

HOW TO PROVE IT: CHAPTER 3

Kyle Stratton

These are the exercises for Chapter 3 from the third edition of *How to Prove It* by Daniel J. Velleman. They are numbered (Chapter).(Section).(Exercise).

3.1.1. Consider the following theorem. (This theorem was proven in the introduction.)

Theorem 1. *Suppose n is an integer larger than 1 and n is not prime. Then $2^n - 1$ is not prime.*

- (1) Identify the hypotheses and the conclusion of the theorem. Are the hypotheses true when $n = 6$? What does the theorem tell you in this instance? Is it right?
- (2) What can you conclude from the theorem in the case $n = 15$? Check directly that this conclusion is correct.
- (3) What can you conclude from the theorem in the case $n = 11$?

Proof.

- (1) This theorem has three hypotheses: n is an integer, $n > 1$, and n is not prime. The conclusion of the theorem is that $2^n - 1$ is not prime. In the case when $n = 6 = 2 \times 3$, all of the hypotheses are satisfied, so the theorem tells us that $2^6 - 1$ is not prime. We can directly check that $2^6 - 1 = 63 = 3^2 \times 7$ is not prime.
- (2) In the case when $n = 15 = 3 \times 5$, all of the hypotheses are satisfied. This means that the theorem tells us that $2^{15} - 1$ is not prime. As discussed in Part (1) of Exercise I.1, $2^{15} - 1 = 32767 = 31 \times 1057$.
- (3) In the case when $n = 11$, not all of the hypotheses are satisfied. In particular, 11 is prime. Because not all of the hypotheses of the theorem are satisfied, we cannot draw any conclusions from it. In particular, the theorem does not tell us anything about the primality of $2^{11} - 1$.

□

3.1.2. Consider the following theorem. (The theorem is correct, but we will not ask you to prove it here.)

Theorem 2. *Suppose that $b^2 > 4ac$. Then the quadratic equation $ax^2 + bx + c = 0$ has exactly two real solutions.*

- (1) Identify the hypotheses and conclusion of the theorem.
- (2) To give an instance of the theorem, you must specify values for a , b , and c , but not x . Why?
- (3) What can you conclude from the theorem in the case $a = 2$, $b = -5$, $c = 3$? Check directly that this conclusion is correct.
- (4) What can you conclude from the theorem in the case $a = 2$, $b = 4$, $c = 3$?

Proof.

- (1) This theorem has one implicit hypothesis, that a, b, c are all real numbers, and one explicit hypothesis, that $b^2 > 4ac$. The conclusion of the theorem is that the quadratic equation $ax^2 + bx + c = 0$ has exactly two real solutions.
- (2) To give an instance of the theorem, we only need to specify values for a, b , and c since those are the only variables listed in the hypothesis. The values of x associated with a specific instance of the theorem are determined by the given values of a, b, c , since the x values are the two real solutions to the quadratic equation $ax^2 + bx + c = 0$. In other words, x is a dummy variable for the set $S = \{x \in \mathbb{R} \mid ax^2 + bx + c = 0\}$ for given values of a, b, c . When phrased this way, the conclusion of theorem states that S contains exactly two distinct elements.
- (3) In the case $a = 2, b = -5, c = 3$, we have $b^2 = (-5)^2 = 25$ and $4ac = 4(2)(3) = 24$. Thus, the hypotheses $b^2 > 4ac$ is satisfied, and the theorem applies. We can then conclude that the quadratic equation $2x^2 - 5x + 3 = 0$ has two real solutions. Factoring the quadratic as $(2x - 3)(x - 1) = 0$, we can directly check that the two real solutions are $x = 3/2$ and $x = 1$.
- (4) In the case $a = 2, b = 4, c = 3$, we have $b^2 = 4^2 = 16$ and $4ac = 4(2)(3) = 24$. In other words, $b^2 \not> 4ac$. Since not all of the hypotheses of the theorem are satisfied, we cannot draw any conclusions from it. In particular, the theorem does not tell us anything about the solution set of the quadratic equation $2x^2 + 4x + 3 = 0$.

□

3.1.3. Consider the following incorrect theorem.

Theorem 3. *Suppose n is a natural number larger than 2, and n is not a prime number. Then $2n + 13$ is not a prime number.*

What are the hypotheses and conclusion of this theorem? Show that the theorem is incorrect by finding a counterexample.

Proof. The theorem has three hypotheses: n is a natural number, $n > 2$, and n is not prime. The conclusion of the theorem is that $2n + 13$ is not a prime number. To see that this theorem is incorrect, consider the case of $n = 8$. This value of n is a natural number greater than 2 that is not prime, so it satisfies all of the hypotheses of the theorem. However, $2n + 13 = 2(8) + 13 = 29$ is a prime number. Since we could find an instance of the theorem where all of the hypotheses are satisfied but an incorrect conclusion is drawn, the theorem itself is incorrect. □

3.1.4. Complete the following alternative proof of the theorem in Example 3.1.2.

Theorem 4. *Suppose a and b are real numbers. If $0 < a < b$ then $a^2 < b^2$.*

Proof. Suppose $0 < a < b$. Then $b - a > 0$. [Fill in a proof of $b^2 - a^2 > 0$ here.] Since $b^2 - a^2 > 0$, it follows that $a^2 < b^2$. Therefore, if $0 < a < b$ then $a^2 < b^2$. □

Proof. Suppose $0 < a < b$. Then $b - a > 0$. In addition, since $0 < a < b$, we also know that $b + a > 0$. We can then multiply both sides of the inequality $b - a > 0$ by $b + a$ to get $(b - a)(b + a) = b^2 - a^2 > 0$. Since $b^2 - a^2 > 0$, it follows that $a^2 < b^2$. Therefore, if $0 < a < b$ then $a^2 < b^2$. □

3.1.5. Suppose a and b are real numbers. Prove that if $a < b < 0$ then $a^2 > b^2$.

Proof. Suppose $a < b < 0$. Then $a - b < 0$ and $a + b < 0$. We can then multiply both sides of the inequality $a - b < 0$ by $a + b$ to get $(a - b)(a + b) = a^2 - b^2 > 0$. Since $a^2 - b^2 > 0$, it follows that $a^2 > b^2$. Therefore, if $a < b < 0$ then $a^2 > b^2$.

