Discrete Mathematics and Its Applications

SIXTH EDITION

STUDENT SOLUTION MANUAL

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Answers to Odd-Numbered Exercises

CHAPTER 1

Section 1.1

1. a) Yes, T **b)** Yes, F **c)** Yes, T **d)** Yes, F **e)** No **f)** No **3. a)** Today is not Thursday. **b)** There is pollution in New Jersey. **c)** $2 + 1 \neq 3$. **d)** The summer in Maine is not hot or it is not sunny. **5. a)** Sharks have not been spotted near the shore. **b)** Swimming at the New Jersey shore is allowed, and sharks have been spotted near the shore. **c)** Swimming at the New Jersey shore is not allowed, or sharks have been spotted near the shore. **d)** If swimming at the New Jersey shore is allowed, then sharks have not been spotted near the shore. **e)** If sharks have not been spotted near the shore, then swimming at the New Jersey shore is allowed. **f)** If swimming at the New Jersey shore is not allowed, then sharks have not been spotted near the shore. **g)** Swimming at the New Jersey shore is allowed if and only if sharks have not been spotted near the shore. **h)** Swimming at the New Jersey shore is not allowed, and either swimming at the New Jersey shore is allowed or sharks have not been spotted near the shore. (Note that we were able to incorporate the parentheses by using the word "either" in the second half of the sentence.) **7. a)** $p \wedge q$ **b)** $p \wedge \neg q$ **c)** $\neg p \wedge \neg q$ **d)** $p \vee q$ **e)** $p \rightarrow q$ **f)** $(p \vee q) \wedge (p \rightarrow \neg q)$ **g)** $q \leftrightarrow p$ **9. a)** $\neg p$ **b)** $p \wedge \neg q$ **c)** $p \rightarrow q$ **d)** $\neg p \rightarrow \neg q$ **e)** $p \rightarrow q$ **f)** $q \wedge \neg p$ **g)** $q \rightarrow p$ **11. a)** $r \wedge \neg p$ **b)** $\neg p \wedge q \wedge r$ **c)** $r \rightarrow (q \leftrightarrow \neg p)$ **d)** $\neg q \wedge \neg p \wedge r$ **e)** $(q \rightarrow (\neg r \wedge \neg p)) \wedge \neg((\neg r \wedge \neg p) \rightarrow q)$ **f)** $(p \wedge r) \rightarrow \neg q$ **13. a)** False **b)** True **c)** True **d)** True **15. a)** Exclusive or: You get only one beverage. **b)** Inclusive or: Long passwords can have any combination of symbols. **c)** Inclusive or: A student with both courses is even more qualified. **d)** Either interpretation possible; a traveler might wish to pay with a mixture of the two currencies, or the store may not allow that. **17. a)** Inclusive or: It is allowable to take discrete mathematics if you have had calculus or computer science, or both. Exclusive or: It is allowable to take discrete mathematics if you have had calculus or computer science, but not if you have had both. Most likely the inclusive or is intended. **b)** Inclusive or: You can take the rebate, or you can get a low-interest loan, or you can get both the rebate and a low-interest loan. Exclusive or: You can take the rebate, or you can get a low-interest loan, but you cannot get both the rebate and a low-interest loan. Most likely the exclusive or is intended. **c)** Inclusive or: You can order two items from column A and none from column B, or three items from column B and none from column A, or five items including two from column A and three from column B. Exclusive or: You can order two itemsfrom column A or three items from column B, but not both. Almost certainly the exclusive or is intended. **d)** Inclusive or: More than 2 feet of snow or windchill below -100, or both, will close school. Exclusive or: More than 2 feet of snow or windchill below -100, but not both, will close school. Certainly the inclusive or is intended. **19. a)** If the wind blows from the northeast, then it snows. **b)** If it stays warm for a week, then the apple trees will bloom. **c)** If the Pistons win the championship, then they beat the Lakers. **d)** If you get to the top of Long's Peak, then you must have walked 8 miles. **e)** If you are world-famous, then you will get tenure as a professor. **f)** If you drive more than 400 miles, then you will need to buy gasoline. **g)** If your guarantee is good, then you must have bought your CD player less than 90 days ago. **h)** If the water is not too cold, then Jan will go swimming. **21. a)** You buy an ice cream cone if and only if it is hot outside. **b)** You win the contest if and only if you hold the only winning ticket. **c)** You get promoted if and only if you have connections. **d)** Your mind will decay if and only if you watch television. **e)** The train runs late if and only if it is a day I take the train. **23. a)** Converse: "I will ski tomorrow only if it snows today." Contrapositive: "If I do not ski tomorrow, then it will not have snowed today." Inverse: "If it does not snow today, then I will not ski tomorrow." **b)** Converse: "If I come to class, then there will be a quiz." Contrapositive: "If I do not come to class, then there will not be a quiz." Inverse: "If there is not going to be a quiz, then I don't come to class." **c)** Converse: "A positive integer is a prime if it has no divisors other than 1 and itself." Contrapositive: "If a positive integer has a divisor other than 1 and itself, then it is not prime." Inverse: "If a positive integer is not prime, then it has a divisor other than 1 and itself." **25. a)** 2 **b)** 16 **c)** 64 **d)** 16

27. a)

p	$\neg p$	$p \wedge \neg p$
T	F	F
F	T	F

b)

p	$\neg p$	$p \wedge \neg p$
T	F	T
F	T	T

c)

p	q	$\neg q$	$p \vee \neg q$	$(p \vee \neg q) \rightarrow q$
T	T	F	T	T
T	F	T	T	F
F	T	F	F	T
F	F	T	T	F

d)

p	q	$p \vee q$	$p \wedge q$	$(p \vee q) \rightarrow (p \wedge q)$
T	T	T	T	T
T	F	T	F	F
F	T	T	F	F
F	F	F	F	T

e)

p	q	$p \to q$	$\neg q$	$\neg p$	$\neg q \to \neg p$	$(p \to q) \leftrightarrow (\neg q \to \neg p)$
T	T	T	F	F	T	T
T	F	F	T	F	F	T
F	T	T	F	T	T	T
F	F	T	T	T	T	T

f)

p	q	$p \to q$	$q \to p$	$(p \to q) \to (q \to p)$
T	T	T	T	T
T	F	F	T	T
F	T	T	F	F
F	F	T	T	T

29. For parts (a), (b), (c), (d), and (f) we have this table.

p	q	$(p \vee q) \to (p \oplus q)$	$(p \oplus q) \to (p \wedge q)$	$(p \vee q) \oplus (p \wedge q)$	$(p \leftrightarrow q) \oplus (\neg p \leftrightarrow q)$	$(p \oplus q) \to (p \oplus \neg q)$
T	T	F	T	F	T	T
T	F	T	F	T	T	F
F	T	T	F	T	T	F
F	F	T	T	F	T	T

For part (e) we have this table.

p	q	r	$\neg p$	$\neg r$	$p \leftrightarrow q$	$\neg p \leftrightarrow \neg r$	$(p \leftrightarrow q) \oplus (\neg p \leftrightarrow \neg r)$
T	T	T	F	F	T	T	F
T	T	F	F	T	T	F	T
T	F	T	F	F	F	T	T
T	F	F	F	T	F	F	F
F	T	T	T	F	F	F	F
F	T	F	T	T	F	T	T
F	F	T	T	F	T	F	T
F	F	F	T	T	T	T	F

31.

p	q	$p \to \neg q$	$\neg p \leftrightarrow q$	$(p \to q) \vee (\neg p \to q)$	$(p \to q) \wedge (\neg p \to q)$	$(p \leftrightarrow q) \vee (\neg p \leftrightarrow q)$	$(\neg p \leftrightarrow \neg q) \leftrightarrow (p \leftrightarrow q)$
T	T	F	F	T	T	T	T
T	F	T	T	T	F	T	T
F	T	T	T	T	T	T	T
F	F	T	F	T	F	T	T

33.

p	q	r	$p \to (\neg q \vee r)$	$\neg p \to (q \to r)$	$(p \to q) \vee (\neg p \to r)$	$(p \to q) \wedge (\neg p \to r)$	$(p \leftrightarrow q) \vee (\neg q \leftrightarrow r)$	$(\neg p \leftrightarrow \neg q) \leftrightarrow (q \leftrightarrow r)$
T	T	T	T	T	T	T	T	T
T	T	F	F	T	T	T	T	F
T	F	T	T	T	T	F	T	T
T	F	F	T	T	T	F	F	F
F	T	T	T	T	T	T	F	F
F	T	F	T	F	T	F	T	T
F	F	T	T	T	T	T	T	F
F	F	F	T	T	T	F	T	T

35.

p	q	r	s	$p \leftrightarrow q$	$r \leftrightarrow s$	$(p \leftrightarrow q) \leftrightarrow (r \leftrightarrow s)$
T	T	T	T	T	T	T
T	T	T	F	T	F	F
T	T	F	T	T	F	F
T	T	F	F	T	T	T
T	F	T	T	F	T	F
T	F	T	F	F	F	T
T	F	F	T	F	F	T
T	F	F	F	F	T	F
F	T	T	T	F	T	F
F	T	T	F	F	F	T
F	T	F	T	F	F	T
F	T	F	F	F	T	F
F	F	T	T	T	T	T
F	F	T	F	T	F	F
F	F	F	T	T	F	F
F	F	F	F	T	T	T

37. a) Bitwise *OR* is 111 1111; bitwise *AND* is 000 0000; bitwise *XOR* is 111 1111. **b)** Bitwise *OR* is 1111 1010; bitwise *AND* is 1010 0000; bitwise *XOR* is 0101 1010. **c)** Bitwise *OR* is 10 0111 1001; bitwise *AND* is 00 0100 0000; bitwise *XOR* is 10 0011 1001. **d)** Bitwise *OR* is 11 1111 1111; bitwise *AND* is 00 0000 0000; bitwise *XOR* is 11 1111 1111. **39.** 0.2, 0.6 **41.** 0.8, 0.6 **43. a)** The 99th statement is true and the rest are false. **b)** Statements 1 through 50 are all true and statements 51 through 100 are all false. **c)** This cannot happen; it is a paradox, showing that these cannot be statements. **45.** "If I were to ask you whether the right branch leads to the ruins, would you answer yes?" **47. a)** $q \to p$ **b)** $q \wedge \neg p$ **c)** $q \to p$ **d)** $\neg q \to \neg p$ **49.** Not consistent **51.** Consistent **53.** NEW **AND** JERSEY **AND** BEACHES, (JERSEY **AND** BEACHES) **NOT** NEW **55.** *A* is a knight and *B* is a knave. **57.** *A* is a knight and *B* is a knight. **59.** *A* is a knave and *B* is a knight. **61.** In order of decreasing salary: Fred, Maggie, Janice **63.** The detective can determine that the butler and cook are lying but cannot determine whether the gardener is telling the truth or whether the handyman is telling the truth. **65.** The Japanese man owns the zebra, and the Norwegian drinks water.

Section 1.2

1. The equivalences follow by showing that the appropriate pairs of columns of this table agree.

p	$p \wedge T$	$p \vee \mathbf{F}$	$p \wedge F$	$p \vee \mathbf{T}$	$p \vee p$	$p \wedge p$
T	T	T	F	T	T	T
F	F	F	F	T	F	F

3. a)

p	q	$p \vee q$	$q \vee p$
T	T	T	T
T	F	T	T
F	T	T	T
F	F	F	F

b)

p	q	$p \wedge q$	$q \wedge p$
T	T	T	T
T	F	F	F
F	T	F	F
F	F	F	F

5.

p	q	r	$q \vee r$	$p \wedge (q \vee r)$	$p \wedge q$	$p \wedge r$	$(p \wedge q) \vee (p \wedge r)$
T	T	T	T	T	T	T	T
T	T	F	T	T	T	F	T
T	F	T	T	T	F	T	T
T	F	F	F	F	F	F	F
F	T	T	T	F	F	F	F
F	T	F	T	F	F	F	F
F	F	T	T	F	F	F	F
F	F	F	F	F	F	F	F

7. a) Jan is not rich, or Jan is not happy. **b)** Carlos will not bicycle tomorrow, and Carlos will not run tomorrow. **c)** Mei does not walk to class, and Mei does not take the bus to class. **d)** Ibrahim is not smart, or Ibrahim is not hard working.

9. a)

p	q	$p \wedge q$	$(p \wedge q) \to p$
T	T	T	T
T	F	F	T
F	T	F	T
F	F	F	T

b)

p	q	$p \vee q$	$p \to (p \vee q)$
T	T	T	T
T	F	T	T
F	T	T	T
F	F	F	T

c)

p	q	$\neg p$	$p \to q$	$\neg p \to (p \to q)$
T	T	F	T	T
T	F	F	F	T
F	T	T	T	T
F	F	T	T	T

d)

p	q	$p \wedge q$	$p \to q$	$(p \wedge q) \to (p \to q)$
T	T	T	T	T
T	F	F	F	T
F	T	F	T	T
F	F	F	T	T

e)

p	q	$p \to q$	$\neg(p \to q)$	$\neg(p \to q) \to p$
T	T	T	F	T
T	F	F	T	T
F	T	T	F	T
F	F	T	F	T

f)

p	q	$p \to q$	$\neg(p \to q)$	$\neg q$	$\neg(p \to q) \to \neg q$
T	T	T	F	F	T
T	F	F	T	T	T
F	T	T	F	F	T
F	F	T	F	T	T

11. In each case we will show that if the hypothesis is true, then the conclusion is also. **a)** If the hypothesis $p \wedge q$ is true, then by the definition of conjunction, the conclusion p must also be true. **b)** If the hypothesis p is true, by the definition of disjunction, the conclusion $p \vee q$ is also true. **c)** If the hypothesis $\neg p$ is true, that is, if p is false, then the conclusion $p \to q$ is true. **d)** If the hypothesis $p \wedge q$ is true, then both p and q are true, so the conclusion $p \to q$ is also true. **e)** If the hypothesis $\neg(p \to q)$ is true, then $p \to q$ is false, so the conclusion p is true (and q is false). **f)** If the hypothesis $\neg(p \to q)$ is true, then $p \to q$ is false, so p is true and q is false. Hence, the conclusion $\neg q$ is true. **13.** That the fourth column of the truth table shown is identical to the first column proves part **(a)**, and that the sixth column is identical to the first column proves part **(b)**.

p	q	$p \wedge q$	$p \vee (p \wedge q)$	$p \vee q$	$p \wedge (p \vee q)$
T	T	T	T	T	T
T	F	F	T	T	T
F	T	F	F	T	F
F	F	F	F	F	F

15. It is a tautology. **17.** Each of these is true precisely when p and q have opposite truth values. **19.** The proposition $\neg p \leftrightarrow q$ is true when $\neg p$ and q have the same truth values, which means that p and q have different truth values. Similarly, $p \leftrightarrow \neg q$ is true in exactly the same cases. Therefore, these two expressions are logically equivalent. **21.** The proposition $\neg(p \leftrightarrow q)$ is true when $p \leftrightarrow q$ is false, which means that p and q have different truth values. Because this is precisely when $\neg p \leftrightarrow q$ is true, the two expressions are logically equivalent. **23.** For $(p \to r) \wedge (q \to r)$ to be false, one of the two conditional statements must be false, which happens exactly when r is false and at least one of p and q is true. But these are precisely the cases in which $p \vee q$ is true and r is false, which is precisely when $(p \vee q) \to r$ is false. Because the two propositions are false in exactly the same situations, they are logically equivalent. **25.** For $(p \to r) \vee (q \to r)$ to be false, both of the two conditional statements must be false, which happens exactly when r is false and both p and q are true. But this is precisely the case in which $p \wedge q$ is true and r is false, which is precisely when $(p \wedge q) \to r$ is false. Because the two propositions are false in exactly the same situations, they are logically equivalent. **27.** This fact was observed in Section 1 when the biconditional was first defined. Each of these is true precisely when p and q have the same truth values. **29.** The last column is all Ts.

p	q	r	$p \to q$	$q \to r$	$(p \to q) \wedge (q \to r)$	$p \to r$	$(p \to q) \wedge (q \to r) \to (p \to r)$
T	T	T	T	T	T	T	T
T	T	F	T	F	F	F	T
T	F	T	F	T	F	T	T
T	F	F	F	T	F	F	T
F	T	T	T	T	T	T	T
F	T	F	T	F	F	T	T
F	F	T	T	T	T	T	T
F	F	F	T	T	T	T	T

31. These are not logically equivalent because when p, q, and r are all false, $(p \to q) \to r$ is false, but $p \to (q \to r)$ is true. **33.** Many answers are possible. If we let r be true and p, q, and s be false, then $(p \to q) \to (r \to s)$ will be false, but $(p \to r) \to (q \to s)$ will be true. **35. a)** $p \vee \neg q \vee \neg r$ **b)** $(p \vee q \vee r) \wedge s$ **c)** $(p \wedge \mathbf{T}) \vee (q \wedge \mathbf{F})$ **37.** If we take duals twice, every $\vee$ changes to an $\wedge$ and then back to an $\vee$, every $\wedge$ changes to an $\vee$ and then back to an $\wedge$, every **T** changes to an **F** and then back to a **T**, every **F** changes to a **T** and then back to an **F**. Hence, $(s^*)^* = s$. **39.** Let p and q be equivalent compound propositions involving only the operators $\wedge$, $\vee$, and $\neg$, and **T** and **F**. Note that $\neg p$ and $\neg q$ are also equivalent. Use De Morgan's laws as many times as necessary to push negations in as far as possible within these compound propositions, changing $\vee$s to $\wedge$s, and vice versa, and changing **T**s to **F**s, and vice versa. This shows that $\neg p$ and $\neg q$ are the same as p^* and q^* except that each atomic proposition p_i within them is replaced by its negation. From this we can conclude that p^* and q^* are equivalent because $\neg p$ and $\neg q$ are. **41.** $(p \wedge q \wedge \neg r) \vee (p \wedge \neg q \wedge r) \vee (\neg p \wedge q \wedge r)$ **43.** Given a compound proposition p, form its truth table and then write down a proposition q in disjunctive normal form that is logically equivalent to p. Because q involves only $\neg$, $\wedge$, and $\vee$, this shows that these three operators form a functionally complete set. **45.** By Exercise 43, given a compound proposition p, we can write down a proposition q that is logically equivalent to p and involves only $\neg$, $\wedge$, and $\vee$. By De Morgan's law we can eliminate all the $\wedge$'s by replacing each occurrence of $p_1 \wedge p_2 \wedge \cdots \wedge p_n$ with $\neg(\neg p_1 \vee \neg p_2 \vee \cdots \vee \neg p_n)$. **47.** $\neg(p \wedge q)$ is true when either p or q, or both, are false, and is false when both p and q are true. Because this was the definition of $p \mid q$, the two compound propositions are logically equivalent. **49.** $\neg(p \vee q)$ is true when both p and q are false, and is false otherwise. Because this was the definition of $p \downarrow q$, the two are logically equivalent. **51.** $((p \downarrow p) \downarrow q) \downarrow ((p \downarrow p) \downarrow q)$ **53.** This follows immediately from the truth table or definition of $p \mid q$. **55.** 16 **57.** If the database is open, then either the system is in its initial state or the monitor is put in a closed state. **59.** All nine **61.** To determine whether c is a tautology apply an algorithm for satisfiability to $\neg c$. If the algorithm says that $\neg c$ is satisfiable, then we report that c is not a tautology, and if the algorithm says that $\neg c$ is not satisfiable, then we report that c is a tautology.

Section 1.3

1. a) T **b)** T **c)** F **3. a)** T **b)** F **c)** F **d)** F **5. a)** There is a student who spends more than 5 hours every weekday in class. **b)** Every student spends more than 5 hours every weekday in class. **c)** There is a student who does not spend more than 5 hours every weekday in class. **d)** No student spends more than 5 hours every weekday in class. **7. a)** Every comedian is funny. **b)** Every person is a funny comedian. **c)** There exists a person such that if she or he is a comedian, then she or he is funny. **d)** Some comedians are funny. **9. a)** $\exists x(P(x) \wedge Q(x))$ **b)** $\exists x(P(x) \wedge \neg Q(x))$ **c)** $\forall x(P(x) \vee Q(x))$ **d)** $\forall x \neg(P(x) \vee Q(x))$ **11. a)** T **b)** T **c)** F **d)** F **e)** T **f)** F **13. a)** True **b)** True **c)** True **d)** True **15. a)** True **b)** False **c)** True **d)** False **17. a)** $P(0) \vee P(1) \vee P(2) \vee P(3) \vee P(4)$ **b)** $P(0) \wedge P(1) \wedge P(2) \wedge P(3) \wedge P(4)$ **c)** $\neg P(0) \vee \neg P(1) \vee \neg P(2) \vee \neg P(3) \vee \neg P(4)$ **d)** $\neg P(0) \wedge \neg P(1) \wedge \neg P(2) \wedge \neg P(3) \wedge \neg P(4)$ **e)** $\neg(P(0) \vee P(1) \vee P(2) \vee P(3) \vee P(4))$ **f)** $\neg(P(0) \wedge P(1) \wedge P(2) \wedge P(3) \wedge P(4))$ **19. a)** $P(1) \vee P(2) \vee P(3) \vee P(4) \vee P(5)$ **b)** $P(1) \wedge P(2) \wedge P(3) \wedge P(4) \wedge P(5)$ **c)** $\neg(P(1) \vee P(2) \vee P(3) \vee P(4) \vee P(5))$ **d)** $\neg(P(1) \wedge P(2) \wedge P(3) \wedge P(4) \wedge P(5))$ **e)** $(P(1) \wedge P(2) \wedge P(4) \wedge P(5)) \vee (\neg P(1) \vee \neg P(2) \vee \neg P(3) \vee \neg P(4) \vee \neg P(5))$ **21.** Many answers are possible. **a)** All students in your discrete mathematics class; all students in the world **b)** All United States senators; all college football players **c)** George W. Bush and Jeb Bush; all politicians in the United States **d)** Bill Clinton and George W. Bush; all politicians in the United States **23.** Let $C(x)$ be the propositional function "x is in your class." **a)** $\exists x H(x)$ and $\exists x(C(x) \wedge H(x))$, where $H(x)$ is "x can speak Hindi" **b)** $\forall x F(x)$ and $\forall x(C(x) \rightarrow F(x))$, where $F(x)$ is "x is friendly" **c)** $\exists x \neg B(x)$ and $\exists x(C(x) \wedge \neg B(x))$, where $B(x)$ is "x was born in California" **d)** $\exists x M(x)$ and $\exists x(C(x) \wedge M(x))$, where $M(x)$ is "x has been in a movie" **e)** $\forall x \neg L(x)$ and $\forall x(C(x) \rightarrow \neg L(x))$, where $L(x)$ is "x has taken a course in logic programming" **25.** Let $P(x)$ be "x is perfect"; let $F(x)$ be "x is your friend"; and let the domain be all people. **a)** $\forall x \neg P(x)$ **b)** $\neg \forall x\, P(x)$ **c)** $\forall x(F(x) \rightarrow P(x))$ **d)** $\exists x(F(x) \wedge P(x))$ **e)** $\forall x(F(x) \wedge P(x))$ or $(\forall x\, F(x)) \wedge (\forall x\, P(x))$ **f)** $(\neg \forall x\, F(x)) \vee (\exists x\, \neg P(x))$ **27.** Let $Y(x)$ be the propositional function that x is in your school or class, as appropriate. **a)** If we let $V(x)$ be "x has lived in Vietnam," then we have $\exists x V(x)$ if the domain is just your schoolmates, or $\exists x(Y(x) \wedge V(x))$ if the domain is all people. If we let $D(x, y)$ mean that person x has lived in country y, then we can rewrite this last one as $\exists x(Y(x) \wedge D(x, \text{Vietnam}))$. **b)** If we let $H(x)$ be "x can speak Hindi," then we have $\exists x \neg H(x)$ if the domain is just your schoolmates, or $\exists x(Y(x) \wedge \neg H(x))$ if the domain is all people. If we let $S(x, y)$ mean that person x can speak language y, then we can rewrite this last one as $\exists x(Y(x) \wedge \neg S(x, \text{Hindi}))$. **c)** If we let $J(x)$, $P(x)$, and $C(x)$ be the propositional functions asserting x's knowledge of Java, Prolog, and C++, respectively, then we have $\exists x(J(x) \wedge P(x) \wedge C(x))$ if the domain is just your schoolmates, or $\exists x(Y(x) \wedge J(x) \wedge P(x) \wedge C(x))$ if the domain is all people. If we let $K(x, y)$ mean that person x knows programming language y, then we can rewrite this last one as $\exists x(Y(x) \wedge K(x, \text{Java}) \wedge K(x, \text{Prolog}) \wedge K(x, \text{C++}))$. **d)** If we let $T(x)$ be "x enjoys Thai food," then we have $\forall x\, T(x)$ if the domain is just your classmates, or $\forall x(Y(x) \rightarrow T(x))$ if the domain is all people. If we let $E(x, y)$ mean that person x enjoys food of type y, then we can rewrite this last one as $\forall x(Y(x) \rightarrow E(x, \text{Thai}))$. **e)** If we let $H(x)$ be "x plays hockey," then we have $\exists x \neg H(x)$ if the domain is just your classmates, or $\exists x(Y(x) \wedge \neg H(x))$ if the domain is all people. If we let $P(x, y)$ mean that person x plays game y, then we can rewrite this last one as $\exists x(Y(x) \wedge \neg P(x, \text{hockey}))$. **29.** Let $T(x)$ mean that x is a tautology and $C(x)$ mean that x is a contradiction. **a)** $\exists x\, T(x)$ **b)** $\forall x(C(x) \rightarrow T(\neg x))$ **c)** $\exists x \exists y(\neg T(x) \wedge \neg C(x) \wedge \neg T(y) \wedge \neg C(y) \wedge T(x \vee y))$ **d)** $\forall x \forall y((T(x) \wedge T(y)) \rightarrow T(x \wedge y))$ **31. a)** $Q(0,0,0) \wedge Q(0,1,0)$ **b)** $Q(0,1,1) \vee Q(1,1,1) \vee Q(2,1,1)$ **c)** $\neg Q(0,0,0) \vee \neg Q(0,0,1)$ **d)** $\neg Q(0,0,1) \vee \neg Q(1,0,1) \vee \neg Q(2,0,1)$ **33. a)** Let $T(x)$ be the predicate that x can learn new tricks, and let the domain be old dogs. Original is $\exists x\, T(x)$. Negation is $\forall x \neg T(x)$: "No old dogs can learn new tricks." **b)** Let $C(x)$ be the predicate that x knows calculus, and let the domain be rabbits. Original is $\neg \exists x\, C(x)$. Negation is $\exists x\, C(x)$: "There is a rabbit that knows calculus." **c)** Let $F(x)$ be the predicate that x can fly, and let the domain be birds. Original is $\forall x\, F(x)$. Negation is $\exists x \neg F(x)$: "There is a bird who cannot fly." **d)** Let $T(x)$ be the predicate that x can talk, and let the domain be dogs. Original is $\neg \exists x\, T(x)$. Negation is $\exists x\, T(x)$: "There is a dog that talks." **e)** Let $F(x)$ and $R(x)$ be the predicates that x knows French and knows Russian, respectively, and let the domain be people in this class. Original is $\neg \exists x(F(x) \wedge R(x))$. Negation is $\exists x(F(x) \wedge R(x))$: "There is someone in this class who knows French and Russian." **35. a)** There is no counterexample. **b)** $x = 0$ **c)** $x = 2$ **37. a)** $\forall x((F(x, 25{,}000) \vee S(x, 25)) \rightarrow E(x))$, where $E(x)$ is "Person x qualifies as an elite flyer in a given year," $F(x, y)$ is "Person x flies more than y miles in a given year," and $S(x, y)$ is "Person x takes more than y flights in a given year" **b)** $\forall x(((M(x) \wedge T(x, 3)) \vee (\neg M(x) \wedge T(x, 3.5))) \rightarrow Q(x))$, where $Q(x)$ is "Person x qualifies for the marathon," $M(x)$ is "Person x is a man," and $T(x, y)$ is "Person x has run the marathon in less than y hours" **c)** $M \rightarrow ((H(60) \vee (H(45) \wedge T)) \wedge \forall y\, G(\text{B}, y))$, where M is the proposition "The student received a masters degree," $H(x)$ is "The student took at least x course hours," T is the proposition "The student wrote a thesis," and $G(x, y)$ is "The person got grade x or higher in course y" **d)** $\exists x\, ((T(x, 21) \wedge G(x, 4.0))$, where $T(x, y)$ is "Person x took more than y credit hours" and $G(x, p)$ is "Person x earned grade point average p" (we assume that we are talking about one given semester)

39. a) If there is a printer that is both out of service and busy, then some job has been lost. **b)** If every printer is busy, then there is a job in the queue. **c)** If there is a job that is both queued and lost, then some printer is out of service. **d)** If every printer is busy and every job is queued, then some job is lost. **41. a)** $(\exists x\ F(x, 10)) \to \exists x\ S(x)$, where $F(x, y)$ is "Disk x has more than y kilobytes of free space," and $S(x)$ is "Mail message x can be saved" **b)** $(\exists x\ A(x)) \to \forall x(Q(x) \to T(x))$, where $A(x)$ is "Alert x is active," $Q(x)$ is "Message x is queued," and $T(x)$ is "Message x is transmitted" **c)** $\forall x((x \neq \text{main console}) \to T(x))$, where $T(x)$ is "The diagnostic monitor tracks the status of system x" **d)** $\forall x(\neg L(x) \to B(x))$, where $L(x)$ is "The host of the conference call put participant x on a special list" and $B(x)$ is "Participant x was billed" **43.** They are not equivalent. Let $P(x)$ be any propositional function that is sometimes true and sometimes false, and let $Q(x)$ be any propositional function that is always false. Then $\forall x(P(x) \to Q(x))$ is false but $\forall x P(x) \to \forall x Q(x)$ is true. **45.** Both statements are true precisely when at least one of $P(x)$ and $Q(x)$ is true for at least one value of x in the domain. **47. a)** If A is true, then both sides are logically equivalent to $\forall x P(x)$. If A is false, the left-hand side is clearly false. Furthermore, for every x, $P(x) \wedge A$ is false, so the right-hand side is false. Hence, the two sides are logically equivalent. **b)** If A is true, then both sides are logically equivalent to $\exists x\ P(x)$. If A is false, the left-hand side is clearly false. Furthermore, for every x, $P(x) \wedge A$ is false, so $\exists x(P(x) \wedge A)$ is false. Hence, the two sides are logically equivalent. **49.** We can establish these equivalences by arguing that one side is true if and only if the other side is true. **a)** Suppose that A is true. Then for each x, $P(x) \to A$ is true; therefore the left-hand side is always true in this case. By similar reasoning the right-hand side is always true in this case. Therefore, the two propositions are logically equivalent when A is true. On the other hand, suppose that A is false. There are two subcases. If $P(x)$ is false for every x, then $P(x) \to A$ is vacuously true, so the left-hand side is vacuously true. The same reasoning shows that the right-hand side is also true, because in this subcase $\exists x P(x)$ is false. For the second subcase, suppose that $P(x)$ is true for some x. Then for that x, $P(x) \to A$ is false, so the left-hand side is false. The right-hand side is also false, because in this subcase $\exists x P(x)$ is true but A is false. Thus in all cases, the two propositions have the same truth value. **b)** If A is true, then both sides are trivially true, because the conditional statements have true conclusions. If A is false, then there are two subcases. If $P(x)$ is false for some x, then $P(x) \to A$ is vacuously true for that x, so the left-hand side is true. The same reasoning shows that the right-hand side is true, because in this subcase $\forall x P(x)$ is false. For the second subcase, suppose that $P(x)$ is true for every x. Then for every x, $P(x) \to A$ is false, so the left-hand side is false (there is no x making the conditional statement true). The right-hand side is also false, because it is a conditional statement with a true hypothesis and a false conclusion. Thus in all cases, the two propositions have the same truth value. **51.** To show these are not logically equivalent, let $P(x)$ be the statement "x is positive," and let $Q(x)$ be the statement "x is negative" with domain the set of integers. Then $\exists x\ P(x) \wedge \exists x\ Q(x)$ is true, but $\exists x(P(x) \wedge Q(x))$ is false. **53. a)** True **b)** False, unless the domain consists of just one element **c)** True **55. a)** Yes **b)** No **c)** juana, kiko **d)** math273, cs301 **e)** juana, kiko **57.** `sibling(X,Y) :- mother(M,X), mother(M,Y), father(F,X), father(F,Y)` **59. a)** $\forall x(P(x) \to \neg Q(x))$ **b)** $\forall x(Q(x) \to R(x))$ **c)** $\forall x(P(x) \to \neg R(x))$ **d)** The conclusion does not follow. There may be vain professors, because the premises do not rule out the possibility that there are other vain people besides ignorant ones. **61. a)** $\forall x(P(x) \to \neg Q(x))$ **b)** $\forall x(R(x) \to \neg S(x))$ **c)** $\forall x(\neg Q(x) \to S(x))$ **d)** $\forall x(P(x) \to \neg R(x))$ **e)** The conclusion follows. Suppose x is a baby. Then by the first premise, x is illogical, so by the third premise, x is despised. The second premise says that if x could manage a crocodile, then x would not be despised. Therefore, x cannot manage a crocodile.

Section 1.4

1. a) For every real number x there exists a real number y such that x is less than y. **b)** For every real number x and real number y, if x and y are both nonnegative, then their product is nonnegative. **c)** For every real number x and real number y, there exists a real number z such that $xy = z$. **3. a)** There is some student in your class who has sent a message to some student in your class. **b)** There is some student in your class who has sent a message to every student in your class. **c)** Every student in your class has sent a message to at least one student in your class. **d)** There is a student in your class who has been sent a message by every student in your class. **e)** Every student in your class has been sent a message from at least one student in your class. **f)** Every student in the class has sent a message to every student in the class. **5. a)** Sarah Smith has visited www.att.com. **b)** At least one person has visited www.imdb.org. **c)** Jose Orez has visited at least one website. **d)** There is a website that both Ashok Puri and Cindy Yoon have visited. **e)** There is a person besides David Belcher who has visited all the websites that David Belcher has visited. **f)** There are two different people who have visited exactly the same websites. **7. a)** Abdallah Hussein does not like Japanese cuisine. **b)** Some student at your school likes Korean cuisine, and everyone at your school likes Mexican cuisine. **c)** There is some cuisine that either Monique Arsenault or Jay Johnson likes. **d)** For every pair of distinct students at your school, there is some cuisine that at least one them does not like. **e)** There are two students at your school who like exactly the same set of cuisines. **f)** For every pair of students at your school, there is some cuisine about which they have the same opinion (either they both like it or they both do not like it). **9. a)** $\forall x L(x, \text{Jerry})$ **b)** $\forall x \exists y L(x, y)$ **c)** $\exists y \forall x L(x, y)$ **d)** $\forall x \exists y \neg L(x, y)$ **e)** $\exists x \neg L(\text{Lydia}, x)$ **f)** $\exists x \forall y \neg L(y, x)$ **g)** $\exists x(\forall y L(y, x) \wedge \forall z((\forall w L(w, z)) \to z = x))$ **h)** $\exists x \exists y(x \neq y \wedge L(\text{Lynn}, x) \wedge L(\text{Lynn}, y) \wedge \forall z(L(\text{Lynn}, z) \to (z = x \vee z = y)))$ **i)** $\forall x L(x, x)$ **j)** $\exists x \forall y (L(x,y) \leftrightarrow x = y)$ **11. a)** $A(\text{Lois, Professor Michaels})$

b) $\forall x(S(x) \to A(x, \text{Professor Gross}))$ **c)** $\forall x(F(x) \to (A(x, \text{Professor Miller}) \vee A(\text{Professor Miller}, x)))$ **d)** $\exists x(S(x) \wedge \forall y(F(y) \to \neg A(x, y)))$ **e)** $\exists x(F(x) \wedge \forall y(S(y) \to \neg A(y, x)))$ **f)** $\forall y(F(y) \to \exists x(S(x) \vee A(x, y)))$ **g)** $\exists x(F(x) \wedge \forall y((F(y) \wedge (y \neq x)) \to A(x, y)))$ **h)** $\exists x(S(x) \wedge \forall y(F(y) \to \neg A(y, x)))$ **13. a)** $\neg M(\text{Chou, Koko})$ **b)** $\neg M(\text{Arlene, Sarah}) \wedge \neg T(\text{Arlene, Sarah})$ **c)** $\neg M$ (Deborah, Jose) **d)** $\forall x M(x, \text{Ken})$ **e)** $\forall x \neg T(x, \text{Nina})$ **f)** $\forall x(T\text{-}x, \text{Avi}) \vee M(x, \text{Avi}))$ **g)** $\exists x \forall y(y \neq x \to M(x, y))$ **h)** $\exists x \forall y(y \neq x \to (M(x, y) \vee T(x, y)))$ **i)** $\exists x \exists y(x \neq y \wedge M(x, y) \wedge M(y, x))$ **j)** $\exists x M(x, x)$ **k)** $\exists x \forall y(x \neq y \to (\neg M(x, y) \wedge \neg T(y, x)))$ **l)** $\forall x(\exists y(x \neq y \wedge (M(y, x) \vee T(y, x))))$ **m)** $\exists x \exists y(x \neq y \wedge M(x, y) \wedge T(y, x))$ **n)** $\exists x \exists y(x \neq y \wedge \forall z((z \neq x \wedge z \neq y) \to (M(x, z) \vee M(y, z) \vee T(x, z) \vee T(y, z))))$ **15. a)** $\forall x P(x)$, where $P(x)$ is "x needs a course in discrete mathematics" and the domain consists of all computer science students **b)** $\exists x P(x)$, where $P(x)$ is "x owns a personal computer" and the domain consists of all students in this class **c)** $\forall x \exists y P(x, y)$, where $P(x, y)$ is "x has taken y," the domain for x consists of all students in this class, and the domain for y consists of all computer science classes **d)** $\exists x \exists y P(x, y)$, where $P(x, y)$ and domains are the same as in part (c) **e)** $\forall x \forall y P(x, y)$, where $P(x, y)$ is "x has been in y," the domain for x consists of all students in this class, and the domain for y consists of all buildings on campus **f)** $\exists x \exists y \forall z(P(z, y) \to Q(x, z))$, where $P(z, y)$ is "z is in y" and $Q(x, z)$ is "x has been in z"; the domain for x consists of all students in the class, the domain for y consists of all buildings on campus, and the domain of z consists of all rooms. **g)** $\forall x \forall y \exists z(P(z, y) \wedge Q(x, z))$, with same environment as in part (f) **17. a)** $\forall u \exists m(A(u, m) \wedge \forall n(n \neq m \to \neg A(u, n)))$, where $A(u, m)$ means that user u has access to mailbox m **b)** $\exists p \forall e(H(e) \wedge S(p, \text{running})) \to S$ (kernel, working correctly), where $H(e)$ means that error condition e is in effect and $S(x, y)$ means that the status of x is y **c)** $\forall u \forall s(E(s, .\text{edu}) \to A(u, s))$, where $E(s, x)$ means that website s has extension x, and $A(u, s)$ means that user u can access website s **d)** $\exists x \exists y(x \neq y \wedge \forall z((\forall s\, M(z, s)) \leftrightarrow (z = x \vee z = y)))$, where $M(a, b)$ means that system a monitors remote server b **19. a)** $\forall x \forall y((x < 0) \wedge (y < 0) \to (x + y < 0))$ **b)** $\neg \forall x \forall y((x > 0) \wedge (y > 0) \to (x - y > 0))$ **c)** $\forall x \forall y(x^2 + y^2 \geq (x + y)^2)$ **d)** $\forall x \forall y(|xy| = |x||y|)$ **21.** $\forall x \exists a \exists b \exists c \exists d((x > 0) \to x = a^2 + b^2 + c^2 + d^2)$, where the domain consists of all integers **23. a)** $\forall x\, \forall y((x < 0) \wedge (y < 0) \to (xy > 0))$ **b)** $\forall x(x - x = 0)$ **c)** $\forall x \exists a \exists b(a \neq b \wedge \forall c(c^2 = x \leftrightarrow (c = a \vee c = b)))$ **d)** $\forall x((x < 0) \to \neg \exists y(x = y^2))$ **25. a)** There is a multiplicative identity for the real numbers. **b)** The product of two negative real numbers is always a positive real number. **c)** There exist real numbers x and y such that x^2 exceeds y but x is less than y. **d)** The real numbers are closed under the operation of addition. **27. a)** True **b)** True **c)** True **d)** True **e)** True **f)** False **g)** False **h)** True **i)** False **29. a)** $P(1,1) \wedge P(1,2) \wedge P(1,3) \wedge P(2,1) \wedge P(2,2) \wedge P(2,3) \wedge P(3,1) \wedge P(3,2) \wedge P(3,3)$ **b)** $P(1,1) \vee P(1,2) \vee P(1,3) \vee P(2,1) \vee P(2,2) \vee P(2,3) \vee P(3,1) \vee P(3,2) \vee P(3,3)$ **c)** $(P(1,1) \wedge P(1,2) \wedge P(1,3)) \vee (P(2,1) \wedge P(2,2) \wedge P(2,3)) \vee (P(3,1) \wedge P(3,2) \wedge P(3,3))$ **d)** $(P(1,1) \vee P(2,1) \vee P(3,1)) \wedge (P(1,2) \vee P(2,2) \vee P(3,2)) \wedge (P(1,3) \vee P(2,3) \vee P(3,3))$ **31. a)** $\exists x \forall y \exists z \neg T(x, y, z)$ **b)** $\exists x \forall y \neg P(x, y) \wedge \exists x \forall y \neg Q(x, y)$ **c)** $\exists x \forall y(\neg P(x, y) \vee \forall z \neg R(x, y, z))$ **d)** $\exists x \forall y(P(x, y) \wedge \neg Q(x, y))$ **33. a)** $\exists x \exists y \neg P(x, y)$ **b)** $\exists y \forall x \neg P(x, y)$ **c)** $\exists y \exists x(\neg P(x, y) \wedge \neg Q(x, y))$ **d)** $(\forall x \forall y P(x, y)) \vee (\exists x \exists y \neg Q(x, y))$ **e)** $\exists x(\forall y \exists z \neg P(x, y, z) \vee \forall z \exists y \neg P(x, y, z))$ **35.** Any domain with four or more members makes the statement true; any domain with three or fewer members makes the statement false. **37. a)** There is someone in this class such that for every two different math courses, these are not the two and only two math courses this person has taken. **b)** Every person has either visited Libya or has not visited a country other than Libya. **c)** Someone has climbed every mountain in the Himalayas. **d)** There is someone who has neither been in a movie with Kevin Bacon nor has been in a movie with someone who has been in a movie with Kevin Bacon. **39. a)** $x = 2,\ y = -2$ **b)** $x = -4$ **c)** $x = 17, y = -1$ **41.** $\forall x\, \forall y\, \forall z((x \cdot y) \cdot z = x \cdot (y \cdot z))$ **43.** $\forall m \forall b(m \neq 0 \to \exists x(mx + b = 0 \wedge \forall w(mw + b = 0 \to w = x)))$ **45. a)** True **b)** False **c)** True **47.** $\neg(\exists x \forall y P(x, y)) \leftrightarrow \forall x(\neg \forall y P(x, y)) \leftrightarrow \forall x \exists y \neg P(x, y)$ **49. a)** Suppose that $\forall x P(x) \wedge \exists x Q(x)$ is true. Then $P(x)$ is true for all x and there is an element y for which $Q(y)$ is true. Because $P(x) \wedge Q(y)$ is true for all x and there is a y for which $Q(y)$ is true, $\forall x \exists y(P(x) \wedge Q(y))$ is true. Conversely, suppose that the second proposition is true. Let x be an element in the domain. There is a y such that $Q(y)$ is true, so $\exists x Q(x)$ is true. Because $\forall x P(x)$ is also true, it follows that the first proposition is true. **b)** Suppose that $\forall x P(x) \vee \exists x Q(x)$ is true. Then either $P(x)$ is true for all x, or there exists a y for which $Q(y)$ is true. In the former case, $P(x) \vee Q(y)$ is true for all x, so $\forall x \exists y(P(x) \vee Q(y))$ is true. In the latter case, $Q(y)$ is true for a particular y, so $P(x) \vee Q(y)$ is true for all x and consequently $\forall x \exists y(P(x) \vee Q(y))$ is true. Conversely, suppose that the second proposition is true. If $P(x)$ is true for all x, then the first proposition is true. If not, $P(x)$ is false for some x, and for this x there must be a y such that $P(x) \vee Q(y)$ is true. Hence, $Q(y)$ must be true, so $\exists y Q(y)$ is true. It follows that the first proposition must hold. **51.** We will show how an expression can be put into prenex normal form (PNF) if subexpressions in it can be put into PNF. Then, working from the inside out, any expression can be put in PNF. (To formalize the argument, it is necessary to use the method of structural induction that will be discussed in Section 4.3.) By Exercise 45 of Section 1.2, we can assume that the proposition uses only $\vee$ and $\neg$ as logical connectives. Now note that any proposition with no quantifiers is already in PNF. (This is the basis case of the argument.) Now suppose that the proposition is of the form $Qx P(x)$, where Q is a quantifier. Because $P(x)$ is a shorter expression than the original proposition, we can put it into PNF. Then Qx followed by this PNF is again in PNF and is equivalent to the original proposition. Next, suppose that the proposition is of the form $\neg P$. If P is already in PNF, we slide the negation sign past all the quantifiers using the equivalences in Table 2 in Section 1.3. Finally, assume that proposition is of the form $P \vee Q$, where each of P and Q is in PNF. If only one of P and Q has quantifiers, then we can use Exercise 46 in Section 1.3 to bring the quantifier in front of both. If both P and Q have quantifiers, we can use Exercise 45 in Section 1.3, Exercise 48, or part (b) of Exercise 49 to rewrite $P \vee Q$ with two quantifiers preceding the disjunction of a proposition of the form $R \vee S$, and then put $R \vee S$ into PNF.

Section 1.5

1. Modus ponens; valid; the conclusion is true, because the hypotheses are true. **3. a)** Addition **b)** Simplification **c)** Modus ponens **d)** Modus tollens **e)** Hypothetical syllogism **5.** Let w be "Randy works hard," let d be "Randy is a dull boy," and let j be "Randy will get the job." The hypotheses are w, $w \to d$, and $d \to \neg j$. Using modus ponens and the first two hypotheses, d follows. Using modus ponens and the last hypothesis, $\neg j$, which is the desired conclusion, "Randy will not get the job," follows. **7.** Universal instantiation is used to conclude that "If Socrates is a man, then Socrates is mortal." Modus ponens is then used to conclude that Socrates is mortal. **9. a)** Valid conclusions are "I did not take Tuesday off," "I took Thursday off," "It rained on Thursday." **b)** "I did not eat spicy foods and it did not thunder" is a valid conclusion. **c)** "I am clever" is a valid conclusion. **d)** "Ralph is not a CS major" is a valid conclusion. **e)** "That you buy lots of stuff is good for the U.S. and is good for you" is a valid conclusion. **f)** "Mice gnaw their food" and "Rabbits are not rodents" are valid conclusions. **11.** Suppose that $p_1, p_2, \ldots, p_n$ are true. We want to establish that $q \to r$ is true. If q is false, then we are done, vacuously. Otherwise, q is true, so by the validity of the given argument form (that whenever $p_1, p_2, \ldots, p_n, q$ are true, then r must be true), we know that r is true. **13. a)** Let $c(x)$ be "x is in this class," $j(x)$ be "x knows how to write programs in JAVA," and $h(x)$ be "x can get a high-paying job." The premises are $c(\text{Doug})$, $j(\text{Doug})$, $\forall x(j(x) \to h(x))$. Using universal instantiation and the last premise, $j(\text{Doug}) \to h(\text{Doug})$ follows. Applying modus ponens to this conclusion and the second premise, $h(\text{Doug})$ follows. Using conjunction and the first premise, $c(\text{Doug}) \wedge h(\text{Doug})$ follows. Finally, using existential generalization, the desired conclusion, $\exists x(c(x) \wedge h(x))$ follows. **b)** Let $c(x)$ be "x is in this class," $w(x)$ be "x enjoys whale watching," and $p(x)$ be "x cares about ocean pollution." The premises are $\exists x(c(x) \wedge w(x))$ and $\forall x(w(x) \to p(x))$. From the first premise, $c(y) \wedge w(y)$ for a particular person y. Using simplification, $w(y)$ follows. Using the second premise and universal instantiation, $w(y) \to p(y)$ follows. Using modus ponens, $p(y)$ follows, and by conjunction, $c(y) \wedge p(y)$ follows. Finally, by existential generalization, the desired conclusion, $\exists x(c(x) \wedge p(x))$, follows. **c)** Let $c(x)$ be "x is in this class," $p(x)$ be "x owns a PC," and $w(x)$ be "x can use a word-processing program." The premises are $c(\text{Zeke})$, $\forall x(c(x) \to p(x))$, and $\forall x(p(x) \to w(x))$. Using the second premise and universal instantiation, $c(\text{Zeke}) \to p(\text{Zeke})$ follows. Using the first premise and modus ponens, $p(\text{Zeke})$ follows. Using the third premise and universal instantiation, $p(\text{Zeke}) \to w(\text{Zeke})$ follows. Finally, using modus ponens, $w(\text{Zeke})$, the desired conclusion, follows. **d)** Let $j(x)$ be "x is in New Jersey," $f(x)$ be "x lives within 50 miles of the ocean," and $s(x)$ be "x has seen the ocean." The premises are $\forall x(j(x) \to f(x))$ and $\exists x(j(x) \wedge \neg s(x))$. The second hypothesis and existential instantiation imply that $j(y) \wedge \neg s(y)$ for a particular person y. By simplification, $j(y)$ for this person y. Using universal instantiation and the first premise, $j(y) \to f(y)$, and by modus ponens, $f(y)$ follows. By simplification, $\neg s(y)$ follows from $j(y) \wedge \neg s(y)$. So $f(y) \wedge \neg s(y)$ follows by conjunction. Finally, the desired conclusion, $\exists x(f(x) \wedge \neg s(x))$, follows by existential generalization. **15. a)** Correct, using universal instantiation and modus ponens **b)** Invalid; fallacy of affirming the conclusion **c)** Invalid; fallacy of denying the hypothesis **d)** Correct, using universal instantiation and modus tollens **17.** We know that *some* x exists that makes $H(x)$ true, but we cannot conclude that Lola is one such x. **19. a)** Fallacy of affirming the conclusion **b)** Fallacy of begging the question **c)** Valid argument using modus tollens **d)** Fallacy of denying the hypothesis **21.** By the second premise, there is some lion that does not drink coffee. Let Leo be such a creature. By simplification we know that Leo is a lion. By modus ponens we know from the first premise that Leo is fierce. Hence, Leo is fierce and does not drink coffee. By the definition of the existential quantifier, there exist fierce creatures that do not drink coffee, that is, some fierce creatures do not drink coffee. **23.** The error occurs in step (5), because we cannot assume, as is being done here, that the c that makes P true is the same as the c that makes Q true. **25.** We are given the premises $\forall x(P(x) \to Q(x))$ and $\neg Q(a)$. We want to show $\neg P(a)$. Suppose, to the contrary, that $\neg P(a)$ is not true. Then $P(a)$ is true. Therefore by universal modus ponens, we have $Q(a)$. But this contradicts the given premise $\neg Q(a)$. Therefore our supposition must have been wrong, and so $\neg P(a)$ is true, as desired.

27.

Step	Reason
1. $\forall x(P(x) \wedge R(x))$	Premise
2. $P(a) \wedge R(a)$	Universal instantiation from (1)
3. $P(a)$	Simplification from (2)
4. $\forall x(P(x) \to (Q(x) \wedge S(x)))$	Premise
5. $Q(a) \wedge S(a)$	Universal modus ponens from (3) and (4)
6. $S(a)$	Simplification from (5)
7. $R(a)$	Simplification from (2)
8. $R(a) \wedge S(a)$	Conjunction from (7) and (6)
9. $\forall x(R(x) \wedge S(x))$	Universal generalization from (5)

29.

Step	Reason
1. $\exists x \neg P(x)$	Premise
2. $\neg P(c)$	Existential instantiation from (1)
3. $\forall x(P(x) \vee Q(x))$	Premise
4. $P(c) \vee Q(c)$	Universal instantiation from (3)
5. $Q(c)$	Disjunctive syllogism from (4) and (2)
6. $\forall x(\neg Q(x) \vee S(x))$	Premise

7. $\neg Q(c) \vee S(c)$	Universal instantiation from (6)
8. $S(c)$	Disjunctive syllogism from (5) and (7)
9. $\forall x(R(x) \rightarrow \neg S(x))$	Premise
10. $R(c) \rightarrow \neg S(c)$	Universal instantiation from (9)
11. $\neg R(c)$	Modus tollens from (8) and (10)
12. $\exists x \neg R(x)$	Existential generalization from (11)

31. Let p be "It is raining"; let q be "Yvette has her umbrella"; let r be "Yvette gets wet." Assumptions are $\neg p \vee q, \neg q \vee \neg r$, and $p \vee \neg r$. Resolution on the first two gives $\neg p \vee \neg r$. Resolution on this and the third assumption gives $\neg r$, as desired. **33.** Assume that this proposition is satisfiable. Using resolution on the first two clauses enables us to conclude $q \vee q$; in other words, we know that q has to be true. Using resolution on the last two clauses enables us to conclude $\neg q \vee \neg q$; in other words, we know that $\neg q$ has to be true. This is a contradiction. So this proposition is not satisfiable. **35.** Valid

Section 1.6

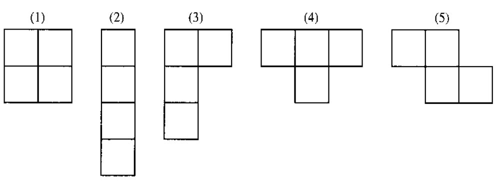
1. Let $n = 2k + 1$ and $m = 2l + 1$ be odd integers. Then $n + m = 2(k + l + 1)$ is even. **3.** Suppose that n is even. Then $n = 2k$ for some integer k. Therefore, $n^2 = (2k)^2 = 4k^2 = 2(2k^2)$. Because we have written n^2 as 2 times an integer, we conclude that n^2 is even. **5.** Direct proof: Suppose that $m + n$ and $n + p$ are even. Then $m + n = 2s$ for some integer s and $n + p = 2t$ for some integer t. If we add these, we get $m + p + 2n = 2s + 2t$. Subtracting $2n$ from both sides and factoring, we have $m + p = 2s + 2t - 2n = 2(s + t - n)$. Because we have written $m + p$ as 2 times an integer, we conclude that $m + p$ is even. **7.** Because n is odd, we can write $n = 2k + 1$ for some integer k. Then $(k + 1)^2 - k^2 = k^2 + 2k + 1 - k^2 = 2k + 1 = n$. **9.** Suppose that r is rational and i is irrational and $s = r + i$ is rational. Then by Example 7, $s + (-r) = i$ is rational, which is a contradiction. **11.** Because $\sqrt{2} \cdot \sqrt{2} = 2$ is rational and $\sqrt{2}$ is irrational, the product of two irrational numbers is not necessarily irrational. **13.** Proof by contraposition: If $1/x$ were rational, then by definition $1/x = p/q$ for some integers p and q with $q \neq 0$. Because $1/x$ cannot be 0 (if it were, then we'd have the contradiction $1 = x \cdot 0$ by multiplying both sides by x), we know that $p \neq 0$. Now $x = 1/(1/x) = 1/(p/q) = q/p$ by the usual rules of algebra and arithmetic. Hence, x can be written as the quotient of two integers with the denominator nonzero. Thus by definition, x is rational. **15.** Assume that it is not true that $x \geq 1$ or $y \geq 1$. Then $x < 1$ and $y < 1$. Adding these two inequalities, we obtain $x + y < 2$, which is the negation of $x + y \geq 2$. **17. a)** Assume that n is odd, so $n = 2k + 1$ for some integer k. Then $n^3 + 5 = 2(4k^3 + 6k^2 + 3k + 3)$. Because $n^3 + 5$ is two times some integer, it is even. **b)** Suppose that $n^3 + 5$ is odd and n is odd. Because n is odd and the product of two odd numbers is odd, it follows that n^2 is odd and then that n^3 is odd. But then $5 = (n^3 + 5) - n^3$ would have to be even because it is the difference of two odd numbers. Therefore, the supposition that $n^3 + 5$ and n were both odd is wrong. **19.** The proposition is vacuously true because 0 is not a positive integer. Vacuous proof. **21.** $P(1)$ is true because $(a + b)^1 = a + b \geq a^1 + b^1 = a + b$. Direct proof. **23.** If we chose 9 or fewer days on each day of the week, this would account for at most $9 \cdot 7 = 63$ days. But we chose 64 days. This contradiction shows that at least 10 of the days we chose must be on the same day of the week. **25.** Suppose by way of contradiction that a/b is a rational root, where a and b are integers and this fraction is in lowest terms (that is, a and b have no common divisor greater than 1). Plug this proposed root into the equation to obtain $a^3/b^3 + a/b + 1 = 0$. Multiply through by b^3 to obtain $a^3 + ab^2 + b^3 = 0$. If a and b are both odd, then the left-hand side is the sum of three odd numbers and therefore must be odd. If a is odd and b is even, then the left-hand side is odd + even + even, which is again odd. Similarly, if a is even and b is odd, then the left-hand side is even + even + odd, which is again odd. Because the fraction a/b is in simplest terms, it cannot happen that both a and b are even. Thus in all cases, the left-hand side is odd, and therefore cannot equal 0. This contradiction shows that no such root exists. **27.** First, assume that n is odd, so that $n = 2k + 1$ for some integer k. Then $5n + 6 = 5(2k + 1) + 6 = 10k + 11 = 2(5k + 5) + 1$. Hence, $5n + 6$ is odd. To prove the converse, suppose that n is even, so that $n = 2k$ for some integer k. Then $5n + 6 = 10k + 6 = 2(5k + 3)$, so $5n + 6$ is even. Hence, n is odd if and only if $5n + 6$ is odd. **29.** This proposition is true. Suppose that m is neither 1 nor -1. Then mn has a factor m larger than 1. On the other hand, $mn = 1$, and 1 has no such factor. Hence, $m = 1$ or $m = -1$. In the first case $n = 1$, and in the second case $n = -1$, because $n = 1/m$. **31.** We prove that all these are equivalent to x being even. If x is even, then $x = 2k$ for some integer k. Therefore $3x + 2 = 3 \cdot 2k + 2 = 6k + 2 = 2(3k + 1)$, which is even, because it has been written in the form $2t$, where $t = 3k + 1$. Similarly, $x + 5 = 2k + 5 = 2k + 4 + 1 = 2(k + 2) + 1$, so $x + 5$ is odd; and $x^2 = (2k)^2 = 2(2k^2)$, so x^2 is even. For the converses, we will use a proof by contraposition. So assume that x is not even; thus x is odd and we can write $x = 2k + 1$ for some integer k. Then $3x + 2 = 3(2k + 1) + 2 = 6k + 5 = 2(3k + 2) + 1$, which is odd (i.e., not even), because it has been written in the form $2t + 1$, where $t = 3k + 2$. Similarly, $x + 5 = 2k + 1 + 5 = 2(k + 3)$, so $x + 5$ is even (i.e., not odd). That x^2 is odd was already proved in Example 1. **33.** We give proofs by contraposition of $(i) \rightarrow (ii)$, $(ii) \rightarrow (i)$, $(i) \rightarrow (iii)$, and $(iii) \rightarrow (i)$. For the first of these, suppose that $3x + 2$ is rational, namely, equal to p/q for some integers p and q with $q \neq 0$. Then we can write $x = ((p/q) - 2)/3 = (p - 2q)/(3q)$, where $3q \neq 0$. This shows that x is rational. For the second conditional statement, suppose that x is rational, namely, equal to p/q for some integers p and q with $q \neq 0$. Then we can write $3x + 2 = (3p + 2q)/q$, where $q \neq 0$. This shows that $3x + 2$ is rational. For the third conditional statement, suppose that $x/2$ is rational, namely, equal to p/q for some integers p and q with $q \neq 0$. Then we can write $x = 2p/q$, where $q \neq 0$. This shows that x is rational. And for the fourth conditional statement, suppose that x is rational, namely, equal to p/q for some integers p and q with $q \neq 0$. Then we can write $x/2 = p/(2q)$, where $2q \neq 0$. This shows that $x/2$ is rational.

35. No **37.** Suppose that $p_1 \to p_4 \to p_2 \to p_5 \to p_3 \to p_1$. To prove that one of these propositions implies any of the others, just use hypothetical syllogism repeatedly. **39.** We will give a proof by contradiction. Suppose that $a_1, a_2, \ldots, a_n$ are all less than A, where A is the average of these numbers. Then $a_1 + a_2 + \cdots + a_n < nA$. Dividing both sides by n shows that $A = (a_1 + a_2 + \cdots + a_n)/n < A$, which is a contradiction. **41.** We will show that the four statements are equivalent by showing that (i) implies (ii), (ii) implies (iii), (iii) implies (iv), and (iv) implies (i). First, assume that n is even. Then $n = 2k$ for some integer k. Then $n + 1 = 2k + 1$, so $n + 1$ is odd. This shows that (i) implies (ii). Next, suppose that $n + 1$ is odd, so $n + 1 = 2k + 1$ for some integer k. Then $3n + 1 = 2n + (n + 1) = 2(n + k) + 1$, which shows that $3n + 1$ is odd, showing that (ii) implies (iii). Next, suppose that $3n + 1$ is odd, so $3n + 1 = 2k + 1$ for some integer k. Then $3n = (2k + 1) - 1 = 2k$, so $3n$ is even. This shows that (iii) implies (iv). Finally, suppose that n is not even. Then n is odd, so $n = 2k + 1$ for some integer k. Then $3n = 3(2k + 1) = 6k + 3 = 2(3k + 1) + 1$, so $3n$ is odd. This completes a proof by contraposition that (iv) implies (i).

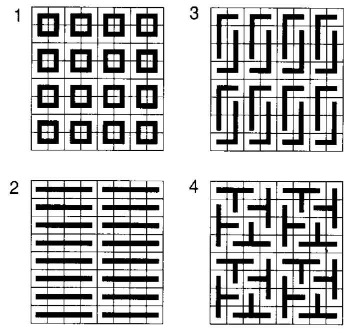
Section 1.7

1. $1^2 + 1 = 2 \geq 2 = 2^1$; $2^2 + 1 = 5 \geq 4 = 2^2$; $3^2 + 1 = 10 \geq 8 = 2^3$; $4^2 + 1 = 17 \geq 16 = 2^4$ **3.** If $x \leq y$, then $\max(x, y) + \min(x, y) = y + x = x + y$. If $x \geq y$, then $\max(x, y) + \min(x, y) = x + y$. Because these are the only two cases, the equality always holds. **5.** There are four cases. *Case 1:* $x \geq 0$ and $y \geq 0$. Then $|x| + |y| = x + y = |x + y|$. *Case 2:* $x < 0$ and $y < 0$. Then $|x| + |y| = -x + (-y) = -(x + y) = |x + y|$ because $x + y < 0$. *Case 3:* $x \geq 0$ and $y < 0$. Then $|x| + |y| = x + (-y)$. If $x \geq -y$, then $|x + y| = x + y$. But because $y < 0$, $-y > y$, so $|x| + |y| = x + (-y) > x + y = |x + y|$. If $x < -y$, then $|x + y| = -(x + y) = -x + (-y)$. But because $x \geq 0$, $x \geq -x$, so $|x| + |y| = x + (-y) \geq -x + (-y) = |x + y|$. *Case 4:* $x < 0$ and $y \geq 0$. Identical to Case 3 with the roles of x and y reversed. **7.** 10,001, 10,002, …, 10,100 are all nonsquares, because $100^2 = 10{,}000$ and $101^2 = 10{,}201$; constructive. **9.** $8 = 2^3$ and $9 = 3^2$ **11.** Let $x = 2$ and $y = \sqrt{2}$. If $x^y = 2^{\sqrt{2}}$ is irrational, we are done. If not, then let $x = 2^{\sqrt{2}}$ and $y = \sqrt{2}/4$. Then $x^y = (2^{\sqrt{2}})^{\sqrt{2}/4} = 2^{\sqrt{2}\cdot(\sqrt{2})/4} = 2^{1/2} = \sqrt{2}$. **13. a)** This statement asserts the existence of x with a certain property. If we let $y = x$, then we see that $P(x)$ is true. If y is anything other than x, then $P(x)$ is not true. Thus, x is the unique element that makes P true. **b)** The first clause here says that there is an element that makes P true. The second clause says that whenever two elements both make P true, they are in fact the same element. Together these say that P is satisfied by exactly one element. **c)** This statement asserts the existence of an x that makes P true and has the further property that whenever we find an element that makes P true, that element is x. In other words, x is the unique element that makes P true. **15.** The equation $|a - c| = |b - c|$ is equivalent to the disjunction of two equations: $a - c = b - c$ or $a - c = -b + c$. The first of these is equivalent to $a = b$, which contradicts the assumptions made in this problem, so the original equation is equivalent to $a - c = -b + c$. By adding $b + c$ to both sides and dividing by 2, we see that this equation is equivalent to $c = (a + b)/2$. Thus, there is a unique solution. Furthermore, this c is an integer, because the sum of the odd integers a and b is even. **17.** We are being asked to solve $n = (k - 2) + (k + 3)$ for k. Using the usual, reversible, rules of algebra, we see that this equation is equivalent to $k = (n - 1)/2$. In other words, this is the one and only value of k that makes our equation true. Because n is odd, $n - 1$ is even, so k is an integer. **19.** If x is itself an integer, then we can take $n = x$ and $\epsilon = 0$. No other solution is possible in this case, because if the integer n is greater than x, then n is at least $x + 1$, which would make $\epsilon \geq 1$. If x is not an integer, then round it up to the next integer, and call that integer n. Let $\epsilon = n - x$. Clearly $0 \leq \epsilon < 1$; this is the only ϵ that will work with this n, and n cannot be any larger, because ϵ is constrained to be less than 1. **21.** The harmonic mean of distinct positive real numbers x and y is always less than their geometric mean. To prove $2xy/(x + y) < \sqrt{xy}$, multiply both sides by $(x + y)/(2\sqrt{xy})$ to obtain the equivalent inequality $\sqrt{xy} < (x + y)/2$, which is proved in Example 14. **23.** The parity (oddness or evenness) of the sum of the numbers written on the board never changes, because $j + k$ and $|j - k|$ have the same parity (and at each step we reduce the sum by $j + k$ but increase it by $|j - k|$). Therefore the integer at the end of the process must have the same parity as $1 + 2 + \cdots + (2n) = n(2n + 1)$, which is odd because n is odd. **25.** Without loss of generality we can assume that n is nonnegative, because the fourth power of an integer and the fourth power of its negative are the same. We divide an arbitrary positive integer n by 10, obtaining a quotient k and remainder l, whence $n = 10k + l$, and l is an integer between 0 and 9, inclusive. Then we compute n^4 in each of these 10 cases. We get the following values, where X is some integer that is a multiple of 10, whose exact value we do not care about. $(10k + 0)^4 = 10{,}000k^4 = 10{,}000k^4 + 0$, $(10k + 1)^4 = 10{,}000k^4 + X \cdot k^3 + X \cdot k^2 + X \cdot k + 1$, $(10k + 2)^4 = 10{,}000k^4 + X \cdot k^3 + X \cdot k^2 + X \cdot k + 16$, $(10k + 3)^4 = 10{,}000k^4 + X \cdot k^3 + X \cdot k^2 + X \cdot k + 81$, $(10k + 4)^4 = 10{,}000k^4 + X \cdot k^3 + X \cdot k^2 + X \cdot k + 256$, $(10k + 5)^4 = 10{,}000k^4 + X \cdot k^3 + X \cdot k^2 + X \cdot k + 625$, $(10k + 6)^4 = 10{,}000k^4 + X \cdot k^3 + X \cdot k^2 + X \cdot k + 1296$, $(10k + 7)^4 = 10{,}000k^4 + X \cdot k^3 + X \cdot k^2 + X \cdot k + 2401$, $(10k + 8)^4 = 10{,}000k^4 + X \cdot k^3 + X \cdot k^2 + X \cdot k + 4096$, $(10k + 9)^4 = 10{,}000k^4 + X \cdot k^3 + X \cdot k^2 + X \cdot k + 6561$. Because each coefficient indicated by X is a multiple of 10, the corresponding term has no effect on the ones digit of the answer. Therefore the ones digits are 0, 1, 6, 1, 6, 5, 6, 1, 6, 1, respectively, so it is always a 0, 1, 5, or 6. **27.** Because $n^3 > 100$ for all $n > 4$, we need only note that $n = 1, n = 2, n = 3$, and $n = 4$ do not satisfy $n^2 + n^3 = 100$. **29.** Because $5^4 = 625$, both x and y must be less than 5. Then $x^4 + y^4 \leq 4^4 + 4^4 = 512 < 625$. **31.** If it is not true that $a \leq \sqrt[3]{n}$, $b \leq \sqrt[3]{n}$, or $c \leq \sqrt[3]{n}$, then $a > \sqrt[3]{n}$, $b > \sqrt[3]{n}$, and $c > \sqrt[3]{n}$. Multiplying these inequalities of positive numbers together we obtain $abc < (\sqrt[3]{n})^3 = n$, which implies the negation of our hypothesis that $n = abc$. **33.** By finding a common denominator, we can assume that the given rational numbers are a/b and c/b, where b is a positive integer and a and c are integers with $a < c$. In particular, $(a+1)/b \le c/b$. Thus, $x = (a + \frac{1}{2}\sqrt{2})/b$ is between the two given rational numbers, because $0 < \sqrt{2} < 2$. Furthermore, x is irrational, because if x were rational, then $2(bx - a) = \sqrt{2}$ would be as well, in violation of Example 10 in Section 1.6. **35. a)** Without loss of generality, we can assume that the x sequence is already sorted into nondecreasing order, because we can relabel the indices. There are only a finite number of possible orderings for the y sequence, so if we can show that we can increase the sum (or at least keep it the same) whenever we find y_i and y_j that are out of order (i.e., $i < j$ but $y_i > y_j$) by switching them, then we will have shown that the sum is largest when the y sequence is in nondecreasing order. Indeed, if we perform the swap, then we have added $x_i y_j + x_j y_i$ to the sum and subtracted $x_i y_i + x_j y_j$. The net effect is to have added $x_i y_j + x_j y_i - x_i y_i - x_j y_j = (x_j - x_i)(y_i - y_j)$, which is nonnegative by our ordering assumptions. **b)** Similar to part (a) **37. a)** $6 \to 3 \to 10 \to 5 \to 16 \to 8 \to 4 \to 2 \to 1$ **b)** $7 \to 22 \to 11 \to 34 \to 17 \to 52 \to 26 \to 13 \to 40 \to 20 \to 10 \to 5 \to 16 \to 8 \to 4 \to 2 \to 1$ **c)** $17 \to 52 \to 26 \to 13 \to 40 \to 20 \to 10 \to 5 \to 16 \to 8 \to 4 \to 2 \to 1$ **d)** $21 \to 64 \to 32 \to 16 \to 8 \to 4 \to 2 \to 1$ **39.** Without loss of generality, assume that the upper left and upper right corners of the board are removed. Place three dominoes horizontally to fill the remaining portion of the first row, and fill each of the other seven rows with four horizontal dominoes. **41.** Because there is an even number of squares in all, either there is an even number of squares in each row or there is an even number of squares in each column. In the former case, tile the board in the obvious way by placing the dominoes horizontally, and in the latter case, tile the board in the obvious way by placing the dominoes vertically. **43.** We can rotate the board if necessary to make the removed squares be 1 and 16. Square 2 must be covered by a domino. If that domino is placed to cover squares 2 and 6, then the following domino placements are forced in succession: 5-9, 13-14, and 10-11, at which point there is no way to cover square 15. Otherwise, square 2 must be covered by a domino placed at 2-3. Then the following domino placements are forced: 4-8, 11-12, 6-7, 5-9, and 10-14, and again there is no way to cover square 15. **45.** Remove the two black squares adjacent to a white corner, and remove two white squares other than that corner. Then no domino can cover that white corner.

47. a)



b) The picture shows tilings for the first four patterns.



To show that pattern 5 cannot tile the checkerboard, label the squares from 1 to 64, one row at a time from the top, from left to right in each row. Thus, square 1 is the upper left corner, and square 64 is the lower right. Suppose we did have a tiling. By symmetry and without loss of generality, we may suppose that the tile is positioned in the upper left corner, covering squares 1, 2, 10, and 11. This forces a tile to be adjacent to it on the right, covering squares 3, 4, 12, and 13. Continue in this manner and we are forced to have a tile covering squares 6, 7, 15, and 16. This makes it impossible to cover square 8. Thus, no tiling is possible.

Supplementary Exercises

1. a) $q \to p$ **b)** $q \wedge p$ **c)** $\neg q \vee \neg p$ **d)** $q \leftrightarrow p$ **3. a)** The proposition cannot be false unless $\neg p$ is false, so p is true. If p is true and q is true, then $\neg q \wedge (p \to q)$ is false, so the conditional statement is true. If p is true and q is false, then $p \to q$ is false, so $\neg q \wedge (p \to q)$ is false and the conditional statement is true. **b)** The proposition cannot be false unless q is false. If q is false and p is true, then $(p \vee q) \wedge \neg p$ is false, and the conditional statement is true. If q is false and p is false, then $(p \vee q) \wedge \neg p$ is false, and the conditional statement is true. **5.** $\neg q \to \neg p$; $p \to q$; $\neg p \to \neg q$ **7.** $(p \wedge q \wedge r \wedge \neg s) \vee (p \wedge q \wedge \neg r \wedge s) \vee (p \wedge \neg q \wedge r \wedge s) \vee (\neg p \wedge q \wedge r \wedge s)$ **9.** Translating these statements into symbols, using the obvious letters, we have $\neg t \to \neg g$, $\neg g \to \neg q$, $r \to q$, and $\neg t \wedge r$. Assume the statements are consistent. The fourth statement tells us that $\neg t$ must be true. Therefore by modus ponens with the first statement, we know that $\neg g$ is true, hence (from the second statement), that $\neg q$ is true. Also, the fourth statement tells us that r must be true, and so again modus ponens (third statement) makes q true. This is a contradiction: $q \wedge \neg q$. Thus the statements are inconsistent. **11.** Brenda **13.** The premises cannot both be true, because they are contradictory. Therefore it is (vacuously) true that whenever all the premises are true, the conclusion is also true, which by definition makes this a valid argument. Because the premises are not both true, we cannot conclude that the conclusion is true. **15. a)** F **b)** T **c)** F **d)** T **e)** F **f)** T **17.** Many answers are possible. One example is United States senators.

