Answers to
Theory of Computation: Making Connections

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This is a draft (date: October 3, 2020). I apologize for errors; I’d be glad for reports. I am currently visiting exercises at the end of the fourth chapter, so earlier answers are likely to be right while I cannot vouch for later ones.

Cover: Flauros, the sixty-fourth demon and the Duke of Hell, who gives true answers of all things past, present, and future. Although, you should verify what he says for yourself. From Dictionnaire Infernal, Jacques Albin Simon Collin de Plancy, 1863.
Chapter I: Mechanical Computation

I.1.10

(a) Here is the sequence of tapes traced out in the course of the computation of the predecessor of 2.

\[
\begin{array}{c|c}
\text{Step} & \text{Configuration} \\
0 & 1 \ 1 \\
1 & 1 \ 1 \\
2 & 1 \ 1 \\
3 & 1 \ 1 \\
4 & 1 \ 1 \\
5 & 1 \ 1 \\
6 & 1 \ 1 \\
7 & 1 \ 1 \\
\end{array}
\]

(b) This is the tape diagram sequence for the sum of 2 and 2.

\[
\begin{array}{c|c}
\text{Step} & \text{Configuration} \\
0 & 1 \ 1 \ 1 \ 1 \\
1 & 1 \ 1 \ 1 \\
2 & 1 \ 1 \ 1 \\
3 & 1 \ 1 \ 1 \\
4 & 1 \ 1 \ 1 \\
5 & 1 \ 1 \ 1 \\
6 & 1 \ 1 \ 1 \\
7 & 1 \ 1 \ 1 \\
8 & 1 \ 1 \ 1 \\
9 & 1 \ 1 \ 1 \\
10 & 1 \ 1 \ 1 \\
11 & 1 \ 1 \ 1 \\
12 & 1 \ 1 \ 1 \\
\end{array}
\]

(c) This is the predecessor computation.

\[
\langle q_0, 1, \epsilon, 1 \rangle \rightarrow \langle q_0, 1, 1, \epsilon \rangle \rightarrow \langle q_0, B, 11, \epsilon \rangle \rightarrow \langle q_1, 1, 1, \epsilon \rangle \rightarrow \langle q_1, B, 1, \epsilon \rangle \rightarrow \langle q_2, 1, \epsilon, \epsilon \rangle
\]

There is no instruction for state \( q_3 \) so \( \langle q_3, 1, \epsilon, \epsilon \rangle \) is a halting configuration.

The sum of 2 and 2 is a little longer.

\[
\langle q_0, 1, \epsilon, 1B11 \rangle \rightarrow \langle q_0, 1, 1, B11 \rangle \rightarrow \langle q_0, B, 11, 11 \rangle \rightarrow \langle q_1, B, 11, 11 \rangle \rightarrow \langle q_1, 1, 11, 11 \rangle
\]

I.1.11

(a) To show that some operation on negative numbers (or any mathematical object, for that matter) can be computed, name a representation for them with strings over a finite alphabet and then show how to use a Turing machine to do mechanical computations on those strings. For instance, to show that multiplication of two integers is mechanical, we could use the alphabet \( \sum = \{ B, 0, \ldots, 9, +, - \} \) and represent each integer as a pair \( \langle \text{sign}, \text{natural number} \rangle \). Making a Turing machine that has four cases, for the four possible pairs of signs, is tedious but perfectly possible.
(b) If by “problem” we mean that the machine fails to halt, this is not the source of the problem. Rather, this machine is a straightforward infinite loop.

(c) We could give a machine states that are not sequential. The only limitation is that we use the convention that the initial state is $q_0$. For instance, this machine fits the definition $P = \{ q_0 \overrightarrow{B} q_{50}, q_0 \overrightarrow{11} q_{50}, q_{50} \overrightarrow{11} q_1, q_{50} \overrightarrow{11} q_1 \}$, and on any input reaches state $q_{50}$ after one step.

I.1.12 The halting state is $q_4$ and the working states are $q_0, q_1, q_2$ and $q_3$.

I.1.13 The trace is not too interesting.

\begin{tabular}{|c|c|c|c|}
\hline
\textbf{Step} & \textbf{Configuration} & \textbf{Step} & \textbf{Configuration} \\
\hline
0 & $q_0$ & 4 & $q_0$  \\
1 & $q_0$ & 5 & $q_0$  \\
2 & $q_0$ & 6 & $q_0$  \\
3 & $q_0$ & 7 & $q_0$  \\
\hline
\end{tabular}

I.1.14

(a) The result of running the mystery machine on input 11 is this.

\begin{tabular}{|c|c|c|}
\hline
\textbf{Step} & \textbf{Configuration} & \textbf{Step} & \textbf{Configuration} \\
\hline
0 & 1 1 & 2 & 1 1  \\
1 & 1 1 & 3 & 1 1  \\
\hline
\end{tabular}

(b) On input 1011 it gives this.

\begin{tabular}{|c|c|c|}
\hline
\textbf{Step} & \textbf{Configuration} & \textbf{Step} & \textbf{Configuration} \\
\hline
0 & 1 0 1 1 & 2 & 1 0 1 1  \\
1 & 1 0 1 1 & 3 & 1 0 1 1  \\
\hline
\end{tabular}

(c) The input 110 gives this.

\begin{tabular}{|c|c|c|}
\hline
\textbf{Step} & \textbf{Configuration} & \textbf{Step} & \textbf{Configuration} \\
\hline
0 & 1 1 0 & 3 & 1 1 0  \\
1 & 1 1 0 & 4 & 1 1 0  \\
2 & 1 1 0 &  \\
\hline
\end{tabular}

(d) With the input 1101 the machine gives this sequence of tapes.
(e) This is what happens when the initial tape is empty.

I.1.15 This is the transition table.

<table>
<thead>
<tr>
<th>Step</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1 1 0 1 q0</td>
</tr>
<tr>
<td>1</td>
<td>1 1 0 1 q1</td>
</tr>
<tr>
<td>2</td>
<td>1 1 0 1 q0</td>
</tr>
<tr>
<td>3</td>
<td>1 1 0 1 q0</td>
</tr>
</tbody>
</table>

\[ \Delta \begin{array}{ccc}
\emptyset & 0 & 1 \\
q_0 & Bq_4 & Rq_0, Rq_1 \\
q_1 & Bq_4 & Rq_2, Rq_0 \\
q_2 & Bq_4 & Rq_0, Rq_3 \\
q_3 & - & -
\end{array} \]

I.1.16 The machine \( \mathcal{P}_{\text{blankones}} = \{ q_0Bq_2, q_01Bq_1, q_1BRq_0, q_11q_0 \} \) does this on a tape with two 1's.

I.1.17

(a) This machine does the job; note that the head never moves.

\[ \mathcal{P}_{\text{singlebitnot}} = \{ q_0Bq_1, q_001q_1, q_010q_1 \} \]

This shows input \( \sigma = 0 \).