Note that an alternative strategy would be to mimic the proof of the theorem in Example 3.1.2 and instead multiply the given inequality by the negative numbers a and b , respectively. This would then result in the chain of inequalities $a^2 > ab > b^2 > 0$, which also gives the desired conclusion. \square

3.1.6. Suppose a and b are real numbers. Prove that if $0 < a < b$ then $1/b < 1/a$.

Proof. Suppose $0 < a < b$. Dividing both sides of the inequality $a < b$ by the positive number a gives us $1 < b/a$. We can then divide both sides of $1 < b/a$ by the positive number b to conclude $1/b < 1/a$. Therefore, if $0 < a < b$ then $1/b < 1/a$. \square

3.1.7. Suppose a is a real number. Prove that if $a^3 > a$ then $a^5 > a$. (*Hint: One approach is to start by completing the following equation: $a^5 - a = (a^3 - a) \cdot \underline{\hspace{1cm}}$.*)

Proof. Suppose $a^3 > a$, which we can rewrite as $a^3 - a > 0$. Following the hint, we note that we can factor $a^5 - a$ as $(a^3 - a)(a^2 + 1)$. Since $a^2 \geq 0$ for all $a \in \mathbb{R}$, we know that $a^2 + 1 > 0$. Thus, multiplying the inequality $a^3 - a > 0$ by the positive number $a^2 + 1$ gives us $0 < (a^3 - a)(a^2 + 1) = a^5 - a$. In other words, we conclude that $a^5 > a$. Therefore, if $a^3 > a$ then $a^5 > a$. \square

3.1.8. Suppose $A \setminus B \subseteq C \cap D$ and $x \in A$. Prove that if $x \notin D$ then $x \in B$.

Proof. We prove the contrapositive statement: if $x \notin B$ then $x \in D$. Suppose $x \notin B$. Then, since we also know that $x \in A$, it follows that $x \in A \setminus B$. As $A \setminus B \subseteq C \cap D$, it then follows that $x \in C \cap D$. In other words, $x \in C$ and $x \in D$. The last inclusion, that $x \in D$, is what we wanted to prove to complete the proof of the contrapositive statement. Therefore, if $x \notin B$ then $x \in D$. \square

3.1.9. Suppose $A \cap B \subseteq C \setminus D$. Prove that if $x \in A$, then if $x \in D$ then $x \notin B$.

Proof. Suppose $x \in A$. We prove the contrapositive statement: if $x \in B$ then $x \notin D$. Now suppose $x \in B$. Then, since $x \in A$ as well, it follows that $x \in A \cap B$. As $A \cap B \subseteq C \setminus D$, it then follows that $x \in C \setminus D$. From this, we conclude that $x \notin D$, which completes our proof of the contrapositive statement. Therefore, if $x \in A$, then if $x \in D$ then $x \notin B$. \square

3.1.10. Suppose a and b are real numbers. Prove that if $a < b$ then $(a + b)/2 < b$.

Proof. Suppose $a < b$. Adding b to both sides of the inequality then gives us $a + b < 2b$. Next we divide both sides by 2 to obtain the desired inequality: $(a + b)/2 < b$. Therefore, if $a < b$ then $(a + b)/2 < b$. \square

3.1.11. Suppose x is a real number and $x \neq 0$. Prove that if $(\sqrt[3]{x} + 5)/(x^2 + 6) = 1/x$ then $x \neq 8$.

Proof. We prove the contrapositive statement: if $x = 8$ then $(\sqrt[3]{x} + 5)/(x^2 + 6) \neq 1/x$. Suppose $x = 8$. Then $1/x = 1/8$ and $(\sqrt[3]{x} + 5)/(x^2 + 6) = (\sqrt[3]{8} + 5)/(8^2 + 6) = 1/10$. Since $1/8 \neq 1/10$, this completes the proof of the contrapositive statement. Therefore, we conclude that $(\sqrt[3]{x} + 5)/(x^2 + 6) = 1/x$ then $x \neq 8$. \square

3.1.12. Suppose a, b, c , and d are real numbers, $0 < a < b$, and $d > 0$. Prove that if $ac \geq bd$ then $c > d$.

Proof. Suppose $ac \geq bd$. Since $b > a$ and $d > 0$, we can multiply both sides of the first inequality by d to obtain $bd > ad$. Then, since $ac \geq bd$, we have $ac \geq bd > ad$. It then follows that $ac > ad$. Dividing both sides of the inequality by the positive number a , we see that $c > d$. Thus, we conclude that if $ac \geq bd$ then $c > d$.