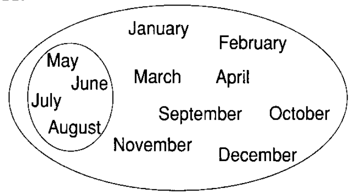
19. $\forall x \exists y \exists z (y \neq z \wedge \forall w(P(w,x) \leftrightarrow (w = y \vee w = z)))$ **21. a)** $\neg \exists x P(x)$ **b)** $\exists x(P(x) \wedge \forall y(P(y) \rightarrow y = x))$ **c)** $\exists x_1 \exists x_2 (P(x_1) \wedge P(x_2) \wedge x_1 \neq x_2 \wedge \forall y(P(y) \rightarrow (y = x_1 \vee y = x_2)))$ **d)** $\exists x_1 \exists x_2 \exists x_3 (P(x_1) \wedge P(x_2) \wedge P(x_3) \wedge x_1 \neq x_2 \wedge x_1 \neq x_3 \wedge x_2 \neq x_3 \wedge \forall y(P(y) \rightarrow (y = x_1 \vee y = x_2 \vee y = x_3)))$ **23.** Suppose that $\exists x(P(x) \rightarrow Q(x))$ is true. Then either $Q(x_0)$ is true for some x_0, in which case $\forall x P(x) \rightarrow \exists x\, Q(x)$ is true; or $P(x_0)$ is false for some x_0, in which case $\forall x P(x) \rightarrow \exists x Q(x)$ is true. Conversely, suppose that $\exists x(P(x) \rightarrow Q(x))$ is false. That means that $\forall x(P(x) \wedge \neg Q(x))$ is true, which implies $\forall x P(x)$ and $\forall x(\neg Q(x))$. This latter proposition is equivalent to $\neg \exists x Q(x)$. Thus, $\forall x P(x) \rightarrow \exists x Q(x)$ is false. **25.** No **27.** $\forall x \forall z \exists y T(x, y, z)$, where $T(x, y, z)$ is the statement that student x has taken class y in department z, where the domains are the set of students in the class, the set of courses at this university, and the set of departments in the school of mathematical sciences **29.** $\exists! x \exists! y T(x, y)$ and $\exists x \forall z((\exists y \forall w(T(z, w) \leftrightarrow w = y)) \leftrightarrow z = x)$, where $T(x, y)$ means that student x has taken class y and the domain is all students in this class **31.** $P(a) \rightarrow Q(a)$ and $Q(a) \rightarrow R(a)$ by universal instantiation; then $\neg Q(a)$ by modus tollens and $\neg P(a)$ by modus tollens **33.** We give a proof by contraposition and show that if $\sqrt{x}$ is rational, then x is rational, assuming throughout that $x \geq 0$. Suppose that $\sqrt{x} = p/q$ is rational, $q \neq 0$. Then $x = (\sqrt{x})^2 = p^2/q^2$ is also rational (q^2 is again nonzero). **35.** We can give a constructive proof by letting $m = 10^{500} + 1$. Then $m^2 = (10^{500} + 1)^2 > (10^{500})^2 = 10^{1000}$. **37.** 23 cannot be written as the sum of eight cubes. **39.** 223 cannot be written as the sum of 36 fifth powers.

CHAPTER 2

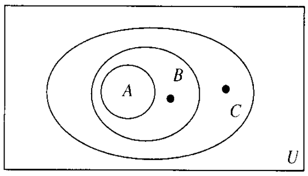
Section 2.1

1. a) $\{-1, 1\}$ **b)** $\{1,2,3,4,5,6,7,8,9,10,11\}$ **c)** $\{0,1,4,9,16,25,36,49,64,81\}$ **d)** $\emptyset$ **3. a)** Yes **b)** No **c)** No **5. a)** Yes **b)** No **c)** Yes **d)** No **e)** No **f)** No **7. a)** False **b)** False **c)** False **d)** True **e)** False **f)** False **g)** True **9. a)** True **b)** True **c)** False **d)** True **e)** True **f)** False

11.



13. The dots in certain regions indicate that those regions are not empty.



15. Suppose that $x \in A$. Because $A \subseteq B$, this implies that $x \in B$. Because $B \subseteq C$, we see that $x \in C$. Because $x \in A$ implies that $x \in C$, it follows that $A \subseteq C$. **17. a)** 1 **b)** 1 **c)** 2 **d)** 3 **19. a)** $\{\emptyset, \{a\}\}$ **b)** $\{\emptyset, \{a\}, \{b\}, \{a, b\}\}$ **c)** $\{\emptyset, \{\emptyset\}, \{\{\emptyset\}\}, \{\emptyset, \{\emptyset\}\}\}$ **21. a)** 8 **b)** 16 **c)** 2 **23. a)** $\{(a, y), (b, y), (c, y), (d, y), (a, z), (b, z), (c, z), (d, z)\}$ **b)** $\{(y, a), (y, b), (y, c), (y, d), (z, a), (z, b), (z, c), (z, d)\}$ **25.** The set of triples (a, b, c), where a is an airline and b and c are cities **27.** $\emptyset \times A = \{(x, y) \mid x \in \emptyset \text{ and } y \in A\} = \emptyset = \{(x, y) \mid x \in A \text{ and } y \in \emptyset\} = A \times \emptyset$ **29.** mn **31.** The elements of $A \times B \times C$ consist of 3-tuples (a, b, c), where $a \in A$, $b \in B$, and $c \in C$, whereas the elements of $(A \times B) \times C$ look like $((a, b), c)$—ordered pairs, the first coordinate of which is again an ordered pair. **33. a)** The square of a real number is never -1. True **b)** There exists an integer whose square is 2. False **c)** The square of every integer is positive. False **d)** There is a real number equal to its own square. True **35. a)** $\{-1, 0, 1\}$ **b)** $\mathbf{Z} - \{0, 1\}$ **c)** $\emptyset$ **37.** We must show that $\{\{a\}, \{a, b\}\} = \{\{c\}, \{c, d\}\}$ if and only if $a = c$ and $b = d$. The "if" part is immediate. So assume these two sets are equal. First, consider the case when $a \neq b$. Then $\{\{a\}, \{a, b\}\}$ contains exactly two elements, one of which contains one element. Thus, $\{\{c\}, \{c, d\}\}$ must have the same property, so $c \neq d$ and $\{c\}$ is the element containing exactly one element. Hence, $\{a\} = \{c\}$, which implies that $a = c$. Also, the two-element sets $\{a, b\}$ and $\{c, d\}$ must be equal. Because $a = c$ and $a \neq b$, it follows that $b = d$. Second, suppose that $a = b$. Then $\{\{a\}, \{a, b\}\} = \{\{a\}\}$, a set with one element. Hence, $\{\{c\}, \{c, d\}\}$ has only one element, which can happen only when $c = d$, and the set is $\{\{c\}\}$. It then follows that $a = c$ and $b = d$. **39.** Let $S = \{a_1, a_2, \ldots, a_n\}$. Represent each subset of S with a bit string of length n, where the ith bit is 1 if and only if $a_i \in S$. To generate all subsets of S, list all 2^n bit strings of length n (for instance, in increasing order), and write down the corresponding subsets.

Section 2.2

1. a) The set of students who live within one mile of school and who walk to classes **b)** The set of students who live within one mile of school or who walk to classes (or who do both) **c)** The set of students who live within one mile of school but do not walk to classes **d)** The set of students who walk to classes but live more than one mile away from school **3. a)** $\{0,1,2,3,4,5,6\}$ **b)** $\{3\}$ **c)** $\{1, 2, 4, 5\}$ **d)** $\{0, 6\}$ **5.** $\overline{\overline{A}} = \{x \mid \neg(x \in \overline{A})\} = \{x \mid \neg(\neg x \in A)\} = \{x \mid x \in A\} = A$ **7. a)** $A \cup U = \{x \mid x \in A \vee x \in U\} = \{x \mid x \in A \vee \mathbf{T}\} = \{x \mid \mathbf{T}\} = U$ **b)** $A \cap \emptyset = \{x \mid x \in A \wedge x \in \emptyset\} = \{x \mid x \in$

$A \wedge \mathbf{F}\} = \{x \mid \mathbf{F}\} = \emptyset$ **9. a)** $A \cup \overline{A} = \{x \mid x \in A \vee x \notin A\} = U$ **b)** $A \cap \overline{A} = \{x \mid x \in A \wedge x \notin A\} = \emptyset$ **11. a)** $A \cup B = \{x \mid x \in A \vee x \in B\} = \{x \mid x \in B \vee x \in A\} = B \cup A$ **b)** $A \cap B = \{x \mid x \in A \wedge x \in B\} = \{x \mid x \in B \wedge x \in A\} = B \cap A$ **13.** Suppose $x \in A \cap (A \cup B)$. Then $x \in A$ and $x \in A \cup B$ by the definition of intersection. Because $x \in A$, we have proved that the left-hand side is a subset of the right-hand side. Conversely, let $x \in A$. Then by the definition of union, $x \in A \cup B$ as well. Therefore $x \in A \cap (A \cup B)$ by the definition of intersection, so the right-hand side is a subset of the left-hand side. **15. a)** $x \in \overline{(A \cup B)} \equiv x \notin (A \cup B) \equiv \neg(x \in A \vee x \in B) \equiv \neg(x \in A) \wedge \neg(x \in B) \equiv x \notin A \wedge x \notin B \equiv x \in \overline{A} \wedge x \in \overline{B} \equiv x \in \overline{A} \cap \overline{B}$

b)

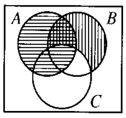
A	B	$A \cup B$	$\overline{(A \cup B)}$	$\overline{A}$	$\overline{B}$	$\overline{A} \cap \overline{B}$
1	1	1	0	0	0	0
1	0	1	0	0	1	0
0	1	1	0	1	0	0
0	0	0	1	1	1	1

17. a) $x \in \overline{A \cap B \cap C} \equiv x \notin A \cap B \cap C \equiv x \notin A \vee x \notin B \vee x \notin C \equiv x \in \overline{A} \vee x \in \overline{B} \vee x \in \overline{C} \equiv x \in \overline{A} \cup \overline{B} \cup \overline{C}$

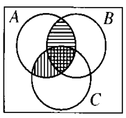
b)

A	B	C	$A \cap B \cap C$	$\overline{(A \cap B \cap C)}$	$\overline{A}$	$\overline{B}$	$\overline{C}$	$\overline{A} \cup \overline{B} \cup \overline{C}$
1	1	1	1	0	0	0	0	0
1	1	0	0	1	0	0	1	1
1	0	1	0	1	0	1	0	1
1	0	0	0	1	0	1	1	1
0	1	1	0	1	1	0	0	1
0	1	0	0	1	1	0	1	1
0	0	1	0	1	1	1	0	1
0	0	0	0	1	1	1	1	1

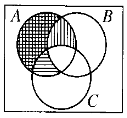
19. Both sides equal $\{x \mid x \in A \wedge x \notin B\}$. **21.** $x \in A \cup (B \cup C) \equiv (x \in A) \vee (x \in (B \cup C)) \equiv (x \in A) \vee (x \in B \vee x \in C) \equiv (x \in A \vee x \in B) \vee (x \in C) \equiv x \in (A \cup B) \cup C$ **23.** $x \in A \cup (B \cap C) \equiv (x \in A) \vee (x \in (B \cap C)) \equiv (x \in A) \vee (x \in B \wedge x \in C) \equiv (x \in A \vee x \in B) \wedge (x \in A \vee x \in C) \equiv x \in (A \cup B) \cap (A \cup C)$ **25. a)** $\{4,6\}$ **b)** $\{0,1,2,3,4,5,6,7,8,9,10\}$ **c)** $\{4,5,6,8,10\}$ **d)** $\{0,2,4,5,6,7,8,9,10\}$ **27. a)** The double-shaded portion is the desired set.



b) The desired set is the entire shaded portion.



c) The desired set is the entire shaded portion.

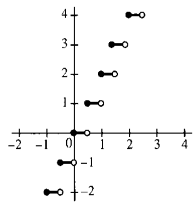


29. a) $B \subseteq A$ **b)** $A \subseteq B$ **c)** $A \cap B = \emptyset$ **d)** Nothing, because this is always true **e)** $A = B$ **31.** $A \subseteq B \equiv \forall x(x \in A \rightarrow x \in B) \equiv \forall x(x \notin B \rightarrow x \notin A) \equiv \forall x(x \in \overline{B} \rightarrow x \in \overline{A}) \equiv \overline{B} \subseteq \overline{A}$ **33.** The set of students who are computer science majors but not mathematics majors or who are mathematics majors but not computer science majors **35.** An element is in $(A \cup B) - (A \cap B)$ if it is in the union of A and B but not in the intersection of A and B, which means that it is in either A or B but not in both A and B. This is exactly what it means for an element to belong to $A \oplus B$. **37. a)** $A \oplus A = (A - A) \cup (A - A) = \emptyset \cup \emptyset = \emptyset$ **b)** $A \oplus \emptyset = (A - \emptyset) \cup (\emptyset - A) = A \cup \emptyset = A$ **c)** $A \oplus U = (A - U) \cup (U - A) = \emptyset \cup \overline{A} = \overline{A}$ **d)** $A \oplus \overline{A} = (A - \overline{A}) \cup (\overline{A} - A) = A \cup \overline{A} = U$ **39.** $B = \emptyset$ **41.** Yes **43.** Yes **45. a)** $\{1, 2, 3, \ldots, n\}$ **b)** $\{1\}$ **47. a)** A_n **b)** $\{0, 1\}$ **49. a)** $\mathbf{Z}$, $\{-1, 0, 1\}$ **b)** $\mathbf{Z} - \{0\}$, $\emptyset$ **c)** $\mathbf{R}$, $[-1, 1]$ **d)** $[1, \infty)$, $\emptyset$ **51. a)** $\{1, 2, 3, 4, 7, 8, 9, 10\}$ **b)** $\{2, 4, 5, 6, 7\}$ **c)** $\{1, 10\}$ **53.** The bit in the ith position of the bit string of the difference of two sets is 1 if the ith bit of the first string is 1 and the ith bit of the second string is 0, and is 0 otherwise. **55. a)** 11 1110 0000 0000 0000 0000 0000 $\vee$ 01 1100 1000 0000 0100 0101 0000 = 11 1110 1000 0000 0100 0101 0000, representing $\{a, b, c, d, e, g, p, t, v\}$ **b)** 11 1110 0000 0000 0000 0000 0000 $\wedge$ 01 1100 1000 0000 0100 0101 0000 = 01 1100 0000 0000 0000 0000 0000, representing $\{b, c, d\}$ **c)** (11 1110 0000 0000 0000 0000 0000 $\vee$ 00 0110 0110 0001 1000 0110 0110) $\wedge$ (01 1100 1000 0000 0100 0101 0000 $\vee$ 00 1010 0010 0000 1000 0010 0111) = 11 1110 0110 0001 1000 0110 0110 $\wedge$ 01 1110 1010 0000 1100 0111 0111 = 01 1110 0010 0000 1000 0110 0110, representing $\{b, c, d, e, i, o, t, u, x, y\}$ **d)** 11 1110 0000 0000 0000 0000 0000 $\vee$ 01 1100 1000 0000 0100 0101 0000 $\vee$ 00 1010 0010 0000 1000 0010 0111 $\vee$ 00 0110 0110 0001 1000 0110 0110 = 11 1110 1110 0001 1100 0111 0111, representing $\{a,b,c,d,e,g,h,i,n,o,p,t,u,v,x,y,z\}$ **57. a)** $\{1, 2, 3, \{1, 2, 3\}\}$ **b)** $\{\emptyset\}$ **c)** $\{\emptyset, \{\emptyset\}\}$ **d)** $\{\emptyset, \{\emptyset\}, \{\emptyset, \{\emptyset\}\}\}$ **59. a)** $\{3 \cdot a, 3 \cdot b, 1 \cdot c, 4 \cdot d\}$ **b)** $\{2 \cdot a, 2 \cdot b\}$ **c)** $\{1 \cdot a, 1 \cdot c\}$ **d)** $\{1 \cdot b, 4 \cdot d\}$ **e)** $\{5 \cdot a, 5 \cdot b, 1 \cdot c, 4 \cdot d\}$ **61.** $\overline{F} = \{0.4$ Alice, 0.1 Brian, 0.6 Fred, 0.9 Oscar, 0.5 Rita$\}$, $\overline{R} = \{0.6$ Alice, 0.2 Brian, 0.8 Fred, 0.1 Oscar, 0.3 Rita$\}$ **63.** $F \cap R = \{0.4$ Alice, 0.8 Brian, 0.2 Fred, 0.1 Oscar, 0.5 Rita$\}$

Section 2.3

1. a) $f(0)$ is not defined. **b)** $f(x)$ is not defined for $x < 0$. **c)** $f(x)$ is not well-defined because there are two distinct values assigned to each x. **3. a)** Not a function **b)** A function **c)** Not a function **5. a)** Domain the set of bit strings; range the set of integers **b)** Domain the set of bit strings; range the set of even nonnegative integers **c)** Domain the set of bit strings; range the set of nonnegative integers not exceeding 7 **d)** Domain the set of positive integers; range the set of squares of positive integers $= \{1, 4, 9, 16, \ldots\}$ **7. a)** Domain $\mathbf{Z}^+ \times \mathbf{Z}^+$; range $\mathbf{Z}^+$ **b)** Domain $\mathbf{Z}^+$; range $\{0, 1, 2, 3, 4, 5, 6, 7, 8, 9\}$ **c)** Domain the set of bit strings; range $\mathbf{N}$ **d)** Domain the set of bit strings; range $\mathbf{N}$ **9. a)** 1 **b)** 0 **c)** 0 **d)** -1 **e)** 3 **f)** -1 **g)** 2 **h)** 1 **11.** Only the function in part (a) **13.** Only the functions in parts (a) and (d) **15. a)** Onto **b)** Not onto **c)** Onto **d)** Not onto **e)** Onto **17. a)** The function $f(x)$ with $f(x) = 3x + 1$ when $x \geq 0$ and $f(x) = -3x + 2$ when $x < 0$ **b)** $f(x) = |x| + 1$ **c)** The function $f(x)$ with $f(x) = 2x + 1$ when $x \geq 0$ and $f(x) = -2x$ when $x < 0$ **d)** $f(x) = x^2 + 1$ **19. a)** Yes **b)** No **c)** Yes **d)** No **21.** Suppose that f is strictly decreasing. This means that $f(x) > f(y)$ whenever $x < y$. To show that g is strictly increasing, suppose that $x < y$. Then $g(x) = 1/f(x) < 1/f(y) = g(y)$. Conversely, suppose that g is strictly increasing. This means that $g(x) < g(y)$ whenever $x < y$. To show that f is strictly decreasing, suppose that $x < y$. Then $f(x) = 1/g(x) > 1/g(y) = f(y)$. **23.** Many answers are possible. One example is $f(x) = 17$. **25.** The function is not one-to-one, so it is not invertible. On the restricted domain, the function is the identity function on the nonnegative real numbers, $f(x) = x$, so it is its own inverse. **27. a)** $f(S) = \{0, 1, 3\}$ **b)** $f(S) = \{0, 1, 3, 5, 8\}$ **c)** $f(S) = \{0, 8, 16, 40\}$ **d)** $f(S) = \{1, 12, 33, 65\}$ **29. a)** Let x and y be distinct elements of A. Because g is one-to-one, $g(x)$ and $g(y)$ are distinct elements of B. Because f is one-to-one, $f(g(x)) = (f \circ g)(x)$ and $f(g(y)) = (f \circ g)(y)$ are distinct elements of C. Hence, $f \circ g$ is one-to-one. **b)** Let $y \in C$. Because f is onto, $y = f(b)$ for some $b \in B$. Now because g is onto, $b = g(x)$ for some $x \in A$. Hence, $y = f(b) = f(g(x)) = (f \circ g)(x)$. It follows that $f \circ g$ is onto. **31.** No. For example, suppose that $A = \{a\}$, $B = \{b, c\}$, and $C = \{d\}$. Let $g(a) = b$, $f(b) = d$, and $f(c) = d$. Then f and $f \circ g$ are onto, but g is not. **33.** $(f + g)(x) = x^2 + x + 3$, $(fg)(x) = x^3 + 2x^2 + x + 2$ **35.** f is one-to-one because $f(x_1) = f(x_2) \to ax_1 + b = ax_2 + b \to ax_1 = ax_2 \to x_1 = x_2$. f is onto because $f((y - b)/a) = y$. $f^{-1}(y) = (y - b)/a$. **37.** Let $f(1) = a$, $f(2) = a$. Let $S = \{1\}$ and $T = \{2\}$. Then $f(S \cap T) = f(\emptyset) = \emptyset$, but $f(S) \cap f(T) = \{a\} \cap \{a\} = \{a\}$. **39. a)** $\{x \mid 0 \leq x < 1\}$ **b)** $\{x \mid -1 \leq x < 2\}$ **c)** $\emptyset$ **41.** $f^{-1}(\overline{S}) = \{x \in A \mid f(x) \notin S\} = \overline{\{x \in A \mid f(x) \in S\}} = \overline{f^{-1}(S)}$ **43.** Let $x = \lfloor x \rfloor + \epsilon$, where ϵ is a real number with $0 \leq \epsilon < 1$. If $\epsilon < \frac{1}{2}$, then $\lfloor x \rfloor - 1 < x - \frac{1}{2} < \lfloor x \rfloor$, so $\lceil x - \frac{1}{2} \rceil = \lfloor x \rfloor$ and this is the integer closest to x. If $\epsilon > \frac{1}{2}$, then $\lfloor x \rfloor < x - \frac{1}{2} < \lfloor x \rfloor + 1$, so $\lceil x - \frac{1}{2} \rceil = \lfloor x \rfloor + 1$ and this is the integer closest to x. If $\epsilon = \frac{1}{2}$, then $\lceil x - \frac{1}{2} \rceil = \lfloor x \rfloor$, which is the smaller of the two integers that surround x and are the same distance from x. **45.** Write the real number x as $\lfloor x \rfloor + \epsilon$, where ϵ is a real number with $0 \leq \epsilon < 1$. Because $\epsilon = x - \lfloor x \rfloor$, it follows that $0 \leq -\lfloor x \rfloor < 1$. The first two inequalities, $x - 1 < \lfloor x \rfloor$ and $\lfloor x \rfloor \leq x$, follow directly. For the other two inequalities, write $x = \lceil x \rceil - \epsilon'$, where $0 \leq \epsilon' < 1$. Then $0 \leq \lceil x \rceil - x < 1$, and the desired inequality follows. **47. a)** If $x < n$, because $\lfloor x \rfloor \leq x$, it follows that $\lfloor x \rfloor < n$. Suppose that $x \geq n$. By the definition of the floor function, it follows that $\lfloor x \rfloor \geq n$. This means that if $\lfloor x \rfloor < n$, then $x < n$. **b)** If $n < x$, then because $x \leq \lceil x \rceil$, it follows that $n \leq \lceil x \rceil$. Suppose that $n \geq x$. By the definition of the ceiling function, it follows that $\lceil x \rceil \leq n$. This means that if $n < \lceil x \rceil$, then $n < x$. **49.** If n is even, then $n = 2k$ for some integer k. Thus, $\lfloor n/2 \rfloor = \lfloor k \rfloor = k = n/2$. If n is odd, then $n = 2k + 1$ for some integer k. Thus, $\lfloor n/2 \rfloor = \lfloor k + \frac{1}{2} \rfloor = k = (n - 1)/2$. **51.** Assume that $x \geq 0$. The left-hand side is $\lceil -x \rceil$ and the right-hand side is $-\lfloor x \rfloor$. If x is an integer, then both sides equal $-x$. Otherwise, let $x = n + \epsilon$, where n is a natural number and ϵ is a real number with $0 \leq \epsilon < 1$. Then $\lceil -x \rceil = \lceil -n - \epsilon \rceil = -n$ and $-\lfloor x \rfloor = -\lfloor n + \epsilon \rfloor = -n$ also. When $x < 0$, the equation also holds because it can be obtained by substituting $-x$ for x. **53.** $\lceil b \rceil - \lfloor a \rfloor - 1$ **55. a)** 1 **b)** 3 **c)** 126 **d)** 3600 **57. a)** 100 **b)** 256 **c)** 1030 **d)** 30,200

59.



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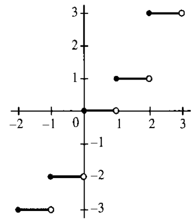
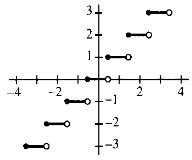
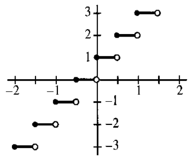


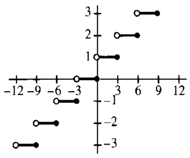
63. a)



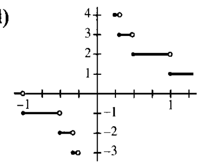
b)



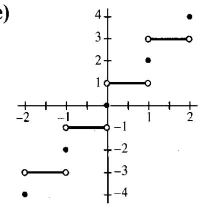
c)



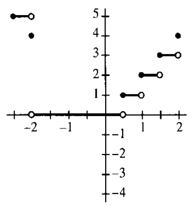
d)



e)



f)



g) See part (a). **65.** $f^{-1}(y) = (y - 1)^{1/3}$ **67. a)** $f_{A \cap B}(x) = 1 \leftrightarrow x \in A \cap B \leftrightarrow x \in A$ and $x \in B \leftrightarrow f_A(x) = 1$ and

$f_B(x) = 1 \leftrightarrow f_A(x)f_B(x) = 1$ **b)** $f_{A\cup B}(x) = 1 \leftrightarrow x \in A \cup B \leftrightarrow x \in A$ or $x \in B \leftrightarrow f_A(x) = 1$ or $f_B(x) = 1 \leftrightarrow f_A(x) + f_B(x) - f_A(x)f_B(x) = 1$ **c)** $f_{\overline{A}}(x) = 1 \leftrightarrow x \in \overline{A} \leftrightarrow x \notin A \leftrightarrow f_A(x) = 0 \leftrightarrow 1 - f_A(x) = 1$ **d)** $f_{A\oplus B}(x) = 1 \leftrightarrow x \in A \oplus B \leftrightarrow (x \in A$ and $x \notin B)$ or $(x \notin A$ and $x \in B) \leftrightarrow f_A(x) + f_B(x) - 2f_A(x)f_B(x) = 1$ **69. a)** True; because $\lfloor x \rfloor$ is already an integer, $\lceil \lfloor x \rfloor \rceil = \lfloor x \rfloor$. **b)** False; $x = \frac{1}{2}$ is a counterexample. **c)** True; if x or y is an integer, then by property 4b in Table 1, the difference is 0. If neither x nor y is an integer, then $x = n + \epsilon$ and $y = m + \delta$, where n and m are integers and ϵ and δ are positive real numbers less than 1. Then $m + n < x + y < m + n + 2$, so $\lceil x + y \rceil$ is either $m + n + 1$ or $m + n + 2$. Therefore, the given expression is either $(n + 1) + (m + 1) - (m + n + 1) = 1$ or $(n + 1) + (m + 1) - (m + n + 2) = 0$, as desired. **d)** False; $x = \frac{1}{4}$ and $y = 3$ is a counterexample. **e)** False; $x = \frac{1}{2}$ is a counterexample. **71. a)** If x is a positive integer, then the two sides are equal. So suppose that $x = n^2 + m + \epsilon$, where n^2 is the largest perfect square less than x, m is a nonnegative integer, and $0 < \epsilon \le 1$. Then both $\sqrt{x}$ and $\sqrt{\lfloor x \rfloor} = \sqrt{n^2 + m}$ are between n and $n + 1$, so both sides equal n. **b)** If x is a positive integer, then the two sides are equal. So suppose that $x = n^2 - m - \epsilon$, where n^2 is the smallest perfect square greater than x, m is a nonnegative integer, and ϵ is a real number with $0 < \epsilon \le 1$. Then both $\sqrt{x}$ and $\sqrt{\lceil x \rceil} = \sqrt{n^2 - m}$ are between $n - 1$ and n. Therefore, both sides of the equation equal n. **73. a)** Domain is $\mathbf{Z}$; codomain is $\mathbf{R}$; domain of definition is the set of nonzero integers; the set of values for which f is undefined is $\{0\}$; not a total function. **b)** Domain is $\mathbf{Z}$; codomain is $\mathbf{Z}$; domain of definition is $\mathbf{Z}$; set of values for which f is undefined is $\emptyset$; total function. **c)** Domain is $\mathbf{Z} \times \mathbf{Z}$; codomain is $\mathbf{Q}$; domain of definition is $\mathbf{Z} \times (\mathbf{Z} - \{0\})$; set of values for which f is undefined is $\mathbf{Z} \times \{0\}$; not a total function. **d)** Domain is $\mathbf{Z} \times \mathbf{Z}$; codomain is $\mathbf{Z}$; domain of definition is $\mathbf{Z} \times \mathbf{Z}$; set of values for which f is undefined is $\emptyset$; total function. **e)** Domain is $\mathbf{Z} \times \mathbf{Z}$; codomain is $\mathbf{Z}$; domain of definitions is $\{(m, n) \mid m > n\}$; set of values for which f is undefined is $\{(m, n) \mid m \le n\}$; not a total function. **75. a)** By definition, to say that S has cardinality m is to say that S has exactly m distinct elements. Therefore we can assign the first object to 1, the second to 2, and so on. This provides the one-to-one correspondence. **b)** By part (a), there is a bijection f from S to $\{1, 2, \ldots, m\}$ and a bijection g from T to $\{1, 2, \ldots, m\}$. Then the composition $g^{-1} \circ f$ is the desired bijection from S to T. **77.** It is clear from the formula that the range of values the function takes on for a fixed value of $m + n$, say $m + n = x$, is $(x - 2)(x - 1)/2 + 1$ through $(x - 2)(x - 1)/2 + (x - 1)$, because m can assume the values $1, 2, 3, \ldots, (x - 1)$ under these conditions, and the first term in the formula is a fixed positive integer when $m + n$ is fixed. To show that this function is one-to-one and onto, we merely need to show that the range of values for $x + 1$ picks up precisely where the range of values for x left off, i.e., that $f(x - 1, 1) + 1 = f(1, x)$. We have $f(x - 1, 1) + 1 = \frac{(x-2)(x-1)}{2} + (x - 1) + 1 = \frac{x^2 - x + 2}{2} = \frac{(x-1)x}{2} + 1 = f(1, x)$.

Section 2.4

1. a) 3 **b)** -1 **c)** 787 **d)** 2639 **3. a)** $a_0 = 2, a_1 = 3, a_2 = 5, a_3 = 9$ **b)** $a_0 = 1, a_1 = 4, a_2 = 27, a_3 = 256$ **c)** $a_0 = 0, a_1 = 0, a_2 = 1, a_3 = 1$ **d)** $a_0 = 0, a_1 = 1, a_2 = 2, a_3 = 3$ **5. a)** $2, 5, 8, 11, 14, 17, 20, 23, 26, 29$ **b)** $1, 1, 1, 2, 2, 2, 3, 3, 3, 4$ **c)** $1, 1, 3, 3, 5, 5, 7, 7, 9, 9$ **d)** $-1, -2, -2, 8, 88, 656, 4912, 40064, 362368, 3627776$ **e)** $3, 6, 12, 24, 48, 96, 192, 384, 768, 1536$ **f)** $1, 1, 2, 3, 5, 8, 13, 21, 34, 55$ **g)** $1, 2, 2, 3, 3, 3, 3, 4, 4, 4$ **h)** $3, 3, 5, 4, 4, 3, 5, 5, 4, 3$ **7.** Each term could be twice the previous term; the nth term could be obtained from the previous term by adding $n - 1$; the terms could be the positive integers that are not multiples of 3; there are infinitely many other possibilities. **9. a)** One 1 and one 0, followed by two 1s and two 0s, followed by three 1s and three 0s, and so on; 1, 1, 1 **b)** The positive integers are listed in increasing order with each even positive integer listed twice; 9, 10, 10. **c)** The terms in odd-numbered locations are the successive powers of 2; the terms in even-numbered locations are all 0; 32, 0, 64. **d)** $a_n = 3 \cdot 2^{n-1}$; 384, 768, 1536 **e)** $a_n = 15 - 7(n - 1) = 22 - 7n$; $-34, -41, -48$ **f)** $a_n = (n^2 + n + 4)/2$; 57, 68, 80 **g)** $a_n = 2n^3$; 1024, 1458, 2000 **h)** $a_n = n! + 1$; 362881, 3628801, 39916801 **11.** Among the integers $1, 2, \ldots, a_n$, where a_n is the nth positive integer not a perfect square, the nonsquares are $a_1, a_2, \ldots, a_n$ and the squares are $1^2, 2^2, \ldots, k^2$, where k is the integer with $k^2 < n + k < (k + 1)^2$. Consequently, $a_n = n + k$, where $k^2 < a_n < (k + 1)^2$. To find k, first note that $k^2 < n + k < (k + 1)^2$, so $k^2 + 1 \le n + k \le (k + 1)^2 - 1$. Hence, $(k - \frac{1}{2})^2 + \frac{3}{4} = k^2 - k + 1 \le n \le k^2 + k = (k + \frac{1}{2})^2 - \frac{1}{4}$. It follows that $k - \frac{1}{2} < \sqrt{n} < k + \frac{1}{2}$, so $k = \{\sqrt{n}\}$ and $a_n = n + k = n + \{\sqrt{n}\}$. **13. a)** 20 **b)** 11 **c)** 30 **d)** 511 **15. a)** 1533 **b)** 510 **c)** 4923 **d)** 9842 **17. a)** 21 **b)** 78 **c)** 18 **d)** 18 **19.** $\sum_{j=1}^{n}(a_j - a_{j-1}) = a_n - a_0$ **21. a)** n^2 **b)** $n(n + 1)/2$ **23.** 15150 **25.** $\frac{n(n+1)(2n+1)}{3} + \frac{n(n+1)}{2} + (n + 1)(m - (n + 1)^2 + 1)$, where $n = \lfloor\sqrt{m}\rfloor - 1$ **27. a)** 0 **b)** 1680 **c)** 1 **d)** 1024 **29.** 34 **31. a)** Countable, $-1, -2, -3, -4, \ldots$ **b)** Countable, $0, 2, -2, 4, -4, \ldots$ **c)** Uncountable **d)** Countable, $0, 7, -7, 14, -14, \ldots$ **33. a)** Countable: match n with the string of n 1s. **b)** Countable. To find a correspondence, follow the path in Example 20, but omit fractions in the top three rows (as well as continuing to omit fractions not in lowest terms). **c)** Uncountable **d)** Uncountable **35.** Assume that $A - B$ is countable. Then, because $A = (A - B) \cup B$, the elements of A can be listed in a sequence by alternating elements of $A - B$ and elements of B. This contradicts the uncountability of A. **37.** Assume that B is countable. Then the elements of B can be listed as $b_1, b_2, b_3, \ldots$. Because A is a subset of B, taking the subsequence of $\{b_n\}$ that contains the terms that are in A gives a listing of the elements of A. Because A is uncountable, this is impossible. **39.** We are given bijections f from A to B and g from C to D. Then the function from $A \times C$ to $B \times D$ that sends (a, c) to $(f(a), g(c))$ is a bijection. **41.** Suppose that $A_1, A_2, A_3, \ldots$ are countable sets. Because A_i is countable, we can list its elements in a sequence as $a_{i1}, a_{i2}, a_{i3}, \ldots$. The elements of the set $\bigcup_{i=1}^{n} A_i$ can be listed by listing all terms a_{ij} with $i + j = 2$, then all terms a_{ij} with $i + j = 3$, then all terms a_{ij} with $i + j = 4$, and so on. **43.** There are a finite number of bit strings of length m, namely, 2^m. The set of all bit, strings is the union of the sets of bit strings of length m for $m = 0, 1, 2, \ldots$. Because the union of a countable number of countable sets is countable (see Exercise 41), there are a countable number of bit strings. **45.** For any finite alphabet there are a finite number of strings of length n, whenever n is a positive integer. It follows by the result of Exercise 41 that there are only a countable number of strings from any given finite alphabet. Because the set of all computer programs in a particular language is a subset of the set of all strings of a finite alphabet, which is a countable set by the result from Exercise 36, it is itself a countable set. **47.** Exercise 45 shows that there are only a countable number of computer programs. Consequently, there are only a countable number of computable functions. Because, as Exercise 46 shows, there are an uncountable number of functions, not all functions are computable.

Supplementary Exercises

1. a) $\overline{A}$ **b)** $A \cap B$ **c)** $A - B$ **d)** $\overline{A} \cap \overline{B}$ **e)** $A \oplus B$ **3.** Yes **5.** $A-(A-B) = A-(A \cap \overline{B}) = A \cap \overline{(A \cap \overline{B})} = A \cap (\overline{A} \cup B) = (A \cap \overline{A}) \cup (A \cap B) = \emptyset \cup (A \cap B) = A \cap B$ **7.** Let $A = \{1\}, B = \emptyset, C = \{1\}$. Then $(A - B) - C = \emptyset$, but $A - (B - C) = \{1\}$. **9.** No. For example, let $A = B = \{a, b\}$, $C = \emptyset$, and $D = \{a\}$. Then $(A - B) - (C - D) = \emptyset - \emptyset = \emptyset$, but $(A - C) - (B - D) = \{a, b\} - \{b\} = \{a\}$. **11. a)** $|\emptyset| \le |A \cap B| \le |A| \le |A \cup B| \le |U|$ **b)** $|\emptyset| \le |A - B| \le |A \oplus B| \le |A \cup B| \le |A| + |B|$ **13. a)** Yes, no **b)** Yes, no **c)** f has inverse with $f^{-1}(a) = 3$, $f^{-1}(b) = 4$, $f^{-1}(c) = 2$, $f^{-1}(d) = 1$; g has no inverse. **15.** Let $f(a) = f(b) = 1$, $f(c) = f(d) = 2$, $S = \{a, c\}$, $T = \{b, d\}$. Then $f(S \cap T) = f(\emptyset) = \emptyset$, but $f(S) \cap f(T) = \{1, 2\} \cap \{1, 2\} = \{1, 2\}$. **17.** Let $x \in A$. Then $S_f(\{x\}) = \{f(y) \mid y \in \{x\}\} = \{f(x)\}$. By the same reasoning, $S_g(\{x\}) = \{g(x)\}$. Because $S_f = S_g$, we can conclude that $\{f(x)\} = \{g(x)\}$, and so necessarily $f(x) = g(x)$. **19.** The equation is true if and only if the sum of the fractional parts of x and y is less than 1. **21.** The equation is true if and only if either both x and y are integers, or x is not an integer but the sum of the fractional parts of x and y is less than or equal to 1. **23.** If x is an integer, then $\lfloor x \rfloor + \lfloor m - x \rfloor = x + m - x = m$. Otherwise, write x in terms of its integer and fractional parts: $x = n + \epsilon$, where $n = \lfloor x \rfloor$ and $0 < \epsilon < 1$. In this case $\lfloor x \rfloor + \lfloor m - x \rfloor = \lfloor n + \epsilon \rfloor + \lfloor m - n - \epsilon \rfloor = n + m - n - 1 = m - 1$. **25.** Write $n = 2k + 1$ for some integer k. Then $n^2 = 4k^2 + 4k + 1$, so $n^2/4 = k^2 + k + \frac{1}{4}$. Therefore, $\lceil n^2/4 \rceil = k^2 + k + 1$. But $(n^2 + 3)/4 = (4k^2 + 4k + 1 + 3)/4 = k^2 + k + 1$. **27.** Let $x = n + (r/m) + \epsilon$, where n is an integer, r is a nonnegative integer less than m, and ϵ is a real number with $0 \le \epsilon < 1/m$. The left-hand side is $\lfloor nm + r + m\epsilon \rfloor = nm + r$. On the right-hand side, the terms $\lfloor x \rfloor$ through $\lfloor x + (m + r - 1)/m \rfloor$ are all just n and the terms from $\lfloor x + (m - r)/m \rfloor$ on are all $n + 1$. Therefore, the right-hand side is $(m - r)n + r(n + 1) = nm + r$, as well. **29.** 101 **31.** $a_1 = 1$; $a_{2n+1} = n \cdot a_{2n}$ for all $n > 0$; and $a_{2n} = n + a_{2n-1}$ for all $n > 0$. The next four terms are 5346, 5353, 37471, and 37479.

CHAPTER 3

Section 3.1

1. $max := 1$, $i := 2$, $max := 8$, $i := 3$, $max := 12$, $i := 4$, $i := 5$, $i := 6$, $i := 7$, $max := 14$, $i := 8$, $i := 9$, $i := 10$, $i := 11$

3.
```
procedure sum(a_1, ..., a_n: integers)
  sum := a_1
  for i := 2 to n
    sum := sum + a_i
  {sum has desired value}
```

5.
```
procedure duplicates(a_1, a_2, ..., a_n: integers in
    nondecreasing order)
  k := 0 {this counts the duplicates}
  j := 2
  while j ≤ n
  begin
    if a_j = a_{j-1} then
    begin
      k := k + 1
      c_k := a_j
      while (j ≤ n and a_j = c_k)
        j := j + 1
    end
  j := j + 1
  end {c_1, c_2, ..., c_k is the desired list}
```

7.
```
procedure last even location(a_1, a_2, ..., a_n: integers)
  k := 0
  for i := 1 to n
    if a_i is even then k := i
  end {k is the desired location (or 0 if there are no evens)}
```

9.
```
procedure palindrome check(a_1 a_2 ... a_n: string)
  answer := true
  for i := 1 to ⌊n/2⌋
    if a_i ≠ a_{n+1-i} then answer := false
  end {answer is true iff string is a palindrome}
```

11.
```
procedure interchange(x, y: real numbers)
  z := x
  x := y
  y := z
```
The minimum number of assignments needed is three.

13. Linear search: $i := 1, i := 2, i := 3, i := 4, i := 5, i := 6$, $i := 7$, $location := 7$; binary search: $i := 1$, $j := 8$, $m := 4$, $i := 5$, $m := 6$, $i := 7$, $m := 7$, $j := 7$, $location := 7$

15.
```
procedure insert(x, a_1, a_2, ..., a_n: integers)
  {the list is in order: a_1 ≤ a_2 ≤ ··· ≤ a_n}
  a_{n+1} := x + 1
  i := 1
```

```
while x > a_i
  i := i + 1
for j := 0 to n − i
  a_{n−j+1} := a_{n−j}
a_i := x
{x has been inserted into correct position}
```

17.
```
procedure first largest(a_1, ..., a_n: integers)
max := a_1
location := 1
for i := 2 to n
begin
  if max < a_i then
  begin
    max := a_i
    location := i
  end
end
```

19.
```
procedure mean-median-max-min(a, b, c: integers)
mean := (a + b + c)/3
{the six different orderings of a, b, c with respect
   to ≥ will be handled separately}
if a > b then
begin
  if b > c then
  median := b; max := a; min := c
end
  ...
(The rest of the algorithm is similar.)
```

21.
```
procedure first-three (a_1, a_2, ..., a_n: integers)
if a_1 > a_2 then interchange a_1 and a_2
if a_2 > a_3 then interchange a_2 and a_3
if a_1 > a_2 then interchange a_1 and a_2
```

23.
```
procedure onto(f: function from A to B where
     A = {a_1, ..., a_n}, B = {b_1, ..., b_m}, a_1, ..., a_n,
     b_1, ..., b_m are integers)
for i := 1 to m
  hit(b_i) := 0
count := 0
for j := 1 to n
  if hit(f(a_j)) = 0 then
  begin
    hit(f(a_j)) := 1
    count := count + 1
  end
if count = m then onto := true
else onto := false
```

25.
```
procedure ones(a: bit string, a = a_1 a_2 ... a_n)
ones:= 0
for i := 1 to n
begin
  if a_i := 1 then
    ones := ones + 1
  end {ones is the number of ones in the bit
strings a}
```

27.
```
procedure ternary search(s: integer, a_1, a_2, ..., a_n:
  increasing integers)
i := 1
j := n
while i < j − 1
begin
  l = ⌊(i + j)/3⌋
  u = ⌊2(i + j)/3⌋
  if x > a_u then i := u + 1
  else if x > a_l then
  begin
    i := l + 1
    j := u
  end
  else j := l
end
if x = a_i then location := i
else if x = a_j then location := j
else location := 0
{location is the subscript of the term equal to x
  (0 if not found)}
```

29.
```
procedure find a mode(a_1, a_2, ..., a_n: nondecreasing
     integers)
modecount := 0
i := 1
while i ≤ n
begin
  value := a_i
  count := 1
  while i ≤ n and a_i = value
  begin
    count := count + 1
    i := i + 1
  end
  if count > modecount then
  begin
    modecount := count
    mode := value
  end
end
{mode is the first value occurring most often}
```

31.
```
procedure find duplicate(a_1, a_2, ..., a_n: integers)
location := 0
i := 2
while i ≤ n and location = 0
begin
  j := 1
  while j < i and location = 0
    if a_i = a_j then location := i
    else j := j + 1
  i := i + 1
end
{location is the subscript of the first value that
  repeats a previous value in the sequence}
```

33.
```
procedure find decrease(a_1, a_2, ..., a_n: positive
    integers)
location := 0
i := 2
while i ≤ n and location = 0
```

if $a_i < a_{i-1}$ **then** *location* $:= i$
else $i := i + 1$
{*location* is the subscript of the first value less than the immediately preceding one}

35. At the end of the first pass: 1, 3, 5, 4, 7; at the end of the second pass: 1, 3, 4, 5, 7; at the end of the third pass: 1, 3, 4, 5, 7; at the end of the fourth pass: 1, 3, 4, 5, 7

37. **procedure** *better bubblesort* ($a_1, \ldots, a_n$: integers)
$i := 1$; *done* $:=$ **false**
while ($i < n$ and *done* $=$ **false**)
begin
done $:=$ **true**
for $j := 1$ **to** $n - i$
if $a_j > a_{j+1}$ **then**
begin
interchange a_j and a_{j+1}
done $:=$ **false**
end
$i := i + 1$
end $\{a_1, \ldots, a_n$ is in increasing order$\}$

39. At the end of the first, second, and third passes: 1, 3, 5, 7, 4; at the end of the fourth pass: 1, 3, 4, 5, 7 **41. a)** 1, 5, 4, 3, 2; 1, 2, 4, 3, 5; 1, 2, 3, 4, 5; 1, 2, 3, 4, 5 **b)** 1, 4, 3, 2, 5; 1, 2, 3, 4, 5; 1, 2, 3, 4, 5; 1, 2, 3, 4, 5 **c)** 1, 2, 3, 4, 5; 1, 2, 3, 4, 5; 1, 2, 3, 4, 5; 1, 2, 3, 4, 5 **43.** We carry out the linear search algorithm given as Algorithm 2 in this section, except that we replace $x \neq a_i$ by $x < a_i$, and we replace the **else** clause with **else** *location* $:= n + 1$. **45.** $2 + 3 + 4 + \cdots + n = (n^2 + n - 2)/2$ **47.** Find the location for the 2 in the list 3 (one comparison), and insert it in front of the 3, so the list now reads 2, 3, 4, 5, 1, 6. Find the location for the 4 (compare it to the 2 and then the 3), and insert it, leaving 2, 3, 4, 5, 1, 6. Find the location for the 5 (compare it to the 3 and then the 4), and insert it, leaving 2, 3, 4, 5, 1, 6. Find the location for the 1 (compare it to the 3 and then the 2 and then the 2 again), and insert it, leaving 1, 2, 3, 4, 5, 6. Find the location for the 6 (compare it to the 3 and then the 4 and then the 5), and insert it, giving the final answer 1, 2, 3, 4, 5, 6.

49. **procedure** *binary insertion sort*($a_1, a_2, \ldots, a_n$: real numbers with $n \geq 2$)
for $j := 2$ **to** n
begin
{binary search for insertion location i}
left $:= 1$
right $:= j - 1$
while *left* $<$ *right*
begin
middle $:= \lfloor (\mathit{left} + \mathit{right})/2 \rfloor$
if $a_j > a_{middle}$ **then** *left* $:=$ *middle* $+ 1$
else *right* $:=$ *middle*
end
if $a_j < a_{left}$ **then** $i :=$ *left* **else** $i :=$ *left* $+ 1$
{insert a_j in location i by moving a_i through a_{j-1} toward back of list}
$m := a_j$
for $k := 0$ **to** $j - i - 1$
$a_{j-k} := a_{j-k-1}$
$a_i := m$
end $\{a_1, a_2, \ldots, a_n$ are sorted$\}$

51. The variation from Exercise 50 **53. a)** Two quarters, one penny **b)** Two quarters, one dime, one nickel, four pennies **c)** A three quarters, one penny **d)** Two quarters, one dime **55.** Greedy algorithm uses fewest coins in parts (a), (c), and (d). **a)** Two quarters, one penny **b)** Two quarters, one dime, nine pennies **c)** Three quarters, one penny **d)** Two quarters, one dime **57. a)** The variable f will give the finishing time of the talk last selected, starting out with f equal to the time the hall becomes available. Order the talks in increasing order of the ending times, and start at the top of the list. At each stage of the algorithm, go down the list of talks from where it left off, and find the first one whose starting time is not less than f. Schedule that talk and update f to record its finishing time. **b)** The 9:00–9:45 talk, the 9:50–10:15 talk, the 10:15–10:45 talk, the 11:00–11:15 talk **59. a)** Here we assume that the men are the suitors and the women the suitees.

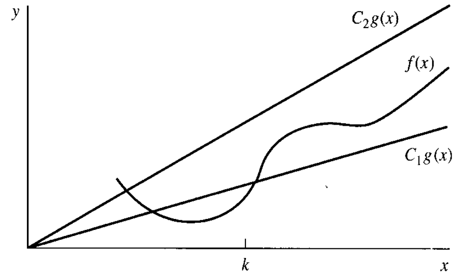
procedure *stable*($M_1, M_2, \ldots, M_s, W_1, W_2, \ldots, W_s$: preference lists)
for $i := 1$ **to** s
mark man i as rejected
for $i := 1$ **to** s
set man i's rejection list to be empty
for $j := 1$ **to** s
set woman j's proposal list to be empty
while rejected men remain
begin
for $i := 1$ **to** s
if man i is marked rejected **then** add i to the proposal list for the woman j who ranks highest on his preference list but does not appear on his rejection list, and mark i as not rejected
for $j := 1$ **to** s
if woman j's proposal list is nonempty **then** remove from j's proposal list all men i except the man i_0 who ranks highest on her preference list, and for each such man i mark him as rejected and add j to his rejection list
end
for $j := 1$ **to** s
match j with the one man on j's proposal list
{This matching is stable.}

b) There are at most s^2 iterations of the **while** loop, so the algorithm must terminate. Indeed, if at the conclusion of the **while** loop rejected men remain, then some man must have been rejected and so his rejection list grew. Thus, each pass through the **while** loop, at least one more of the s^2 possible rejections will have been recorded, unless the loop is about to terminate. Furthermore, when the **while** loop terminates, each man will have one pending proposal, and each woman will have at most one pending proposal, so the assignment must be one-to-one. **c)** If the assignment is not stable, then there is a man m and a woman w such that m prefers w to the woman w' with whom he is matched, and w prefers m to the man with whom she is matched. But m must have proposed to w before he proposed to w', because he prefers the former. Because m did not end up matched with w, she must have rejected him. Women reject a suitor only when they get a better proposal, and they eventually get matched with a pending suitor, so the woman with whom w is matched must be better in her eyes than m, contradicting our original assumption. Therefore the marriage is stable. **61.** Run the two programs on their inputs concurrently and report which one halts.

Section 3.2

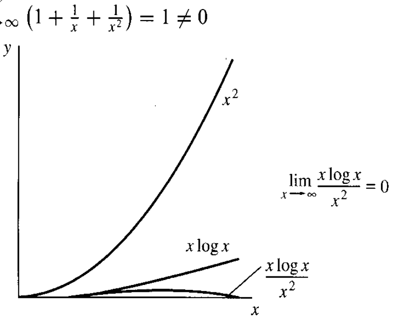
1. The choices of C and k are not unique. **a)** $C = 1, k = 10$ **b)** $C = 4, k = 7$ **c)** No **d)** $C = 5, k = 1$ **e)** $C = 1, k = 0$ **f)** $C = 1$, $k = 2$ **3.** $x^4 + 9x^3 + 4x + 7 \le 4x^4$ for all $x > 9$; witnesses $C = 4$, $k = 9$ **5.** $(x^2 + 1)/(x + 1) = x - 1 + 2/(x + 1) < x$ for all $x > 1$; witnesses $C = 1, k = 1$ **7.** The choices of C and k are not unique. **a)** $n = 3, C = 3, k = 1$ **b)** $n = 3, C = 4, k = 1$ **c)** $n = 1, C = 2, k = 1$ **d)** $n = 0$, $C = 2$, $k = 1$ **9.** $x^2 + 4x + 17 \le 3x^3$ for all $x > 17$, so $x^2 + 4x + 17$ is $O(x^3)$, with witnesses $C = 3, k = 17$. However, if x^3 were $O(x^2 + 4x + 17)$, then $x^3 \le C(x^2 + 4x + 17) \le 3Cx^2$ for some C, for all sufficiently large x, which implies that $x \le 3C$ for all sufficiently large x, which is impossible. Hence, x^3 is not $O(x^2 + 4x + 17)$. **11.** $3x^4 + 1 \le 4x^4 = 8(x^4/2)$ for all $x > 1$, so $3x^4 + 1$ is $O(x^4/2)$, with witnesses $C = 8$, $k = 1$. Also $x^4/2 \le 3x^4 + 1$ for all $x > 0$, so $x^4/2$ is $O(3x^4 + 1)$, with witnesses $C = 1$, $k = 0$. **13.** Because $2^n \le 3^n$ for all $n > 0$, it follows that 2^n is $O(3^n)$, with witnesses $C = 1$, $k = 0$. However, if 3^n were $O(2^n)$, then for some C, $3^n \le C \cdot 2^n$ for all sufficiently large n. This says that $C \ge (3/2)^n$ for all sufficiently large n, which is impossible. Hence, 3^n is not $O(2^n)$. **15.** All functions for which there exist real numbers k and C with $|f(x)| \le C$ for $x > k$. These are the functions $f(x)$ that are bounded for all sufficiently large x. **17.** There are constants C_1, C_2, k_1, and k_2 such that $|f(x)| \le C_1|g(x)|$ for all $x > k_1$ and $|g(x)| \le C_2|h(x)|$ for all $x > k_2$. Hence, for $x > \max(k_1, k_2)$ it follows that $|f(x)| \le C_1|g(x)| \le C_1C_2|h(x)|$. This shows that $f(x)$ is $O(h(x))$. **19. a)** $O(n^3)$ **b)** $O(n^5)$ **c)** $O(n^3 \cdot n!)$ **21. a)** $O(n^2 \log n)$ **b)** $O(n^2(\log n)^2)$ **c)** $O(n^{2^n})$ **23. a)** Neither $\Theta(x^2)$ nor $\Omega(x^2)$ **b)** $\Theta(x^2)$ and $\Omega(x^2)$ **c)** Neither $\Theta(x^2)$ nor $\Omega(x^2)$ **d)** $\Omega(x^2)$, but not $\Theta(x^2)$ **e)** $\Omega(x^2)$, but not $\Theta(x^2)$ **f)** $\Omega(x^2)$ and $\Theta(x^2)$ **25.** If $f(x)$ is $\Theta(g(x))$, then there exist constants C_1 and C_2 with $C_1|g(x)| \le |f(x)| \le C_2|g(x)|$. It follows that $|f(x)| \le C_2|g(x)|$ and $|g(x)| \le (1/C_1)|f(x)|$ for $x > k$. Thus, $f(x)$ is $O(g(x))$ and $g(x)$ is $O(f(x))$. Conversely, suppose that $f(x)$ is $O(g(x))$ and $g(x)$ is $O(f(x))$. Then there are constants C_1, C_2, k_1, and k_2 such that $|f(x)| \le C_1|g(x)|$ for $x > k_1$ and $|g(x)| \le C_2|f(x)|$ for $x > k_2$. We can assume that $C_2 > 0$ (we can always make C_2 larger). Then we have $(1/C_2)|g(x)| \le |f(x)| \le C_1|g(x)|$ for $x > \max(k_1, k_2)$. Hence, $f(x)$ is $\Theta(g(x))$. **27.** If $f(x)$ is $\Theta(g(x))$, then $f(x)$ is both $O(g(x))$ and $\Omega(g(x))$. Hence, there are positive constants C_1, k_1, C_2, and k_2 such that $|f(x)| \le C_2|g(x)|$ for all $x > k_2$ and $|f(x)| \ge C_1|g(x)|$ for all $x > k_1$. It follows that $C_1|g(x)| \le |f(x)| \le C_2|g(x)|$ whenever $x > k$, where $k = \max(k_1, k_2)$. Conversely, if there are positive constants C_1, C_2, and k such that $C_1|g(x)| \le |f(x)| \le C_2|g(x)|$ for $x > k$, then taking $k_1 = k_2 = k$ shows that $f(x)$ is both $O(g(x))$ and $\Theta(g(x))$.

29.



31. If $f(x)$ is $\Theta(1)$, then $|f(x)|$ is bounded between positive constants C_1 and C_2. In other words, $f(x)$ cannot grow larger than a fixed bound or smaller than the negative of this bound and must not get closer to 0 than some fixed bound. **33.** Because $f(x)$ is $O(g(x))$, there are constants C and l such that $|f(x)| \le C|g(x)|$ for $x > l$. Hence, $|f^k(x)| \le C^k|g^k(x)|$ for $x > l$, so $f^k(x)$ is $O(g^k(x))$ by taking the constant to be C^k. **35.** Because $f(x)$ and $g(x)$ are increasing and unbounded, we can assume $f(x) \ge 1$ and $g(x) \ge 1$ for sufficiently large x. There are constants C and k with $f(x) \le Cg(x)$ for $x > k$. This implies that $\log f(x) \le \log C + \log g(x) < 2 \log g(x)$ for sufficiently large x. Hence, $\log f(x)$ is $O(\log g(x))$. **37.** By definition there are positive constraints C_1, C_1', C_2, C_2', k_1, k_1', k_2, and k_2' such that $f_1(x) \ge C_1|g(x)|$ for all $x > k_1$, $f_1(x) \le C_1'|g(x)|$ for all $x > k_1'$, $f_2(x) \ge C_2|g(x)|$ for all $x > k_2$, and $f_2(x) \le C_2'|g(x)|$ for all $x > k_2'$. Adding the first and third inequalities shows that $f_1(x) + f_2(x) \ge (C_1 + C_2)|g(x)|$ for all $x > k$ where $k = \max(k_1, k_2)$. Adding the second and fourth inequalities shows that $f_1(x) + f_2(x) \le (C_1' + C_2')|g(x)|$ for all $x > k'$ where $k' = \max(k_1', k_2')$. Hence, $f_1(x) + f_2(x)$ is $\Theta(g(x))$. This is no longer true if f_1 and f_2 can assume negative values. **39.** This is false. Let $f_1 = x^2 + 2x$, $f_2(x) = x^2 + x$, and $g(x) = x^2$. Then $f_1(x)$ and $f_2(x)$ are both $O(g(x))$, but $(f_1 - f_2)(x)$ is not. **41.** Take $f(n)$ to be the function with $f(n) = n$ if n is an odd positive integer and $f(n) = 1$ if n is an even positive integer and $g(n)$ to be the function with $g(n) = 1$ if n is an odd positive integer and $g(n) = n$ if n is an even positive integer. **43.** There are positive constants C_1, C_2, C_1', C_2', k_1, k_1', k_2, and k_2' such that $|f_1(x)| \ge C_1|g_1(x)|$ for all $x > k_1$, $|f_1(x)| \le C_1'|g_1(x)|$ for all $x \ge k_1'$, $|f_2(x)| > C_2|g_2(x)|$ for all $x > k_2$, and $|f_2(x)| \le C_2'|g_2(x)|$ for all $x > k_2'$. Because f_2 and g_2 are never zero, the last two inequalities can be rewritten as $|1/f_2(x)| \le (1/C_2)|1/g_2(x)|$ for all $x > k_2$ and $|1/f_2(x)| \ge (1/C_2')|1/g_2(x)|$ for all $x > k_2'$. Multiplying the first and rewritten fourth inequalities shows that $|f_1(x)/f_2(x)| \ge (C_1/C_2')|g_1(x)/g_2(x)|$ for all $x > \max(k_1, k_2')$, and multiplying the second and rewritten third inequalities gives $|f_1(x)/f_2(x)| \le (C_1'/C_2)|g_1(x)/g_2(x)|$ for all $x > \max(k_1', k_2)$. It follows that f_1/f_2 is big-Theta of g_1/g_2. **45.** There exist positive constants $C_1, C_2, k_1, k_2, k_1', k_2'$ such that $|f(x, y)| \le C_1|g(x, y)|$ for all $x > k_1$ and $y > k_2$ and $|f(x, y)| \geq C_2|g(x, y)|$ for all $x > k_1'$ and $y > k_2'$. **47.** $(x^2 + xy + x\log y)^3 < (3x^2y^3) = 27x^6y^3$ for $x > 1$ and $y > 1$, because $x^2 < x^2y, xy < x^2y$, and $x \log y < x^2y$. Hence, $(x^2 + xy + x\log y)^3$ is $O(x^6y^3)$. **49.** For all positive real numbers x and y, $\lfloor xy \rfloor \leq xy$. Hence, $\lfloor xy \rfloor$ is $O(xy)$ from the definition, taking $C = 1$ and $k_1 = k_2 = 0$. **51. a)** $\lim_{x\to\infty} x^2/x^3 = \lim_{x\to\infty} 1/x = 0$ **b)** $\lim_{x\to\infty} \frac{x\log x}{x^2} = \lim_{x\to\infty} \frac{\log x}{x} = \lim_{x\to\infty} \frac{1}{x \ln 2} = 0$ (using L'Hôpital's rule) **c)** $\lim_{x\to\infty} \frac{x^2}{2^x} = \lim_{x\to\infty} \frac{2x}{2^x \cdot \ln 2} = \lim_{x\to\infty} \frac{2}{2^x \cdot (\ln 2)^2} = 0$ (using L'Hôpital's rule) **d)** $\lim_{x\to\infty} \frac{x^2+x+1}{x^2} = \lim_{x\to\infty} \left(1 + \frac{1}{x} + \frac{1}{x^2}\right) = 1 \neq 0$

53.



55. No. Take $f(x) = 1/x^2$ and $g(x) = 1/x$. **57. a)** Because $\lim_{x\to\infty} f(x)/g(x) = 0$, $|f(x)|/|g(x)| < 1$ for sufficiently large x. Hence, $|f(x)| < |g(x)|$ for $x > k$ for some constant k. Therefore, $f(x)$ is $O(g(x))$. **b)** Let $f(x) = g(x) = x$. Then $f(x)$ is $O(g(x))$, but $f(x)$ is not $o(g(x))$ because $f(x)/g(x) = 1$. **59.** Because $f_2(x)$ is $o(g(x))$, from Exercise 57(a) it follows that $f_2(x)$ is $O(g(x))$. By Corollary 1, we have $f_1(x) + f_2(x)$ is $O(g(x))$. **61.** We can easily show that $(n - i)(i + 1) \geq n$ for $i = 0, 1, \ldots, n - 1$. Hence, $(n!)^2 = (n \cdot 1)((n - 1) \cdot 2) \cdot ((n - 2) \cdot 3) \cdots (2 \cdot (n - 1)) \cdot (1 \cdot n) \geq n^n$. Therefore, $2 \log n! \geq n \log n$. **63.** Compute that $\log 5! \approx 6.9$ and $(5 \log 5)/4 \approx 2.9$, so the inequality holds for $n = 5$. Assume $n \geq 6$. Because $n!$ is the product of all the integers from n down to 1, we have $n! > n(n - 1)(n - 2) \cdots \lceil n/2 \rceil$ (because at least the term 2 is missing). Note that there are more than $n/2$ terms in this product, and each term is at least as big as $n/2$. Therefore the product is greater than $(n/2)^{(n/2)}$. Taking the log of both sides of the inequality, we have $\log n! > \log\left(\frac{n}{2}\right)^{n/2} = \frac{n}{2}\log\frac{n}{2} = \frac{n}{2}(\log n - 1) > (n \log n)/4$, because $n > 4$ implies $\log n - 1 > (\log n)/2$. **65.** All are not asymptotic.

Section 3.3

1. $2n - 1$ **3.** Linear **5.** $O(n)$ **7. a)** $power := 1, y := 1$; $i := 1$, $power := 2$, $y := 3$; $i := 2$, $power := 4, y := 15$ **b)** $2n$ multiplications and n additions **9. a)** $2^{10^9} \approx 10^{3 \times 10^8}$ **b)** 10^9 **c)** 3.96×10^7 **d)** 3.16×10^4 **e)** 29 **f)** 12 **11. a)** 36 years **b)** 13 days **c)** 19 minutes **13.** The average number of comparisons is $(3n+4)/2$. **15.** $O(\log n)$ **17.** $O(n)$ **19.** $O(n^2)$ **21.** $O(n)$ **23.** $O(n)$ **25.** $O(\log n)$ comparisons; $O(n^2)$ swaps **27. a)** doubles **b)** increases by 1

Section 3.4

1. a) Yes **b)** No **c)** Yes **d)** No **3.** Suppose that $a \mid b$. Then there exists an integer k such that $ka = b$. Because $a(ck) = bc$ it follows that $a \mid bc$. **5.** If $a \mid b$ and $b \mid a$, there are integers c and d such that $b = ac$ and $a = bd$. Hence, $a = acd$. Because $a \neq 0$ it follows that $cd = 1$. Thus either $c = d = 1$ or $c = d = -1$. Hence, either $a = b$ or $a = -b$. **7.** Because $ac \mid bc$ there is an integer k such that $ack = bc$. Hence, $ak = b$, so $a \mid b$. **9. a)** $2, 5$ **b)** $-11, 10$ **c)** $34, 7$ **d)** $77, 0$ **e)** $0, 0$ **f)** $0, 3$ **g)** $-1, 2$ **h)** $4, 0$ **11.** If $a \mathbin{\mathbf{mod}} m = b \mathbin{\mathbf{mod}} m$, then a and b have the same remainder when divided by m. Hence, $a = q_1m + r$ and $b = q_2m + r$, where $0 \leq r < m$. It follows that $a - b = (q_1 - q_2)m$, so $m \mid (a - b)$. It follows that $a \equiv b \pmod{m}$. **13.** There is some b with $(b - 1)k < n \leq bk$. Hence, $(b - 1)k \leq n - 1 < bk$. Divide by k to obtain $b - 1 < n/k \leq b$ and $b - 1 \leq (n - 1)/k < b$. Hence, $\lceil n/k \rceil = b$ and $\lfloor (n - 1)/k \rfloor = b - 1$. **15.** $x \mathbin{\mathbf{mod}} m$ if $x \mathbin{\mathbf{mod}} m \leq \lceil m/2 \rceil$ and $(x \mathbin{\mathbf{mod}} m) - m$ if $x \mathbin{\mathbf{mod}} m > \lceil m/2 \rceil$ **17. a)** 1 **b)** 2 **c)** 3 **d)** 9 **19. a)** No **b)** No **c)** Yes **d)** No **21.** Let $m = tn$. Because $a \equiv b \pmod{m}$ there exists an integer s such that $a = b + sm$. Hence, $a = b + (st)n$, so $a \equiv b \pmod{n}$. **23. a)** Let $m = c = 2, a = 0$, and $b = 1$. Then $0 = ac \equiv bc = 2 \pmod{2}$, but $0 = a \not\equiv b = 1 \pmod{2}$. **b)** Let $m = 5$, $a = b = 3$, $c = 1$, and $d = 6$. Then $3 \equiv 3 \pmod{5}$ and $1 \equiv 6 \pmod{5}$, but $3^1 = 3 \not\equiv 4 \equiv 729 = 3^6 \pmod{5}$. **25.** Because $a \equiv b \pmod{m}$, there exists an integer s such that $a = b + sm$, so $a - b = sm$. Then $a^k - b^k = (a - b)(a^{k-1} + a^{k-2}b + \cdots + ab^{k-2} + b^{k-1})$, $k \geq 2$, is also a multiple of m. It follows that $a^k \equiv b^k \pmod{m}$. **27. a)** 7, 19, 7, 7, 18, 0 **b)** Take the next available space **mod** 31. **29.** 2, 6, 7, 10, 8, 2, 6, 7, 10, 8, ... **31. a)** GR QRW SDVV JR **b)** QB ABG CNFF TB **c)** QX UXM AHJJ ZX **33.** 4 **35.** The check digit of the ISBN for this book is valid because $1 \cdot 0 + 2 \cdot 0 + 3 \cdot 7 + 4 \cdot 2 + 5 \cdot 8 + 6 \cdot 8 + 7 \cdot 0 + 8 \cdot 0 + 9 \cdot 8 + 10 \cdot 2 \equiv 0 \pmod{11}$.

Section 3.5

1. 29, 71, 97 prime; 21, 111, 143 not prime **3. a)** $2^3 \cdot 11$ **b)** $2 \cdot 3^2 \cdot 7$ **c)** 3^6 **d)** $7 \cdot 11 \cdot 13$ **e)** $11 \cdot 101$ **f)** $2 \cdot 3^3 \cdot 5 \cdot 7 \cdot 13 \cdot 37$ **5.** $2^8 \cdot 3^4 \cdot 5^2 \cdot 7$ **7.** Suppose that $\log_2 3 = a/b$ where $a, b \in \mathbf{Z}^+$ and $b \neq 0$. Then $2^{a/b} = 3$, so $2^a = 3^b$. This violates the Fundamental Theorem of Arithmetic. Hence, $\log_2 3$ is irrational. **9.** 3, 5, and 7 are primes of the desired form. **11.** 1, 7, 11, 13, 17, 19, 23, 29 **13. a)** Yes **b)** No **c)** Yes **d)** Yes **15.** Suppose that n is not prime, so that $n = ab$, where a and b are integers greater than 1. Because $a > 1$, by the identity in the hint, $2^a - 1$ is a factor of $2^n - 1$ that is greater than 1, and the second factor in this identity is also greater than 1. Hence, $2^n - 1$ is not prime. **17. a)** 2 **b)** 4 **c)** 12 **19.** $\phi(p^k) = p^k - p^{k-1}$ **21. a)** $3^5 \cdot 5^3$ **b)** 1 **c)** 23^{17} **d)** $41 \cdot 43 \cdot 53$ **e)** 1

f) 1111 **23. a)** $2^{11} \cdot 3^7 \cdot 5^9 \cdot 7^3$ **b)** $2^9 \cdot 3^7 \cdot 5^5 \cdot 7^3 \cdot 11 \cdot 13 \cdot 17$ **c)** 23^{31} **d)** $41 \cdot 43 \cdot 53$ **e)** $2^{12}3^{13}5^{17}7^{21}$ **f)** Undefined **25.** gcd (92928, 123552) = 1056; lcm(92928, 123552) = 10,872,576; both products are 11,481,440,256. **27.** Because $\min(x, y) + \max(x, y) = x + y$, the exponent of p_i in the prime factorization of $\gcd(a, b) \cdot \operatorname{lcm}(a, b)$ is the sum of the exponents of p_i in the prime factorizations of a and b. **29. a)** $a_n = 1$ if n is prime and $a_n = 0$ otherwise. **b)** a_n is the smallest prime factor of n with $a_1 = 1$. **c)** a_n is the number of positive divisors of n. **d)** $a_n = 1$ if n has no divisors that are perfect squares greater than 1 and $a_n = 0$ otherwise. **e)** a_n is the largest prime less than or equal to n. **f)** a_n is the product of the first $n - 1$ primes. **31.** Because every second integer is divisible by 2, the product is divisible by 2. Because every third integer is divisible by 3, the product is divisible by 3. Therefore the product has both 2 and 3 in its prime factorization and is therefore divisible by $3 \cdot 2 = 6$. **33.** $n = 1601$ is a counterexample. **35.** Suppose that there are only finitely many primes of the form $4k + 3$, namely $q_1, q_2, \ldots, q_n$, where $q_1 = 3$, $q_2 = 7$, and so on. Let $Q = 4q_1q_2 \cdots q_n - 1$. Note that Q is of the form $4k + 3$ (where $k = q_1q_2 \cdots q_n - 1$). If Q is prime, then we have found a prime of the desired form different from all those listed. If Q is not prime, then Q has at least one prime factor not in the list $q_1, q_2, \ldots, q_n$, because the remainder when Q is divided by q_j is $q_j - 1$, and $q_j - 1 \neq 0$. Because all odd primes are either of the form $4k + 1$ or of the form $4k + 3$, and the product of primes of the form $4k + 1$ is also of this form (because $(4k + 1)(4m + 1) = 4(4km + k + m) + 1$), there must be a factor of Q of the form $4k + 3$ different from the primes we listed. **37.** Given a positive integer x, we show that there is exactly one positive rational number m/n (in lowest terms) such that $K(m/n) = x$. From the prime factorization of x, read off the m and n such that $K(m/n) = x$. The primes that occur to even powers are the primes that occur in the prime factorization of m, with the exponents being half the corresponding exponents in x; and the primes that occur to odd powers are the primes that occur in the prime factorization of n, with the exponents being half of one more than the exponents in x.