(b) This machine does ‘and’. Note that the states are not numbered sequentially; sometimes making a gap is convenient when you are writing the machine. For instance, here state \( q_{100} \) is used as the halting state,
since it was clear there would not be a hundred states and so this one would be available. Similarly, \( q_{10} \) is for what the machine does if the first bit is 0 while \( q_{20} \) is for the case where the first bit is 1.

\[
P_{\text{singlebitand}} = \{ q_0Bq_{100}, q_0\partial Bq_{10}, q_01Bq_{20}, q_10\partial Rq_{11}, q_10\partial Bq_{100}, q_{10}1\partial q_{100}, \\
q_{11}BBq_{100}, q_{11}\partial Bq_{100}, q_{11}1\partial q_{100}, q_{20}B\partial Rq_{21}, q_{20}R\partial q_{100}, q_{20}\partial q_{100}, \\
q_{21}BBq_{100}, q_{21}\partial Bq_{100}, q_{21}1\partial q_{100} \}
\]

This shows what the machine does on input \( \sigma = 01 \).

<table>
<thead>
<tr>
<th>Step</th>
<th>Configuration</th>
<th>Step</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>01</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>( q_0 )</td>
<td></td>
<td>( q_{11} )</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>( q_{10} )</td>
<td></td>
<td>( q_{100} )</td>
</tr>
</tbody>
</table>

(c) This is the ‘or’ machine. As in the prior item, the states are not numbered sequentially. Note also that this machine is basically the same as the ‘or’ machine.

\[
P_{\text{singlebitor}} = \{ q_0Bq_{100}, q_0\partial Bq_{10}, q_01Bq_{20}, q_10\partial Bq_{11}, q_10\partial Bq_{100}, q_{10}1\partial q_{100}, \\
q_{11}BBq_{100}, q_{11}\partial Bq_{100}, q_{11}1\partial q_{100}, q_{20}B\partial Rq_{21}, q_{20}R\partial q_{100}, q_{20}\partial q_{100}, \\
q_{21}BBq_{100}, q_{21}\partial 1q_{100}, q_{21}1\partial q_{100} \}
\]

Here is what it does on input \( \sigma = 01 \).

<table>
<thead>
<tr>
<th>Step</th>
<th>Configuration</th>
<th>Step</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>01</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>( q_0 )</td>
<td></td>
<td>( q_{11} )</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>( q_{10} )</td>
<td></td>
<td>( q_{100} )</td>
</tr>
</tbody>
</table>

I.1.18 This machine uses \( q_0 \) to slide to the right end, appends the 01, and uses \( q_2 \) to slide back to the left.

\[
P_{\text{append01}} = \{ q_0\partial 0q_1, q_0\partial Rq_0, q_01Rq_0, q_1B1q_2, q_1\partial Rq_1, q_11Lq_2, q_2B\partial q_3, q_2\partial Lq_2, q_21Lq_2 \}
\]

This example shows what the machine does, on input \( \sigma = 11 \).

<table>
<thead>
<tr>
<th>Step</th>
<th>Configuration</th>
<th>Step</th>
<th>Configuration</th>
<th>Step</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>11</td>
<td>4</td>
<td>110</td>
<td>8</td>
<td>1101</td>
</tr>
<tr>
<td></td>
<td>( q_0 )</td>
<td></td>
<td>( q_1 )</td>
<td></td>
<td>( q_2 )</td>
</tr>
<tr>
<td>1</td>
<td>11</td>
<td>5</td>
<td>1101</td>
<td>9</td>
<td>1101</td>
</tr>
<tr>
<td></td>
<td>( q_0 )</td>
<td></td>
<td>( q_2 )</td>
<td></td>
<td>( q_2 )</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>6</td>
<td>1101</td>
<td>10</td>
<td>1101</td>
</tr>
<tr>
<td></td>
<td>( q_0 )</td>
<td></td>
<td>( q_2 )</td>
<td></td>
<td>( q_3 )</td>
</tr>
<tr>
<td>3</td>
<td>110</td>
<td>7</td>
<td>1101</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( q_1 )</td>
<td></td>
<td>( q_2 )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

I.1.19 This machine works.

\[
P_{\text{constantthree}} = \{ q_0Bq_2, q_01Bq_1, q_1BRq_0, q_11q_0, q_2B1q_2, q_21Rq_3, q_3B1q_3, q_31Rq_4, \\
q_4B1q_4, q_411q_5, q_5B1q_5, q_51Lq_6, q_6Bq_7, q_61Lq_7 \}
\]

Here is the machine acting on an input of 2.
I.1.20 This machine computes successor.

\[ P_{\text{successor}} = \{ q_0 B1q_1, q_0 1Lq_0 \} \]

An example is this tape sequence for input 3.

### Step Configuration

<table>
<thead>
<tr>
<th>Step</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1 1</td>
</tr>
<tr>
<td></td>
<td>( q_0 )</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>( q_1 )</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>( q_0 )</td>
</tr>
<tr>
<td>3</td>
<td>( q_1 )</td>
</tr>
<tr>
<td>4</td>
<td>( q_0 )</td>
</tr>
</tbody>
</table>

I.1.21

(A) We begin with the head at the start of a sequence of 1’s. Erase that first 1, then slide to the end of the sequence, and past a blank. Put two 1’s, and then slide back to the start of the initial sequence. Iterate that.

The machine has nine instructions and alphabet \( \Sigma = \{ 1, \text{str}B \} \).

\[ P_{\text{doubler}} = \{ q_0 1Bq_9, q_0 1Bq_1, q_1 BRq_2, q_1 1Rq_2, q_2 BRq_3, q_2 1Rq_2, q_3 B1q_4, q_3 1Rq_3, q_4 BBq_4, q_4 1Rq_5, q_5 B1q_6, q_5 11q_6, q_6 BLq_7, q_6 1Lq_6, q_7 BRq_8, q_7 1Lq_7, q_8 BRq_9, q_8 11q_9 \} \]

Here is the sequence of tapes for the input 2. It shows the blanks because there can be two of them, which can be confusing. It is in halves just to allow a page break in the middle.

### Step Configuration

<table>
<thead>
<tr>
<th>Step</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1 1</td>
</tr>
<tr>
<td></td>
<td>( q_0 )</td>
</tr>
<tr>
<td>1</td>
<td>1 1 1</td>
</tr>
<tr>
<td></td>
<td>( q_1 )</td>
</tr>
<tr>
<td>2</td>
<td>1 1 1 1 1</td>
</tr>
<tr>
<td></td>
<td>( q_2 )</td>
</tr>
<tr>
<td>3</td>
<td>1 1 1 1 1 1</td>
</tr>
<tr>
<td></td>
<td>( q_3 )</td>
</tr>
<tr>
<td>4</td>
<td>1 1 1 1 1 1</td>
</tr>
</tbody>
</table>

This is the second half.
(b) To double a number represented in binary just append a 0 to the right side. The machine has three instructions and \( \Sigma = \{0, 1, B\} \).

\[
P_{\text{doublerbinary}} = \{q_0BBq_3, q_000q_3, q_01Rq_1, q_1B0q_2, q_10Rq_1, q_11Rq_1, q_2BRq_3, q_20Lq_2, q_21Lq_2\}
\]

On input 6 it gives this tape sequence.