Note that we could also approach this proof by proving the contrapositive statement: if $c \leq d$ then $ac < bd$. \square

3.1.13. Suppose x and y are real numbers, and that $3x + 2y \leq 5$. Prove that if $x > 1$ then $y < 1$.

Proof. Suppose $x > 1$. Then, $3x + 2y > 3 + 2y$. Combining this with the given inequality, $3x + 2y \leq 5$, we have $3 + 2y < 3x + 2y \leq 5$. In particular, $3 + 2y < 5$. After isolating y in the inequality, we end up with the desired result: $y < 1$. Therefore, we conclude that if $x > 1$ then $y < 1$.

Note that we could also approach this proof by proving the contrapositive statement: if $y \geq 1$ then $x \leq 1$. \square

3.1.14. Suppose x and y are real numbers. Prove that if $x^2 + y = -3$ and $2x - y = 2$ then $x = -1$.

Proof. Suppose that $x^2 + y = -3$ and $2x - y = 2$. We can add the two equations together to obtain $x^2 + 2x = -1$. After rearranging, this becomes $x^2 + 2x + 1 = 0$, which we can factor as $(x + 1)^2 = 0$. Therefore, it follows that $x = -1$. Thus, we conclude that if $x^2 + y = -3$ and $2x - y = 2$ then $x = -1$. \square

3.1.15. Prove the first theorem in Example 3.1.1.

Theorem 5. Suppose $x > 3$ and $y < 2$. Then $x^2 - 2y > 5$.

(Hint: You might find it useful to apply the theorem from Example 3.1.2, which stated that if a and b are real numbers such that $0 < a < b$, then $a^2 < b^2$.)

Proof. We follow the hint and apply the fact that if a and b are real numbers such that $0 < a < b$ then $a^2 < b^2$ with $a = 3$ and $b = x$ to conclude that $x^2 > 9$. Next, since $y < 2$, it follows that $-2y > -4$. Adding the inequalities $x^2 > 9$ and $-2y > -4$ together gives us the desired inequality: $x^2 - 2y > 5$. \square

3.1.16. Consider the following theorem.

Theorem 6. Suppose x is a real number and $x \neq 4$. If $(2x - 5)/(x - 4) = 3$ then $x = 7$.

(1) What is wrong with the following proof of the theorem?

Proof. Suppose $x = 7$. Then $(2x - 5)/(x - 4) = (2 \cdot 7 - 5)/(7 - 4) = 9/3 = 3$. Therefore if $(2x - 5)/(x - 4) = 3$ then $x = 7$. \square

- (2) Give a correct proof of the theorem.

Proof.

- (1) The problem with the incorrect proof of the theorem is that it starts by assuming that the conclusion, that $x = 7$, is true when that is the ultimate fact that we are trying to prove. In other words, it is instead a proof of the converse statement: if $x = 7$ then $(2x - 5)/(x - 4) = 3$, which is a completely different statement.
- (2) Suppose $(2x - 5)/(x - 4) = 3$. We can then clear the denominator of the left-hand side by multiplying the equation by $x - 4$. This gives us the equation $2x - 5 = 3(x - 4)$, or in other words $2x - 5 = 3x - 12$. We subtract $2x$ from both sides and then add 12 to both sides to see that $x = 7$. Therefore, we conclude that if $(2x - 5)/(x - 4) = 3$ then $x = 7$. \square

3.1.17. Consider the following incorrect theorem.

Theorem 7. Suppose that x and y are real numbers and $x \neq 3$. If $x^2y = 9y$ then $y = 0$.

- (1) What's wrong with the following proof of the theorem?

Proof. Suppose that $x^2y = 9y$. Then $(x^2 - 9)y = 0$. Since $x \neq 3$, $x^2 \neq 9$, so $x^2 - 9 \neq 0$. Therefore we can divide both sides of the equation $(x^2 - 9)y = 0$ by $x^2 - 9$, which leads to the conclusion that $y = 0$. Thus, if $x^2y = 9y$ then $y = 0$. \square

- (2) Show that the theorem is incorrect by finding a counterexample.

Proof.

- (1) The attempted proof makes a mistake in the statement "Since $x \neq 3$, $x^2 \neq 9$, so $x^2 - 9 \neq 0$." We only know that $x \neq 3$, but otherwise x could be any other real number. In particular, we could have $x = -3$, which would then result in $x^2 = 9$. Since the rest of the proof hinges on the assumption that $x^2 \neq 9$, it is rendered invalid.
- (2) Consider $x = -3$ and $y = 1$. In this case, $x^2y = (-3)^2(1) = 9$ and $9y = 9(1) = 9$, but $y \neq 0$. Therefore, this counter example shows that the theorem is incorrect, since we were able to find values of x and y which satisfy the hypotheses but then lead to an incorrect conclusion. \square

3.2.1. This problem could be solved by using truth tables, but don't do it that way. Instead, use the methods for writing proofs discussed so far in this chapter.

- (1) Suppose $P \rightarrow Q$ and $Q \rightarrow R$ are both true. Prove that $P \rightarrow R$ is true.
- (2) Suppose $\neg R \rightarrow (P \rightarrow \neg Q)$ is true. Prove that $P \rightarrow (Q \rightarrow R)$ is true.

Proof.

