

## Page 25

## 1.3 1.3 Propositional Equivalences

## 1.3 Propositional Equivalences

## Introduction

An important type of step used in a mathematical argument is the replacement of a statement with another statement with the same truth value. Because of this, methods that produce propositions with the same truth value as a given compound proposition are used extensively in the construction of mathematical arguments. Note that we will use the term “compound proposition” to refer to an expression formed from propositional variables using logical operators, such as  $p \wedge q$ .

We begin our discussion with a classification of compound propositions according to their possible truth values.

## DEFINITION 1

A compound proposition that is always true, no matter what the truth values of the propositional variables that occur in it, is called a *tautology*. A compound proposition that is always false is called a *contradiction*. A compound proposition that is neither a tautology nor a contradiction is called a *contingency*.

Tautologies and contradictions are often important in mathematical reasoning. Example 1 illustrates these types of compound propositions.

## EXAMPLE 1

We can construct examples of tautologies and contradictions using just one propositional variable. Consider the truth tables of  $p \vee \neg p$  and  $p \wedge \neg p$ , shown in Table 1. Because  $p \vee \neg p$  is always true, it is a tautology. Because  $p \wedge \neg p$  is always false, it is a contradiction.

TABLE 1 Examples of a Tautology and a Contradiction.			
$p$	$\neg p$	$p \vee \neg p$	$p \wedge \neg p$
T	F	T	F
F	T	T	F

Table 1  
Examples of a Tautology and a Contradiction.

$p \quad \neg p \quad p \vee \neg p \quad p \wedge \neg p$

T F    T    F

F T    T    F

## Logical Equivalences



Compound propositions that have the same truth values in all possible cases are called logically equivalent. We can also define this notion as follows.

## DEFINITION 2

The compound propositions  $p$  and  $q$  are called *logically equivalent* if  $p \leftrightarrow q$  is a tautology. The notation  $p \equiv q$  denotes that  $p$  and  $q$  are logically equivalent.

**Remark:** The symbol  $\equiv$  is not a logical connective, and  $p \equiv q$  is not a compound proposition but rather is the statement that  $p \leftrightarrow q$  is a tautology. The symbol  $\Leftrightarrow$  is sometimes used instead of  $\equiv$  to denote logical equivalence.



One way to determine whether two compound propositions are equivalent is to use a truth table. In particular, the compound propositions  $p$  and  $q$  are equivalent if and only if the columns giving their truth values agree. Example 2 illustrates this method to establish an extremely important and useful logical equivalence, namely, that of  $\neg(p \vee q)$  with  $\neg p \wedge \neg q$ . This logical equivalence is one of the two **De Morgan laws**, shown in Table 2, named after the English mathematician Augustus De Morgan, of the mid-nineteenth century.

TABLE 2 De Morgan's Laws.
$\neg(p \wedge q) \equiv \neg p \vee \neg q$
$\neg(p \vee q) \equiv \neg p \wedge \neg q$

Table 2  
De Morgan's Laws.

$$\neg(p \wedge q) \equiv \neg p \vee \neg q$$

$$\neg(p \vee q) \equiv \neg p \wedge \neg q$$

Page 26  
EXAMPLE 2

Show that  $\neg(p \vee q)$  and  $\neg p \wedge \neg q$  are logically equivalent.

Solution:

The truth tables for these compound propositions are displayed in Table 3. Because the truth values of the compound propositions  $\neg(p \vee q)$  and  $\neg p \wedge \neg q$  agree for all possible combinations of the truth values of  $p$  and  $q$ , it follows that  $\neg(p \vee q) \leftrightarrow (\neg p \wedge \neg q)$  is a tautology and that these compound propositions are logically equivalent.

TABLE 3 Truth Tables for $\neg(p \vee q)$ and $\neg p \wedge \neg q$ .						
$p$	$q$	$p \vee q$	$\neg(p \vee q)$	$\neg p$	$\neg q$	$\neg p \wedge \neg q$
T	T	T	F	F	F	F
T	F	T	F	F	T	F
F	T	T	F	T	F	F
F	F	F	T	T	T	T

Table 3

Truth Tables for  $\neg(p \vee q)$  and  $\neg p \wedge \neg q$ .

$p \quad q \quad \neg(p \vee q) \quad \neg p \quad \neg q \quad \neg p \wedge \neg q$

TT T F F F F

TF T F F T F

FT T F T F F

FF F T T T T

### EXAMPLE 3

Show that  $p \rightarrow q$  and  $\neg p \vee q$  are logically equivalent.

Solution:

We construct the truth table for these compound propositions in Table 4. Because the truth values of  $\neg p \vee q$  and  $p \rightarrow q$  agree, they are logically equivalent.