Section 3.6

1. a) 1110 0111 **b)** 1 0001 1011 0100 **c)** 1 0111 1101 0110 1100 **3. a)** 31 **b)** 513 **c)** 341 **d)** 26,896 **5. a)** 1000 0000 1110 **b)** 1 0011 0101 1010 1011 **c)** 1010 1011 1011 1010 **d)** 1101 1110 1111 1010 11001110 1101 **7.** 1010 1011 1100 1101 1110 1111 **9.** $(\text{B7B})_{16}$ **11.** Adding up to three leading 0s if necessary, write the binary expansion as $(\ldots b_{23}b_{22}b_{21}b_{20}b_{13}b_{12}b_{11}b_{10}b_{03}b_{02}b_{01}b_{00})_2$. The value of this numeral is $b_{00} + 2b_{01} + 4b_{02} + 8b_{03} + 2^4b_{10} + 2^5b_{11} + 2^6b_{12} + 2^7b_{13} + 2^8b_{20} + 2^9b_{21} + 2^{10}b_{22} + 2^{11}b_{23} + \cdots$, which we can rewrite as $b_{00} + 2b_{01} + 4b_{02} + 8b_{03} + (b_{10} + 2b_{11} + 4b_{12} + 8b_{13}) \cdot 2^4 + (b_{20} + 2b_{21} + 4b_{22} + 8b_{23}) \cdot 2^8 + \cdots$. Now $(b_{i3}b_{i2}b_{i1}b_{i0})_2$ translates into the hexadecimal digit h_i. So our number is $h_0 + h_1 \cdot 2^4 + h_2 \cdot 2^8 + \cdots = h_0 + h_1 \cdot 16 + h_2 \cdot 16^2 + \cdots$, which is the hexadecimal expansion $(\ldots h_1h_1h_0)_{16}$. **13.** Group together blocks of three binary digits, adding up to two initial 0s if necessary, and translate each block of three binary digits into a single octal digit. **15.** $(111011100101011010001)_2$, $(1273)_8$ **17.** Convert the given octal numeral to binary using Exercise 14, then convert from binary to hexadecimal using Example 6. **19.** 436 **21.** 27 **23. a)** 6 **b)** 3 **c)** 11 **d)** 3 **e)** 40 **f)** 12 **25.** 8 **27.** The binary expansion of the integer is the unique such sum. **29.** Let $a = (a_{n-1}a_{n-2} \ldots a_1a_0)_{10}$. Then $a = 10^{n-1}a_{n-1} + 10^{n-2}a_{n-2} + \cdots + 10a_1 + a_0 \equiv a_{n-1} + a_{n-2} + \cdots + a_1 + a_0 \pmod 3$, because $10^j \equiv 1 \pmod 3$ for all nonnegative integers j. It follows that $3 \mid a$ if and only if 3 divides the sum of the decimal digits of a. **31.** Let $a = (a_{n-1}a_{n-2} \ldots a_1a_0)_2$. Then $a = a_0 + 2a_1 + 2^2a_2 + \cdots + 2^{n-1}a_{n-1} \equiv a_0 - a_1 + a_2 - a_3 + \cdots \pm a_{n-1} \pmod 3$. It follows that a is divisible by 3 if and only if the sum of the binary digits in the even-numbered positions minus the sum of the binary digits in the odd-numbered positions is divisible by 3. **33. a)** -6 **b)** 13 **c)** -14 **d)** 0 **35.** The one's complement of the sum is found by adding the one's complements of the two integers except that a carry in the leading bit is used as a carry to the last bit of the sum. **37.** If $m \geq 0$, then the leading bit a_{n-1} of the one's complement expansion of m is 0 and the formula reads $m = \sum_{i=0}^{n-2} a_i 2^i$. This is correct because the right-hand side is the binary expansion of m. When m is negative, the leading bit a_{n-1} of the one's complement expansion of m is 1. The remaining $n - 1$ bits can be obtained by subtracting $-m$ from $111\ldots1$ (where there are $n - 1$ 1s), because subtracting a bit from 1 is the same as complementing it. Hence, the bit string $a_{n-2} \ldots a_0$ is the binary expansion of $(2^{n-1} - 1) - (-m)$. Solving the equation $(2^{n-1} - 1) - (-m) = \sum_{i=0}^{n-2} a_i 2^i$ for m gives the desired equation because $a_{n-1} = 1$. **39. a)** -7 **b)** 13 **c)** -15 **d)** -1 **41.** To obtain the two's complement representation of the sum of two integers, add their two's complement representations (as binary integers are added) and ignore any carry out of the leftmost column. However, the answer is invalid if an overflow has occurred. This happens when the leftmost digits in the two's complement representation of the two terms agree and the leftmost digit of the answer differs. **43.** If $m \geq 0$, then the leading bit a_{n-1} is 0 and the formula reads $m = \sum_{i=0}^{n-2} a_i 2^i$. This is correct because the right-hand side is the binary expansion of m. If $m < 0$, its two's complement expansion has 1 as its leading bit and the remaining $n - 1$ bits are the binary expansion of $2^{n-1} - (-m)$. This means that $(2^{n-1}) - (-m) = \sum_{i=0}^{n-2} a_i 2^i$. Solving for m gives the desired equation because $a_{n-1} = 1$. **45.** $4n$

47. procedure *Cantor*(x: positive integer)
$n := 1$; $f := 1$
while $(n + 1) \cdot f \leq x$
begin
$n := n + 1$
$f := f \cdot n$
end
$y := x$
while $n > 0$
begin

```
    a_n := ⌊y/f⌋
    y := y − a_n · f
    f := f/n
    n := n − 1
  end {x = a_n n! + a_{n−1}(n − 1)! + ··· + a_1 1!}
```

49. First step: $c = 0, d = 0, s_0 = 1$; second step: $c = 0, d = 1, s_1 = 0$; third step: $c = 1$, $d = 1$, $s_2 = 0$; fourth step: $c = 1$, $d = 1$, $s_3 = 0$; fifth step: $c = 1$, $d = 1$, $s_4 = 1$; sixth step: $c = 1, s_5 = 1$

51.
```
procedure subtract(a, b: positive integers, a > b,
    a = (a_{n−1}a_{n−2} ... a_1a_0)_2,
    b = (b_{n−1}b_{n−2} ... b_1b_0)_2)
  B := 0 {B is the borrow}
  for j := 0 to n − 1
  begin
    if a_j ≥ b_j + B then
    begin
      s_j := a_j − b_j − B
      B := 0
    end
    else
    begin
      s_j := a_j + 2 − b_j − B
      B := 1
    end
  end {(s_{n−1}s_{n−2} ... s_1s_0)_2 is the difference}
```

53.
```
procedure compare(a, b: positive integers,
    a = (a_n a_{n−1} ... a_1a_0)_2,
    b = (b_n b_{n−1} ... b_1b_0)_2)
  k := n
  while a_k = b_k and k > 0
    k := k − 1
  if a_k = b_k then print "a equals b"
  if a_k > b_k then print "a is greater than b"
  if a_k < b_k then print "a is less than b"
```

55. $O(\log n)$ **57.** The only time-consuming part of the algorithm is the **while** loop, which is iterated q times. The work done inside is a subtraction of integers no bigger than a, which has $\log a$ bits. The result now follows from Example 8.

Section 3.7

1. a) $1 = (-1) \cdot 10 + 1 \cdot 11$ **b)** $1 = 21 \cdot 21 + (-10) \cdot 44$ **c)** $12 = (-1) \cdot 36 + 48$ **d)** $1 = 13 \cdot 55 + (-21) \cdot 34$ **e)** $3 = 11 \cdot 213 + (-20) \cdot 117$ **f)** $223 = 1 \cdot 0 + 1 \cdot 223$ **g)** $1 = 37 \cdot 2347 + (-706) \cdot 123$ **h)** $2 = 1128 \cdot 3454 + (-835) \cdot 4666$ **i)** $1 = 2468 \cdot 9999 + (-2221) \cdot 11111$ **3.** $15 \cdot 7 = 105 \equiv 1 \pmod{26}$ **5.** 7 **7.** 52 **9.** Suppose that b and c are both inverses of a modulo m. Then $ba \equiv 1 \pmod{m}$ and $ca \equiv 1 \pmod{m}$. Hence, $ba \equiv ca \pmod{m}$. Because $\gcd(a, m) = 1$ it follows by Theorem 2 that $b \equiv c \pmod{m}$. **11.** $x \equiv 8 \pmod 9$ **13.** Let $m' = m/\gcd(c, m)$. Because all the common factors of m and c are divided out of m to obtain m', it follows that m' and c are relatively prime. Because m divides $(ac - bc) = (a - b)c$, it follows that m' divides $(a - b)c$. By Lemma 1, we see that m' divides $a - b$, so $a \equiv b \pmod{m'}$. **15.** Suppose that $x^2 \equiv 1 \pmod{p}$. Then p divides $x^2 - 1 = (x + 1)(x - 1)$. By Lemma 2 it follows that $p \mid (x + 1)$ or $p \mid (x - 1)$, so $x \equiv -1 \pmod{p}$ or $x \equiv 1 \pmod{p}$. **17. a)** Suppose that $ia \equiv ja \pmod{p}$, where $1 \le i < j < p$. Then p divides $ja - ia = a(j - i)$. By Theorem 1, because a is not divisible by p, p divides $j - i$, which is impossible because $j - i$ is a positive integer less than p. **b)** By part (a), because no two of $a, 2a, \dots, (p-1)a$ are congruent modulo p, each must be congruent to a different number from 1 to $p - 1$. It follows that $a \cdot 2a \cdot 3a \cdot \cdots \cdot (p-1) \cdot a \equiv 1 \cdot 2 \cdot 3 \cdot \cdots \cdot (p - 1) \pmod{p}$. It follows that $(p - 1)! \cdot a^{p-1} \equiv (p - 1)! \pmod{p}$. **c)** By Wilson's Theorem and part (b), if p does not divide a, it follows that $(-1) \cdot a^{p-1} \equiv -1 \pmod{p}$. Hence, $a^{p-1} \equiv 1 \pmod{p}$. **d)** If $p \mid a$, then $p \mid a^p$. Hence, $a^p \equiv a \equiv 0 \pmod{p}$. If p does not divide a, then $a^{p-1} \equiv a \pmod{p}$, by part (c). Multiplying both sides of this congruence by a gives $a^p \equiv a \pmod{p}$. **19.** All integers of the form $323 + 330k$, where k is an integer **21.** All integers of the form $16 + 252k$, where k is an integer **23.** Suppose that p is a prime appearing in the prime factorization of $m_1 m_2 \cdots m_n$. Because the m_is are relatively prime, p is a factor of exactly one of the m_is, say m_j. Because m_j divides $a - b$, it follows that $a - b$ has the factor p in its prime factorization to a power at least as large as the power to which it appears in the prime factorization of m_j. It follows that $m_1 m_2 \cdots m_n$ divides $a - b$, so $a \equiv b \pmod{m_1 m_2 \cdots m_n}$. **25.** $x \equiv 1 \pmod 6$ **27. a)** By Fermat's Little Theorem, we have $2^{10} \equiv 1 \pmod{11}$. Hence, $2^{340} = (2^{10})^{34} \equiv 1^{34} = 1 \pmod{11}$. **b)** Because $32 \equiv 1 \pmod{31}$, it follows that $2^{340} = (2^5)^{68} = 32^{68} \equiv 1^{68} = 1 \pmod{31}$. **c)** Because 11 and 31 are relatively prime, and $11 \cdot 31 = 341$, it follows by parts (a) and (b) and Exercise 23 that $2^{340} \equiv 1 \pmod{341}$. **29. a)** 3, 4, 8 **b)** 983 **31.** First, $2047 = 23 \cdot 89$ is composite. Write $2047 - 1 = 2046 = 2 \cdot 1023$, so $s = 1$ and $t = 1023$ in the definition. Then $2^{1023} = (2^{11})^{93} = 2048^{93} \equiv 1^{93} = 1 \pmod{2047}$, as desired. **33.** We must show that $b^{2820} \equiv 1 \pmod{2821}$ for all b relatively prime to 2821. Note that $2821 = 7 \cdot 13 \cdot 31$, and if $\gcd(b, 2821) = 1$, then $\gcd(b, 7) = \gcd(b, 13) = \gcd(b, 31) = 1$. Using Fermat's Little Theorem we find that $b^6 \equiv 1 \pmod 7$, $b^{12} \equiv 1 \pmod{13}$, and $b^{30} \equiv 1 \pmod{31}$. It follows that $b^{2820} \equiv (b^6)^{470} \equiv 1 \pmod 7$, $b^{2820} \equiv (b^{12})^{235} \equiv 1 \pmod{13}$, and $b^{2820} \equiv (b^{30})^{94} \equiv 1 \pmod{31}$. By Exercise 23 (or the Chinese Remainder Theorem) it follows that $b^{2820} \equiv 1 \pmod{2821}$, as desired. **35. a)** If we multiply out this expression, we get $n = 1296m^3 + 396m^2 + 36m + 1$. Clearly $6m \mid n - 1$, $12m \mid n - 1$, and $18m \mid n - 1$. Therefore, the conditions of Exercise 34 are met, and we conclude that n is a Carmichael number. **b)** Letting $m = 51$ gives $n = 172{,}947{,}529$. **37.** $0 = (0, 0)$, $1 = (1, 1)$, $2 = (2, 2)$, $3 = (0, 3)$, $4 = (1, 4)$, $5 = (2, 0)$, $6 = (0, 1)$, $7 = (1, 2)$, $8 = (2, 3)$, $9 = (0, 4)$, $10 = (1, 0)$, $11 = (2, 1)$, $12 = (0, 2)$, $13 = (1, 3)$, $14 = (2, 4)$ **39.** We have $m_1 = 99$, $m_2 = 98$, $m_3 = 97$, and $m_4 = 95$, so $m = 99 \cdot 98 \cdot 97 \cdot 95 = 89{,}403{,}930$. We find that $M_1 = m/m_1 = 903{,}070$, $M_2 = m/m_2 = 912{,}285$, $M_3 = m/m_3 = 921{,}690$, and $M_4 = m/m_4 = 941{,}094$. Using the Euclidean algorithm, we compute that $y_1 = 37$, $y_2 = 33$,

$y_3 = 24$, and $y_4 = 4$ are inverses of M_k modulo m_k for $k = 1, 2, 3, 4$, respectively. It follows that the solution is $65 \cdot 903{,}070 \cdot 37 + 2 \cdot 912{,}285 \cdot 33 + 51 \cdot 921{,}690 \cdot 24 + 10 \cdot 941{,}094 \cdot 4 = 3{,}397{,}886{,}480 \equiv 537{,}140 \pmod{89{,}403{,}930}$. **41.** By Exercise 40 it follows that $\gcd(2^b - 1, (2^a - 1) \,\mathbf{mod}\, (2^b - 1)) = \gcd(2^b - 1, 2^{a \,\mathbf{mod}\, b} - 1)$. Because the exponents involved in the calculation are b and a **mod** b, the same as the quantities involved in computing $\gcd(a, b)$, the steps used by the Euclidean algorithm to compute $\gcd(2^a - 1, 2^b - 1)$ run in parallel to those used to compute $\gcd(a, b)$ and show that $\gcd(2^a - 1, 2^b - 1) = 2^{\gcd(a,b)} - 1$. **43.** Suppose that q is an odd prime with $q \mid 2^p - 1$. By Fermat's Little Theorem, $q \mid 2^{q-1} - 1$. From Exercise 41, $\gcd(2^p - 1, 2^{q-1} - 1) = 2^{\gcd(p,q-1)} - 1$. Because q is a common divisor of $2^p - 1$ and $2^{q-1} - 1$, $\gcd(2^p - 1, 2^{q-1} - 1) > 1$. Hence, $\gcd(p, q - 1) = p$, because the only other possibility, namely, $\gcd(p, q - 1) = 1$, gives us $\gcd(2^p - 1, 2^{q-1} - 1) = 1$. Hence, $p \mid q - 1$, and therefore there is a positive integer m such that $q - 1 = mp$. Because q is odd, m must be even, say, $m = 2k$, and so every prime divisor of $2^p - 1$ is of the form $2kp + 1$. Furthermore, the product of numbers of this form is also of this form. Therefore, all divisors of $2^p - 1$ are of this form. **45.** Suppose we know both $n = pq$ and $(p - 1)(q - 1)$. To find p and q, first note that $(p - 1)(q - 1) = pq - p - q + 1 = n - (p + q) + 1$. From this we can find $s = (p + q)$. Because $q = s - p$, we have $n = p(s - p)$. Hence, $p^2 - ps + n = 0$. We now can use the quadratic formula to find p. Once we have found p, we can find q because $q = n/p$. **47.** SILVER **49.** $34 \cdot 144 + (-55) \cdot 89 = 1$
51.
```
procedure extended Euclidean (a, b: positive
        integers)
  x := a
  y := b
  oldolds := 1
  olds := 0
  oldoldt := 0
  oldt := 1
  while y ≠ 0
  begin
    q := x div y
    r := x mod y
    x := y
    y := r
    s := oldolds − q · olds
    t := oldoldt − q · oldt
    oldolds := olds
    oldoldt := oldt
    olds := s
    oldt := t
  end {gcd(a, b) is x, and (oldolds)a + (oldoldt)b = x}
```
53. Assume that s is a solution of $x^2 \equiv a \pmod{p}$. Then because $(-s)^2 = s^2$, $-s$ is also a solution. Furthermore, $s \not\equiv -s \pmod{p}$. Otherwise, $p \mid 2s$, which implies that $p \mid s$, and this implies, using the original assumption, that $p \mid a$, which is a contradiction. Furthermore, if s and t are incongruent solutions modulo p, then because $s^2 \equiv t^2 \pmod{p}$, $p \mid (s^2 - t^2)$. This implies that $p \mid (s + t)(s - t)$, and by Lemma 2, $p \mid (s - t)$ or $p \mid (s + t)$, so $s \equiv t \pmod{p}$ or $s \equiv -t \pmod{p}$. Hence, there are at most two solutions. **55.** The value of $\left(\frac{a}{p}\right)$ depends only on whether a is a quadratic residue modulo p, that is, whether $x^2 \equiv a \pmod{p}$ has a solution. Because this depends only on the equivalence class of a modulo p, it follows that $\left(\frac{a}{p}\right) = \left(\frac{b}{p}\right)$ if $a \equiv b \pmod{p}$. **57.** By Exercise 56, $\left(\frac{a}{p}\right)\left(\frac{b}{p}\right) = a^{(p-1)/2} b^{(p-1)/2} = (ab)^{(p-1)/2} \equiv \left(\frac{ab}{p}\right) \pmod{p}$. **59.** $x \equiv 8, 13, 22$, or $27 \pmod{35}$ **61.** Suppose that we use a prime for n. To find a private decryption key from the corresponding public encryption key e, one would need to find a number d that is an inverse for e modulo $n - 1$ so that the calculation shown before Example 12 can go through. But finding such a d is easy using the Euclidean algorithm, because the person doing this would already know $n - 1$. In particular, to find d, one can work backward through the steps of the Euclidean algorithm to express 1 as a linear combination of e and $n - 1$; then d is the coefficient of e in this linear combination.

Section 3.8

1. a) 3×4 **b)** $\begin{bmatrix} 1 \\ 4 \\ 3 \end{bmatrix}$ **c)** $[2 \;\; 0 \;\; 4 \;\; 6]$ **d)** 1
e) $\begin{bmatrix} 1 & 2 & 1 \\ 1 & 0 & 1 \\ 1 & 4 & 3 \\ 3 & 6 & 7 \end{bmatrix}$ **3. a)** $\begin{bmatrix} 1 & 11 \\ 2 & 18 \end{bmatrix}$ **b)** $\begin{bmatrix} 2 & -2 & -3 \\ 1 & 0 & 2 \\ 9 & -4 & 4 \end{bmatrix}$
c) $\begin{bmatrix} -4 & 15 & -4 & 1 \\ -3 & 10 & 2 & -3 \\ 0 & 2 & -8 & 6 \\ 1 & -8 & 18 & -13 \end{bmatrix}$ **5.** $\begin{bmatrix} 9/5 & -6/5 \\ -1/5 & 4/5 \end{bmatrix}$
7. $\mathbf{0} + \mathbf{A} = [0 + a_{ij}] = [a_{ij} + 0] = \mathbf{0} + \mathbf{A}$ **9.** $\mathbf{A} + (\mathbf{B} + \mathbf{C}) = [a_{ij} + (b_{ij} + c_{ij})] = [(a_{ij} + b_{ij}) + c_{ij}] = (\mathbf{A} + \mathbf{B}) + \mathbf{C}$ **11.** The number of rows of $\mathbf{A}$ equals the number of columns of $\mathbf{B}$, and the number of columns of $\mathbf{A}$ equals the number of rows of $\mathbf{B}$. **13.** $\mathbf{A}(\mathbf{BC}) = \left[\sum_q a_{iq} \left(\sum_r b_{qr} c_{rl}\right)\right] = \left[\sum_q \sum_r a_{iq} b_{qr} c_{rl}\right] = \left[\sum_r \sum_q a_{iq} b_{qr} c_{rl}\right] = \left[\sum_r \left(\sum_q a_{iq} b_{qr}\right) c_{rl}\right] = (\mathbf{AB})\mathbf{C}$ **15.** $\mathbf{A}^n = \begin{bmatrix} 1 & n \\ 0 & 1 \end{bmatrix}$ **17. a)** Let $\mathbf{A} = [a_{ij}]$ and $\mathbf{B} = [b_{ij}]$. Then $\mathbf{A} + \mathbf{B} = [a_{ij} + b_{ij}]$. We have $(\mathbf{A} + \mathbf{B})^t = [a_{ji} + b_{ji}] = [a_{ji}] + [b_{ji}] = \mathbf{A}^t + \mathbf{B}^t$. **b)** Using the same notation as in part (a), we have $\mathbf{B}^t \mathbf{A}^t = \left[\sum_q b_{qi} a_{jq}\right] = \left[\sum_q a_{jq} b_{qi}\right] = (\mathbf{AB})^t$, because the (i, j)th entry is the (j, i)th entry of $\mathbf{AB}$. **19.** The result follows because $\begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} d & -b \\ -c & a \end{bmatrix} = \begin{bmatrix} ad - bc & 0 \\ 0 & ad - bc \end{bmatrix} = (ad - bc)\mathbf{I}_2 = \begin{bmatrix} d & -b \\ -c & a \end{bmatrix} \begin{bmatrix} a & b \\ c & d \end{bmatrix}$. **21.** $\mathbf{A}^n (\mathbf{A}^{-1})^n = \mathbf{A}(\mathbf{A} \cdots (\mathbf{A}(\mathbf{A}\mathbf{A}^{-1})\mathbf{A}^{-1}) \cdots \mathbf{A}^{-1})\mathbf{A}^{-1}$ by the associative law. Because $\mathbf{A}\mathbf{A}^{-1} = \mathbf{I}$, working from the inside shows that $\mathbf{A}^n (\mathbf{A}^{-1})^n = \mathbf{I}$. Similarly $(\mathbf{A}^{-1})^n \mathbf{A}^n = \mathbf{I}$. Therefore $(\mathbf{A}^n)^{-1} =$

$(\mathbf{A}^{-1})^n$. **23.** There are m_2 multiplications used to find each of the m_1m_3 entries of the product. Hence, $m_1m_2m_3$ multiplications are used. **25.** $\mathbf{A}_1((\mathbf{A}_2\mathbf{A}_3)\mathbf{A}_4)$ **27.** $x_1 = 1$, $x_2 = -1$, $x_3 = -2$

29. a) $\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 0 & 1 \end{bmatrix}$ **b)** $\begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$ **c)** $\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 0 & 1 \end{bmatrix}$

31. a) $\begin{bmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ 1 & 0 & 1 \end{bmatrix}$ **b)** $\begin{bmatrix} 1 & 0 & 0 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}$ **c)** $\begin{bmatrix} 1 & 0 & 0 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$

33. a) $\mathbf{A} \vee \mathbf{B} = [a_{ij} \vee b_{ij}] = [b_{ij} \vee a_{ij}] = \mathbf{B} \vee \mathbf{A}$ **b)** $\mathbf{A} \wedge \mathbf{B} = [a_{ij} \wedge b_{ij}] = [b_{ij} \wedge a_{ij}] = \mathbf{B} \wedge \mathbf{A}$ **35. a)** $\mathbf{A} \vee (\mathbf{B} \wedge \mathbf{C}) = [a_{ij}] \vee [b_{ij} \wedge c_{ij}] = [a_{ij} \vee (b_{ij} \wedge c_{ij})] = [(a_{ij} \vee b_{ij}) \wedge (a_{ij} \vee c_{ij})] = [a_{ij} \vee b_{ij}] \wedge [a_{ij} \vee c_{ij}] = (\mathbf{A} \vee \mathbf{B}) \wedge (\mathbf{A} \vee \mathbf{C})$ **b)** $\mathbf{A} \wedge (\mathbf{B} \vee \mathbf{C}) = [a_{ij}] \wedge [b_{ij} \vee c_{ij}] = [a_{ij} \wedge (b_{ij} \vee c_{ij})] = [(a_{ij} \wedge b_{ij}) \vee (a_{ij} \wedge c_{ij})] = [a_{ij} \wedge b_{ij}] \vee [a_{ij} \wedge c_{ij}] = (\mathbf{A} \wedge \mathbf{B}) \vee (\mathbf{A} \wedge \mathbf{C})$ **37.** $\mathbf{A} \odot (\mathbf{B} \odot \mathbf{C}) = \left[\bigvee_q a_{iq} \wedge \left(\bigvee_r (b_{qr} \wedge c_{rl})\right)\right] = \left[\bigvee_q \bigvee_r (a_{iq} \wedge b_{qr} \wedge c_{rl})\right] = \left[\bigvee_r \bigvee_q (a_{iq} \wedge b_{qr} \wedge c_{rl})\right] = \left[\bigvee_r \left(\bigvee_q (a_{iq} \wedge b_{qr})\right) \wedge c_{rl}\right] = (\mathbf{A} \odot \mathbf{B}) \odot \mathbf{C}$

Supplementary Exercises

1. a)
```
procedure last max(a1, ..., an: integers)
  max := a1
  last := 1
  i := 2
  while i ≤ n
  begin
    if ai ≥ max then
    begin
      max := ai
      last := i
    end
    i := i + 1
  end {last is the location of final occurrence of
    largest integer in list}
```
b) $2n - 1 = O(n)$ comparisons

3. a)
```
procedure pair zeros(b1b2 ... bn: bit string,
    n ≥ 2)
  x := b1
  y := b2
  k := 2
  while (k < n and (x ≠ 0 or y ≠ 0))
  begin
    k := k + 1
    x := y
    y := bk
  end
  if (x = 0 and y = 0) then print "YES"
  else print "NO"
```
b) $O(n)$ comparisons

5. a) and b)
```
procedure smallest and largest(a1, a2, ..., an: integers)
min := a1
max := a1
for i := 2 to n
begin
  if ai < min then min := ai
  if ai > max then max := ai
end {min is the smallest integer among the input, and
  max is the largest}
```
c) $2n - 2$

7. Before any comparisons are done, there is a possibility that each element could be the maximum and a possibility that it could be the minimum. This means that there are $2n$ different possibilities, and $2n - 2$ of them have to be eliminated through comparisons of elements, because we need to find the unique maximum and the unique minimum. We classify comparisons of two elements as "virgin" or "nonvirgin," depending on whether or not both elements being compared have been in any previous comparison. A virgin comparison eliminates the possibility that the larger one is the minimum and that the smaller one is the maximum; thus each virgin comparison eliminates two possibilities, but it clearly cannot do more. A nonvirgin comparison must be between two elements that are still in the running to be the maximum or two elements that are still in the running to be the minimum, and at least one of these elements must *not* be in the running for the other category. For example, we might be comparing x and y, where all we know is that x has been eliminated as the minimum. If we find that $x > y$ in this case, then only one possibility has been ruled out—we now know that y is not the maximum. Thus in the worst case, a nonvirgin comparison eliminates only one possibility. (The cases of other nonvirgin comparisons are similar.) Now there are at most $\lfloor n/2 \rfloor$ comparisons of elements that have not been compared before, each removing two possibilities; they remove $2\lfloor n/2 \rfloor$ possibilities altogether. Therefore we need $2n - 2 - 2\lfloor n/2 \rfloor$ more comparisons that, as we have argued, can remove only one possibility each, in order to find the answers in the worst case, because $2n - 2$ possibilities have to be eliminated. This gives us a total of $2n - 2 - 2\lfloor n/2 \rfloor + \lfloor n/2 \rfloor$ comparisons in all. But $2n - 2 - 2\lfloor n/2 \rfloor + \lfloor n/2 \rfloor = 2n - 2 - \lfloor n/2 \rfloor = 2n - 2 + \lceil -n/2 \rceil = \lceil 2n - n/2 \rceil - 2 = \lceil 3n/2 \rceil - 2$, as desired. **9.** At end of first pass: 3, 1, 4, 5, 2, 6; at end of second pass: 1, 3, 2, 4, 5, 6; at end of third pass: 1, 2, 3, 4, 5, 6; fourth pass finds nothing to exchange and algorithm terminates **11.** There are possibly as many as n passes through the list, and each pass uses $O(n)$ comparisons. Thus there are $O(n^2)$ comparisons in all. **13.** Because $\log n < n$, we have $(n \log n + n^2)^3 \le (n^2 + n^2)^3 \le (2n^2)^3 = 8n^6$ for all $n > 0$. This proves that $(n \log n + n^2)^3$ is $O(n^6)$, with witnesses $C = 8$ and $k = 0$. **15.** $O(x^2 2^x)$ **17.** Note that $\frac{n!}{2^n} = \frac{n}{2} \cdot \frac{n-1}{2} \cdots \frac{3}{2} \cdot \frac{2}{2} \cdot \frac{1}{2} > \frac{n}{2} \cdot 1 \cdot 1 \cdots 1 \cdot \frac{1}{2} = \frac{n}{4}$. **19.** 5, 22, -12, -29 **21.** Because $ac \equiv bc \pmod{m}$ there is an integer k such that $ac = bc + km$. Hence, $a - b = km/c$. Because $a - b$ is an integer, $c \mid km$. Letting $d = \gcd(m, c)$, write $c = de$. Because no factor of e divides m/d, it follows that $d \mid m$ and $e \mid k$.

Thus $a - b = (k/e)(m/d)$, where $k/e \in \mathbf{Z}$ and $m/d \in \mathbf{Z}$. Therefore $a \equiv b \pmod{m/d}$. **23.** 1 **25.** 1 **27.** $(a_n a_{n-1} \ldots a_1 a_0)_{10} = \sum_{k=0}^{n} 10^k a_k \equiv \sum_{k=0}^{n} a_k \pmod 9$ because $10^k \equiv 1 \pmod 9$ for every nonnegative integer k. **29.** If not, then suppose that $q_1, q_2, \ldots, q_n$ are all the primes of the form $6k+5$. Let $Q = 6q_1q_2\cdots q_n - 1$. Note that Q is of the form $6k+5$, where $k = q_1q_2\cdots q_n - 1$. Let $Q = p_1p_2\cdots p_t$ be the prime factorization of Q. No p_i is 2, 3, or any q_j, because the remainder when Q is divided by 2 is 1, by 3 is 2, and by q_j is $q_j - 1$. All odd primes other than 3 are of the form $6k+1$ or $6k+5$, and the product of primes of the form $6k+1$ is also of this form. Therefore at least one of the p_i's must be of the form $6k+5$, a contradiction. **31. a)** Not mutually relatively prime **b)** Mutually relatively prime **c)** Mutually relatively prime **d)** Mutually relatively prime **33. a)** The decryption function is $g(q) = \bar{a}(q - b)$ **mod** 26, where $\bar{a}$ is an inverse of a modulo 26. **b)** PLEASE SEND MONEY **35.** $x \equiv 28 \pmod{30}$ **37.** Recall that a nonconstant polynomial can take on the same value only a finite number of times. Thus f can take on the values 0 and ± 1 only finitely many times, so if there is not some y such that $f(y)$ is composite, then there must be some x_0 such that $\pm f(x_0)$ is prime, say p. Look at $f(x_0 + kp)$. When we plug $x_0 + kp$ in for x in the polynomial and multiply it out, every term will contain a factor of p except for the terms that form $f(x_0)$. Therefore $f(x_0 + kp) = f(x_0) + mp = (m \pm 1)p$ for some integer m. As k varies, this value can be 0, p, or $-p$ only finitely many times; therefore it must be a composite number for some values of k. **39.** Assume that every even integer greater than 2 is the sum of two primes, and let n be an integer greater than 5. If n is odd, write $n = 3 + (n-3)$ and decompose $n - 3 = p + q$ into the sum of two primes; if n is even, then write $n = 2 + (n-2)$ and decompose $n - 2 = p + q$ into the sum of two primes. For the converse, assume that every integer greater than 5 is the sum of three primes, and let n be an even integer greater than 2. Write $n + 2$ as the sum of three primes, one of which is necessarily 2, so $n + 2 = 2 + p + q$, whence $n = p + q$. **41.** $\mathbf{A}^{4n} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, $\mathbf{A}^{4n+1} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$, $\mathbf{A}^{4n+2} = \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}$, $\mathbf{A}^{4n+3} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$, for $n \geq 0$ **43.** Suppose that $\mathbf{A} = \begin{bmatrix} a & b \\ c & d \end{bmatrix}$. Let $\mathbf{B} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$. Because $\mathbf{AB} = \mathbf{BA}$, it follows that $c = 0$ and $a = d$. Let $\mathbf{B} = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix}$. Because $\mathbf{AB} = \mathbf{BA}$, it follows that $b = 0$. Hence, $\mathbf{A} = \begin{bmatrix} a & 0 \\ 0 & a \end{bmatrix} = a\mathbf{I}$.

45. procedure *triangular matrix multiplication*($\mathbf{A}, \mathbf{B}$: upper triangular $n \times n$ matrices, $\mathbf{A} = [a_{ij}]$, $\mathbf{B} = [b_{ij}]$)

for $i := 1$ **to** n
  for $j := i$ **to** n
  begin
    $c_{ij} := 0$
    for $k := i$ **to** j
      $c_{ij} := c_{ij} + a_{ik}b_{kj}$
  end

47. $(\mathbf{AB})(\mathbf{B}^{-1}\mathbf{A}^{-1}) = \mathbf{A}(\mathbf{BB}^{-1})\mathbf{A}^{-1} = \mathbf{AIA}^{-1} = \mathbf{AA}^{-1} = \mathbf{I}$. Similarly, $(\mathbf{B}^{-1}\mathbf{A}^{-1})(\mathbf{AB}) = \mathbf{I}$. Hence, $(\mathbf{AB})^{-1} = \mathbf{B}^{-1}\mathbf{A}^{-1}$. **49. a)** Let $\mathbf{A} \odot \mathbf{0} = [b_{ij}]$. Then $b_{ij} = (a_{i1} \wedge 0) \vee \cdots \vee (a_{ip} \wedge 0) = 0$. Hence, $\mathbf{A} \odot \mathbf{0} = \mathbf{0}$. Similarly $\mathbf{0} \odot \mathbf{A} = 0$. **b)** $\mathbf{A} \vee \mathbf{0} = [a_{ij} \vee 0] = [a_{ij}] = \mathbf{A}$. Hence $\mathbf{A} \vee \mathbf{0} = \mathbf{A}$. Similarly $\mathbf{0} \vee \mathbf{A} = \mathbf{A}$. **c)** $\mathbf{A} \wedge \mathbf{0} = [a_{ij} \wedge 0] = [0] = \mathbf{0}$. Hence $\mathbf{A} \wedge \mathbf{0} = \mathbf{0}$. Similarly $\mathbf{0} \wedge \mathbf{A} = \mathbf{0}$. **51.** We assume that someone has chosen a positive integer less than 2^n, which we are to guess. We ask the person to write the number in binary, using leading 0s if necessary to make it n bits long. We then ask "Is the first bit a 1?", "Is the second bit a 1?", "Is the third bit a 1?", and so on. After we know the answers to these n questions, we will know the number, because we will know its binary expansion.

CHAPTER 4

Section 4.1

1. Let $P(n)$ be the statement that the train stops at station n. *Basis step:* We are told that $P(1)$ is true. *Inductive step:* We are told that $P(n)$ implies $P(n+1)$ for each $n \geq 1$. Therefore by the principle of mathematical induction, $P(n)$ is true for all positive integers n. **3. a)** $1^2 = 1 \cdot 2 \cdot 3/6$ **b)** Both sides of $P(1)$ shown in part (a) equal 1. **c)** $1^2 + 2^2 + \cdots + k^2 = k(k+1)(2k+1)/6$ **d)** For each $k \geq 1$ that $P(k)$ implies $P(k+1)$; in other words, that assuming the inductive hypothesis [see part (c)] we can show $1^2 + 2^2 + \cdots + k^2 + (k+1)^2 = (k+1)(k+2)(2k+3)/6$ **e)** $(1^2 + 2^2 + \cdots + k^2) + (k+1)^2 = [k(k+1)(2k+1)/6] + (k+1)^2 = [(k+1)/6][k(2k+1) + 6(k+1)] = [(k+1)/6](2k^2 + 7k + 6) = [(k+1)/6](k+2)(2k+3) = (k+1)(k+2)(2k+3)/6$ **f)** We have completed both the basis step and the inductive step, so by the principle of mathematical induction, the statement is true for every positive integer n. **5.** Let $P(n)$ be "$1^2 + 3^2 + \cdots + (2n+1)^2 = (n+1)(2n+1)(2n+3)/3$." *Basis step:* $P(0)$ is true because $1^2 = 1 = (0+1)(2 \cdot 0 + 1)(2 \cdot 0 + 3)/3$. *Inductive step:* Assume that $P(k)$ is true. Then $1^2 + 3^2 + \cdots + (2k+1)^2 + [2(k+1)+1]^2 = (k+1)(2k+1)(2k+3)/3 + (2k+3)^2 = (2k+3)[(k+1)(2k+1)/3 + (2k+3)] = (2k+3)(2k^2 + 9k + 10)/3 = (2k+3)(2k+5)(k+2)/3 = [(k+1)+1][2(k+1)+1][2(k+1)+3]/3$. **7.** Let $P(n)$ be "$\sum_{j=0}^{n} 3 \cdot 5^j = 3(5^{n+1} - 1)/4$." *Basis step:* $P(0)$ is true because $\sum_{j=0}^{0} 3 \cdot 5^j = 3 = 3(5^1 - 1)/4$. *Inductive step:* Assume that $\sum_{j=0}^{k} 3 \cdot 5^j = 3(5^{k+1} - 1)/4$. Then $\sum_{j=0}^{k+1} 3 \cdot 5^j = (\sum_{j=0}^{k} 3 \cdot 5^j) + 3 \cdot 5^{k+1} = 3(5^{k+1} - 1)/4 + 3 \cdot 5^{k+1} = 3(5^{k+1} + 4 \cdot 5^{k+1} - 1)/4 = 3(5^{k+2} - 1)/4$. **9. a)** $2 + 4 + 6 + \cdots + 2n = n(n+1)$ **b)** *Basis step:* $2 = 1 \cdot (1+1)$ is true. *Inductive step:* Assume that $2 + 4 + 6 + \cdots + 2k = k(k+1)$. Then $(2 + 4 + 6 + \cdots + 2k) + 2(k+1) = k(k+1) + 2(k+1) = (k+1)(k+2)$. **11. a)** $\sum_{j=1}^{n} 1/2^j =$

$(2^n-1)/2^n$ **b)** *Basis step:* $P(1)$ is true because $\frac{1}{2}=(2^1-1)/2^1$. *Inductive step:* Assume that $\sum_{j=1}^{k}1/2^j=(2^k-1)/2^k$. Then $\sum_{j=1}^{k+1}\frac{1}{2^j}=(\sum_{j=1}^{k}\frac{1}{2^j})+\frac{1}{2^{k+1}}=\frac{2^k-1}{2^k}+\frac{1}{2^{k+1}}=\frac{2^{k+1}-2+1}{2^{k+1}}=\frac{2^{k+1}-1}{2^{k+1}}$. **13.** Let $P(n)$ be "$1^2-2^2+3^2-\cdots+(-1)^{n-1}n^2=(-1)^{n-1}n(n+1)/2$." *Basis step:* $P(1)$ is true because $1^2=1=(-1)^0 1^2$. *Inductive step:* Assume that $P(k)$ is true. Then $1^2-2^2+3^2-\cdots+(-1)^{k-1}k^2+(-1)^k(k+1)^2=(-1)^{k-1}k(k+1)/2+(-1)^k(k+1)^2=(-1)^k(k+1)[-k/2+(k+1)]=(-1)^k(k+1)[(k/2)+1]=(-1)^k(k+1)(k+2)/2$. **15.** Let $P(n)$ be "$1\cdot 2+2\cdot 3+\cdots+n(n+1)=n(n+1)(n+2)/3$." *Basis step:* $P(1)$ is true because $1\cdot 2=2=1(1+1)(1+2)/3$. *Inductive step:* Assume that $P(k)$ is true. Then $1\cdot 2+2\cdot 3+\cdots+k(k+1)+(k+1)(k+2)=[k(k+1)(k+2)/3]+(k+1)(k+2)=(k+1)(k+2)[(k/3)+1]=(k+1)(k+2)(k+3)/3$. **17.** Let $P(n)$ be the statement that $1^4+2^4+3^4+\cdots+n^4=n(n+1)(2n+1)(3n^2+3n-1)/30$. $P(1)$ is true because $1\cdot 2\cdot 3\cdot 5/30=1$. Assume that $P(k)$ is true. Then $(1^4+2^4+3^4+\cdots+k^4)+(k+1)^4=k(k+1)(2k+1)(3k^2+3k-1)/30+(k+1)^4=[(k+1)/30][k(2k+1)(3k^2+3k-1)+30(k+1)^3]=[(k+1)/30](6k^4+39k^3+91k^2+89k+30)=[(k+1)/30](k+2)(2k+3)[3(k+1)^2+3(k+1)-1]$. This demonstrates that $P(k+1)$ is true. **19. a)** $1+\frac{1}{4}<2-\frac{1}{2}$ **b)** This is true because $5/4$ is less than $6/4$. **c)** $1+\frac{1}{4}+\cdots+\frac{1}{k^2}<2-\frac{1}{k}$ **d)** For each $k\geq 2$ that $P(k)$ implies $P(k+1)$; in other words, we want to show that assuming the inductive hypothesis [see part (c)] we can show $1+\frac{1}{4}+\cdots+\frac{1}{k^2}+\frac{1}{(k+1)^2}<2-\frac{1}{k+1}$ **e)** $1+\frac{1}{4}+\cdots+\frac{1}{k^2}+\frac{1}{(k+1)^2}<2-\frac{1}{k}+\frac{1}{(k+1)^2}=2-\left[\frac{1}{k}-\frac{1}{(k+1)^2}\right]=2-\left[\frac{k^2+2k+1-k}{k(k+1)^2}\right]=2-\frac{k^2+k}{k(k+1)^2}-\frac{1}{k(k+1)^2}=2-\frac{1}{k+1}-\frac{1}{k(k+1)^2}<2-\frac{1}{k+1}$ **f)** We have completed both the basis step and the inductive step, so by the principle of mathematical induction, the statement is true for every integer n greater than 1. **21.** Let $P(n)$ be "$2^n>n^2$." *Basis step:* $P(5)$ is true because $2^5=32>25=5^2$. *Inductive step:* Assume that $P(k)$ is true, that is, $2^k>k^2$. Then $2^{k+1}=2\cdot 2^k>k^2+k^2>k^2+4k\geq k^2+2k+1=(k+1)^2$ because $k>4$. **23.** By inspection we find that the inequality $2n+3\leq 2^n$ does not hold for $n=0,1,2,3$. Let $P(n)$ be the proposition that this inequality holds for the positive integer n. $P(4)$, the basis case, is true because $2\cdot 4+3=11\leq 16=2^4$. For the inductive step assume that $P(k)$ is true. Then, by the inductive hypothesis, $2(k+1)+3=(2k+3)+2<2^k+2$. But because $k\geq 1$, $2^k+2\leq 2^k+2^k=2^{k+1}$. This shows that $P(k+1)$ is true. **25.** Let $P(n)$ be "$1+nh\leq(1+h)^n$, $h>-1$." *Basis step:* $P(0)$ is true because $1+0\cdot h=1\leq 1=(1+h)^0$. *Inductive step:* Assume $1+kh\leq(1+h)^k$. Then because $(1+h)>0$, $(1+h)^{k+1}=(1+h)(1+h)^k\geq(1+h)(1+kh)=1+(k+1)h+kh^2\geq 1+(k+1)h$. **27.** Let $P(n)$ be "$1/\sqrt{1}+1/\sqrt{2}+1/\sqrt{3}+\cdots+1/\sqrt{n}>2\left(\sqrt{n+1}-1\right)$." *Basis step:* $P(1)$ is true because $1>2\left(\sqrt{2}-1\right)$. *Inductive step:* Assume that $P(k)$ is true. Then $1+1/\sqrt{2}+\cdots+1/\sqrt{k}+1/\sqrt{k+1}>2\left(\sqrt{k+1}-1\right)+1/\sqrt{k+1}$. If we show that $2\left(\sqrt{k+1}-1\right)+1/\sqrt{k+1}>2\left(\sqrt{k+2}-1\right)$, it follows that $P(k+1)$ is true. This inequality is equivalent to $2\left(\sqrt{k+2}-\sqrt{k+1}\right)<1/\sqrt{k+1}$, which is equivalent to $2\left(\sqrt{k+2}-\sqrt{k+1}\right)\left(\sqrt{k+2}+\sqrt{k+1}\right)<\sqrt{k+1}/\sqrt{k+1}+\sqrt{k+2}/\sqrt{k+1}$. This is equivalent to $2<1+\sqrt{k+2}/\sqrt{k+1}$, which is clearly true. **29.** Let $P(n)$ be "$H_{2^n}\leq 1+n$." *Basis step:* $P(0)$ is true because $H_{2^0}=H_1=1\leq 1+0$. *Inductive step:* Assume that $H_{2^k}\leq 1+k$. Then $H_{2^{k+1}}=H_{2^k}+\sum_{j=2^k+1}^{2^{k+1}}\frac{1}{j}\leq 1+k+2^k\left(\frac{1}{2^{k+1}}\right)<1+k+1=1+(k+1)$. **31.** *Basis step:* $1^2+1=2$ is divisible by 2. *Inductive step:* Assume the inductive hypothesis, that k^2+k is divisible by 2. Then $(k+1)^2+(k+1)=k^2+2k+1+k+1=(k^2+k)+2(k+1)$, the sum of a multiple of 2 (by the inductive hypothesis) and a multiple of 2 (by definition), hence, divisible by 2. **33.** Let $P(n)$ be "n^5-n is divisible by 5." *Basis step:* $P(0)$ is true because $0^5-0=0$ is divisible by 5. *Inductive step:* Assume that $P(k)$ is true, that is, k^5-5 is divisible by 5. Then $(k+1)^5-(k+1)=(k^5+5k^4+10k^3+10k^2+5k+1)-(k+1)=(k^5-k)+5(k^4+2k^3+2k^2+k)$ is also divisible by 5, because both terms in this sum are divisible by 5. **35.** Let $P(n)$ be the proposition that $(2n-1)^2-1$ is divisible by 8. The basis case $P(1)$ is true because $8\mid 0$. Now assume that $P(k)$ is true. Because $[(2(k+1)-1]^2-1=[(2k-1)^2-1]+8k$, $P(k+1)$ is true because both terms on the right-hand side are divisible by 8. This shows that $P(n)$ is true for all positive integers n, so m^2-1 is divisible by 8 whenever m is an odd positive integer. **37.** *Basis step:* $11^{1+1}+12^{2\cdot 1-1}=121+12=133$ *Inductive step:* Assume the inductive hypothesis, that $11^{n+1}+12^{2n-1}$ is divisible by 133. Then $11^{(n+1)+1}+12^{2(n+1)-1}=11\cdot 11^{n+1}+144\cdot 12^{2n-1}=11\cdot 11^{n+1}+(11+133)\cdot 12^{2n-1}=11(11^{n+1}+12^{2n-1})+133\cdot 12^{2n-1}$. The expression in parentheses is divisible by 133 by the inductive hypothesis, and obviously the second term is divisible by 133, so the entire quantity is divisible by 133, as desired. **39.** *Basis step:* $A_1\subseteq B_1$ tautologically implies that $\bigcap_{j=1}^{1}A_j\subseteq\bigcap_{j=1}^{1}B_j$. *Inductive step:* Assume the inductive hypothesis that if $A_j\subseteq B_j$ for $j=1,2,\ldots,k$, then $\bigcap_{j=1}^{k}A_j\subseteq\bigcap_{j=1}^{k}B_j$. We want to show that if $A_j\subseteq B_j$ for $j=1,2,\ldots,k+1$, then $\bigcap_{j=1}^{k+1}A_j\subseteq\bigcap_{j=1}^{k+1}B_j$. Let x be an arbitrary element of $\bigcap_{j=1}^{k+1}A_j=\left(\bigcap_{j=1}^{k}A_j\right)\cap A_{k+1}$. Because $x\in\bigcap_{j=1}^{k}A_j$, we know by the inductive hypothesis that $x\in\bigcap_{j=1}^{k}B_j$; because $x\in A_{k+1}$, we know from the given fact that $A_{k+1}\subseteq B_{k+1}$ that $x\in B_{k+1}$. Therefore, $x\in\left(\bigcap_{j=1}^{k}B_j\right)\cap B_{k+1}=\bigcap_{j=1}^{k+1}B_j$. **41.** Let $P(n)$ be "$(A_1\cup A_2\cup\cdots\cup A_n)\cap B=(A_1\cap B)\cup(A_2\cap B)\cup\cdots\cup(A_n\cap B)$." *Basis step:* $P(1)$ is trivially true. *Inductive step:* Assume that $P(k)$ is true. Then $(A_1\cup A_2\cup\cdots\cup A_k\cup A_{k+1})\cap B=[(A_1\cup A_2\cup\cdots\cup A_k)\cup A_{k+1}]\cap B=[(A_1\cup A_2\cup\cdots\cup A_k)\cap B]\cup(A_{k+1}\cap B)=[(A_1\cap B)\cup(A_2\cap B)\cup\cdots\cup(A_k\cap B)]\cup(A_{k+1}\cap B)=(A_1\cap B)\cup(A_2\cap B)\cup\cdots\cup(A_k\cap B)\cup(A_{k+1}\cap B)$. **43.** Let $P(n)$ be "$\overline{\bigcup_{k=1}^{n}A_k}=\bigcap_{k=1}^{n}\overline{A_k}$." *Basis step:* $P(1)$ is trivially true. *Inductive step:* Assume that $P(k)$ is true. Then $\overline{\bigcup_{j=1}^{k+1}A_j}=\overline{\left(\bigcup_{j=1}^{k}A_j\right)\cup A_{k+1}}=\overline{\left(\bigcup_{j=1}^{k}A_j\right)}\cap\overline{A_{k+1}}=\left(\bigcap_{j=1}^{k}\overline{A_j}\right)\cap\overline{A_{k+1}}=\bigcap_{j=1}^{k+1}\overline{A_j}$.

45. Let $P(n)$ be the statement that a set with n elements has $n(n-1)/2$ two-element subsets. $P(2)$, the basis case, is true, because a set with two elements has one subset with two elements—namely, itself—and $2(2-1)/2=1$. Now assume that $P(k)$ is true. Let S be a set with $k+1$ elements. Choose an element a in S and let $T=S-\{a\}$. A two-element subset of S either contains a or does not. Those subsets not containing a are the subsets of T with two elements; by the inductive hypothesis there are $k(k-1)/2$ of these. There are k subsets of S with two elements that contain a, because such a subset contains a and one of the k elements in T. Hence, there are $k(k-1)/2+k=(k+1)k/2$ two-element subsets of S. This completes the inductive proof. **47.** The two sets do not overlap if $n+1=2$. In fact, the conditional statement $P(1)\to P(2)$ is false. **49.** The mistake is in applying the inductive hypothesis to look at $\max(x-1, y-1)$, because even though x and y are positive integers, $x-1$ and $y-1$ need not be (one or both could be 0). **51.** We use the notation (i, j) to mean the square in row i and column j and use induction on $i+j$ to show that every square can be reached by the knight. *Basis step:* There are six base cases, for the cases when $i+j\le 2$. The knight is already at $(0,0)$ to start, so the empty sequence of moves reaches that square. To reach $(1,0)$, the knight moves $(0,0)\to(2,1)\to(0,2)\to(1,0)$. Similarly, to reach $(0,1)$, the knight moves $(0,0)\to(1,2)\to(2,0)\to(0,1)$. Note that the knight has reached $(2,0)$ and $(0,2)$ in the process. For the last basis step there is $(0,0)\to(1,2)\to(2,0)\to(0,1)\to(2,2)\to(0,3)\to(1,1)$. *Inductive step:* Assume the inductive hypothesis, that the knight can reach any square (i, j) for which $i+j=k$, where k is an integer greater than 1. We must show how the knight can reach each square (i, j) when $i+j=k+1$. Because $k+1\ge 3$, at least one of i and j is at least 2. If $i\ge 2$, then by the inductive hypothesis, there is a sequence of moves ending at $(i-2, j+1)$, because $i-2+j+1=i+j-1=k$; from there it is just one step to (i, j); similarly, if $j\ge 2$. **53.** *Basis step:* The base cases $n=0$ and $n=1$ are true because the derivative of x^0 is 0 and the derivative of $x^1=x$ is 1. *Inductive step:* Using the product rule, the inductive hypothesis, and the basis step shows that $\frac{d}{dx}x^{k+1}=\frac{d}{dx}(x\cdot x^k)=x\cdot\frac{d}{dx}x^k+x^k\frac{d}{dx}x=x\cdot kx^{k-1}+x^k\cdot 1=kx^k+x^k=(k+1)x^k$. **55.** *Basis step:* For $k=0$, $1\equiv 1 \pmod{m}$. *Inductive step:* Suppose that $a\equiv b \pmod{m}$ and $a^k\equiv b^k \pmod{m}$; we must show that $a^{k=1}\equiv b^{k+1} \pmod{m}$. By Theorem 5 from Section 3.4, $a\cdot a^k\equiv b\cdot b^k \pmod{m}$, which by definition says that $a^{k+1}\equiv b^{k+1} \pmod{m}$. **57.** Let $P(n)$ be "$[(p_1\to p_2)\wedge(p_2\to p_3)\wedge\cdots\wedge(p_{n-1}\to p_n)]\to[(p_1\wedge\cdots\wedge p_{n-1})\to p_n]$." *Basis step:* $P(2)$ is true because $(p_1\to p_2)\to(p_1\to p_2)$ is a tautology. *Inductive step:* Assume $P(k)$ is true. To show $[(p_1\to p_2)\wedge\cdots\wedge(p_{k-1}\to p_k)\wedge(p_k\to p_{k+1})]\to[(p_1\wedge\cdots\wedge p_{k-1}\wedge p_k)\to p_{k+1}]$ is a tautology, assume that the hypothesis of this conditional statement is true. Because both the hypothesis and $P(k)$ are true, it follows that $(p_1\wedge\cdots\wedge p_{k-1})\to p_k$ is true. Because this is true, and because $p_k\to p_{k+1}$ is true (it is part of the assumption) it follows by hypothetical syllogism that $(p_1\wedge\cdots\wedge p_{k-1})\to p_{k+1}$ is true. The weaker statement $(p_1\wedge\cdots\wedge p_{k-1}\wedge p_k)\to p_{k+1}$ follows from this. **59.** We will first prove the result when n is a power of 2, that is, if $n=2^k$, $k=1,2,\ldots$. Let $P(k)$ be the statement $A\ge G$, where A and G are the arithmetic and geometric means, respectively, of a set of $n=2^k$ positive real numbers. *Basis step:* $k=1$ and $n=2^1=2$. Note that $(\sqrt{a_1}-\sqrt{a_2})^2\ge 0$. Expanding this shows that $a_1-2\sqrt{a_1a_2}+a_2\ge 0$, that is, $(a_1+a_2)/2\ge(a_1a_2)^{1/2}$. *Inductive step:* Assume that $P(k)$ is true, with $n=2^k$. We will show that $P(k+1)$ is true. We have $2^{k+1}=2n$. Now $(a_1+a_2+\cdots+a_{2n})/(2n)=[(a_1+a_2+\cdots+a_n)/n+(a_{n+1}+a_{n+2}+\cdots+a_{2n})/n]/2$ and similarly $(a_1a_2\cdots a_{2n})^{1/(2n)}=[(a_1\cdots a_n)^{1/n}(a_{n+1}\cdots a_{2n})^{1/n}]^{1/2}$. To simplify the notation, let $A(x, y,\ldots)$ and $G(x, y,\ldots)$ denote the arithmetic mean and geometric mean of $x, y,\ldots$, respectively. Also, if $x\le x'$, $y\le y'$, and so on, then $A(x, y,\ldots)\le A(x', y',\ldots)$ and $G(x, y,\ldots)\le G(x', y',\ldots)$. Hence, $A(a_1,\ldots,a_{2n})=A(A(a_1,\ldots,a_n), A(a_{n+1},\ldots,a_{2n}))\ge A(G(a_1,\ldots,a_n), G(a_{n+1},\ldots,a_{2n}))\ge G(G(a_1,\ldots,a_n), G(a_{n+1},\ldots,a_{2n}))=G(a_1,\ldots,a_{2n})$. This finishes the proof for powers of 2. Now if n is not a power of 2, let m be the next higher power of 2, and let $a_{n+1},\ldots,a_m$ all equal $A(a_1,\ldots,a_n)=\overline{a}$. Then we have $[(a_1a_2\cdots a_n)\overline{a}^{m-n}]^{1/m}\le A(a_1,\ldots,a_m)$, because m is a power of 2. Because $A(a_1,\ldots,a_m)=\overline{a}$, it follows that $(a_1\cdots a_n)^{1/m}\overline{a}^{1-n/m}\le\overline{a}^{n/m}$. Raising both sides to the (m/n)th power gives $G(a_1,\ldots,a_n)\le A(a_1,\ldots,a_n)$. **61.** *Basis step:* For $n=1$, the left-hand side is just $\frac{1}{1}$, which is 1. For $n=2$, there are three nonempty subsets $\{1\}$, $\{2\}$, and $\{1,2\}$, so the left-hand side is $\frac{1}{1}+\frac{1}{2}+\frac{1}{1\cdot 2}=2$. *Inductive step:* Assume that the statement is true for k. The set of the first $k+1$ positive integers has many nonempty subsets, but they fall into three categories: a nonempty subset of the first k positive integers together with $k+1$, a nonempty subset of the first k positive integers, or just $\{k+1\}$. By the inductive hypothesis, the sum of the first category is k. For the second category, we can factor out $1/(k+1)$ from each term of the sum and what remains is just k by the inductive hypothesis, so this part of the sum is $k/(k+1)$. Finally, the third category simply yields $1/(k+1)$. Hence, the entire summation is $k+k/(k+1)+1/(k+1)=k+1$. **63.** *Basis step:* If $A_1\subseteq A_2$, then A_1 satisfies the condition of being a subset of each set in the collection; otherwise $A_2\subseteq A_1$, so A_2 satisfies the condition. *Inductive step:* Assume the inductive hypothesis, that the conditional statement is true for k sets, and suppose we are given $k+1$ sets that satisfy the given conditions. By the inductive hypothesis, there must be a set A_i for some $i\le k$ such that $A_i\subseteq A_j$ for $1\le j\le k$. If $A_i\subseteq A_{k+1}$, then we are done. Otherwise, we know that $A_{k+1}\subseteq A_i$, and this tells us that A_{k+1} satisfies the condition of being a subset of A_j for $1\le j\le k+1$. **65.** $G(1)=0$, $G(2)=1$, $G(3)=3$, $G(4)=4$ **67.** To show that $2n-4$ calls are sufficient to exchange all the gossip, select persons 1, 2, 3, and 4 to be the central committee. Every person outside the central committee calls one person on the central committee. At this point the central committee members *as a group* know all the scandals. They then exchange information among themselves by making the calls 1-2, 3-4, 1-3, and 2-4 in that order. At this

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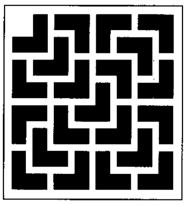
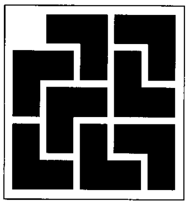
point, *every* central committee member knows all the scandals. Finally, again every person outside the central committee calls one person on the central committee, at which point everyone knows all the scandals. [The total number of calls is $(n-4)+4+(n-4)=2n-4$.] That this cannot be done with fewer than $2n-4$ calls is much harder to prove; see the website `http://www.cs.cornell.edu/vogels/Epidemics/gossips-telephones.pdf` for details. **69.** We prove this by mathematical induction. The basis step ($n = 2$) is true tautologically. For $n = 3$, suppose that the intervals are (a, b), (c, d), and (e, f), where without loss of generality we can assume that $a \le c \le e$. Because $(a, b) \cap (e, f) \ne \emptyset$, we must have $e < b$; for a similar reason, $e < d$. It follows that the number halfway between e and the smaller of b and d is common to all three intervals. Now for the inductive step, assume that whenever we have k intervals that have pairwise nonempty intersections then there is a point common to all the intervals, and suppose that we are given intervals $I_1, I_2, \ldots, I_{k+1}$ that have pairwise nonempty intersections. For each i from 1 to k, let $J_i = I_i \cap I_{k+1}$. We claim that the collection $J_1, J_2, \ldots, J_k$ satisfies the inductive hypothesis, that is, that $J_{i_1} \cap J_{i_2} \ne \emptyset$ for each choice of subscripts i_1 and i_2. This follows from the $n = 3$ case proved above, using the sets I_{i_1}, I_{i_2}, and I_{k+1}. We can now invoke the inductive hypothesis to conclude that there is a number common to all of the sets J_i for $i = 1, 2, \ldots, k$, which perforce is in the intersection of all the sets I_i for $i = 1, 2, \ldots, k+1$. **71.** Pair up the people. Have the people stand at mutually distinct small distances from their partners but far away from everyone else. Then each person throws a pie at his or her partner, so everyone gets hit.

73.



75. Let $P(n)$ be the statement that every $2^n \times 2^n \times 2^n$ checkerboard with a $1 \times 1 \times 1$ cube removed can be covered by tiles that are $2 \times 2 \times 2$ cubes each with a $1 \times 1 \times 1$ cube removed. The basis step, $P(1)$, holds because one tile coincides with the solid to be tiled. Now assume that $P(k)$ holds. Now consider a $2^{k+1} \times 2^{k+1} \times 2^{k+1}$ cube with a $1 \times 1 \times 1$ cube removed. Split this object into eight pieces using planes parallel to its faces and running through its center. The missing $1 \times 1 \times 1$ piece occurs in one of these eight pieces. Now position one tile with its center at the center of the large object so that the missing $1 \times 1 \times 1$ cube lies in the octant in which the large object is missing a $1 \times 1 \times 1$ cube. This creates eight $2^k \times 2^k \times 2^k$ cubes, each missing a $1 \times 1 \times 1$ cube. By the inductive hypothesis we can fill each of these eight objects with tiles. Putting these tilings together produces the desired tiling.

77.



79. Let $Q(n)$ be $P(n+b-1)$. The statement that $P(n)$ is true for $n = b, b+1, b+2, \ldots$ is the same as the statement that $Q(m)$ is true for all positive integers m. We are given that $P(b)$ is true [i.e., that $Q(1)$ is true], and that $P(k) \to P(k+1)$ for all $k \ge b$ [i.e., that $Q(m) \to Q(m+1)$ for all positive integers m]. Therefore, by the principle of mathematical induction, $Q(m)$ is true for all positive integers m.

Section 4.2

1. *Basis step:* We are told we can run one mile, so $P(1)$ is true. *Inductive step:* Assume the inductive hypothesis, that we can run any number of miles from 1 to k. We must show that we can run $k+1$ miles. If $k = 1$, then we are already told that we can run two miles. If $k > 1$, then the inductive hypothesis tells us that we can run $k-1$ miles, so we can run $(k-1)+2 = k+1$ miles. **3. a)** $P(8)$ is true, because we can form 8 cents of postage with one 3-cent stamp and one 5-cent stamp. $P(9)$ is true, because we can form 9 cents of postage with three 3-cent stamps. $P(10)$ is true, because we can form 10 cents of postage with two 5-cent stamps. **b)** The statement that using just 3-cent and 5-cent stamps we can form j cents postage for all j with $8 \le j \le k$, where we assume that $k \ge 10$ **c)** Assuming the inductive hypothesis, we can form $k+1$ cents postage using just 3-cent and 5-cent stamps **d)** Because $k \ge 10$, we know that $P(k-2)$ is true, that is, that we can form $k-2$ cents of postage. Put one more 3-cent stamp on the envelope, and we have formed $k+1$ cents of postage. **e)** We have completed both the basis step and the inductive step, so by the principle of strong induction, the statement is true for every integer n greater than or equal to 8. **5. a)** 4, 8, 11, 12, 15, 16, 19, 20, 22, 23, 24, 26, 27, 28, and all values greater than or equal to 30 **b)** Let $P(n)$ be the statement that we can form n cents of postage using just 4-cent and 11-cent stamps. We want to prove that $P(n)$ is true for all $n \ge 30$. For the basis step, $30 = 11 + 11 + 4 + 4$. Assume that we can form k cents of postage (the inductive hypothesis); we will show how to form $k+1$ cents of postage. If the k cents included an 11-cent stamp, then replace it by three 4-cent stamps. Otherwise, k cents was formed from just 4-cent stamps. Because $k \ge 30$, there must be at least eight 4-cent stamps involved. Replace eight 4-cent stamps by three 11-cent stamps, and we have formed $k+1$ cents in postage. **c)** $P(n)$ is the same as in part (b). To prove that $P(n)$ is true for all $n \ge 30$, we check for the basis step that

$30 = 11 + 11 + 4 + 4$, $31 = 11 + 4 + 4 + 4 + 4 + 4$, $32 = 4 + 4 + 4 + 4 + 4 + 4 + 4 + 4$, and $33 = 11 + 11 + 11$. For the inductive step, assume the inductive hypothesis, that $P(j)$ is true for all j with $30 \le j \le k$, where k is an arbitrary integer greater than or equal to 33. We want to show that $P(k+1)$ is true. Because $k - 3 \ge 30$, we know that $P(k-3)$ is true, that is, that we can form $k - 3$ cents of postage. Put one more 4-cent stamp on the envelope, and we have formed $k + 1$ cents of postage. In this proof, our inductive hypothesis was that $P(j)$ was true for all values of j between 30 and k inclusive, rather than just that $P(30)$ was true. **7.** We can form all amounts except \$1 and \$3. Let $P(n)$ be the statement that we can form n dollars using just 2-dollar and 5-dollar bills. We want to prove that $P(n)$ is true for all $n \ge 5$. (It is clear that \$1 and \$3 cannot be formed and that \$2 and \$4 can be formed.) For the basis step, note that $5 = 5$ and $6 = 2 + 2 + 2$. Assume the inductive hypothesis, that $P(j)$ is true for all j with $5 \le j \le k$, where k is an arbitrary integer greater than or equal to 6. We want to show that $P(k+1)$ is true. Because $k - 1 \ge 5$, we know that $P(k-1)$ is true, that is, that we can form $k - 1$ dollars. Add another 2-dollar bill, and we have formed $k + 1$ dollars. **9.** Let $P(n)$ be the statement that there is no positive integer b such that $\sqrt{2} = n/b$. *Basis step:* $P(1)$ is true because $\sqrt{2} > 1 \ge 1/b$ for all positive integers b. *Inductive step:* Assume that $P(j)$ is true for all $j \le k$, where k is an arbitrary positive integer; we prove that $P(k+1)$ is true by contradiction. Assume that $\sqrt{2} = (k+1)/b$ for some positive integer b. Then $2b^2 = (k+1)^2$, so $(k+1)^2$ is even, and hence, $k + 1$ is even. So write $k + 1 = 2t$ for some positive integer t, whence $2b^2 = 4t^2$ and $b^2 = 2t^2$. By the same reasoning as before, b is even, so $b = 2s$ for some positive integer s. Then $\sqrt{2} = (k+1)/b = (2t)/(2s) = t/s$. But $t \le k$, so this contradicts the inductive hypothesis, and our proof of the inductive step is complete. **11.** *Basis step:* There are four base cases. If $n = 1 = 4 \cdot 0 + 1$, then clearly the second player wins. If there are two, three, or four matches ($n = 4 \cdot 0 + 2$, $n = 4 \cdot 0 + 3$, or $n = 4 \cdot 1$), then the first player can win by removing all but one match. *Inductive step:* Assume the strong inductive hypothesis, that in games with k or fewer matches, the first player can win if $k \equiv 0$, 2, or 3 (mod 4) and the second player can win if $k \equiv 1$ (mod 4). Suppose we have a game with $k + 1$ matches, with $k \ge 4$. If $k + 1 \equiv 0$ (mod 4), then the first player can remove three matches, leaving $k - 2$ matches for the other player. Because $k - 2 \equiv 1$ (mod 4), by the inductive hypothesis, this is a game that the second player at that point (who is the first player in our game) can win. Similarly, if $k + 1 \equiv 2$ (mod 4), then the first player can remove one match; and if $k + 1 \equiv 3$ (mod 4), then the first player can remove two matches. Finally, if $k + 1 \equiv 1$ (mod 4), then the first player must leave k, $k - 1$, or $k - 2$ matches for the other player. Because $k \equiv 0$ (mod 4), $k - 1 \equiv 3$ (mod 4), and $k - 2 \equiv 2$ (mod 4), so by the inductive hypothesis, this is a game that the first player at that point (who is the second player in our game) can win. **13.** Let $P(n)$ be the statement that exactly $n - 1$ moves are required to assemble a puzzle with n pieces. Now $P(1)$ is trivially true. Assume that $P(j)$ is true for all $j \le k$, and consider a puzzle with $k + 1$ pieces. The final move must be the joining of two blocks, of size j and $k + 1 - j$ for some integer j with $1 \le j \le k$. By the inductive hypothesis, it required $j - 1$ moves to construct the one block, and $k + 1 - j - 1 = k - j$ moves to construct the other. Therefore, $1 + (j-1) + (k-j) = k$ moves are required in all, so $P(k+1)$ is true. **15.** Let the Chomp board have n rows and n columns. We claim that the first player can win the game by making the first move to leave just the top row and leftmost column. Let $P(n)$ be the statement that if a player has presented his opponent with a Chomp configuration consisting of just n cookies in the top row and n cookies in the leftmost column, then he can win the game. We will prove $\forall n P(n)$ by strong induction. We know that $P(1)$ is true, because the opponent is forced to take the poisoned cookie at his first turn. Fix $k \ge 1$ and assume that $P(j)$ is true for all $j \le k$. We claim that $P(k+1)$ is true. It is the opponent's turn to move. If she picks the poisoned cookie, then the game is over and she loses. Otherwise, assume she picks the cookie in the top row in column j, or the cookie in the left column in row j, for some j with $2 \le j \le k + 1$. The first player now picks the cookie in the left column in row j, or the cookie in the top row in column j, respectively. This leaves the position covered by $P(j-1)$ for his opponent, so by the inductive hypothesis, he can win. **17.** Let $P(n)$ be the statement that if a simple polygon with n sides is triangulated, then at least two of the triangles in the triangulation have two sides that border the exterior of the polygon. We will prove $\forall n \ge 4\, P(n)$. The statement is clearly true for $n = 4$, because there is only one diagonal, leaving two triangles with the desired property. Fix $k \ge 4$ and assume that $P(j)$ is true for all j with $4 \le j \le k$. Consider a polygon with $k + 1$ sides, and some triangulation of it. Pick one of the diagonals in this triangulation. First suppose that this diagonal divides the polygon into one triangle and one polygon with k sides. Then the triangle has two sides that border the exterior. Furthermore, the k-gon has, by the inductive hypothesis, two triangles that have two sides that border the exterior of that k-gon, and only one of these triangles can fail to be a triangle that has two sides that border the exterior of the original polygon. The only other case is that this diagonal divides the polygon into two polygons with j sides and $k + 3 - j$ sides for some j with $4 \le j \le k - 1$. By the inductive hypothesis, each of these two polygons has two triangles that have two sides that border their exterior, and in each case only one of these triangles can fail to be a triangle that has two sides that border the exterior of the original polygon. **19.** Let $P(n)$ be the statement that the area of a simple polygon with n sides and vertices all at lattice points is given by $I(P) + B(P)/2 - 1$. We will prove $P(n)$ for all $n \ge 3$. We begin with an additivity lemma: If P is a simple polygon with all vertices at the lattice points, divided into polygons P_1 and P_2 by a diagonal, then $I(P) + B(P)/2 - 1 = [I(P_1) + B(P_1)/2 - 1] + [I(P_2) + B(P_2)/2 - 1]$. To prove this, suppose there are k lattice points on the diagonal, not counting its endpoints. Then $I(P) = I(P_1) + I(P_2) + k$ and $B(P) = B(P_1) + B(P_2) - 2k - 2$; and the result follows by simple algebra. What this says in particular is that if Pick's formula gives the correct area for P_1 and P_2, then it must give the correct formula for P, whose area is the sum of the areas for P_1 and P_2; and similarly if Pick's formula gives the correct area for P and one of the P_i's, then it must give the correct formula for the other P_i. Next we prove the theorem for rectangles whose sides are parallel to the coordinate axes. Such a rectangle necessarily has vertices at (a, b), (a, c), (d, b), and (d, c), where a, b, c, and d are integers with $b < c$ and $a < d$. Its area is $(c - b)(d - a)$. Also, $B = 2(c - b + d - a)$ and $I = (c - b - 1)(d - a - 1) = (c - b)(d - a) - (c - b) - (d - a) + 1$. Therefore, $I + B/2 - 1 = (c - b)(d - a) - (c - b) - (d - a) + 1 + (c - b + d - a) - 1 = (c - b)(d - a)$, which is the desired area. Next consider a right triangle whose legs are parallel to the coordinate axes. This triangle is half a rectangle of the type just considered, for which Pick's formula holds, so by the additivity lemma, it holds for the triangle as well. (The values of B and I are the same for each of the two triangles, so if Picks's formula gave an answer that was either too small or too large, then it would give a correspondingly wrong answer for the rectangle.) For the next step, consider an arbitrary triangle with vertices at the lattice points that is not of the type already considered. Embed it in as small a rectangle as possible. There are several possible ways this can happen, but in any case (and adding one more edge in one case), the rectangle will have been partitioned into the given triangle and two or three right triangles with sides parallel to the coordinate axes. Again by the additivity lemma, we are guaranteed that Pick's formula gives the correct area for the given triangle. This completes the proof of $P(3)$, the basis step in our strong induction proof. For the inductive step, given an arbitrary polygon, use Lemma 1 in the text to split it into two polygons. Then by the additivity lemma above and the inductive hypothesis, we know that Pick's formula gives the correct area for this polygon. **21. a)** In the left figure $\angle abp$ is smallest, but $\overline{bp}$ is not an interior diagonal. **b)** In the right figure $\overline{bd}$ is not an interior diagonal. **c)** In the right figure $\overline{bd}$ is not an interior diagonal. **23. a)** When we try to prove the inductive step and find a triangle in each subpolygon with at least two sides bordering the exterior, it may happen in each case that the triangle we are guaranteed in fact borders the diagonal (which is part of the boundary of that polygon). This leaves us with no triangles guaranteed to touch the boundary of the *original* polygon. **b)** We proved the stronger statement $\forall n \geq 4\, T(n)$ in Exercise 17. **25. a)** The inductive step here allows us to conclude that $P(3), P(5), \ldots$ are all true, but we can conclude nothing about $P(2), P(4), \ldots$. **b)** $P(n)$ is true for all positive integers n, using strong induction. **c)** The inductive step here enables us to conclude that $P(2), P(4), P(8), P(16), \ldots$ are all true, but we can conclude nothing about $P(n)$ when n is not a power of 2. **d)** This is mathematical induction; we can conclude that $P(n)$ is true for all positive integers n. **27.** Suppose, for a proof by contradiction, that there is some positive integer n such that $P(n)$ is not true. Let m be the smallest positive integer greater than n for which $P(m)$ *is* true; we know that such an m exists because $P(m)$ is true for infinitely many values of m. But we know that $P(m) \to P(m - 1)$, so $P(m - 1)$ is also true. Thus, $m - 1$ cannot be greater than n, so $m - 1 = n$ and $P(n)$ is in fact true. This contradiction shows that $P(n)$ is true for all n. **29.** The error is in going from the base case $n = 0$ to the next case, $n = 1$; we cannot write 1 as the sum of two smaller natural numbers. **31.** Assume that the well-ordering property holds. Suppose that $P(1)$ is true and that the conditional statement $[P(1) \wedge P(2) \wedge \cdots \wedge P(n)] \to P(n + 1)$ is true for every positive integer n. Let S be the set of positive integers n for which $P(n)$ is false. We will show $S = \emptyset$. Assume that $S \neq \emptyset$. Then by the well-ordering property there is a least integer m in S. We know that m cannot be 1 because $P(1)$ is true. Because $n = m$ is the least integer such that $P(n)$ is false, $P(1), P(2), \ldots, P(m - 1)$ are true, and $m - 1 \geq 1$. Because $[P(1) \wedge P(2) \wedge \cdots \wedge P(m - 1)] \to P(m)$ is true, it follows that $P(m)$ must also be true, which is a contradiction. Hence, $S = \emptyset$. **33.** In each case, give a proof by contradiction based on a "smallest counterexample," that is, values of n and k such that $P(n, k)$ is not true and n and k are smallest in some sense. **a)** Choose a counterexample with $n + k$ as small as possible. We cannot have $n = 1$ and $k = 1$, because we are given that $P(1, 1)$ is true. Therefore, either $n > 1$ or $k > 1$. In the former case, by our choice of counterexample, we know that $P(n - 1, k)$ is true. But the inductive step then forces $P(n, k)$ to be true, a contradiction. **b)** Choose a counterexample with n as small as possible. We cannot have $n = 1$, because we are given that $P(1, k)$ is true for all k. Therefore, $n > 1$. By our choice of counterexample, we know that $P(n - 1, k)$ is true. But the inductive step then forces $P(n, k)$ to be true, a contradiction. **c)** Choose a counterexample with k as small as possible. We cannot have $k = 1$, because we are given that $P(n, 1)$ is true for all n. Therefore, $k > 1$. By our choice of counterexample, we know that $P(n, k - 1)$ is true. But the inductive step then forces $P(n, k)$ to be true, a contradiction. **35.** Let $P(n)$ be the statement that if $x_1, x_2, \ldots, x_n$ are n distinct real numbers, then $n - 1$ multiplications are used to find the product of these numbers no matter how parentheses are inserted in the product. We will prove that $P(n)$ is true using strong induction. The basis case $P(1)$ is true because $1 - 1 = 0$ multiplications are required to find the product of x_1, a product with only one factor. Suppose that $P(k)$ is true for $1 \leq k \leq n$. The last multiplication used to find the product of the $n + 1$ distinct real numbers $x_1, x_2, \ldots, x_n, x_{n+1}$ is a multiplication of the product of the first k of these numbers for some k and the product of the last $n + 1 - k$ of them. By the inductive hypothesis, $k - 1$ multiplications are used to find the product of k of the numbers, no matter how parentheses were inserted in the product of these numbers, and $n - k$ multiplications are used to find the product of the other $n + 1 - k$ of them, no matter how parentheses were inserted in the product of these numbers. Because one more multiplication is required to find the product of all $n + 1$ numbers, the total number of multiplications used equals $(k - 1) + (n - k) + 1 = n$. Hence, $P(n + 1)$ is true. **37.** Assume that $a = dq + r = dq' + r'$ with $0 \leq r < d$ and $0 \leq r' < d$. Then $d(q - q') = r' - r$. It follows that d divides $r' - r$. Because $-d < r' - r < d$, we have $r' - r = 0$. Hence, $r' = r$. It follows that $q = q'$.