- (1) Suppose P is true. Then, since by the assumption $P \rightarrow Q$ is also true, we apply modus ponens to conclude that Q is true. Now we apply modus ponens again, this time the fact that Q is true and the assumption $Q \rightarrow R$ is true to conclude that R is true. Therefore, $P \rightarrow R$ is true.
- (2) Suppose P is true. Now we want to show that $Q \rightarrow R$ is true. This is equivalent to proving the contrapositive statement, $\neg R \rightarrow \neg Q$. To prove $\neg R \rightarrow \neg Q$, suppose $\neg R$ is true. Then, we can combine this assumption with the given assumption that $\neg R \rightarrow (P \rightarrow \neg Q)$ is true to conclude that $P \rightarrow \neg Q$ is true by modus ponens. Now we apply modus ponens again with P and $P \rightarrow \neg Q$ to conclude that $\neg Q$ is true. Therefore, $\neg R \rightarrow \neg Q$ is true, so we conclude that $Q \rightarrow R$ is true. Finally, we conclude that $P \rightarrow (Q \rightarrow R)$ is true.

□

3.2.2. This problem could be solved using truth tables, but don't do it that way. Instead, use the methods for writing proofs discussed so far in this chapter.

- (1) Suppose $P \rightarrow Q$ and $R \rightarrow \neg Q$ are both true. Prove that $P \rightarrow \neg R$ is true.
- (2) Suppose that P is true. Prove that $Q \rightarrow \neg(Q \rightarrow \neg P)$ is true.

Proof.

- (1) Suppose P is true. Then, since P and $P \rightarrow Q$ are both true, we conclude that Q is true by modus ponens. Next, since Q and $R \rightarrow \neg Q$ are both true, we conclude that $\neg R$ is true by modus tollens. Therefore, we conclude that $P \rightarrow \neg R$ is true.
- (2) We prove the equivalent contrapositive statement: that $(Q \rightarrow \neg P) \rightarrow \neg Q$ is true. Suppose $Q \rightarrow \neg P$ is true. Then, since P is true by assumption, we use modus tollens to conclude that $\neg Q$ is true. Thus, $(Q \rightarrow \neg P) \rightarrow \neg Q$ is true. In other words, we conclude that $Q \rightarrow \neg(Q \rightarrow \neg P)$ is true.

□

3.2.3. Suppose $A \subseteq C$, and B and C are disjoint. Prove that if $x \in A$ then $x \notin B$.

Proof. Suppose $x \in A$. Then, since $A \subseteq C$, we also know that $x \in C$. Since B and C are disjoint, the fact that $x \in C$ means that $x \notin B$. Therefore, we conclude that if $x \in A$ then $x \notin B$.

□

3.2.4. Suppose that $A \setminus B$ is disjoint from C and $x \in A$. Prove that if $x \in C$ then $x \in B$.

Proof. We prove the equivalent contrapositive statement: if $x \notin B$ then $x \notin C$. Suppose $x \notin B$. Then, since by assumption $x \in A$, $x \in A \setminus B$. Since $A \setminus B$ is disjoint from C , it follows that $x \notin C$. Thus, if $x \notin B$ then $x \notin C$. In other words, we conclude that if $x \in C$ then $x \in B$.

□

3.2.5. Prove that it cannot be the case that $x \in A \setminus B$ and $x \in B \setminus C$.

Proof. Suppose $x \in A \setminus B$ and $x \in B \setminus C$. Since $x \in A \setminus B$, it follows that $x \in A$ and $x \notin B$. Similarly, since $x \in B \setminus C$, it follows that $x \in B$ and $x \in C$. However, having $x \notin B$ and $x \in B$ is a contradiction. Therefore, we conclude that it cannot be the case that $x \in A \setminus B$ and $x \in B \setminus C$.

□

3.2.6. Use the method of proof by contradiction to prove the theorem in Example 3.2.1.

Theorem 8. Suppose $A \cap C \subseteq B$ and $a \in C$. Prove that $a \notin A \setminus B$.

Proof. Suppose, towards a contradiction, that $a \in A \setminus B$. In other words, $a \in A$ and $a \notin B$. Since also $a \in C$, we have $a \in A \cap C \subseteq B$. Therefore, $a \in B$. But this contradicts that $a \notin B$. Thus, we conclude that $a \notin A \setminus B$. \square

3.2.7. Use the method of proof by contradiction to prove the theorem in Example 3.2.5.

Theorem 9. Suppose $A \subseteq B$, $a \in A$, and $a \notin B \setminus C$. Prove that $a \in C$.

Proof. Suppose, towards a contradiction, that $a \notin C$. Since $a \in A$ and $A \subseteq B$, it follows that $a \in B$. Then, since $a \in B$ and $a \notin C$, $a \in B \setminus C$. This, however, contradicts the fact that $a \notin B \setminus C$. Therefore, we conclude that $a \in C$. \square

3.2.8. Suppose that $y + x = 2y - x$, and x and y are not both zero. Prove that $y \neq 0$.

Proof. Suppose, towards a contradiction, that $y = 0$. Substituting $y = 0$ into the equation $y + x = 2y - x$ gives us $x = -x$, which implies that $x = 0$. However, having $y = 0$ and $x = 0$ contradicts the fact that x and y are not both zero. Thus, we conclude that $y \neq 0$. \square

3.2.9. Suppose that a and b are nonzero real numbers. Prove that if $a < 1/a < b < 1/b$ then $a < -1$.

Proof. Suppose $a < 1/a < b < 1/b$. We then break the proof into two steps: proving that $a < 0$ and then proving that $a < -1$.

