equivalent to $\neg(P \rightarrow Q)$.

Solution. To be completed by you!