TABLE 4 Truth Tables for $\neg p \vee q$ and $p \rightarrow q$ .				
$p$	$q$	$\neg p$	$\neg p \vee q$	$p \rightarrow q$
T	T	F	T	T
T	F	F	F	F
F	T	T	T	T
F	F	T	T	T

Table 4

Truth Tables for  $\neg p \vee q$  and  $p \rightarrow q$ .

$p \quad q \quad \neg p \quad \neg p \vee q \quad p \rightarrow q$

TT F T T

TF F    F    F

FT T    T    T

FF T    T    T

We will now establish a logical equivalence of two compound propositions involving three different propositional variables  $p$ ,  $q$ , and  $r$ . To use a truth table to establish such a logical equivalence, we need eight rows, one for each possible combination of truth values of these three variables. We symbolically represent these combinations by listing the truth values of  $p$ ,  $q$ , and  $r$ , respectively. These eight combinations of truth values are TTT, TTF, TFT, TFF, FTT, FTF, FFT, and FFF; we use this order when we display the rows of the truth table. Note that we need to double the number of rows in the truth tables we use to show that compound propositions are equivalent for each additional propositional variable, so that 16 rows are needed to establish the logical equivalence of two compound propositions involving four propositional variables, and so on. In general,  $2^n$  rows are required if a compound proposition involves  $n$  propositional variables.

Page 27

## EXAMPLE 4

Show that  $p \vee (q \wedge r)$  and  $(p \vee q) \wedge (p \vee r)$  are logically equivalent. This is the *distributive law* of disjunction over conjunction.

Solution:

We construct the truth table for these compound propositions in Table 5. Because the truth values of  $p \vee (q \wedge r)$  and  $(p \vee q) \wedge (p \vee r)$  agree, these compound propositions are logically equivalent.

<b>TABLE 5 A Demonstration That <math>p \vee (q \wedge r)</math> and <math>(p \vee q) \wedge (p \vee r)</math> Are Logically Equivalent.</b>							
$p$	$q$	$r$	$q \wedge r$	$p \vee (q \wedge r)$	$p \vee q$	$p \vee r$	$(p \vee q) \wedge (p \vee r)$
T	T	T	T	T	T	T	T
T	T	F	F	T	T	T	T
T	F	T	F	T	T	T	T
T	F	F	F	T	T	T	T
F	T	T	T	T	T	T	T
F	T	F	F	F	T	F	F
F	F	T	F	F	F	T	F
F	F	F	F	F	F	F	F

Table 5

A Demonstration That  $p \vee (q \wedge r)$  and  $(p \vee q) \wedge (p \vee r)$  Are Logically Equivalent.

$p \quad q \quad r \quad q \wedge r \quad p \vee (q \wedge r) \quad p \vee q \quad p \vee r \quad (p \vee q) \wedge (p \vee r)$

TTT	T	T	T	T	T
TTF	F	T	T	T	T
TFT	F	T	T	T	T
TFF	F	T	T	T	T
FTT	T	T	T	T	T
FTF	F	F	T	F	F
FFT	F	F	F	T	F
FFF	F	F	F	F	F

Table 6 contains some important equivalences. In these equivalences, **T** denotes the compound proposition that is always true and **F** denotes the compound proposition that is always false. We also display some useful equivalences for compound propositions involving conditional statements and biconditional statements in Tables 7 and 8, respectively. The reader is asked to verify the equivalences in Tables 6–8 in the exercises.

<b>TABLE 6</b> Logical Equivalences.	
<i>Equivalence</i>	<i>Name</i>
$p \wedge \mathbf{T} \equiv p$ $p \vee \mathbf{F} \equiv p$	Identity laws
$p \vee \mathbf{T} \equiv \mathbf{T}$ $p \wedge \mathbf{F} \equiv \mathbf{F}$	Domination laws
$p \vee p \equiv p$ $p \wedge p \equiv p$	Idempotent laws
$\neg(\neg p) \equiv p$	Double negation law
$p \vee q \equiv q \vee p$ $p \wedge q \equiv q \wedge p$	Commutative laws
$(p \vee q) \vee r \equiv p \vee (q \vee r)$ $(p \wedge q) \wedge r \equiv p \wedge (q \wedge r)$	Associative laws
$p \vee (q \wedge r) \equiv (p \vee q) \wedge (p \vee r)$ $p \wedge (q \vee r) \equiv (p \wedge q) \vee (p \wedge r)$	Distributive laws
$\neg(p \wedge q) \equiv \neg p \vee \neg q$ $\neg(p \vee q) \equiv \neg p \wedge \neg q$	De Morgan's laws
$p \vee (p \wedge q) \equiv p$ $p \wedge (p \vee q) \equiv p$	Absorption laws
$p \vee \neg p \equiv \mathbf{T}$ $p \wedge \neg p \equiv \mathbf{F}$	Negation laws