Lemma 10. $a < 0$

Proof. Suppose, towards a contradiction, that $a \geq 0$. Since a is nonzero, we can assume, without loss of generality, that $a > 0$. Then, since $0 < a < b$, we can apply Exercise 3.1.6 to conclude that $1/b < 1/a$. This, however, contradicts the fact that $1/a < 1/b$. Thus, we conclude that $a < 0$. \square

Now that we have proved that $a < 0$ in the above lemma, we move on to showing that $a < -1$. We once again use proof by contradiction. Suppose, towards a contradiction, that $a \geq -1$. In other words, $-1 \leq a < 0$. Since a is negative, dividing both sides of the inequality $a \geq -1$ gives us $1 \leq -1/a$. Rearranging this inequality results in $-1 \geq 1/a$. Thus, we have $a \geq -1 \geq 1/a$, or most importantly, $a \geq 1/a$. This however, contradicts the fact that $a < 1/a$, so we must instead have $a < -1$, as desired. Therefore, we conclude that if $a < 1/a < b < 1/b$ then $a < -1$. \square

3.2.10. Suppose that x and y are real numbers. Prove that if $x^2y = 2x + y$, then if $y \neq 0$ then $x \neq 0$.

Proof. Suppose $x^2y = 2x + y$. Now our goal is to prove that if $y \neq 0$ then $x \neq 0$. We do this by proving the contrapositive statement: if $x = 0$ then $y = 0$. Now suppose that $x = 0$. Plugging this value for x into $x^2y = 2x + y$ gives us $0 = y$, which is exactly what we wanted to show. Thus, if $x = 0$ then $y = 0$. In other words, if $y \neq 0$ then $x \neq 0$. We then conclude that if $x^2y = 2x + y$, then if $y \neq 0$ then $x \neq 0$. \square

3.2.11. Suppose that x and y are real numbers. Prove that if $x \neq 0$, then if $y = (3x^2 + 2y)/(x^2 + 2)$ then $y = 3$.

Proof. Suppose $x \neq 0$, and then suppose $y = (3x^2 + 2y)/(x^2 + 2)$. Multiplying both sides of the equation by $x^2 + 2$ gives us $x^2y + 2y = 3x^2 + 2y$. After subtracting $2y$ from both sides, we are left with $x^2y = 3x^2$. Since $x \neq 0$, $x^2 \neq 0$ as well, so we can divide both sides by x^2 to conclude that $y = 3$. Therefore, we conclude that if $x \neq 0$, then if $y = (3x^2 + 2y)/(x^2 + 2)$, then $y = 3$. \square

3.2.12. Consider the following incorrect theorem.

Theorem 11. Suppose x and y are real numbers and $x + y = 10$. Then $x \neq 3$ and $y \neq 8$.

- (1) What's wrong with the following proof of the theorem?

Proof. Suppose the conclusion of the theorem is false. Then $x = 3$ and $y = 8$. But then $x + y = 11$, which contradicts the given information that $x + y = 10$. Therefore, the conclusion must be true. \square

- (2) Show that the theorem is incorrect by finding a counterexample.

Proof.

- (1) The proof incorrectly negates the conclusion when attempting to begin the proof by contradiction. The conclusion, that $x \neq 3$ and $y \neq 8$, has the logical form $(x \neq 3) \wedge (y \neq 8)$, so its negation is $(x = 3) \vee (y = 8)$, by DeMorgan's laws. Thus, the correct negation of the conclusion is that $x = 3$ **or** $y = 8$.
- (2) One counterexample is the case of $x = 3$ and $y = 7$. These are two real numbers such that $x + y = 10$, but they do not satisfy the conclusion that $x \neq 3$ **and** $y \neq 8$, as only $y \neq 8$. \square

3.2.13. Consider the following incorrect theorem.

Theorem 12. Suppose that $A \subseteq C$, $B \subseteq C$, and $x \in A$. Then $x \in B$.

- (1) What's wrong with the following proof of the theorem?

Proof. Suppose that $x \notin B$. Since $x \in A$ and $A \subseteq C$, $x \in C$. Since $x \notin B$ and $B \subseteq C$, $x \notin C$. But now we have proven both $x \in C$ and $x \notin C$, so we have reached a contradiction. Therefore $x \in B$. \square

- (2) Show that the theorem is incorrect by finding a counterexample.

Proof.

- (1) The proof incorrectly concludes that since $x \notin B$ and $B \subseteq C$, $x \notin C$. This is an incorrect conclusion because B may be a proper subset of C , or in other words $C \setminus B$ may be nonempty. We can also confirm the incorrectness of this conclusion by examining the logical form of the statement $B \subseteq C$, which is $\forall x(x \in B \rightarrow x \in C)$. This is equivalent to $\forall x(x \notin B \vee x \in C)$, which is still true in the case when there are elements x such that $x \notin B$ and $x \in C$.
- (2) Consider the case where $A = \{1\}$, $B = \{2\}$, $C = \{1, 2\}$, and $x = 1$. Clearly $x \in A$, $A \subseteq C$, and $B \subseteq C$, but $x \notin B$. \square

3.2.14. Use truth tables so show that modus tollens is a valid rule of inference.

Proof. Recall that modus tollens says that if $P \rightarrow Q$ is true and Q is false, then you can conclude that P must also be false. We now construct a truth table to evaluate the validity of this form of argument.

P	Q	$P \rightarrow Q$	$\neg Q$	$\neg P$
T	T	T	F	F
T	F	F	T	F
F	T	T	F	T
F	F	T	T	T

This form of argument is valid because whenever all of the premises, $P \rightarrow Q$ and $\neg Q$, are true, the conclusion, $\neg P$, is also true, as indicated by the blue highlighted row. \square

3.2.15. Use truth tables to check the correctness of the theorem in Example 3.2.4.

Theorem 13. Suppose $P \rightarrow (Q \rightarrow R)$. Prove that $\neg R \rightarrow (P \rightarrow \neg Q)$.

Proof.