I.1.22 This Turing machine works.

\[
P_{\text{odd}} = \{q_0BBq_{100}, q_01Rq_1, q_1BLq_{100}, q_11Bq_2, q_2BLq_3, q_21Lq_3, q_3BBq_4, q_31Bq_4, q_4BRq_5, q_411q_5, q_5BRq_0, q_511q_0\}
\]

For instance, on input 3 it does this

and on 4 it does this.
I.1.23 While this Turing machine is moving right, if it hits a comma then it replaces it with a 1 and closes up to the left. That is, it scans left to the start of the string, erases the first 1, and then starts moving right again.

\[ P_{\text{addany}} = \{ q_0BLq_{10}, q_01Rq_{10}, q_01q_1, q_1BRq_{2}, q_11Lq_{1}, q_1, Lq_{1}, q_2BRq_{0}, q_21Bq_{2}, q_{10}BRq_{100}, q_{10}1Lq_{10}, q_{10}, Lq_{10} \} \]

For instance, on input 11,1,11 it does this.

(It is split into two sets of tables to give the formatter a place to put a page break.)
I.1.24 No. Given a configuration $C = \langle q, s, \tau_L, \tau_R \rangle$, one preceeding configuration is $\hat{C} = \hat{C}$ with $I = qssq$.

I.1.25

(A) The machine can flip the first bit, slide right and flip the second bit, etc. The fact that we know the number of bits in advance means that we can just have four groups of states: first flip and slide, second flip and slide, etc. (We could do an arbitrary number of bits but it would be a little harder.) At the end we slide left to position the head at the left end of the non-blank characters.

   Although the question says that you need not produce a machine, here is one. In this machine, state $q_0$ flips the first bit and then $q_1$ slides right. The next flip and slide combination is $q_2$ and $q_3$, etc., until the machine gets to the fourth bit. Then it moves the head back to the start with $q_7$.

   \[
   T_{\text{bitwise NOT}} = \{q_0BBq_1, q_001q_1, q_010q_1, q_1BRq_2, q_10Rq_2, q_11Rq_2, q_2BBq_3, q_201q_3, q_210q_3, q_3BRq_4, q_30Rq_4, q_31Rq_4, q_4BBq_5, q_401q_5, q_410q_5, q_5BRq_6, q_50Rq_6, q_51Rq_6, q_6BBq_7, q_601q_7, q_610q_7, q_7BRq_8, q_70Lq_7, q_71Lq_7\} \]

   For instance, on input 0110 it does this.

<table>
<thead>
<tr>
<th>Step</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0110</td>
</tr>
<tr>
<td>1</td>
<td>1110</td>
</tr>
<tr>
<td>2</td>
<td>1110</td>
</tr>
<tr>
<td>3</td>
<td>1010</td>
</tr>
<tr>
<td>4</td>
<td>1010</td>
</tr>
</tbody>
</table>

   (B) The machine has two cases, depending on what it finds for $b_3$. If $b_3 = 0$ then it moves right, copying the next bit into the current one, and then at the end it appends a 0. Likewise, if $b_3 = 1$ then it moves right, copying, and then at the end it appends a 1. As with the prior item, because we know in advance that there are four bits we can just have three groups of states.

   (C) One implementation is to expect two four-bit strings, $a_3a_2a_1a_0$ and $b_3b_2b_1b_0$, separated by a blank. The machine reads $a_3$ and goes into one of two states, $r_0$ or $r_1$, depending on whether $a_3 = 0$ or $a_3 = 1$. From state $r_0$ it slides past the blank separator, then reads $b_3$, and changes it to the logical ‘and’ of $b_3$ and 0. Similarly, from state $r_1$ it slides past the blank separator, reads $b_3$, and changes it to the logical ‘and’ of $b_3$ and 1. Repeat that for a total of four iterations.

I.1.26

(A) Under the convention that the machine starts with its head under the first non-blank character if there are any, $P = \{q_0BBq_1, q_011q_0\}$ will halt only if the input is blank.

(B) The machine $P = \{q_0BBq_0, q_011q_1\}$ will fail to halt only if the input is blank.

(C) The machine $P = \{q_0BRq_1, q_01Rq_1, q_1BBq_1, q_111q_2\}$ will halt if and only if the second character is 1. (Trying the same idea for the first character won’t work because of our convention that the first character is blank only if all characters are blank, so there is only one input string with a blank first character.)

I.1.27 The strategy here is to scan right. If the machine sees a b then it goes into a state, $q_{20}$ that signifies it has seen one b and if the next character is also a b then it will halt and go to the accepting state. If it sees an a then it goes into state $q_{10}$, signifying that the number of b’s in the consecutive count is zero.

   \[
   T_{\text{twob}} = \{q_0BBq_4, q_0aRq_{10}, q_0bRq_{20}, q_1BBq_4, q_10aRq_{10}, q_10bRq_{20}, q_2BBq_4, q_20aRq_0, q_20bbq_3\} \]

   As an example, on input abba it does this.
Note that it ends in the accept state. In contrast, on input aba the machine ends in the reject state.

\[ P_{eq} = \{ q_0Bq_50, q_01Bq_1, q_1Bq_2, q_111q_2, q_2Bq_3, q_21Rq_2, q_3BLq_75, q_31Rq_4, q_4BLq_5, q_41Rq_4, \\
q_5Bq_6, q_51Bq_6, q_6BLq_7, q_611q_7, q_7BLq_8, q_71Lq_7, q_8BRq_0, q_81Lq_8, \\
q_9BRq_51, q_{50}11q_{51}, q_{51}B1q_{100}, q_{51}1Bq_{52}, q_{52}BRq_{51}, q_{52}11q_{51}, \\
q_{75}BLq_{76}, q_{75}11q_{76}, q_{76}BLq_{100}, q_{76}1Bq_{77}, q_{77}BLq_{76}, q_{77}1Lq_{76} \} \]

For instance, on inputs 2 and 3 it does this.

(This tape sequence is split in two to leave a place for a line break.)
I.1.29 The strategy is to blank out the first character, slide to the end, and then blank out the final character (if it matches the first), and then repeat. When the string is empty, the machine puts a 1 on the tape, showing success.