Table 6  
Logical Equivalences

**Equivalence*****Name***

$p \wedge \mathbf{T} \equiv p$

Identity laws

$p \vee \mathbf{F} \equiv p$

$p \vee \mathbf{T} \equiv \mathbf{T}$

Domination laws

$p \wedge \mathbf{F} \equiv \mathbf{F}$

$p \vee p \equiv p$

Idempotent laws

$p \wedge p \equiv p$

$\neg(\neg p) \equiv p$

Double negation law

$p \vee q \equiv q \vee p$

Commutative laws

$$p \wedge q \equiv q \wedge p$$

$$(p \wedge q) \wedge r \equiv p \wedge (q \wedge r) \quad \text{Associative laws}$$

$$(p \vee q) \vee r \equiv p \vee (q \vee r)$$

$$p \wedge (q \vee r) \equiv (p \wedge q) \vee (p \wedge r) \quad \text{Distributive laws}$$

$$p \vee (q \wedge r) \equiv (p \vee q) \wedge (p \vee r)$$

$$\neg(p \wedge q) \equiv \neg p \vee \neg q \quad \text{De Morgan's laws}$$

$$\neg(p \vee q) \equiv \neg p \wedge \neg q$$

$$p \wedge (p \vee q) \equiv p \quad \text{Absorption laws}$$

$$p \vee (p \wedge q) \equiv p$$

$$p \vee \neg p \equiv \mathbf{T} \quad \text{Negation laws}$$

$$p \wedge \neg p \equiv \mathbf{F}$$

**TABLE 7** Logical Equivalences  
Involving Conditional Statements.

$$p \rightarrow q \equiv \neg p \vee q$$

$$p \rightarrow q \equiv \neg q \rightarrow \neg p$$

$$p \vee q \equiv \neg p \rightarrow q$$

$$p \wedge q \equiv \neg(p \rightarrow \neg q)$$

$$\neg(p \rightarrow q) \equiv p \wedge \neg q$$

$$(p \rightarrow q) \wedge (p \rightarrow r) \equiv p \rightarrow (q \wedge r)$$

$$(p \rightarrow r) \wedge (q \rightarrow r) \equiv (p \vee q) \rightarrow r$$

$$(p \rightarrow q) \vee (p \rightarrow r) \equiv p \rightarrow (q \vee r)$$

$$(p \rightarrow r) \vee (q \rightarrow r) \equiv (p \wedge q) \rightarrow r$$

Table 7  
Logical Equivalences Involving Conditional Statements.

$$p \rightarrow q \equiv \neg p \vee q$$

$$p \rightarrow q \equiv \neg q \rightarrow \neg p$$

$$p \vee q \equiv \neg p \rightarrow q$$

$$p \wedge q \equiv \neg (p \rightarrow \neg q)$$

$$\neg(p \rightarrow q) \equiv p \wedge \neg q$$

$$(p \rightarrow q) \wedge (p \rightarrow r) \equiv p \rightarrow (q \wedge r)$$

$$(p \rightarrow r) \wedge (q \rightarrow r) \equiv (p \vee q) \rightarrow r$$

$$(p \rightarrow q) \wedge (p \rightarrow r) \equiv p \rightarrow (q \wedge r)$$

$$(p \rightarrow r) \wedge (q \rightarrow r) \equiv (p \wedge q) \rightarrow r$$

**TABLE 8 Logical Equivalences Involving Biconditional Statements.**

$$p \leftrightarrow q \equiv (p \rightarrow q) \wedge (q \rightarrow p)$$

$$p \leftrightarrow q \equiv \neg p \leftrightarrow \neg q$$

$$p \leftrightarrow q \equiv (p \wedge q) \vee (\neg p \wedge \neg q)$$

$$\neg(p \leftrightarrow q) \equiv p \leftrightarrow \neg q$$

Table 8  
Logical Equivalences Involving Biconditional Statements.

$$p \sqcap q \equiv (p \rightarrow q) \wedge (q \rightarrow p)$$

$$p \sqcap q \equiv \neg p \sqcap \neg q$$

$$p \sqcap q \equiv (p \wedge q) \vee (\neg p \wedge \neg q)$$

$$\neg(p \sqcap q) \equiv p \sqcap \neg q$$

marginal text

The identities in Table 6 are a special case of Boolean algebra identities found in Table 5 of Section 12.1. See Table 1 in Section 2.2 for analogous set identities.

Page 28

The associative law for disjunction shows that the expression  $p \vee q \vee r$  is well defined, in the sense that it does not matter whether we first take the disjunction of  $p$  with  $q$  and then the disjunction of  $p \vee q$  with  $r$ , or if we first take the disjunction of  $q$  and  $r$  and then take the disjunction of  $p$  with  $q \vee r$ . Similarly, the expression  $p \wedge q \wedge r$  is well defined. By extending this reasoning, it follows that  $p_1 \vee p_2 \vee \cdots \vee p_n$  and



$p_1 \wedge p_2 \wedge \dots \wedge p_n$  are well defined whenever  $p_1, p_2, \dots, p_n$  are propositions.