39. This is a paradox caused by self-reference. The answer is clearly "no." There are a finite number of English words, so only a finite number of strings of 15 words or fewer; therefore, only a finite number of positive integers can be so described, not all of them. **41.** Suppose that the well-ordering property were false. Let S be a nonempty set of nonnegative integers that has no least element. Let $P(n)$ be the statement "$i \notin S$ for $i = 0, 1, \ldots, n$." $P(0)$ is true because if $0 \in S$ then S has a least element, namely, 0. Now suppose that $P(n)$ is true. Thus, $0 \notin S, 1 \notin S, \ldots, n \notin S$. Clearly, $n+1$ cannot be in S, for if it were, it would be its least element. Thus $P(n+1)$ is true. So by the principle of mathematical induction, $n \notin S$ for all nonnegative integers n. Thus, $S = \emptyset$, a contradiction. **43.** This follows immediately from Exercise 41 (if we take the principle of mathematical induction as an axiom) and from this exercise together with the discussion following the formal statement of strong induction in the text, which showed that strong induction implies the principle of mathematical induction (if we take strong induction as an axiom).

Section 4.3

1. a) $f(1) = 3, f(2) = 5, f(3) = 7, f(4) = 9$ **b)** $f(1) = 3, f(2) = 9, f(3) = 27, f(4) = 81$ **c)** $f(1) = 2, f(2) = 4, f(3) = 16, f(4) = 65{,}536$ **d)** $f(1) = 3, f(2) = 13, f(3) = 183, f(4) = 33{,}673$ **3. a)** $f(2) = -1, f(3) = 5, f(4) = 2, f(5) = 17$ **b)** $f(2) = -4, f(3) = 32, f(4) = -4096, f(5) = 536{,}870{,}912$ **c)** $f(2) = 8, f(3) = 176, f(4) = 92{,}672, f(5) = 25{,}764, 174, 848$ **d)** $f(2) = -\frac{1}{2}, f(3) = -4, f(4) = \frac{1}{8}, f(5) = -32$ **5. a)** Not valid **b)** $f(n) = 1 - n$. *Basis step:* $f(0) = 1 = 1 - 0$. *Inductive step:* if $f(k) = 1 - k$, then $f(k+1) = f(k) - 1 = 1 - k - 1 = 1 - (k+1)$. **c)** $f(n) = 4 - n$ if $n > 0$, and $f(0) = 2$. *Basis step:* $f(0) = 2$ and $f(1) = 3 = 4 - 1$. *Inductive step* (with $k \ge 1$): $f(k+1) = f(k) - 1 = (4 - k) - 1 = 4 - (k+1)$. **d)** $f(n) = 2^{\lfloor (n+1)/2 \rfloor}$. *Basis step:* $f(0) = 1 = 2^{\lfloor (0+1)/2 \rfloor}$ and $f(1) = 2 = 2^{\lfloor (1+1)/2 \rfloor}$. *Inductive step* (with $k \ge 1$): $f(k+1) = 2f(k-1) = 2 \cdot 2^{\lfloor k/2 \rfloor} = 2^{\lfloor k/2 \rfloor + 1} = 2^{\lfloor ((k+1)+1)/2 \rfloor}$. **e)** $f(n) = 3^n$. *Basis step:* Trivial. *Inductive step:* For odd n, $f(n) = 3f(n-1) = 3 \cdot 3^{n-1} = 3^n$; and for even $n > 1$, $f(n) = 9f(n-2) = 9 \cdot 3^{n-2} = 3^n$. **7.** There are many possible correct answers. We will supply relatively simple ones. **a)** $a_{n+1} = a_n + 6$ for $n \ge 1$ and $a_1 = 6$ **b)** $a_{n+1} = a_n + 2$ for $n \ge 1$ and $a_1 = 3$ **c)** $a_{n+1} = 10a_n$ for $n \ge 1$ and $a_1 = 10$ **d)** $a_{n+1} = a_n$ for $n \ge 1$ and $a_1 = 5$ **9.** $F(0) = 0, F(n) = F(n-1) + n$ for $n \ge 1$ **11.** $P_m(0) = 0, P_m(n+1) = P_m(n) + m$ **13.** Let $P(n)$ be "$f_1 + f_3 + \cdots + f_{2n-1} = f_{2n}$." *Basis step:* $P(1)$ is true because $f_1 = 1 = f_2$. *Inductive step:* Assume that $P(k)$ is true. Then $f_1 + f_3 + \cdots + f_{2k-1} + f_{2k+1} = f_{2k} + f_{2k+1} = f_{2k+2} + f_{2(k+1)}$. **15.** *Basis step:* $f_0 f_1 + f_1 f_2 = 0 \cdot 1 + 1 \cdot 1 = 1^2 = f_2^2$. *Inductive step:* Assume that $f_0 f_1 + f_1 f_2 + \cdots + f_{2k-1} f_{2k} = f_{2k}^2$. Then $f_0 f_1 + f_1 f_2 + \cdots + f_{2k-1} f_{2k} + f_{2k} f_{2k+1} + f_{2k+1} f_{2k+2} = f_{2k}^2 + f_{2k} f_{2k+1} + f_{2k+1} f_{2k+2} = f_{2k}(f_{2k} + f_{2k+1}) + f_{2k+1} f_{2k+2} = f_{2k} f_{2k+2} + f_{2k+1} f_{2k+2} = (f_{2k} + f_{2k+1}) f_{2k+2} = f_{2k+2}^2$. **17.** The number of divisions used by the Euclidean algorithm to find $\gcd(f_{n+1}, f_n)$ is 0 for $n = 0$, 1 for $n = 1$, and $n - 1$ for $n \ge 2$. To prove this result for $n \ge 2$ we use mathematical induction. For $n = 2$, one division shows that $\gcd(f_3, f_2) = \gcd(2, 1) = \gcd(1, 0) = 1$. Now assume that $k - 1$ divisions are used to find $\gcd(f_{k+1}, f_k)$. To find $\gcd(f_{k+2}, f_{k+1})$, first divide f_{k+2} by f_{k+1} to obtain $f_{k+2} = 1 \cdot f_{k+1} + f_k$. After one division we have $\gcd(f_{k+2}, f_{k+1}) = \gcd(f_{k+1}, f_k)$. By the inductive hypothesis it follows that exactly $k - 1$ more divisions are required. This shows that k divisions are required to find $\gcd(f_{k+2}, f_{k+1})$, finishing the inductive proof. **19.** $|A| = -1$. Hence, $|A^n| = (-1)^n$. It follows that $f_{n+1} f_{n-1} - f_n^2 = (-1)^n$. **21. a)** Proof by induction. *Basis step:* For $n = 1$, $\max(-a_1) = -a_1 = -\min(a_1)$. For $n = 2$, there are two cases. If $a_2 \ge a_1$, then $-a_1 \ge -a_2$, so $\max(-a_1, -a_2) = -a_1 = -\min(a_1, a_2)$. If $a_2 < a_1$, then $-a_1 < -a_2$, so $\max(-a_1, -a_2) = -a_2 = -\min(a_1, a_2)$. *Inductive step:* Assume true for k with $k \ge 2$. Then $\max(-a_1, -a_2, \ldots, -a_k, -a_{k+1}) = \max(\max(-a_1, \ldots, -a_k), -a_{k+1}) = \max(-\min(a_1, \ldots, a_k), -a_{k+1}) = -\min(\min(a_1, \ldots, a_k), a_{k+1}) = -\min(a_1, \ldots, a_{k+1})$. **b)** Proof by mathematical induction. *Basis step:* For $n = 1$, the result is the identity $a_1 + b_1 = a_1 + b_1$. For $n = 2$, first consider the case in which $a_1 + b_1 \ge a_2 + b_2$. Then $\max(a_1 + b_1, a_2 + b_2) = a_1 + b_1$. Also note that $a_1 \le \max(a_1, a_2)$ and $b_1 \le \max(b_1, b_2)$, so $a_1 + b_1 \le \max(a_1, a_2) + \max(b_1, b_2)$. Therefore, $\max(a_1 + b_1, a_2 + b_2) = a_1 + b_1 \le \max(a_1, a_2) + \max(b_1, b_2)$. The case with $a_1 + b_1 < a_2 + b_2$ is similar. *Inductive step:* Assume that the result is true for k. Then $\max(a_1 + b_1, a_2 + b_2, \ldots, a_k + b_k, a_{k+1} + b_{k+1}) = \max(\max(a_1 + b_1, a_2 + b_2, \ldots, a_k + b_k), a_{k+1} + b_{k+1}) \le \max(\max(a_1, a_2, \ldots, a_k) + \max(b_1, b_2, \ldots, b_k), a_{k+1} + b_{k+1}) \le \max(\max(a_1, a_2, \ldots, a_k), a_{k+1}) + \max(\max(b_1, b_2, \ldots, b_k), b_{k+1}) = \max(a_1, a_2, \ldots, a_k, a_{k+1}) + \max(b_1, b_2, \ldots, b_k, b_{k+1})$. **c)** Same as part (b), but replace every occurrence of "max" by "min" and invert each inequality. **23.** $5 \in S$, and $x + y \in S$ if $x, y \in S$. **25. a)** $0 \in S$, and if $x \in S$, then $x + 2 \in S$ and $x - 2 \in S$. **b)** $2 \in S$, and if $x \in S$, then $x + 3 \in S$. **c)** $1 \in S, 2 \in S, 3 \in S, 4 \in S$, and if $x \in S$, then $x + 5 \in S$. **27. a)** (0, 1), (1, 1), (2, 1); (0, 2), (1, 2), (2, 2), (3, 2), (4, 2); (0, 3), (1, 3), (2, 3), (3, 3), (4, 3), (5, 3), (6, 3); (0, 4), (1, 4), (2, 4), (3, 4), (4, 4), (5, 4), (6, 4), (7, 4), (8, 4) **b)** Let $P(n)$ be the statement that $a \le 2b$ whenever $(a, b) \in S$ is obtained by n applications of the recursive step. *Basis step:* $P(0)$ is true, because the only element of S obtained with no applications of the recursive step is (0, 0), and indeed $0 \le 2 \cdot 0$. *Inductive step:* Assume that $a \le 2b$ whenever $(a, b) \in S$ is obtained by k or fewer applications of the recursive step, and consider an element obtained with $k + 1$ applications of the recursive step. Because the final application of the recursive step to an element (a, b) must be applied to an element obtained with fewer applications of the recursive step, we know that $a \le 2b$. Add $0 \le 2$, $1 \le 2$, and $2 \le 2$, respectively, to obtain $a \le 2(b+1)$, $a + 1 \le 2(b+1)$, and $a + 2 \le 2(b+1)$, as desired. **c)** This holds for the basis step, because $0 \le 0$. If this holds for (a, b), then it also holds for the elements obtained from (a, b) in the recursive step, because adding $0 \leq 2$, $1 \leq 2$, and $2 \leq 2$, respectively, to $a \leq 2b$ yields $a \leq 2(b+1)$, $a+1 \leq 2(b+1)$, and $a+2 \leq 2(b+1)$. **29. a)** Define S by $(1, 1) \in S$, and if $(a, b) \in S$, then $(a+2, b) \in S$, $(a, b+2) \in S$, and $(a+1, b+1) \in S$. All elements put in S satisfy the condition, because $(1, 1)$ has an even sum of coordinates, and if (a, b) has an even sum of coordinates, then so do $(a+2, b)$, $(a, b+2)$, and $(a+1, b+1)$. Conversely, we show by induction on the sum of the coordinates that if $a+b$ is even, then $(a, b) \in S$. If the sum is 2, then $(a, b) = (1, 1)$, and the basis step put (a, b) into S. Otherwise the sum is at least 4, and at least one of $(a-2, b)$, $(a, b-2)$, and $(a-1, b-1)$ must have positive integer coordinates whose sum is an even number smaller than $a+b$, and therefore must be in S. Then one application of the recursive step shows that $(a, b) \in S$. **b)** Define S by $(1, 1)$, $(1, 2)$, and $(2, 1)$ are in S, and if $(a, b) \in S$, then $(a+2, b)$ and $(a, b+2)$ are in S. To prove that our definition works, we note first that $(1, 1)$, $(1, 2)$, and $(2, 1)$ all have an odd coordinate, and if (a, b) has an odd coordinate, then so do $(a+2, b)$ and $(a, b+2)$. Conversely, we show by induction on the sum of the coordinates that if (a, b) has at least one odd coordinate, then $(a, b) \in S$. If $(a, b) = (1, 1)$ or $(a, b) = (1, 2)$ or $(a, b) = (2, 1)$, then the basis step put (a, b) into S. Otherwise either a or b is at least 3, so at least one of $(a-2, b)$ and $(a, b-2)$ must have positive integer coordinates whose sum is smaller than $a+b$, and therefore must be in S. Then one application of the recursive step shows that $(a, b) \in S$. **c)** $(1, 6) \in S$ and $(2, 3) \in S$, and if $(a, b) \in S$, then $(a+2, b) \in S$ and $(a, b+6) \in S$. To prove that our definition works, we note first that $(1, 6)$ and $(2, 3)$ satisfy the condition, and if (a, b) satisfies the condition, then so do $(a+2, b)$ and $(a, b+6)$. Conversely we show by induction on the sum of the coordinates that if (a, b) satisfies the condition, then $(a, b) \in S$. For sums 5 and 7, the only points are $(1, 6)$, which the basis step put into S, $(2, 3)$, which the basis step put into S, and $(4, 3) = (2+2, 3)$, which is in S by one application of the recursive definition. For a sum greater than 7, either $a \geq 3$, or $a \leq 2$ and $b \geq 9$, in which case either $(a-2, b)$ or $(a, b-6)$ must have positive integer coordinates whose sum is smaller than $a+b$ and satisfy the condition for being in S. Then one application of the recursive step shows that $(a, b) \in S$. **31.** If x is a set or a variable representing a set, then x is a well-formed formula. If x and y are well-formed formulae, then so are $\overline{x}$, $(x \cup y)$, $(x \cap y)$, and $(x - y)$. **33. a)** If $x \in D = \{0, 1, 2, 3, 4, 5, 6, 7, 8, 9\}$, then $m(x) = x$; if $s = tx$, where $t \in D^*$ and $x \in D$, then $m(s) = \min(m(s), x)$. **b)** Let $t = wx$, where $w \in D^*$ and $x \in D$. If $w = \lambda$, then $m(st) = m(sx) = \min(m(s), x) = \min(m(s), m(x))$ by the recursive step and the basis step of the definition of m. Otherwise, $m(st) = m((sw)x) = \min(m(sw), x)$ by the definition of m. Now $m(sw) = \min(m(s), m(w))$ by the inductive hypothesis of the structural induction, so $m(st) = \min(\min(m(s), m(w)), x) = \min(m(s), \min(m(w), x))$ by the meaning of min. But $\min(m(w), x) = m(wx) = m(t)$ by the recursive step of the definition of m. Thus, $m(st) = \min(m(s), m(t))$. **35.** $\lambda^R = \lambda$ and $(ux)^R = xu^R$ for $x \in \Sigma$, $u \in \Sigma^*$. **37.** $w^0 = \lambda$ and $w^{n+1} = ww^n$. **39.** When the string consists of n 0s followed by n 1s for some nonnegative integer n **41.** Let $P(i)$ be "$l(w^i) = i \cdot l(w)$." $P(0)$ is true because $l(w^0) = 0 = 0 \cdot l(w)$. Assume $P(i)$ is true. Then $l(w^{i+1}) = l(ww^i) = l(w) + l(w^i) = l(w) + i \cdot l(w) = (i+1) \cdot l(w)$. **43.** *Basis step:* For the full binary tree consisting of just a root the result is true because $n(T) = 1$ and $h(T) = 0$, and $1 \geq 2 \cdot 0 + 1$. *Inductive step:* Assume that $n(T_1) \geq 2h(T_1) + 1$ and $n(T_2) \geq 2h(T_2) + 1$. By the recursive definitions of $n(T)$ and $h(T)$, we have $n(T) = 1 + n(T_1) + n(T_2)$ and $h(T) = 1 + \max(h(T_1), h(T_2))$. Therefore $n(T) = 1 + n(T_1) + n(T_2) \geq 1 + 2h(T_1) + 1 + 2h(T_2) + 1 \geq 1 + 2 \cdot \max(h(T_1), h(T_2)) + 2 = 1 + 2(\max(h(T_1), h(T_2)) + 1) = 1 + 2h(T)$. **45.** *Basis step:* $a_{0,0} = 0 = 0 + 0$. *Inductive step:* Assume that $a_{m',n'} = m' + n'$ whenever (m', n') is less than (m, n) in the lexicographic ordering of $\mathbf{N} \times \mathbf{N}$. If $n = 0$ then $a_{m,n} = a_{m-1,n} + 1 = m - 1 + n + 1 = m + n$. If $n > 0$, then $a_{m,n} = a_{m,n-1} + 1 = m + n - 1 + 1 = m + n$. **47. a)** $P_{m,m} = P_m$ because a number exceeding m cannot be used in a partition of m. **b)** Because there is only one way to partition 1, namely, $1 = 1$, it follows that $P_{1,n} = 1$. Because there is only one way to partition m into 1s, $P_{m,1} = 1$. When $n > m$ it follows that $P_{m,n} = P_{m,m}$ because a number exceeding m cannot be used. $P_{m,m} = 1 + P_{m,m-1}$ because one extra partition, namely, $m = m$, arises when m is allowed in the partition. $P_{m,n} = P_{m,n-1} + P_{m-n,n}$ if $m > n$ because a partition of m into integers not exceeding n either does not use any ns and hence, is counted in $P_{m,n-1}$ or else uses an n and a partition of $m - n$, and hence, is counted in $P_{m-n,n}$. **c)** $P_5 = 7$, $P_6 = 11$ **49.** Let $P(n)$ be "$A(n, 2) = 4$." *Basis step:* $P(1)$ is true because $A(1, 2) = A(0, A(1, 1)) = A(0, 2) = 2 \cdot 2 = 4$. *Inductive step:* Assume that $P(n)$ is true, that is, $A(n, 2) = 4$. Then $A(n+1, 2) = A(n, A(n+1, 1)) = A(n, 2) = 4$. **51. a)** 16 **b)** 65,536 **53.** Use a double induction argument to prove the stronger statement: $A(m, k) > A(m, l)$ when $k > l$. *Basis step:* When $m = 0$ the statement is true because $k > l$ implies that $A(0, k) = 2k > 2l = A(0, l)$. *Inductive step:* Assume that $A(m, x) > A(m, y)$ for all nonnegative integers x and y with $x > y$. We will show that this implies that $A(m+1, k) > A(m+1, l)$ if $k > l$. *Basis steps:* When $l = 0$ and $k > 0$, $A(m+1, l) = 0$ and either $A(m+1, k) = 2$ or $A(m+1, k) = A(m, A(m+1, k-1))$. If $m = 0$, this is $2A(1, k-1) = 2^k$. If $m > 0$, this is greater than 0 by the inductive hypothesis. In all cases, $A(m+1, k) > 0$, and in fact, $A(m+1, k) \geq 2$. If $l = 1$ and $k > 1$, then $A(m+1, l) = 2$ and $A(m+1, k) = A(m, A(m+1, k-1))$, with $A(m+1, k-1) \geq 2$. Hence, by the inductive hypothesis, $A(m, A(m+1, k-1)) \geq A(m, 2) > A(m, 1) = 2$. *Inductive step:* Assume that $A(m+1, r) > A(m+1, s)$ for all $r > s$, $s = 0, 1, \ldots, l$. Then if $k + 1 > l + 1$ it follows that $A(m+1, k+1) = A(m, A(m+1, k)) > A(m, A(m+1, l)) = A(m+1, l+1)$. **55.** From Exercise 54 it follows that $A(i, j) \geq A(i-1, j) \geq \cdots \geq A(0, j) = 2j \geq j$. **57.** Let $P(n)$ be "$F(n)$ is well-defined." Then $P(0)$ is true because $F(0)$ is specified. Assume that $P(k)$ is true for all $k < n$. Then $F(n)$ is well-defined at n because $F(n)$ is given in terms of $F(0), F(1), \ldots, F(n-1)$. So $P(n)$ is true for all integers n. **59. a)** The value of $F(1)$ is ambiguous. **b)** $F(2)$ is not defined because $F(0)$ is not defined. **c)** $F(3)$ is ambiguous and $F(4)$ is not defined because $F(\frac{4}{3})$ makes no sense. **d)** The definition of $F(1)$ is ambiguous because both the second and third clause seem to apply. **e)** $F(2)$ cannot be computed because trying to compute $F(2)$ gives $F(2) = 1 + F(F(1)) = 1 + F(2)$. **61. a)** 1 **b)** 2 **c)** 3 **d)** 3 **e)** 4 **f)** 4 **g)** 5 **63.** $f_0^*(n) = \lceil n/a \rceil$ **65.** $f_2^*(n) = \lceil \log \log n \rceil$ for $n \geq 2$, $f_2^*(1) = 0$

Section 4.4

1. First, we use the recursive step to write $5! = 5 \cdot 4!$. We then use the recursive step repeatedly to write $4! = 4 \cdot 3!$, $3! = 3 \cdot 2!$, $2! = 2 \cdot 1!$, and $1! = 1 \cdot 0!$. Inserting the value of $0! = 1$, and working back through the steps, we see that $1! = 1 \cdot 1 = 1$, $2! = 2 \cdot 1! = 2 \cdot 1 = 2$, $3! = 3 \cdot 2! = 3 \cdot 2 = 6$, $4! = 4 \cdot 3! = 4 \cdot 6 = 24$, and $5! = 5 \cdot 4! = 5 \cdot 24 = 120$. **3.** First, because $n = 11$ is odd, we use the **else** clause to see that $mpower(3, 11, 5) = (mpower(3, 5, 5)^2 \textbf{ mod } 5 \cdot 3 \textbf{ mod } 5) \textbf{ mod } 5$. We next use the **else** clause again to see that $mpower(3, 5, 5) = (mpower(3, 2, 5)^2 \textbf{ mod } 5 \cdot 3 \textbf{ mod } 5) \textbf{ mod } 5$. Then we use the **else if** clause to see that $mpower(3, 2, 5) = mpower(3, 1, 5)^2 \textbf{ mod } 5$. Using the **else** clause again, we have $mpower(3, 1, 5) = (mpower(3, 0, 5)^2 \textbf{ mod } 5 \cdot 3 \textbf{ mod } 5) \textbf{ mod } 5$. Finally, using the **if** clause, we see that $mpower(3, 0, 5) = 1$. Working backward it follows that $mpower(3, 1, 5) = (1^2 \textbf{ mod } 5 \cdot 3 \textbf{ mod } 5) \textbf{ mod } 5 = 3$, $mpower(3, 2, 5) = 3^2 \textbf{ mod } 5 = 4$, $mpower(3, 5, 5) = (4^2 \textbf{ mod } 5 \cdot 3 \textbf{ mod } 5) \textbf{ mod } 5 = 3$, and finally $mpower(3, 11, 5) = (3^2 \textbf{ mod } 5 \cdot 3 \textbf{ mod } 5) \textbf{ mod } 5 = 2$. We conclude that $3^{11} \textbf{ mod } 5 = 2$. **5.** With this input, the algorithm uses the **else** clause to find that $\gcd(8, 13) = \gcd(13 \textbf{ mod } 8, 8) = \gcd(5, 8)$. It uses this clause again to find that $\gcd(5, 8) = \gcd(8 \textbf{ mod } 5, 5) = \gcd(3, 5)$, then to get $\gcd(3, 5) = \gcd(5 \textbf{ mod } 3, 3) = \gcd(2, 3)$, then $\gcd(2, 3) = \gcd(3 \textbf{ mod } 2, 2) = \gcd(1, 2)$, and once more to get $\gcd(1, 2) = \gcd(2 \textbf{ mod } 1, 1) = \gcd(0, 1)$. Finally, to find $\gcd(0, 1)$ it uses the first step with $a = 0$ to find that $\gcd(0, 1) = 1$. Consequently, the algorithm finds that $\gcd(8, 13) = 1$.

7. procedure *mult* (n: positive integer, x: integer)
  if $n = 1$ **then** $mult(n, x) := x$
  else $mult(n, x) := x + mult(n - 1, x)$

9. procedure *sum of odds* (n: positive integer)
  if $n = 1$ **then** *sum of odds* $(n) := 1$
  else *sum of odds*(n) :=*sum of odds* $(n - 1) + 2n - 1$

11. procedure *smallest* $(a_1, \ldots, a_n$: integers)
  if $n = 1$ **then** $smallest(a_1, \ldots, a_n) = a_1$
  else $smallest(a_1, \ldots, a_n) :=$
    $\min(smallest(a_1, \ldots, a_{n-1}), a_n)$

13. procedure *modfactorial*(n, m: positive integers)
  if $n = 1$ **then** $modfactorial(n, m) := 1$
  else $modfactorial(n, m) :=$
    $(n \cdot modfactorial(n - 1, m))$ **mod** m

15. procedure gcd(a, b: nonnegative integers)
  $\{a < b$ assumed to hold$\}$
  if $a = 0$ **then** $\gcd(a, b) := b$
  else if $a = b - a$ **then** $\gcd(a, b) := a$
  else if $a < b - a$ **then** $\gcd(a, b) := \gcd(a, b - a)$
  else $\gcd(a, b) := \gcd(b - a, a)$

17. procedure *multiply* $(x, y$: nonnegative integers)
  if $y = 0$ **then** $multiply(x, y) := 0$
  else if y is even **then**
    $multiply(x, y) := 2 \cdot multiply(x, y/2)$
  else $multiply(x, y) := 2 \cdot multiply(x, (y-1)/2) + x$

19. We use strong induction on a. *Basis step:* If $a = 0$, we know that $\gcd(0, b) = b$ for all $b > 0$, and that is precisely what the **if** clause does. *Inductive step:* Fix $k > 0$, assume the inductive hypothesis—that the algorithm works correctly for all values of its first argument less than k—and consider what happens with input (k, b), where $k < b$. Because $k > 0$, the **else** clause is executed, and the answer is whatever the algorithm gives as output for inputs $(b \textbf{ mod } k, k)$. Because $b \textbf{ mod } k < k$, the input pair is valid. By our inductive hypothesis, this output is in fact $\gcd(b \textbf{ mod } k, k)$, which equals $\gcd(k, b)$ by Lemma 1 in Section 3.6. **21.** If $n = 1$, then $nx = x$, and the algorithm correctly returns x. Assume that the algorithm correctly computes kx. To compute $(k + 1)x$ it recursively computes the product of $k + 1 - 1 = k$ and x, and then adds x. By the inductive hypothesis, it computes that product correctly, so the answer returned is $kx + x = (k + 1)x$, which is correct.

23. procedure *square* (n: nonnegative integer)
  if $n = 0$ **then** $square(n) := 0$
  else $square(n) := square(n - 1) + 2(n - 1) + 1$

Let $P(n)$ be the statement that this algorithm correctly computes n^2. Because $0^2 = 0$, the algorithm works correctly (using the **if** clause) if the input is 0. Assume that the algorithm works correctly for input k. Then for input $k + 1$, it gives as output (because of the **else** clause) its output when the input is k, plus $2(k + 1 - 1) + 1$. By the inductive hypothesis, its output at k is k^2, so its output at $k + 1$ is $k^2 + 2(k + 1 - 1) + 1 = k^2 + 2k + 1 = (k + 1)^2$, as desired. **25.** n multiplications versus 2^n **27.** $O(\log n)$ versus n

29. procedure a(n: nonnegative integer)
  if $n = 0$ **then** $a(n) := 1$
  else if $n = 1$ **then** $a(n) := 2$
  else $a(n) := a(n - 1) * a(n - 2)$

31. Iterative

33. procedure *iterative*(n: nonnegative integer)
  if $n = 0$ **then** $z := 1$
  else if $n = 1$ **then** $z := 2$
  else
  begin
    $x := 1$
    $y := 2$
    $z := 3$
    for $i := 1$ **to** $n - 2$
    begin
      $w := x + y + z$
      $x := y$
      $y := z$
      $z := w$
    end

end
$\{z$ is the nth term of the sequence$\}$

35. We first give a recursive procedure and then an iterative procedure.
procedure $r(n$: nonnegative integer)
if $n < 3$ **then** $r(n) := 2n + 1$
else $r(n) = r(n-1) \cdot (r(n-2))^2 \cdot (r(n-3))^3$

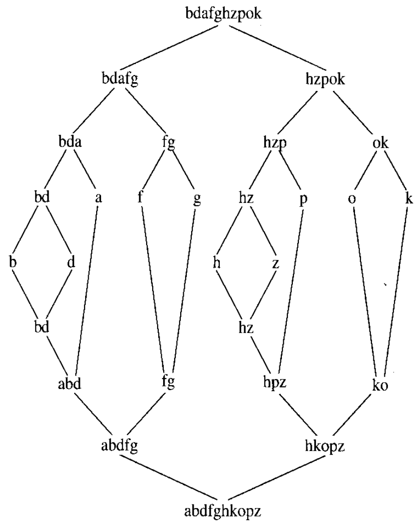
procedure $i(n$: nonnegative integer)
if $n = 0$ **then** $z := 1$
else if $n = 1$ **then** $z := 3$
else
begin
$x := 1$
$y := 3$
$z := 5$
for $i := 1$ **to** $n - 2$
begin
$w := z * y^2 * x^3$
$x := y$
$y := z$
$z := w$
end
end
$\{z$ is the nth term of the sequence$\}$
The iterative version is more efficient.

37. procedure *reverse* (w: bit string)
$n :=$ length(w)
if $n \le 1$ **then** *reverse*(w) $:= w$
else *reverse*(w) $:=$
substr(w, n, n)*reverse*$($*substr*$(w, 1, n-1))$
$\{$*substr*(w, a, b) is the substring of w consisting of the symbols in the ath through bth positions$\}$

39. The procedure correctly gives the reversal of λ as λ (basis step), and because the reversal of a string consists of its last character followed by the reversal of its first $n-1$ characters (see Exercise 35 in Section 4.3), the algorithm behaves correctly when $n > 0$ by the inductive hypothesis. **41.** The algorithm implements the idea of Example 13 in Section 4.1. If $n = 1$ (basis step), place the one right triomino so that its armpit corresponds to the hole in the 2×2 board. If $n > 1$, then divide the board into four boards, each of size $2^{n-1} \times 2^{n-1}$, notice which quarter the hole occurs in, position one right triomino at the center of the board with its armpit in the quarter where the missing square is (see Figure 8 in Section 4.1), and invoke the algorithm recursively four times—once on each of the $2^{n-1} \times 2^{n-1}$ boards, each of which has one square missing (either because it was missing to begin with, or because it is covered by the central triomino).

43. procedure $A(m, n$: nonnegative integers)
if $m = 0$ **then** $A(m, n) := 2n$
else if $n = 0$ **then** $A(m, n) := 0$
else if $n = 1$ **then** $A(m, n) := 2$
else $A(m, n) := A(m-1, A(m, n-1))$

45.



47. Let the two lists be $1, 2, \ldots, m-1, m+n-1$ and $m, m+1, \ldots, m+n-2, m+n$, respectively. **49.** If $n = 1$, then the algorithm does nothing, which is correct because a list with one element is already sorted. Assume that the algorithm works correctly for $n = 1$ through $n = k$. If $n = k + 1$, then the list is split into two lists, L_1 and L_2. By the inductive hypothesis, *mergesort* correctly sorts each of these sublists; furthermore, *merge* correctly merges two sorted lists into one because with each comparison the smallest element in $L_1 \cup L_2$ not yet put into L is put there. **51.** $O(n)$ **53.** 6 **55.** $O(n^2)$

Section 4.5

1. Suppose that $x = 0$. The program segment first assigns the value 1 to y and then assigns the value $x + y = 0 + 1 = 1$ to z. **3.** Suppose that $y = 3$. The program segment assigns the value 2 to x and then assigns the value $x + y = 2 + 3 = 5$ to z. Because $y = 3 > 0$ it then assigns the value $z + 1 = 5 + 1 = 6$ to z.

5. $(p \wedge \mathit{condition}1)\{S_1\}q$
$(p \wedge \neg\mathit{condition}1 \wedge \mathit{condition}2)\{S_2\}q$
$\vdots$
$(p \wedge \neg\mathit{condition}1 \wedge \neg\mathit{condition}2 \cdots \wedge \neg\mathit{condition}(n-1))\{S_n\}q$
$\therefore\ p\{$**if** *condition*1 **then** S_1; **else if** *condition*2 **then** $S_2; \ldots;$ **else** $S_n\}q$

7. We will show that p : "$\mathit{power} = x^{i-1}$ and $i \le n + 1$" is a loop invariant. Note that p is true initially, because before the loop starts, $i = 1$ and $\mathit{power} = 1 = x^0 = x^{1-1}$. Next, we must show that if p is true and $i \le n$ after an execution of the loop, then p remains true after one more execution. The loop increments i by 1. Hence, because $i \le n$ before this pass, $i \le n + 1$ after this pass. Also the loop assigns $\mathit{power} \cdot x$ to *power*. By the inductive hypothesis we see that *power* is assigned the value $x^{i-1} \cdot x = x^i$. Hence, p remains true. Furthermore, the loop terminates after n traversals of the loop with $i = n + 1$ because i is assigned the value 1 prior to entering the loop, is incremented by 1 on each pass, and the loop terminates when $i > n$. Consequently, at termination $power = x^n$, as desired. **9.** Suppose that p is "m and n are integers." Then if the condition $n < 0$ is true, $a = -n = |n|$ after S_1 is executed. If the condition $n < 0$ is false, then $a = n = |n|$ after S_1 is executed. Hence, $p\{S_1\}q$ is true where q is $p \wedge (a = |n|)$. Because S_2 assigns the value 0 to both k and x, it is clear that $q\{S_2\}r$ is true where r is $q \wedge (k = 0) \wedge (x = 0)$. Suppose that r is true. Let $P(k)$ be "$x = mk$ and $k \leq a$." We can show that $P(k)$ is a loop invariant for the loop in S_3. $P(0)$ is true because before the loop is entered $x = 0 = m \cdot 0$ and $0 \leq a$. Now assume $P(k)$ is true and $k < a$. Then $P(k + 1)$ is true because x is assigned the value $x + m = mk + m = m(k + 1)$. The loop terminates when $k = a$, and at that point $x = ma$. Hence, $r\{S_3\}s$ is true where s is "$a = |n|$ and $x = ma$." Now assume that s is true. Then if $n < 0$ it follows that $a = -n$, so $x = -mn$. In this case S_4 assigns $-x = mn$ to *product*. If $n > 0$ then $x = ma = mn$, so S_4 assigns mn to *product*. Hence, $s\{S_4\}t$ is true. **11.** Suppose that the initial assertion p is true. Then because $p\{S\}q_0$ is true, q_0 is true after the segment S is executed. Because $q_0 \to q_1$ is true, it also follows that q_1 is true after S is executed. Hence, $p\{S\}q_1$ is true. **13.** We will use the proposition p, "$\gcd(a, b) = \gcd(x, y)$ and $y \geq 0$," as the loop invariant. Note that p is true before the loop is entered, because at that point $x = a$, $y = b$, and y is a positive integer, using the initial assertion. Now assume that p is true and $y > 0$; then the loop will be executed again. Inside the loop, x and y are replaced by y and x **mod** y, respectively. By Lemma 1 of Section 3.6, $\gcd(x, y) = \gcd(y, x \textbf{ mod } y)$. Therefore, after execution of the loop, the value of $\gcd(x, y)$ is the same as it was before. Moreover, because y is the remainder, it is at least 0. Hence, p remains true, so it is a loop invariant. Furthermore, if the loop terminates, then $y = 0$. In this case, we have $\gcd(x, y) = x$, the final assertion. Therefore, the program, which gives x as its output, has correctly computed $\gcd(a, b)$. Finally, we can prove the loop must terminate, because each iteration causes the value of y to decrease by at least 1. Therefore, the loop can be iterated at most b times.

Supplementary Exercises

1. Let $P(n)$ be the statement that this equation holds. *Basis step:* $P(1)$ says $2/3 = 1 - (1/3^1)$, which is true. *Inductive step:* Assume that $P(k)$ is true. Then $2/3 + 2/9 + 2/27 + \cdots + 2/3^n + 2/3^{n+1} = 1 - 1/3^n + 2/3^{n+1}$ (by the inductive hypothesis), and this equals $1 - 1/3^{n+1}$, as desired. **3.** Let $P(n)$ be "$1 \cdot 1 + 2 \cdot 2 + \cdots + n \cdot 2^{n-1} = (n-1)2^n + 1$." *Basis step:* $P(1)$ is true because $1 \cdot 1 = 1 = (1-1)2^1 + 1$. *Inductive step:* Assume that $P(k)$ is true. Then $1 \cdot 1 + 2 \cdot 2 + \cdots + k \cdot 2^{k-1} + (k+1) \cdot 2^k = (k-1)2^k + 1 + (k+1)2^k = 2k \cdot 2^k + 1 = [(k+1) - 1]2^{k+1} + 1$. **5.** Let $P(n)$ be "$1/(1 \cdot 4) + \cdots + 1/[(3n-2)(3n+1)] = n/(3n+1)$." *Basis step:* $P(1)$ is true because $1/(1 \cdot 4) = 1/4$. *Inductive step:* Assume $P(k)$ is true. Then $1/(1 \cdot 4) + \cdots + 1/[(3k-2)(3k+1)] + 1/[(3k+1)(3k+4)] = k/(3k+1) + 1/[(3k+1)(3k+4)] = [k(3k+4) + 1]/[(3k+1)(3k+4)] = [(3k+1)(k+1)]/[(3k+1)(3k+4)] = (k+1)/(3k+4)$. **7.** Let $P(n)$ be "$2^n > n^3$." *Basis step:* $P(10)$ is true because $1024 > 1000$. *Inductive step:* Assume $P(k)$ is true. Then $(k+1)^3 = k^3 + 3k^2 + 3k + 1 \leq k^3 + 9k^2 \leq k^3 + k^3 = 2k^3 < 2 \cdot 2^k = 2^{k+1}$. **9.** Let $P(n)$ be "$a - b$ is a factor of $a^n - b^n$." *Basis step:* $P(1)$ is trivially true. Assume $P(k)$ is true. Then $a^{k+1} - b^{k+1} = a^{k+1} - ab^k + ab^k - b^{k+1} = a(a^k - b^k) + b^k(a - b)$. Then because $a - b$ is a factor of $a^k - b^k$ and $a - b$ is a factor of $a - b$, it follows that $a - b$ is a factor of $a^{k+1} - b^{k+1}$. **11.** Let $P(n)$ be "$a + (a + d) + \cdots + (a + nd) = (n + 1)(2a + nd)/2$." *Basis step:* $P(1)$ is true because $a + (a + d) = 2a + d = 2(2a + d)/2$. *Inductive step:* Assume that $P(k)$ is true. Then $a + (a + d) + \cdots + (a + kd) + [a + (k + 1)d] = (k + 1)(2a + kd)/2 + a + (k + 1)d = \frac{1}{2}(2ak + 2a + k^2d + kd + 2a + 2kd + 2d) = \frac{1}{2}(2ak + 4a + k^2d + 3kd + 2d) = \frac{1}{2}(k + 2)[2a + (k + 1)d]$. **13.** *Basis step:* This is true for $n = 1$ because $5/6 = 10/12$. *Inductive step:* Assume that the equation holds for $n = k$, and consider $n = k + 1$. Then $\sum_{i=1}^{k+1} \frac{i+4}{i(i+1)(i+2)} = \sum_{i=1}^{k} \frac{i+4}{i(i+1)(i+2)} + \frac{k+5}{(k+1)(k+2)(k+3)} = \frac{k(3k+7)}{2(k+1)(k+2)} + \frac{k+5}{(k+1)(k+2)(k+3)}$ (by the inductive hypothesis) $= \frac{1}{(k+1)(k+2)} \cdot (\frac{k(3k+7)}{2} + \frac{k+5}{k+3}) = \frac{1}{2(k+1)(k+2)(k+3)} \cdot [k(3k+7)(k+3) + 2(k+5)] = \frac{1}{2(k+1)(k+2)(k+3)} \cdot (3k^3 + 16k^2 + 23k + 10) = \frac{1}{2(k+1)(k+2)(k+3)} \cdot (3k+10)(k+1)^2 = \frac{1}{2(k+2)(k+3)} \cdot (3k+10)(k+1) = \frac{(k+1)(3(k+1)+7)}{2((k+1)+1)((k+1)+2)}$, as desired. **15.** *Basis step:* The statement is true for $n = 1$ because the derivative of $g(x) = xe^x$ is $x \cdot e^x + e^x = (x + 1)e^x$ by the product rule. *Inductive step:* Assume that the statement is true for $n = k$, i.e., the kth derivative is given by $g^{(k)} = (x + k)e^x$. Differentiating by the product rule gives the $(k + 1)$st derivative: $g^{(k+1)} = (x + k)e^x + e^x = [x + (k + 1)]e^x$, as desired. **17.** We will use strong induction to show that f_n is even if $n \equiv 0 \pmod 3$ and is odd otherwise. *Basis step:* This follows because $f_0 = 0$ is even and $f_1 = 1$ is odd. *Inductive step:* Assume that if $j \leq k$, then f_j is even if $j \equiv 0 \pmod 3$ and is odd otherwise. Now suppose $k + 1 \equiv 0 \pmod 3$. Then $f_{k+1} = f_k + f_{k-1}$ is even because f_k and f_{k-1} are both odd. If $k + 1 \equiv 1 \pmod 3$, then $f_{k+1} = f_k + f_{k-1}$ is odd because f_k is even and f_{k-1} is odd. Finally, if $k + 1 \equiv 2 \pmod 3$, then $f_{k+1} = f_k + f_{k-1}$ is odd because f_k is odd and f_{k-1} is even. **19.** Let $P(n)$ be the statement that $f_k f_n + f_{k+1} f_{n+1} = f_{n+k+1}$ for every nonnegative integer k. *Basis step:* This consists of showing that $P(0)$ and $P(1)$ both hold. $P(0)$ is true because $f_k f_0 + f_{k+1} f_1 = f_{k+1} \cdot 0 + f_{k+1} \cdot 1 = f_1$. Because $f_k f_1 + f_{k+1} f_2 = f_k + f_{k+1} = f_{k+2}$, it follows that $P(1)$ is true. *Inductive step:* Now assume that $P(j)$ holds. Then, by the inductive hypothesis and the recursive definition of the Fibonacci numbers, it follows that $f_{k+1} f_{j+1} + f_{k+2} f_{j+2} = f_k(f_{j-1} + f_j) + f_{k+1}(f_j + f_{j+1}) = (f_k f_{j-1} + f_{k+1} f_j) + (f_k f_j + f_{k+1} f_{j+1}) = f_{j-1+k+1} + f_{j+k+1} = f_{j+k+2}$. This shows that $P(j + 1)$ is true. **21.** Let $P(n)$ be the statement $l_0^2 + l_1^2 + \cdots + l_n^2 = l_n l_{n+1} + 2$. *Basis step:* $P(0)$ and

$P(1)$ both hold because $l_0^2 = 2^2 = 2 \cdot 1 + 2 = l_0 l_1 + 2$ and $l_0^2 + l_1^2 = 2^2 + 1^2 = 1 \cdot 3 + 2 = l_1 l_3 + 2$. *Inductive step:* Assume that $P(k)$ holds. Then by the inductive hypothesis $l_0^2 + l_1^2 + \cdots + l_k^2 + l_{k+1}^2 = l_k l_{k+1} + 2 + l_{k+1}^2 = l_{k+1}(l_k + l_{k+1}) + 2 = l_{k+1} l_{k+2} + 2$. This shows that $P(k+1)$ holds. **23.** Let $P(n)$ be the statement that the identity holds for the integer n. *Basis step:* $P(1)$ is obviously true. *Inductive step:* Assume that $P(k)$ is true. Then $\cos(k+1)x + i\sin(k+1)x = \cos(kx+x) + i\sin(kx+x) = \cos kx \cos x - \sin kx \sin x + i(\sin kx \cos x + \cos kx \sin x) = \cos x (\cos kx + i \sin kx)(\cos x + i \sin x) = (\cos x + i \sin x)^k (\cos x + i \sin x) = (\cos x + i \sin x)^{k+1}$. It follows that $P(k+1)$ is true. **25.** Rewrite the right-hand side as $2^{n+1}(n^2 - 2n + 3) - 6$. For $n = 1$ we have $2 = 4 \cdot 2 - 6$. Assume that the equation holds for $n = k$, and consider $n = k + 1$. Then $\sum_{j=1}^{k+1} j^2 2^j = \sum_{j=1}^{k} j^2 2^j + (k+1)^2 2^{k+1} = 2^{k+1}(k^2 - 2k + 3) - 6 + (k^2 + 2k + 1)2^{k+1}$ (by the inductive hypothesis) $= 2^{k+1}(2k^2 + 4) - 6 = 2^{k+2}(k^2 + 2) - 6 = 2^{k+2}[(k+1)^2 - 2(k+1) + 3] - 6$. **27.** Let $P(n)$ be the statement that this equation holds. *Basis step:* In $P(2)$ both sides reduce to $1/3$. *Inductive step:* Assume that $P(k)$ is true. Then $\sum_{j=1}^{k+1} 1/(j^2 - 1) = \left(\sum_{j=1}^{k} 1/(j^2 - 1)\right) + 1/[(k+1)^2 - 1] = (k-1)(3k+2)/[4k(k+1)] + 1/[(k+1)^2 - 1]$ by the inductive hypothesis. This simplifies to $(k-1)(3k+2)/[4k(k+1)] + 1/(k^2 + 2k) = (3k^3 + 5k^2)/[4k(k+1)(k+2)] = \{[(k+1) - 1][3(k+1) + 2]\}/[4(k+1)(k+2)]$, which is exactly what $P(k+1)$ asserts. **29.** Let $P(n)$ be the assertion that at least $n + 1$ lines are needed to cover the lattice points in the given triangular region. *Basis step:* $P(0)$ is true, because we need at least one line to cover the one point at $(0, 0)$. *Inductive step:* Assume the inductive hypothesis, that at least $k + 1$ lines are needed to cover the lattice points with $x \geq 0$, $y \geq 0$, and $x + y \leq k$. Consider the triangle of lattice points defined by $x \geq 0$, $y \geq 0$, and $x + y \leq k + 1$. By way of contradiction, assume that $k + 1$ lines could cover this set. Then these lines must cover the $k + 2$ points on the line $x + y = k + 1$. But only the line $x + y = k + 1$ itself can cover more than one of these points, because two distinct lines intersect in at most one point. Therefore none of the $k + 1$ lines that are needed (by the inductive hypothesis) to cover the set of lattice points within the triangle but not on this line can cover more than one of the points on this line, and this leaves at least one point uncovered. Therefore our assumption that $k + 1$ lines could cover the larger set is wrong, and our proof is complete. **31.** Let $P(n)$ be $\mathbf{B}^k = \mathbf{M}\mathbf{A}^k\mathbf{M}^{-1}$. *Basis step:* Part of the given conditions. *Inductive step:* Assume the inductive hypothesis. Then $\mathbf{B}^{k+1} = \mathbf{B}\mathbf{B}^k = \mathbf{M}\mathbf{A}\mathbf{M}^{-1}\mathbf{B}^k = \mathbf{M}\mathbf{A}\mathbf{M}^{-1}\mathbf{M}\mathbf{A}^k\mathbf{M}^{-1}$ (by the inductive hypothesis) $= \mathbf{M}\mathbf{A}\mathbf{I}\mathbf{A}^k\mathbf{M}^{-1} = \mathbf{M}\mathbf{A}\mathbf{A}^k\mathbf{M}^{-1} = \mathbf{M}\mathbf{A}^{k+1}\mathbf{M}^{-1}$. **33.** We prove by mathematical induction the following stronger statement: For every $n \geq 3$, we can write $n!$ as the sum of n of its distinct positive divisors, one of which is 1. That is, we can write $n! = a_1 + a_2 + \cdots + a_n$, where each a_i is a divisor of $n!$, the divisors are listed in strictly decreasing order, and $a_n = 1$. *Basis step:* $3! = 3 + 2 + 1$. *Inductive step:* Assume that we can write $k!$ as a sum of the desired form, say $k! = a_1 + a_2 + \cdots + a_k$, where each a_i is a divisor of $n!$, the divisors are listed in strictly decreasing order, and $a_n = 1$. Consider $(k+1)!$. Then we have $(k+1)! = (k+1)k! = (k+1)(a_1 + a_2 + \cdots + a_k) = (k+1)a_1 + (k+1)a_2 + \cdots + (k+1)a_k = (k+1)a_1 + (k+1)a_2 + \cdots + k \cdot a_k + a_k$. Because each a_i was a divisor of $k!$, each $(k+1)a_i$ is a divisor of $(k+1)!$. Furthermore, $k \cdot a_k = k$, which is a divisor of $(k+1)!$, and $a_k = 1$, so the new last summand is again 1. (Notice also that our list of summands is still in strictly decreasing order.) Thus we have written $(k+1)!$ in the desired form. **35.** When $n = 1$ the statement is vacuously true. Assume that the statement is true for $n = k$, and consider $k + 1$ people standing in a line, with a woman first and a man last. If the kth person is a woman, then we have that woman standing in front of the man at the end. If the kth person is a man, then the first k people in line satisfy the conditions of the inductive hypothesis for the first k people in line, so again we can conclude that there is a woman directly in front of a man somewhere in the line. **37.** *Basis step:* When $n = 1$ there is one circle, and we can color the inside blue and the outside red to satisfy the conditions. *Inductive step:* Assume the inductive hypothesis that if there are k circles, then the regions can be 2-colored such that no regions with a common boundary have the same color, and consider a situation with $k + 1$ circles. Remove one of the circles, producing a picture with k circles, and invoke the inductive hypothesis to color it in the prescribed manner. Then replace the removed circle and change the color of every region inside this circle. The resulting figure satisfies the condition, because if two regions have a common boundary, then either that boundary involved the new circle, in which case the regions on either side used to be the same region and now the inside portion is different from the outside, or else the boundary did not involve the new circle, in which case the regions are colored differently because they were colored differently before the new circle was restored. **39.** If $n = 1$ then the equation reads $1 \cdot 1 = 1 \cdot 2/2$, which is true. Assume that the equation is true for n and consider it for $n + 1$. Then $\sum_{j=1}^{n+1}(2j - 1)\left(\sum_{k=j}^{n+1} \frac{1}{k}\right) = \sum_{j=1}^{n}(2j - 1)\left(\sum_{k=j}^{n+1} \frac{1}{k}\right) + [2(n+1) - 1] \cdot \frac{1}{n+1} = \sum_{j=1}^{n}(2j - 1)\left(\frac{1}{n+1} + \sum_{k=j}^{n} \frac{1}{k}\right) + \frac{2n+1}{n+1} = \left(\frac{1}{n+1}\sum_{j=1}^{n}(2j - 1)\right) + \left(\sum_{j=1}^{n}(2j - 1)\sum_{k=j}^{n} \frac{1}{k}\right) + \frac{2n+1}{n+1} = \left(\frac{1}{n+1} \cdot n^2\right) + \frac{n(n+1)}{2} + \frac{2n+1}{n+1}$ (by the inductive hypothesis) $= \frac{2n^2 + n(n+1)^2 + (4n+2)}{2(n+1)} = \frac{2(n+1)^2 + n(n+1)^2}{2(n+1)} = \frac{(n+1)(n+2)}{2}$. **41. a)** 92 **b)** 91 **c)** 91 **d)** 91 **e)** 91 **f)** 91 **43.** The basis step is incorrect because $n \neq 1$ for the sum shown. **45.** Let $P(n)$ be "the plane is divided into $n^2 - n + 2$ regions by n circles if every two of these circles have two common points but no three have a common point." *Basis step:* $P(1)$ is true because a circle divides the plane into $2 = 1^2 - 1 + 2$ regions. *Inductive step:* Assume that $P(k)$ is true, that is, k circles with the specified properties divide the plane into $k^2 - k + 2$ regions. Suppose that a $(k+1)$st circle is added. This circle intersects each of the other k circles in two points, so these points of intersection form $2k$ new arcs, each of which splits an old region. Hence, there are $2k$ regions split, which shows that there are $2k$ more regions than there were previously. Hence, $k+1$ circles satisfying the specified properties divide the plane into $k^2-k+2+2k=(k^2+2k+1)-(k+1)+2=(k+1)^2-(k+1)+2$ regions. **47.** Suppose $\sqrt{2}$ were rational. Then $\sqrt{2}=a/b$, where a and b are positive integers. It follows that the set $S=\{n\sqrt{2}\mid n\in\mathbf{N}\}\cap\mathbf{N}$ is a nonempty set of positive integers, because $b\sqrt{2}=a$ belongs to S. Let t be the least element of S, which exists by the well-ordering property. Then $t=s\sqrt{2}$ for some integer s. We have $t-s=s\sqrt{2}-s=s(\sqrt{2}-1)$, so $t-s$ is a positive integer because $\sqrt{2}>1$. Hence, $t-s$ belongs to S. This is a contradiction because $t-s=s\sqrt{2}-s<s$. Hence, $\sqrt{2}$ is irrational. **49. a)** Let $d=\gcd(a_1,a_2,\dots,a_n)$. Then d is a divisor of each a_i and so must be a divisor of $\gcd(a_{n-1},a_n)$. Hence, d is a common divisor of $a_1,a_2,\dots,a_{n-2}$, and $\gcd(a_{n-1},a_n)$. To show that it is the greatest common divisor of these numbers, suppose that c is a common divisor of them. Then c is a divisor of a_i for $i=1,2,\dots,n-2$ and a divisor of $\gcd(a_{n-1},a_n)$, so it is a divisor of a_{n-1} and a_n. Hence, c is a common divisor of $a_1,a_2,\dots,a_{n-1}$, and a_n. Hence, it is a divisor of d, the greatest common divisor of $a_1,a_2,\dots,a_n$. It follows that d is the greatest common divisor, as claimed. **b)** If $n=2$, apply the Euclidean algorithm. Otherwise, apply the Euclidean algorithm to a_{n-1} and a_n, obtaining $d=\gcd(a_{n-1},a_n)$, and then apply the algorithm recursively to a_1, $a_2,\dots,a_{n-2},d$. **51.** $f(n)=n^2$. Let $P(n)$ be "$f(n)=n^2$." *Basis step:* $P(1)$ is true because $f(1)=1=1^2$, which follows from the definition of f. *Inductive step:* Assume $f(n)=n^2$. Then $f(n+1)=f((n+1)-1)+2(n+1)-1=f(n)+2n+1=n^2+2n+1=(n+1)^2$. **53. a)** λ, 0, 1, 00, 01, 11, 000, 001, 011, 111, 0000, 0001, 0011, 0111, 1111, 00000, 00001, 00011, 00111, 01111, 11111 **b)** $S=\{\alpha\beta\mid\alpha$ is a string of m 0s and β is a string of n 1s, $m\ge 0, n\ge 0\}$ **55.** Apply the first recursive step to λ to get $()\in B$. Apply the second recursive step to this string to get $()()\in B$. Apply the first recursive step to this string to get $(()())\in B$. By Exercise 58, $(()))$ is not in B because the number of left parentheses does not equal the number of right parentheses. **57.** λ, (), (()), ()() **59. a)** 0 **b)** -2 **c)** 2 **d)** 0

61. procedure *generate(n*: nonnegative integer)
  if n is odd **then**
  begin
   $S:=S(n-1);T:=T(n-1)$
  end
  else if $n=0$ **then**
  begin
   $S:=\emptyset;T:=\{\lambda\}$
  end
  else
  begin
   $T_1:=T(n-2);S_1:=S(n-2)$
   $T:=T_1\cup\{(x)\mid x\in T_1\cup S_1$ and $l(x)=n-2\}$
   $S:=S_1\cup\{xy\mid x\in T_1$ and $y\in T_1\cup S_1$
    and $l(xy)=n\}$
  end $\{T\cup S$ is the set of balanced strings of length at most $n\}$

63. If $x\le y$ initially, then $x:=y$ is not executed, so $x\le y$ is a true final assertion. If $x>y$ initially, then $x:=y$ is executed, so $x\le y$ is again a true final assertion.

65. procedure *zerocount*$(a_1,a_2,\dots,a_n$: list of integers)
  if $n=1$ **then**
   if $a_1=0$ **then** *zerocount*$(a_1,a_2,\dots,a_n):=1$
   else *zerocount*$(a_1,a_2,\dots,a_n):=0$
  else
   if $a_n=0$ **then** *zerocount*$(a_1,a_2,\dots,a_n):=$
    zerocount$(a_1,a_2,\dots,a_{n-1})+1$
   else *zerocount*$(a_1,a_2,\dots,a_n):=$
    zerocount$(a_1,a_2,\dots,a_{n-1})$

67. We will prove that $a(n)$ is a natural number and $a(n)\le n$. This is true for the base case $n=0$ because $a(0)=0$. Now assume that $a(n-1)$ is a natural number and $a(n-1)\le n-1$. Then $a(a(n-1))$ is a applied to a natural number less than or equal to $n-1$. Hence, $a(a(n-1))$ is also a natural number minus than or equal to $n-1$. Therefore, $n-a(a(n-1))$ is n minus some natural number less than or equal to $n-1$, which is a natural number less than or equal to n. **69.** From Exercise 68, $a(n)=\lfloor(n+1)\mu\rfloor$ and $a(n-1)=\lfloor n\mu\rfloor$. Because $\mu<1$, these two values are equal or they differ by 1. First suppose that $\mu n-\lfloor\mu n\rfloor<1-\mu$. This is equivalent to $\mu(n+1)<1+\lfloor\mu n\rfloor$. If this is true, then $\lfloor\mu(n+1)\rfloor=\lfloor\mu n\rfloor$. On the other hand, if $\mu n-\lfloor\mu n\rfloor\ge 1-\mu$, then $\mu(n+1)\ge 1+\lfloor\mu n\rfloor$, so $\lfloor\mu(n+1)\rfloor=\lfloor\mu n\rfloor+1$, as desired. **71.** $f(0)=1$, $m(0)=0$; $f(1)=1$, $m(1)=0$; $f(2)=2$, $m(2)=1$; $f(3)=2$, $m(3)=2$; $f(4)=3$, $m(4)=2$; $f(5)=3$, $m(5)=3$; $f(6)=4$, $m(6)=4$; $f(7)=5$, $m(7)=4$; $f(8)=5$, $m(8)=5$; $f(9)=6$, $m(9)=6$ **73.** The last occurrence of n is in the position for which the total number of 1's, 2's, …, n's all together is that position number. But because a_k is the number of occurrences of k, this is just $\sum_{k=1}^{n}a_k$, as desired. Because $f(n)$ is the sum of the first n terms of the sequence, $f(f(n))$ is the sum of the first $f(n)$ terms of the sequence. But because $f(n)$ is the last term whose value is n, this means that the sum is the sum of all terms of the sequence whose value is at most n. Because there are a_k terms of the sequence whose value is k, this sum is $\sum_{k=1}^{n}k\cdot a_k$, as desired

CHAPTER 5

Section 5.1

1. a) 5850 **b)** 343 **3. a)** 4^{10} **b)** 5^{10} **5.** 42 **7.** 26^3 **9.** 676 **11.** 2^8 **13.** $n+1$ (counting the empty string) **15.** 475,255 (counting the empty string) **17.** 1,321,368,961 **19. a)** Seven: 56, 63, 70, 77, 84, 91, 98 **b)** Five: 55, 66, 77, 88, 99 **c)** One: 77 **21. a)** 128 **b)** 450 **c)** 9 **d)** 675 **e)** 450 **f)** 450 **g)** 225 **h)** 75 **23. a)** 990 **b)** 500 **c)** 27 **25.** 3^{50} **27.** 52,457,600 **29.** 20,077,200 **31. a)** 37,822,859,361 **b)** 8,204,716,800 **c)** 40,159,050,880 **d)** 12,113,640,000 **e)** 171,004,205,215 **f)** 72,043,541,640 **g)** 6,230,721,635 **h)** 223,149,655 **33. a)** 0 **b)** 120 **c)** 720 **d)** 2520 **35. a)** 2 if $n=1$, 2 if $n=2$, 0 if $n \geq 3$ **b)** 2^{n-2} for $n > 1$; 1 if $n = 1$ **c)** $2(n-1)$ **37.** $(n+1)^m$ **39.** If n is even, $2^{n/2}$; if n is odd, $2^{(n+1)/2}$ **41. a)** 240 **b)** 480 **c)** 360 **43.** 352 **45.** 147 **47.** 33 **49. a)** 9,920,671,339,261,325,541,376 $\approx 9.9 \times 10^{21}$ **b)** 6,641,514,961,387,068,437,760 $\approx 6.6 \times 10^{21}$ **c)** 9,920,671,339.261325541376 seconds, which is about 314,000 years **51.** 7,104,000,000,000 **53.** 18 **55.** 17 **57.** 22 **59.** Let $P(m)$ be the sum rule for m tasks. For the basis case take $m = 2$. This is just the sum rule for two tasks. Now assume that $P(m)$ is true. Consider $m + 1$ tasks, $T_1, T_2, \ldots, T_m, T_{m+1}$, which can be done in $n_1, n_2, \ldots, n_m, n_{m+1}$ ways, respectively, such that no two of these tasks can be done at the same time. To do one of these tasks, we can either do one of the first m of these or do task T_{m+1}. By the sum rule for two tasks, the number of ways to do this is the sum of the number of ways to do one of the first m tasks, plus n_{m+1}. By the inductive hypothesis, this is $n_1 + n_2 + \cdots + n_m + n_{m+1}$, as desired. **61.** $n(n-3)/2$

Section 5.2

1. Because there are six classes, but only five weekdays, the pigeonhole principle shows that at least two classes must be held on the same day. **3. a)** 3 **b)** 14 **5.** Because there are four possible remainders when an integer is divided by 4, the pigeonhole principle implies that given five integers, at least two have the same remainder. **7.** Let $a, a+1, \ldots, a+n-1$ be the integers in the sequence. The integers $(a+i)$ **mod** n, $i = 0, 1, 2, \ldots, n-1$, are distinct, because $0 < (a+j) - (a+k) < n$ whenever $0 \leq k < j \leq n-1$. Because there are n possible values for $(a+i)$ **mod** n and there are n different integers in the set, each of these values is taken on exactly once. It follows that there is exactly one integer in the sequence that is divisible by n. **9.** 4951 **11.** The midpoint of the segment joining the points (a, b, c) and (d, e, f) is $((a+d)/2, (b+e)/2, (c+f)/2)$. It has integer coefficients if and only if a and d have the same parity, b and e have the same parity, and c and f have the same parity. Because there are eight possible triples of parity [such as (*even*, *odd*, *even*)], by the pigeonhole principle at least two of the nine points have the same triple of parities. The midpoint of the segment joining two such points has integer coefficients. **13. a)** Group the first eight positive integers into four subsets of two integers each so that the integers of each subset add up to 9: $\{1, 8\}$, $\{2, 7\}$, $\{3, 6\}$, and $\{4, 5\}$. If five integers are selected from the first eight positive integers, by the pigeonhole principle at least two of them come from the same subset. Two such integers have a sum of 9, as desired. **b)** No. Take $\{1, 2, 3, 4\}$, for example. **15.** 4 **17.** 21,251 **19. a)** If there were fewer than 9 freshmen, fewer than 9 sophomores, and fewer than 9 juniors in the class, there would be no more than 8 with each of these three class standings, for a total of at most 24 students, contradicting the fact that there are 25 students in the class. **b)** If there were fewer than 3 freshmen, fewer than 19 sophomores, and fewer than 5 juniors, then there would be at most 2 freshmen, at most 18 sophomores, and at most 4 juniors, for a total of at most 24 students. This contradicts the fact that there are 25 students in the class. **21.** 4, 3, 2, 1, 8, 7, 6, 5, 12, 11, 10, 9, 16, 15, 14, 13
23.

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procedure long(a_1, ..., a_n: positive integers)
  {first find longest increasing subsequence}
  max := 0; set := 00...00 {n bits}
  for i := 1 to 2^n
  begin
    last := 0; count := 0, OK := true
    for j := 1 to n
    begin
      if set(j) = 1 then
      begin
        if a_j > last then last := a_j
        count := count + 1
      end
      else OK := false
    end
    if count > max then
    begin
      max := count
      best := set
    end
    set := set + 1 (binary addition)
  end {max is length and best indicates the sequence}
  {repeat for decreasing subsequence with only
     changes being a_j < last instead of a_j > last
     and last := ∞ instead of last := 0}
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25. By symmetry we need prove only the first statement. Let A be one of the people. Either A has at least four friends, or A has at least six enemies among the other nine people (because $3 + 5 < 9$). Suppose, in the first case, that B, C, D, and E are all A's friends. If any two of these are friends with each other, then we have found three mutual friends. Otherwise $\{B, C, D, E\}$ is a set of four mutual enemies. In the second case, let $\{B, C, D, E, F, G\}$ be a set of enemies of A. By Example 11, among B, C, D, E, F, and G there are either three mutual friends or three mutual enemies, who form, with A, a set of four mutual enemies. **27.** We need to show two things: that if we have a group of n people, then among them we must find either a pair of friends or a subset of n of them all of whom are mutual enemies; and that there exists a group of $n-1$ people for which this is not possible. For the first statement, if there is any pair of friends, then the condition is satisfied, and if not, then every pair of people are enemies, so the second condition is satisfied. For the second statement, if we have a group of $n-1$ people all of whom are enemies of each other, then there is neither a pair of friends nor a subset of n of them all of whom are mutual enemies. **29.** There are 6,432,816 possibilities for the three initials and a birthday. So, by the generalized pigeonhole principle, there are at least $\lceil 36{,}000{,}000/6{,}432{,}816 \rceil = 6$ people who share the same initials and birthday. **31.** 18 **33.** Because there are six computers, the number of other computers a computer is connected to is an integer between 0 and 5, inclusive. However, 0 and 5 cannot both occur. To see this, note that if some computer is connected to no others, then no computer is connected to all five others, and if some computer is connected to all five others, then no computer is connected to no others.

Hence, by the pigeonhole principle, because there are at most five possibilities for the number of computers a computer is connected to, there are at least two computers in the set of six connected to the same number of others. **35.** Label the computers C_1 through C_{100}, and label the printers P_1 through P_{20}. If we connect C_k to P_k for $k = 1, 2, \ldots, 20$ and connect each of the computers C_{21} through C_{100} to *all* the printers, then we have used a total of $20 + 80 \cdot 20 = 1620$ cables. Clearly this is sufficient, because if computers C_1 through C_{20} need printers, then they can use the printers with the same subscripts, and if any computers with higher subscripts need a printer instead of one or more of these, then they can use the printers that are not being used, because they are connected to all the printers. Now we must show that 1619 cables is not enough. Because there are 1619 cables and 20 printers, the average number of computers per printer is 1619/20, which is less than 81. Therefore some printer must be connected to fewer than 81 computers. That means it is connected to 80 or fewer computers, so there are 20 computers that are not connected to it. If those 20 computers all needed a printer simultaneously, then they would be out of luck, because they are connected to at most the 19 other printers. **37.** Let a_i be the number of matches completed by hour i. Then $1 \le a_1 < a_2 < \cdots < a_{75} \le 125$. Also $25 \le a_1 + 24 < a_2 + 24 < \cdots < a_{75} + 24 \le 149$. There are 150 numbers $a_1, \ldots, a_{75}, a_1 + 24, \ldots, a_{75} + 24$. By the pigeonhole principle, at least two are equal. Because all the a_is are distinct and all the $(a_i + 24)$s are distinct, it follows that $a_i = a_j + 24$ for some $i > j$. Thus, in the period from the $(j + 1)$st to the ith hour, there are exactly 24 matches. **39.** Use the generalized pigeonhole principle, placing the $|S|$ objects $f(s)$ for $s \in S$ in $|T|$ boxes, one for each element of T. **41.** Let d_j be $jx - N(jx)$, where $N(jx)$ is the integer closest to jx for $1 \le j \le n$. Each d_j is an irrational number between $-1/2$ and $1/2$. We will assume that n is even; the case where n is odd is messier. Consider the n intervals $\{x \mid j/n < x < (j + 1)/n\}$, $\{x \mid -(j + 1)/n < x < -j/n\}$ for $j = 0, 1, \ldots, (n/2) - 1$. If d_j belongs to the interval $\{x \mid 0 < x < 1/n\}$ or to the interval $\{x \mid -1/n < x < 0\}$ for some j, we are done. If not, because there are $n - 2$ intervals and n numbers d_j, the pigeonhole principle tells us that there is an interval $\{x \mid (k - 1)/n < x < k/n\}$ containing d_r and d_s with $r < s$. The proof can be finished by showing that $(s - r)x$ is within $1/n$ of its nearest integer. **43. a)** Assume that $i_k \le n$ for all k. Then by the generalized pigeonhole principle, at least $\lceil (n^2 + 1)/n \rceil = n + 1$ of the numbers $i_1, i_2, \ldots, i_{n^2+1}$ are equal. **b)** If $a_{k_j} < a_{k_{j+1}}$, then the subsequence consisting of a_{k_j} followed by the increasing subsequence of length $i_{k_{j+1}}$ starting at $a_{k_{j+1}}$ contradicts the fact that $i_{k_j} = i_{k_{j+1}}$. Hence, $a_{k_j} > a_{k_{j+1}}$. **c)** If there is no increasing subsequence of length greater than n, then parts (a) and (b) apply. Therefore, we have $a_{k_{n+1}} > a_{k_n} > \cdots > a_{k_2} > a_{k_1}$, a decreasing sequence of length $n + 1$.