P	Q	R	$P \rightarrow (Q \rightarrow R)$	$\neg R \rightarrow (P \rightarrow \neg Q)$
T	T	T	T	T
T	T	F	F	F
T	F	T	T	T
T	F	F	T	T
F	T	T	T	T
F	T	F	T	T
F	F	T	T	T
F	F	F	T	T

This theorem is correct because whenever the premise, $P \rightarrow (Q \rightarrow R)$ is true, the conclusion $\neg R \rightarrow (P \rightarrow \neg Q)$ is also true, as indicated by the blue highlighted rows.

We can also see that the theorem is correct by comparing the logical form of the premise with the logical form of the conclusion. The premise, $P \rightarrow (Q \rightarrow R)$, is equivalent to $\neg P \vee (\neg Q \vee R)$, or simply $\neg P \vee \neg Q \vee R$ by associativity of disjunction. Similarly, the conclusion, $\neg R \rightarrow (P \rightarrow \neg Q)$ is equivalent to $R \vee (\neg P \vee \neg Q)$, which is equivalent to $\neg P \vee \neg Q \vee R$ by associativity and commutativity of disjunction. Since the premise and conclusion are equivalent logical statements, the conclusion is true whenever the premise is true. \square

3.2.16. Use truth tables to check the correctness of the statements in Exercise 3.2.1.

Proof.

- (1) Recall that the statement was “Suppose $P \rightarrow Q$ and $Q \rightarrow R$ are both true. Prove that $P \rightarrow R$ is true.”

P	Q	R	$P \rightarrow Q$	$Q \rightarrow R$	$P \rightarrow R$
T	T	T	T	T	T
T	T	F	T	F	F
T	F	T	F	T	T
T	F	F	F	T	F
F	T	T	T	T	T
F	T	F	T	F	T
F	F	T	T	T	T
F	F	F	T	T	T

This statement is correct because whenever the premises, $P \rightarrow Q$ and $Q \rightarrow R$ are both true, the conclusion $P \rightarrow R$ is also true, as indicated by the blue highlighted rows.

- (2) Recall that the statement was “Suppose $\neg R \rightarrow (P \rightarrow \neg Q)$ is true. Prove that $P \rightarrow (Q \rightarrow R)$ is true.”

P	Q	R	$\neg R \rightarrow (P \rightarrow \neg Q)$	$P \rightarrow (Q \rightarrow R)$
T	T	T	T	T
T	T	F	F	F
T	F	T	T	T
T	F	F	T	T
F	T	T	T	T
F	T	F	T	T
F	F	T	T	T
F	F	F	T	T

This statement is correct because whenever the premise, $\neg R \rightarrow (P \rightarrow \neg Q)$ is true, the conclusion $P \rightarrow (Q \rightarrow R)$ is also true, as indicated by the blue highlighted rows.

Our analysis from Exercise 3.2.15 also provides another perspective for the correctness of the statement, because the premise, $\neg R \rightarrow (P \rightarrow \neg Q)$, and the conclusion, $P \rightarrow (Q \rightarrow R)$, have equivalent logical forms.

□

3.2.17. Use truth tables to check the correctness of the statements in Exercise 3.2.2.

Proof.

- (1) Recall that the statement was “Suppose $P \rightarrow Q$ and $R \rightarrow \neg Q$ are both true. Prove that $P \rightarrow \neg R$ is true.”

P	Q	R	$P \rightarrow Q$	$R \rightarrow \neg Q$	$P \rightarrow \neg R$
T	T	T	T	F	F
T	T	F	T	T	T
T	F	T	F	T	F
T	F	F	F	T	T
F	T	T	T	F	T
F	T	F	T	T	T
F	F	T	T	T	T
F	F	F	T	T	T

This statement is correct because whenever the premises, $P \rightarrow Q$ and $R \rightarrow \neg Q$ are both true, the conclusion $P \rightarrow \neg R$ is also true, as indicated by the blue highlighted rows.

- (2) Recall that the statement was “Suppose that P is true. Prove that $Q \rightarrow \neg(Q \rightarrow \neg P)$ is true.”

P	Q	P	$Q \rightarrow \neg(Q \rightarrow \neg P)$
T	T	T	T
T	F	T	T
F	T	F	F
F	F	F	T

The statement is correct because whenever the premise P is true, the conclusion $Q \rightarrow \neg(Q \rightarrow \neg P)$ is also true, as indicated by the blue highlighted rows.

Note that we can more easily fill out the truth table by observing that the conclusion is logically equivalent to the simpler statement $\neg Q \vee P$.

□

3.2.18. Can the proof in Example 3.2.2 be modified to prove that if $x^2 + y = 13$ and $x \neq 3$ then $y \neq 4$? Explain. Below is the theorem from Example 3.2.2 and its proof.