Furthermore, note that De Morgan's laws extend to

$$\neg(p_1 \vee p_2 \vee \dots \vee p_n) \equiv (\neg p_1 \wedge \neg p_2 \wedge \dots \wedge \neg p_n)$$

and

$$\neg(p_1 \wedge p_2 \wedge \dots \wedge p_n) \equiv (\neg p_1 \vee \neg p_2 \vee \dots \vee \neg p_n).$$

We will sometimes use the notation  $\bigvee_{j=1}^n p_j$  for  $p_1 \vee p_2 \vee \dots \vee p_n$  and  $\bigwedge_{j=1}^n p_j$  for  $p_1 \wedge p_2 \wedge \dots \wedge p_n$ . Using this notation, the extended version of De Morgan's laws can be written concisely as

$\neg(\bigvee_{j=1}^n p_j) \equiv \bigwedge_{j=1}^n \neg p_j$  and  $\neg(\bigwedge_{j=1}^n p_j) \equiv \bigvee_{j=1}^n \neg p_j$ . (Methods for proving these identities will be given in Section 5.1.)

### Using De Morgan's Laws

The two logical equivalences known as De Morgan's laws are particularly important. They tell us how to negate conjunctions and how to negate disjunctions. In particular, the equivalence  $\neg(p \vee q) \equiv \neg p \wedge \neg q$  tells us that the negation of a disjunction is formed by taking the conjunction of the negations of the component propositions. Similarly, the equivalence  $\neg(p \wedge q) \equiv \neg p \vee \neg q$  tells us that the negation of a conjunction is formed by taking the disjunction of the negations of the component propositions. Example 5 illustrates the use of De Morgan's laws.

marginal text

When using De Morgan's laws, remember to change the logical connective after you negate.

Page 29

#### EXAMPLE 5

Use De Morgan's laws to express the negations of “Miguel has a cellphone and he has a laptop computer” and “Heather will go to the concert or Steve will go to the concert.”



Solution:

Let  $p$  be “Miguel has a cellphone” and  $q$  be “Miguel has a laptop computer.” Then “Miguel has a cellphone and he has a laptop computer” can be represented by  $p \wedge q$ . By the first of De Morgan's laws,  $\neg(p \wedge q)$  is equivalent to  $\neg p \vee \neg q$ . Consequently, we can express the negation of our original statement as “Miguel does not have a cellphone or he does not have a laptop computer.”

Let  $r$  be “Heather will go to the concert” and  $s$  be “Steve will go to the concert.” Then “Heather will go to the concert or Steve will go to the concert” can be represented by  $r \vee s$ . By the second of De Morgan's laws,  $\neg(r \vee s)$  is equivalent to  $\neg r \wedge \neg s$ . Consequently, we can express the negation of our original statement as “Heather will not go to the concert and Steve will not go to the concert.”

## Constructing New Logical Equivalences

The logical equivalences in Table 6, as well as any others that have been established (such as those shown in Tables 7 and 8), can be used to construct additional logical equivalences. The reason for this is that a proposition in a compound proposition can be replaced by a compound proposition that is logically equivalent to it without changing the truth value of the original compound proposition. This technique is illustrated in Examples 6–8, where we also use the fact that if  $p$  and  $q$  are logically equivalent and  $q$  and  $r$  are logically equivalent, then  $p$  and  $r$  are logically equivalent (see Exercise 56).

### EXAMPLE 6

Show that  $\neg(p \rightarrow q)$  and  $p \wedge \neg q$  are logically equivalent.



Solution:

We could use a truth table to show that these compound propositions are equivalent (similar to what we did in Example 4). Indeed, it would not be hard to do so. However, we want to illustrate how to use logical identities that we already know to establish new logical identities, something that is of practical importance for establishing equivalences of compound propositions with a large number of variables. So, we will establish this equivalence by developing a series of logical equivalences, using one of the equivalences in Table 6 at a time, starting with  $\neg(p \rightarrow q)$  and ending with  $p \wedge \neg q$ . We have the following equivalences.

$$\begin{aligned}\neg(p \rightarrow q) &\equiv \neg(\neg p \vee q) && \text{by Example 3} \\ &\equiv \neg(\neg p) \wedge \neg q && \text{by the second De Morgan law} \\ &\equiv p \wedge \neg q && \text{by the double negation law}\end{aligned}$$



AUGUSTUS DE MORGAN (1806–1871)

Augustus De Morgan was born in India, where his father was a colonel in the Indian army. De Morgan's family moved to England when he was 7 months old. He attended private schools, where in his early teens he developed a strong interest in mathematics. De Morgan studied at Trinity College, Cambridge, graduating in 1827. Although he considered medicine or law, he decided on mathematics for his career. He won a position at University College, London, in 1828, but resigned after the college dismissed a fellow professor without giving reasons. However, he resumed this position in 1836 when his successor died, remaining until 1866.