The machine below remembers that the first character was an a by moving to state $q_{20}$. It remembers a b by moving to state $q_{30}$. Starting in $q_{40}$ it moves back to the start of the remaining input string. State $q_{60}$ is for the cases where the machine detects that the input was not a palindrome, while state $q_{80}$ is for when the machine finds it is one. Finally, states $q_1, ..., q_4$ handle the case that the input string (either the initial string or what is left of the initial string after some end-trimming) has one character.

$$P_{\text{pal}} = \{ q_0Bq_{80}, q_0aq_{1}, q_0bBq_{3}, q_1BRq_{2}, q_1ARq_{2}, q_1bRq_{2}, q_2BLq_{80}, q_2aaq_{20}, q_2bbq_{20},$$

$$q_3BRq_{4}, q_3bRq_{4}, q_3Bq_{30}, q_4BLq_{80}, q_4aq_{30}, q_4bbq_{30},$$

$$q_2BLq_{21}, q_2BRq_{20}, q_2bRq_{20}, q_2BBq_{60}, q_2bBq_{40}, q_2bbq_{60},$$

$$q_3BLq_{31}, q_3bRq_{30}, q_3Bq_{60}, q_3Bq_{60}, q_3aBq_{60}, q_3bbq_{40},$$

$$q_4BLq_{41}, q_4aLq_{41}, q_4Bq_{41}, q_4Aq_{41}, q_4bLq_{41},$$

$$q_6BBq_{100}, q_6BBq_{61}, q_6bbq_{61}, q_6BLq_{60}, q_6aBq_{60}, q_6bBq_{60}, q_6bBq_{60},$$

$$q_8Bq_{100}, q_8aBq_{100}, q_8bBq_{100} \}$$

As an example, this is the action of the machine on abba.

(The tape sequence is in two parts to leave room for a page break.)
<table>
<thead>
<tr>
<th>Step</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>( bb ) ( q_0 )</td>
</tr>
<tr>
<td>13</td>
<td>( b ) ( q_1 )</td>
</tr>
<tr>
<td>14</td>
<td>( b ) ( q_4 )</td>
</tr>
<tr>
<td>15</td>
<td>( b ) ( q_{31} )</td>
</tr>
<tr>
<td>16</td>
<td>( b ) ( q_{30} )</td>
</tr>
<tr>
<td>17</td>
<td>( b ) ( q_{31} )</td>
</tr>
<tr>
<td>18</td>
<td>( b ) ( q_{40} )</td>
</tr>
<tr>
<td>19</td>
<td>( b ) ( q_{41} )</td>
</tr>
</tbody>
</table>

A second example is the action of the machine on \( aba \).

<table>
<thead>
<tr>
<th>Step</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>( aba ) ( q_0 )</td>
</tr>
<tr>
<td>1</td>
<td>( b a ) ( q_1 )</td>
</tr>
<tr>
<td>2</td>
<td>( b a ) ( q_2 )</td>
</tr>
<tr>
<td>3</td>
<td>( b a ) ( q_{20} )</td>
</tr>
<tr>
<td>4</td>
<td>( b a ) ( q_{20} )</td>
</tr>
<tr>
<td>5</td>
<td>( b a ) ( q_{20} )</td>
</tr>
<tr>
<td>6</td>
<td>( b a ) ( q_{21} )</td>
</tr>
<tr>
<td>7</td>
<td>( b ) ( q_{40} )</td>
</tr>
<tr>
<td>8</td>
<td>( b ) ( q_{41} )</td>
</tr>
<tr>
<td>9</td>
<td>( b ) ( q_{41} )</td>
</tr>
</tbody>
</table>

I.1.30 The strategy is to make two copies of the starting block of 1's, then move the head to the start of the first of the two copies. This is an example initial configuration.

The machine strips the leading 1, moves right, puts in the 1 that will start the first copy block, and then puts in the 1 to start the second block. With that, the head moves back to the start.

Now comes the complication. The machine strips the leading 1, then moves right and puts in a 1 at the end of the first copy block. But the place where it must put this 1 is the blank separating the two copy blocks. So it must then move right and put in a blank before moving to the end of the second copy block. At that end it puts two 1's, the first to mark the stripped leading 1 and the second to mark the inserted blank. With that, the head moves back to the start.

The machine iterates the prior sequence of steps until it finds that the leading sequence of 1's is now blank. To finish, it moves the head to the start of the first copy block.

I.1.31 Let the machine have the same configuration at two different steps \( C(t) = C(\hat{t}) \) with \( t < \hat{t} \). By determinism, \( C(t + 1) = C(\hat{t} + 1) \). Likewise, \( C(t + i) = C(\hat{t} + i) \) for \( i = 2, \ldots \). This means that the machine cycles every \( \hat{t} - t \) steps, because \( i = \hat{t} - t \) gives that \( C(t + (\hat{t} - t)) = C(\hat{t} + (\hat{t} - t)) \) but \( C(t + (\hat{t} - t)) = C(\hat{t}) \).
This sufficient condition is not necessary, since we can make a machine that never repeats its configuration
but also never halts. One way is to make a machine that writes a 1 to the tape, then moves right, and then
repeats.

I.1.32 Consider this configuration, with the machine in state \(q_5\).

\[
\begin{array}{c}
1 \\
1 \\
1 \\
q_5 \\
\end{array}
\]

It could have arrived at that configuration after this configuration and instruction.

\[
\begin{array}{c}
1 \\
1 \\
1 \\
q_4 \\
\end{array}
\]

\(q_4\) R \(q_5\)

or this

\[
\begin{array}{c}
1 \\
1 \\
1 \\
q_4 \\
\end{array}
\]

\(q_4\) L \(q_5\)

or for that matter, this.

\[
\begin{array}{c}
1 \\
1 \\
1 \\
q_4 \\
\end{array}
\]

\(q_4\) \(1\) \(q_5\)

I.2.2 Church's Thesis is an assertion that 'mechanically computable' (by a discrete and deterministic machine) is
equivalent to 'computable by a Turing machine'. It is not a theorem because we cannot derive it from the
traditional axioms for mathematics.

In some ways it is more like a definition than a theorem. But it is not a usual definition, where as a
convenience we take a word so that we don't have to keep saying a phrase over and over, as where we define
'bachelor' as 'unmarried man' or 'linearly dependent' as \(x_0 = a_1 x_1 + \cdots + a_n x_n\). Rather, it is more like Calculus's
definition of the derivative in that it expresses the introduction of a fundamental concept.

I.2.3

(a) As with a program, a Turing Machine can implement an algorithm. But an algorithm may be implemented
by more than one Turing Machine. For instance, we can do a shell sort of a list of five numbers with two
different Turing Machines, if only by renaming some of the states. In the words of M Davis (Davis 2016),
"[Church's Thesis] says nothing about what algorithms ARE. It is about what algorithms can and can not
DO." Comment: there is no widely agreed-upon definition of algorithm, which is odd as algorithms are a
central study in Computer Science.

(b) A Turing Machine is a single-purpose device. For instance, we may write a Turing Machine to multiply
two of its inputs. But today we use "computer" to mean a general-purpose, that is, programmable, device.
Comment: we will later see that there are general-purpose Turing Machines, so the distinction is blurry, one
of connotation rather than of precise definition.

I.2.4

(a) The tape, as given in the definition, is not infinite. It is unbounded.

For an analogy, consider the dictionary definition of a book. In that definition there is no upper limit on
the number of pages. But no book, no actual bound collection of pages, has infinitely many. So also, no
halting Turing machine computation uses infinitely much tape (the number of tape squares used is less than
or equal to the number of steps in the computation).