Section 5.3

1. *abc, acb, bac, bca, cab, cba* **3.** 720 **5. a)** 120 **b)** 720 **c)** 8 **d)** 6720 **e)** 40,320 **f)** 3,628,800 **7.** 15,120 **9.** 1320 **11. a)** 210 **b)** 386 **c)** 848 **d)** 252 **13.** $2(n!)^2$ **15.** 65,780 **17.** $2^{100} - 5051$ **19. a)** 1024 **b)** 45 **c)** 176 **d)** 252 **21. a)** 120 **b)** 24 **c)** 120 **d)** 24 **e)** 6 **f)** 0 **23.** 609,638,400 **25. a)** 94,109,400 **b)** 941,094 **c)** 3,764,376 **d)** 90,345,024 **e)** 114,072 **f)** 2328 **g)** 24 **h)** 79,727,040 **i)** 3,764,376 **j)** 109,440 **27. a)** 12,650 **b)** 303,600 **29. a)** 37,927 **b)** 18,915 **31. a)** 122,523,030 **b)** 72,930,375 **c)** 223,149,655 **d)** 100,626,625 **33.** 54,600 **35.** 45 **37.** 912 **39.** 11,232,000 **41.** 13 **43.** 873

Section 5.4

1. $x^4 + 4x^3y + 6x^2y^2 + 4xy^3 + y^4$ **3.** $x^6 + 6x^5y + 15x^4y^2 + 20x^3y^3 + 15x^2y^4 + 6xy^5 + y^6$ **5.** 101 **7.** $-2^{10}\binom{19}{9} = -94{,}595{,}072$ **9.** $-2^{101}3^{99}\binom{200}{99}$ **11.** $(-1)^{(200-k)/3}\binom{100}{(200-k)/3}$ if $k \equiv 2 \pmod 3$ and $-100 \le k \le 200$; 0 otherwise **13.** 1 9 36 84 126 126 84 36 9 1 **15.** The sum of *all* the positive numbers $\binom{n}{k}$, as k runs from 0 to n, is 2^n, so each one of them is no bigger than this sum. **17.** $\binom{n}{k} = \frac{n(n-1)(n-2)\cdots(n-k+1)}{k(k-1)(k-2)\cdots 2} \le \frac{n \cdot n \cdot \cdots \cdot n}{2 \cdot 2 \cdot \cdots \cdot 2} = n^k/2^{k-1}$ **19.** $\binom{n}{k-1} + \binom{n}{k} = \frac{n!}{(k-1)!(n-k+1)!} + \frac{n!}{k!(n-k)!} = \frac{n!}{k!(n-k+1)!} \cdot [k + (n - k + 1)] = \frac{(n+1)!}{k!(n+1-k)!} = \binom{n+1}{k}$ **21. a)** We show that each side counts the number of ways to choose from a set with n elements a subset with k elements and a distinguished element of that set. For the left-hand side, first choose the k-set (this can be done in $\binom{n}{k}$ ways) and then choose one of the k elements in this subset to be the distinguished element (this can be done in k ways). For the right-hand side, first choose the distinguished element out of the entire n-set (this can be done in n ways), and then choose the remaining $k - 1$ elements of the subset from the remaining $n - 1$ elements of the set (this can be done in $\binom{n-1}{k-1}$ ways). **b)** $k\binom{n}{k} = k \cdot \frac{n!}{k!(n-k)!} = \frac{n \cdot (n-1)!}{(k-1)!(n-k)!} = n\binom{n-1}{k-1}$ **23.** $\binom{n+1}{k} = \frac{(n+1)!}{k!(n+1-k)!} = \frac{(n+1)}{k} \frac{n!}{(k-1)![n-(k-1)]!} = (n + 1)\binom{n}{k-1}/k$. This identity together with $\binom{n}{0} = 1$ gives a recursive definition. **25.** $\binom{2n}{n+1} + \binom{2n}{n} = \binom{2n+1}{n+1} = \frac{1}{2}\left[\binom{2n+1}{n+1} + \binom{2n+1}{n+1}\right] = \frac{1}{2}\left[\binom{2n+1}{n+1} + \binom{2n+1}{n}\right] = \frac{1}{2}\binom{2n+2}{n+1}$ **27. a)** $\binom{n+r+1}{r}$ counts the number of ways to choose a sequence of r 0s and $n + 1$ 1s by choosing the positions of the 0s. Alternately, suppose that the $(j + 1)$st term is the last term equal to 1, so that $n \le j \le n + r$. Once we have determined where the last 1 is, we decide where the 0s are to be placed in the j spaces before the last 1. There are n 1s and $j - n$ 0s in this range. By the sum rule it follows that there are $\sum_{j=n}^{n+r}\binom{j}{j-n} = \sum_{k=0}^{r}\binom{n+k}{k}$ ways to do this. **b)** Let $P(r)$ be the statement to be proved. The basis step is the equation $\binom{n}{0} = \binom{n+1}{0}$, which is just $1 = 1$. Assume that $P(r)$ is true. Then $\sum_{k=0}^{r+1}\binom{n+k}{k} = \sum_{k=0}^{r}\binom{n+k}{k} + \binom{n+r+1}{r+1} = \binom{n+r+1}{r} + \binom{n+r+1}{r+1} = \binom{n+r+2}{r+1}$, using the inductive hypothesis and Pascal's Identity. **29.** We can choose the leader first in n different ways. We can then choose the rest of the committee in 2^{n-1} ways. Hence, there are $n2^{n-1}$ ways to choose the committee and its leader. Meanwhile, the number of ways to select a committee with k people is $\binom{n}{k}$. Once we have chosen a committee with k people, there are k ways to choose its leader. Hence, there are $\sum_{k=1}^{n} k\binom{n}{k}$ ways to choose the committee and its leader. Hence, $\sum_{k=1}^{n} k\binom{n}{k} = n2^{n-1}$. **31.** Let the set have n elements. From Corollary 2 we have $\binom{n}{0} - \binom{n}{1} + \binom{n}{2} - \cdots + (-1)^n\binom{n}{n} = 0$. It follows that $\binom{n}{0} + \binom{n}{2} + \binom{n}{4} + \cdots = \binom{n}{1} + \binom{n}{3} + \binom{n}{5} + \cdots$. The left-hand side gives the number of subsets with an even number of elements, and the right-hand side gives the number of subsets with an odd number of elements. **33. a)** A path of the desired type consists of m moves to the right and n moves up. Each such path can be represented by a bit string of length $m + n$ with m 0s and n 1s, where a 0 represents a move to the right and a 1 a move up. **b)** The number of bit strings of length $m + n$ containing exactly n 1s equals $\binom{m+n}{n} = \binom{m+n}{m}$ because such a string is determined by specifying the positions of the n 1s or by specifying the positions of the m 0s. **35.** By Exercise 33 the number of paths of length n of the type described in that exercise equals 2^n, the number of bit strings of length n. On the other hand, a path of length n of the type described in Exercise 33 must end at a point that has n as the sum of its coordinates, say $(n - k, k)$ for some k between 0 and n, inclusive. By Exercise 33, the number of such paths ending at $(n - k, k)$ equals $\binom{n-k+k}{k} = \binom{n}{k}$. Hence, $\sum_{k=0}^{n}\binom{n}{k} = 2^n$. **37.** By Exercise 33 the number of paths from $(0, 0)$ to $(n + 1, r)$ of the type described in that exercise equals $\binom{n+r+1}{r}$. But such a path starts by going j steps vertically for some j with $0 \le j \le r$. The number of these paths beginning with j vertical steps equals the number of paths of the type described in Exercise 33 that go from $(1, j)$ to $(n + 1, r)$. This is the same as the number of such paths that go from $(0, 0)$ to $(n, r - j)$, which by Exercise 33 equals $\binom{n+r-j}{r-j}$. Because $\sum_{j=0}^{r}\binom{n+r-j}{r-j} = \sum_{k=0}^{r}\binom{n+k}{k}$, it follows that $\sum_{k=1}^{r}\binom{n+k}{k} = \binom{n+r-1}{r}$. **39. a)** $\binom{n+1}{2}$ **b)** $\binom{n+2}{3}$ **c)** $\binom{2n-2}{n-1}$ **d)** $\binom{n-1}{\lfloor (n-1)/2 \rfloor}$ **e)** Largest odd entry in nth row of Pascal's triangle **f)** $\binom{3n-3}{n-1}$

Section 5.5

1. 243 **3.** 26^6 **5.** 125 **7.** 35 **9. a)** 1716 **b)** 50,388 **c)** 2,629,575 **d)** 330 **e)** 9,724 **11.** 9 **13.** 4,504,501 **15. a)** 10,626 **b)** 1,365 **c)** 11,649 **d)** 106 **17.** 2,520 **19.** 302,702,400 **21.** 3003 **23.** 7,484,400 **25.** 30,492 **27.** $C(59, 50)$ **29.** 35 **31.** 83,160 **33.** 63 **35.** 19,635 **37.** 210 **39.** 27,720 **41.** $52!/(7!^5 17!)$ **43.** Approximately 6.5×10^{32} **45. a)** $C(k + n - 1, n)$ **b)** $(k + n - 1)!/(k - 1)!$ **47.** There are $C(n, n_1)$ ways to choose n_1 objects for the first box. Once these objects are chosen, there are $C(n - n_1, n_2)$ ways to choose objects for the second box. Similarly, there are $C(n - n_1 - n_2, n_3)$ ways to choose objects for the third box. Continue in this way until there is $C(n - n_1 - n_2 - \cdots - n_{k-1}, n_k) = C(n_k, n_k) = 1$ way to choose the objects for the last box (because $n_1 + n_2 + \cdots + n_k = n$). By the product rule, the number of ways to make the entire assignment is $C(n, n_1)C(n - n_1, n_2)C(n - n_1 - n_2, n_3) \cdots C(n - n_1 - n_2 - \cdots - n_{k-1}, n_k)$, which equals $n!/(n_1!n_2! \cdots n_k!)$, as straightforward simplification shows. **49. a)** Because $x_1 \le x_2 \le \cdots \le x_r$, it follows that $x_1 + 0 < x_2 + 1 < \cdots < x_r + r - 1$. The inequalities are strict because $x_j + j - 1 < x_{j+1} + j$ as long as $x_j \le x_{j+1}$. Because $1 \le x_j \le n + r - 1$, this sequence is made up of r distinct elements from T. **b)** Suppose that $1 \le x_1 < x_2 < \cdots < x_r \le n + r - 1$. Let $y_k = x_k - (k - 1)$. Then it is not hard to see that $y_k \le y_{k+1}$ for $k = 1, 2, \ldots, r - 1$ and that $1 \le y_k \le n$ for $k = 1, 2, \ldots r$. It follows that $\{y_1, y_2, \ldots, y_r\}$ is an r-combination with repetitions allowed of S. **c)** From parts (a) and (b) it follows that there is a one-to-one correspondence of r-combinations with repetitions allowed of S and r-combinations of T, a set with $n + r - 1$ elements. We conclude that there are $C(n + r - 1, r)$ r-combinations with repetitions allowed of S. **51.** 65 **53.** 65 **55.** 2 **57.** 3 **59. a)** 150 **b)** 25 **c)** 6 **d)** 2 **61.** 90,720 **63.** The terms in the expansion are of the form $x_1^{n_1}x_2^{n_2} \cdots x_m^{n_m}$, where $n_1 + n_2 + \cdots + n_m = n$. Such a term arises from choosing the x_1 in n_1 factors, the x_2 in n_2 factors, …, and the x_m in n_m factors. This can be done in $C(n; n_1, n_2, \ldots, n_m)$ ways, because a choice is a permutation of n_1 labels "1," n_2 labels "2," …, and n_m labels "m." **65.** 2520

Section 5.6

1. 14532, 15432, 21345, 23451, 23514, 31452, 31542, 43521, 45213, 45321 **3. a)** 2134 **b)** 54132 **c)** 12534 **d)** 45312 **e)** 6714253 **f)** 31542678 **5.** 1234, 1243, 1324, 1342, 1423, 1432, 2134, 2143, 2314, 2341, 2413, 2431, 3124, 3142, 3214, 3241, 3412, 3421, 4123, 4132, 4213, 4231, 4312, 4321 **7.** $\{1, 2, 3\}$, $\{1, 2, 4\}$, $\{1, 2, 5\}$, $\{1, 3, 4\}$, $\{1, 3, 5\}$, $\{1, 4, 5\}$, $\{2, 3, 4\}$, $\{2, 3, 5\}$, $\{2, 4, 5\}$, $\{3, 4, 5\}$ **9.** The bit string representing the next larger r-combination must differ from the bit string representing the original one in position i because positions $i + 1, \ldots, r$ are occupied by the largest possible numbers. Also $a_i + 1$ is the smallest possible number we can put in position i if we want a combination greater than the original one. Then $a_i + 2, \ldots, a_i + r - i + 1$ are the smallest allowable numbers for positions $i + 1$ to r. Thus, we have produced the next r-combination. **11.** 123, 132, 213, 231, 312, 321, 124, 142, 214, 241, 412, 421, 125, 152, 215, 251, 512, 521, 134, 143, 314, 341, 413, 431, 135, 153, 315, 351, 513, 531, 145, 154, 415, 451, 514, 541, 234, 243, 324, 342, 423, 432, 235, 253, 325, 352, 523, 532, 245, 254, 425, 452, 524, 542, 345, 354, 435, 453, 534, 543 **13.** We will show that it is a bijection by showing that it has an inverse. Given a positive integer less than $n!$, let $a_1, a_2, \ldots, a_{n-1}$ be its Cantor digits. Put n in position $n - a_{n-1}$; then clearly, a_{n-1} is the number of integers less than n that follow n in the permutation. Then put $n - 1$ in free position $(n - 1) - a_{n-2}$, where we have numbered the free positions $1, 2, \ldots, n - 1$ (excluding the position that n is already in). Continue until 1 is placed in the only free position left. Because we have constructed an inverse, the correspondence is a bijection.

15.
```
procedure Cantor permutation(n, i: integers with
    n ≥ 1 and 0 ≤ i < n!)
x := n
for j := 1 to n
    p_j := 0
for k := 1 to n − 1
begin
    c := ⌊x/(n − k)!⌋; x := x − c(n − k)!; h := n
    while p_h ≠ 0
        h := h − 1
    for j := 1 to c
    begin
        h := h − 1
        while p_h ≠ 0
            h := h − 1
    end
    p_h := n − k + 1
end
h := 1
while p_h ≠ 0
    h := h + 1
p_h := 1
    {p_1 p_2 ··· p_n is the permutation corresponding
     to i}
```

Supplementary Exercises

1. a) 151,200 **b)** 1,000,000 **c)** 210 **d)** 5005 **3.** 3^{100} **5.** 24,600 **7. a)** 4,060 **b)** 2688 **c)** 25,009,600 **9. a)** 192 **b)** 301 **c)** 300 **d)** 300 **11.** 639 **13.** The maximum possible sum is 240, and the minimum possible sum is 15. So the number of possible sums is 226. Because there are 252 subsets with five elements of a set with 10 elements, by the pigeonhole principle it follows that at least two have the same sum. **15. a)** 50 **b)** 50 **c)** 14 **d)** 5 **17.** Let a_1, $a_2, \ldots, a_m$ be the integers, and let $d_i = \sum_{j=1}^{i} a_j$. If $d_i \equiv 0 \pmod{m}$ for some i, we are done. Otherwise d_1 **mod** m, d_2 **mod** $m, \ldots, d_m$ **mod** m are m integers with values in $\{1, 2, \ldots, m-1\}$. By the pigeonhole principle $d_k = d_l$ for some $1 \le k < l \le m$. Then $\sum_{j=k+1}^{l} a_j = d_l - d_k \equiv 0 \pmod{m}$. **19.** The decimal expansion of the rational number a/b can be obtained by division of b into a, where a is written with a decimal point and an arbitrarily long string of 0s following it. The basic step is finding the next digit of the quotient, namely, $\lfloor r/b \rfloor$, where r is the remainder with the next digit of the dividend brought down. The current remainder is obtained from the previous remainder by subtracting b times the previous digit of the quotient. Eventually the dividend has nothing but 0s to bring down. Furthermore, there are only b possible remainders. Thus, at some point, by the pigeonhole principle, we will have the same situation as had previously arisen. From that point onward, the calculation must follow the same pattern. In particular, the quotient will repeat. **21. a)** 125,970 **b)** 20 **c)** 141,120,525 **d)** 141,120,505 **e)** 177,100 **f)** 141,078,021 **23. a)** 10 **b)** 8 **c)** 7 **25.** 3^n **27.** $C(n+2, r+1) = C(n+1, r+1) + C(n+1, r) = 2C(n+1, r+1) - C(n+1, r+1) + C(n+1, r) = 2C(n+1, r+1) - (C(n, r+1) + C(n, r)) + (C(n, r) + C(n, r-1)) = 2C(n+1, r+1) - C(n, r+1) + C(n, r-1)$ **29.** Substitute $x = 1$ and $y = 3$ into the Binomial Theorem. **31.** $C(n+1, 5)$ **33.** 3,491,888,400 **35.** 5^{24} **37. a)** 45 **b)** 57 **c)** 12 **39. a)** 386 **b)** 56 **c)** 512 **41.** 0 if $n < m$; $C(n-1, n-m)$ if $n \ge m$ **43. a)** 15,625 **b)** 202 **c)** 210 **d)** 10

45.
```
procedure next permutation (n: positive integer,
    a_1, a_2, ..., a_r: positive integers not exceeding
    n with a_1 a_2 ... a_r ≠ nn ... n)
i := r
while a_i = n
begin
    a_i := 1
    i := i − 1
end
a_i := a_i + 1
{a_1 a_2 ... a_r is the next permutation in lexicographic
  order}
```

47. We must show that if there are $R(m, n-1) + R(m-1, n)$ people at a party, then there must be at least m mutual friends or n mutual enemies. Consider one person; let's call him Jerry. Then there are $R(m-1, n) + R(m, n-1) - 1$ other people at the party, and by the pigeonhole principle there must be at least $R(m-1, n)$ friends of Jerry or $R(m, n-1)$ enemies of Jerry among these people. First let's suppose there are $R(m-1, n)$ friends of Jerry. By the definition of R, among these people we are guaranteed to find either $m-1$ mutual friends or n mutual enemies. In the former case, these $m-1$ mutual friends together with Jerry are a set of m mutual friends; and in the latter case, we have the desired set of n mutual enemies. The other situation is similar: Suppose there are $R(m, n-1)$ enemies of Jerry; we are guaranteed to find among them either m mutual friends or $n-1$ mutual enemies. In the former case, we have the desired set of m mutual friends, and in the latter case, these $n-1$ mutual enemies together with Jerry are a set of n mutual enemies.

CHAPTER 6

Section 6.1

1. 1/13 **3.** 1/2 **5.** 1/2 **7.** 1/64 **9.** 47/52 **11.** $1/C(52, 5)$ **13.** $1 - [C(48, 5)/C(52, 5)]$ **15.** $C(13, 2) C(4, 2)C(4, 2)C(44, 1)/C(52, 5)$ **17.** $10{,}240/C(52, 5)$ **19.** $1{,}302{,}540/C(52, 5)$ **21.** 1/64 **23.** 8/25 **25. a)** $1/C(50, 6) = 1/15{,}890{,}700$ **b)** $1/C(52, 6) = 1/20{,}358{,}520$ **c)** $1/C(56, 6) = 1/32{,}468{,}436$ **d)** $1/C(60, 6) = 1/50{,}063{,}860$ **27. a)** 139,128/319,865 **b)** 212,667/511,313 **c)** 151,340/386,529 **d)** 163,647/446,276 **29.** $1/C(100, 8)$ **31.** 3/100 **33. a)** 1/7,880,400 **b)** 1/8,000,000 **35. a)** 9/19 **b)** 81/361 **c)** 1/19 **d)** 1,889,568/2,476,099 **e)** 48/361 **37.** Three dice **39.** The door the contestant chooses is chosen at random without knowing where the prize is, but the door chosen by the host is not chosen at random, because he always avoids opening the door with the prize. This makes any argument based on symmetry invalid. **41. a)** $671/1296$ **b)** $1 - 35^{24}/36^{24}$; no **c)** Yes

Section 6.2

1. $p(T) = 1/4$, $p(H) = 3/4$ **3.** $p(1) = p(3) = p(5) = p(6) = 1/16$; $p(2) = p(4) = 3/8$ **5.** $9/49$ **7. a)** $1/2$ **b)** $1/2$ **c)** $1/3$ **d)** $1/4$ **e)** $1/4$ **9. a)** $1/26!$ **b)** $1/26$ **c)** $1/2$ **d)** $1/26$ **e)** $1/650$ **f)** $1/15{,}600$ **11.** Clearly, $p(E \cup F) \geq p(E) = 0.7$. Also, $p(E \cup F) \leq 1$. If we apply Theorem 2 from Section 6.1, we can rewrite this as $p(E) + p(F) - p(E \cap F) \leq 1$, or $0.7 + 0.5 - p(E \cap F) \leq 1$. Solving for $p(E \cap F)$ gives $p(E \cap F) \geq 0.2$. **13.** Because $p(E \cup F) = p(E) + p(F) - p(E \cap F)$ and $p(E \cup F) \leq 1$, it follows that $1 \geq p(E) + p(F) - p(E \cap F)$. From this inequality we conclude that $p(E) + p(F) \leq 1 + p(E \cap F)$. **15.** We will use mathematical induction to prove that the inequality holds for $n \geq 2$. Let $P(n)$ be the statement that $p(\bigcup_{j=1}^{n} E_j) \leq \sum_{j=1}^{n} p(E_j)$. *Basis step:* $P(2)$ is true because $p(E_1 \cup E_2) = p(E_1) + p(E_2) - p(E_1 \cap E_2) \leq p(E_1) + p(E_2)$. *Inductive step:* Assume that $P(k)$ is true. Using the basis case and the inductive hypothesis, it follows that $p(\bigcup_{j=1}^{k+1} E_j) \leq p(\bigcup_{j=1}^{k} E_j) + p(E_{k+1}) \leq \sum_{j=1}^{k+1} p(E_j)$. This shows that $P(k+1)$ is true, completing the proof by mathematical induction. **17.** Because $E \cup \overline{E}$ is the entire sample space S, the event F can be split into two disjoint events: $F = S \cap F = (E \cup \overline{E}) \cap F = (E \cap F) \cup (\overline{E} \cap F)$, using the distributive law. Therefore, $p(F) = p((E \cap F) \cup (\overline{E} \cap F)) = p(E \cap F) + p(\overline{E} \cap F)$, because these two events are disjoint. Subtracting $p(E \cap F)$ from both sides, using the fact that $p(E \cap F) = p(E) \cdot p(F)$ (the hypothesis that E and F are independent), and factoring, we have $p(F)[1 - p(E)] = p(\overline{E} \cap F)$. Because $1 - p(E) = p(\overline{E})$, this says that $p(\overline{E} \cap F) = p(\overline{E}) \cdot p(F)$, as desired. **19. a)** $1/12$ **b)** $1 - \frac{11}{12} \cdot \frac{10}{12} \cdot \cdots \cdot \frac{13-n}{12}$ **c)** 5 **21.** 614 **23.** $1/4$ **25.** $3/8$ **27. a)** Not independent **b)** Not independent **c)** Not independent **29.** $3/16$ **31. a)** $1/32 = 0.03125$ **b)** $0.49^5 \approx 0.02825$ **c)** 0.03795012 **33. a)** $5/8$ **b)** 0.627649 **c)** 0.6431 **35. a)** p^n **b)** $1 - p^n$ **c)** $p^n + n \cdot p^{n-1} \cdot (1-p)$ **d)** $1 - [p^n + n \cdot p^{n-1} \cdot (1-p)]$ **37.** $p(\bigcup_{i=1}^{\infty} E_i)$ is the sum of $p(s)$ for each outcome s in $\bigcup_{i=1}^{\infty} E_i$. Because the E_is are pairwise disjoint, this is the sum of the probabilities of all the outcomes in any of the E_is, which is what $\sum_{i=1}^{\infty} p(E_i)$ is. (We can rearrange the summands and still get the same answer because this series converges absolutely.) **39. a)** $\overline{E} = \bigcup_{j=1}^{\binom{m}{k}} F_j$, so the given inequality now follows from Boole's Inequality (Exercise 15). **b)** The probability that a particular player not in the jth set beats all k of the players in the jth set is $(1/2)^k = 2^{-k}$. Therefore, the probability that this player does not do so is $1 - 2^{-k}$, so the probability that all $m - k$ of the players not in the jth set are unable to boast of a perfect record against everyone in the jth set is $(1 - 2^{-k})^{m-k}$. That is precisely $p(F_j)$. **c)** The first inequality follows immediately, because all the summands are the same and there are $\binom{m}{k}$ of them. If this probability is less than 1, then it must be possible that $\overline{E}$ fails, i.e., that E happens. So there is a tournament that meets the conditions of the problem as long as the second inequality holds. **d)** $m \geq 21$ for $k = 2$, and $m \geq 91$ for $k = 3$

41.
```
procedure probabilistic prime(n, k)
    composite := false
    i := 0
    while composite = false and i < k
    begin
        i := i + 1
        choose b uniformly at random with 1 < b < n
        apply Miller's test to base b
        if n fails the test then composite := true
    end
    if composite = true then print ("composite")
    else print ("probably prime")
```

Section 6.3

NOTE: In the answers for Section 6.3, all probabilities given in decimal form are rounded to three decimal places. **1.** $3/5$ **3.** $3/4$ **5.** 0.481 **7. a)** 0.999 **b)** 0.324 **9. a)** 0.740 **b)** 0.260 **c)** 0.002 **d)** 0.998 **11.** 0.724 **13.** $3/17$ **15. a)** $1/3$ **b)** $p(M = j \mid W = k) = 1$ if i, j, and k are distinct; $p(M = j \mid W = k) = 0$ if $j = k$ or $j = i$; $p(M = j \mid W = k) = 1/2$ if $i = k$ and $j \neq i$ **c)** $2/3$ **d)** You should change doors, because you now have a 2/3 chance to win by switching. **17.** The definition of conditional probability tells us that $p(F_j \mid E) = p(E \cap F_j)/p(E)$. For the numerator, again using the definition of conditional probability, we have $p(E \cap F_j) = p(E \mid F_j)p(F_j)$, as desired. For the denominator, we show that $p(E) = \sum_{i=1}^{n} p(E \mid F_i)p(F_i)$. The events $E \cap F_i$ partition the event E; that is, $(E \cap F_{i_1}) \cap (E \cap F_{i_2}) = \emptyset$ when $i_i \neq i_2$ (because the F_i's are mutually exclusive), and $\bigcup_{i=1}^{n}(E \cap F_{i_1}) = E$ (because the $\bigcup_{i=1}^{n} F_i = S$). Therefore, $p(E) = \sum_{i=1}^{n} p(E \cap F_i) = \sum_{i=1}^{n} p(E \mid F_i)p(F_i)$. **19.** No **21.** Yes **23.** By Bayes' Theorem, $p(S \mid E_1 \cap E_2) = p(E_1 \cap E_2 \mid S)p(S)/[p(E_1 \cap E_2 \mid S)p(S) + p(E_1 \cap E_2 \mid \overline{S})p(\overline{S})]$. Because we are assuming no prior knowledge about whether a message is or is not spam, we set $p(S) = p(\overline{S}) = 0.5$, and so the equation above simplifies to $p(S \mid E_1 \cap E_2) = p(E_1 \cap E_2 \mid S)/[p(E_1 \cap E_2 \mid S) + p(E_1 \cap E_2 \mid \overline{S})]$. Because of the assumed independence of E_1, E_2, and S, we have $p(E_1 \cap E_2 \mid S) = p(E_1 \mid S) \cdot p(E_2 \mid S)$, and similarly for $\overline{S}$.

Section 6.4

1. 2.5 **3.** $5/3$ **5.** $336/49$ **7.** 170 **9.** $(4n+6)/3$ **11.** $50{,}700{,}551/10{,}077{,}696 \approx 5.03$ **13.** 6 **15.** $p(X \geq j) = \sum_{k=j}^{\infty} p(X = k) = \sum_{k=j}^{\infty} (1-p)^{k-1}p = p(1-p)^{j-1} \sum_{k=0}^{\infty} (1-p)^k = p(1-p)^{j-1}/(1-(1-p)) = (1-p)^{j-1}$ **17.** 2302 **19.** $(7/2) \cdot 7 \neq 329/12$ **21.** $p + (n-1)p(1-p)$ **23.** $5/2$ **25. a)** 0 **b)** n **27. a)** We are told that X_1 and X_2 are independent. To see that X_1 and X_3 are independent, we enumerate the eight possibilities for (X_1, X_2, X_3) and find that $(0,0,0), (1,0,1), (0,1,1), (1,1,0)$ each have probability $1/4$ and the others have probability 0 (because of the definition of X_3). Thus, $p(X_1 = 0 \wedge X_3 = 0) = 1/4$, $p(X_1 = 0) = 1/2$, and $p(X_3 = 0) = 1/2$, so it is true that $p(X_1 = 0 \wedge X_3 = 0) = p(X_1 = 0)p(X_3 = 0)$. Essentially the same calculation shows that $p(X_1 = 0 \wedge X_3 = 1) = p(X_1 = 0)p(X_3 = 1)$, $p(X_1 = 1 \wedge X_3 = 0) = p(X_1 = 1)p(X_3 = 0)$, and $p(X_1 = 1 \wedge X_3 = 1) = p(X_1 = 1)p(X_3 = 1)$. Therefore by definition, X_1 and X_3 are independent. The same reasoning shows that X_2 and X_3 are independent. To see that X_3 and $X_1 + X_2$ are not independent, we observe that $p(X_3 = 1 \wedge X_1 + X_2 = 2) = 0$. But $p(X_3 = 1)p(X_1 + X_2 = 2) = (1/2)(1/4) = 1/8$. **b)** We see from the calculation in part (a) that X_1, X_2, and X_3 are all Bernoulli random variables, so the variance of each is $(1/2)(1/2) = 1/4$. Therefore, $V(X_1) + V(X_2) + V(X_3) = 3/4$. We use the calculations in part (a) to see that $E(X_1 + X_2 + X_3) = 3/2$, and then $V(X_1 + X_2 + X_3) = 3/4$. **c)** In order to use the first part of Theorem 7 to show that $V((X_1 + X_2 + \cdots + X_k) + X_{k+1}) = V(X_1 + X_2 + \cdots + X_k) + V(X_{k+1})$ in the inductive step of a proof by mathematical induction, we would have to know that $X_1 + X_2 + \cdots + X_k$ and X_{k+1} are independent, but we see from part (a) that this is not necessarily true. **29.** $1/100$ **31.** $E(X)/a = \sum_r (r/a) \cdot p(X = r) \geq \sum_{r \geq a} 1 \cdot p(X = r) = p(X \geq a)$ **33. a)** $10/11$ **b)** 0.9984 **35. a)** Each of the $n!$ permutations occurs with probability $1/n!$, so $E(X)$ is the number of comparisons, averaged over all these permutations. **b)** Even if the algorithm continues $n - 1$ rounds, X will be at most $n(n-1)/2$. It follows from the formula for expectation that $E(X) \leq n(n-1)/2$. **c)** The algorithm proceeds by comparing adjacent elements and then swapping them if necessary. Thus, the only way that inverted elements can become uninverted is for them to be compared and swapped. **d)** Because $X(P) \geq I(P)$ for all P, it follows from the definition of expectation that $E(X) \geq E(I)$. **e)** This summation counts 1 for every instance of an inversion. **f)** This follows from Theorem 3. **g)** By Theorem 2 with $n = 1$, the expectation of $I_{j,k}$ is the probability that a_k precedes a_j in the permutation. This is clearly $1/2$ by symmetry. **h)** The summation in part (f) consists of $C(n, 2) = n(n-1)/2$ terms, each equal to $1/2$, so the sum is $n(n-1)/4$. **i)** From part (a) and part (b) we know that $E(X)$, the object of interest, is at most $n(n-1)/2$, and from part (d) and part (h) we know that $E(X)$ is at least $n(n-1)/4$, both of which are $\Theta(n^2)$. **37.** 1 **39.** $V(X + Y) = E((X+Y)^2) - E(X+Y)^2 = E(X^2 + 2XY + Y^2) - [E(X) + E(Y)]^2 = E(X^2) + 2E(XY) + E(Y^2) - E(X)^2 - 2E(X)E(Y) - E(Y)^2 = E(X^2) - E(X)^2 + 2[E(XY) - E(X)E(Y)] + E(Y^2) - E(Y)^2 = V(X) + 2\,\mathrm{Cov}(X, Y) + V(Y)$ **41.** $[(n-1)/n]^m$ **43.** $(n-1)^m/n^{m-1}$

Supplementary Exercises

1. 1/109,668 **3. a)** $1/C(52, 13)$ **b)** $4/C(52, 13)$ **c)** $2{,}944{,}656/C(52, 13)$ **d)** $35{,}335{,}872/C(52, 13)$ **5. a)** $9/2$ **b)** $21/4$ **7. a)** 9 **b)** $21/2$ **9. a)** 8 **b)** $49/6$ **11. a)** $n/2^{n-1}$ **b)** $p(1-p)^{k-1}$, where $p = n/2^{n-1}$ **c)** $2^{n-1}/n$ **13.** $\frac{(m-1)(n-1)+\gcd(m,n)-1}{mn-1}$ **15. a)** $2/3$ **b)** $2/3$ **17.** $1/32$ **19. a)** The probability that one wins 2^n dollars is $1/2^n$, because that happens precisely when the player gets $n - 1$ tails followed by a head. The expected value of the winnings is therefore the sum of 2^n times $1/2^n$ as n goes from 1 to infinity. Because each of these terms is 1, the sum is infinite. In other words, one should be willing to wager any amount of money and expect to come out ahead in the long run. **b)** \$9, \$9 **21. a)** $1/3$ when $S = \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12\}$, $A = \{1, 2, 3, 4, 5, 6, 7, 8, 9\}$, and $B = \{1, 2, 3, 4\}$; $1/12$ when $S = \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12\}$, $A = \{4, 5, 6, 7, 8, 9, 10, 11, 12\}$, and $B = \{1, 2, 3, 4\}$ **b)** 1 when $S = \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12\}$, $A = \{4, 5, 6, 7, 8, 9, 10, 11, 12\}$, and $B = \{1, 2, 3, 4\}$; $3/4$ when $S = \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12\}$, $A = \{1, 2, 3, 4, 5, 6, 7, 8, 9\}$, and $B = \{1, 2, 3, 4\}$ **23. a)** $p(E_1 \cap E_2) = p(E_1)p(E_2)$, $p(E_1 \cap E_3) = p(E_1)p(E_3)$, $p(E_2 \cap E_3) = p(E_2)p(E_3)$, $p(E_1 \cap E_2 \cap E_3) = p(E_1)p(E_2)p(E_3)$ **b)** Yes **c)** Yes; yes **d)** Yes; no **e)** $2^n - n - 1$ **25.** $V(aX + b) = E((aX + b)^2) - E(aX + b)^2 = E(a^2X^2 + 2abX + b^2) - [aE(X) + b]^2 = E(a^2X^2) + E(2abX) + E(b^2) - [a^2E(X)^2 + 2abE(X) + b^2] = a^2E(X^2) + 2abE(X) + b^2 - a^2E(X)^2 - 2abE(X) - b^2 = a^2[E(X^2) - E(X)^2] = a^2V(X)$ **27.** To count every element in the sample space exactly once, we must include every element in each of the sets and then take away the double counting of the elements in the intersections. Thus $p(E_1 \cup E_2 \cup \cdots \cup E_m) = p(E_1) + p(E_2) + \cdots + p(E_m) - p(E_1 \cap E_2) - p(E_1 \cap E_3) - \cdots - p(E_1 \cap E_m) - p(E_2 \cap E_3) - p(E_2 \cap E_4) - \cdots - p(E_2 \cap E_m) - \cdots - p(E_{m-1} \cap E_m) = qm - (m(m-1)/2)r$, because $C(m, 2)$ terms are being subtracted. But $p(E_1 \cup E_2 \cup \cdots \cup E_m) = 1$, so we have $qm - [m(m-1)/2]r = 1$. Because $r \geq 0$, this equation tells us that $qm \geq 1$, so $q \geq 1/m$. Because $q \leq 1$, this equation also implies that $[m(m-1)/2]r = qm - 1 \leq m - 1$, from which it follows that $r \leq 2/m$. **29. a)** We purchase the cards until we have gotten one of each type. That means we have purchased X cards in all. On the other hand, that also means that we purchased X_0 cards until we got the first type we got, and then purchased X_1 more cards until we got the second type we got, and so on. Thus, X is the sum of the X_j's. **b)** Once j distinct types have been obtained, there are $n - j$ new types available out of a total of n types available. Because it is equally likely that we get each type, the probability of success on the next purchase (getting a new type) is $(n-j)/n$. **c)** This follows immediately from the definition of geometric distribution, the definition of X_j, and part (b). **d)** From part (c) it follows that $E(X_j) = n/(n-j)$. Thus by the linearity of expectation and part (a), we have $E(X) = E(X_0) + E(X_1) + \cdots + E(X_{n-1}) = \frac{n}{n} + \frac{n}{n-1} + \cdots + \frac{n}{1} = n\left(\frac{1}{n} + \frac{1}{n-1} + \cdots + \frac{1}{1}\right)$. **e)** About 224.46 **31.** $24 \cdot 13^4/(52 \cdot 51 \cdot 50 \cdot 49)$

CHAPTER 7

Section 7.1

1. a) 2, 12, 72, 432, 2592 **b)** 2, 4, 16, 256, 65,536 **c)** 1, 2, 5, 11, 26 **d)** 1, 1, 6, 27, 204 **e)** 1, 2, 0, 1, 3

3. a) 6, 17, 49, 143, 421 **b)** $49 = 5 \cdot 17 - 6 \cdot 6$, $143 = 5 \cdot 49 - 6 \cdot 17$, $421 = 5 \cdot 143 - 6 \cdot 49$ **c)** $5a_{n-1} - 6a_{n-2} = 5(2^{n-1} + 5 \cdot 3^{n-1}) - 6(2^{n-2} + 5 \cdot 3^{n-2}) = 2^{n-2}(10 - 6) + 3^{n-2}(75 - 30) = 2^{n-2} \cdot 4 + 3^{n-2} \cdot 9 \cdot 5 = 2^n + 3^n \cdot 5 = a_n$ **5. a)** Yes **b)** No **c)** No **d)** Yes **e)** Yes **f)** Yes **g)** No **h)** No **7. a)** $a_{n-1} + 2a_{n-2} + 2n - 9 = -(n-1) + 2 + 2[-(n-2) + 2] + 2n - 9 = -n + 2 = a_n$ **b)** $a_{n-1} + 2a_{n-2} + 2n - 9 = 5(-1)^{n-1} - (n-1) + 2 + 2[5(-1)^{n-2} - (n-2) + 2] + 2n - 9 = 5(-1)^{n-2}(-1 + 2) - n + 2 = a_n$ **c)** $a_{n-1} + 2a_{n-2} + 2n - 9 = 3(-1)^{n-1} + 2^{n-1} - (n-1) + 2 + 2[3(-1)^{n-2} + 2^{n-2} - (n-2) + 2] + 2n - 9 = 3(-1)^{n-2}(-1 + 2) + 2^{n-2}(2 + 2) - n + 2 = a_n$ **d)** $a_{n-1} + 2a_{n-2} + 2n - 9 = 7 \cdot 2^{n-1} - (n-1) + 2 + 2[7 \cdot 2^{n-2} - (n-2) + 2] + 2n - 9 = 2^{n-2}(7 \cdot 2 + 2 \cdot 7) - n + 2 = a_n$ **9. a)** $a_n = 2 \cdot 3^n$ **b)** $a_n = 2n + 3$ **c)** $a_n = 1 + n(n+1)/2$ **d)** $a_n = n^2 + 4n + 4$ **e)** $a_n = 1$ **f)** $a_n = (3^{n+1} - 1)/2$ **g)** $a_n = 5n!$ **h)** $a_n = 2^n n!$ **11. a)** $a_n = 3a_{n-1}$ **b)** 5,904,900 **13. a)** $a_n = n + a_{n-1}$, $a_0 = 0$ **b)** $a_{12} = 78$ **c)** $a_n = n(n+1)/2$ **15.** $B(k) = [1 + (0.07/12)]B(k-1) - 100$, with $B(0) = 5000$ **17.** Let $P(n)$ be "$H_n = 2^n - 1$." *Basis step:* $P(1)$ is true because $H_1 = 1$. *Inductive step:* Assume that $H_n = 2^n - 1$. Then because $H_{n+1} = 2H_n + 1$, it follows that $H_{n+1} = 2(2^n - 1) + 1 = 2^{n+1} - 1$. **19. a)** $a_n = 2a_{n-1} + a_{n-5}$ for $n \geq 5$ **b)** $a_0 = 1, a_1 = 2, a_3 = 8, a_4 = 16$ **c)** 1217 **21.** 9494 **23. a)** $a_n = a_{n-1} + a_{n-2} + 2^{n-2}$ for $n \geq 2$ **b)** $a_0 = 0, a_1 = 0$ **c)** 94 **25. a)** $a_n = a_{n-1} + a_{n-2} + a_{n-3}$ for $n \geq 3$ **b)** $a_0 = 1$, $a_1 = 2, a_2 = 4$ **c)** 81 **27. a)** $a_n = a_{n-1} + a_{n-2}$ for $n \geq 2$ **b)** $a_0 = 1, a_1 = 1$ **c)** 34 **29. a)** $a_n = 2a_{n-1} + 2a_{n-2}$ for $n \geq 2$ **b)** $a_0 = 1, a_1 = 3$ **c)** 448 **31. a)** $a_n = 2a_{n-1} + a_{n-2}$ for $n \geq 2$ **b)** $a_0 = 1, a_1 = 3$ **c)** 239 **33. a)** $a_n = 2a_{n-1}$ for $n \geq 2$ **b)** $a_1 = 3$ **c)** 96 **35. a)** $a_n = a_{n-1} + a_{n-2}$ for $n \geq 2$ **b)** $a_0 = 1$, $a_1 = 1$ **c)** 89 **37. a)** $R_n = n + R_{n-1}$, $R_0 = 1$ **b)** $R_n = n(n+1)/2 + 1$ **39. a)** $S_n = S_{n-1} + (n^2 - n + 2)/2$, $S_0 = 1$ **b)** $S_n = (n^3 + 5n + 6)/6$ **41.** 64 **43. a)** $a_n = 2a_{n-1} + 2a_{n-2}$ **b)** $a_0 = 1, a_1 = 3$ **c)** 1224 **45.** Clearly, $S(m, 1) = 1$ for $m \geq 1$. If $m \geq n$, then a function that is not onto from the set with m elements to the set with n elements can be specified by picking the size of the range, which is an integer between 1 and $n - 1$ inclusive, picking the elements of the range, which can be done in $C(n, k)$ ways, and picking an onto function onto the range, which can be done in $S(m, k)$ ways. Hence, there are $\sum_{k=1}^{n-1} C(n,k)S(m,k)$ functions that are not onto. But there are n^m functions altogether, so $S(m,n) = n^m - \sum_{k=1}^{n-1} C(n,k)S(m,k)$. **47. a)** $C_5 = C_0C_4 + C_1C_3 + C_2C_2 + C_3C_1 + C_4C_0 = 1 \cdot 14 + 1 \cdot 5 + 2 \cdot 2 + 5 \cdot 1 + 14 \cdot 1 = 42$ **b)** $C(10, 5)/6 = 42$ **49.** $J(1) = 1, J(2) = 1, J(3) = 3, J(4) = 1, J(5) = 3, J(6) = 5, J(7) = 7$, $J(8) = 1$, $J(9) = 3$, $J(10) = 5$, $J(11) = 7$, $J(12) = 9$, $J(13) = 11, J(14) = 13, J(15) = 15, J(16) = 1$ **51.** First, suppose that the number of people is even, say $2n$. After going around the circle once and returning to the first person, because the people at locations with even numbers have been eliminated, there are exactly n people left and the person currently at location i is the person who was originally at location $2i - 1$. Therefore, the survivor [originally in location $J(2n)$] is now in location $J(n)$; this was the person who was at location $2J(n) - 1$. Hence, $J(2n) = 2J(n) - 1$. Similarly, when there are an odd number of people, say $2n + 1$, then after going around the circle once and then eliminating person 1, there are n people left and the person currently at location i is the person who was at location $2i + 1$. Therefore, the survivor will be the player currently occupying location $J(n)$, namely, the person who was originally at location $2J(n) + 1$. Hence, $J(2n + 1) = 2J(n) + 1$. The base case is $J(1) = 1$. **53.** 73, 977, 3617 **55.** These nine moves solve the puzzle: Move disk 1 from peg 1 to peg 2; move disk 2 from peg 1 to peg 3; move disk 1 from peg 2 to peg 3; move disk 3 from peg 1 to peg 2; move disk 4 from peg 1 to peg 4; move disk 3 from peg 2 to peg 4; move disk 1 from peg 3 to peg 2; move disk 2 from peg 3 to peg 4; move disk 1 from peg 2 to peg 4. To see that at least nine moves are required, first note that at least seven moves are required no matter how many pegs are present: three to unstack the disks, one to move the largest disk 4, and three more moves to restack them. At least two other moves are needed, because to move disk 4 from peg 1 to peg 4 the other three disks must be on pegs 2 and 3, so at least one move is needed to restack them and one move to unstack them. **57.** The base cases are obvious. If $n > 1$, the algorithm consists of three stages. In the first stage, by the inductive hypothesis, $R(n - k)$ moves are used to transfer the smallest $n - k$ disks to peg 2. Then using the usual three-peg Tower of Hanoi algorithm, it takes $2^k - 1$ moves to transfer the rest of the disks (the largest k disks) to peg 4, avoiding peg 2. Then again by the inductive hypothesis, it takes $R(n - k)$ moves to transfer the smallest $n - k$ disks to peg 4; all the pegs are available for this, because the largest disks, now on peg 4, do not interfere. This establishes the recurrence relation. **59.** First note that $R(n) = \sum_{j=1}^{n}[R(j) - R(j-1)]$ [which follows because the sum is telescoping and $R(0) = 0$]. By Exercise 58, this is the sum of $2^{k'-1}$ for this range of values of j. Therefore, the sum is $\sum_{i=1}^{k} i2^{i-1}$, except that if n is not a triangular number, then the last few values when $i = k$ are missing, and that is what the final term in the given expression accounts for. **61.** By Exercise 59, $R(n)$ is no larger than $\sum_{i=1}^{k} i2^{i-1}$. It can be shown that this sum equals $(k+1)2^k - 2^{k+1} + 1$, so it is no greater than $(k+1)2^k$. Because $n > k(k-1)/2$, the quadratic formula can be used to show that $k < 1 + \sqrt{2n}$ for all $n > 1$. Therefore, $R(n)$ is bounded above by $(1 + \sqrt{2n} + 1)2^{1+\sqrt{2n}} < 8\sqrt{n}2^{\sqrt{2n}}$ for all $n > 2$. Hence, $R(n)$ is $O(\sqrt{n}2^{\sqrt{2n}})$. **63. a)** 0 **b)** 0 **c)** 2 **d)** $2^{n-1} - 2^{n-2}$ **65.** $a_n - 2\nabla a_n + \nabla^2 a_n = a_n - 2(a_n - a_{n-1}) + (\nabla a_n - \nabla a_{n-1}) = -a_n + 2a_{n-1} + [(a_n - a_{n-1}) - (a_{n-1} - a_{n-2})] = -a_n + 2a_{n-1} + (a_n - 2a_{n-1} + a_{n-2}) = a_{n-2}$ **67.** $a_n = a_{n-1} + a_{n-2} = (a_n - \nabla a_n) + (a_n - 2\nabla a_n + \nabla^2 a_n) = 2a_n - 3\nabla a_n + \nabla^2 a_n$, or $a_n = 3\nabla a_n - \nabla^2 a_n$

Section 7.2

1. a) Degree 3 **b)** No **c)** Degree 4 **d)** No **e)** No **f)** Degree 2 **g)** No **3. a)** $a_n = 3 \cdot 2^n$ **b)** $a_n = 2$ **c)** $a_n =$

$3 \cdot 2^n - 2 \cdot 3^n$ **d)** $a_n = 6 \cdot 2^n - 2 \cdot n2^n$ **e)** $a_n = n(-2)^{n-1}$ **f)** $a_n = 2^n - (-2)^n$ **g)** $a_n = (1/2)^{n+1} - (-1/2)^{n+1}$ **5.** $a_n = \frac{1}{\sqrt{5}}\left(\frac{1+\sqrt{5}}{2}\right)^{n+1} - \frac{1}{\sqrt{5}}\left(\frac{1-\sqrt{5}}{2}\right)^{n+1}$ **7.** $[2^{n+1} + (-1)^n]/3$ **9. a)** $P_n = 1.2P_{n-1} + 0.45P_{n-2}$, $P_0 = 100{,}000$, $P_1 = 120{,}000$ **b)** $P_n = (250{,}000/3)(3/2)^n + (50{,}000/3)(-3/10)^n$ **11. a)** *Basis step:* For $n = 1$ we have $1 = 0 + 1$, and for $n = 2$ we have $3 = 1 + 2$. *Inductive step:* Assume true for $k \leq n$. Then $L_{n+1} = L_n + L_{n-1} = f_{n-1} + f_{n+1} + f_{n-2} + f_n = (f_{n-1} + f_{n-2}) + (f_{n+1} + f_n) = f_n + f_{n+2}$. **b)** $L_n = \left(\frac{1+\sqrt{5}}{2}\right)^n + \left(\frac{1-\sqrt{5}}{2}\right)^n$ **13.** $a_n = 8(-1)^n - 3(-2)^n + 4 \cdot 3^n$ **15.** $a_n = 5 + 3(-2)^n - 3^n$ **17.** Let $a_n = C(n, 0) + C(n-1, 1) + \cdots + C(n-k, k)$ where $k = \lfloor n/2 \rfloor$. First, assume that n is even, so that $k = n/2$, and the last term is $C(k, k)$. By Pascal's Identity we have $a_n = 1 + C(n-2, 0) + C(n-2, 1) + C(n-3, 1) + C(n-3, 2) + \cdots + C(n-k, k-2) + C(n-k, k-1) + 1 = 1 + C(n-2, 1) + C(n-3, 2) + \cdots + C(n-k, k-1) + C(n-2, 0) + C(n-3, 1) + \cdots + C(n-k, k-2) + 1 = a_{n-1} + a_{n-2}$ because $\lfloor (n-1)/2 \rfloor = k - 1 = \lfloor (n-2)/2 \rfloor$. A similar calculation works when n is odd. Hence, $\{a_n\}$ satisfies the recurrence relation $a_n = a_{n-1} + a_{n-2}$ for all positive integers n, $n \geq 2$. Also, $a_1 = C(1, 0) = 1$ and $a_2 = C(2, 0) + C(1, 1) = 2$, which are f_2 and f_3. It follows that $a_n = f_{n+1}$ for all positive integers n. **19.** $a_n = (n^2 + 3n + 5)(-1)^n$ **21.** $(a_{1,0} + a_{1,1}n + a_{1,2}n^2 + a_{1,3}n^3) + (a_{2,0} + a_{2,1}n + a_{2,2}n^2)(-2)^n + (a_{3,0} + a_{3,1}n)3^n + a_{4,0}(-4)^n$ **23. a)** $3a_{n-1} + 2^n = 3(-2)^n + 2^n = 2^n(-3 + 1) = -2^{n+1} = a_n$ **b)** $a_n = \alpha 3^n - 2^{n+1}$ **c)** $a_n = 3^{n+1} - 2^{n+1}$ **25. a)** $A = -1$, $B = -7$ **b)** $a_n = \alpha 2^n - n - 7$ **c)** $a_n = 11 \cdot 2^n - n - 7$ **27. a)** $p_3n^3 + p_2n^2 + p_1n + p_0$ **b)** $n^2 p_0(-2)^n$ **c)** $n^2(p_1n + p_0)2^n$ **d)** $(p_2n^2 + p_1n + p_0)4^n$ **e)** $n^2(p_2n^2 + p_1n + p_0)(-2)^n$ **f)** $n^2(p_4n^4 + p_3n^3 + p_2n^2 + p_1n + p_0)2^n$ **g)** p_0 **29. a)** $a_n = \alpha 2^n + 3^{n+1}$ **b)** $a_n = -2 \cdot 2^n + 3^{n+1}$ **31.** $a_n = \alpha 2^n + \beta 3^n - n \cdot 2^{n+1} + 3n/2 + 21/4$ **33.** $a_n = (\alpha + \beta n + n^2 + n^3/6)2^n$ **35.** $a_n = -4 \cdot 2^n - n^2/4 - 5n/2 + 1/8 + (39/8)3^n$ **37.** $a_n = n(n+1)(n+2)/6$ **39. a)** $1, -1, i, -i$ **b)** $a_n = \frac{1}{4} - \frac{1}{4}(-1)^n + \frac{2+i}{4}i^n + \frac{2-i}{4}(-i)^n$ **41. a)** Using the formula for f_n, we see that $\left|f_n - \frac{1}{\sqrt{5}}\left(\frac{1+\sqrt{5}}{2}\right)^n\right| = \left|\frac{1}{\sqrt{5}}\left(\frac{1-\sqrt{5}}{2}\right)^n\right| < 1/\sqrt{5} < 1/2$. This means that f_n is the integer closest to $\frac{1}{\sqrt{5}}\left(\frac{1+\sqrt{5}}{2}\right)^n$. **b)** Less when n is even; greater when n is odd **43.** $a_n = f_{n-1} + 2f_n - 1$ **45. a)** $a_n = 3a_{n-1} + 4a_{n-2}$, $a_0 = 2$, $a_1 = 6$ **b)** $a_n = [4^{n+1} + (-1)^n]/5$ **47. a)** $a_n = 2a_{n+1} + (n-1)10{,}000$ **b)** $a_n = 70{,}000 \cdot 2^{n-1} - 10{,}000n - 10{,}000$ **49.** $a_n = 5n^2/12 + 13n/12 + 1$ **51.** See Chapter 11, Section 5 in [Ma93]. **53.** $6^n \cdot 4^{n-1}/n$

Section 7.3

1. 14 **3.** The first step is $(1110)_2(1010)_2 = (2^4 + 2^2)(11)_2(10)_2 + 2^2[(11)_2 - (10)_2][(10)_2 - (10)_2] + (2^2 + 1)(10)_2 \cdot (10)_2$. The product is $(10001100)_2$. **5.** $C = 50, 665C + 729 = 33{,}979$ **7. a)** 2 **b)** 4 **c)** 7 **9. a)** 79 **b)** 48,829 **c)** 30,517,579 **11.** $O(\log n)$ **13.** $O(n^{\log_3 2})$ **15.** 5 **17. a)** *Basis step:* If the sequence has just one element, then the one person on the list is the winner. *Recursive step:* Divide the list into two parts—the first half and the second half—as equally as possible. Apply the algorithm recursively to each half to come up with at most two names. Then run through the entire list to count the number of occurrences of each of those names to decide which, if either, is the winner. **b)** $O(n \log n)$ **19. a)** $f(n) = f(n/2) + 2$ **b)** $O(\log n)$ **21. a)** 7 **b)** $O(\log n)$

23. a)
```
procedure largest sum(a_1, ..., a_n)
  best := 0 {empty subsequence has sum 0}
  for i := 1 to n
  begin
    sum := 0
    for j := i + 1 to n
    begin
      sum := sum + a_j
      if sum > best then best := sum
    end
  end
  {best is the maximum possible sum of numbers
    in the list}
```
b) $O(n^2)$ **c)** We divide the list into a first half and a second half and apply the algorithm recursively to find the largest sum of consecutive terms for each half. The largest sum of consecutive terms in the entire sequence is either one of these two numbers or the sum of a sequence of consecutive terms that crosses the middle of the list. To find the largest possible sum of a sequence of consecutive terms that crosses the middle of the list, we start at the middle and move forward to find the largest possible sum in the second half of the list, and move backward to find the largest possible sum in the first half of the list; the desired sum is the sum of these two quantities. The final answer is then the largest of this sum and the two answers obtained recursively. The base case is that the largest sum of a sequence of one term is the larger of that number and 0. **d)** 11, 9, 14 **e)** $S(n) = 2S(n/2) + n$, $C(n) = 2C(n/2) + n + 2$, $S(1) = 0$, $C(1) = 1$ **f)** $O(n \log n)$, better than $O(n^2)$ **25.** $(1, 6)$ and $(3, 6)$ at distance 2 **27.** The algorithm is essentially the same as the algorithm given in Example 12. The central strip still has width $2d$ but we need to consider just two boxes of size $d \times d$ rather than eight boxes of size $(d/2) \times (d/2)$. The recurrence relation is the same as the recurrence relation in Example 12, except that the coefficient 7 is replaced by 1. **29.** With $k = \log_b n$, it follows that $f(n) = a^k f(1) + \sum_{j=0}^{k-1} a^j c(n/b^j)^d = a^k f(1) + \sum_{j=0}^{k-1} cn^d = a^k f(1) + kcn^d = a^{\log_b n} f(1) + c(\log_b n)n^d = n^{\log_b a} f(1) + cn^d \log_b n = n^d f(1) + cn^d \log_b n$. **31.** Let $k = \log_b n$ where n is a power of b. *Basis step:* If $n = 1$ and $k = 0$, then $c_1n^d + c_2n^{\log_b a} = c_1 + c_2 = b^dc/(b^d - a) + f(1) + b^dc/(a - b^d) = f(1)$. *Inductive step:* Assume true for k, where $n = b^k$. Then for $n = b^{k+1}$, $f(n) = af(n/b) + cn^d = a\{[b^dc/(b^d - a)](n/b)^d + [f(1) + b^dc/(a - b^d)] \cdot (n/b)^{\log_b a}\} + cn^d = b^dc/(b^d - a)n^d a/b^d + [f(1) + b^dc/(a - b^d)]n^{\log_b a} + cn^d = n^d[ac/(b^d - a) + c(b^d - a)/(b^d - a)] + [f(1) + b^dc/(a - b^dc)]n^{\log_b a} = [b^dc/(b^d - a)]n^d + [f(1) + b^dc/(a - b^d)]n^{\log_b a}$. **33.** If

$a > b^d$, then $\log_b a > d$, so the second term dominates, giving $O(n^{\log_b a})$. **35.** $O(n^{\log_4 5})$ **37.** $O(n^3)$

Section 7.4

1. $f(x) = 2(x^6 - 1)/(x - 1)$ **3. a)** $f(x) = 2x(1 - x^6)/(1 - x)$ **b)** $x^3/(1 - x)$ **c)** $x/(1 - x^3)$ **d)** $2/(1 - 2x)$ **e)** $(1 + x)^7$ **f)** $2/(1 + x)$ **g)** $[1/(1 - x)] - x^2$ **h)** $x^3/(1 - x)^2$ **5. a)** $5/(1 - x)$ **b)** $1/(1 - 3x)$ **c)** $2x^3/(1 - x)$ **d)** $(3 - x)/(1 - x)^2$ **e)** $(1 + x)^8$ **f)** $1/(1 - x)^5$ **7. a)** $a_0 = -64$, $a_1 = 144$, $a_2 = -108$, $a_3 = 27$, and $a_n = 0$ for all $n \geq 4$ **b)** The only nonzero coefficients are $a_0 = 1$, $a_3 = 3$, $a_6 = 3$, $a_9 = 1$. **c)** $a_n = 5^n$ **d)** $a_n = (-3)^{n-3}$ for $n \geq 3$, and $a_0 = a_1 = a_2 = 0$ **e)** $a_0 = 8$, $a_1 = 3$, $a_2 = 2$, $a_n = 0$ for odd n greater than 2 and $a_n = 1$ for even n greater than 2 **f)** $a_n = 1$ if n is a positive multiple 4, $a_n = -1$ if $n < 4$, and $a_n = 0$ otherwise **g)** $a_n = n - 1$ for $n \geq 2$ and $a_0 = a_1 = 0$ **h)** $a_n = 2^{n+1}/n!$ **9. a)** 6 **b)** 3 **c)** 9 **d)** 0 **e)** 5 **11. a)** 1024 **b)** 11 **c)** 66 **d)** 292,864 **e)** 20,412 **13.** 10 **15.** 50 **17.** 20 **19.** $f(x) = 1/[(1 - x)(1 - x^2)(1 - x^5)(1 - x^{10})]$ **21.** 15 **23. a)** $x^4(1 + x + x^2 + x^3)^2/(1 - x)$ **b)** 6 **25. a)** The coefficient of x^r in the power series expansion of $1/[(1 - x^3)(1 - x^4)(1 - x^{20})]$ **b)** $1/(1 - x^3 - x^4 - x^{20})$ **c)** 7 **d)** 3224 **27. a)** 3 **b)** 29 **c)** 29 **d)** 242 **29. a)** 10 **b)** 49 **c)** 2 **d)** 4 **31. a)** $G(x) - a_0 - a_1x - a_2x^2$ **b)** $G(x^2)$ **c)** $x^4G(x)$ **d)** $G(2x)$ **e)** $\int_0^x G(t)dt$ **f)** $G(x)/(1 - x)$ **33.** $a_k = 2 \cdot 3^k - 1$ **35.** $a_k = 18 \cdot 3^k - 12 \cdot 2^k$ **37.** $a_k = k^2 + 8k + 20 + (6k - 18)2^k$ **39.** Let $G(x) = \sum_{k=0}^{\infty} f_kx^k$. After shifting indices of summation and adding series, we see that $G(x) - xG(x) - x^2G(x) = f_0 + (f_1 - f_0)x + \sum_{k=2}^{\infty}(f_k - f_{k-1} - f_{k-2})x^k = 0 + x + \sum_{k=2}^{\infty} 0x^k$. Hence, $G(x) - xG(x) - x^2G(x) = x$. Solving for $G(x)$ gives $G(x) = x/(1 - x - x^2)$. By the method of partial fractions, it can be shown that $x/(1 - x - x^2) = (1/\sqrt{5})[1/(1 - \alpha x) - 1/(1 - \beta x)]$, where $\alpha = (1 + \sqrt{5})/2$ and $\beta = (1 - \sqrt{5})/2$. Using the fact that $1/(1 - \alpha x) = \sum_{k=0}^{\infty} \alpha^k x^k$, it follows that $G(x) = (1/\sqrt{5}) \cdot \sum_{k=0}^{\infty}(\alpha^k - \beta^k)x^k$. Hence, $f_k = (1/\sqrt{5}) \cdot (\alpha^k - \beta^k)$. **41. a)** Let $G(x) = \sum_{n=0}^{\infty} C_nx^n$ be the generating function for $\{C_n\}$. Then $G(x)^2 = \sum_{n=0}^{\infty}(\sum_{k=0}^{n} C_kC_{n-k})x^n = \sum_{n=1}^{\infty}(\sum_{k=0}^{n-1} C_k C_{n-1-k})x^{n-1} = \sum_{n=1}^{\infty} C_nx^{n-1}$. Hence, $xG(x)^2 = \sum_{n=1}^{\infty} C_nx^n$, which implies that $xG(x)^2 - G(x) + 1 = 0$. Applying the quadratic formula shows that $G(x) = \frac{1 \pm \sqrt{1-4x}}{2x}$. We choose the minus sign in this formula because the choice of the plus sign leads to a division by zero. **b)** By Exercise 40, $(1 - 4x)^{-1/2} = \sum_{n=0}^{\infty} \binom{2n}{n}x^n$. Integrating term by term (which is valid by a theorem from calculus) shows that $\int_0^x (1 - 4t)^{-1/2}dt = \sum_{n=0}^{\infty} \frac{1}{n+1}\binom{2n}{n}x^{n+1} = x\sum_{n=0}^{\infty} \frac{1}{n+1}\binom{2n}{n}x^n$. Because $\int_0^x (1 - 4t)^{-1/2}dt = \frac{1-\sqrt{1-4x}}{2} = xG(x)$, equating coefficients shows that $C_n = \frac{1}{n+1}\binom{2n}{n}$. **43.** Applying the Binomial Theorem to the equality $(1 + x)^{m+n} = (1 + x)^m(1 + x)^n$, shows that $\sum_{r=0}^{m+n} C(m + n, r)x^r = \sum_{r=0}^{m} C(m, r)x^r \cdot \sum_{r=0} C(n, r)x^r = \sum_{r=0}^{m+n} \left[\sum_{k=0}^{r} C(m, r - k)C(n, k)\right] x^r$. Comparing coefficients gives the desired identity. **45. a)** $2e^x$ **b)** e^{-x} **c)** e^{3x} **d)** $xe^x + e^x$ **e)** $(e^x - 1)/x$ **47. a)** $a_n = (-1)^n$ **b)** $a_n = 3 \cdot 2^n$ **c)** $a_n = 3^n - 3 \cdot 2^n$ **d)** $a_n = (-2)^n$ for $n \geq 2$, $a_1 = -3$, $a_0 = 2$ **e)** $a_n = (-2)^n + n!$ **f)** $a_n = (-3)^n + n! \cdot 2^n$ for $n \geq 2$, $a_0 = 1$, $a_1 = -2$ **g)** $a_n = 0$ if n is odd and $a_n = n!/(n/2)!$ if n is even **49. a)** $a_n = 6a_{n-1} + 8^{n-1}$ for $n \geq 1$, $a_0 = 1$ **b)** The general solution of the associated linear homogeneous recurrence relation is $a_n^{(h)} = \alpha 6^n$. A particular solution is $a_n^{(p)} = \frac{1}{2} \cdot 8^n$. Hence, the general solution is $a_n = \alpha 6^n + \frac{1}{2} \cdot 8^n$. Using the initial condition, it follows that $\alpha = \frac{1}{2}$. Hence, $a_n = (6^n + 8^n)/2$. **c)** Let $G(x) = \sum_{k=0}^{\infty} a_kx^k$. Using the recurrence relation for $\{a_k\}$, it can be shown that $G(x) - 6xG(x) = (1 - 7x)/(1 - 8x)$. Hence, $G(x) = (1 - 7x)/[(1 - 6x)(1 - 8x)]$. Using partial fractions, it follows that $G(x) = (1/2)/(1 - 6x) + (1/2)/(1 - 8x)$. With the help of Table 1, it follows that $a_n = (6^n + 8^n)/2$. **51.** $\frac{1}{1-x} \cdot \frac{1}{1-x^2} \cdot \frac{1}{1-x^3} \cdots$ **53.** $(1 + x)(1 + x)^2(1 + x)^3 \cdots$ **55.** The generating functions obtained in Exercises 52 and 53 are equal because $(1 + x)(1 + x^2)(1 + x^3) \cdots = \frac{1-x^2}{1-x} \cdot \frac{1-x^4}{1-x^2} \cdot \frac{1-x^6}{1-x^3} \cdots = \frac{1}{1-x} \cdot \frac{1}{1-x^3} \cdot \frac{1}{1-x^5} \cdots$. **57. a)** $G_X(1) = \sum_{k=0}^{\infty} p(X = k) \cdot 1^k = \sum_{k=0}^{\infty} P(X = k) = 1$ **b)** $G'_X(1) = \frac{d}{dx}\sum_{k=0}^{\infty} p(X = k) \cdot x^k|_{x=1} = \sum_{k=0}^{\infty} p(X = k) \cdot k \cdot x^{k-1}|_{x=1} = \sum_{k=0}^{\infty} p(X = k) \cdot k = E(X)$ **c)** $G''_X(1) = \frac{d^2}{dx^2}\sum_{k=0}^{\infty} p(X = k) \cdot x^k|_{x=1} = \sum_{k=0}^{\infty} p(X = k) \cdot k(k - 1) \cdot x^{k-2}|_{x=1} = \sum_{k=0}^{\infty} p(X = k) \cdot (k^2 - k) = V(X) + E(X)^2 - E(X)$. Combining this with part (b) gives the desired results. **59. a)** $G(x) = p^m/(1 - qx)^m$ **b)** $V(x) = mq/p^2$

Section 7.5

1. a) 30 **b)** 29 **c)** 24 **d)** 18 **3.** 1% **5. a)** 300 **b)** 150 **c)** 175 **d)** 100 **7.** 492 **9.** 974 **11.** 55 **13.** 248 **15.** 50,138 **17.** 234 **19.** $|A_1 \cup A_2 \cup A_3 \cup A_4 \cup A_5| = |A_1| + |A_2| + |A_3| + |A_4| + |A_5| - |A_1 \cap A_2| - |A_1 \cap A_3| - |A_1 \cap A_4| - |A_1 \cap A_5| - |A_2 \cap A_3| - |A_2 \cap A_4| - |A_2 \cap A_5| - |A_3 \cap A_4| - |A_3 \cap A_5| - |A_4 \cap A_5| + |A_1 \cap A_2 \cap A_3| + |A_1 \cap A_2 \cap A_4| + |A_1 \cap A_2 \cap A_5| + |A_1 \cap A_3 \cap A_4| + |A_1 \cap A_3 \cap A_5| + |A_1 \cap A_4 \cap A_5| + |A_2 \cap A_3 \cap A_4| + |A_2 \cap A_3 \cap A_5| + |A_2 \cap A_4 \cap A_5| + |A_3 \cap A_4 \cap A_5| - |A_1 \cap A_2 \cap A_3 \cap A_4| - |A_1 \cap A_2 \cap A_3 \cap A_5| - |A_1 \cap A_2 \cap A_4 \cap A_5| - |A_1 \cap A_3 \cap A_4 \cap A_5| - |A_2 \cap A_3 \cap A_4 \cap A_5| + |A_1 \cap A_2 \cap A_3 \cap A_4 \cap A_5|$ **21.** $|A_1 \cup A_2 \cup A_3 \cup A_4 \cup A_5 \cup A_6| = |A_1| + |A_2| + |A_3| + |A_4| + |A_5| + |A_6| - |A_1 \cap A_2| - |A_1 \cap A_3| - |A_1 \cap A_4| - |A_1 \cap A_5| - |A_1 \cap A_6| - |A_2 \cap A_3| - |A_2 \cap A_4| - |A_2 \cap A_5| - |A_2 \cap A_6| - |A_3 \cap A_4| - |A_3 \cap A_5| - |A_3 \cap A_6| - |A_4 \cap A_5| - |A_4 \cap A_6| - |A_5 \cap A_6|$ **23.** $p(E_1 \cup E_2 \cup E_3) = p(E_1) + p(E_2) + p(E_3) - p(E_1 \cap E_2) - p(E_1 \cap E_3) - p(E_2 \cap E_3) + p(E_1 \cap E_2 \cap E_3)$ **25.** 4972/71,295 **27.** $p(E_1 \cup E_2 \cup E_3 \cup E_4 \cup E_5) = p(E_1) + p(E_2) + p(E_3) + p(E_4) + p(E_5) - p(E_1 \cap E_2) - p(E_1 \cap E_3) - p(E_1 \cap E_4) - p(E_1 \cap E_5) - p(E_2 \cap E_3) - p(E_2 \cap E_4) - p(E_2 \cap E_5) - p(E_3 \cap E_4) - p(E_3 \cap E_5) - p(E_4 \cap E_5) + p(E_1 \cap E_2 \cap E_3) + p(E_1 \cap E_2 \cap E_4) + p(E_1 \cap E_2 \cap E_5) + p(E_1 \cap E_3 \cap E_4) + p(E_1 \cap E_3 \cap E_5) + p(E_1 \cap E_4 \cap E_5) + p(E_2 \cap E_3 \cap E_4) + P(E_2 \cap E_3 \cap E_5) + p(E_2 \cap E_4 \cap E_5) + p(E_3 \cap E_4 \cap E_5)$ **29.** $p\left(\bigcup_{i=1}^{n} E_i\right) = \sum_{1 \leq i \leq n} p(E_i) -$

$\sum_{1\le i<j\le n} p(E_i \cap E_j) + \sum_{1\le i<j<k\le n} p(E_i \cap E_j \cap E_k) - \cdots + (-1)^{n+1} p\left(\bigcap_{i=1}^{n} E_i\right)$

Section 7.6

1. 75 **3.** 6 **5.** 46 **7.** 9875 **9.** 540 **11.** 2100 **13.** 1854 **15. a)** $D_{100}/100!$ **b)** $100D_{99}/100!$ **c)** $C(100,2)/100!$ **d)** 0 **e)** $1/100!$ **17.** 2,170,680 **19.** By Exercise 18 we have $D_n - nD_{n-1} = -[D_{n-1} - (n-1)D_{n-2}]$. Iterating, we have $D_n - nD_{n-1} = -[D_{n-1} - (n-1)D_{n-2}] = -[-(D_{n-2} - (n-2)D_{n-3})] = D_{n-2} - (n-2)D_{n-3} = \cdots = (-1)^n(D_2 - 2D_1) = (-1)^n$ because $D_2 = 1$ and $D_1 = 0$. **21.** When n is odd **23.** $\phi(n) = n - \sum_{i=1}^{m} \frac{n}{p_i} + \sum_{1\le i<j\le m} \frac{n}{p_i p_j} - \cdots \pm \frac{n}{p_1 p_2 \cdots p_m} = n \prod_{i=1}^{m}\left(a - \frac{1}{p_i}\right)$ **25.** 4 **27.** There are n^m functions from a set with m elements to a set with n elements, $C(n,1)(n-1)^m$ functions from a set with m elements to a set with n elements that miss exactly one element, $C(n,2)(n-2)^m$ functions from a set with m elements to a set with n elements that miss exactly two elements, and so on, with $C(n, n-1)\cdot 1^m$ functions from a set with m elements to a set with n elements that miss exactly $n-1$ elements. Hence, by the principle of inclusion–exclusion, there are $n^m - C(n,1)(n-1)^m + C(n,2)(n-2)^m - \cdots + (-1)^{n-1}C(n,n-1)\cdot 1^m$ onto functions.

Supplementary Exercises

1. a) $A_n = 4A_{n-1}$ **b)** $A_1 = 40$ **c)** $A_n = 10\cdot 4^n$ **3. a)** $M_n = M_{n-1} + 160{,}000$ **b)** $M_1 = 186{,}000$ **c)** $M_n = 160{,}000n + 26{,}000$ **d)** $T_n = T_{n-1} + 160{,}000n + 26{,}000$ **e)** $T_n = 80{,}000n^2 + 106{,}000n$ **5. a)** $a_n = a_{n-2} + a_{n-3}$ **b)** $a_1 = 0, a_2 = 1, a_3 = 1$ **c)** $a_{12} = 12$ **7. a)** 2 **b)** 5 **c)** 8 **d)** 16 **9.** $a_n = 2^n$ **11.** $a_n = 2 + 4n/3 + n^2/2 + n^3/6$ **13.** $a_n = a_{n-2} + a_{n-3}$ **15.** $O(n^4)$ **17.** $O(n)$ **19. a)** $18n + 18$ **b)** 18 **c)** 0 **21.** $\Delta(a_n b_n) = a_{n+1}b_{n+1} - a_n b_n = a_{n+1}(b_{n+1} - b_n) + b_n(a_{n+1} - a_n) = a_{n+1}\Delta b_n + b_n \Delta a_n$ **23. a)** Let $G(x) = \sum_{n=0}^{\infty} a_n x^n$. Then $G'(x) = \sum_{n=1}^{\infty} n a_n x^{n-1} = \sum_{n=0}^{\infty}(n+1)a_{n+1}x^n$. Therefore, $G'(x) - G'(x) = \sum_{n=0}^{\infty}[(n+1)a_{n+1} - a_n]x^n = \sum_{n=0} x^n/n! = e^x$, as desired. That $G(0) = a_0 = 1$ is given. **b)** We have $[e^{-x}G(x)]' = e^{-x}G'(x) - e^{-x}G(x) = e^{-x}[G'(x) - G(x)] = e^{-x}\cdot e^x = 1$. Hence, $e^{-x}G(x) = x + c$, where c is a constant. Consequently, $G(x) = xe^x + ce^x$. Because $G(0) = 1$, it follows that $c = 1$. **c)** We have $G(x) = \sum_{n=0}^{\infty} x^{n+1}/n! + \sum_{n=0}^{\infty} x^n/n! = \sum_{n=1}^{\infty} x^n/(n-1)! + \sum_{n=0}^{\infty} x^n/n!$. Therefore, $a_n = 1/(n-1)! + 1/n!$ for all $n \ge 1$, and $a_0 = 1$. **25.** 7 **27.** 110 **29.** 0 **31. a)** 19 **b)** 65 **c)** 122 **d)** 167 **e)** 168 **33.** $D_{n-1}/(n-1)!$ **35.** 11/32

CHAPTER 8

Section 8.1

1. a) $\{(0,0),(1,1),(2,2),(3,3)\}$ **b)** $\{(1,3),(2,2),(3,1),(4,0)\}$ **c)** $\{(1,0),(2,0),(2,1),(3,0),(3,1),(3,2),(4,0),(4,1),(4,2),(4,3)\}$ **d)** $\{(1,0),(1,1),(1,2),(1,3),(2,0),(2,2),(3,0),(3,3),(4,0)\}$ **e)** $\{(0,1),(1,0),(1,1),(1,2),(1,3),(2,1),(2,3),(3,1),(3,2),(4,1),(4,3)\}$ **f)** $\{(1,2),(2,1),(2,2)\}$ **3. a)** Transitive **b)** Reflexive, symmetric, transitive **c)** Symmetric **d)** Antisymmetric **e)** Reflexive, symmetric, antisymmetric, transitive **f)** None of these properties **5. a)** Reflexive, transitive **b)** Symmetric **c)** Symmetric **d)** Symmetric **7. a)** Symmetric **b)** Symmetric, transitive **c)** Symmetric **d)** Reflexive, symmetric, transitive **e)** Reflexive, transitive **f)** Reflexive, symmetric, transitive **g)** Antisymmetric **h)** Antisymmetric, transitive **9.** (c), (d), (f) **11. a)** Not irreflexive **b)** Not irreflexive **c)** Not irreflexive **d)** Not irreflexive **13.** Yes, for instance $\{(1,1)\}$ on $\{1,2\}$ **15.** $(a,b) \in R$ if and only if a is taller than b **17.** (a) **19.** None **21.** $\forall a \forall b[(a,b) \in R \to (b,a) \notin R]$ **23.** 2^{mn} **25. a)** $\{(a,b) \mid b \text{ divides } a\}$ **b)** $\{(a,b) \mid a \text{ does not divide } b\}$ **27.** The graph of f^{-1} **29. a)** $\{(a,b) \mid a$ is required to read or has read $b\}$ **b)** $\{(a,b) \mid a$ is required to read and has read $b\}$ **c)** $\{(a,b) \mid$ either a is required to read b but has not read it or a has read b but is not required to$\}$ **d)** $\{(a,b) \mid a$ is required to read b but has not read it$\}$ **e)** $\{(a,b) \mid a$ has read b but is not required to$\}$ **31.** $S \circ R = \{(a,b) \mid a$ is a parent of b and b has a sibling$\}$, $R \circ S = \{(a,b) \mid a$ is an aunt or uncle of $b\}$ **33. a)** $\mathbf{R}^2$ **b)** R_6 **c)** R_3 **d)** R_3 **e)** $\emptyset$ **f)** R_1 **g)** R_4 **h)** R_4 **35. a)** R_1 **b)** R_2 **c)** R_3 **d)** $\mathbf{R}^2$ **e)** R_3 **f)** $\mathbf{R}^2$ **g)** $\mathbf{R}^2$ **h)** $\mathbf{R}^2$ **37.** b got his or her doctorate under someone who got his or her doctorate under a; there is a sequence of $n+1$ people, starting with a and ending with b, such that each is the advisor of the next person in the sequence **39. a)** $\{(a,b) \mid a - b \equiv 0, 3, 4, 6, 8, \text{ or } 9 \pmod{12}\}$ **b)** $\{(a,b) \mid a \equiv b \pmod{12}\}$ **c)** $\{(a,b) \mid a - b \equiv 3, 6, \text{ or } 9 \pmod{12}\}$ **d)** $\{(a,b) \mid a - b \equiv 4 \text{ or } 8 \pmod{12}\}$ **e)** $\{(a,b) \mid a - b \equiv 3, 4, 6, 8, \text{ or } 9 \pmod{12}\}$ **41.** 8 **43. a)** 65,536 **b)** 32,768 **45. a)** $2^{n(n+1)/2}$ **b)** $2^n 3^{n(n-1)/2}$ **c)** $3^{n(n-1)/2}$ **d)** $2^{n(n-1)}$ **e)** $2^{n(n-1)/2}$ **f)** $2^{n^2} - 2\cdot 2^{n(n-1)}$ **47.** There may be no such b. **49.** If R is symmetric and $(a,b) \in R$, then $(b,a) \in R$, so $(a,b) \in R^{-1}$. Hence, $R \subseteq R^{-1}$. Similarly, $R^{-1} \subseteq R$. So $R = R^{-1}$. Conversely, if $R = R^{-1}$ and $(a,b) \in R$, then $(a,b) \in R^{-1}$, so $(b,a) \in R$. Thus R is symmetric. **51.** R is reflexive if and only if $(a,a) \in R$ for all $a \in A$ if and only if $(a,a) \in R^{-1}$ [because $(a,a) \in R$ if and only if $(a,a) \in R^{-1}$] if and only if R^{-1} is reflexive. **53.** Use mathematical induction. The result is trivial for $n = 1$. Assume R^n is reflexive and transitive. By Theorem 1, $R^{n+1} \subseteq R$. To see that $R \subseteq R^{n+1} = R^n \circ R$, let $(a,b) \in R$. By the inductive hypothesis, $R^n = R$ and hence, is reflexive. Thus $(b,b) \in R^n$. Therefore $(a,b) \in R^{n+1}$. **55.** Use mathematical induction. The result is trivial for $n = 1$. Assume R^n is reflexive. Then $(a,a) \in R^n$ for all $a \in A$ and $(a,a) \in R$. Thus $(a,a) \in R^n \circ R = R^{n+1}$ for all $a \in A$. **57.** No, for instance, take $R = \{(1,2),(2,1)\}$.