De Morgan was a noted teacher who stressed principles over techniques. His students included many famous mathematicians, including Augusta Ada, Countess of Lovelace, who was Charles Babbage's collaborator in his work on computing machines (see page 31 for biographical notes on Augusta Ada). (De Morgan cautioned the countess against studying too much mathematics, because it might interfere with her childbearing abilities!)

De Morgan was an extremely prolific writer, publishing more than 1000 articles in more than 15

periodicals. De Morgan also wrote textbooks on many subjects, including logic, probability, calculus, and algebra. In 1838 he presented what was perhaps the first clear explanation of an important proof technique known as *mathematical induction* (discussed in Section 5.1 of this text), a term he coined. In the 1840s De Morgan made fundamental contributions to the development of symbolic logic. He invented notations that helped him prove propositional equivalences, such as the laws that are named after him. In 1842 De Morgan presented what is considered to be the first precise definition of a limit and developed new tests for convergence of infinite series. De Morgan was also interested in the history of mathematics and wrote biographies of Newton and Halley.

In 1837 De Morgan married Sophia Frend, who wrote his biography in 1882. De Morgan's research, writing, and teaching left little time for his family or social life. Nevertheless, he was noted for his kindness, humor, and wide range of knowledge.

Page 30

### EXAMPLE 7

Show that  $\neg(p \vee (\neg p \wedge q))$  and  $\neg p \wedge \neg q$  are logically equivalent by developing a series of logical equivalences.

Solution:

We will use one of the equivalences in Table 6 at a time, starting with  $\neg(p \vee (\neg p \wedge q))$  and ending with  $\neg p \wedge \neg q$ . (*Note:* we could also easily establish this equivalence using a truth table.) We have the following equivalences.

$$\begin{aligned}
 \neg(p \vee (\neg p \wedge q)) &\equiv \neg p \wedge \neg(\neg p \wedge q) && \text{by the second De Morgan law} \\
 &\equiv \neg p \wedge [\neg(\neg p) \vee \neg q] && \text{by the first De Morgan law} \\
 &\equiv \neg p \wedge (p \vee \neg q) && \text{by the double negation law} \\
 &\equiv (\neg p \wedge p) \vee (\neg p \wedge \neg q) && \text{by the second distributive law} \\
 &\equiv \mathbf{F} \vee (\neg p \wedge \neg q) && \text{because } \neg p \wedge p \equiv \mathbf{F} \\
 &\equiv (\neg p \wedge \neg q) \vee \mathbf{F} && \text{by the commutative law for disjunction} \\
 &\equiv \neg p \wedge \neg q && \text{by the identity law for } \mathbf{F}
 \end{aligned}$$

Consequently  $\neg(p \vee (\neg p \wedge q))$  and  $\neg p \wedge \neg q$  are logically equivalent.

### EXAMPLE 8

Show that  $(p \wedge q) \rightarrow (p \vee q)$  is a tautology.

Solution:

To show that this statement is a tautology, we will use logical equivalences to demonstrate that it is logically equivalent to **T**. (*Note:* This could also be done using a truth table.)

$$\begin{aligned}
 (p \wedge q) \rightarrow (p \vee q) &\equiv \neg(p \wedge q) \vee (p \vee q) && \text{by Example 3} \\
 &\equiv (\neg p \vee \neg q) \vee (p \vee q) && \text{by the first De Morgan law} \\
 &\equiv (\neg p \vee p) \vee (\neg q \vee q) && \text{by the associative and commutative} \\
 &&& \text{laws for disjunction} \\
 &\equiv \mathbf{T} \vee \mathbf{T} && \text{by Example 1 and the commutative} \\
 &&& \text{law for disjunction} \\
 &\equiv \mathbf{T} && \text{by the domination law}
 \end{aligned}$$

Propositional Satisfiability

A compound proposition is satisfiable if there is an assignment of truth values to its variables that makes it true. When no such assignments exists, that is, when the compound proposition is false for all assignments of truth values to its variables, the compound proposition is **unsatisfiable**. Note that a compound proposition is unsatisfiable if and only if its negation is true for all assignments of truth values to the variables, that is, if and only if its negation is a tautology.

When we find a particular assignment of truth values that makes a compound proposition true, we have shown that it is satisfiable; such an assignment is called a **solution** of this particular satisfiability problem. However, to show that a compound proposition is unsatisfiable, we need to show that *every* assignment of truth values to its variables makes it false. Although we can always use a truth table to determine whether a compound proposition is satisfiable, it is often more efficient not to, as Example 9 demonstrates.

Page 31

### EXAMPLE 9

Determine whether each of the compound propositions  $(p \vee \neg q) \wedge (q \vee \neg R) \wedge (r \vee \neg p)$ ,  $(p \vee q \vee r) \wedge (\neg p \vee \neg q \vee \neg R)$ , and  $(p \vee \neg q) \wedge (q \vee \neg R) \wedge (r \vee \neg p) \wedge (p \vee q \vee r) \wedge (\neg p \vee \neg q \vee \neg R)$  is satisfiable.