While it is true that you can easily write a Turing machine that does not halt and that just keeps using
more and more tape, at no step of the calculation is the amount of tape infinite. It never runs out — it is
unbounded — but it is never infinite.

(b) It is a model. A model necessarily discards some aspects of the situation it models. See (Wikipedia 2016).
(Besides, just to be argumentative for the sheer pleasure of it, whether the universe is finite — either just
currently finite, or finite into any unbounded future — is not clear. In any event it is not a mathematical
question.)

I.2.5 Church's Thesis is the third.
The role of Church’s Thesis here is that it allows us to avoid exhibiting Turing machines as sets of four-tuples to do these computations. Instead we can describe how to do them inside a usual programming environment.

(a) Let \( f_0 \) be computed by the Turing machine \( P_0 \) and let \( f_1 \) be computed by \( TM_1 \). For \( x \in \mathbb{N} \) this will compute \( h(x) \): run \( P_0 \) on input \( x \) for one step, then \( P_1 \) on \( x \) for a step, then \( P_0 \) for another step, etc., until each halts. When that happens, if it ever does, output 1.

(b) As with the prior item, for \( x \in \mathbb{N} \) compute the function on input \( x \) by: run \( P_0 \) on \( x \) for one step, then \( P_1 \) on \( x \) for a step, then \( P_0 \) for another step, etc. The difference here is that if either halts then output 1.

(c) Suppose \( f \) is computed by \( P \). Fix \( x \in \mathbb{N} \). Run \( P \) on input 0 for a step. Then run \( P \) on input 0 for an additional step and run \( P \) on 1 for a step. After that, run \( P \) on input 0 for another step, run \( P \) on 1 for another step, and start a run of \( P \) on input 2. In this way we cycle among the machine running on different inputs.

Whenever a computation of \( P \) on some input \( i \) halts, check whether what is left on its tape equals \( x \). If so, output 1.

(d) Let \( f_0 \) be computed by the Turing machine \( P_0 \) and let \( f_1 \) be computed by \( TM_1 \). For \( x \in \mathbb{N} \), run \( P_0 \) on input \( x \) until it halts. Suppose the output is \( y \). Run \( P_1 \) on \( y \) until it halts, and then the output is \( h(x) \). Since each function \( f_0 \) and \( f_1 \) was given as total, that output will appear eventually, and so \( h \) is also total.

(e) This is the same as the prior item except that the function \( h \) will be partial since there is some input for which \( P_0 \) does not halt.

I.2.10 Here is a procedure that is intuitively mechanically computable, and so by Church’s Thesis is computable. Let the input be \( n \). For \( i = 0 \) compute \( f(i) \) and see if it equals \( n \). If so, output 0. If not we iterate: take \( i = 1 \) and compute \( f(1) \). If so, output 0. Otherwise, repeat until the procedure outputs some value; if it never does
I.3.11 This procedure is intuitively mechanically computable and so by Church's Thesis is computable. Let the input be $n$. Run the Turing machine computing $f$ on input $n$ until it halts, if it ever does. If so then run the Turing machine computing $g(n)$ until it halts, if ever. After that, if after that ever comes, output 1. Otherwise we are in the second case of $h$'s specification.

I.2.12 You end with nothing since there is no bill still in your possession.

I.2.13 The strategy is to move right on tape 0, writing the complementary bit onto tape 1 until the tape 0 head hits a blank. Then the machine moves left on tape 1. (Below, rather than write the pair of characters as $\langle x, y \rangle$ we just have $xy$.)

I.2.14 The strategy is to move right on the two tapes, writing the logical and onto tape 1 until on both tapes the heads hit blanks. Then the machine moves left on tape 1. (Below, instead of writing the character pair as $\langle x, y \rangle$, we just write $xy$.)

I.3.7 A total recursive function is any computable function $\phi$ that terminates on all inputs. A primitive recursive function is one that can be derived as in Definition 3.6.

Every primitive recursive function is a total recursive function. The converse does not hold — there are total recursive functions that are not primitive recursive — but at this point in the book you have not yet seen that. It is covered in the next section.

I.3.8 There the definition gives 1.

I.3.9

(a) $f(0) = 0$, $f(1) = f(2 \cdot 1 - 2) = f(0) = 0$

(b) By definition $f(2) = f(2 \cdot 2 - 2) = f(2)$ gives what amounts to an infinite loop.

I.3.10

(a) $n$

\[
\begin{array}{|c|c|c|c|c|c|c|c|c|c|c|c|}
\hline
\Delta & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset \\
\hline
q_0 & 00, q_1 & 00, q_1 & 00, q_1 & 00, q_1 & 00, q_1 & 00, q_1 & 00, q_1 & 00, q_1 & 00, q_1 & 00, q_1 & 00, q_1 \\
\hline
\end{array}
\]

I.3.11 One way to show that is to note that it is the composition plus two $= S \circ S(x)$. Another way is to use the addition function with a second argument of $(S \circ S) \circ Z$, where $Z$ is the zero function that takes no inputs.

I.3.12 Starting with this

\[
is_{\text{zero}}(y) = \begin{cases} 1 & \text{if } y = 0 \\ 0 & \text{if } y = S(z) \end{cases}
\]
we get it to fit the schema by taking $g(x_0, \ldots x_{k-1})$ to be the function of no arguments $S(Z())$ and taking $h(is\_zero(z), x_0, \ldots x_{k-1}, z)$ to be the two-argument zero function.

I.3.13

$$
\begin{array}{c|cccccccccc}
(A) & n & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 \\
\hline
n & 0 & 1 & 2 & 3 & 6 & 10 & 15 & 21 & 28 & 36 & 45 & 55 \\
\end{array}
$$

(b) Writing

$$
t(y) = \begin{cases} 
0 & \text{if } y = 0 \\
h(t(z), z) & \text{if } y = S(z) 
\end{cases}
$$

gives that $g$ is the constant $g = 0$ and that $h(t(z), z) = S(\text{plus}(t(z), z))$.

I.3.14

$$
\begin{array}{c|cccccccccccc}
(A) & n & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 \\
\hline
n & 0 & 1 & 4 & 9 & 16 & 25 & 36 & 49 & 64 & 81 & 100 \\
\end{array}
$$

(b) Writing

$$
s(y) = \begin{cases} 
g() & \text{if } y = 0 \\
h(s(z), z) & \text{if } y = S(z) 
\end{cases}
$$

Here, $g$ is the constant function, the function of no arguments, $g() = 0$. And, $h(s(z), z) = \text{plus}(s(z), \text{pred}(\text{product}(2, S(z))))$.

I.3.15

$$
\begin{array}{c|cccccccccccc}
(A) & n & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 \\
\hline
n & 0 & 1 & 8 & 27 & 64 & 125 \\
\end{array}
$$

(b) Write

$$
d(y) = \begin{cases} 
g() & \text{if } y = 0 \\
h(d(z), z) & \text{if } y = S(z) 
\end{cases}
$$

where $g$ is the constant $g() = 0$ and $h(d(z), z) = S(\text{plus}(d(z), \text{plus}(\text{product}(3, S(z)), \text{product}(3, \text{product}(S(z), S(z))))))$.