Theorem 14. *If $x^2 + y = 13$ and $y \neq 4$ then $x \neq 3$.*

Proof. Suppose $x^2 + y = 13$ and $y \neq 4$. Suppose $x = 3$. Substituting this into the equation $x^2 + y = 13$, we get $9 + y = 13$, so $y = 4$. But this contradicts the fact that $y \neq 4$. Therefore $x \neq 3$. Thus, if $x^2 + y = 13$ and $y \neq 4$ then $x \neq 3$. □

Proof. The proof in Example 3.2.2 cannot be modified to prove that if $x^2 + y = 13$ and $x \neq 3$ then $y \neq 4$? This is because the statement “If $x^2 + y = 13$ and $x \neq 3$ then $y \neq 4$,” is false. To see why, consider the case when $x = -3$, which satisfies the hypothesis that $x \neq 3$. In this situation, when also $x^2 + y = 13$, we can plug in $x = -3$ to obtain the equation $9 + y = 13$. From the equation $9 + y = 13$ it follows that $y = 4$, which does not satisfy the conclusion $y \neq 4$. Since we have found a situation where the premises of the statement are true, but the conclusion is false, the statement itself is false. □

3.3.1. In Exercise 2.2.7 you used logical equivalences to show that $\exists x(P(x) \rightarrow Q(x))$ is equivalent to $\forall x P(x) \rightarrow \exists x Q(x)$. Now use the methods of this section to prove that if

$\exists x(P(x) \rightarrow Q(x))$ is true, then $\forall xP(x) \rightarrow \exists xQ(x)$ is true. (Note: The other direction of the equivalence is quite a bit harder to prove. See Exercise 3.5.30.)

Proof. Suppose that $\exists x(P(x) \rightarrow Q(x))$ is true. Now our goal is to prove that the statement $\forall xP(x) \rightarrow \exists xQ(x)$ is true. We then suppose that $\forall xP(x)$ is true and update our goal to proving that $\exists xQ(x)$ is true. Since $\exists x(P(x) \rightarrow Q(x))$ is true, there exists $x = x_0$ such that $P(x_0) \rightarrow Q(x_0)$ is true. Then, since $\forall xP(x)$ is true, the statement $P(x_0)$, in particular, is true. Because $P(x_0) \rightarrow Q(x_0)$ is true and $P(x_0)$ is true, we conclude that $Q(x_0)$ is true as well. In other words, we have found that there exists x such that $Q(x)$ is true. Thus, the statement $\forall xP(x) \rightarrow \exists xQ(x)$ is true, and we ultimately conclude that if $\exists x(P(x) \rightarrow Q(x))$ is true, then $\forall xP(x) \rightarrow \exists xQ(x)$ is true as well. This completes the proof. \square

3.3.2. Prove that if A and $B \setminus C$ are disjoint, then $A \cap B \subseteq C$.

Proof. \square

3.3.3. Prove that if $A \subseteq B \setminus C$ then A and C are disjoint.

Proof. \square

3.3.4. Suppose $A \subseteq \mathcal{P}(A)$. Prove that $\mathcal{P}(A) \subseteq \mathcal{P}(\mathcal{P}(A))$.

Proof. \square

3.3.5. The hypothesis of the theorem in Exercise 3.3.4 is $A \subseteq \mathcal{P}(A)$.

- (1) Can you think of a set A for which this hypothesis is true?
- (2) Can you think of another?

Proof. \square

3.3.6. Suppose x is a real number.

- (1) Prove that if $x \neq 1$ then there is a real number y such that $(y + 1)/(y - 2) = x$.
- (2) Prove that if there is a real number y such that $(y + 1)/(y - 2) = x$, then $x \neq 1$.

Proof. \square

3.3.7. Prove that for every real number x , if $x > 2$ then there is a real number y such that $y + 1/y = x$.

Proof. \square

3.3.8. Prove that if \mathcal{F} is a family of sets and $A \in \mathcal{F}$, then $A \subseteq \bigcup \mathcal{F}$.

Proof. \square

3.3.9. Prove that if \mathcal{F} is a family of sets and $A \in \mathcal{F}$, then $\bigcap \mathcal{F} \subseteq A$.

Proof. \square

3.3.10. Suppose that \mathcal{F} is a nonempty family of sets, B is a set, and for all $A \in \mathcal{F}$ that $B \subseteq A$. Prove that $B \subseteq \bigcap \mathcal{F}$.

Proof. \square

3.3.11. Suppose that \mathcal{F} is a family of sets. Prove that if $\emptyset \in \mathcal{F}$ then $\bigcap \mathcal{F} = \emptyset$.

Proof.

□

3.3.12. Suppose \mathcal{F} and \mathcal{G} are families of sets. Prove that if $\mathcal{F} \subseteq \mathcal{G}$ then $\bigcup \mathcal{F} \subseteq \bigcup \mathcal{G}$. *Note: In my digital copy of the book this exercise has a typo and asks for a proof of the incorrect statement that if $\mathcal{F} \subseteq \mathcal{G}$ then $\bigcup \mathcal{F} \subseteq \mathcal{G}$.*

Proof.

□

3.3.13. Suppose \mathcal{F} and \mathcal{G} are nonempty families of sets. Prove that if $\mathcal{F} \subseteq \mathcal{G}$ then $\bigcap \mathcal{G} \subseteq \bigcap \mathcal{F}$.

Proof.

□

3.3.14. Suppose that $\{A_i \mid i \in I\}$ is an indexed family of sets. Prove that $\bigcup_{i \in I} \mathcal{P}(A_i) \subseteq \mathcal{P}(\bigcup_{i \in I} A_i)$. (*Hint: First make sure you know what all the notation means!*)

Proof.

□

3.3.15. Suppose $\{A_i \mid i \in I\}$ is an indexed family of sets and $I \neq \emptyset$. Prove that $\bigcap_{i \in I} A_i \in \bigcap_{i \in I} \mathcal{P}(A_i)$. *Note: In my digital copy of the book this exercise has a typo and says that $I = \emptyset$.*

Proof.

□

3.3.16. Prove the converse of the statement proven in Example 3.3.5. In other words, prove that if $\mathcal{F} \subseteq \mathcal{P}(B)$ then $\bigcup \mathcal{F} \subseteq B$.

Proof.