Solution:

Instead of using truth table to solve this problem, we will reason about truth values. Note that  $(p \vee \neg q) \wedge (q \vee \neg R) \wedge (r \vee \neg p)$  is true when the three variable  $p$ ,  $q$ , and  $r$  have the same truth value (see Exercise 40 of Section 1.1). Hence, it is satisfiable as there is at least one assignment of truth values for  $p$ ,  $q$ , and  $r$  that makes it true. Similarly, note that  $(p \vee q \vee r) \wedge (\neg p \vee \neg q \vee \neg R)$  is true when at least one of  $p$ ,  $q$ , and  $r$  is true and at least one is false (see Exercise 41 of Section 1.1). Hence,  $(p \vee q \vee r) \wedge (\neg p \vee \neg q \vee \neg R)$  is satisfiable, as there is at least one assignment of truth values for  $p$ ,  $q$ , and  $r$  that makes it true.

Finally, note that for  $(p \vee \neg q) \wedge (q \vee \neg R) \wedge (r \vee \neg p) \wedge (p \vee q \vee r) \wedge (\neg p \vee \neg q \vee \neg R)$  to be true,  $(p \vee \neg q) \wedge (q \vee \neg R) \wedge (r \vee \neg p)$  and  $(p \vee q \vee r) \wedge (\neg p \vee \neg q \vee \neg R)$  must both be true. For the first to be true, the three variables must have the same truth values, and for the second to be true, at least one of three variables must be true and at least one must be false. However, these conditions are contradictory. From these observations we conclude that no assignment of truth values to  $p$ ,  $q$ , and  $r$  makes  $(p \vee \neg q) \wedge (q \vee \neg R) \wedge (r \vee \neg p) \wedge (p \vee q \vee r) \wedge (\neg p \vee \neg q \vee \neg R)$  true. Hence, it is unsatisfiable.



**AUGUSTA ADA, COUNTESS OF LOVELACE (1815–1852)** Augusta Ada was the only child from the marriage of the famous poet Lord Byron and Lady Byron, Annabella Millbanke, who separated when Ada was 1 month old, because of Lord Byron's scandalous affair with his half sister. The Lord Byron had quite a reputation, being described by one of his lovers as “mad, bad, and dangerous to know.” Lady Byron was noted for her intellect and had a passion for mathematics; she was called by Lord Byron “The Princess of Parallelograms.” Augusta was raised by her mother, who encouraged her intellectual talents especially in music and mathematics, to counter what Lady Byron considered dangerous poetic tendencies. At this time, women were not allowed to attend universities and could not join learned societies. Nevertheless, Augusta pursued her mathematical studies independently and with mathematicians, including William Frend. She was also encouraged by another female mathematician, Mary Somerville, and in 1834 at a dinner party hosted by Mary Somerville, she learned about Charles

Babbage's ideas for a calculating machine, called the Analytic Engine. In 1838 Augusta Ada married Lord King, later elevated to Earl of Lovelace. Together they had three children.

Augusta Ada continued her mathematical studies after her marriage. Charles Babbage had continued work on his Analytic Engine and lectured on this in Europe. In 1842 Babbage asked Augusta Ada to translate an article in French describing Babbage's invention. When Babbage saw her translation, he suggested she add her own notes, and the resulting work was three times the length of the original. The most complete accounts of the Analytic Engine are found in Augusta Ada's notes. In her notes, she compared the working of the Analytic Engine to that of the Jacquard loom, with Babbage's punch cards analogous to the cards used to create patterns on the loom. Furthermore, she recognized the promise of the machine as a general purpose computer much better than Babbage did. She stated that the "engine is the material expression of any indefinite function of any degree of generality and complexity." Her notes on the Analytic Engine anticipate many future developments, including computer-generated music. Augusta Ada published her writings under her initials A.A.L. concealing her identity as a woman as did many women at a time when women were not considered to be the intellectual equals of men. After 1845 she and Babbage worked toward the development of a system to predict horse races. Unfortunately, their system did not work well, leaving Augusta Ada heavily in debt at the time of her death at an unfortunately young age from uterine cancer.

In 1953 Augusta Ada's notes on the Analytic Engine were republished more than 100 years after they were written, and after they had been long forgotten. In his work in the 1950s on the capacity of computers to think (and his famous Turing Test), Alan Turing responded to Augusta Ada's statement that "The Analytic Engine has no pretensions whatever to originate anything. It can do whatever we know how to order it to perform." This "dialogue" between Turing and Augusta Ada is still the subject of controversy. Because of her fundamental contributions to computing, the programming language Ada is named in honor of the Countess of Lovelace.