I.3.16

$$
\begin{array}{c|cccccccccccc}
(A) & n & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 \\
\hline
n & 1 & 3 & 7 & 15 & 31 & 63 & 127 & 255 & 511 & 1023 \\
\end{array}
$$

(b) Write

$$
H(y) = \begin{cases} 
g() & \text{if } y = 0 \\
h(H(z), z) & \text{if } y = S(z) 
\end{cases}
$$

where $g$ is the constant $g() = 1$ and $h(H(z), z) = S(\text{product}(H(z), 2))$.

I.3.17 The derivation for factorial is this.

$$
\text{fact}(y) = \begin{cases} 
1 & \text{if } y = 0 \\
\text{product}(\text{fact}(z), S(z)) & \text{if } y = S(z) 
\end{cases}
$$

Here $g$ is a function of no inputs $g() = 1$ and $h(a, b) = \text{product}(a, S(b))$.

I.3.18 These are easy to compute by hand. But for fun we can write a program.

```scheme
(define (gcd-euclid n m)
 (if (= m 0)
     n
     (gcd-euclid m (remainder n m)))))
```

This version of the same program will mechanically give us the recursive calls.

```scheme
(define (gcd-euclid-verbose n m)
 (if (= m 0)
     (begin
       (printf " return ~a\n" n)
     n)
     (begin
       (printf " call (gcd-euclid ~a ~a)\n" m (remainder n m))
       (gcd-euclid-verbose m (remainder n m)))))
```
I.3.20

(a) This only takes two steps.

\[
\begin{align*}
&\texttt{call (gcd-euclid 28 12)} \\
&\texttt{call (gcd-euclid 12 4)} \\
&\texttt{call (gcd-euclid 4 0)} \\
&\texttt{return 4}
\end{align*}
\]

(b) This also happens quickly.

\[
\begin{align*}
&\texttt{call (gcd-euclid 104 20)} \\
&\texttt{call (gcd-euclid 20 4)} \\
&\texttt{call (gcd-euclid 4 0)} \\
&\texttt{return 4}
\end{align*}
\]

(c) These two are relatively prime.

\[
\begin{align*}
&\texttt{call (gcd-euclid 309 25)} \\
&\texttt{call (gcd-euclid 25 9)} \\
&\texttt{call (gcd-euclid 9 7)} \\
&\texttt{call (gcd-euclid 7 2)} \\
&\texttt{call (gcd-euclid 2 1)} \\
&\texttt{call (gcd-euclid 1 0)} \\
&\texttt{return 1}
\end{align*}
\]

I.3.19

(a) The constant function that always returns zero \(C_0(\bar{x})\) is included in the definition of primitive recursion, Definition 3.6, as \(Z(\bar{x}) = 0\). The function that always returns 1 is then \(C_1(\bar{x}) \Rightarrow (C_0(\bar{x}))\), the function that returns 2 is \(C_2(\bar{x}) \Rightarrow (\langle C_0(\bar{x})\rangle)\), etc.

(b) Since the parts of the right-hand side of \(\max\{x, y\} = y + (x - y)\) are all primitive recursive, then the max function is also primitive recursive. Similarly for \(\min\{x, y\} = x + y + \max\{x, y\}\).

(c) For any \(x, y \in \mathbb{N}\) either \(x - y \geq 0\) or \(y - x \geq 0\). Thus \(\text{absdiff}\{x, y\} = \text{propersub}\{x, y\} + \text{propersub}\{y, x\}\) and since addition is primitive recursive, \(\text{absdiff}\{x, y\}\) is therefore primitive recursive.

(d) This primitive recursion defines \(\text{sign}\).

\[
\text{sign}(y) = \begin{cases} 
0 & \text{if } y = 0 \\
1 & \text{if } y \Rightarrow (z)
\end{cases}
\]

(e) A primitive recursion will do

\[
\text{negsign}(y) = \begin{cases} 
1 & \text{if } y = 0 \\
0 & \text{if } y \Rightarrow (z)
\end{cases}
\]

but we can also observe that \(\text{negsign}(y) = 1 - \text{sign}(y)\), that is, \(\text{negsign}(y) = \text{propersub}(1, \text{sign}(y))\).

(f) The one is \(\text{lessthan}(x, y) = \text{sign}(\text{propersub}(y, x))\) while the other is \(\text{greaterthan}(x, y) = \text{sign}(\text{propersub}(x, y))\).

I.3.21

(a) The table is straightforward.

\[
\begin{array}{c|cccccccc}
\text{a} & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\
\hline
\text{rem}(a, 3) & 0 & 1 & 2 & 0 & 1 & 2 & 0 & 1
\end{array}
\]

(b) The relationship is not true when \(\text{rem}(a, 3) = 2\).
(c) This follows from the prior item.

\[
\begin{align*}
\text{rem}(a, 3) &= \begin{cases} 
0 & \text{if } a = 0 \\
0 & \text{if } a = S(z) \text{ and } \text{rem}(z, 3) + 1 = 3 \\
\text{rem}(z, 3) + 1 & \text{if } a = S(z) \text{ and } \text{rem}(z, 3) + 1 \neq 3
\end{cases}
\end{align*}
\]

(d) Here is the explicit definition given in the form for primitive recursion.

\[
\begin{align*}
\text{rem}(a, 3) &= \begin{cases} 
0 & \text{if } a = 0 \\
\text{product}(\text{rem}(z, 3)), \text{notequal}(\text{rem}(z, 3), 3) & \text{if } a = S(z)
\end{cases}
\end{align*}
\]

(e) Change the 3’s to b’s.

\[
\begin{align*}
\text{rem}(a, b) &= \begin{cases} 
0 & \text{if } a = 0 \\
\text{product}(\text{rem}(z, b)), \text{notequal}(\text{rem}(z, b), b) & \text{if } a = S(z)
\end{cases}
\end{align*}
\]

I.3.22

(a) The division is easy.

\[
\begin{array}{ccccccccccc}
a & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 \\
\text{div}(a, 3) & 0 & 0 & 0 & 1 & 1 & 1 & 2 & 2 & 2 & 3 & 3
\end{array}
\]

(b) One way to say it is that div(a + 1, 3) = div(a, 3) except when rem(a + 1, 3) = 0.