Section 8.2

1. $\{(1,2,3),(1,2,4),(1,3,4),(2,3,4)\}$ **3.** (Nadir, 122, 34, Detroit, 08:10), (Acme, 221, 22, Denver, 08:17), (Acme, 122, 33, Anchorage, 08:22), (Acme, 323, 34, Honolulu 08:30), (Nadir, 199, 13, Detroit, 08:47), (Acme, 222, 22, Denver, 09:10), (Nadir, 322, 34, Detroit, 09:44) **5.** Airline and flight number, airline and departure time **7. a)** Yes **b)** No **c)** No **9. a)** Social Security number **b)** There are no two people with the same name who happen to have the same street address. **c)** There are no two people with the same name living together. **11.** (Nadir, 122, 34, Detroit, 08: 10), (Nadir, 199, 13, Detroit, 08: 47), (Nadir, 322, 34, Detroit, 09: 44) **13.** (Nadir, 122, 34, Detroit, 08: 10), (Nadir, 199, 13, Detroit, 08: 47), (Nadir, 322, 34, Detroit, 09: 44), (Acme, 221, 22, Denver, 08: 17), (Acme, 222, 22, Denver, 09: 10) **15.** $P_{3,5,6}$

17.

Airline	*Destination*
Nadir	Detroit
Acme	Denver
Acme	Anchorage
Acme	Honolulu

19.

Supplier	*Part_ number*	*Project*	*Quantity*	*Color_ code*
23	1092	1	2	2
23	1101	3	1	1
23	9048	4	12	2
31	4975	3	6	2
31	3477	2	25	2
32	6984	4	10	1
32	9191	2	80	4
33	1001	1	14	8

21. Both sides of this equation pick out the subset of R consisting of those n-tuples satisfying both conditions C_1 and C_2. **23.** Both sides of this equation pick out the set of n-tuples that are in R, are in S, and satisfy condition C. **25.** Both sides of this equation pick out the m-tuples consisting of i_1th, i_2th, ..., i_mth components of n-tuples in either R or S. **27.** Let $R = \{(a, b)\}$ and $S = \{(a, c)\}$, $n = 2$, $m = 1$, and $i_1 = 1$; $P_1(R - S) = \{(a)\}$, but $P_1(R) - P_1(S) = \emptyset$. **29. a)** J_2 followed by $P_{1,3}$ **b)** (23, 1), (23, 3), (31, 3), (32, 4) **31.** There is no primary key.

Section 8.3

1. a) $\begin{bmatrix} 1 & 1 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$ **b)** $\begin{bmatrix} 0 & 1 & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$ **c)** $\begin{bmatrix} 1 & 1 & 1 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{bmatrix}$ **d)** $\begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}$

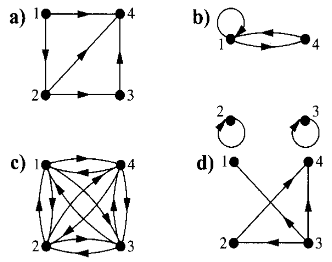
3. a) (1, 1), (1, 3), (2, 2), (3, 1), (3, 3) **b)** (1, 2), (2, 2), (3, 2) **c)** (1, 1), (1, 2), (1, 3), (2, 1), (2, 3), (3, 1), (3, 2), (3, 3) **5.** The relation is irreflexive if and only if the main diagonal of the matrix contains only 0s. **7. a)** Reflexive, symmetric, transitive **b)** Antisymmetric, transitive **c)** Symmetric **9. a)** 4950 **b)** 9900 **c)** 99 **d)** 100 **e)** 1 **11.** Change each 0 to a 1 and each 1 to a 0.

13. a) $\begin{bmatrix} 0 & 1 & 1 \\ 1 & 1 & 0 \\ 1 & 0 & 1 \end{bmatrix}$ **b)** $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$ **c)** $\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$

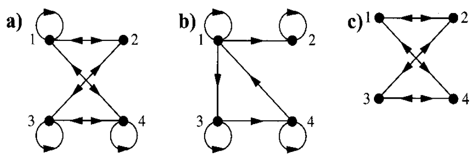
15. a) $\begin{bmatrix} 0 & 0 & 1 \\ 1 & 1 & 0 \\ 0 & 1 & 1 \end{bmatrix}$ **b)** $\begin{bmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$ **c)** $\begin{bmatrix} 0 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$

17. $n^2 - k$

19.



21. For simplicity we have indicated pairs of edges between the same two vertices in opposite directions by using a double arrowhead, rather than drawing two separate lines.

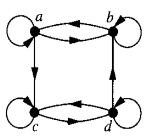


23. $\{(a, b), (a, c), (b, c), (c, b)\}$ **25.** $(a, c), (b, a), (c, d), (d, b)$ **27.** $\{(a, a), (a, b), (a, c), (b, a), (b, b), (b, c), (c, a), (c, b), (d, d)\}$ **29.** The relation is asymmetric if and only if the directed graph has no loops and no closed paths of length 2. **31.** Exercise 23: irreflexive. Exercise 24: reflexive, antisymmetric, transitive. Exercise 25: irreflexive, antisymmetric. **33.** Reverse the direction on every edge in the digraph for R. **35.** Proof by mathematical induction. *Basis step:* Trivial for $n = 1$. *Inductive step:* Assume true for k. Because $R^{k+1} = R^k \circ R$, its matrix is $\mathbf{M}_R \odot \mathbf{M}_{R^k}$. By the inductive hypothesis this is $\mathbf{M}_R \odot \mathbf{M}_R^{[k]} = \mathbf{M}_R^{[k+1]}$.

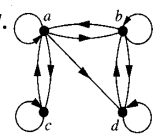
Section 8.4

1. a) $\{(0, 0), (0, 1), (1, 1), (1, 2), (2, 0), (2, 2), (3, 0), (3, 3)\}$ **b)** $\{(0, 1), (0, 2), (0, 3), (1, 0), (1, 1), (1, 2), (2, 0), (2, 1), (2, 2), (3, 0)\}$ **3.** $\{(a, b) \mid a \text{ divides } b \text{ or } b \text{ divides } a\}$

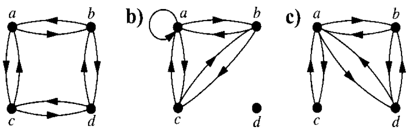
5.



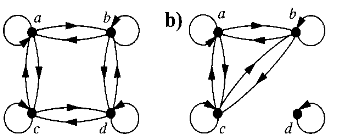
7.



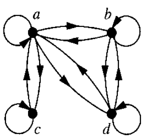
9. a) **b)** **c)**



11. a) **b)**



c)



13. The symmetric closure of R is $R \cup R^{-1}$. $\mathbf{M}_{R\cup R^{-1}} = \mathbf{M}_R \vee \mathbf{M}_{R^{-1}} = \mathbf{M}_R \vee \mathbf{M}_R^t$. **15.** Only when R is irreflexive, in which case it is its own closure. **17.** *a, a, a, a; a, b, e, a; a, d, e, a; b, c, c, b; b, e, a, b; c, b, c, c; c, c, b, c; c, c, c, c; d, e, a, d; d, e, e, d; e, a, b, e; e, a, d, e; e, d, e, e; e, e, d, e; e, e, e, e* **19. a)** $\{(1,1), (1,5), (2,3), (3,1), (3,2), (3,3), (3,4), (4,1), (4,5), (5,3), (5,4)\}$ **b)** $\{(1,1), (1,2), (1,3), (1,4), (2,1), (2,5), (3,1), (3,3), (3,4), (3,5), (4,1), (4,2), (4,3), (4,4), (5,1), (5,3), (5,5)\}$ **c)** $\{(1,1), (1,3), (1,4), (1,5), (2,1), (2,2), (2,3), (2,4), (3,1), (3,2), (3,3), (3,4), (3,5), (4,1), (4,3), (4,4), (4,5), (5,1), (5,2), (5,3), (5,4), (5,5)\}$ **d)** $\{(1,1), (1,2), (1,3), (1,4), (1,5), (2,1), (2,3), (2,4), (2,5), (3,1), (3,2), (3,3), (3,4), (3,5), (4,1), (4,2), (4,3), (4,4), (4,5), (5,1), (5,2), (5,3), (5,4), (5,5)\}$ **e)** $\{(1,1), (1,2), (1,3), (1,4), (1,5), (2,1), (2,2), (2,3), (2,4), (2,5), (3,1), (3,2), (3,3), (3,4), (3,5), (4,1), (4,2), (4,3), (4,4), (4,5), (5,1), (5,2), (5,3), (5,4), (5,5)\}$ **f)** $\{(1,1), (1,2), (1,3), (1,4), (1,5), (2,1), (2,2), (2,3), (2,4), (2,5), (3,1), (3,2), (3,3), (3,4), (3,5), (4,1), (4,2), (4,3), (4,4), (4,5), (5,1), (5,2), (5,3), (5,4), (5,5)\}$ **21. a)** If there is a student c who shares a class with a and a class with b **b)** If there are two students c and d such that a and c share a class, c and d share a class, and d and b share a class **c)** If there is a sequence $s_0, \ldots, s_n$ of students with $n \geq 1$ such that $s_0 = a$, $s_n = b$, and for each $i = 1, 2, \ldots, n$, s_i and s_{i-1} share a class **23.** The result follows from $(R^*)^{-1} = \left(\bigcup_{n=1}^{\infty} R^n\right)^{-1} = \bigcup_{n=1}^{\infty}(R^n)^{-1} = \bigcup_{n=1}^{\infty} R^n = R^*$.

25. a) $\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix}$ **b)** $\begin{bmatrix} 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 1 \end{bmatrix}$

c) $\begin{bmatrix} 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix}$ **d)** $\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix}$

27. Answers same as for Exercise 25. **29. a)** $\{(1,1), (1,2), (1,4), (2,2), (3,3), (4,1), (4,2), (4,4)\}$ **b)** $\{(1,1), (1,2), (1,4), (2,1), (2,2), (2,4), (3,3), (4,1), (4,2), (4,4)\}$ **c)** $\{(1,1), (1,2), (1,4), (2,1), (2,2), (2,4), (3,3), (4,1), (4,2), (4,4)\}$ **31.** Algorithm 1: $O(n^{3.8})$; Algorithm 2: $O(n^3)$ **33.** Initialize with $\mathbf{A} := \mathbf{M}_R \vee \mathbf{I}_n$ and loop only for $i := 2$ to $n-1$. **35. a)** Because R is reflexive, every relation containing it must also be reflexive. **b)** Both $\{(0,0), (0,1), (0,2), (1,1), (2,2)\}$ and $\{(0,0), (0,1), (1,0), (1,1), (2,2)\}$ contain R and have an odd number of elements, but neither is a subset of the other.

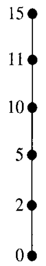
Section 8.5

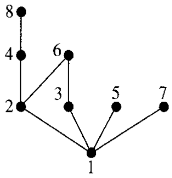
1. a) Equivalence relation **b)** Not reflexive, not transitive **c)** Equivalence relation **d)** Not transitive **e)** Not symmetric, not transitive **3. a)** Equivalence relation **b)** Not transitive **c)** Not reflexive, not symmetric, not transitive **d)** Equivalence relation **e)** Not reflexive, not transitive **5.** Many answers are possible. (1) Two buildings are equivalent if they were opened during the same year; an equivalence class consists of the set of buildings opened in a given year (as long as there was at least one building opened that year). (2) Two buildings are equivalent if they have the same number of stories; the equivalence classes are the set of 1-story buildings, the set of 2-story buildings, and so on (one class for each n for which there is at least one n-story building). (3) Every building in which you have a class is equivalent to every building in which you have a class (including itself), and every building in which you don't have a class is equivalent to every building in which you don't have a class (including itself); there are two equivalence classes—the set of buildings in which you have a class and the set of buildings in which you don't have a class (assuming these are nonempty). **7.** The statement "p is equivalent to q" means that p and q have the same entries in their truth tables. R is reflexive, because p has the same truth table as p. R is symmetric, for if p and q have the same truth table, then q and p have the same truth table. If p and q have the same entries in their truth tables and q and r have the same entries in their truth tables, then p and r also do, so R is transitive. The equivalence class of $\mathbf{T}$ is the set of all tautologies; the equivalence class of $\mathbf{F}$ is the set of all contradictions. **9. a)** $(x,x) \in R$ because $f(x) = f(x)$. Hence, R is reflexive. $(x,y) \in R$ if and only if $f(x) = f(y)$, which holds if and only if $f(y) = f(x)$ if and only if $(y,x) \in R$. Hence, R is symmetric. If $(x,y) \in R$ and $(y,z) \in R$, then $f(x) = f(y)$ and $f(y) = f(z)$. Hence, $f(x) = f(z)$. Thus, $(x,z) \in R$. It follows that R is transitive. **b)** The sets $f^{-1}(b)$ for b in the range of f **11.** Let x be a string of length 3 or more. Because x agrees with itself in the first three bits, $(x,x) \in R$. Hence, R is reflexive. Suppose that $(x,y) \in R$. Then x and y agree in the first three bits. Hence, y and x agree in the first three bits. Thus, $(y,x) \in R$. If (x,y) and (y,z) are in R, then x and y agree in the first three bits, as do y and z. Hence, x and z agree in the first three bits. Hence, $(x,z) \in R$. It follows that R

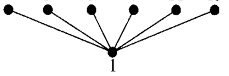
is transitive. **13.** This follows from Exercise 9, where f is the function that takes a bit string of length 3 or more to the ordered pair with its first bit as the first component and the third bit as its second component. **15.** For reflexivity, $((a, b), (a, b)) \in R$ because $a + b = b + a$. For symmetry, if $((a, b), (c, d)) \in R$, then $a + d = b + c$, so $c + b = d + a$, so $((c, d), (a, b)) \in R$. For transitivity, if $((a, b), (c, d)) \in R$ and $((c, d), (e, f)) \in R$, then $a + d = b + c$ and $c + e = d + f$, so $a + d + c + e = b + c + d + f$, so $a + e = b + f$, so $((a, b), (e, f)) \in R$. An easier solution is to note that by algebra, the given condition is the same as the condition that $f((a, b)) = f((c, d))$, where $f((x, y)) = x - y$; therefore by Exercise 9 this is an equivalence relation. **17. a)** This follows from Exercise 9, where the function f from the set of differentiable functions (from **R** to **R**) to the set of functions (from **R** to **R**) is the differentiation operator. **b)** The set of all functions of the form $g(x) = x^2 + C$ for some constant C **19.** This follows from Exercise 9, where the function f from the set of all URLs to the set of all Web pages is the function that assigns to each URL the Web page for that URL. **21.** No **23.** No **25.** R is reflexive because a bit string s has the same number of 1s as itself. R is symmetric because s and t having the same number of 1s implies that t and s do. R is transitive because s and t having the same number of 1s, and t and u having the same number of 1s implies that s and u have the same number of 1s. **27. a)** The sets of people of the same age **b)** The sets of people with the same two parents **29.** The set of all bit strings with exactly two 1s. **31. a)** The set of all bit strings that begin 010 **b)** The set of all bit strings that begin 101 **c)** The set of all bit strings that begin 111 **d)** The set of all bit strings that begin 010 **33.** Each of the 15 bit strings of length less than four is in an equivalence class by itself: $[\lambda]_{R_4} = \{\lambda\}$, $[0]_{R_4} = \{0\}$, $[1]_{R_4} = \{1\}$, $[00]_{R_4} = \{00\}$, $[01]_{R_4} = \{01\}, \ldots,$ $[111]_{R_4} = \{111\}$. The remaining 16 equivalence classes are determined by the bit strings of length 4: $[0000]_{R_4} = \{0000,$ $00000, 00001, 000000, 000001, 000010, 000011, 0000000,$ $\ldots\}$, $[0001]_{R_4} = \{0001, 00010, 00011, 000100, 000101,$ $000110, 000111, 0001000, \ldots\}, \ldots, [1111]_{R_4} = \{1111,$ $11110, 11111, 111100, 111101, 111110, 111111, 1111000,$ $\ldots\}$ **35. a)** $[2]_5 = \{i \mid i \equiv 2 \pmod 5\} = \{\ldots, -8, -3, 2, 7,$ $12, \ldots\}$ **b)** $[3]_5 = \{i \mid i \equiv 3 \pmod 5\} = \{\ldots, -7, -2, 3,$ $8, 13, \ldots\}$ **c)** $[6]_5 = \{i \mid i \equiv 6 \pmod 5\} = \{\ldots, -9, -4, 1,$ $6, 11, \ldots\}$ **d)** $[-3]_5 = \{i \mid i \equiv -3 \pmod 5\} = \{\ldots, -8,$ $-3, 2, 7, 12, \ldots\}$ **37.** $\{6n + k \mid n \in \mathbf{Z}\}$ for $k \in \{0, 1, 2,$ $3, 4, 5\}$ **39. a)** $[(1, 2)] = \{(a, b) \mid a - b = -1\} = \{(1, 2),$ $(3, 4), (4, 5), (5, 6), \ldots\}$ **b)** Each equivalence class can be interpreted as an integer (negative, positive, or zero); specifically, $[a, b]$ can be interpreted as $a - b$. **41. a)** No **b)** Yes **c)** Yes **d)** No **43.** (a), (c), (e) **45.** (b), (d), (e) **47. a)** $\{(0, 0), (1, 1), (1, 2), (2, 1), (2, 2), (3, 3),$ $(3, 4), (3, 5), (4, 3), (4, 4), (4, 5), (5, 3), (5, 4), (5, 5)\}$ **b)** $\{(0, 0), (0, 1), (1, 0), (1, 1), (2, 2), (2, 3), (3, 2), (3, 3),$ $(4, 4), (4, 5), (5, 4), (5, 5)\}$ **c)** $\{(0, 0), (0, 1), (0, 2), (1, 0), (1, 1),$ $(1, 2), (2, 0), (2, 1), (2, 2), (3, 3), (3, 4), (3, 5), (4, 3), (4, 4), (4, 5),$ $(5, 3), (5, 4), (5, 5)\}$ **d)** $\{(0, 0), (1, 1), (2, 2), (3, 3), (4, 4),$ $(5, 5)\}$ **49.** $[0]_6 \subseteq [0]_3$, $[1]_6 \subseteq [1]_3$, $[2]_6 \subseteq [2]_3$, $[3]_6 \subseteq [0]_3$, $[4]_6 \subseteq [1]_3$, $[5]_6 \subseteq [2]_3$ **51.** Let A be a set in the first partition. Pick a particular element x of A. The set of all bit strings of length 16 that agree with x on the last eight bits is one of the sets in the second partition, and clearly every string in A is in that set. **53.** We claim that each equivalence class $[x]_{R_{31}}$ is a subset of the equivalence class $[x]_{R_8}$. To show this, choose an arbitrary element $y \in [x]_{R_{31}}$. Then y is equivalent to x under R_{31}, so either $y = x$ or y and x are each at least 31 characters long and agree on their first 31 characters. Because strings that are at least 31 characters long and agree on their first 31 characters perforce are at least 8 characters long and agree on their first 8 characters, we know that either $y = x$ or y and x are each at least 8 characters long and agree on their first 8 characters. This means that y is equivalent to x under R_8, so $y \in [x]_{R_8}$. **55.** $\{(a, a), (a, b), (a, c), (b, a),$ $(b, b), (b, c), (c, a), (c, b), (c, c), (d, d), (d, e), (e, d), (e, e)\}$ **57. a)** **Z** **b)** $\{n + \frac{1}{2} \mid n \in \mathbf{Z}\}$ **59. a)** R is reflexive because any coloring can be obtained from itself via a 360-degree rotation. To see that R is symmetric and transitive, use the fact that each rotation is the composition of two reflections and conversely the composition of two reflections is a rotation. Hence, (C_1, C_2) belongs to R if and only if C_2 can be obtained from C_1 by a composition of reflections. So if (C_1, C_2) belongs to R, so does (C_2, C_1) because the inverse of the composition of reflections is also a composition of reflections (in the opposite order). Hence, R is symmetric. To see that R is transitive, suppose (C_1, C_2) and (C_2, C_3) belong to R. Taking the composition of the reflections in each case yields a composition of reflections, showing that (C_1, C_3) belongs to R. **b)** We express colorings with sequences of length four, with r and b denoting red and blue, respectively. We list letters denoting the colors of the upper left square, upper right square, lower left square, and lower right square, in that order. The equivalence classes are: $\{rrrr\}$, $\{bbbb\}$, $\{rrrb, rrbr, rbrr, brrr\}$, $\{bbbr, bbrb, brbb, rbbb\}$, $\{rbbr, brrb\}$, $\{rrbb, brbr, bbrr, rbrb\}$. **61.** 5 **63.** Yes **65.** R **67.** First form the reflexive closure of R, then form the symmetric closure of the reflexive closure, and finally form the transitive closure of the symmetric closure of the reflexive closure. **69.** $p(0) = 1$, $p(1) = 1$, $p(2) = 2$, $p(3) = 5$, $p(4) = 15$, $p(5) = 52$, $p(6) = 203$, $p(7) = 877$, $p(8) = 4140$, $p(9) = 21147$, $p(10) = 115975$

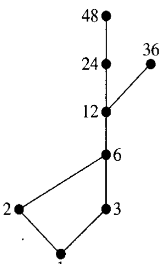
Section 8.6

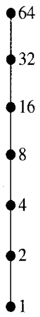
1. a) Is a partial ordering **b)** Not antisymmetric, not transitive **c)** Is a partial ordering **d)** Is a partial ordering **e)** Not antisymmetric, not transitive **3. a)** No **b)** No **c)** Yes **5. a)** Yes **b)** No **c)** Yes **d)** No **7. a)** No **b)** Yes **c)** No **9.** No **11.** Yes **13. a)** $\{(0, 0), (1, 0),$ $(1, 1), (2, 0), (2, 1), (2, 2)\}$ **b)** $(\mathbf{Z}, \leq)$ **c)** $(P(\mathbf{Z}), \subseteq)$ **d)** $(\mathbf{Z}^+,$ "is a multiple of") **15. a)** $\{0\}$ and $\{1\}$, for instance **b)** 4 and 6, for instance **17. a)** $(1, 1, 2) < (1, 2, 1)$ **b)** $(0, 1,$ $2, 3) < (0, 1, 3, 2)$ **c)** $(0, 1, 1, 1, 0) < (1, 0, 1, 0, 1)$ **19.** $0 <$ $0001 < 001 < 01 < 010 < 0101 < 011 < 11$

21. 

23. a) 

b) 

c) 

d) 

25. (a, b), (a, c), (a, d), (b, c), (b, d), (a, a), (b, b), (c, c), (d, d) **27.** (a, a), (a, g), (a, d), (a, e), (a, f), (b, b), (b, g), (b, d), (b, e), (b, f), (c, c), (c, g), (c, d), (c, e), (c, f), (g, d), (g, e), (g, f), (g, g), (d, d), (e, e), (f, f) **29.** $(\emptyset, \{a\})$, $(\emptyset, \{b\})$, $(\emptyset, \{c\})$, $(\{a\}, \{a, b\})$, $(\{a\}, \{a, c\})$, $(\{b\}, \{a, b\})$, $(\{b\}, \{b, c\})$, $(\{c\}, \{a, c\})$, $(\{c\}, \{b, c\})$, $(\{a, b\}, \{a, b, c\})$, $(\{a, c\}, \{a, b, c\})$ $(\{b, c\}, \{a, b, c\})$ **31.** Let $(S, \preccurlyeq)$ be a finite poset. We will show that this poset is the reflexive transitive closure of its covering relation. Suppose that (a, b) is in the reflexive transitive closure of the covering relation. Then $a = b$ or $a \prec b$, so $a \preccurlyeq b$, or else there is a sequence $a_1, a_2, \ldots, a_n$ such that $a \prec a_1 \prec a_2 \prec \cdots \prec a_n \prec b$, in which case again $a \preccurlyeq b$ by the transitivity of $\preccurlyeq$. Conversely, suppose that $a \prec b$. If $a = b$ then (a, b) is in the reflexive transitive closure of the covering relation. If $a \prec b$ and there is no z such that $a \prec z \prec b$, then (a, b) is in the covering relation and therefore in its reflexive transitive closure. Otherwise, let $a \prec a_1 \prec a_2 \prec \cdots \prec a_n \prec b$ be a longest possible sequence of this form (which exists because the poset is finite). Then no intermediate elements can be inserted, so each pair $(a, a_1), (a_1, a_2), \ldots, (a_n, b)$ is in the covering relation, so again (a, b) is in its reflexive transitive closure. **33. a)** 24, 45 **b)** 3, 5 **c)** No **d)** No **e)** 15, 45 **f)** 15 **g)** 15, 5, 3 **h)** 15 **35. a)** $\{1,2\}, \{1,3,4\}, \{2,3,4\}$ **b)** $\{1\}$, $\{2\}, \{4\}$ **c)** No **d)** No **e)** $\{2, 4\}, \{2, 3, 4\}$ **f)** $\{2, 4\}$ **g)** $\{3, 4\}, \{4\}$ **h)** $\{3, 4\}$ **37.** Because $(a, b) \preccurlyeq (a, b)$, $\preccurlyeq$ is reflexive. If $(a_1, a_2) \preccurlyeq (b_1, b_2)$ and $(a_1, a_2) \neq (b_1, b_2)$, either $a_1 \prec b_1$, or $a_1 = b_1$ and $a_2 \prec b_2$. In either case, (b_1, b_2) is not less than or equal to (a_1, a_2). Hence, $\preccurlyeq$ is antisymmetric. Suppose that $(a_1, a_2) \prec (b_1, b_2) \prec (c_1, c_2)$. Then if $a_1 \prec b_1$ or $b_1 \prec c_1$, we have $a_1 \prec c_1$, so $(a_1, a_2) \prec (c_1, c_2)$, but if $a_1 = b_1 = c_1$, then $a_2 \prec b_2 \prec c_2$, which implies that $(a_1, a_2) \prec (c_1, c_2)$. Hence, $\preccurlyeq$ is transitive. **39.** Because $(s, t) \preceq (s, t)$, $\preccurlyeq$ is reflexive. If $(s, t) \preccurlyeq (u, v)$ and $(u, v) \preccurlyeq (s, t)$, then $s \preccurlyeq u \preccurlyeq s$ and $t \preccurlyeq v \preccurlyeq t$; hence, $s = u$ and $t = v$. Hence, $\preccurlyeq$ is antisymmetric. Suppose that $(s, t) \preccurlyeq (u, v) \preccurlyeq (w, x)$. Then $s \preccurlyeq u$, $t \preccurlyeq v$, $u \preccurlyeq w$, and $v \preccurlyeq x$. It follows that $s \preccurlyeq w$ and $t \preccurlyeq x$. Hence, $(s, t) \preccurlyeq (w, x)$. Hence, $\preccurlyeq$ is transitive. **41. a)** Suppose that x is maximal and that y is the largest element. Then $x \preccurlyeq y$. Because x is not less than y, it follows that $x = y$. By Exercise 40(a) y is unique. Hence, x is unique. **b)** Suppose that x is minimal and that y is the smallest element. Then $x \succcurlyeq y$. Because x is not greater than y, it follows that $x = y$. By Exercise 40(b) y is unique. Hence, x is unique. **43. a)** Yes **b)** No **c)** Yes **45.** Use mathematical induction. Let $P(n)$ be "Every subset with n elements from a lattice has a least upper bound and a greatest lower bound." *Basis step:* $P(1)$ is true because the least upper bound and greatest lower bound of $\{x\}$ are both x. *Inductive step:* Assume that $P(k)$ is true. Let S be a set with $k + 1$ elements. Let $x \in S$ and $S' = S - \{x\}$. Because S' has k elements, by the inductive hypothesis, it has a least upper bound y and a greatest lower bound a. Now because we are in a lattice, there are elements $z = \text{lub}(x, y)$ and $b = \text{glb}(x, a)$. We are done if we can show that z is the least upper bound of S and b is the greatest lower bound of S. To show that z is the least upper bound of S, first note that if $w \in S$, then $w = x$ or $w \in S'$. If $w = x$ then $w \preccurlyeq z$ because z is the least upper bound of x and y. If $w \in S'$, then $w \preccurlyeq z$ because $w \preccurlyeq y$, which is true because y is the least upper bound of S', and $y \preccurlyeq z$, which is true because $z = \text{lub}(x, y)$. To see that z is the least upper bound of S, suppose that u is an upper bound of S. Note that such an element u must be an upper bound of x and y, but because $z = \text{lub}(x, y)$, it follows that $z \preccurlyeq u$. We omit the similar argument that b is the greatest lower bound of S. **47. a)** No **b)** Yes **c)** (*Proprietary*, {*Cheetah, Puma*}), (*Restricted*, {*Cheetah, Puma*}), (*Registered*, {*Cheetah, Puma*}), (*Proprietary*, {*Cheetah, Puma, Impala*}), (*Restricted*, {*Cheetah, Puma, Impala*}), (*Registered*, {*Cheetah, Puma, Impala*}) **d)** (*Nonproprietary*, {*Impala, Puma*}), (*Proprietary*, {*Impala, Puma*}), (*Restricted*, {*Impala, Puma*}), (*Nonproprietary*, {*Impala*}), (*Proprietary*, {*Impala*}), (*Restricted*, {*Impala*}), (*Nonproprietary*, {*Puma*}), (*Proprietary*, {*Puma*}), (*Restricted*, {*Puma*}), (*Nonproprietary*, $\emptyset$), (*Proprietary*, $\emptyset$), (*Restricted*, $\emptyset$) **49.** Let Π be the set of all partitions of a set S with $P_1 \preccurlyeq P_2$ if P_1 is a refinement of P_2, that is, if every set in P_1 is a subset of a set in P_2. First, we show that $(\Pi, \preccurlyeq)$ is a poset. Because $P \preccurlyeq P$ for every partition P, $\preccurlyeq$ is reflexive. Now suppose that $P_1 \preccurlyeq P_2$ and $P_2 \preccurlyeq P_1$. Let $T \in P_1$. Because $P_1 \preccurlyeq P_2$, there is a set $T' \in P_2$ such that $T \subseteq T'$. Because $P_2 \preccurlyeq P_1$ there is a set $T'' \in P_1$ such that $T' \subseteq T''$. It follows that $T \subseteq T''$. But because P_1 is a partition, $T = T''$, which implies that $T = T'$ because $T \subseteq T' \subseteq T''$. Thus, $T \in P_2$. By reversing the roles of P_1 and P_2 it follows that every set in P_2 is also in P_1. Hence, $P_1 = P_2$ and $\preccurlyeq$ is antisymmetric. Next, suppose that $P_1 \preccurlyeq P_2$ and $P_2 \preccurlyeq P_3$. Let $T \in P_1$. Then there is a set $T' \in P_2$ such that $T \subseteq T'$. Because $P_2 \preccurlyeq P_3$ there is a set $T'' \in P_3$ such that $T' \subseteq T''$. This means that $T \subseteq T''$. Hence, $P_1 \preccurlyeq P_3$. It follows that $\preccurlyeq$ is transitive. The greatest lower bound of the partitions P_1 and P_2 is the partition P whose subsets are the nonempty sets of the form $T_1 \cap T_2$ where $T_1 \in P_1$ and $T_2 \in P_2$. We omit the justification of this statement here. The least upper bound of the partitions P_1 and P_2 is the partition that corresponds to the equivalence relation in which $x \in S$ is related to $y \in S$ if there is a sequence $x = x_0, x_1, x_2, \ldots, x_n = y$ for some nonnegative integer n such that for each i from 1 to n, x_{i-1} and x_i are in the same element of P_1 or of P_2. We omit the details that this is an equivalence relation and the details of the proof that this is the least upper bound of the two partitions. **51.** By Exercise 45 there is a least upper bound and a greatest lower bound for the entire finite lattice. By definition these elements are the greatest and least elements, respectively. **53.** The least element of a subset of $\mathbf{Z}^+ \times \mathbf{Z}^+$ is that pair that has the smallest possible first coordinate, and, if there is more than one such pair, that pair among those that has the smallest second coordinate. **55.** If x is an integer in a decreasing sequence of elements of this poset, then at most $|x|$ elements can follow x in the sequence, namely, integers whose absolute values are $|x| - 1$, $|x| - 2, \ldots, 1, 0$. Therefore there can be no infinite decreasing sequence. This is not a totally ordered set, because 5 and -5, for example, are incomparable. **57.** To find which of two rational numbers is larger, write them with a positive common denominator and compare numerators. To show that this set is dense, suppose that $x < y$ are two rational numbers. Then their average, i.e., $(x + y)/2$, is a rational number between them. **59.** Let $(S, \preccurlyeq)$ be a partially ordered set. It is enough to show that every nonempty subset of S contains a least element if and only if there is no infinite decreasing sequence of elements $a_1, a_2, a_3, \ldots$ in S (i.e., where $a_{i+1} \prec a_i$ for all i). An infinite decreasing sequence of elements clearly has no least element. Conversely, let A be any nonempty subset of S that has no least element. Because A is nonempty, choose $a_1 \in A$. Because a_1 is not the least element of A, choose $a_2 \in A$ with $a_2 \prec a_1$. Because a_2 is not the least element of A, choose $a_3 \in A$ with $a_3 \prec a_2$. Continue in this manner, producing an infinite decreasing sequence in S. **61.** $a \prec_t b \prec_t c \prec_t d \prec_t e \prec_t f \prec_t g \prec_t h \prec_t i \prec_t j \prec_t k \prec_t l \prec_t m$ **63.** $C \prec A \prec B \prec D \prec E \prec F \prec G$ **65.** Determine user needs $\prec$ Write functional requirements $\prec$ Set up test sites $\prec$ Develop system requirements $\prec$ Write documentation $\prec$ Develop module $A \prec$ Develop module $B \prec$ Develop module $C \prec$ Integrate modules $\prec \alpha$ test $\prec \beta$ test $\prec$ Completion

Supplementary Exercises

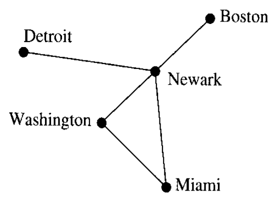
1. a) Irreflexive (we do not include the empty string), symmetric **b)** Irreflexive, symmetric **c)** Irreflexive, antisymmetric, transitive **3.** $((a, b), (a, b)) \in R$ because $a + b = a + b$. Hence, R is reflexive. If $((a, b), (c, d)) \in R$ then $a + d = b + c$, so that $c + b = d + a$. It follows that $((c, d), (a, b)) \in R$. Hence, R is symmetric. Suppose that $((a, b), (c, d))$ and $((c, d), (e, f))$ belong to R. Then $a + d = b + c$ and $c + f = d + e$. Adding these two equations and subtracting $c + d$ from both sides gives $a + f = b + e$. Hence, $((a, b), (e, f))$ belongs to R. Hence, R is transitive. **5.** Suppose that $(a, b) \in R$. Because $(b, b) \in R$ it follows that $(a, b) \in R^2$. **7.** Yes, yes **9.** Yes, yes **11.** Two records with identical keys in the projection would have identical keys in the original. **13.** $(\Delta \cup R)^{-1} = \Delta^{-1} \cup R^{-1} = \Delta \cup R^{-1}$ **15. a)** $R = \{(a, b), (a, c)\}$. The transitive closure of the symmetric closure of R is $\{(a, a), (a, b), (a, c), (b, a), (b, b), (b, c), (c, a), (c, b), (c, c)\}$ and is different from the symmetric closure of the transitive closure of R, which is $\{(a, b), (a, c), (b, a), (c, a)\}$. **b)** Suppose that (a, b) is in the symmetric closure of the transitive closure of R. We must show that (a, b) is in the transitive closure of the symmetric closure of R. We know that at least one of (a, b) and (b, a) is in the transitive closure of R. Hence, there is either a path from a to b in R or a path from b to a in R (or both). In the former case, there is a path from a to b in the symmetric closure of R. In the latter case, we can form a path from a to b in the symmetric closure of R by reversing the directions of all the edges in a path from b to a, going backward. Hence, (a, b) is in the transitive closure of the symmetric closure of R. **17.** The closure of S with respect to property **P** is a relation with property **P** that contains R because $R \subseteq S$. Hence, the closure of S with respect to property **P** contains the closure of R with respect to property **P**. **19.** Use the basic idea of Warshall's algorithm, except let $w_{ij}^{[k]}$ equal the length of the longest path from v_i to v_j using interior vertices with subscripts not exceeding k, and equal to -1 if there is no such path. To find $w_{ij}^{[k]}$ from the entries of $\mathbf{W}_{k-1}$, determine for each pair (i, j) whether there are paths from v_i to v_k and from v_k to v_j using no vertices labeled greater than k. If either $w_{ik}^{[k-1]}$ or $w_{kj}^{[k-1]}$ is -1, then such a pair of paths does not exist, so set $w_{ij}^{[k]} = w_{ij}^{[k-1]}$. If such a pair of paths exists, then there are two possibilities. If $w_{kk}^{[k-1]} > 0$, there are paths of arbitrary long length from v_i to v_j, so set $w_{ij}^{[k]} = \infty$. If $w_{kk}^{[k-1]} = 0$, set $w_{ij}^{[k-1]} = \max(w_{ij}^{[k-1]}, w_{ik}^{[k-1]} + w_{kj}^{[k-1]})$. (Initially take $\mathbf{W}_0 = \mathbf{M}_R$.) **21.** 25 **23.** Because $A_i \cap B_j$ is a subset of A_i and of B_j, the collection of subsets is a refinement of each of the given partitions. We must show that it is a partition. By construction, each of these sets is nonempty. To see that their union is S, suppose that $s \in S$. Because P_1 and P_2 are partitions of S, there are sets A_i and B_j such that $s \in A_i$ and $s \in B_j$. Therefore $s \in A_i \cap B_j$. Hence, the union of these sets is S. To see that they are pairwise disjoint, note that unless $i = i'$ and $j = j'$, $(A_i \cap B_j) \cap (A_{i'} \cap B_{j'}) =$

$(A_i \cap A_{i'}) \cap (B_j \cap B_{j'}) = \emptyset$. **25.** The subset relation is a partial ordering on any collection of sets, because it is reflexive, antisymmetric, and transitive. Here the collection of sets is $\mathbf{R}(S)$. **27.** Find recipe $\prec$ Buy seafood $\prec$ Buy groceries $\prec$ Wash shellfish $\prec$ Cut ginger and garlic $\prec$ Clean fish $\prec$ Steam rice $\prec$ Cut fish $\prec$ Wash vegetables $\prec$ Chop water chestnuts $\prec$ Make garnishes $\prec$ Cook in wok $\prec$ Arrange on platter $\prec$ Serve **29. a)** The only antichain with more than one element is $\{c, d\}$. **b)** The only antichains with more than one element are $\{b, c\}$, $\{c, e\}$, and $\{d, e\}$. **c)** The only antichains with more than one element are $\{a, b\}$, $\{a, c\}$, $\{b, c\}$, $\{a, b, c\}$, $\{d, e\}$, $\{d, f\}$, $\{e, f\}$, and $\{d, e, f\}$. **31.** Let $(S, \preccurlyeq)$ be a finite poset, and let A be a maximal chain. Because $(A, \preccurlyeq)$ is also a poset it must have a minimal element m. Suppose that m is not minimal in S. Then there would be an element a of S with $a \prec m$. However, this would make the set $A \cup \{a\}$ a larger chain than A. To show this, we must show that a is comparable with every element of A. Because m is comparable with every element of A and m is minimal, it follows that $m \prec x$ when x is in A and $x \neq m$. Because $a \prec m$ and $m \prec x$, the transitive law shows that $a \prec x$ for every element of A. **33.** Let aRb denote that a is a descendant of b. By Exercise 32, if no set of $n + 1$ people none of whom is a descendant of any other (an antichain) exists, then $k \leq n$, so the set can be partitioned into $k \leq n$ chains. By the pigeonhole principle, at least one of these chains contains at least $m + 1$ people. **35.** We prove by contradiction that if S has no infinite decreasing sequence and $\forall x\, (\{\forall y[y \prec x \rightarrow P(y)]\} \rightarrow P(x))$, then $P(x)$ is true for all $x \in S$. If it does not hold that $P(x)$ is true for all $x \in S$, let x_1 be an element of S such that $P(x_1)$ is not true. Then by the conditional statement already given, it must be the case that $\forall y[y \prec x_1 \rightarrow P(y)]$ is not true. This means that there is some x_2 with $x_2 \prec x_1$ such that $P(x_2)$ is not true. Again invoking the conditional statement, we get an $x_3 \prec x_2$ such that $P(x_3)$ is not true, and so on forever. This contradicts the well-foundedness of our poset. Therefore, $P(x)$ is true for all $x \in S$. **37.** Suppose that R is a quasi-ordering. Because R is reflexive, if $a \in A$, then $(a, a) \in R$. This implies that $(a, a) \in R^{-1}$. Hence, $a \in R \cap R^{-1}$. It follows that $R \cap R^{-1}$ is reflexive. $R \cap R^{-1}$ is symmetric for any relation R because, for any relation R, if $(a, b) \in R$ then $(b, a) \in R^{-1}$ and vice versa. To show that $R \cap R^{-1}$ is transitive, suppose that $(a, b) \in R \cap R^{-1}$ and $(b, c) \in R \cap R^{-1}$. Because $(a, b) \in R$ and $(b, c) \in R$, $(a, c) \in R$, because R is transitive. Similarly, because $(a, b) \in R^{-1}$ and $(b, c) \in R^{-1}$, $(b, a) \in R$ and $(c, b) \in R$, so $(c, a) \in R$ and $(a, c) \in R^{-1}$. Hence, $(a, c) \in R \cap R^{-1}$. It follows that $R \cap R^{-1}$ is an equivalence relation. **39. a)** Because $\text{glb}(x, y) = \text{glb}(y, x)$ and $\text{lub}(x, y) = \text{lub}(y, x)$, it follows that $x \wedge y = y \wedge x$ and $x \vee y = y \vee x$. **b)** Using the definition, $(x \wedge y) \wedge z$ is a lower bound of x, y, and z that is greater than every other lower bound. Because x, y, and z play interchangeable roles, $x \wedge (y \wedge z)$ is the same element. Similarly, $(x \vee y) \vee z$ is an upper bound of x, y, and z that is less than every other upper bound. Because x, y, and z play interchangeable roles, $x \vee (y \vee z)$ is the same element. **c)** To show that $x \wedge (x \vee y) = x$ it is sufficient to show that x is the greatest lower bound of x, and $x \vee y$. Note that x is a lower bound of x, and because $x \vee y$ is by definition greater than x, x is a lower bound for it as well. Therefore, x is a lower bound. But any lower bound of x has to be less than x, so x is the greatest lower bound. The second statement is the dual of the first; we omit its proof. **d)** x is a lower, and an upper, bound for itself and itself, and the greatest, and least, such bound. **41. a)** Because 1 is the only element greater than or equal to 1, it is the only upper bound for 1 and therefore the only possible value of the least upper bound of x and 1. **b)** Because $x \preccurlyeq 1$, x is a lower bound for both x and 1 and no other lower bound can be greater than x, so $x \wedge 1 = x$. **c)** Because $0 \preccurlyeq x$, x is an upper bound for both x and 0 and no other bound can be less than x, so $x \vee 0 = x$. **d)** Because 0 is the only element less than or equal to 0, it is the only lower bound for 0 and therefore the only possible value of the greatest lower bound of x and 0. **43.** $L = (S, \subseteq)$ where $S = \{\emptyset, \{1\}, \{2\}, \{3\}, \{1, 2\}, \{2, 3\}, \{1, 2, 3\}\}$ **45.** Yes **47.** The complement of a subset $X \subseteq S$ is its complement $S - X$. To prove this, note that $X \vee (S - X) = 1$ and $X \wedge (S - X) = 0$ because $X \cup (S - X) = S$ and $X \cap (S - X) = \emptyset$. **49.** Think of the rectangular grid as representing elements in a matrix. Thus we number from top to bottom and within that from left to right. The partial order is that $(a, b) \preceq (c, d)$ iff $a \leq c$ and $b \leq d$. Note that $(1, 1)$ is the least element under this relation. The rules for Chomp as explained in Chapter 1 coincide with the rules stated in the preamble here. But now we can identify the point (a, b) with the natural number $p^{a-1}q^{b-1}$ for all a and b with $1 \leq a \leq m$ and $1 \leq b \leq n$. This identifies the points in the rectangular grid with the set S in this exercise, and the partial order $\preceq$ just described is the same as the divides relation, because $p^{a-1}q^{b-1} \mid p^{c-1}q^{d-1}$ if and only if the exponent on p on the left does not exceed the exponent of p on the right, and similarly for q.

CHAPTER 9

Section 9.1

1. a)



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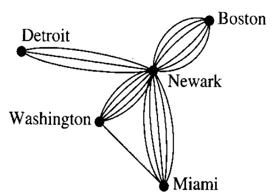

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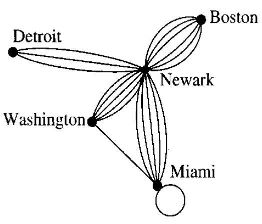

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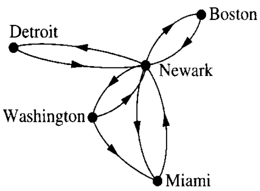

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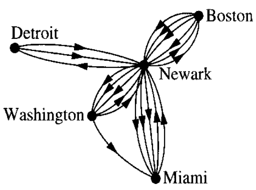
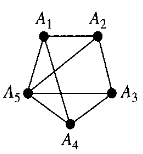


3. Simple graph **5.** Pseudograph **7.** Directed graph **9.** Directed multigraph **11.** If uRv, then there is an edge associated with $\{u, v\}$. But $\{u, v\} = \{v, u\}$, so this edge is associated with $\{v, u\}$ and therefore vRu. Thus, by definition, R is a symmetric relation. A simple graph does not allow loops; therefore, uRu never holds, and so by definition R is irreflexive.

13. a)



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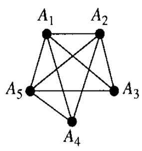

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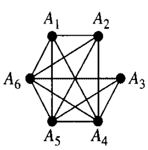

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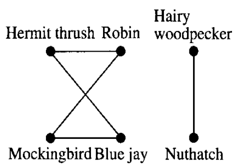

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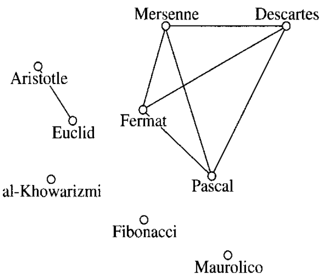

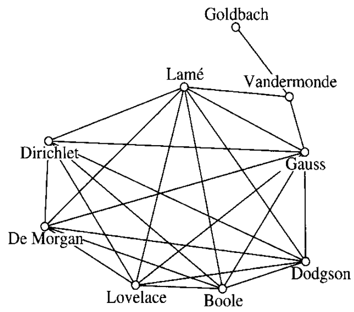

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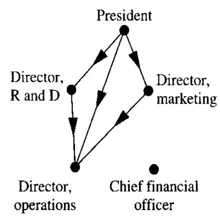

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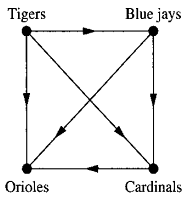
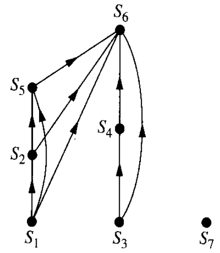


23. We find the telephone numbers in the call graph for February that are not present in the call graph for January and vice versa. For each number we find, we make a list of the numbers they called or were called by using the edges in the call graph. We examine these lists to find new telephone numbers in February that had similar calling patterns to defunct telephone numbers in January. **25.** We use the graph model that has e-mail addresses as vertices and for each message sent, an edge from the e-mail address of the sender to the e-mail address of the recipient. For each e-mail address, we can make a list of other addresses they sent messages to and a list of other address from which they received messages. If two e-mail addresses had almost the same pattern, we conclude that these addresses might have belonged to the same person who had recently changed his or her e-mail address. **27.** Let V be the set of people at the party. Let E be the set of ordered pairs

(u, v) in $V \times V$ such that u knows v's name. The edges are directed, but multiple edges are not allowed. Literally, there is a loop at each vertex, but for simplicity, the model could omit the loops. **29.** Let the set of vertices be a set of people, and two vertices are joined by an edge if the two people were ever married. Ignoring complications, this graph has the property that there are two types of vertices (men and women), and every edge joins vertices of opposite types.

31.

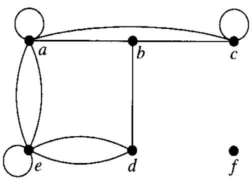


33. Represent people in the group by vertices. Put a directed edge into the graph for every pair of vertices. Label the edge from the vertex representing A to the vertex representing B with a + (plus) if A likes B, a − (minus) if A dislikes B, and a 0 if A is neutral about B.

Section 9.2

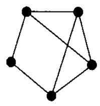
1. $v = 6$; $e = 6$; $\deg(a) = 2$, $\deg(b) = 4$, $\deg(c) = 1$, $\deg(d) = 0$, $\deg(e) = 2$, $\deg(f) = 3$; c is pendant; d is isolated. **3.** $v = 9$; $e = 12$; $\deg(a) = 3$, $\deg(b) = 2$, $\deg(c) = 4$, $\deg(d) = 0$, $\deg(e) = 6$, $\deg(f) = 0$; $\deg(g) = 4$; $\deg(h) = 2$; $\deg(i) = 3$; d and f are isolated. **5.** No, because the sum of the degrees of the vertices cannot be odd **7.** $v = 4$; $e = 7$; $\deg^-(a) = 3$, $\deg^-(b) = 1$, $\deg^-(c) = 2$, $\deg^-(d) = 1$, $\deg^+(a) = 1$, $\deg^+(b) = 2$, $\deg^+(c) = 1$, $\deg^+(d) = 3$ **9.** 5 vertices, 13 edges; $\deg^-(a) = 6$, $\deg^+(a) = 1$, $\deg^-(b) = 1$, $\deg^+(b) = 5$, $\deg^-(c) = 2$, $\deg^+(c) = 5$, $\deg^-(d) = 4$, $\deg^+(d) = 2$, $\deg^-(e) = 0$, $\deg^+(e) = 0$

11.



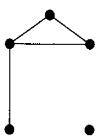
13. The number of collaborators v has; someone who has never collaborated; someone who has just one collaborator **15.** In the directed graph $\deg^-(v)$ = number of calls v received, $\deg^+(v)$ = number of calls v made; in the undirected graph, $\deg(v)$ is the number of calls either made or received by v. **17.** $(\deg^+(v), \deg^-(v))$ is the win–loss record of v. **19.** Construct the simple graph model in which V is the set of people in the group and there is an edge associated with $\{u, v\}$ if u and v know each other. Then the degree of vertex v is the number of people v knows. By the result of Exercise 18, there are two vertices with the same degree. Therefore there are two people who know the same number of other people in the group. **21.** Bipartite **23.** Not bipartite **25.** Not bipartite **27. a)** Let V = {Zamora, Agraharam, Smith, Chou, Macintyre, planning, publicity, sales, marketing, development, industry relations} and E = {{Zamora, planning}, {Zamora, sales}, {Zamora, marketing}, {Zamora,industry relations}, {Agraharam, planning}, {Agraharam, development}, {Smith, publicity}, {Smith, sales}, {Smith, industry relations}, {Chou, planning}, {Chou, sales}, {Chou, industry relations}, {Macintyre, planning}, {Macintyre, publicity}, {Macintyre, sales}, {Macintyre, industry relations}}. **b)** Many answers are possible, such as Zamora–planning, Agraharam–development, Smith–publicity, Chou–sales, and Macintyre–industry relations. **29. a)** n vertices, $n(n-1)/2$ edges **b)** n vertices, n edges **c)** $n + 1$ vertices, $2n$ edges **d)** $m + n$ vertices, mn edges **e)** 2^n vertices, $n2^{n-1}$ edges **31. a)** 3, 3, 3, 3 **b)** 2, 2, 2, 2 **c)** 4,3,3,3,3 **d)** 3,3,2,2,2 **e)** 3, 3, 3, 3, 3, 3, 3, 3 **33.** Each of the n vertices is adjacent to each of the other $n - 1$ vertices, so the degree sequence is $n-1, n-1, \ldots, n-1$ (n terms). **35.** 7

37. a) Yes



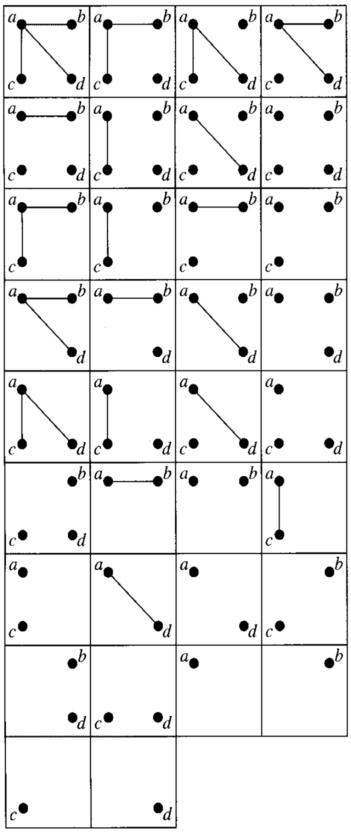
b) No, sum of degrees is odd. **c)** No **d)** No, sum of degrees is odd.

e) Yes



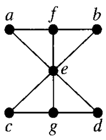
f) No, sum of degrees is odd. **39.** First, suppose that $d_1, d_2, \ldots, d_n$ is graphic. We must show that the sequence whose terms are $d_2 - 1, d_3 - 1, \ldots, d_{d_1+1} - 1, d_{d_1+2}, d_{d_1+3}, \ldots, d_n$ is graphic once it is put into nonincreasing order. In Exercise 38 it is proved that if the original sequence is graphic, then in fact there is a graph having this degree sequence in which the vertex of degree d_1 is adjacent to the vertices of degrees $d_2, d_3, \ldots, d_{d_1+1}$. Remove from this graph the vertex of highest degree (d_1). The resulting graph has the desired degree sequence. Conversely, suppose that $d_1, d_2, \ldots, d_n$ is a nonincreasing sequence such that the sequence $d_2 - 1, d_3 - 1, \ldots, d_{d_1+1} - 1, d_{d_1+2}, d_{d_1+3}, \ldots, d_n$ is graphic once it is put into nonincreasing order. Take a graph with this latter degree sequence, where vertex v_i has degree $d_i - 1$ for $2 \le i \le d_1 + 1$ and vertex v_i has degree d_i for $d_1 + 2 \le i \le n$. Adjoin one new vertex (call it v_1), and put in an edge from v_1 to each of the vertices $v_2, v_3, \ldots, v_{d_1+1}$. The resulting graph has degree sequence $d_1, d_2, \ldots, d_n$. **41.** Let $d_1, d_2, \ldots, d_n$ be a nonincreasing sequence of nonnegative integers with an even sum. Construct a graph as follows: Take vertices $v_1, v_2, \ldots, v_n$ and put $\lfloor d_i/2 \rfloor$ loops at vertex v_i, for $i = 1, 2, \ldots, n$. For each i, vertex v_i now has degree either d_i or $d_i - 1$. Because the original sum was even, the number of vertices for which $\deg(v_i) = d_i - 1$ is even. Pair them up arbitrarily, and put in an edge joining the vertices in each pair. **43.** 17

45.



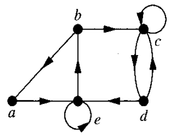
47. a) For all $n \geq 1$ **b)** For all $n \geq 3$ **c)** For $n = 3$ **d)** For all $n \geq 0$ **49.** 5

51.

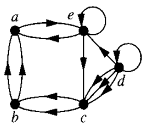


53. a) The graph with n vertices and no edges **b)** The disjoint union of K_m and K_n **c)** The graph with vertices $\{v_1, \ldots, v_n\}$ with an edge between v_i and v_j unless $i \equiv j \pm 1 \pmod{n}$ **d)** The graph whose vertices are represented by bit strings of length n with an edge between two vertices if the associated bit strings differ in more than one bit **55.** $v(v-1)/2 - e$ **57.** $n - 1 - d_n, n - 1 - d_{n-1}, \ldots, n - 1 - d_2, n - 1 - d_1$ **59.** The union of G and $\overline{G}$ contains an edge between each pair of the n vertices. Hence, this union is K_n.

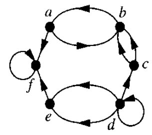
61. Exercise 7:



Exercise 8:

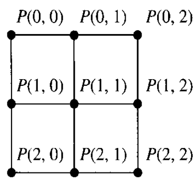


Exercise 9:



63. A directed graph $G = (V, E)$ is its own converse if and only if it satisfies the condition $(u, v) \in E$ if and only if $(v, u) \in E$. But this is precisely the condition that the associated relation must satisfy to be symmetric.

65.



67. We can connect $P(i, j)$ and $P(k, l)$ by using $|i - k|$ hops to connect $P(i, j)$ and $P(k, j)$ and $|j - l|$ hops to connect $P(k, j)$ and $P(k, l)$. Hence, the total number of hops required to connect $P(i, j)$ and $P(k, l)$ does not exceed $|i - k| + |j - l|$. This is less than or equal to $m + m = 2m$, which is $O(m)$.

Section 9.3

1.

Vertex	*Adjacent Vertices*
a	b, c, d
b	a, d
c	a, d
d	a, b, c

3.

Vertex	*Terminal Vertices*
a	a, b, c, d
b	d
c	a, b
d	b, c, d

5. $\begin{bmatrix} 0 & 1 & 1 & 1 \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{bmatrix}$

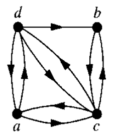
where vertices are listed in alphabetical order

7. $\begin{bmatrix} 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 \\ 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 1 \end{bmatrix}$ **9. a)** $\begin{bmatrix} 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{bmatrix}$

b) $\begin{bmatrix} 0 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix}$ **c)** $\begin{bmatrix} 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \end{bmatrix}$

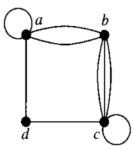
d) $\begin{bmatrix} 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \end{bmatrix}$ **e)** $\begin{bmatrix} 0 & 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 & 0 \end{bmatrix}$

f) $\begin{bmatrix} 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 \end{bmatrix}$

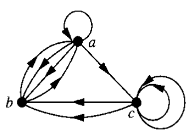
11. 

13. $\begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 2 \\ 1 & 1 & 0 & 1 \\ 0 & 2 & 1 & 0 \end{bmatrix}$

15. $\begin{bmatrix} 1 & 0 & 2 & 1 \\ 0 & 1 & 1 & 2 \\ 2 & 1 & 1 & 0 \\ 1 & 2 & 0 & 1 \end{bmatrix}$

17. 

19. $\begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 \end{bmatrix}$ **21.** $\begin{bmatrix} 1 & 1 & 2 & 1 \\ 1 & 0 & 0 & 2 \\ 1 & 0 & 1 & 1 \\ 0 & 2 & 1 & 0 \end{bmatrix}$

23. 

25. Yes

27. Exercise 13: $\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 0 \\ 1 & 1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 1 & 1 \end{bmatrix}$

Exercise 14: $\begin{bmatrix} 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 0 & 1 & 1 & 1 \end{bmatrix}$

Exercise 15: $\begin{bmatrix} 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 0 & 1 \end{bmatrix}$

29. $\deg(v)$ − number of loops at v; $\deg^{-}(v)$ **31.** 2 if e is not a loop, 1 if e is a loop

33. a) $\begin{bmatrix} 1 & 1 & \cdots & 1 & 0 & \cdots & 0 \\ 1 & 0 & \cdots & 0 & 1 & \cdots & 0 \\ 0 & 1 & \cdots & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & & \vdots & \vdots & & \vdots \\ 0 & 0 & \cdots & 0 & 0 & \cdots & 1 \\ 0 & 0 & \cdots & 1 & 0 & \cdots & 1 \end{bmatrix}$

b) $\begin{bmatrix} 1 & 0 & \cdots & 0 & 1 \\ 1 & 1 & \cdots & 0 & 0 \\ 0 & 1 & \cdots & 0 & 0 \\ \vdots & \vdots & & \vdots & \vdots \\ 0 & 0 & \cdots & 1 & 0 \\ 0 & 0 & \cdots & 1 & 1 \end{bmatrix}$

c) $\begin{bmatrix} 0 & 0 & \cdots & 0 & 1 & 1 & \cdots & 1 \\ & & & & 1 & 0 & \cdots & 0 \\ & & \mathbf{B} & & 0 & 1 & \cdots & 0 \\ & & & & \vdots & \vdots & & \vdots \\ & & & & 0 & 0 & \cdots & 1 \end{bmatrix}$

where **B** is the answer to (b)

d) $\begin{bmatrix} 1 & 1 & \cdots & 1 & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & & \vdots & \vdots & & \vdots \\ 0 & 0 & \cdots & 0 & 0 & \cdots & 1 \\ 1 & 0 & & 0 & 1 & \cdots & 0 \\ 0 & 1 & & 0 & 0 & & \\ \vdots & \vdots & & \vdots & \vdots & & \\ 0 & 0 & \cdots & 1 & 0 & \cdots & 1 \end{bmatrix}$

35. Isomorphic **37.** Isomorphic **39.** Isomorphic **41.** Not isomorphic **43.** Isomorphic **45.** G is isomorphic to itself by the identity function, so isomorphism is reflexive. Suppose that G is isomorphic to H. Then there exists a one-to-one correspondence f from G to H that preserves adjacency and nonadjacency. It follows that f^{-1} is a one-to-one correspondence from H to G that preserves adjacency and nonadjacency. Hence, isomorphism is symmetric. If G is isomorphic to H and H is isomorphic to K, then there are one-to-one correspondences f and g from G to H and from H to K that preserve adjacency and nonadjacency. It follows that $g \circ f$ is a one-to-one correspondence from G to K that preserves adjacency and nonadjacency. Hence, isomorphism is transitive. **47.** All zeros **49.** Label the vertices in order so that all of the vertices in the first set of the partition of the vertex set come first. Because no edges join vertices in the same set of the partition, the matrix has the desired form. **51.** C_5 **53.** $n = 5$ only **55.** 4 **57. a)** Yes **b)** No **c)** No **59.** $G = (V_1, E_1)$ is isomorphic to $H =$

(V_2, E_2) if and only if there exist functions f from V_1 to V_2 and g from E_1 to E_2 such that each is a one-to-one correspondence and for every edge e in E_1 the endpoints of $g(e)$ are $f(v)$ and $f(w)$ where v and w are the endpoints of e. **61.** Yes **63.** Yes **65.** If f is an isomorphism from a directed graph G to a directed graph H, then f is also an isomorphism from G^{conv} to H^{conv}. To see this note that (u, v) is an edge of G^{conv} if and only if (v, u) is an edge of G if and only if $(f(v), f(u))$ is an edge of H if and only if $(f(u), f(v))$ is an edge of H^{conv}. **67.** Many answers are possible; for example, C_6 and $C_3 \cup C_3$. **69.** The product is $[a_{ij}]$ where a_{ij} is the number of edges from v_i to v_j when $i \neq j$ and a_{ii} is the number of edges incident to v_i. **71.** The graphs in Exercise 41 provide a devil's pair.

Section 9.4

1. a) Path of length 4; not a circuit; not simple **b)** Not a path **c)** Not a path **d)** Simple circuit of length 5 **3.** No **5.** No **7.** Maximal sets of people with the property that for any two of them, we can find a string of acquaintances that takes us from one to the other **9.** If a person has Erdős number n, then there is a path of length n from that person to Erdős in the collaboration graph, so by definition, that means that that person is in the same component as Erdős. If a person is in the same component as Erdős, then there is a path from that person to Erdős, and the length of the shortest such path is that person's Erdős number. **11. a)** Weakly connected **b)** Weakly connected **c)** Not strongly or weakly connected **13.** The maximal sets of phone numbers for which it is possible to find directed paths between every two different numbers in the set **15. a)** $\{a, b, f\}$, $\{c, d, e\}$ **b)** $\{a, b, c, d, e, h\}$, $\{f\}$, $\{g\}$ **c)** $\{a, b, d, e, f, g, h, i\}$, $\{c\}$ **17. a)** 2 **b)** 7 **c)** 20 **d)** 61 **19.** Not isomorphic (G has a triangle; H does not) **21.** Isomorphic (the path $u_1, u_2, u_7, u_6, u_5, u_4, u_3, u_8, u_1$ corresponds to the path $v_1, v_2, v_3, v_4, v_5, v_8, v_7, v_6, v_1$) **23. a)** 3 **b)** 0 **c)** 27 **d)** 0 **25. a)** 1 **b)** 0 **c)** 2 **d)** 1 **e)** 5 **f)** 3 **27.** R is reflexive by definition. Assume that $(u, v) \in R$; then there is a path from u to v. Then $(v, u) \in R$ because there is a path from v to u, namely, the path from u to v traversed backward. Assume that $(u, v) \in R$ and $(v, w) \in R$; then there are paths from u to v and from v to w. Putting these two paths together gives a path from u to w. Hence, $(u, w) \in R$. It follows that R is transitive. **29.** c **31.** b, c, e, i **33.** If a vertex is pendant it is clearly not a cut vertex. So an endpoint of a cut edge that is a cut vertex is not pendant. Removal of a cut edge produces a graph with more connected components than in the original graph. If an endpoint of a cut edge is not pendant, the connected component it is in after the removal of the cut edge contains more than just this vertex. Consequently, removal of that vertex and all edges incident to it, including the original cut edge, produces a graph with more connected components than were in the original graph. Hence, an endpoint of a cut edge that is not pendant is a cut vertex. **35.** Assume there exists a connected graph G with at most one vertex that is not a cut vertex. Define the distance between the vertices u and v, denoted by $d(u, v)$, to be the length of the shortest path between u and v in G. Let s and t be vertices in G such that $d(s, t)$ is a maximum. Either s or t (or both) is a cut vertex, so without loss of generality suppose that s is a cut vertex. Let w belong to the connected component that does not contain t of the graph obtained by deleting s and all edges incident to s from G. Because every path from w to t contains s, $d(w, t) > d(s, t)$, which is a contradiction. **37. a)** Denver–Chicago, Boston–New York **b)** Seattle–Portland, Portland–San Francisco, Salt Lake City–Denver, New York–Boston, Boston–Burlington, Boston–Bangor **39.** A set of people who collectively influence everyone (directly or indirectly); {Deborah} **41.** An edge cannot connect two vertices in different connected components. Because there are at most $C(n_i, 2)$ edges in the connected component with n_i vertices, it follows that there are at most $\sum_{i=1}^{k} C(n_i, 2)$ edges in the graph. **43.** Suppose that G is not connected. Then it has a component of k vertices for some k, $1 \leq k \leq n-1$. The most edges G could have is $C(k, 2) + C(n-k, 2) = [k(k-1) + (n-k)(n-k-1)]/2 = k^2 - nk + (n^2 - n)/2$. This quadratic function of f is minimized at $k = n/2$ and maximized at $k = 1$ or $k = n - 1$. Hence, if G is not connected, the number of edges does not exceed the value of this function at 1 and at $n-1$, namely, $(n-1)(n-2)/2$. **45. a)** 1 **b)** 2 **c)** 6 **d)** 21 **47.** 2 **49.** Let the paths P_1 and P_2 be $u = x_0, x_1, \ldots, x_n = v$, respectively. Because P_1 and P_2 do not contain the same set of edges, they must eventually diverge. If this happens only after one of them has ended, the rest of the other path is a simple circuit from v to v. Otherwise, we can suppose that $x_0 = y_0, x_1 = y_1, \ldots, x_i = y_i$, but $x_{i+1} \neq y_{i+1}$. Follow the path y_i, y_{i+1}, y_{i+2}, and so on, until it once again encounters a vertex on P_1. Once we are back on P_1, follow it, forward or backward as necessary, back to x_i. Because $x_i = y_i$, this forms a circuit that must be simple, because no edge among the x_ks can be repeated and no edge among the x_ks can equal one of the Y_ls that we used. **51.** The graph G is connected if and only if every off-diagonal entry of $\mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \cdots + \mathbf{A}^{n-1}$ is positive, where $\mathbf{A}$ is the adjacency matrix of G. **53.** If the graph is bipartite, say with parts A and B, then the vertices in every path must alternately lie in A and B. Therefore a path that starts in A, say, will end in B after an odd number of steps and in A after an even number of steps. Because a circuit ends at the same vertex where it starts, the length must be even. Conversely, suppose that all circuits have even length; we must show that the graph is bipartite. We can assume that the graph is connected, because if it is not, then we can just work on one component at a time. Let v be a vertex of the graph, and let A be the set of all vertices to which there is a path of odd length starting at v, and let B be the set of all vertices to which there is a path of even length starting at v. Because the component is connected, every vertex lies in A or B. No vertex can lie in both A and B, because if one did, then following the odd-length path from v to that vertex and then back along the even-length path from that vertex to v would produce an odd circuit, contrary to the hypothesis. Thus, the set of vertices has been partitioned into two sets. To show that every edge has endpoints in different parts, suppose that xy is an edge, where $x \in A$. Then the odd-length path from v to x followed by xy produces an even-length path from v to y, so $y \in B$. (Similarly, if $x \in B$.) **55.** $(H_1W_1H_2W_2\langle\text{boat}\rangle, \emptyset) \rightarrow (H_2W_2, H_1W_1\langle\text{boat}\rangle) \rightarrow (H_1H_2W_2\langle\text{boat}\rangle, W_1) \rightarrow (W_2, H_1W_1H_2\langle\text{boat}\rangle) \rightarrow (H_2W_2\langle\text{boat}\rangle, H_1W_1) \rightarrow (\emptyset, H_1W_1H_2W_2\langle\text{boat}\rangle)$

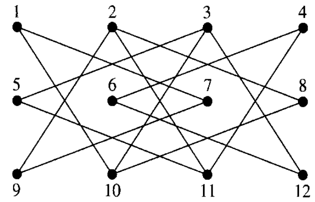
Section 9.5

1. Neither **3.** No Euler circuit; $a, e, c, e, b, e, d, b, a, c, d$ **5.** $a, b, c, d, c, e, d, b, e, a, e, a$ **7.** $a, i, h, g, d, e, f, g, c, e, h, d, c, a, b, i, c, b, h, a$ **9.** No, A still has odd degree. **11.** When the graph in which vertices represent intersections and edges streets has an Euler path **13.** Yes **15.** No **17.** If there is an Euler path, as we follow it each vertex except the starting and ending vertices must have equal in-degree and out-degree, because whenever we come to a vertex along an edge, we leave it along another edge. The starting vertex must have out-degree 1 larger than its in-degree, because we use one edge leading out of this vertex and whenever we visit it again we use one edge leading into it and one leaving it. Similarly, the ending vertex must have in-degree 1 greater than its out-degree. Because the Euler path with directions erased produces a path between any two vertices, in the underlying undirected graph, the graph is weakly connected. Conversely, suppose the graph meets the degree conditions stated. If we add one more edge from the vertex of deficient out-degree to the vertex of deficient in-degree, then the graph has every vertex with equal in-degree and out-degree. Because the graph is still weakly connected, by Exercise 16 this new graph has an Euler circuit. Now delete the added edge to obtain the Euler path. **19.** Neither **21.** No Euler circuit; $a, d, e, d, b, a, e, c, e, b, c, b, e$ **23.** Neither **25.** Follow the same procedure as Algorithm 1, taking care to follow the directions of edges. **27. a)** $n = 2$ **b)** None **c)** None **d)** $n = 1$ **29.** Exercise 1:1 time; Exercises 2–7: 0 times **31.** a, b, c, d, e, a is a Hamilton circuit. **33.** No Hamilton circuit exists, because once a purported circuit has reached e it would have nowhere to go. **35.** No Hamilton circuit exists, because every edge in the graph is incident to a vertex of degree 2 and therefore must be in the circuit. **37.** a, b, c, f, d, e is a Hamilton path. **39.** f, e, d, a, b, c is a Hamilton path. **41.** No Hamilton path exists. There are eight vertices of degree 2, and only two of them can be end vertices of a path. For each of the other six, their two incident edges must be in the path. It is not hard to see that if there is to be a Hamilton path, exactly one of the inside corner vertices must be an end, and that this is impossible. **43.** $a, b, c, f, i, h, g, d, e$ is a Hamilton path. **45.** $m = n \geq 2$ **47. a)** (i) No, (ii) No, (iii) Yes **b)** (i) No, (ii) No, (iii) Yes **c)** (i) Yes, (ii) Yes, (iii) Yes **d)** (i) Yes, (ii) Yes, (iii) Yes **49.** The result is trivial for $n = 1$: code is 0, 1. Assume we have a Gray code of order n. Let $c_1, \ldots, c_k$, $k = 2^n$ be such a code. Then $0c_1, \ldots, 0c_k, 1c_k, \ldots, 1c_1$ is a Gray code of order $n + 1$.

51. **procedure** *Fleury* ($G = (V, E)$: connected multigraph with the degrees of all vertices even, $V = \{v_1, \ldots, v_n\}$)
$v := v_1$
circuit $:= v$
$H := G$
while H has edges
begin
$e :=$ first edge with endpoint v in H (with respect to listing of V) such that e is not a cut edge of H, if one exists, and simply the first edge in H with endpoint v otherwise
$w :=$ other endpoint of e
circuit $:=$ *circuit* with e, w added
$v := w$
$H := H - e$
end {*circuit* is an Euler circuit}

53. If G has an Euler circuit, it is also an Euler path. If not, add an edge between the two vertices of odd degree and apply the algorithm to get an Euler circuit. Then delete the new edge. **55.** Suppose $G = (V, E)$ is a bipartite graph with $V = V_1 \cup V_2$, where no edge connects a vertex in V_1 and a vertex in V_2. Suppose that G has a Hamilton circuit. Such a circuit must be of the form $a_1, b_1, a_2, b_2, \ldots, a_k, b_k, a_1$, where $a_i \in V_1$ and $b_i \in V_2$ for $i = 1, 2, \ldots, k$. Because the Hamilton circuit visits each vertex exactly once, except for v_1, where it begins and ends, the number of vertices in the graph equals $2k$, an even number. Hence, a bipartite graph with an odd number of vertices cannot have a Hamilton circuit.