Page 32

## Applications of Satisfiability

Many problems, in diverse areas such as robotics, software testing, computer-aided design, machine vision, integrated circuit design, computer networking, and genetics, can be modeled in terms of propositional satisfiability. Although most of these applications are beyond the scope of this book, we will study one application here. In particular, we will show how to use propositional satisfiability to model Sudoku puzzles.

## SUDOKU

**SUDOKU** A **Sudoku puzzle** is represented by a  $9 \times 9$  grid made up of nine  $3 \times 3$  subgrids, known as **blocks**, as shown in Figure 1. For each puzzle, some of the 81 cells, called **givens**, are assigned one of the numbers 1, 2, ..., 9, and the other cells are blank. The puzzle is solved by assigning a number to each blank cell so that every row, every column, and every one of the nine  $3 \times 3$  blocks contains each of the nine possible numbers. Note that instead of using a  $9 \times 9$  grid, Sudoku puzzles can be based on  $n^2 \times n^2$  grids, for any positive integer  $n$ , with the  $n^2 \times n^2$  grid made up of  $n^2$   $n \times n$  subgrids.





	2	9				4		
			5			1		
	4							
				4	2			
6							7	
5								
7			3					5
	1			9				
							6	

FIGURE 1

A  $9 \times 9$  Sudoku puzzle.

The popularity of Sudoku dates back to the 1980s when it was introduced in Japan. It took 20 years for Sudoku to spread to rest of the world, but by 2005, Sudoku puzzles were a worldwide craze. The name Sudoku is short for the Japanese *suuji wa dokushin ni kagiru*, which means “the digits must remain single.” The modern game of Sudoku was apparently designed in the late 1970s by an American puzzle designer. The basic ideas of Sudoku date back even further; puzzles printed in French newspapers in the 1890s were quite similar, but not identical, to modern Sudoku.

Sudoku puzzles designed for entertainment have two additional important properties. First, they have exactly one solution. Second, they can be solved using reasoning alone, that is, without resorting to searching all possible assignments of numbers to the cells. As a Sudoku puzzle is solved, entries in blank cells are successively determined by already known values. For instance, in the grid in Figure 1, the number 4 must appear in exactly one cell in the second row. How can we determine which of the seven blank cells it must appear? First, we observe that 4 cannot appear in one of the first three cells or in one of the last three cells of this row, because it already appears in another cell in the block each of these cells is in. We can also see that 4 cannot appear in the fifth cell in this row, as it already appears in the fifth column in the fourth row. This means that 4 must appear in the sixth cell of the second row.

Many strategies based on logic and mathematics have been devised for solving Sudoku puzzles (see [Da10], for example). Here, we discuss one of the ways that have been developed for solving Sudoku puzzles with the aid of a computer, which depends on modeling the puzzle as a propositional satisfiability problem. Using the model we describe, particular Sudoku puzzles can be solved using software developed to solve satisfiability problems. Currently, Sudoku puzzles can be solved in less than 10 milliseconds this way. It should be noted that there are many other approaches for solving Sudoku puzzles via computers using other techniques.

Page 33

To encode a Sudoku puzzle, let  $p(i, j, n)$  denote the proposition that is true when the number  $n$  is in the cell in the  $i$ th row and  $j$ th column. There are  $9 \times 9 \times 9 = 729$  such propositions, as  $i, j$ , and  $n$  all range from 1 to 9. For example, for the puzzle in Figure 1, the number 6 is given as the value in the fifth row and first column. Hence, we see that  $p(5, 1, 6)$  is true, but  $p(5, j, 6)$  is false for  $j = 2, 3, \dots, 9$ .

Given a particular Sudoku puzzle, we begin by encoding each of the given values. Then, we construct compound propositions that assert that every row contains every number, every column contains every number, every  $3 \times 3$  block contains every number, and each cell contains no more than one number. It follows, as the reader should verify, that the Sudoku puzzle is solved by finding an assignment of truth values to the 729 propositions  $p(i, j, n)$  with  $i, j$ , and  $n$  each ranging from 1 to 9 that makes the conjunction of all these compound propositions true. After listing these assertions, we will explain how

to construct the assertion that every row contains every integer from 1 to 9. We will leave the construction of the other assertions that every column contains every number and each of the nine  $3 \times 3$  blocks contains every number to the exercises.

- For each cell with a given value, we assert  $p(i, j, n)$  when the cell in row  $i$  and column  $j$  has the given value  $n$ .
- We assert that every row contains every number:

$$\bigwedge_{i=1}^9 \bigwedge_{n=1}^9 \bigvee_{j=1}^9 p(i, j, n)$$

- We assert that every column contains every number:

$$\bigwedge_{j=1}^9 \bigwedge_{n=1}^9 \bigvee_{i=1}^9 p(i, j, n)$$

- We assert that each of the nine  $3 \times 3$  blocks contains every number:

$$\bigwedge_{r=0}^2 \bigwedge_{s=0}^2 \bigwedge_{n=1}^9 \bigvee_{i=1}^3 \bigvee_{j=1}^3 p(3r + i, 3s + j, n)$$

- To assert that no cell contains more than one number, we take the conjunction over all values of  $n, n', i$ , and  $j$  where each variable ranges from 1 to 9 and  $n \neq n'$  of  $p(i, j, n) \rightarrow \neg p(i, j, n')$ .

marginal text



It is tricky setting up the two inner indices so that all nine cells in each square block are examined.