(c) Based on the prior item, this is the explicit definition given in the form for primitive recursion (again, the order of the two inputs is not important).

\[
\begin{align*}
\text{div}(a, 3) &= \begin{cases} 
0 & \text{if } a = 0 \\
\text{plus}(\text{div}(z, 3), \text{equal}(\text{rem}(z, 3), 0)) & \text{if } a = S(z)
\end{cases}
\end{align*}
\]

(d) Replace the 3’s with b’s.

\[
\begin{align*}
\text{div}(a, b) &= \begin{cases} 
0 & \text{if } a = 0 \\
\text{plus}(\text{div}(z, b), \text{equal}(\text{rem}(z, b), 0)) & \text{if } a = S(z)
\end{cases}
\end{align*}
\]

I.3.23

(a) Since g is given as primitive recursive, this function is also primitive recursive \(h(a, b) = \text{plus}(a, g(b))\) because it uses composition. With that, this primitive recursion will do the bounded sum.

\[
\begin{align*}
f(y) &= \begin{cases} 
0 & \text{if } y = 0 \\
h(f(z), z) & \text{if } y \geq (z)
\end{cases}
\end{align*}
\]

(b) This is similar to bounded sum.

(c) Consider the bounded product function.

\[
P_p(\bar{x}, m) = \prod_{0 \leq i < m} p(\bar{x}, i)
\]

Note that (i) if \(P_p(\bar{x}, m) = 1\) then \(P_p(\bar{x}, i) = 1\) for all \(i < m\), and (ii) if \(P_p(\bar{x}, m) = 0\) then \(P_p(\bar{x}, i) = 0\) for all \(i \geq m\).

Next consider the bounded sum function.

\[
S_{P_p}(\bar{x}, m) = \sum_{0 \leq i < m} P_p(\bar{x}, m)
\]

Because of (i) and (ii), \(S_{P_p}(\bar{x}, m)\) is the least number \(i\) such that \(p(\bar{x}, i) = 0\), as desired.

Now just define \(M(\bar{x}, m)\) by cases.

\[
M(\bar{x}, m) = \begin{cases} 
m & \text{if } S_{P_p}(\bar{x}, m) = 0 \\
S_{P_p}(\bar{x}, m) & \text{otherwise}
\end{cases}
\]
I.3.24  

(a) This is the idea.  

\[ U(\bar{x}, m) = \begin{cases} 1 & \text{if } m = 0 \\ p(\bar{x}, m) \cdot U(\bar{x}, z) & \text{if } m \geq (z) \end{cases} \]

To be formal we have to do some more work such as expressing the multiplication \( p(\bar{x}, m) \cdot U(\bar{x}, z) \) as product(\( p(\bar{x}, m), U(\bar{x}, z) \)).

(b) Take \( E(\bar{x}, m) = 1 - \hat{E}(\bar{x}, m) \), where the latter function is below.

\[ \hat{E}(\bar{x}, m) = \begin{cases} 0 & \text{if } m = 0 \\ (1 - p(\bar{x}, m)) \cdot \hat{E}(\bar{x}, z) & \text{if } m \geq (z) \end{cases} \]

(c) This follows straight from the definition on noting that one suitable bound on the quotient \( k \) is the dividend \( y \), that is, \( \text{divides}(x, y) = \exists k \leq y[y = x \cdot k] \).

(d) As in the prior item, we need only find a suitable bound. Here, \( \text{prime}(y) = 1 \) if and only if both \( 1 < y \) and there is no \( x < y \) with \( x > 1 \) and \( \text{divides}(x, y) \), All of those components are primitive recursive.

I.3.25  

This starts with bounded minimization.

\[ [x/y] = \min_{t \leq x} [(t + 1) \cdot y > x] \]

For instance, \( [9/2] = \min_{t \leq 9} [(t + 1) \cdot 2 > 9] \) gives \( t + 1 = 5 \), so \( t = 4 \). Putting it in terms of previously defined functions, for instance changing the multiplication dot to a call to the plus function, is routine.

I.3.26  

(a) Here are the first eleven values of \( F \).

<table>
<thead>
<tr>
<th>( n )</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F(n) )</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>8</td>
<td>13</td>
<td>21</td>
<td>34</td>
<td>55</td>
</tr>
</tbody>
</table>

I.3.27  

(a) The arithmetic is straightforward. Note the anti-diagonals.

\[ \begin{array}{cccc} \hline x & 0 & 1 & 2 & 3 & 4 \\
0 & 0 & 1 & 3 & 6 & 10 \\
1 & 2 & 4 & 7 & 11 & 16 \\
2 & 5 & 8 & 12 & 17 & 23 \\
3 & 9 & 13 & 18 & 24 & 31 \\
4 & 14 & 19 & 25 & 32 & 40 \\
\hline \end{array} \]

(b) In \( C(x, y) = 0 + 1 + 2 + \cdots + (x + y) + y \), the sum \( x + y \) is primitive recursive from the section body. It then follows that the function \( 0 + 1 + \cdots (x + y) \) is primitive recursive, since it is a bounded sum. With that, adding \( y \) shows that \( C \) is primitive recursive.

I.3.28  

(a) \( P(3, 2) = P(2, 2) + P(2, 1) = P(1, 2) + P(1, 1) + P(1, 1) + P(0, 0) = 0 + 1 + 1 + 1 = 3 \).

(b) \( P(3, 0) = 1, P(3, 1) = 3, P(3, 3) = 1 \).

(c) The row is \( \langle 1, 4, 6, 4, 1 \rangle \).

I.3.29  

This is an implementation.

\[ \begin{array}{l}
\text{(define } (M x))
\quad \text{(if } (\leq x 100))
\quad \text{(M (M (+ x 11))}
\quad \text{(- x 10)))}
\end{array} \]

These are the output values.

\[ M(x) = \begin{cases} 91 & \text{if } x \in \{0, \ldots 101\} \\ x - 10 & \text{otherwise} \end{cases} \]
That this function is primitive recursive follows from Exercise 3.19.

**I.3.30** We use induction. Every initial function in Definition 3.6 is total. Every primitive recursive function is derived from the initial functions using a finite number of applications of function composition and primitive recursion. Both of these combiners yield total function outputs from total function inputs.

**I.3.31** (Davis 1982) Suppose that if two functions \( f, \hat{f} : \mathbb{N}^{n+1} \to \mathbb{N} \) both satisfy Definition 3.2. We will show that for all \( \langle x_0, \ldots, x_n-1, y \rangle \in \mathbb{N}^{n+1} \) the two are equal \( f(x_0, \ldots, x_n-1, y) = \hat{f}(x_0, \ldots, x_n-1, y) \), by induction on \( y \).

For the base step, they are equal when \( y = 0 \) because they both equal \( d(x_0, \ldots, x_n-1) \). For the inductive step, suppose that they are equal for \( y = 0, \ldots, y = k \) and consider the \( y = k + 1 \) case.

\[
f(x_0, \ldots, x_n-1, k + 1) = g(f(x_0, \ldots, x_n-1, k), x_0, \ldots, x_n-1, k)
= g(\hat{f}(x_0, \ldots, x_n-1, k), x_0, \ldots, x_n-1, k) = \hat{f}(x_0, \ldots, x_n-1, k + 1)
\]

The second equality follows from the induction hypothesis.

**I.4.9** The value \( H_4(2,0) = 1 \) is immediate from the definition. Next, \( H_4(2,1) = H_3(2,H_4(2,0)) \), giving \( H_2(2,H_3(2,0)) = H_1(2,H_2(2,0)) = 2 \).