□

3.3.17. Suppose \mathcal{F} and \mathcal{G} are nonempty families of sets, and every element of \mathcal{F} is a subset of every element of \mathcal{G} . Prove that $\bigcup \mathcal{F} \subseteq \bigcap \mathcal{G}$.

Proof.

□

3.3.18. In this problem all variables range over \mathbb{Z} , the set of all integers.

- (1) Prove that if a divides b and a divides c , then a divides $b + c$.
- (2) Prove that if ac divides bc and $c \neq 0$, then a divides b .

Proof.

□

3.3.19.

- (1) Prove that for all real numbers x and y there is a real number z such that $x + z = y - z$.
- (2) Would the statement in Part (1) be correct if “real number” were changed to “integer”? Justify your answer.

Proof.

□

3.3.20. Consider the following theorem:

Theorem 15. *For every real number x , $x^2 \geq 0$.*

What’s wrong with the following proof of the theorem?

Proof. Suppose not. Then for every for every real number x , $x^2 < 0$. In particular, plugging in $x = 3$ we would get $9 < 0$, which is clearly false. This contradiction shows that for every number x , $x^2 \geq 0$. \square

Proof. \square

3.3.21. Consider the following incorrect theorem:

Theorem 16. *If $\forall x \in A(x \neq 0)$ and $A \subseteq B$ then $\forall x \in B(x \neq 0)$.*

(1) What's wrong with the following proof of the theorem?

Proof. Suppose that $\forall x \in A(x \neq 0)$ and $A \subseteq B$. Let x be an arbitrary element of A . Since $\forall x \in A(x \neq 0)$, we can conclude that $x \neq 0$. Also, since $A \subseteq B$, $x \in B$. Since $x \in B$, $x \neq 0$, and x was arbitrary, we can conclude that $\forall x \in B(x \neq 0)$. \square

(2) Find a counterexample to the theorem. In other words, find an example of sets A and B for which the hypotheses of the theorem are true but the conclusion is false.

Proof. \square

3.3.22. Consider the following incorrect theorem:

Theorem 17. $\exists x \in \mathbb{R} \forall y \in \mathbb{R}(xy^2 = y - x)$.

What's wrong with the following proof of the theorem?

Proof. Let $x = y/(y^2 + 1)$. Then

$$y - x = y - \frac{y}{y^2 + 1} = \frac{y^3}{y^2 + 1} = \frac{y}{y^2 + 1} \cdot y^2 = xy^2.$$

\square

Proof. \square

3.3.23. Consider the following incorrect theorem:

Theorem 18. *Suppose \mathcal{F} and \mathcal{G} are families of sets. If $\bigcup \mathcal{F}$ and $\bigcup \mathcal{G}$ are disjoint, then so are \mathcal{F} and \mathcal{G} .*

(1) What's wrong with the following proof of the theorem?

Proof. Suppose $\bigcup \mathcal{F}$ and $\bigcup \mathcal{G}$ are disjoint. Suppose \mathcal{F} and \mathcal{G} are not disjoint. Then we can choose some set A such that $A \in \mathcal{F}$ and $A \in \mathcal{G}$. Since $A \in \mathcal{F}$, by Exercise 3.3.8, $A \subseteq \bigcup \mathcal{F}$, so every element of A is in $\bigcup \mathcal{F}$. Similarly, since $A \in \mathcal{G}$, every element of A is in $\bigcup \mathcal{G}$. But then every element of A is in both $\bigcup \mathcal{F}$ and $\bigcup \mathcal{G}$, and this is impossible since $\bigcup \mathcal{F}$ and $\bigcup \mathcal{G}$ are disjoint. Thus, we have reached a contradiction, so \mathcal{F} and \mathcal{G} must be disjoint. \square

(2) Find a counterexample to the theorem.

Proof. \square

3.3.24. Consider the following putative theorem:

Theorem 19. For all real numbers x and y , $x^2 + xy - 2y^2 = 0$.

- (1) What's wrong with the following proof of the theorem?

Proof. Let x and y be equal to some arbitrary real number r . Then

$$x^2 + xy - 2y^2 = r^2 + r \cdot r - 2r^2 = 0.$$

Since x and y were both arbitrary, this shows that for all real number x and y , $x^2 + xy - 2y^2 = 0$. □

- (2) Is the theorem correct? Justify your answer with either a proof or a counterexample.

Proof. □

3.3.25. Prove that for every real number x there is a real number y such that for every real number z , $yz = (x + z)^2 - (x^2 + z^2)$.

Proof. □

3.3.26.

- (1) Comparing the various rules for dealing with quantifiers in proofs, you should see a similarity between the rules for goals of the form $\forall xP(x)$ and givens of the form $\exists xP(x)$. What is this similarity? What about the rules for goals of the form $\exists xP(x)$ and givens of the form $\forall xP(x)$?
- (2) Can you think of a reason why these similarities might be expected? (*Hint: Think about how a proof by contradiction works when the goal starts with a quantifier.*)

Proof. □

3.4.1.

Proof. □

3.4.2.

Proof. □

3.4.3.

Proof. □

3.4.4.

Proof. □

3.4.5.

Proof. □

3.4.6.

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3.4.7.

Proof. □

3.4.8.

Proof.

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3.4.9.

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3.4.10.

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3.4.11.

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3.4.27.

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3.5.1.

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3.5.30.

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3.5.31.

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3.5.32.

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3.5.33.

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3.6.1.

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3.6.11.

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3.6.12.

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3.6.13.

Proof.

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3.7.1.

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3.7.10.

Proof.

□