57.



59. We represent the squares of a 3×4 chessboard as follows:

1	2	3	4
5	6	7	8
9	10	11	12

A knight's tour can be made by following the moves 8, 10, 1, 7, 9, 2, 11, 5, 3, 12, 6, 4. **61.** We represent the squares of a 4×4 chessboard as follows:

1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16

There are only two moves from each of the four corner squares. If we include all the edges 1–10, 1–7, 16–10, and 16–7, a circuit is completed too soon, so at least one of these edges must be missing. Without loss of generality, assume the path starts 1–10, 10–16, 16–7. Now the only moves from square 3 are to squares 5, 10, and 12, and square 10 already has two incident edges. Therefore, 3–5 and 3–12 must be in the Hamilton circuit. Similarly, edges 8–2 and 8–15 must be in the circuit. Now the only moves from square 9 are to squares 2, 7, and 15. If there were edges from square 9 to both squares 2 and 15, a circuit would be completed too soon. Therefore the edge 9–7 must be in the circuit giving square 7 its full complement of edges. But now square 14 is forced to be joined to squares 5 and 12, completing a circuit too soon (5–14–12–3–5). This contradiction shows that there is no knight's tour on the 4×4 board. **63.** Because there are mn squares on an $m \times n$ board, if both m and n are odd, there are an odd number of squares. Because by Exercise 62 the corresponding graph is bipartite, by Exercise 55 it has no Hamilton circuit. Hence, there is no reentrant knight's tour. **65. a)** If G does not have a Hamilton circuit, continue as long as possible adding missing edges one at a time in such a way that we do not obtain a graph with a Hamilton circuit. This cannot go on forever, because once we've formed the complete graph by adding all missing edges, there is a Hamilton circuit. Whenever the process stops, we have obtained a (necessarily noncomplete) graph H with the desired property. **b)** Add one more edge to H. This produces a Hamilton circuit, which uses the added edge. The path consisting of this circuit with the added edge omitted is a Hamilton path in H. **c)** Clearly v_1 and v_n are not adjacent in H, because H has no Hamilton circuit. Therefore they are not adjacent in G. But the hypothesis was that the sum of the degrees of vertices not adjacent in G was at least n. This inequality can be rewritten as $n - \deg(v_n) \le \deg(v_1)$. But $n - \deg(v_n)$ is just the number of vertices not adjacent to v_n. **d)** Because there is no vertex following v_n in the Hamilton path, v_n is not in S. Each one of the $\deg(v_1)$ vertices adjacent to v_1 gives rise to an element of S, so S contains $\deg(v_1)$ vertices. **e)** By part (c) there are at most $\deg(v_1) - 1$ vertices other than v_n not adjacent to v_n, and by part (d) there are $\deg(v_1)$ vertices in S, none of which is v_n. Therefore at least one vertex of S is adjacent to v_n. By definition, if v_k is this vertex, then H contains edges $v_k v_n$ and $v_1 v_{k+1}$, where $1 < k < n - 1$. **f)** Now $v_1, v_2, \ldots, v_{k-1}, v_k, v_n, v_{n-1}, \ldots, v_{k+1}, v_1$ is a Hamilton circuit in H, contradicting the construction of H. Therefore, our assumption that G did not originally have a Hamilton circuit is wrong, and our proof by contradiction is complete.

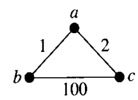
Section 9.6

1. a) Vertices are the stops, edges join adjacent stops, weights are the times required to travel between adjacent stops. **b)** Same as part (a), except weights are distances between adjacent stops. **c)** Same as part (a), except weights are fares between stops. **3.** 16 **5.** Exercise 2: *a, b, e, d, z*; Exercise 3: *a, c, d, e, g, z*; Exercise 4: *a, b, e, h, l, m, p, s, z* **7. a)** *a, c, d* **b)** *a, c, d, f* **c)** *c, d, f* **e)** *b, d, e, g, z* **9. a)** Direct **b)** Via New York **c)** Via Atlanta and Chicago **d)** Via New York **11. a)** Via Chicago **b)** Via Chicago **c)** Via Los Angeles **d)** Via Chicago **13. a)** Via Chicago **b)** Via Chicago **c)** Via Los Angeles **d)** Via Chicago **15.** Do not stop the algorithm when z is added to the set S. **17. a)** Via Woodbridge, via Woodbridge and Camden **b)** Via Woodbridge, via Woodbridge and Camden **19.** For instance, sightseeing tours, street cleaning

21.

	a	*b*	*c*	*d*	*e*	*z*
a	4	3	2	8	10	13
b	3	2	1	5	7	10
c	2	1	2	6	8	11
d	8	5	6	4	2	5
e	10	7	8	2	4	3
z	13	10	11	5	3	6

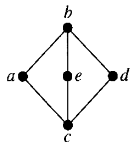
23. $O(n^3)$ **25.** *a-c-b-d-a* (or the same circuit starting at some point but traversing the vertices in the same or reverse order) **27.** San Francisco–Denver–Detroit–New York–Los Angeles–San Francisco (or the same circuit starting at some other point but traversing the vertices in the same or reverse order)
29. Consider this graph:



The circuit *a-b-a-c-a* visits each vertex at least once (and the vertex *a* twice) and has total weight 6. Every Hamilton circuit has total weight 103.

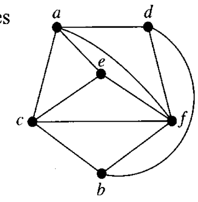
Section 9.7

1. Yes **3.**



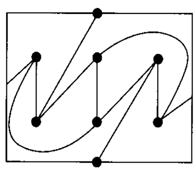
5. No

7. Yes



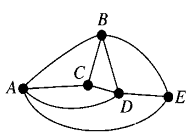
9. No **11.** A triangle is formed by the planar representation of the subgraph of K_5 consisting of the edges connecting v_1, v_2, and v_3. The vertex v_4 must be placed either within the triangle or outside of it. We will consider only the case when v_4 is inside the triangle; the other case is similar. Drawing the three edges from v_1, v_2, and v_3 to v_4 forms four regions. No matter which of these four regions v_5 is in, it is possible to join it to only three, and not all four, of the other vertices. **13.** 8 **15.** Because there are no loops or multiple edges and no simple circuits of length 3, and the degree of the unbounded region is at least 4, each region has degree at least 4. Thus $2e \ge 4r$, or $r \le e/2$. But $r = e - v + 2$, so we have $e - v + 2 \le e/2$, which implies that $e \le 2v - 4$. **17.** As in the argument in the proof of Corollary 1, we have $2e \ge 5r$ and $r = e - v + 2$. Thus $e - v + 2 \le 2e/5$, which implies that $e \le (5/3)v - (10/3)$. **19.** Only (a) and (c) **21.** Not homeomorphic to $K_{3,3}$ **23.** Planar **25.** Nonplanar **27. a)** 1 **b)** 3 **c)** 9 **d)** 2 **e)** 4 **f)** 16 **29.** Draw $K_{m,n}$ as described in the hint. The number of crossings is four times the number in the first quadrant. The vertices on the x-axis to the right of the origin are $(1, 0), (2, 0), \ldots, (m/2, 0)$ and the vertices on the y-axis above the origin are $(0, 1), (0, 2), \ldots, (0, n/2)$. We obtain all crossings by choosing any two numbers a and b with $1 \le a < b \le m/2$ and two numbers r and s with $1 \le r < s \le n/2$; we get exactly one crossing in the graph between the edge connecting $(a, 0)$ and $(0, s)$ and the edge connecting $(b, 0)$ and $(0, r)$. Hence, the number of crossings in the first quadrant is $C\left(\frac{m}{2}, 2\right) \cdot C\left(\frac{n}{2}, 2\right) = \frac{(m/2)(m/2-1)}{2} \cdot \frac{(n/2)(n/2-1)}{2}$. Hence, the total number of crossings is $4 \cdot mn(m-2)(n-2)/64 = mn(m-2)(n-2)/16$. **31. a)** 2 **b)** 2 **c)** 2 **d)** 2 **e)** 2 **f)** 2 **33.** The formula is valid for $n \le 4$. If $n > 4$, by Exercise 32 the thickness of K_n is at least $C(n, 2)/(3n - 6) = (n + 1 + \frac{2}{n-2})/6$ rounded up. Because this quantity is never an integer, it equals the next larger integer rounded down, which equals $\lfloor (n + 7)/6 \rfloor$. **35.** This follows from Exercise 34 because $K_{m,n}$ has mn edges and $m + n$ vertices and has no triangles because it is bipartite.

37.

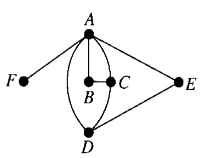


Section 9.8

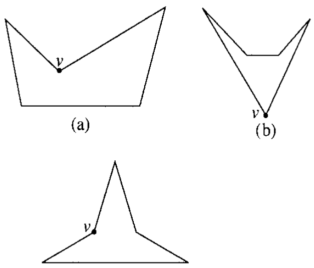
1. Four colors



3. Three colors



5. 3 **7.** 3 **9.** 2 **11.** 3 **13.** Graphs with no edges **15.** 3 if n is even, 4 if n is odd **17.** Period 1: Math 115, Math 185; period 2: Math 116, CS 473; period 3: Math 195, CS 101; period 4: CS 102; period 5: CS 273 **19.** 5 **21.** Exercise 5: 3 Exercise 6: 6 Exercise 7: 3 Exercise 8: 4 Exercise 9: 3 Exercise 10: 6 Exercise 11: 4 **23.** 5 **25.** Color 1: e, f, d; color 2: c, a, i, g; color 3: h, b, j **27.** Color C_6 **29.** Four colors are needed to color W_n when n is an odd integer greater than 1, because three colors are needed for the rim (see Example 4), and the center vertex, being adjacent to all the rim vertices, will require a fourth color. To see that the graph obtained from W_n by deleting one edge can be colored with three colors, consider two cases. If we remove a rim edge, then we can color the rim with two colors, by starting at an endpoint of the removed edge and using the colors alternately around the portion of the rim that remains. The third color is then assigned to the center vertex. If we remove a spoke edge, then we can color the rim by assigning color #1 to the rim endpoint of the removed edge and colors #2 and #3 alternately to the remaining vertices on the rim, and then assign color #1 to the center. **31.** Suppose that G is chromatically k-critical but has a vertex v of degree $k - 2$ or less. Remove from G one of the edges incident to v. By definition of "k-critical," the resulting graph can be colored with $k - 1$ colors. Now restore the missing edge and use this coloring for all vertices except v. Because we had a proper coloring of the smaller graph, no two adjacent vertices have the same color. Furthermore, v has at most $k - 2$ neighbors, so we can color v with an unused color to obtain a proper $(k - 1)$-coloring of G. This contradicts the fact that G has chromatic number k. Therefore, our assumption was wrong, and every vertex of G must have degree at least $k - 1$. **33. a)** 6 **b)** 7 **c)** 9 **d)** 11 **35.** Represent frequencies by colors and zones by vertices. Join two vertices with an edge if the zones these vertices represent interfere with one another. Then a k-tuple coloring is precisely an assignment of frequencies that avoids interference. **37.** We use induction on the number of vertices of the graph. Every graph with five or fewer vertices can be colored with five or fewer colors, because each vertex can get a different color. That takes care of the basis case(s). So we assume that all graphs with k vertices can be 5-colored and consider a graph G with $k + 1$ vertices. By Corollary 2 in Section 9.7, G has a vertex v with degree at most 5. Remove v to form the graph G'. Because G' has only k vertices, we 5-color it by the inductive hypothesis. If the neighbors of v do not use all five colors, then we can 5-color G by assigning to v a color not used by any of its neighbors. The difficulty arises if v has five neighbors, and each has a different color in the 5-coloring of G'. Suppose that the neighbors of v, when considered in clockwise order around v, are a, b, c, m, and p. (This order is determined by the clockwise order of the curves representing the edges incident to v.) Suppose that the colors of the neighbors are azure, blue, chartreuse, magenta, and purple, respectively. Consider the azure-chartreuse subgraph (i.e., the vertices in G colored azure or chartreuse and all the edges between them). If a and c are not in the same component of this graph, then in the component containing a we can interchange these two colors (make the azure vertices chartreuse and vice versa), and G' will still be properly colored. That makes a chartreuse, so we can now color v azure, and G has been properly colored. If a and c are in the same component, then there is a path of vertices alternately colored azure and chartreuse joining a and c. This path together with edges av and vc divides the plane into two regions, with b in one of them and m in the other. If we now interchange blue and magenta on all the vertices in the same region as b, we will still have a proper coloring of G', but now blue is available for v. In this case, too, we have found a proper coloring of G. This completes the inductive step, and the theorem is proved. **39.** We follow the hint. Because the measures of the interior angles of a pentagon total 540°, there cannot be as many as three interior angles of measure more than 180° (reflex angles). If there are no reflex angles, then the pentagon is convex, and a guard placed at any vertex can see all points. If there is one reflex angle, then the pentagon must look essentially like figure (a) below, and a guard at vertex v can see all points. If there are two reflex angles, then they can be adjacent or nonadjacent (figures (b) and (c)); in either case, a guard at vertex v can see all points. [In figure (c), choose the reflex vertex closer to the bottom side.] Thus for all pentagons, one guard suffices, so $g(5) = 1$.



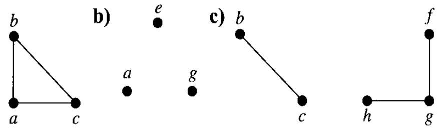
(a) (b) (c)

41. The figure suggested in the hint (generalized to have k prongs for any $k \geq 1$) has $3k$ vertices. The sets of locations from which the tips of different prongs are visible are disjoint. Therefore, a separate guard is needed for each of the k prongs, so at least k guards are needed. This shows that $g(3k) \geq k = \lfloor 3k/3 \rfloor$. If $n = 3k + i$, where $0 \leq i \leq 2$, then $g(n) \geq g(3k) \geq k = \lfloor n/3 \rfloor$.

Supplementary Exercises

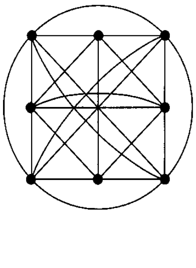
1. 2500 **3.** Yes **5.** Yes **7.** $\sum_{i=1}^{m} n_i$ vertices, $\sum_{i<j} n_i n_j$ edges

9. a) **b)** **c)**

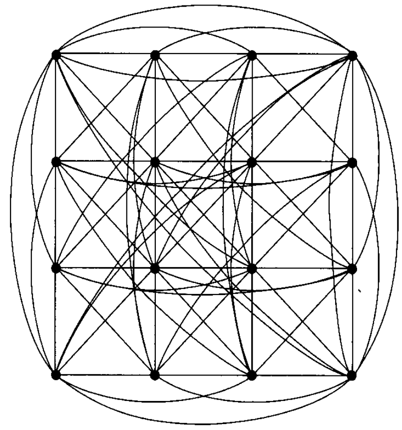


11. Complete subgraphs containing the following sets of vertices: $\{b, c, e, f\}$, $\{a, b, g\}$, $\{a, d, g\}$, $\{d, e, g\}$, $\{b, e, g\}$ **13.** Complete subgraphs containing the following sets of vertices: $\{b, c, d, j, k\}$, $\{a, b, j, k\}$, $\{e, f, g, i\}$, $\{a, b, i\}$, $\{a, i, j\}$, $\{b, d, e\}$, $\{b, e, i\}$, $\{b, i, j\}$, $\{g, h, i\}$, $\{h, i, j\}$ **15.** $\{c, d\}$ is a minimum dominating set.

17. a)



b)



19. a) 1 **b)** 2 **c)** 3 **21. a)** A path from u to v in a graph G induces a path from $f(u)$ to $f(v)$ in an isomorphic graph H. **b)** Suppose f is an isomorphism from G to H. If $v_0, v_1, \ldots, v_n, v_0$ is a Hamilton circuit in G, then $f(v_0), f(v_1), \ldots, f(v_n), f(v_0)$ must be a Hamilton circuit in H because it is still a circuit and $f(v_i) \neq f(v_j)$ for $0 \leq i < j \leq n$. **c)** Suppose f is an isomorphism from G to H. If $v_0, v_1, \ldots, v_n, v_0$ is an Euler circuit in G, then $f(v_0), f(v_1), \ldots, f(v_n), f(v_0)$ must be an Euler circuit in H because it is a circuit that contains each edge exactly once. **d)** Two isomorphic graphs must have the same crossing number because they can be drawn exactly the same way in the plane. **e)** Suppose f is an isomorphism from G to H. Then v is isolated in G if and only if $f(v)$ is isolated in H. Hence, the graphs must have the same number of isolated vertices. **f)** Suppose f is an isomorphism from G to H. If G is bipartite, then the vertex set of G can be partitioned into V_1 and V_2 with no edge connecting a vertex of V_1 with one in V_2. Then the vertex set of H can be partitioned into $f(V_1)$ and $f(V_2)$ with no edge connecting a vertex in $f(V_1)$ and one in $f(V_2)$. **23.** 3 **25. a)** Yes **b)** No **27.** No **29.** Yes **31.** If e is a cut edge with endpoints u and v, then if we direct e from u to v, there will be no path in the directed graph from v to u, or else e would not have been a cut edge. Similar reasoning works if we direct e from v to u. **33.** $n - 1$ **35.** Let the vertices represent the chickens. We include the edge (u, v) in the graph if and only if chicken u dominates chicken v. **37. a)** 4 **b)** 2 **c)** 3 **d)** 4 **e)** 4 **f)** 2 **39. a)** Suppose that $G = (V, E)$. Let $a, b \in V$. We must show that the distance between a and b in $\overline{G}$ is at most 2. If $\{a, b\} \notin E$ this distance is 1, so assume $\{a, b\} \in E$. Because the diameter of G is greater than 3, there are vertices u and v such that the distance in G between u and v is greater than 3. Either u or v, or both, is not in the set $\{a, b\}$. Assume that u is different from both a and b. Either $\{a, u\}$ or $\{b, u\}$ belongs to E; otherwise a, u, b would be a path in $\overline{G}$ of length 2. So, without loss of generality, assume $\{a, u\} \in E$. Thus v cannot be a or b, and by the same reasoning either $\{a, v\} \in E$ or $\{b, v\} \in E$. In either case, this gives a path of length less than or equal to 3 from

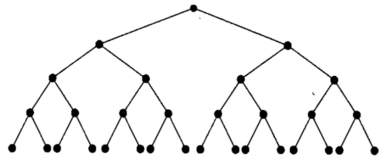
u to v in G, a contradiction. **b)** Suppose $G = (V, E)$. Let $a, b \in V$. We must show that the distance between a and b in $\overline{G}$ does not exceed 3. If $\{a, b\} \notin E$, the result follows, so assume that $\{a, b\} \in E$. Because the diameter of G is greater than or equal to 3, there exist vertices u and v such that the distance in G between u and v is greater than or equal to 3. Either u or v, or both, is not in the set $\{a, b\}$. Assume u is different from both a and b. Either $\{a, u\} \in E$ or $\{b, u\} \in E$; otherwise a, u, b is a path of length 2 in $\overline{G}$. So, without loss of generality, assume $\{a, u\} \in E$. Thus v is different from a and from b. If $\{a, v\} \in E$, then u, a, v is a path of length 2 in G, so $\{a, v\} \notin E$ and thus $\{b, v\} \in E$ (or else there would be a path a, v, b of length 2 in $\overline{G}$). Hence, $\{u, b\} \notin E$; otherwise u, b, v is a path of length 2 in G. Thus, a, v, u, b is a path of length 3 in $\overline{G}$, as desired. **41.** a, b, e, z **43.** a, c, b, d, e, z **45.** If G is planar, then because $e \le 3v - 6$, G has at most 27 edges. (If G is not connected it has even fewer edges.) Similarly, $\overline{G}$ has at most 27 edges. But the union of G and $\overline{G}$ is K_{11}, which has 55 edges, and $55 > 27 + 27$. **47.** Suppose that G is colored with k colors and has independence number i. Because each color class must be an independent set, each color class has no more than i elements. Thus there are at most ki vertices. **49. a)** By Theorem 2 of Section 6.2, the probability of selecting exactly m edges is $C(n, m)p^m(1 - p)^{n-m}$. **b)** By Theorem 2 in Section 6.4, the expected value is np. **c)** To generate a labeled graph G, as we apply the process to pairs of vertices, the random number x chosen must be less than or equal to $1/2$ when G has an edge between that pair of vertices and greater than $1/2$ when G has no edge there. Hence, the probability of making the correct choice is $1/2$ for each edge and $1/2^{C(n,2)}$ overall. Hence, all labeled graphs are equally likely. **51.** Suppose P is monotone increasing. If the property of not having P were not retained whenever edges are removed from a simple graph, there would be a simple graph G not having P and another simple graph G' with the same vertices but with some of the edges of G missing that has P. But P is monotone increasing, so because G' has P, so does G obtained by adding edges to G'. This is a contradiction. The proof of the converse is similar.

CHAPTER 10

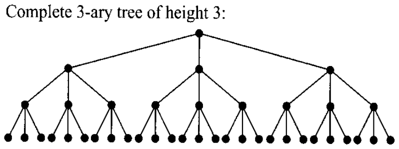
Section 10.1

1. (a), (c), (e) **3. a)** a **b)** $a, b, c, d, f, h, j, q, t$ **c)** $e, g, i, k, l, m, n, o, p, r, s, u$ **d)** q, r **e)** c **f)** p **g)** f, b, a **h)** e, f, l, m, n **5.** No **7.** Level 0: a; level 1: b, c, d; level 2: e through k (in alphabetical order); level 3: l through r; level 4: s, t; level 5: u **9. a)** The entire tree **b)** c, g, h, o, p and the four edges cg, ch, ho, hp **c)** e alone **11. a)** 1 **b)** 2 **13. a)** 3 **b)** 9 **15.** The "only if" part is Theorem 2 and the definition of a tree. Suppose G is a connected simple graph with n vertices and $n - 1$ edges. If G is not a tree, it contains, by Exercise 14, an edge whose removal produces a graph G', which is still connected. If G' is not a tree, remove an edge to produce a connected graph G''. Repeat this procedure until the result is a tree. This requires at most $n - 1$ steps because there are only $n - 1$ edges. By Theorem 2, the resulting graph has $n - 1$ edges because it has n vertices. It follows that no edges were deleted, so G was already a tree. **17.** 9999 **19.** 2000 **21.** 999 **23.** 1,000,000 dollars **25.** No such tree exists by Theorem 4 because it is impossible for $m = 2$ or $m = 84$.

27. Complete binary tree of height 4:

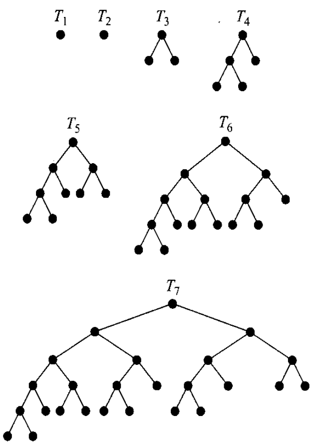


Complete 3-ary tree of height 3:



29. a) By Theorem 3 it follows that $n = mi + 1$. Because $i + l = n$, we have $l = n - i$, so $l = (mi + 1) - i = (m - 1)i + 1$. **b)** We have $n = mi + 1$ and $i + l = n$. Hence, $i = n - l$. It follows that $n = m(n - l) + 1$. Solving for n gives $n = (ml - 1)/(m - 1)$. From $i = n - l$ we obtain $i = [(ml - 1)/(m - 1)] - l = (l - 1)/(m - 1)$. **31.** $n - t$ **33. a)** 1 **b)** 3 **c)** 5 **35. a)** The parent directory **b)** A subdirectory or contained file **c)** A subdirectory or contained file in the same parent directory **d)** All directories in the path name **e)** All subdirectories and files continued in the directory or a subdirectory of this directory, and so on **f)** The length of the path to this directory or file **g)** The depth of the system, i.e., the length of the longest path **37.** Let $n = 2^k$, where k is a positive integer. If $k = 1$, there is nothing to prove because we can add two numbers with $n - 1 = 1$ processor in $\log 2 = 1$ step. Assume we can add $n = 2^k$ numbers in $\log n$ steps using a tree-connected network of $n - 1$ processors. Let $x_1, x_2, \ldots, x_{2n}$ be $2n = 2^{k+1}$ numbers that we wish to add. The tree-connected network of $2n - 1$ processors consists of the tree-connected network of $n - 1$ processors together with two new processors as children of each leaf. In one step we can use the leaves of the larger network to find $x_1 + x_2, x_3 + x_4, \ldots, x_{2n-1} + x_{2n}$, giving us n numbers, which, by the inductive hypothesis, we can add in $\log n$ steps using the rest of the network. Because we have used $\log n + 1$ steps and $\log(2n) = \log 2 + \log n = 1 + \log n$, this completes the proof. **39.** c only **41.** c and h **43.** Suppose a tree T has at least two centers. Let u and v be distinct centers, both with eccentricity e, with u and v not adjacent. Because T is connected, there is a simple path P from u to v. Let c be any other vertex on this path. Because the eccentricity of c is at least e, there is a vertex w such that the unique simple path from c to w has length at least e. Clearly, this path cannot contain both u and v or else there would be a simple circuit. In fact, this path from c to w leaves P and does not return to P once it, possibly, follows part of P toward either u or v. Without loss of generality, assume this path does not follow P toward u. Then the path from u to c to w is simple and of length more than e, a contradiction. Hence, u and v are adjacent. Now because any two centers are adjacent, if there were more than two centers, T would contain K_3, a simple circuit, as a subgraph, which is a contradiction.

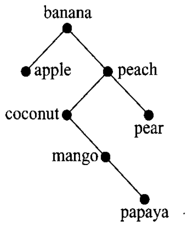
45.



47. The statement is that *every* tree with n vertices has a path of length $n - 1$, and it was shown only that there exists a tree with n vertices having a path of length $n - 1$.

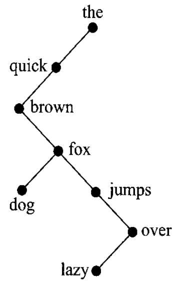
Section 10.2

1.

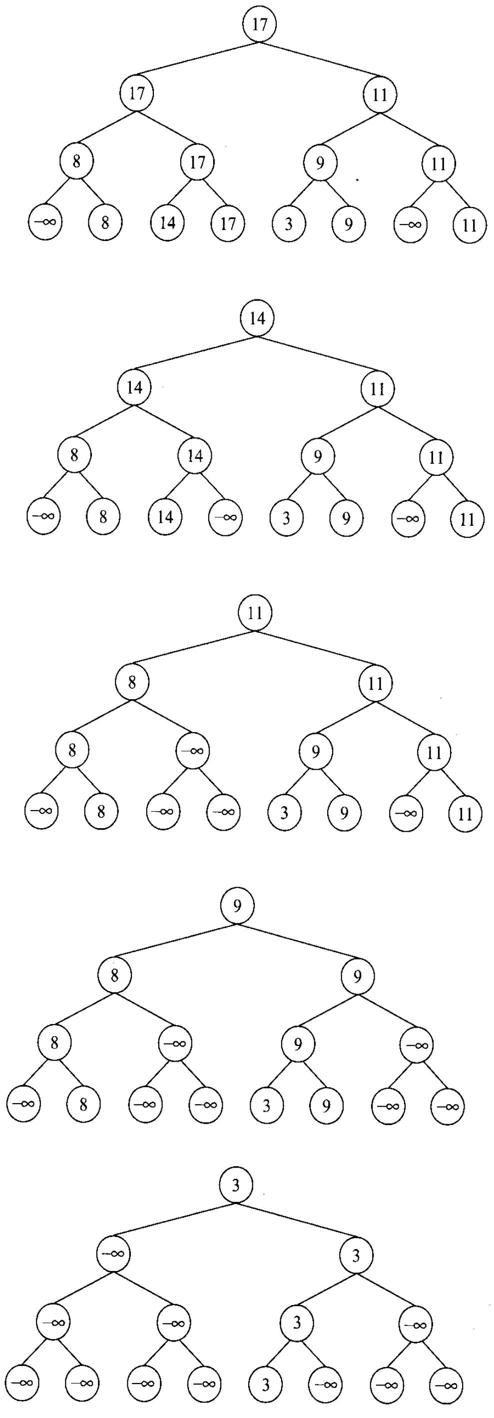


3. a) 3 **b)** 1 **c)** 4 **d)** 5

5.



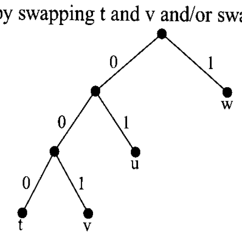
7. At least $\lceil \log_3 4 \rceil = 2$ weighings are needed, because there are only four outcomes (because it is not required to determine whether the coin is lighter or heavier). In fact, two weighings suffice. Begin by weighing coin 1 against coin 2. If they balance, weigh coin 1 against coin 3. If coin 1 and coin 3 are the same weight, coin 4 is the counterfeit coin, and if they are not the same weight, then coin 3 is the counterfeit coin. If coin 1 and coin 2 are not the same weight, again weigh coin 1 against coin 3. If they balance, coin 2 is the counterfeit coin; if they do not balance, coin 1 is the counterfeit coin. **9.** At least $\lceil \log_3 13 \rceil = 3$ weighings are needed. In fact, three weighings suffice. Start by putting coins 1, 2, and 3 on the left-hand side of the balance and coins 4, 5, and 6 on the right-hand side. If equal, apply Example 3 to coins 1, 2, 7, 8, 9, 10, 11, and 12. If unequal, apply Example 3 to 1, 2, 3, 4, 5, 6, 7, and 8. **11.** The least number is five. Call the elements a, b, c, and d. First compare a and b; then compare c and d. Without loss of generality, assume that $a < b$ and $c < d$. Next compare a and c. Whichever is smaller is the smallest element of the set. Again without loss of generality, suppose $a < c$. Finally, compare b with both c and d to completely determine the ordering. **13.** The first two steps are shown in the text. After 22 has been identified as the second largest element, we replace the leaf 22 by $-\infty$ in the tree and recalculate the winner in the path from the leaf where 22 used to be up to the root. Next, we see that 17 is the third largest element, so we repeat the process: replace the leaf 17 by $-\infty$ and recalculate. Next, we see that 14 is the fourth largest element, so we repeat the process: replace the leaf 14 by $-\infty$ and recalculate. Next, we see that 11 is the fifth largest element, so we repeat the process: replace the leaf 11 by $-\infty$ and recalculate. The process continues in this manner. We determine that 9 is the sixth largest element, 8 is the seventh largest element, and 3 is the eighth largest element. The trees produced in all steps, except the second to last, are shown here.



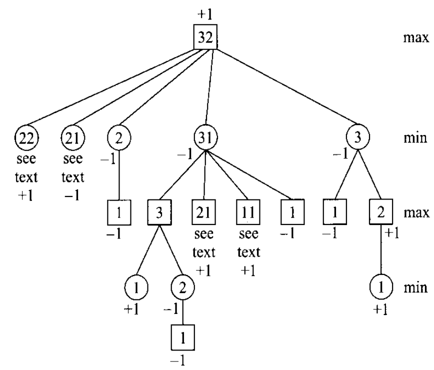
15. The value of a vertex is the list element currently there, and the label is the name (i.e., location) of the leaf responsible for that value.

```
procedure tournament sort(a_1, ..., a_n)
k := ⌈log n⌉
build a binary tree of height k
for i := 1 to n
  set the value of the ith leaf to be a_i and its label to
    be itself
for i := n + 1 to 2^k
  set the value of the ith leaf to be −∞ and its label to
    be itself
for i := k − 1 downto 0
  for each vertex v at level i
    set the value of v to the larger of the values of its
        children and its label to be the label of the child
        with the larger value
for i := 1 to n
begin
  c_i := value at the root
  let v be the label of the root
  set the value of v to be −∞
   while the label at the root is still v
   begin
     v := parent(v)
     set the value of v to the larger of the values of its
       children and its label to be the label of the child
       with the larger value
   end
end {c_1, ..., c_n is the list in nonincreasing order}
```

17. $k-1$, where $n=2^k$ **19. a)** Yes **b)** No **c)** Yes **d)** Yes **21.** a: 000, e: 001, i: 01, k: 1100, o: 1101, p: 11110, u: 11111 **23.** a: 11; b: 101; c: 100; d: 01; e: 00; 2.25 bits (Note: This coding depends on how ties are broken, but the average number of bits is always the same.) **25.** There are four possible answers in all, the one shown here and three more obtained from this one by swapping t and v and/or swapping u and w.

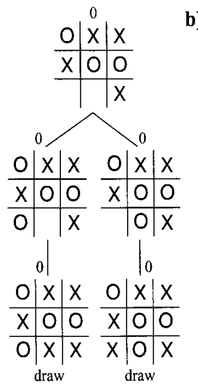


27. A:0001; B:101001; C:11001; D:00000; E:100; F:001100; G:001101; H:0101; I:0100; J:110100101; K:1101000; L:00001; M:10101; N:0110; O:0010; P:101000; Q:1101001000; R:1011; S:0111; T:111; U:00111; V:110101; W:11000; X:11010011; Y:11011; Z:1101001001 **29.** A:2; E:1; N:010; R:011; T:02; Z:00 **31.** n **33.** Because the tree is rather large, we have indicated in some places to "see text." Refer to Figure 9; the subtree rooted at these square or circle vertices is exactly the same as the corresponding subtree in Figure 9. First player wins.

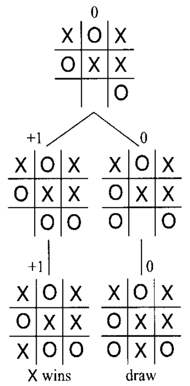


35. a) \$1 **b)** \$3 **c)** −\$3 **37.** See the figures shown next. **a)** 0 **b)** 0 **c)** 1 **d)** This position cannot have occurred in a game; this picture is impossible.

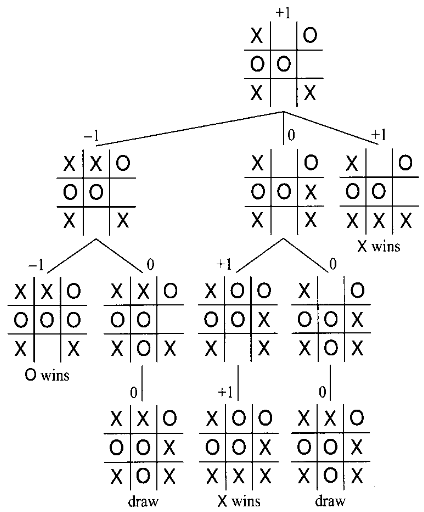
a)



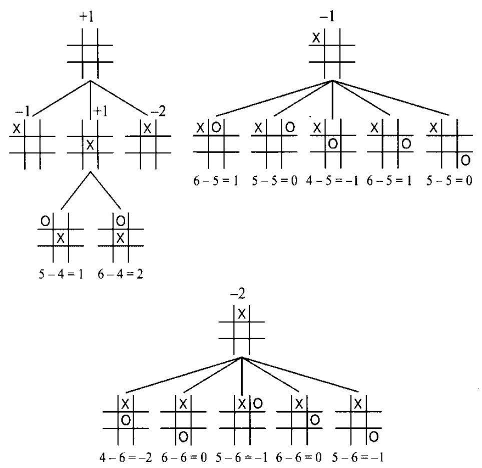
b)



c)

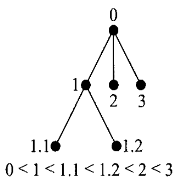


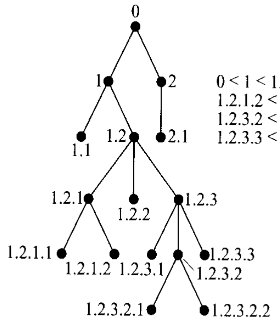
39. Proof by strong induction: *Basis step:* When there are $n = 2$ stones in each pile, if first player takes two stones from a pile, then second player takes one stone from the remaining pile and wins. If first player takes one stone from a pile, then second player takes two stones from the other pile and wins. *Inductive step:* Assume inductive hypothesis that second player can always win if the game starts with two piles of j stones for all $2 \le j \le k$, where $k \ge 2$, and consider a game with two piles containing $k + 1$ stones each. If first player takes all the stones from one of the piles, then second player takes all but one stone from the remaining pile and wins. If first player takes all but one stone from one of the piles, then second player takes all the stones from the other pile and wins. Otherwise first player leaves j stones in one pile, where $2 \le j \le k$, and $k + 1$ stones in the other pile. Second player takes the same number of stones from the larger pile, also leaving j stones there. At this point the game consists of two piles of j stones each. By the inductive hypothesis, the second player in that game, who is also the second player in our actual game, can win, and the proof by strong induction is complete. **41.** 7; 49 **43.** Value of tree is 1. Note: The second and third trees are the subtrees of the two children of the root in the first tree whose subtrees are not shown because of space limitations. They should be thought of as spliced into the first picture.



Section 10.3

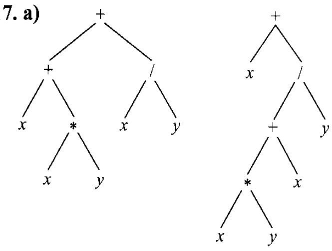
1.



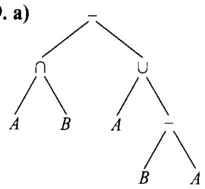
3. 

$0 < 1 < 1.1 < 1.2 < 1.2.1 < 1.2.1.1 < 1.2.1.2 < 1.2.2 < 1.2.3 < 1.2.3.1 < 1.2.3.2 < 1.2.3.2.1 < 1.2.3.2.2 < 1.2.3.3 < 2 < 2.1$

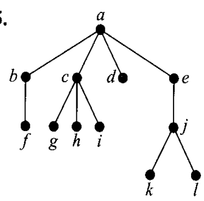
5. No **7.** a, b, d, e, f, g, c **9.** $a, b, e, k, l, m, f, g, n, r, s, c, d, h, o, i, j, p, q$ **11.** $d, b, i, e, m, j, n, o, a, f, c, g, k, h, p, l$ **13.** d, f, g, e, b, c, a **15.** $k, l, m, e, f, r, s, n, g, b, c, o, h, i, p, q, j, d, a$

17. a) 

b) $+ + x * xy/xy$, $+x/ + *xyxy$ **c)** $xxy * +xy/+$, $xxy * x + y/+$ **d)** $((x + (x * y)) + (x/y))$, $(x + (((x * y) + x)/y))$

19. a) 

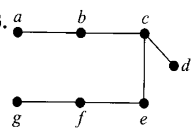
b) $- \cap A B \cup A - B A$ **c)** $A B \cap A B A - \cup -$ **d)** $((A \cap B) - (A \cup (B - A)))$ **21.** 14 **23. a)** 1 **b)** 1 **c)** 4 **d)** 2205

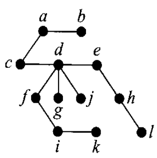
25. 

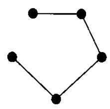
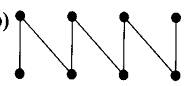
27. Use mathematical induction. The result is trivial for a list with one element. Assume the result is true for a list with n elements. For the inductive step, start at the end. Find the sequence of vertices at the end of the list starting with the last leaf, ending with the root, each vertex being the last child of the one following it. Remove this leaf and apply the inductive hypothesis. **29.** c, d, b, f, g, h, e, a in each case **31.** Proof by mathematical induction. Let $S(X)$ and $O(X)$ represent the number of symbols and number of operators in the well-formed formula X, respectively. The statement is true for well-formed formulae of length 1, because they have 1 symbol and 0 operators. Assume the statement is true for all well-formed formulae of length less than n. A well-formed formula of length n must be of the form $*XY$, where $*$ is an operator and X and Y are well-formed formulae of length less than n. Then by the inductive hypothesis $S(*XY) = S(X) + S(Y) = [O(X) + 1] + [O(Y) + 1] = O(X) + O(Y) + 2$. Because $O(*XY) = 1 + O(X) + O(Y)$, it follows that $S(*XY) = O(*XY) + 1$. **33.** $x\,y + z\,x \circ + x \circ$, $x\,y\,z + + y\,x + +$, $x\,y\,x\,y \circ \circ x\,y \circ \circ z \circ +$, $x\,z \times z\,z + \circ$, $y\,y\,y\,y \circ \circ \circ$, $z\,x + y\,z + \circ$, for instance

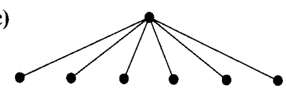
Section 10.4

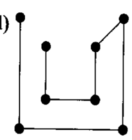
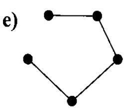
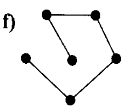
1. $m - n + 1$

3. 

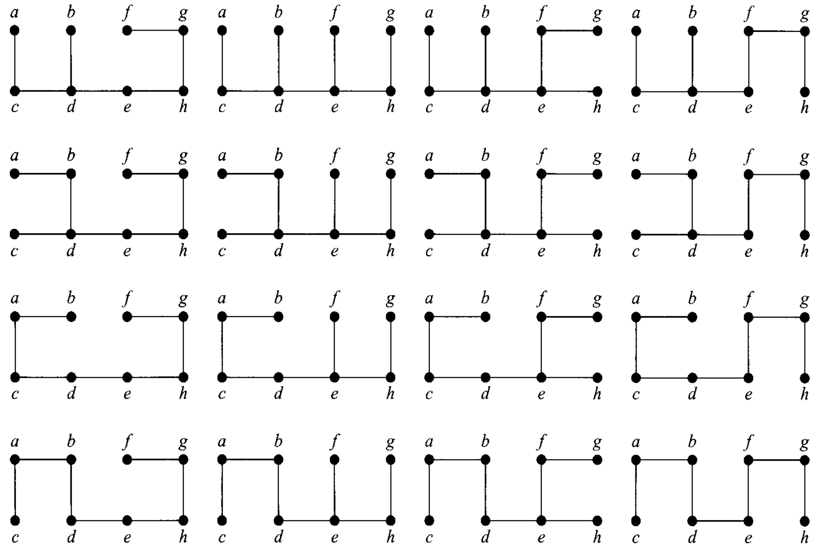
5. 

7. a)  **b)** 

c) 

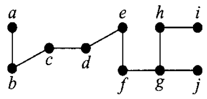
d)  **e)**  **f)** 

9.

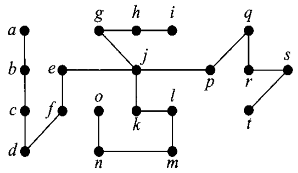


11. a) 3 **b)** 16 **c)** 4 **d)** 5

13.

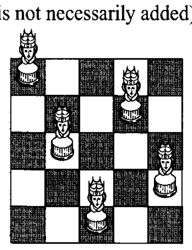


15.

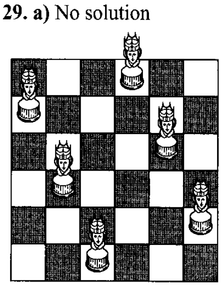


17. a) A path of length 6 **b)** A path of length 5 **c)** A path of length 6 **d)** Depends on order chosen to visit the vertices; may be a path of length 7 **19.** With breadth-first search, the initial vertex is the middle vertex, and the n spokes are added to the tree as this vertex is processed. Thus, the resulting tree is $K_{1,n}$. With depth-first search, we start at the vertex in the middle of the wheel and visit a neighbor—one of the vertices on the rim. From there we move to an adjacent vertex on the rim, and so on all the way around until we have reached every vertex. Thus, the resulting spanning tree is a path of length n. **21.** With breadth-first search, we fan out from a vertex of degree m to all the vertices of degree n as the first step. Next, a vertex of degree n is processed, and the edges from it to all the remaining vertices of degree m are added. The result is a $K_{1,n-1}$ and a $K_{1,m-1}$ with their centers joined by an edge. With depth-first search, we travel back and forth from one partite set to the other until we can go no further. If $m = n$ or $m = n - 1$, then we get a path of length $m + n - 1$. Otherwise, the path ends while some vertices in the larger partite set have not been visited, so we back up one link in the path to a vertex v and then successively visit the remaining vertices in that set from v. The result is a path with extra pendant edges coming out of one end of the path. **23.** A possible set of flights to discontinue are: Boston–New York, Detroit–Boston, Boston–Washington, New York–Washington, New York–Chicago, Atlanta–Washington, Atlanta–Dallas, Atlanta–Los Angeles, Atlanta–St. Louis, St. Louis–Dallas, St. Louis–Detroit, St. Louis–Denver, Dallas–San Diego, Dallas–Los Angeles, Dallas–San Francisco, San Diego–Los Angeles, Los Angeles–San Francisco, San Francisco–Seattle. **25.** Trees **27.** Proof by induction on the length of the path: If the path has length 0, then the result is trivial. If the length is 1, then u is adjacent to v, so u is at level 1 in the breadth-first spanning tree. Assume that the result is true for paths of length l. If the length of a path is $l + 1$, let u' be the next-to-last vertex in a shortest path from v to u. By the inductive hypothesis, u' is at level l in the breadth-first spanning tree. If u were at a level not exceeding l, then clearly the length of the shortest path from v to u would also not exceed l. So u has not been added to the breadth-first spanning tree yet after the vertices of level l have been added. Because u is adjacent to u', it will be added at level $l + 1$ (although the edge connecting u' and u is not necessarily added). **29. a)** No solution

b)

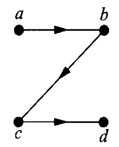


c)

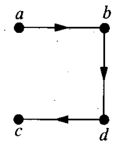


31. Start at a vertex and proceed along a path without repeating vertices as long as possible, allowing the return to the start after all vertices have been visited. When it is impossible to continue along a path, backtrack and try another extension of the current path. **33.** Take the union of the spanning trees of the connected components of G. They are disjoint, so the result is a forest. **35.** $m - n + c$ **37.** Use depth-first search on each component. **39.** If an edge uv is not followed while we are processing vertex u during the depth-first search process, then it must be the case that the vertex v had already been visited. There are two cases. If vertex v was visited after we started processing u, then, because we are not finished processing u yet, v must appear in the subtree rooted at u (and hence, must be a descendant of u). On the other hand, if the processing of v had already begun before we started processing u, then why wasn't this edge followed at that time? It must be that we had not finished processing v, in other words, that we are still forming the subtree rooted at v, so u is a descendant of v, and hence, v is an ancestor of u. **41.** Certainly these two procedures produce the identical spanning trees if the graph we are working with is a tree itself, because in this case there is only one spanning tree (the whole graph). This is the only case in which that happens, however. If the original graph has any other edges, then by Exercise 39 they must be back edges and hence, join a vertex to an ancestor or descendant, whereas by Exercise 40, they must connect vertices at the same level or at levels that differ by 1. Clearly these two possibilities are mutually exclusive. Therefore there can be no edges other than tree edges if the two spanning trees are to be the same. **43.** Because the edges not in the spanning tree are not followed in the process, we can ignore them. Thus we can assume that the graph was a rooted tree to begin with. The basis step is trivial (there is only one vertex), so we assume the inductive hypothesis that breadth-first search applied to trees with n vertices have their vertices visited in order of their level in the tree and consider a tree T with $n + 1$ vertices. The last vertex to be visited during breadth-first search of this tree, say v, is the one that was added last to the list of vertices waiting to be processed. It was added when its parent, say u, was being processed. We must show that v is at the lowest (bottom-most, i.e., numerically greatest) level of the tree. Suppose not; say vertex x, whose parent is vertex w, is at a lower level. Then w is at a lower level than u. Clearly v must be a leaf, because any child of v could not have been seen before v is seen. Consider the tree T' obtained from T by deleting v. By the inductive hypothesis, the vertices in T' must be processed in order of their level in T' (which is the same as their level in T, and the absence of v in T' has no effect on the rest of the algorithm). Therefore u must have been processed before w, and therefore v would have joined the waiting list before x did, a contradiction. Therefore v is at the bottom-most level of the tree, and the proof is complete. **45.** We modify the pseudocode given in Algorithm 2 by initializing m to be 0 at the beginning of the algorithm, and adding the statements "$m := m + 1$" and "assign m to vertex v" after the statement that removes vertex v from L. **47.** If a directed edge uv is not followed while we are processing its tail u during the depth-first search process, then it must be the case that its head v had already been visited. There are three cases. If vertex v was visited after we started processing u, then, because we are not finished processing u yet, v must appear in the subtree rooted at u (and hence, must be a descendant of u), so we have a forward edge. Otherwise, the processing of v must have already begun before we started processing u. If it had not yet finished (i.e., we are still forming the subtree rooted at v), then u is a descendant of v, and hence, v is an ancestor of u (we have a back edge). Finally, if the processing of v had already finished, then by definition we have a cross edge. **49.** Let T be the spanning tree constructed in Figure 3 and T_1, T_2, T_3, and T_4 the spanning trees in Figure 4. Denote by $d(T', T'')$ the distance between T' and T''. Then $d(T, T_1) = 6$, $d(T, T_2) = 4$, $d(T, T_3) = 4$, $d(T, T_4) = 2$, $d(T_1, T_2) = 4$, $d(T_1, T_3) = 4$, $d(T_1, T_4) = 6$, $d(T_2, T_3) = 4$, $d(T_2, T_4) = 2$, and $d(T_3, T_4) = 4$. **51.** Suppose $e_1 = \{u, v\}$ is as specified. Then $T_2 \cup \{e_1\}$ contains a simple circuit C containing e_1. The graph $T_1 - \{e_1\}$ has two connected components; the endpoints of e_1 are in different components. Travel C from u in the direction opposite to e_1 until you come to the first vertex in the same component as v. The edge just crossed is e_2. Clearly, $T_2 \cup \{e_1\} - \{e_2\}$ is a tree, because e_2 was on C. Also $T_1 - \{e_1\} \cup \{e_2\}$ is a tree, because e_2 reunited the two components.

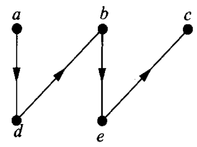
53. Exercise 18:



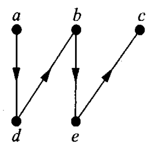
Exercise 19:



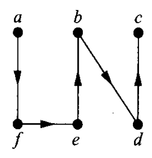
Exercise 20:



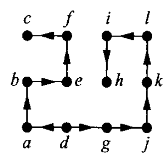
Exercise 21:



Exercise 22:



Exercise 23:

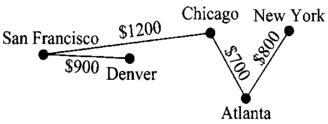


55. First construct an Euler circuit in the directed graph. Then delete from this circuit every edge that goes to a vertex previously visited. **57.** According to Exercise 56, a directed graph contains a circuit if and only if there are any back edges. We can detect back edges as follows. Add a marker on each vertex v to indicate what its status is: not yet seen (the initial situation), seen (i.e., put into T) but not yet finished (i.e., *visit*(v) has not yet terminated), or finished (i.e., *visit*(v) has terminated). A few extra lines in Algorithm 1 will accomplish this bookkeeping. Then to determine whether a directed graph has a circuit, we just have to check when looking at edge uv whether the status of v is "seen." If that ever happens, then we know there is a circuit; if not, then there is no circuit.

Section 10.5

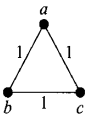
1. Deep Springs–Oasis, Oasis–Dyer, Oasis–Silverspeak, Silverspeak–Goldfield, Lida–Gold Point, Gold Point–Beatty, Lida–Goldfield, Goldfield–Tonopah, Tonopah–Manhattan, Tonopah–Warm Springs **3.** $\{e, f\}, \{c, f\}, \{e, h\}, \{h, i\}, \{b, c\}, \{b, d\}, \{a, d\}, \{g, h\}$

5.



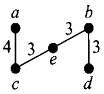
7. $\{e, f\}, \{a, d\}, \{h, i\}, \{b, d\}, \{c, f\}, \{e, h\}, \{b, c\}, \{g, h\}$

9.

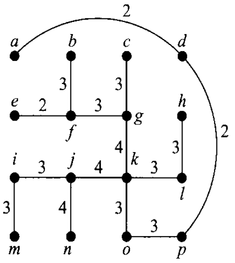


11. Instead of choosing minimum-weight edges at each stage, choose maximum-weight edges at each stage with the same properties.

13.

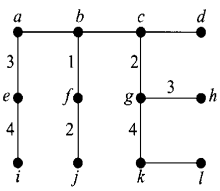


15.



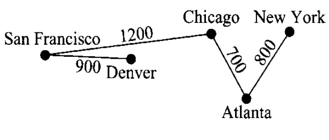
17. First find a minimum spanning tree T of the graph G with n edges. Then for $i = 1$ to $n - 1$, delete only the ith edge of T from G and find a minimum spanning tree of the remaining graph. Pick the one of these $n - 1$ trees with the shortest length. **19.** If all edges have different weights, then a contradiction is obtained in the proof that Prim's algorithm works when an edge e_{k+1} is added to T and an edge e is deleted, instead of possibly producing another spanning tree.

21.

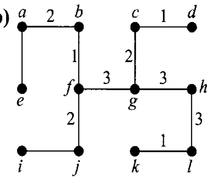


23. Same as Kruskal's algorithm, except start with $T :=$ this set of edges and iterate from $i = 1$ to $i = n - 1 - s$, where s is the number of edges you start with.

25. a)



b)

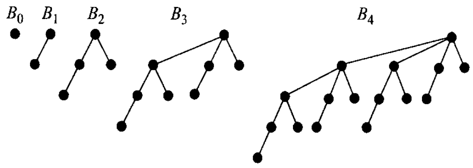


27. By Exercise 24, at each stage of Sollin's algorithm a forest results. Hence, after $n - 1$ edges are chosen, a tree results. It remains to show that this tree is a minimum spanning tree. Let T be a minimum spanning tree with as many edges in common with Sollin's tree S as possible. If $T \neq S$, then there is an edge $e \in S - T$ added at some stage in the algorithm, where prior to that stage all edges in S are also in T. $T \cup \{e\}$ contains a unique simple circuit. Find an edge $e' \in S - T$ and an edge $e'' \in T - S$ on this circuit and "adjacent" when viewing the trees of this stage as "supervertices." Then by the algorithm, $w(e') \leq w(e'')$. So replace T by $T - \{e''\} \cup \{e'\}$ to produce a minimum spanning tree closer to S than T was. **29.** Each of the r trees is joined to at least one other tree by a new edge. Hence, there are at most $r/2$ trees in the result (each new tree contains two or more old trees). To accomplish this, we need to add $r - (r/2) = r/2$ edges. Because the number of edges added is integral, it is at least $\lceil r/2 \rceil$. **31.** If $k \geq \log n$, then $n/2^k \leq 1$, so $\lceil n/2^k \rceil = 1$, so by Exercise 30 the algorithm is finished after at most $\log n$ iterations.

Supplementary Exercises

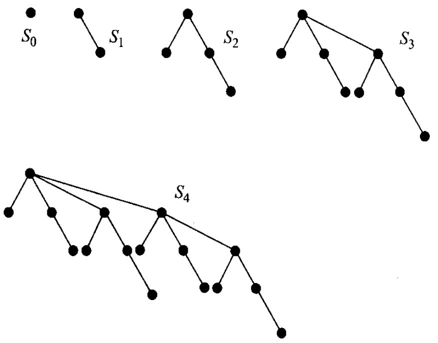
1. Suppose T is a tree. Then clearly T has no simple circuits. If we add an edge e connecting two nonadjacent vertices u and v, then obviously a simple circuit is formed, because when e is added to T the resulting graph has too many edges to be a tree. The only simple circuit formed is made up of the edge e together with the unique path P in T from v to u. Suppose T satisfies the given conditions. All that is needed is to show that T is connected, because there are no simple circuits in the graph. Assume that T is not connected. Then let u and v be in separate connected components. Adding $e = \{u, v\}$ does not satisfy the conditions. **3.** Suppose that a tree T has n vertices of degrees $d_1, d_2, \ldots, d_n$, respectively. Because $2e = \sum_{i=1}^{n} d_i$ and $e = n - 1$, we have $2(n - 1) = \sum_{i=1}^{n} d_i$. Because each $d_i \geq 1$, it follows that $2(n - 1) = n + \sum_{i=1}^{n} (d_i - 1)$, or that $n - 2 = \sum_{i=1}^{n} (d_i - 1)$. Hence, at most $n - 2$ of the terms of this sum can be 1 or more. Hence, at least two of them are 0. It follows that $d_i = 1$ for at least two values of i. **5.** $2n - 2$ **7.** T has no circuits, so it cannot have a subgraph homeomorphic to $K_{3,3}$ or K_5. **9.** Color each connected component separately. For each of these connected components, first root the tree, then color all vertices at even levels red and all vertices at odd levels blue. **11.** Upper bound: k^h; lower bound: $2\lceil k/2 \rceil^{h-1}$

13.



15. Because B_{k+1} is formed from two copies of B_k, one shifted down one level, the height increases by 1 as k increases by 1. Because B_0 had height 0, it follows by induction that B_k has height k. **17.** Because the root of B_{k+1} is the root of B_k with one additional child (namely the root of the other B_k), the degree of the root increases by 1 as k increases by 1. Because B_0 had a root with degree 0, it follows by induction that B_k has a root with degree k.

19.

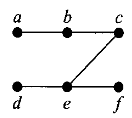


21. Use mathematical induction. The result is trivial for $k = 0$. Suppose it is true for $k-1$. T_{k-1} is the parent tree for T. By induction, the child tree for T can be obtained from $T_0, \ldots, T_{k-2}$ in the manner stated. The final connection of r_{k-2} to r_{k-1} is as stated in the definition of S_k-tree.

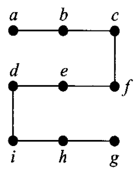
23. **procedure** *level*(T: ordered rooted tree with root r)
queue := sequence consisting of just the root r
while *queue* contains at least one term
begin
v := first vertex in queue
list v
remove v from queue and put children of v onto the end of queue
end

25. Build the tree by inserting a root for the address 0, and then inserting a subtree for each vertex labeled i, for i a positive integer, built up from subtrees for each vertex labeled $i.j$ for j a positive integer, and so on. **27. a)** Yes **b)** No **c)** Yes **29.** The resulting graph has no edge that is in more than one simple circuit of the type described. Hence, it is a cactus.

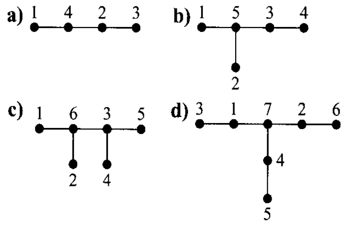
31.



33.



35.



37. 6 **39. a)** 0 for 00, 11 for 01, 100 for 10, 101 for 11 (exact coding depends on how ties were broken, but all versions are equivalent); $0.645n$ for string of length n **b)** 0 for 000, 100 for 001, 101 for 010, 110 for 100, 11100 for 011, 11101 for 101, 11110 for 110, 11111 for 111 (exact coding depends on how ties were broken, but all versions are equivalent); $0.532\overline{6}n$ for string of length n **41.** Let G' be the graph obtained by deleting from G the vertex v and all edges incident to v. A minimum spanning tree of G can be obtained by taking an edge of minimal weight incident to v together with a minimum spanning tree of G'. **43.** Suppose that edge e is the edge of least weight incident to vertex v, and suppose that T is a spanning tree that does not include e. Add e to T, and delete from the simple circuit formed thereby the other edge of the circuit that contains v. The result will be a spanning tree of strictly smaller weight (because the deleted edge has weight greater than the weight of e). This is a contradiction, so T must include e.

CHAPTER 11

Section 11.1

1. a) 1 **b)** 1 **c)** 0 **d)** 0 **3. a)** $(1 \cdot 1) + (\overline{0 \cdot 1} + 0) = 1 + (\overline{0} + 0) = 1 + (1 + 0) = 1 + 1 = 1$
b) $(\mathbf{T} \wedge \mathbf{T}) \vee (\neg(\mathbf{F} \wedge \mathbf{T}) \vee \mathbf{F}) \equiv \mathbf{T}$

5. a)

x	y	z	$\bar{x}y$
1	1	1	0
1	1	0	0
1	0	1	0
1	0	0	0
0	1	1	1
0	1	0	1
0	0	1	0
0	0	0	0

b)

x	y	z	$x + yz$
1	1	1	1
1	1	0	1
1	0	1	1
1	0	0	1
0	1	1	1
0	1	0	0
0	0	1	0
0	0	0	0

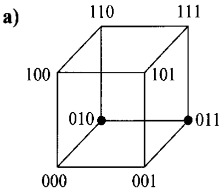
c)

x	y	z	$x\bar{y} + \overline{xyz}$
1	1	1	0
1	1	0	1
1	0	1	1
1	0	0	1
0	1	1	1
0	1	0	1
0	0	1	1
0	0	0	1

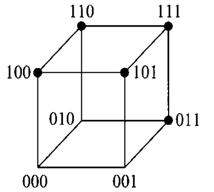
d)

x	y	z	$x(yz + \bar{y}\,\bar{z})$
1	1	1	1
1	1	0	0
1	0	1	0
1	0	0	1
0	1	1	0
0	1	0	0
0	0	1	0
0	0	0	0

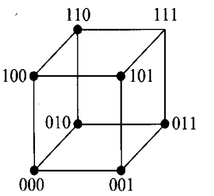
7. a)



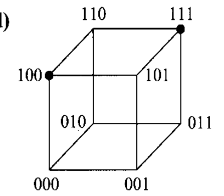
b)



c)



d)



9. (0, 0) and (1, 1) **11.** $x + xy = x \cdot 1 + xy = x(1 + y) = x(y + 1) = x \cdot 1 = x$

13.

x	y	z	$x\overline{y}$	$y\overline{z}$	$\overline{x}z$	$x\overline{y} + y\overline{z} + \overline{x}z$	$\overline{x}y$	$\overline{y}z$	$x\overline{z}$	$\overline{x}y + \overline{y}z + x\overline{z}$
1	1	1	0	0	0	0	0	0	0	0
1	1	0	0	1	0	1	0	0	1	1
1	0	1	1	0	0	1	0	1	0	1
1	0	0	1	0	0	1	0	0	1	1
0	1	1	0	0	1	1	1	0	0	1
0	1	0	0	1	0	1	1	0	0	1
0	0	1	0	0	1	1	0	1	0	1
0	0	0	0	0	0	0	0	0	0	0

15.

x	$x + x$	$x \cdot x$
0	0	0
1	1	1

17.

x	$x + 1$	$x \cdot 0$
0	1	0
1	1	0

19.

x	y	z	$y + z$	$x + (y + z)$	$x + y$	$(x + y) + z$	yz	$x(yz)$	xy	$(xy)z$
1	1	1	1	1	1	1	1	1	1	1
1	1	0	1	1	1	1	0	0	1	0
1	0	1	1	1	1	1	0	0	0	0
1	0	0	0	1	1	1	0	0	0	0
0	1	1	1	1	1	1	1	0	0	0
0	1	0	1	1	1	1	0	0	0	0
0	0	1	1	1	0	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0

21.

x	y	xy	$\overline{(xy)}$	$\overline{x}$	$\overline{y}$	$\overline{x} + \overline{y}$	$x + y$	$\overline{(x + y)}$	$\overline{x}\,\overline{y}$
1	1	1	0	0	0	0	1	0	0
1	0	0	1	0	1	1	1	0	0
0	1	0	1	1	0	1	1	0	0
0	0	0	1	1	1	1	0	1	1

23. $0 \cdot \overline{0} = 0 \cdot 1 = 0$; $1 \cdot \overline{1} = 1 \cdot 0 = 0$

25.

x	y	$x \oplus y$	$x + y$	xy	$\overline{(xy)}$	$(x + y)\overline{(xy)}$	$x\overline{y}$	$\overline{x}y$	$x\overline{y} + \overline{x}y$
1	1	0	1	1	0	0	0	0	0
1	0	1	1	0	1	1	1	0	1
0	1	1	1	0	1	1	0	1	1
0	0	0	0	0	1	0	0	0	0

27. a) True, as a table of values can show **b)** False; take $x = 1, y = 1, z = 1$, for instance **c)** False; take $x = 1, y = 1, z = 0$, for instance **29.** By De Morgan's laws, the complement of an expression is like the dual except that the complement of each variable has been taken. **31.** 16 **33.** If we replace each 0 by **F**, 1 by **T**, Boolean sum by $\vee$, Boolean product by $\wedge$, and $\overline{\ }$ by $\neg$ (and x by p and y by q so that the variables look like they represent propositions, and the equals sign by the logical equivalence symbol), then $\overline{xy} = \overline{x} + \overline{y}$ becomes $\neg(p \wedge q) \equiv \neg p \vee \neg q$ and $\overline{x + y} = \overline{x}\,\overline{y}$ becomes $\neg(p \vee q) \equiv \neg p \wedge \neg q$. **35.** By the domination, distributive, and identity laws, $x \vee x = (x \vee x) \wedge 1 = (x \vee x) \wedge (x \vee \overline{x}) = x \vee (x \wedge \overline{x}) = x \vee 0 = x$. Similarly, $x \wedge x = (x \wedge x) \vee 0 = (x \wedge x) \vee (x \wedge \overline{x}) = x \wedge (x \vee \overline{x}) = x \wedge 1 = x$. **37.** Because $0 \vee 1 = 1$ and $0 \wedge 1 = 0$ by the identity and commutative laws, it follows that $\overline{0} = 1$. Similarly, because $1 \vee 0 = 1$ and $1 \wedge 0 = 1$, it follows that $\overline{1} = 0$. **39.** First, note that $x \wedge 0 = 0$ and $x \vee 1 = 1$ for all x, as can easily be proved. To prove the first identity, it is sufficient to show that $(x \vee y) \vee (\overline{x} \wedge \overline{y}) = 1$ and $(x \vee y) \wedge (\overline{x} \wedge \overline{y}) = 0$. By the associative, commutative, distributive, domination, and identity laws, $(x \vee y) \vee (\overline{x} \wedge \overline{y}) = y \vee [x \vee (\overline{x} \wedge \overline{y})] = y \vee [(x \vee \overline{x}) \wedge (x \vee \overline{y})] = y \vee [1 \wedge (x \vee \overline{y})] = y \vee (x \vee \overline{y}) = (y \vee \overline{y}) \vee x = 1 \vee x = 1$ and $(x \vee y) \wedge (\overline{x} \wedge \overline{y}) = \overline{y} \wedge [\overline{x} \wedge (x \vee y)] = \overline{y} \wedge [(\overline{x} \wedge x) \vee (\overline{x} \wedge y)] = \overline{y} \wedge [0 \vee (\overline{x} \wedge y)] = \overline{y} \wedge (\overline{x} \wedge y) = \overline{x} \wedge (y \wedge \overline{y}) = \overline{x} \wedge 0 = 0$. The second identity is proved in a similar way. **41.** Using the hypotheses, Exercise 35, and the distributive law it follows that $x = x \vee 0 = x \vee (x \vee y) = (x \vee x) \vee y = x \vee y = 0$. Similarly, $y = 0$. To prove the second statement, note that $x = x \wedge 1 = x \wedge (x \wedge y) = (x \wedge x) \wedge y = x \wedge y = 1$. Similarly, $y = 1$. **43.** Use Exercises 39 and 41 in the Supplementary Exercises in Chapter 8 and the definition of a complemented, distributed lattice to establish the five pairs of laws in the definition.

Section 11.2

1. a) $\overline{x}\,\overline{y}z$ **b)** $\overline{x}y\overline{z}$ **c)** $\overline{x}yz$ **d)** $\overline{x}\,\overline{y}\,\overline{z}$ **3. a)** $xyz + xy\overline{z} + x\overline{y}z + x\overline{y}\,\overline{z} + \overline{x}yz + \overline{x}y\overline{z} + \overline{x}\,\overline{y}z$ **b)** $xyz + xy\overline{z} + \overline{x}yz$ **c)** $xyz + xy\overline{z} + x\overline{y}z + x\overline{y}\,\overline{z}$ **d)** $x\overline{y}z + x\overline{y}\,\overline{z}$ **5.** $wxy\overline{z} + wx\overline{y}z + w\overline{x}yz + \overline{w}xyz + \overline{w}x\overline{y}\,\overline{z} + \overline{w}\,\overline{x}\,\overline{y}z + \overline{w}\,\overline{x}y\overline{z} + w\overline{x}\,\overline{y}\,\overline{z}$ **7. a)** $\overline{x} + \overline{y} + z$ **b)** $x + y + z$ **c)** $x + \overline{y} + z$ **9.** $y_1 + y_2 + \cdots + y_n = 0$ if and only if $y_i = 0$ for $i = 1, 2, \ldots, n$. This holds if and only if $x_i = 0$ when $y_i = x_i$ and $x_i = 1$ when $y_i = \overline{x_i}$. **11. a)** $x + y + z$ **b)** $(x + y + z)(x + y + \overline{z})(x + \overline{y} + z)(\overline{x} + y + z)(\overline{x} + y + \overline{z})$ **c)** $(x + y + z)(x + y + \overline{z})(x + \overline{y} + z)(x + \overline{y} + \overline{z})$ **d)** $(x + y + z)(x + y + \overline{z})(x + \overline{y} + z)(x + \overline{y} + \overline{z})(\overline{x} + \overline{y} + z)(\overline{x} + \overline{y} + \overline{z})$

13. a) $x + y + z$ **b)** $x + \overline{[y + \overline{(\overline{x} + z)}]}$ **c)** $\overline{(x + \overline{y})}$ **d)** $\overline{[x + \overline{(\overline{x} + \overline{y} + \overline{z})}]}$

15. a)

x	$\overline{x}$	$x \downarrow x$
1	0	0
0	1	1

b)

x	y	xy	$x \downarrow x$	$y \downarrow y$	$(x \downarrow x) \downarrow (y \downarrow y)$
1	1	1	0	0	1
1	0	0	0	1	0
0	1	0	1	0	0
0	0	0	1	1	0

c)

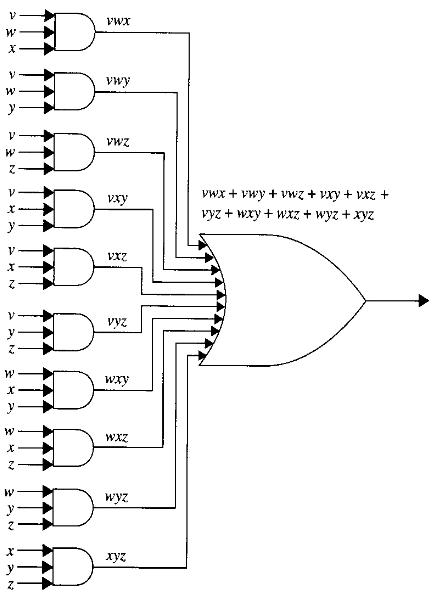
x	y	$x + y$	$(x \downarrow y)$	$(x \downarrow y) \downarrow (x \downarrow y)$
1	1	1	0	1
1	0	1	0	1
0	1	1	0	1
0	0	0	1	0

17. a) $\{[(x \mid x) \mid (y \mid y)] \mid [(x \mid x) \mid (y \mid y)]\} \mid (z \mid z)$ **b)** $\{[(x \mid x) \mid (z \mid z)] \mid y\} \mid \{[(x \mid x) \mid (z \mid z)] \mid y\}$ **c)** x **d)** $[x \mid (y \mid y)] \mid [x \mid (y \mid y)]$ **19.** It is impossible to represent $\overline{x}$ using $+$ and $\cdot$ because there is no way to get the value 0 if the input is 1.

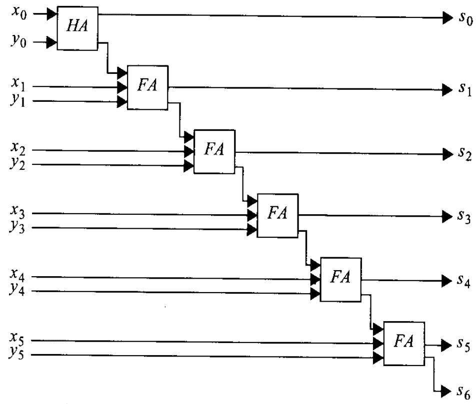
Section 11.3

1. $(x + y)\overline{y}$ **3.** $\overline{(xy)} + (\overline{z} + x)$ **5.** $(x + y + z) + (\overline{x} + y + z) + (\overline{x} + \overline{y} + \overline{z})$

7.

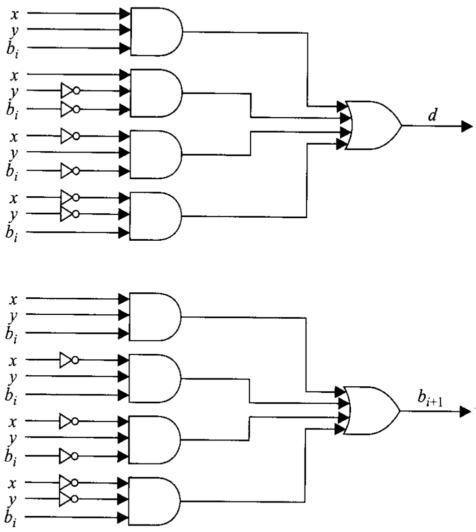


9.

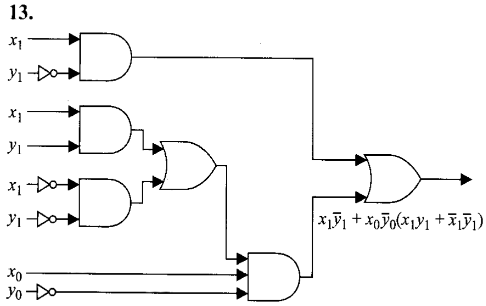


HA = half adder
FA = full adder

11.

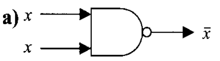


13.

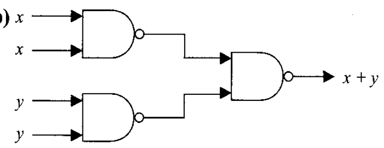


S-74

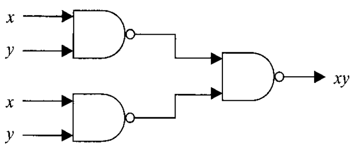
15. a)



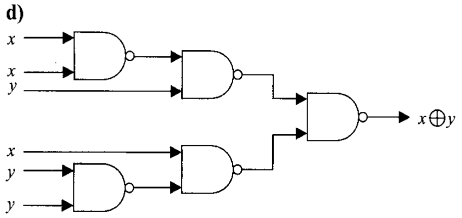
b)



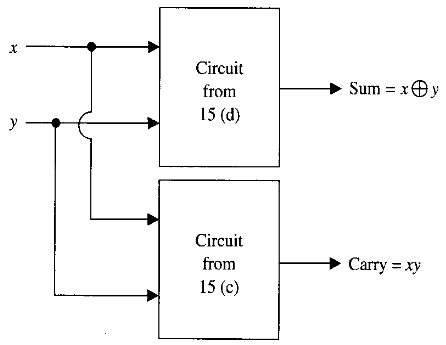
c)



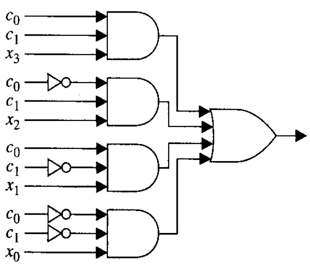
d)



17.



19.