We now explain how to construct the assertion that every row contains every number. First, to assert that row  $i$  contains the number  $n$ , we form  $\bigvee_{j=1}^9 p(i, j, n)$ . To assert that row  $i$  contains all  $n$  numbers, we form the conjunction of these disjunctions over all nine possible values of  $n$ , giving us

$\bigwedge_{n=1}^9 \bigvee_{j=1}^9 p(i, j, n)$ . Finally, to assert that every row contains every number, we take the conjunction of  $\bigwedge_{n=1}^9 \bigvee_{j=1}^9 p(i, j, n)$  over all nine rows. This gives us  $\bigwedge_{i=1}^9 \bigwedge_{n=1}^9 \bigvee_{j=1}^9 p(i, j, n)$ . (Exercises 65 and 66 ask for explanations of the assertions that every column contains every number and that each of the nine  $3 \times 3$  blocks contains every number.)

Given a particular Sudoku puzzle, to solve this puzzle we can find a solution to the satisfiability problems that asks for a set of truth values for the 729 variables  $p(i, j, n)$  that makes the conjunction of all the listed assertions true.

## Page 34

## Solving Satisfiability Problems

A truth table can be used to determine whether a compound proposition is satisfiable, or equivalently, whether its negation is a tautology (see Exercise 60). This can be done by hand for a compound proposition with a small number of variables, but when the number of variables grows, this becomes impractical. For instance, there are  $2^{20} = 1,048,576$  rows in the truth table for a compound proposition with 20 variables. Clearly, you need a computer to help you determine, in this way, whether a compound proposition in 20 variables is satisfiable.



When many applications are modeled, questions concerning the satisfiability of compound propositions with hundreds, thousands, or millions of variables arise. Note, for example, that when there are 1000 variables, checking every one of the 21000 (a number with more than 300 decimal digits) possible combinations of truth values of the variables in a compound proposition cannot be done by a computer in even trillions of years. No procedure is known that a computer can follow to determine in a reasonable amount of time whether an arbitrary compound proposition in such a large number of variables is satisfiable. However, progress has been made developing methods for solving the satisfiability problem for the particular types of compound propositions that arise in practical applications, such as for the solution of Sudoku puzzles. Many computer programs have been developed for solving satisfiability problems which have practical use. In our discussion of the subject of algorithms in Chapter 3, we will discuss this question further. In particular, we will explain the important role the propositional satisfiability problem plays in the study of the complexity of algorithms.



HENRY MAURICE SHEFFER (1883–1964)

Henry Maurice Sheffer, born to Jewish parents in the western Ukraine, emigrated to the United States in 1892 with his parents and six siblings. He studied at the Boston Latin School before entering Harvard, where he completed his undergraduate degree in 1905, his master's in 1907, and his Ph.D. in philosophy in 1908. After holding a postdoctoral position at Harvard, Henry traveled to Europe on a fellowship. Upon returning to the United States, he became an academic nomad, spending one year each at the University of Washington, Cornell, the University of Minnesota, the University of Missouri, and City College in New York. In 1916 he returned to Harvard as a faculty member in the philosophy department. He remained at Harvard until his retirement in 1952.

Sheffer introduced what is now known as the Sheffer stroke in 1913; it became well known only after its use in the 1925 edition of Whitehead and Russell's *Principia Mathematica*. In this same edition Russell wrote that Sheffer had invented a powerful method that could be used to simplify the *Principia*. Because of this comment, Sheffer was something of a mystery man to logicians, especially because Sheffer, who published little in his career, never published the details of this method, only describing it in mimeographed notes and in a brief published abstract.

Sheffer was a dedicated teacher of mathematical logic. He liked his classes to be small and did not like auditors. When strangers appeared in his classroom, Sheffer would order them to leave, even his colleagues or distinguished guests visiting Harvard. Sheffer was barely five feet tall; he was noted for his



wit and vigor, as well as for his nervousness and irritability. Although widely liked, he was quite lonely. He is noted for a quip he spoke at his retirement: “Old professors never die, they just become emeriti.” Sheffer is also credited with coining the term “Boolean algebra” (the subject of Chapter 12 of this text). Sheffer was briefly married and lived most of his later life in small rooms at a hotel packed with his logic books and vast files of slips of paper he used to jot down his ideas. Unfortunately, Sheffer suffered from severe depression during the last two decades of his life.