Section 11.4

1. a)

	y	$\bar{y}$
x		
$\bar{x}$	1	

b) xy and $\overline{x}\,\overline{y}$

3. a)

	y	$\bar{y}$
x		1
$\bar{x}$		

b)

	y	$\bar{y}$
x	1	
$\bar{x}$		1

c)

	y	$\bar{y}$
x	1	1
$\bar{x}$	1	1

5. a)

	yz	$y\bar{z}$	$\bar{y}\bar{z}$	$\bar{y}z$
x				
$\bar{x}$		1		

b) $\bar{x}yz, \bar{x}\,\bar{y}\,\bar{z}, xy\bar{z}$

7. a)

	yz	$y\bar{z}$	$\bar{y}\bar{z}$	$\bar{y}z$
x			1	
$\bar{x}$				

b)

	yz	$y\bar{z}$	$\bar{y}\bar{z}$	$\bar{y}z$
x				
$\bar{x}$	1		1	

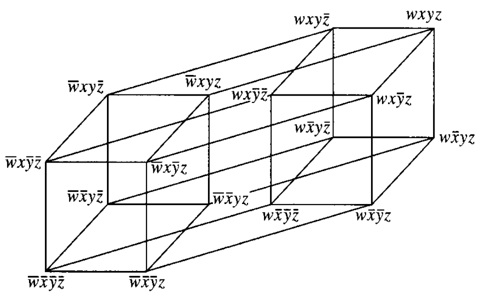
c)

	yz	$y\bar{z}$	$\bar{y}\bar{z}$	$\bar{y}z$
x	1	1		1
$\bar{x}$				1

9. Implicants: xyz, $xy\bar{z}$, $x\,\bar{y}\,\bar{z}$, $\bar{x}y\bar{z}$, xy, $x\bar{z}$, $y\bar{z}$; prime implicants: xy, $x\bar{z}$, $y\bar{z}$; essential prime implicants: xy, $x\bar{z}$, $y\bar{z}$

	yz	$y\bar{z}$	$\bar{y}\bar{z}$	$\bar{y}z$
x	1	1	1	
$\bar{x}$		1		

11. The 3-cube on the right corresponds to w; the 3-cube given by the top surface of the whole figure represents x; the 3-cube given by the back surface of the whole figure represents y; the 3-cube given by the right surfaces of both the left and the right 3-cube represents z. In each case, the opposite 3-face represents the complemented literal. The 2-cube that represents wz is the right face of the 3-cube on the right; the 2-cube that represents $\bar{x}y$ is bottom rear; the 2-cube that represents $\bar{y}\,\bar{z}$ is front left.



13. a)

	yz	$y\bar{z}$	$\bar{y}\bar{z}$	$\bar{y}z$
wx				
$w\bar{x}$				
$\bar{w}\bar{x}$				
$\bar{w}x$		1		

b) $\bar{w}xyz$, $\bar{w}\,\bar{x}yz$, $\bar{w}x\bar{y}\,\bar{z}$, $\bar{w}x\bar{y}\,\bar{z}$

15. a)

	$x_3x_4x_5$	$x_3x_4\bar{x}_5$	$x_3\bar{x}_4\bar{x}_5$	$x_3\bar{x}_4x_5$	$\bar{x}_3\bar{x}_4x_5$	$\bar{x}_3\bar{x}_4\bar{x}_5$	$\bar{x}_3x_4\bar{x}_5$	$\bar{x}_3x_4x_5$
x_1x_2	1	1						
$x_1\bar{x}_2$								
$\bar{x}_1\bar{x}_2$								
$\bar{x}_1x_2$								

b)

	$x_3x_4x_5$	$x_3x_4\bar{x}_5$	$x_3\bar{x}_4\bar{x}_5$	$x_3\bar{x}_4x_5$	$\bar{x}_3\bar{x}_4x_5$	$\bar{x}_3\bar{x}_4\bar{x}_5$	$\bar{x}_3x_4\bar{x}_5$	$\bar{x}_3x_4x_5$
x_1x_2								
$x_1\bar{x}_2$								
$\bar{x}_1\bar{x}_2$	1			1				
$\bar{x}_1x_2$	1			1				

c)

	$x_3x_4x_5$	$x_3x_4\bar{x}_5$	$x_3\bar{x}_4\bar{x}_5$	$x_3\bar{x}_4x_5$	$\bar{x}_3\bar{x}_4x_5$	$\bar{x}_3\bar{x}_4\bar{x}_5$	$\bar{x}_3x_4\bar{x}_5$	$\bar{x}_3x_4x_5$
x_1x_2	1	1					1	1
$x_1\bar{x}_2$								
$\bar{x}_1\bar{x}_2$								
$\bar{x}_1x_2$	1	1					1	1

d)

	$x_3x_4x_5$	$x_3x_4\bar{x}_5$	$x_3\bar{x}_4\bar{x}_5$	$x_3\bar{x}_4x_5$	$\bar{x}_3\bar{x}_4x_5$	$\bar{x}_3\bar{x}_4\bar{x}_5$	$\bar{x}_3x_4\bar{x}_5$	$\bar{x}_3x_4x_5$
x_1x_2					1	1		
$x_1\bar{x}_2$					1	1		
$\bar{x}_1\bar{x}_2$					1	1		
$\bar{x}_1x_2$					1	1		

e)

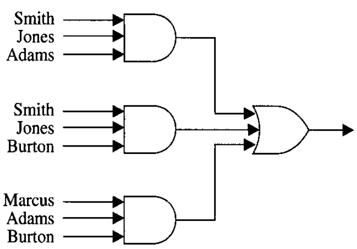
	$x_3x_4x_5$	$x_3x_4\bar{x}_5$	$x_3\bar{x}_4\bar{x}_5$	$x_3\bar{x}_4x_5$	$\bar{x}_3\bar{x}_4x_5$	$\bar{x}_3\bar{x}_4\bar{x}_5$	$\bar{x}_3x_4\bar{x}_5$	$\bar{x}_3x_4x_5$
x_1x_2	1	1	1	1				
$x_1\bar{x}_2$	1	1	1	1				
$\bar{x}_1\bar{x}_2$	1	1	1	1				
$\bar{x}_1x_2$	1	1	1	1				

f)

	$x_3x_4x_5$	$x_3x_4\bar{x}_5$	$x_3\bar{x}_4\bar{x}_5$	$x_3\bar{x}_4x_5$	$\bar{x}_3\bar{x}_4x_5$	$\bar{x}_3\bar{x}_4\bar{x}_5$	$\bar{x}_3x_4\bar{x}_5$	$\bar{x}_3x_4x_5$
x_1x_2		1	1			1	1	
$x_1\bar{x}_2$		1	1			1	1	
$\bar{x}_1\bar{x}_2$		1	1			1	1	
$\bar{x}_1x_2$		1	1			1	1	

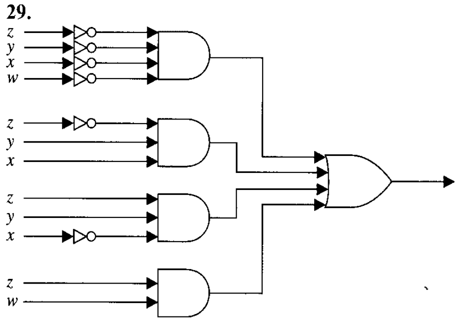
17. a) 64 **b)** 6 **19.** Rows 1 and 4 are considered adjacent. The pairs of columns considered adjacent are: columns 1 and 4, 1 and 12, 1 and 16, 2 and 11, 2 and 15, 3 and 6, 3 and 10, 4 and 9, 5 and 8, 5 and 16, 6 and 15, 7 and 10, 7 and 14, 8 and 13, 9 and 12, 11 and 14, 13 and 16.

21.



23. a) $\bar{x}z$ **b)** y **c)** $x\bar{z} + \bar{x}z + \bar{y}z$ **d)** $xz + \bar{x}y + \bar{y}\bar{z}$ **25. a)** $wxz + wx\bar{y} + w\bar{y}z + w\bar{x}y\bar{z}$ **b)** $x\bar{y}z + \bar{w}\bar{y}z + wxy\bar{z} + w\bar{x}yz + \bar{w}\bar{x}y\bar{z}$ **c)** $\bar{y}z + wxy + w\bar{x}\bar{y} + \bar{w}\bar{x}y\bar{z}$ **d)** $wy + yz + \bar{x}y + wxz + \bar{w}\bar{x}z$ **27.** $x(y + z)$

29.



31. $\bar{x}\bar{z} + xz$ **33.** We use induction on n. If $n = 1$, then we are looking at a line segment, labeled 0 at one end and 1 at the other end. The only possible value of k is also 1, and if the literal is x_1, then the subcube we have is the 0-dimensional subcube consisting of the endpoint labeled 1, and if the literal is $\bar{x}_1$, then the subcube we have is the 0-dimensional subcube consisting of the endpoint labeled 0. Now assume that the statement is true for n; we must show that it is true for $n + 1$. If the literal x_{n+1} (or its complement) is not part of the product, then by the inductive hypothesis, the product when viewed in the setting of n variables corresponds to an $(n - k)$-dimensional subcube of the n-dimensional cube, and the Cartesian product of that subcube with the line segment [0, 1] gives us a subcube one dimension higher in our given $(n + 1)$-dimensional cube, namely having dimension $(n + 1) - k$, as desired. On the other hand, if the literal x_{n+1} (or its complement) is part of the product, then the product of the remaining $k - 1$ literals corresponds to a subcube of dimension $n - (k - 1) = (n + 1) - k$ in the n-dimensional cube, and that slice, at either the 1-end or the 0-end in the last variable, is the desired subcube.

Supplementary Exercises

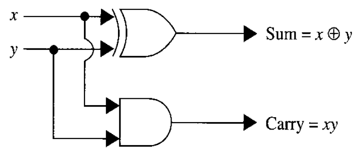
1. a) $x = 0, y = 0, z = 0$; $x = 1, y = 1, z = 1$ **b)** $x = 0, y = 0, z = 0$; $x = 0, y = 0, z = 1$; $x = 0, y = 1, z = 0$; $x = 1, y = 0, z = 1$; $x = 1, y = 1, z = 0$; $x = 1, y = 1, z = 1$ **c)** No values **3. a)** Yes **b)** No **c)** No **d)** Yes **5.** $2^{2^{n-1}}$ **7. a)** If $F(x_1, \ldots, x_n) = 1$, then $(F + G)(x_1, \ldots, x_n) = F(x_1, \ldots, x_n) + G(x_1, \ldots, x_n) = 1$ by the dominance law. Hence, $F \le F + G$. **b)** If $(FG)(x_1, \ldots, x_n) = 1$, then $F(x_1, \ldots, x_n) \cdot G(x_1, \ldots, x_n) = 1$. Hence, $F(x_1, \ldots, x_n) = 1$. It follows that $FG \le F$. **9.** Because $F(x_1, \ldots, x_n) = 1$ implies that $F(x_1, \ldots, x_n) = 1$, $\le$ is reflexive. Suppose that $F \le G$ and $G \le F$. Then $F(x_1, \ldots, x_n) = 1$ if and only if $G(x_1, \ldots, x_n) = 1$. This implies that $F = G$. Hence, $\le$ is antisymmetric. Suppose that $F \le G \le H$. Then if $F(x_1, \ldots, x_n) = 1$, it follows that $G(x_1, \ldots, x_n) = 1$, which implies that $H(x_1, \ldots, x_n) = 1$. Hence, $F \le H$, so that $\le$ is transitive. **11. a)** $x = 1, y = 0, z = 0$ **b)** $x = 1, y = 0, z = 0$ **c)** $x = 1, y = 0, z = 0$

13.

x	y	$x \odot y$	$x \oplus y$	$\overline{(x \oplus y)}$
1	1	1	0	1
1	0	0	1	0
0	1	0	1	0
0	0	1	0	1

15. Yes, as a truth table shows **17. a)** 6 **b)** 5 **c)** 5 **d)** 6

19.



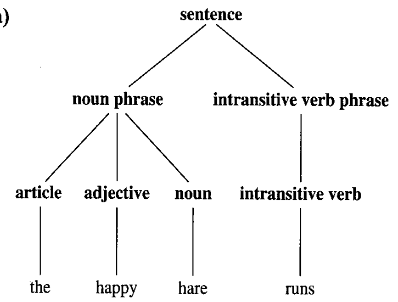
21. $x_3 + x_2\overline{x_1}$ **23.** Suppose it were with weights a and b. Then there would be a real number T such that $xa + yb \geq T$ for (1,0) and (0,1), but with $xa + yb < T$ for (0,0) and (1,1). Hence, $a \geq T, b \geq T, 0 < T$, and $a + b < T$. Thus, a and b are positive, which implies that $a + b > a \geq T$, a contradiction.

CHAPTER 12

Section 12.1

1. a) sentence $\Rightarrow$ **noun phrase intransitive verb phrase** $\Rightarrow$ **article adjective noun intransitive verb phrase** $\Rightarrow$ **article adjective noun intransitive verb** $\Rightarrow \ldots$ (after 3 steps) $\ldots \Rightarrow$ *the happy hare runs.*
b) sentence $\Rightarrow$ **noun phrase intransitive verb phrase** $\Rightarrow$ **article adjective noun intransitive verb phrase** $\Rightarrow$ **article adjective noun intransitive verb adverb**$\ldots$ (after 4 steps)$\ldots \Rightarrow$ *the sleepy tortoise runs quickly*
c) sentence $\Rightarrow$ **noun phrase transitive verb phrase noun phrase** $\Rightarrow$ **article noun transitive verb phrase noun phrase** $\Rightarrow$ **article noun transitive verb noun phrase** $\Rightarrow$ **article noun transitive verb article noun** $\Rightarrow \ldots$(after 4 steps)$\ldots \Rightarrow$ *the tortoise passes the hare*
d) sentence $\Rightarrow$ **noun phrase transitive verb phrase noun phrase** $\Rightarrow$ **article adjective noun transitive verb phrase noun phrase** $\Rightarrow$ **article adjective noun transitive verb noun phrase** $\Rightarrow$ **article adjective noun transitive verb article adjective noun** $\Rightarrow \ldots$(after 6 steps)$\ldots \Rightarrow$ *the sleepy hare passes the happy tortoise*

3. The only way to get a noun, such as *tortoise*, at the end is to have a noun phrase at the end, which can be achieved only via the production **sentence** $\rightarrow$ **noun phrase transitive verb phrase noun phrase**. However, **transitive verb phrase** $\rightarrow$ **transitive verb** $\rightarrow$ *passes*, and this sentence does not contain *passes*.
5. a) $S \Rightarrow 1A \Rightarrow 10B \Rightarrow 101A \Rightarrow 1010B \Rightarrow 10101$ **b)** Because of the productions in this grammar, every 1 must be followed by a 0 unless it occurs at the end of the string. **c)** All strings consisting of a 0 or a 1 followed by one or more repetitions of 01
7. $S \Rightarrow 0S1 \Rightarrow 00S11 \Rightarrow 000S111 \Rightarrow 000111$
9. a) $S \Rightarrow 0S \Rightarrow 00S \Rightarrow 00S1 \Rightarrow 00S11 \Rightarrow 00S111 \Rightarrow 00S1111 \Rightarrow 001111$ **b)** $S \Rightarrow 0S \Rightarrow 00S \Rightarrow 001A \Rightarrow 0011A \Rightarrow 00111A \Rightarrow 001111$ **11.** $S \Rightarrow 0SAB \Rightarrow 00SABAB \Rightarrow 00ABAB \Rightarrow 00AABB \Rightarrow 001ABB \Rightarrow 0011BB \Rightarrow 00112B \Rightarrow 001122$
13. a) $S \rightarrow 0, S \rightarrow 1, S \rightarrow 11$ **b)** $S \rightarrow 1S, S \rightarrow \lambda$ **c)** $S \rightarrow 0A1,\ A \rightarrow 1A,\ A \rightarrow 0A,\ A \rightarrow \lambda$ **d)** $S \rightarrow 0A, A \rightarrow 11A, A \rightarrow \lambda$ **15. a)** $S \rightarrow 00S, S \rightarrow \lambda$ **b)** $S \rightarrow 10A, A \rightarrow 00A, A \rightarrow \lambda$ **c)** $S \rightarrow AAS, S \rightarrow BBS, AB \rightarrow BA, BA \rightarrow AB, S \rightarrow \lambda, A \rightarrow 0, B \rightarrow 1$ **d)** $S \rightarrow 0000000000A, A \rightarrow 0A, A \rightarrow \lambda$ **e)** $S \rightarrow AS, S \rightarrow ABS, S \rightarrow A, AB \rightarrow BA, BA \rightarrow AB, A \rightarrow 0, B \rightarrow 1$ **f)** $S \rightarrow ABS, S \rightarrow \lambda, AB \rightarrow BA, BA \rightarrow AB, A \rightarrow 0, B \rightarrow 1$ **g)** $S \rightarrow ABS, S \rightarrow T, S \rightarrow U, T \rightarrow AT, T \rightarrow A, U \rightarrow BU, U \rightarrow B, AB \rightarrow BA, BA \rightarrow AB, A \rightarrow 0, B \rightarrow 1$ **17. a)** $S \rightarrow 0S, S \rightarrow \lambda$ **b)** $S \rightarrow A0, A \rightarrow 1A, A \rightarrow \lambda$ **c)** $S \rightarrow 000S, S \rightarrow \lambda$ **19. a)** Type 2, not type 3 **b)** Type 3 **c)** Type 0, not type 1 **d)** Type 2, not type 3 **e)** Type 2, not type 3 **f)** Type 0, not type 1 **g)** Type 3 **h)** Type 0, not type 1 **i)** Type 2, not type 3 **j)** Type 2, not type 3 **21.** Let S_1 and S_2 be the start symbols of G_1 and G_2, respectively. Let S be a new start symbol. **a)** Add S and productions $S \rightarrow S_1$ and $S \rightarrow S_2$. **b)** Add S and production $S \rightarrow S_1S_2$. **c)** Add S and production $S \rightarrow \lambda$ and $S \rightarrow S_1S$.
23. a)



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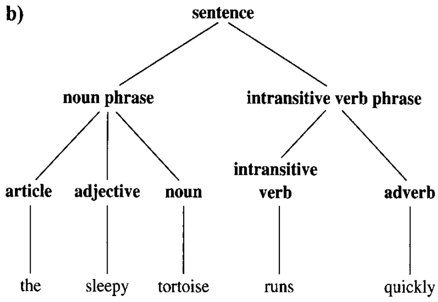
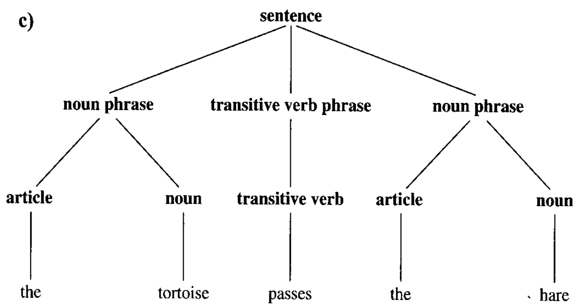
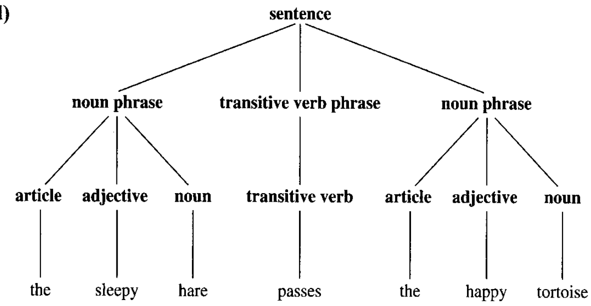
b)



c)

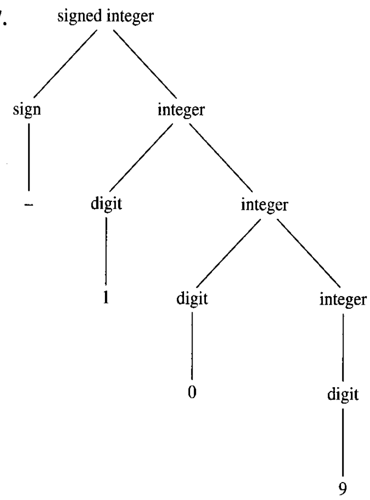


d)



25. a) Yes **b)** No **c)** Yes **d)** No

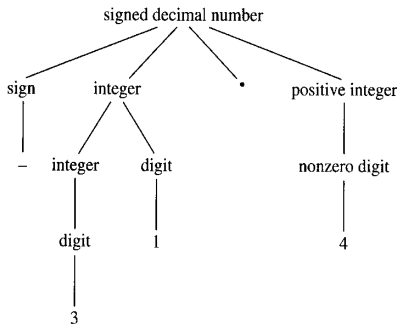
27.



29. a) $S \rightarrow \langle sign \rangle \langle integer \rangle$
$S \rightarrow \langle sign \rangle \langle integer \rangle \,.\, \langle positive\ integer \rangle$
$\langle sign \rangle \rightarrow +$
$\langle sign \rangle \rightarrow -$
$\langle integer \rangle \rightarrow \langle digit \rangle$
$\langle integer \rangle \rightarrow \langle integer \rangle \langle digit \rangle$
$\langle digit \rangle \rightarrow i, i = 1, 2, 3, 4, 5, 6, 7, 8, 9, 0$
$\langle positive\ integer \rangle \rightarrow \langle integer \rangle \langle nonzero\ digit \rangle$
$\langle positive\ integer \rangle \rightarrow \langle nonzero\ digit \rangle \langle integer \rangle$
$\langle positive\ integer \rangle \rightarrow \langle integer \rangle \langle nonzero\ digit \rangle$
$\langle integer \rangle$
$\langle positive\ integer \rangle \rightarrow \langle nonzero\ digit \rangle$
$\langle nonzero\ digit \rangle \rightarrow i, i = 1, 2, 3, 4, 5, 6, 7, 8, 9$

b) $\langle signed\ decimal\ number \rangle ::= \langle sign \rangle \langle integer \rangle \mid$
$\langle sign \rangle \langle integer \rangle \,.\, \langle positive\ integer \rangle$
$\langle sign \rangle ::= + \mid -$
$\langle integer \rangle ::= \langle digit \rangle \mid \langle integer \rangle \langle digit \rangle$
$\langle digit \rangle ::= 0 \mid 1 \mid 2 \mid 3 \mid 4 \mid 5 \mid 6 \mid 7 \mid 8 \mid 9$
$\langle nonzero\ digit \rangle ::= 1 \mid 2 \mid 3 \mid 4 \mid 5 \mid 6 \mid 7 \mid 8 \mid 9$
$\langle positive\ integer \rangle ::= \langle integer \rangle \langle nonzero\ digit \rangle \mid$
$\langle nonzero\ digit \rangle \langle integer \rangle \mid \langle integer \rangle$
$\langle nonzero\ integer \rangle \langle integer \rangle \mid \langle nonzero\ digit \rangle$

c)



31. a) *⟨identifier⟩ ::= ⟨lcletter⟩ | ⟨identifier⟩⟨lcletter⟩*
⟨lcletter⟩ ::= a | b | c | ⋯ | z
b) *⟨identifier⟩ ::= ⟨lcletter⟩⟨lcletter⟩⟨lcletter⟩ | ⟨lcletter⟩⟨lcletter⟩⟨lcletter⟩⟨lcletter⟩ |*
⟨lcletter⟩⟨lcletter⟩⟨lcletter⟩⟨lcletter⟩⟨lcletter⟩ |
⟨lcletter⟩⟨lcletter⟩⟨lcletter⟩⟨lcletter⟩⟨lcletter⟩⟨lcletter⟩
⟨lcletter⟩ ::= a | b | c | ⋯ | z
c) *⟨identifier⟩ ::= ⟨ucletter⟩ | ⟨ucletter⟩⟨letter⟩ | ⟨ucletter⟩⟨letter⟩⟨letter⟩ |*
⟨ucletter⟩⟨letter⟩⟨letter⟩⟨letter⟩ | ⟨ucletter⟩⟨letter⟩⟨letter⟩⟨letter⟩⟨letter⟩ |
⟨ucletter⟩⟨letter⟩⟨letter⟩⟨letter⟩⟨letter⟩⟨letter⟩
⟨letter⟩ ::= ⟨lcletter⟩ | ⟨ucletter⟩
⟨lcletter⟩ ::= a | b | c | ⋯ | z
⟨ucletter⟩ ::= A | B | C | ⋯ | Z
d) *⟨identifier⟩ ::= ⟨lcletter⟩⟨digitorus⟩⟨alphanumeric⟩⟨alphanumeric⟩⟨alphanumeric⟩ |*
⟨lcletter⟩⟨digitorus⟩⟨alphanumeric⟩⟨alphanumeric⟩⟨alphanumeric⟩⟨alphanumeric⟩
⟨digitorus⟩ ::= ⟨digit⟩ | _
⟨alphanumeric⟩ ::= ⟨letter⟩ | ⟨digit⟩
⟨letter⟩ ::= ⟨lcletter⟩ | ⟨ucletter⟩
⟨lcletter⟩ ::= a | b | c | ⋯ | z
⟨ucletter⟩ ::= A | B | C | ⋯ | Z
⟨digit⟩ ::= 0 | 1 | 2 | ⋯ | 9
33. *⟨identifier⟩ ::= ⟨letterorus⟩ | ⟨identifier⟩⟨symbol⟩*
⟨letterorus⟩ ::= ⟨letter⟩ | _
⟨symbol⟩ ::= ⟨letterorus⟩ | ⟨digit⟩
⟨letter⟩ ::= ⟨lcletter⟩ | ⟨ucletter⟩
⟨lcletter⟩ ::= a | b | c | ⋯ | z
⟨ucletter⟩ ::= A | B | C | ⋯ | Z
⟨digit⟩ ::= 0 | 1 | 2 | ⋯ | 9
35. *numeral ::= sign? nonzerodigit digit∗ decimal? | sign?* 0 *decimal?*
sign ::= + | −
nonzerodigit ::= 1 | 2 | ⋯ | 9
digit ::= 0 | *nonzerodigit*
decimal ::= .digit∗
37. *identifier ::= letterorus symbol∗*
letterorus ::= letter | _
symbol ::= letterorus | digit
letter ::= lcletter | ucletter
lcletter ::= a | b | c | ⋯ | z
ucletter ::= A | B | C | ⋯ | Z
digit ::= 0 | 1 | 2 | ⋯ | 9

39. a) ⟨*expression*⟩
⟨*term*⟩⟨*term*⟩⟨*addOperator*⟩
⟨*factor*⟩⟨*factor*⟩⟨*factor*⟩⟨*mulOperator*⟩⟨*addOperator*⟩
⟨*identifier*⟩⟨*identifier*⟩⟨*identifier*⟩⟨*mulOperator*⟩⟨*addOperator*⟩
$a\ b\ c * +$

b) Not generated

c) ⟨*expression*⟩
⟨*term*⟩
⟨*factor*⟩⟨*factor*⟩⟨*mulOperator*⟩
⟨*expression*⟩⟨*factor*⟩⟨*mulOperator*⟩
⟨*term*⟩⟨*term*⟩⟨*addOperator*⟩⟨*factor*⟩⟨*mulOperator*⟩
⟨*factor*⟩⟨*factor*⟩⟨*addOperator*⟩⟨*factor*⟩⟨*mulOperator*⟩
⟨*identifier*⟩⟨*identifier*⟩⟨*addOperator*⟩⟨*identifier*⟩⟨*mulOperator*⟩
$x\ y - z *$

d) ⟨*expression*⟩
⟨*term*⟩
⟨*factor*⟩⟨*factor*⟩⟨*mulOperator*⟩
⟨*factor*⟩⟨*expression*⟩⟨*mulOperator*⟩
⟨*factor*⟩⟨*term*⟩⟨*mulOperator*⟩
⟨*factor*⟩⟨*factor*⟩⟨*factor*⟩⟨*mulOperator*⟩⟨*mulOperator*⟩
⟨*factor*⟩⟨*factor*⟩⟨*expression*⟩⟨*mulOperator*⟩⟨*mulOperator*⟩
⟨*factor*⟩⟨*factor*⟩⟨*term*⟩⟨*term*⟩⟨*addOperator*⟩⟨*mulOperator*⟩⟨*mulOperator*⟩
⟨*factor*⟩⟨*factor*⟩⟨*factor*⟩⟨*factor*⟩⟨*addOperator*⟩⟨*mulOperator*⟩⟨*mulOperator*⟩
⟨*identifier*⟩⟨*identifier*⟩⟨*identifier*⟩⟨*identifier*⟩⟨*addOperator*⟩⟨*mulOperator*⟩⟨*mulOperator*⟩
$w\ x\ y\ z - * /$

e) ⟨*expression*⟩
⟨*term*⟩
⟨*factor*⟩⟨*factor*⟩⟨*mulOperator*⟩
⟨*factor*⟩⟨*expression*⟩⟨*mulOperator*⟩
⟨*factor*⟩⟨*term*⟩⟨*term*⟩⟨*addOperator*⟩⟨*mulOperator*⟩
⟨*factor*⟩⟨*factor*⟩⟨*factor*⟩⟨*addOperator*⟩⟨*mulOperator*⟩
⟨*identifier*⟩⟨*identifier*⟩⟨*identifier*⟩⟨*addOperator*⟩⟨*mulOperator*⟩
$a\ d\ e - *$

41. a) Not generated

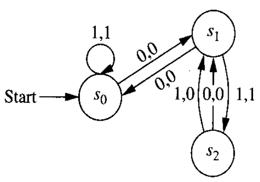
b) ⟨*expression*⟩
⟨*term*⟩⟨*addOperator*⟩⟨*term*⟩
⟨*factor*⟩⟨*mulOperator*⟩⟨*factor*⟩⟨*addOperator*⟩⟨*factor*⟩⟨*mulOperator*⟩⟨*factor*⟩
⟨*identifier*⟩⟨*mulOperator*⟩⟨*identifier*⟩⟨*addOperator*⟩⟨*identifier*⟩⟨*mulOperator*⟩⟨*identifier*⟩
$a/b + c/d$

c) ⟨*expression*⟩
⟨*term*⟩
⟨*factor*⟩⟨*mulOperator*⟩⟨*factor*⟩
⟨*factor*⟩⟨*mulOperator*⟩(⟨*expression*⟩)
⟨*factor*⟩⟨*mulOperator*⟩(⟨*term*⟩⟨*addOperator*⟩⟨*term*⟩)
⟨*factor*⟩⟨*mulOperator*⟩(⟨*factor*⟩⟨*addOperator*⟩⟨*factor*⟩)
⟨*identifier*⟩⟨*mulOperator*⟩(⟨*identifier*⟩⟨*addOperator*⟩⟨*identifier*⟩)
$m * (n + p)$

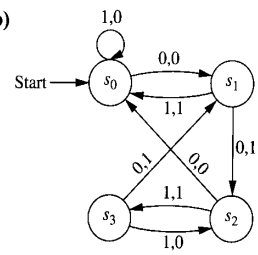
d) Not generated
e) ⟨*expression*⟩
⟨*term*⟩
⟨*factor*⟩ ⟨*mulOperator*⟩ ⟨*factor*⟩
(⟨*expression*⟩)⟨*mulOperator*⟩(⟨*expression*⟩)
(⟨*term*⟩ ⟨*addOperator*⟩ ⟨*term*⟩)⟨*mulOperator*⟩(⟨*term*⟩ ⟨*addOperator*⟩ ⟨*term*⟩)
(⟨*factor*⟩ ⟨*addOperator*⟩ ⟨*factor*⟩)⟨*mulOperator*⟩(⟨*factor*⟩ ⟨*addOperator*⟩ ⟨*factor*⟩)
(⟨*identifier*⟩ ⟨*addOperator*⟩ ⟨*identifier*⟩)⟨*mulOperator*⟩(⟨*identifier*⟩ ⟨*addOperator*⟩ ⟨*identifier*⟩)
$(m+n)*(p-q)$

Section 12.2

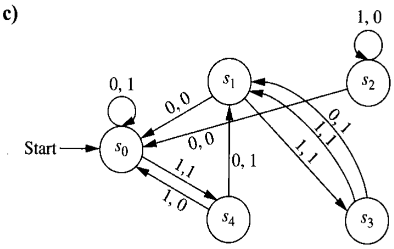
1. a)



b)

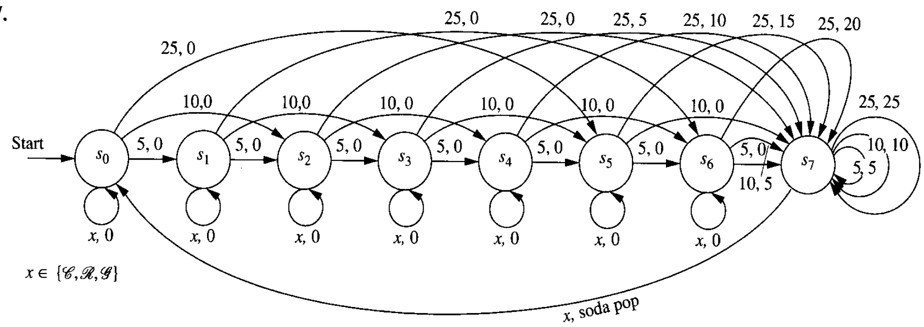


c)



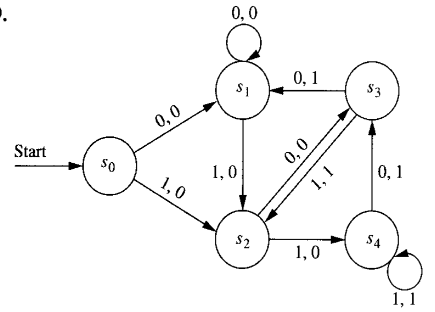
3. a) 01010 **b)** 01000 **c)** 11011 **5. a)** 1100 **b)** 00110110 **c)** 11111111111

7.

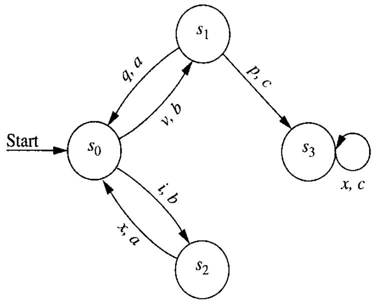


𝒞 = cola
ℛ = root beer
𝒢 = ginger ale

9.

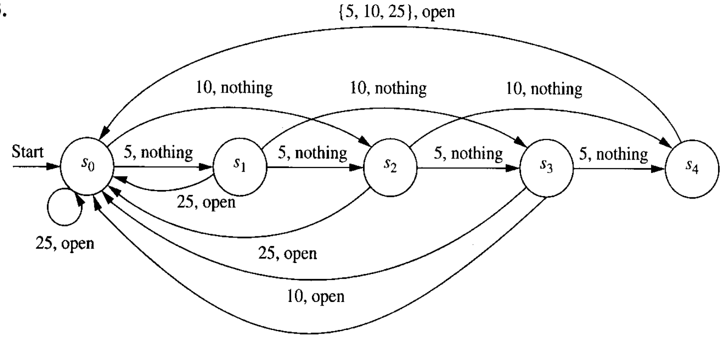


11.



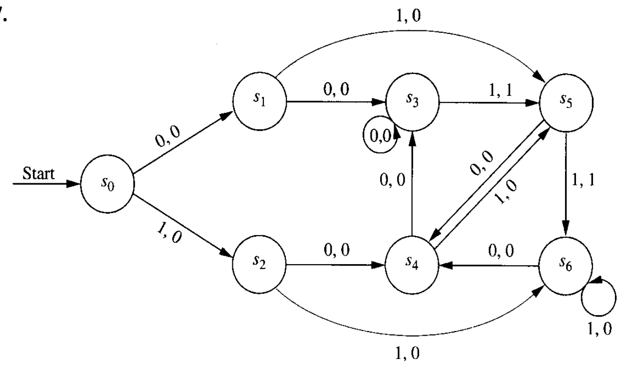
v = Valid ID a = "Enter user ID"
i = Invalid ID b = "Enter password"
p = Valid password c = Prompt
q = Invalid password x = Any input

13.

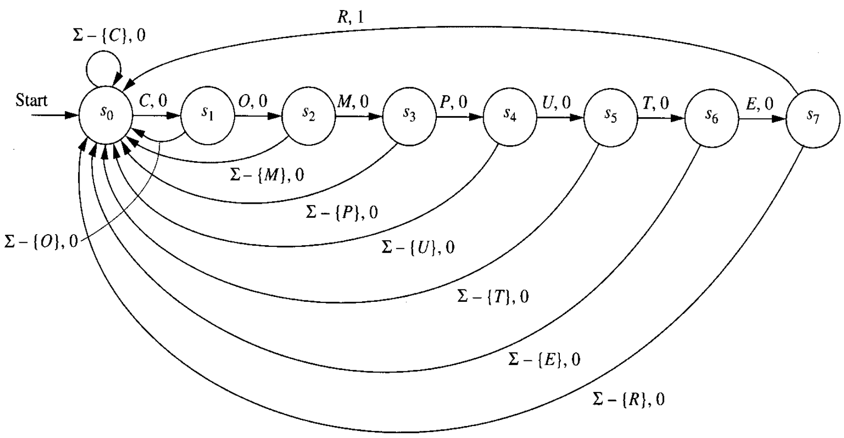


15. Let s_0 be the start state and let s_1 be the state representing a successful call. From s_0, inputs of 2, 3, 4, 5, 6, 7, or 8 send the machine back to s_0 with output of an error message for the user. From s_0 an input of 0 sends the machine to state s_1, with the output being that the 0 is sent to the network. From s_0 an input of 9 sends the machine to state s_2 with no output; from there an input of 1 sends the machine to state s_3 with no output; from there an input of 1 sends the machine to state s_1 with the output being that the 911 is sent to the network. All other inputs while in states s_2 or s_3 send the machine back to s_0 with output of an error message for the user. From s_0 an input of 1 sends the machine to state s_4 with no output; from s_4 an input of 2 sends the machine to state s_5 with no output; and this path continues in a similar manner to the 911 path, looking next for 1, then 2, then any seven digits, at which point the machine goes to state s_1 with the output being that the ten-digit input is sent to the network. Any "incorrect" input while in states s_5 or s_6 (that is, anything except a 1 while in s_5 or a 2 while in s_6) sends the machine back to s_0 with output of an error message for the user. Similarly, from s_4 an input of 8 followed by appropriate successors drives us eventually to s_1, but inappropriate outputs drive us back to s_0 with an error message. Also, inputs while in state s_4 other than 2 or 8 send the machine back to state s_0 with output of an error message for the user.

17.



19.

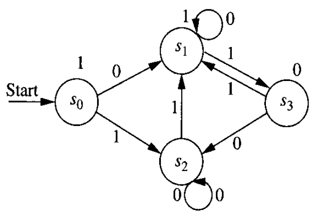


21.

	f		
	Input		
State	**0**	**1**	***g***
s_0	s_1	s_2	1
s_1	s_1	s_0	1
s_2	s_1	s_2	0

23. a) 11111
b) 1000000
c) 100011001100

25.



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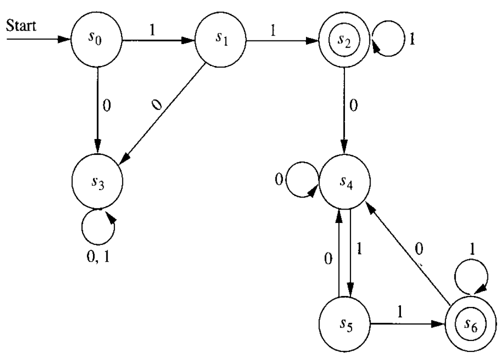
Section 12.3

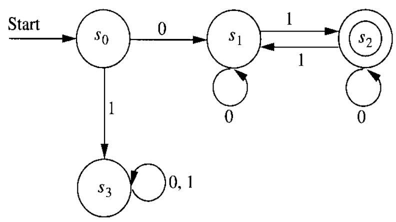
1. a) $\{000, 001, 1100, 1101\}$ **b)** $\{000, 0011, 010, 0111\}$ **c)** $\{00, 011, 110, 1111\}$ **d)** $\{000000, 000001, 000100, 000101, 010000, 010001, 010100, 010101\}$ **3.** $A = \{1, 101\}$, $B = \{0, 11, 000\}$; $A = \{10, 111, 1010, 1000, 10111, 101000\}$, $B = \{\lambda\}$; $A = \{\lambda, 10\}$, $B = \{10, 111, 1000\}$ or $A = \{\lambda\}$, $B = \{10, 111, 1010, 1000, 10111, 101000\}$ **5. a)** The set of strings consisting of zero or more consecutive bit pairs 10 **b)** The set of strings consisting of all 1s such that the number of 1s is divisible by 3, including the null string **c)** The set of strings in which every 1 is immediately preceded by a 0 **d)** The set of strings that begin and end with a 1 and have at least two 1s between every pair of 0s **7.** A string is in A^* if and only if it is a concatenation of an arbitrary number of strings in A. Because each string in A is also in B, it follows that a string in A^* is also a concatenation of strings in B. Hence, $A^* \subseteq B^*$. **9. a)** Yes **b)** Yes **c)** No **d)** No **e)** Yes **f)** Yes **11. a)** Yes **b)** No **c)** Yes **d)** No **13. a)** Yes **b)** Yes **c)** No **d)** No **e)** No **f)** No **15.** We use structural induction on the input string y. The basis step considers $y = \lambda$, and for the inductive step we write $y = wa$, where $w \in I^*$ and $a \in I$. For the basis step, we have $xy = x$, so we must show that $f(s, x) = f(f(s, x), \lambda)$. But part (*i*) of the definition of the extended transition function says that this is true. We then assume the inductive hypothesis that the equation holds for w and prove that $f(s, xwa) = f(f(s, x), wa)$. By part (*ii*) of the definition, the left-hand side of this equation equals $f(f(s, xw), a)$. By the inductive hypothesis, $f(s, xw) = f(f(s, x), w)$, so $f(f(s, xw), a) = f(f(f(s, x), w), a)$. The right-hand side of our desired equality is, by part (*ii*) of the definition, also equal to $f(f(f(s, x), w), a)$, as desired. **17.** $\{0, 10, 11\}\{0, 1\}^*$ **19.** $\{0^m 1^n \mid m \geq 0 \text{ and } n \geq 1\}$ **21.** $\{\lambda\} \cup \{0\}\{1\}^*\{0\} \cup \{10, 11\}\{0, 1\}^* \cup \{0\}\{1\}^*\{01\}\{0, 1\}^* \cup \{0\}\{1\}^*\{00\}\{0\}^*\{1\}\{0, 1\}^*$ **23.** Let s_2 be the only final state, and put transitions from s_2 to itself on either input. Put a transition from the start state s_0 to s_1 on input 0, and a transition from s_1 to s_2 on input 1. Create state s_3, and have the other transitions from s_0 and s_1 (as well as both transitions from s_3) lead to s_3. **25.** Start state s_0, only final state s_3; transitions from s_0 to s_0 on 0, from s_0 to s_1 on 1, from s_1 to s_2 on 0, from s_1 to s_1 on 1, from s_2 to s_0 on 0, from s_2 to s_3 on 1, from s_3 to s_3 on 0, from s_3 to s_3 on 1 **27.** Have five states, with only s_3 final. For $i = 0, 1, 2, 3$, transition from s_i to itself on input 1 and to s_{i+1} on input 0. Both transitions from s_4 are to itself. **29.** Have four states, with only s_3 final. For $i = 0, 1, 2$, transition from s_i to s_{i+1} on input 1 but back to s_0 on input 0. Both transitions from s_3 are to itself.

31.



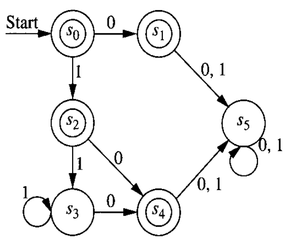
33. Start state s_0, only final state s_1; transitions from s_0 to s_0 on 1, from s_0 to s_1 on 0, from s_1 to s_1 on 1; from s_1 to s_0 on 0

35.



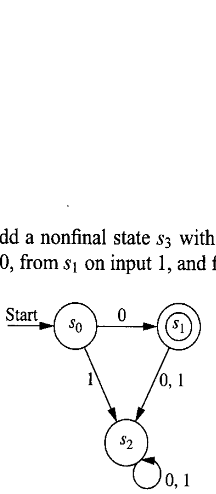
37. Suppose that such a machine exists, with start state s_0 and other state s_1. Because the empty string is not in the language but some strings are accepted, we must have s_1 as the only final state, with at least one transition from s_0 to s_1. Because the string 0 is not in the language, the transition from s_0 on input 0 must be to itself, so the transition from s_0 on input 1 must be to s_1. But this contradicts the fact that 1 is not in the language. **39.** Change each final state to a nonfinal state and vice versa. **41.** Same machine as in Exercise 25, but with s_0, s_1, and s_2 as the final states **43.** $\{0, 01, 11\}$ **45.** $\{\lambda, 0\} \cup \{0^m 1^n \mid m \geq 1, n \geq 1\}$ **47.** $\{10^n \mid n \geq 0\} \cup \{10^n 10^m \mid n, m \geq 0\}$ **49.** The union of the set of all strings that start with a 0 and the set of all strings that have no 0s

51.

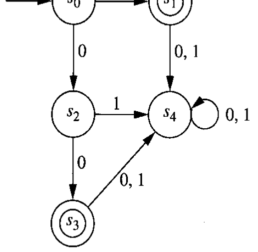


53. Add a nonfinal state s_3 with transitions to s_3 from s_0 on input 0, from s_1 on input 1, and from s_3 on input 0 or 1.

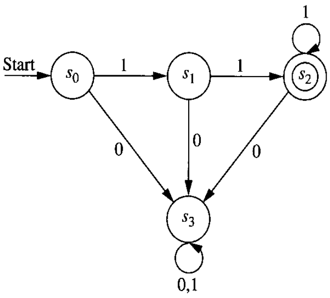
55. a)



b)



c)

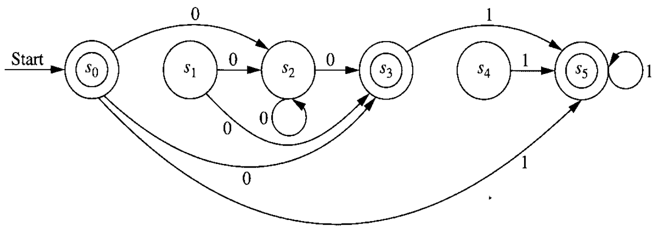


57. Suppose that M is a finite-state automaton that accepts the set of bit strings containing an equal number of 0s and 1s. Suppose M has n states. Consider the string $0^{n+1}1^{n+1}$. By the pigeonhole principle, as M processes this string, it must encounter the same state more than once as it reads the first $n+1$ 0s; so let s be a state it hits at least twice. Then k 0s in the input takes M from state s back to itself for some positive integer k. But then M ends up exactly at the same place after reading $0^{n+1+k}1^{n+1}$ as it will after reading $0^{n+1}1^{n+1}$. Therefore, because M accepts $0^{n+1}1^{n+1}$ it also accepts $0^{n+k+1}1^{n+1}$, which is a contradiction. **59.** We know from Exercise 58d that the equivalence classes of R_k are a refinement of the equivalence classes of R_{k-1} for each positive integer k. The equivalence classes are finite sets, and finite sets cannot be refined indefinitely (the most refined they can be is for each equivalence class to contain just one state). Therefore this sequence of refinements must remain unchanged from some point onward. It remains to show that as soon as we have $R_n = R_{n+1}$, then $R_n = R_m$ for all $m > n$, from which it follows that $R_n = R_*$, and so the equivalence classes for these two relations will be the same. By induction, it suffices to show that if $R_n = R_{n+1}$, then $R_{n+1} = R_{n+2}$. Suppose that $R_{n+1} \neq R_{n+2}$. This means that there are states s and t that are $(n+1)$-equivalent but not $(n+2)$-equivalent. Thus there is a string x of length $n+2$ such that, say, $f(s,x)$ is final but $f(t,x)$ is nonfinal. Write $x = aw$, where $a \in I$. Then $f(s,a)$ and $f(t,a)$ are not $(n+1)$-equivalent, because w drives the first to a final state and the second to a nonfinal state. But $f(s,a)$ and $f(t,a)$ are n-equivalent, because s and t are $(n+1)$-equivalent. This contradicts the fact that $R_n = R_{n+1}$. **61. a)** By the way the machine $\overline{M}$ was constructed, a string will drive M from the start state to a final state if and only if that string drives $\overline{M}$ from the start state to a final state. **b)** For a proof of this theorem, see a source such as *Introduction to Automata Theory, Languages, and Computation* (2nd Edition) by John E. Hopcroft, Rajeev Motwani, and Jeffrey D. Ullman (Addison-Wesley, 2000).

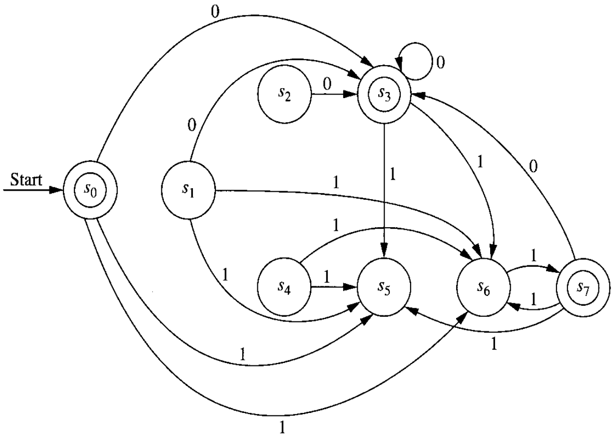
Section 12.4

1. a) Any number of 1s followed by a 0 **b)** Any number of 1s followed by one or more 0s **c)** 111 or 001 **d)** A string of any number of 1s or 00s or some of each in a row **e)** λ or a string that ends with a 1 and has one or more 0s before each 1 **f)** A string of length at least 3 that ends with 00 **3. a)** No **b)** No **c)** Yes **d)** Yes **e)** Yes **f)** No **g)** No **h)** Yes **5. a)** $\mathbf{0 \cup 11 \cup 010}$ **b)** $\mathbf{000000^*}$ **c)** $\mathbf{(0 \cup 1)((0 \cup 1)(0 \cup 1))^*}$ **d)** $\mathbf{0^*10^*}$ **e)** $\mathbf{(1 \cup 01 \cup 001)^*}$ **7. a)** $\mathbf{00^*1}$ **b)** $\mathbf{(0 \cup 1)(0 \cup 1)(0 \cup 1)^*0000^*}$ **c)** $\mathbf{0^*1^* \cup 1^*0^*}$ **d)** $\mathbf{11(111)^*(00)^*}$ **9. a)** Have the start state s_0, nonfinal, with no transitions. **b)** Have the start state s_0, final, with no transitions. **c)** Have the nonfinal start state s_0 and a final state s_1 and the transition from s_0 to s_1 on input a. **11.** Use an inductive proof. If the regular expression for A is $\emptyset$, λ, or x, the result is trivial. Otherwise, suppose the regular expression for A is **BC**. Then $A = BC$ where B is the set generated by **B** and C is the set generated by **C**. By the inductive hypothesis there are regular expressions **B**$'$ and **C**$'$ that generate B^R and C^R, respectively. Because $A^R = (BC)^R = C^R B^R$, **C**$'$**B**$'$ is a regular expression for A^R. If the regular expression for A is $\mathbf{B \cup C}$, then the regular expression for A is $\mathbf{B' \cup C'}$ because $(B \cup C)^R = (B^R) \cup (C^R)$. Finally, if the regular expression for A is $\mathbf{B^*}$, then it is easy to see that $\mathbf{(B')^*}$ is a regular expression for A^R.

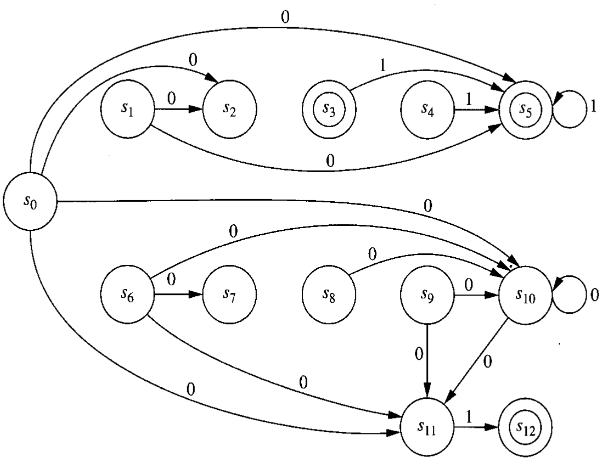
13. a)


Start
s_0
s_1
s_2
s_3
s_4
s_5
0
1

b)


Start
s_0
s_1
s_2
s_3
s_4
s_5
s_6
s_7
0
1

c)


s_0
s_1
s_2
s_3
s_4
s_5
s_6
s_7
s_8
s_9
s_{10}
s_{11}
s_{12}
0
1

15. $S \to 0A$, $S \to 1B$, $S \to 0$, $A \to 0B$, $A \to 1B$, $B \to 0B$, $B \to 1B$ **17.** $S \to 0C$, $S \to 1A$, $S \to 1$, $A \to 1A$, $A \to 0C$, $A \to 1$, $B \to 0B$, $B \to 1B$, $B \to 0$, $B \to 1$, $C \to 0C$, $C \to 1B$, $C \to 1$. **19.** This follows because input that leads to a final state in the automaton corresponds uniquely to a derivation in the grammar. **21.** The "only if" part is clear because I is finite. For the "if" part let the states be $s_{i_0}, s_{i_1}, s_{i_2}, \ldots, s_{i_n}$, where $n = l(x)$. Because $n \geq |S|$, some state is repeated by the pigeonhole principle. Let y be the part of x that causes the loop, so that $x = uyv$ and y sends s_j to s_j, for some j. Then $uy^kv \in L(M)$ for all k. Hence, $L(M)$ is infinite. **23.** Suppose that $L = \{0^{2n}1^n\}$ were regular. Let S be the set of states of a finite-state machine recognizing this set. Let $z = 0^{2n}1^n$ where $3n \geq |S|$. Then by the pumping lemma, $z = 0^{2n}1^n = uvw$, $l(v) \geq 1$, and $uv^iw \in \{0^{2n}1^n \mid n \geq 0\}$. Obviously v cannot contain both 0 and 1, because v^2 would then contain 10. So v is all 0s or all 1s, and hence, uv^2w contains too many 0s or too many 1s, so it is not in L. This contradiction shows that L is not regular. **25.** Suppose that the set of palindromes over $\{0, 1\}$ were regular. Let S be the set of states of a finite-state machine recognizing this set. Let $z = 0^n10^n$, where $n > |S|$. Apply the pumping lemma to get $uv^iw \in L$ for all nonnegative integers i where $l(v) \geq 1$, and $l(uv) \leq |S|$, and $z = 0^n10^n = uvw$. Then v must be a string of 0s (because $|n| > |S|$), so uv^2w is not a palindrome. Hence, the set of palindromes is not regular. **27.** Let $z = 1$; then $111 \notin L$ but $101 \in L$, so 11 and 10 are distinguishable. For the second question, the only way for $1z$ to be in L is for z to end with 01, and that is also the only way for $11z$ to be in L, so 1 and 11 are indistinguishable. **29.** This follows immediately from Exercise 28, because the n distinguishable strings must drive the machine from the start state to n different states. **31.** Any two distinct strings of the same length are distinguishable with respect to the language P of all palindromes, because if x and y are distinct strings of length n, then $xx^R \in P$ but $yx^R \notin P$. Because there are 2^n different strings of length n, Exercise 29 tells us that any deterministic finite-state automaton for recognizing palindromes must have at least 2^n states. Because n is arbitrary, this is impossible.

Section 12.5

1. a) The nonblank portion of the tape contains the string 1111 when the machine halts. **b)** The nonblank portion of the tape contains the string 011 when the machine halts. **c)** The nonblank portion of the tape contains the string 00001 when the machine halts. **d)** The nonblank portion of the tape contains the string 00 when the machine halts. **3. a)** The machine halts (and accepts) at the blank following the input, having changed the tape from 11 to 01. **b)** The machine changes every other occurrence of a 1, if any, starting with the first, to a 0, and otherwise leaves the string unchanged; it halts (and accepts) when it comes to the end of the string. **5. a)** Halts with 01 on the tape, and does not accept **b)** The first 1 (if any) is changed to a 0 and the others are left alone. The input is not accepted.
7. $(s_0, 0, s_1, 1, R)$, $(s_0, 1, s_0, 1, R)$ **9.** $(s_0, 0, s_0, 0, R)$, $(s_0, 1, s_1, 1, R)$, $(s_1, 0, s_1, 0, R)$, $(s_1, 1, s_1, 0, R)$ **11.** $(s_0, 0, s_1, 0, R)$, $(s_0, 1, s_0, 0, R)$, $(s_1, 0, s_1, 0, R)$, $(s_1, 1, s_0, 0, R)$, (s_1, B, s_2, B, R) **13.** $(s_0, 0, s_0, 0, R)$, $(s_0, 1, s_1, 1, R)$, $(s_1, 0, s_1, 0, R)$, $(s_1, 1, s_0, 1, R)$, (s_0, B, s_2, B, R) **15.** If the input string is blank or starts with a 1 the machine halts in nonfinal state s_0. Otherwise, the initial 0 is changed to an M and the machine skips past all the intervening 0s and 1s until it either comes to the end of the input string or else comes to an M. At this point, it backs up one square and enters state s_2. Because the acceptable strings must have a 1 at the right for each 0 at the left, there must be a 1 here if the string is acceptable. Therefore, the only transition out of s_2 occurs when this square contains a 1. If it does, the machine replaces it with an M and makes its way back to the left; if it does not, the machine halts in nonfinal state s_2. On its way back, it stays in s_3 as long as it sees 1s, then stays in s_4 as long as it sees 0s. Eventually either it encouters a 1 while in s_4 at which point it halts without accepting or else it reaches the rightmost M that had been written over a 0 at the start of the string. If it is in s_3 when this happens, then there are no more 0s in the string, so it had better be the case that there are no more 1s either; this is accomplished by the transitions (s_3, M, s_5, M, R) and (s_5, M, s_6, M, R), and s_6 is a final state. Otherwise the machine halts in nonfinal state s_5. If it is in s_4 when this M is encountered, things start all over again, except now the string will have had its leftmost remaining 0 and its rightmost remaining 1 replaced by Ms. So the machine moves, staying in state s_4, to the leftmost remaining 0 and goes back into state s_0 to repeat the process.
17. (s_0, B, s_9, B, L), $(s_0, 0, s_1, 0, L)$, (s_1, B, s_2, E, R), (s_2, M, s_2, M, R), $(s_2, 0, s_3, M, R)$, $(s_3, 0, s_3, 0, R)$, (s_3, M, s_3, M, R), $(s_3, 1, s_4, M, R)$, $(s_4, 1, s_4, 1, R)$, (s_4, M, s_4, M, R), $(s_4, 2, s_5, M, R)$, $(s_5, 2, s_5, 2, R)$, (s_5, B, s_6, B, L), (s_6, M, s_8, M, L), $(s_6, 2, s_7, 2, L)$, $(s_7, 0, s_7, 0, L)$, $(s_7, 1, s_7, 1, L)$, $(s_7, 2, s_7, 2, L)$, (s_7, M, s_7, M, L), (s_7, E, s_2, E, R), (s_8, M, s_8, M, L), (s_8, E, s_9, E, L) where M and E are markers, with E marking the left end of the input
19. $(s_0, 1, s_1, B, R)$, $(s_1, 1, s_2, B, R)$, $(s_2, 1, s_3, B, R)$, $(s_3, 1, s_4, 1, R)$, $(s_1, B, s_4, 1, R)$, $(s_2, B, s_4, 1, R)$, $(s_3, B, s_4, 1, R)$
21. $(s_0, 1, s_1, B, R)$, $(s_1, 1, s_2, B, R)$, (s_1, B, s_6, B, R), $(s_2, 1, s_3, B, R)$, (s_2, B, s_6, B, R), $(s_3, 1, s_4, B, R)$, (s_3, B, s_6, B, R), $(s_4, 1, s_5, B, R)$, (s_4, B, s_6, B, R), $(s_6, B, s_{10}, 1, R)$, $(s_5, 1, s_5, B, R)$, $(s_5, B, s_7, 1, R)$, $(s_7, B, s_8, 1, R)$, $(s_8, B, s_9, 1, R)$, $(s_9, B, s_{10}, 1, R)$
23. $(s_0, 1, s_0, 1, R)$, (s_0, B, s_1, B, L), $(s_1, 1, s_2, 0, L)$, $(s_2, 0, s_2, 0, L)$, $(s_2, 1, s_3, 0, R)$, (s_2, B, s_6, B, R), $(s_3, 0, s_3, 0, R)$, $(s_3, 1, s_3, 1, R)$, $(s_3, B, s_4, 1, R)$, $(s_4, B, s_5, 1, L)$, $(s_5, 1, s_5, 1, L)$, $(s_5, 0, s_2, 0, L)$, $(s_6, 0, s_6, 1, R)$, $(s_6, 1, s_7, 1, R)$, (s_6, B, s_7, B, R)
25. $(s_0, 0, s_0, 0, R)$, $(s_0, *, s_5, B, R)$, $(s_3, *, s_3, *, L)$, $(s_3, 0, s_3, 0, L)$, $(s_3, 1, s_3, 1, L)$, (s_3, B, s_0, B, R),

$(s_5, 1, s_5, B, R)$, $(s_5, 0, s_5, B, R)$, (s_5, B, s_6, B, L), (s_6, B, s_6, B, L), $(s_6, 0, s_7, 1, L)$, $(s_7, 0, s_7, 1, L)$, $(s_0, 1, s_1, 0, R)$, $(s_1, 1, s_1, 1, R)$, $(s_1, *, s_2, *, R)$, $(s_2, 0, s_2, 0, R)$, $(s_2, 1, s_3, 0, L)$, (s_2, B, s_4, B, L), $(s_4, 0, s_4, 1, L)$, $(s_4, *, s_8, B, L)$, $(s_8, 0, s_8, B, L)$, $(s_8, 1, s_8, B, L)$

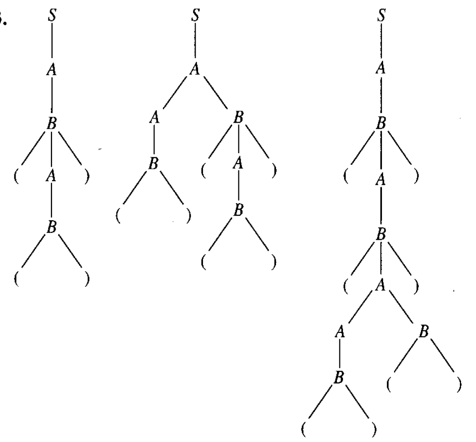
27. Suppose that s_m is the only halt state for the Turing machine in Exercise 22, where m is the largest state number, and suppose that we have designed that machine so that when the machine halts the tape head is reading the leftmost 1 of the answer. Renumber each state in the machine for Exercise 18 by adding m to each subscript, and take the union of the two sets of five-tuples.

29. a) No **b)** Yes **c)** Yes **d)** Yes **31.** $(s_0, B, s_1, 1, L)$, $(s_0, 1, s_1, 1, R)$, $(s_1, B, s_0, 1, R)$

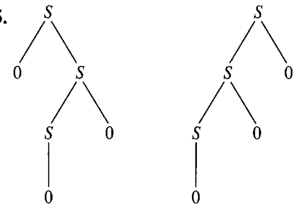
Supplementary Exercises

1. a) $S \to 00S111$, $S \to \lambda$ **b)** $S \to AABS$, $AB \to BA$, $BA \to AB$, $A \to 0$, $B \to 1$, $S \to \lambda$ **c)** $S \to ET$, $T \to 0TA$, $T \to 1TB$, $T \to \lambda$, $0A \to A0$, $1A \to A1$, $0B \to B0$, $1B \to B1$, $EA \to E0$, $EB \to E1$, $E \to \lambda$

3.

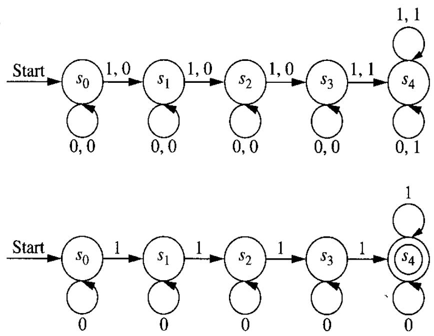


5.

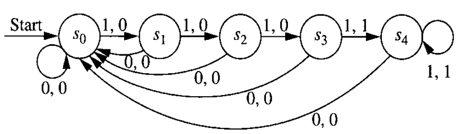


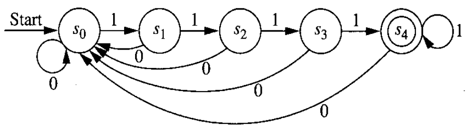
7. No, take $A = \{1, 10\}$ and $B = \{0, 00\}$. **9.** No, take $A = \{00, 000, 00000\}$ and $B = \{00, 000\}$. **11. a)** 1 **b)** 1 **c)** 2 **d)** 3 **e)** 2 **f)** 4

13.



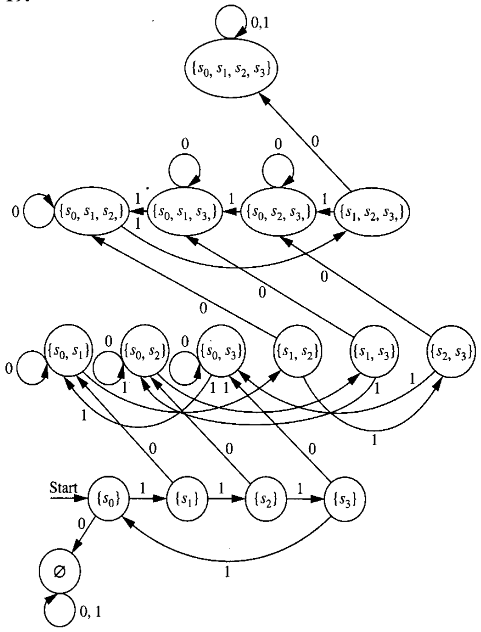
15.



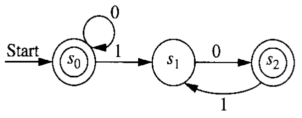


17. a) $n^{nk+1}m^{nk}$ **b)** $n^{nk+1}m^{n}$

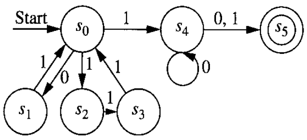
19.



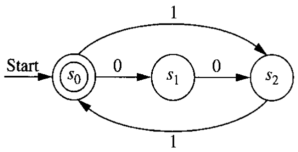
21. a)



b)

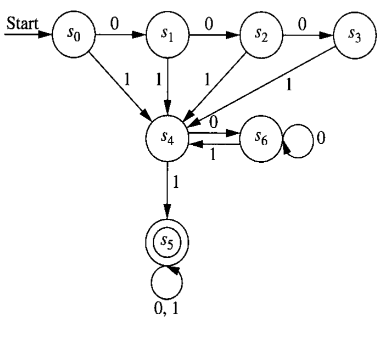


c)

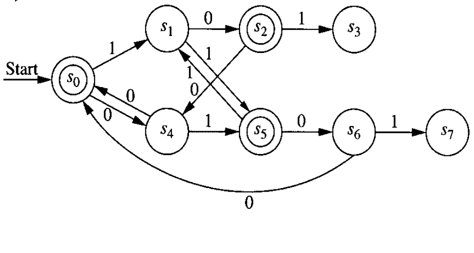


23. Construct the deterministic finite automaton for A with states S and final states F. For $\overline{A}$ use the same automaton but with final states $S - F$.

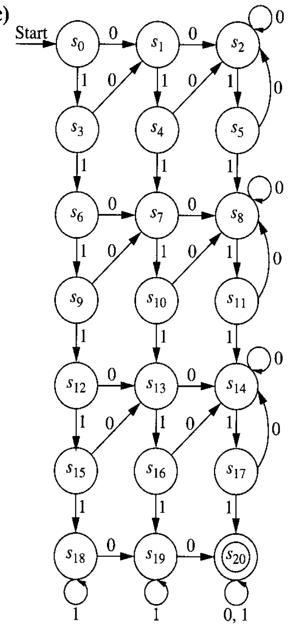
25. a)



b)



c)



27. Suppose that $L = \{1^p \mid p \text{ is prime}\}$ is regular, and let S be the set of states in a finite-state automaton recognizing L. Let $z = 1^p$ where p is a prime with $p > |S|$ (such a prime exists because there are infinitely many primes). By the pumping lemma it must be possible to write $z = uvw$ with $l(uv) \le |S|$, $l(v) \ge 1$, and for all nonnegative integers i, $uv^iw \in L$. Because z is a string of all 1s, $u = 1^a$, $v = 1^b$, and $w = 1^c$, where $a + b + c = p$, $a + b \le n$, and $b \ge 1$. This means that $uv^iw = 1^a 1^{bi} 1^c = 1^{(a+b+c)+b(i-1)} = 1^{p+b(i-1)}$. Now take $i = p + 1$. Then $uv^iw = 1^{p(1+b)}$. Because $p(1 + b)$ is not prime, $uv^iw \notin L$, which is a contradiction. **29.** $(s_0, *, s_5, B, L)$, $(s_0, 0, s_0, 0, R)$, $(s_0, 1, s_1, 0, R)$, $(s_1, *, s_2, *, R)$, $(s_1, 1, s_1, 1, R)$, $(s_2, 0, s_2, 0, R)$, $(s_2, 1, s_3, 0, L)$, (s_2, B, s_4, B, L), $(s_3, *, s_3, *, L)$, $(s_3, 0, s_3, 0, L)$, $(s_3, 1, s_3, 1, L)$, (s_3, B, s_0, B, R), $(s_4, *, s_8, B, L)$, $(s_4, 0, s_4, B, L)$, $(s_5, 0, s_5, B, L)$, (s_5, B, s_6, B, R), $(s_6, 0, s_7, 1, R)$, (s_6, B, s_6, B, R), $(s_7, 0, s_7, 1, R)$, $(s_7, 1, s_7, 1, R)$, $(s_8, 0, s_8, 1, L)$, $(s_8, 1, s_8, 1, L)$

APPENDIXES

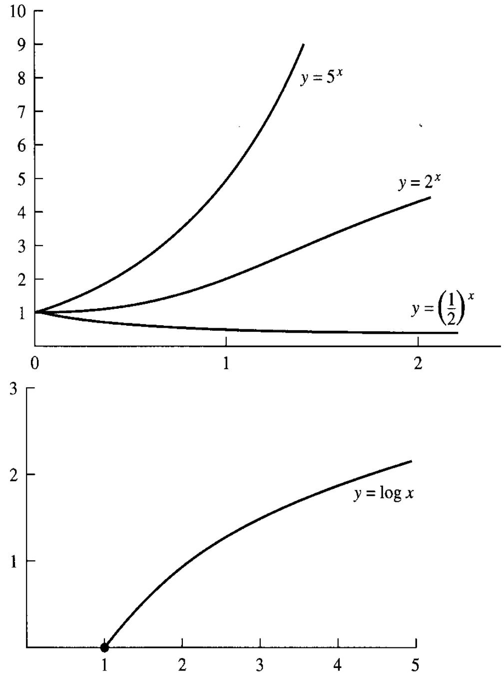
Appendix 1

1. Suppose that $1'$ is also a multiplicative identity for the real numbers. Then, by definition, we have both $1 \cdot 1' = 1$ and $1 \cdot 1' = 1'$, so $1' = 1$. **3.** For the first part, it suffices to show that $[(-x) \cdot y] + (x \cdot y) = 0$, because Theorem 2 guarantees that additive inverses are unique. Thus $[(-x) \cdot y] + (x \cdot y) = (-x + x) \cdot y$ (by the distributive law) $= 0 \cdot y$ (by the inverse law) $= y \cdot 0$ (by the commutative law) $= 0$ (by Theorem 5). The second part is almost identical. **5.** It suffices to show that $[(-x) \cdot (-y)] + [-(x \cdot y)] = 0$, because Theorem 2 guarantees that additive inverses are unique: $[(-x) \cdot (-y)] + [-(x \cdot y)] = [(-x) \cdot (-y)] + [(-x) \cdot y]$ (by Exercise 3) $= (-x) \cdot [(-y) + y]$ (by the distributive law) $= (-x) \cdot 0$ (by the inverse law) $= 0$ (by Theorem 5). **7.** By definition, $-(-x)$ is the additive inverse of $-x$. But $-x$ is the additive inverse of x, so x is the additive inverse of $-x$. Therefore $-(-x) = x$ by Theorem 2. **9.** It suffices to show that $(-x - y) + (x + y) = 0$, because Theorem 2 guarantees that additive inverses are unique: $(-x - y) + (x + y) = [(-x) + (-y)] + (x + y)$ (by definition of subtraction) $= [(-y) + (-x)] + (x + y)$ (by the commutative law) $= (-y) + [(-x) + (x + y)]$ (by the associative law) $= (-y) + [(-x + x) + y]$ (by the associative law) $= (-y) + (0 + y)$ (by the inverse law) $= (-y) + y$ (by the identity law) $= 0$ (by the inverse law). **11.** By definition of division and uniqueness of multiplicative inverses (Theorem 4) it suffices to prove that $[(w/x) + (y/z)] \cdot (x \cdot z) = w \cdot z + x \cdot y$. But this follows after several steps, using the distributive law, the associative and commutative laws for multiplication, and the definition that division is the same as multiplication by the inverse. **13.** We must show that if $x > 0$ and $y > 0$, then $x \cdot y > 0$. By the multiplicative compatibility law, the commutative law, and Theorem 5, we have $x \cdot y > 0 \cdot y = 0$. **15.** First note that if $z < 0$, then $-z > 0$ (add $-z$ to both sides of the hypothesis). Now given $x > y$ and $-z > 0$, we have $x \cdot (-z) > y \cdot (-z)$ by the multiplicative compatibility law. But by Exercise 3 this is equivalent to $-(x \cdot z) > -(y \cdot z)$. Then add $x \cdot z$ and $y \cdot z$ to both sides and apply the various laws in the obvious ways to yield $x \cdot z < y \cdot z$. **17.** The additive compatibility law tells us that $w + y < x + y$ and (together with the commutative law) that $x + y < x + z$. By the transitivity law, this gives the desired conclusion. **19.** By Theorem 8, applied to $1/x$ in place of x, there is an integer n (necessarily positive, because $1/x$ is positive) such that $n > 1/x$. By the multiplicative compatibility law, this means that $n \cdot x > 1$. **21.** We must show that if $(w, x) \sim (w', x')$ and $(y, z) \sim (y', z')$, then $(w + y, x + z) \sim (w' + y', x' + z')$ and that $(w \cdot y + x \cdot z, x \cdot y + w \cdot z) \sim (w' \cdot y' + x' \cdot z', x' \cdot y' + w' \cdot z')$. Thus we are given that $w + x' = x + w'$ and that $y + z' = z + y'$, and we want to show that $w + y + x' + z' = x + z + w' + y'$ and that $w \cdot y + x \cdot z + x' \cdot y' + w' \cdot z' = x \cdot y + w \cdot z + w' \cdot y' + x' \cdot z'$. For the first of the desired conclusions, add the two given equations. For the second, rewrite the given equations as $w - x = w' - x'$ and $y - z = y' - z'$, multiply them, and do the algebra.

Appendix 2

1. a) 2^3 **b)** 2^6 **c)** 2^4 **3. a)** $2y$ **b)** $2y/3$ **c)** $y/2$

5.



Appendix 3

1. After the first block is executed, a has been assigned the original value of b and b has been assigned the original value of c, whereas after the second block is executed, b is assigned the original value of c and a the original value of c as well. **3.** The following **while** construction does the same thing.

i := *initial value*
while *i* ≤ *final value*
begin
  statement
  i := *i* + 1
end