The last three are similar; a script is the best way to proceed. This is a copy of the straightforward transcription given in the section body, for convenience.

```scheme
define (H n x y)
  (cond
   [(= n 0) (+ y 1)]
   [(and (= n 1) (= y 0)) x]
   [(= n 2) 0]
   [(and (> n 2) (= y 0)) 1]
   [else (H (- n 1) x (H n x (- y 1)))]
  )
```

These calls give the answers.

```
> (H 4 2 0)
1
> (H 4 2 1)
2
> (H 4 2 2)
4
> (H 4 2 3)
8
> (H 4 2 4)
65536
```

The last one takes some time; below, the first number is milliseconds of CPU time.

```
> (time (H 4 2 4))
cpu time: 193921 real time: 193804 gc time: 25086
65536
```

Here is the summary.

\[
\begin{array}{cccccc}
  & y & 0 & 1 & 2 & 3 & 4 \\
H(4,2,y) & 1 & 2 & 4 & 16 & 65536 \\
\end{array}
\]

**I.4.10** We can get the values with Lemma 4.2, or the Racket procedure given in the section body.

```
> (for ([y (in-range 10)])
    (printf "(~a,~a) ,
" y (H 1 2 y)))
(0,2) ,
(1,3) ,
(2,4) ,
(3,5) ,
(4,6) ,
(5,7) ,
(6,8) ,
(7,9) ,
(8,10) ,
(9,11) ,
```

This summarizes the output.
Here is a graph.

<table>
<thead>
<tr>
<th>( y )</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H_1(2, y) )</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>( H_2(2, y) )</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td>10</td>
<td>12</td>
<td>14</td>
<td>16</td>
<td>18</td>
</tr>
<tr>
<td>( H_3(2, y) )</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>8</td>
<td>16</td>
<td>32</td>
<td>64</td>
<td>128</td>
<td>256</td>
<td>512</td>
</tr>
</tbody>
</table>

I.4.11 A script yields that \( H_4(3, 3) = 7625797484987 \). If that is seconds then the number of years is about 241 645.76.

I.4.12 We have that \( H_3(3, 3) = 27 \) and \( H_2(2, 2) = 4 \) so the ratio is 6.75.

I.4.13 The proof of Lemma 4.2 shows that \( H_1(x, y) = x + y \). The definition of \( H \) gives

\[
H_2 = \begin{cases} 0 & \text{if } y = 0 \\ H_2(x, H_1(x, y - 1)) & \text{otherwise} \end{cases}
\]

and we will use induction to show \( H_2(x, y) = x \cdot y \). The base step is part of that definition. So suppose that \( H_2(x, y) = x \cdot y \) for \( y = 0, 1, \ldots, k \). For \( y = k + 1 \),

\[
H_2(x, y) = H_1(x, x \cdot k) = x + x \cdot k = x \cdot (1 + k) = x \cdot y
\]

(because \( y = k + 1 \) the ‘otherwise’ branch applies).

The other equality is similar. The key step is \( H_3(x, y) = H_2(x, H_3(x, k)) = H_2(x, x^k) = x \cdot x^k = x^{k+1} = x^y \).

I.4.14 Writing a small script makes the job of computing easier. Here is the table of values.

<table>
<thead>
<tr>
<th>( y )</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k = 0 )</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>( k = 1 )</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>( k = 2 )</td>
<td>3</td>
<td>5</td>
<td>7</td>
<td>9</td>
<td>11</td>
<td>13</td>
<td>15</td>
<td>17</td>
<td>19</td>
<td>21</td>
</tr>
<tr>
<td>( k = 3 )</td>
<td>5</td>
<td>13</td>
<td>29</td>
<td>61</td>
<td>125</td>
<td>253</td>
<td>513</td>
<td>1025</td>
<td>2049</td>
<td>4097</td>
</tr>
<tr>
<td>( k = 4 )</td>
<td>13</td>
<td>65</td>
<td>533</td>
<td>1025</td>
<td>2049</td>
<td>4097</td>
<td>8193</td>
<td>16385</td>
<td>32769</td>
<td>65533</td>
</tr>
</tbody>
</table>

I.4.15 In each application of the recursion, either the first argument decreases or else the first argument remains the same and the third argument decreases. Further, each time that the third argument reaches zero, the first argument decreases, so it eventually reaches zero as well. If the first argument is zero then the computation terminates.

I.4.16 No. All such functions are total, they halt on all inputs, while some computable functions are not total.

I.4.17 This Racket program illustrates the definition.

```racket
(define (g x y)
  (+ x y))
```
\( (\text{define } (f \ x)) \)
\( (\text{define } (f-\ \text{helper } x \ y)) \)
\( (\text{if } (= 100 (g \ x \ y)) \)
\( y \)
\( (f-\ \text{helper } x \ (* 1 \ y)))) \)
\( (\text{let } ([y \ 0]) \)
\( (f-\ \text{helper } x \ 0))) \)

(a) \( f(0) = 100 \)
(b) \( f(1) = 99 \)
(c) \( f(50) = 50 \)
(d) \( f(100) = 0 \)
(e) This is not defined.

This is another description of \( f \).

\[ f(x) = \begin{cases} 
100 - x & \text{if } x \leq 100 \\
\text{undefined} & \text{otherwise}
\end{cases} \]

I.4.18

(a) This Racket script helps with the calculations.

\[
\begin{align*}
\text{;; g Function given in exercise} \\
& (\text{define } (g \ x \ y)) \\
& \quad (\text{ceiling } ( - ((/ (\text{add!} \ x) (\text{add!} \ y))) )) \\
\text{;; f Compute from g by mu-recursion} \\
& (\text{define } (f \ x)) \\
& \quad (\text{define } (f-\ \text{helper } y)) \\
& \quad \quad (\text{if } (= 0 (g \ x \ y)) \\
& \quad \quad \quad y) \\
& \quad \quad (f-\ \text{helper } (\text{add!} \ y))) \\
& \quad (\text{let } ([y \ 0]) \)
& \quad (f-\ \text{helper } x \ 0)))
\end{align*}
\]

This table gives \( f(x) \) for \( 0 \leq x < 6 \) and includes the relevant values of \( g(x, y) \).

<table>
<thead>
<tr>
<th>( g(x, y) )</th>
<th>( y = 0 )</th>
<th>( y = 1 )</th>
<th>( y = 2 )</th>
<th>( y = 3 )</th>
<th>( y = 4 )</th>
<th>( y = 5 )</th>
<th>( f(x) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x = 0 )</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>( x = 1 )</td>
<td>1</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>( x = 2 )</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>( x = 3 )</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>( x = 4 )</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>( x = 5 )</td>
<td>5</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>5</td>
</tr>
</tbody>
</table>

(b) We will argue that \( f(x) = x \). Fix \( x \). To have \( g(x, y) = 0 \) we need that \( (x + 1)/(y + 1) \) is less than or equal to 1. The first \( y \) giving that is \( x \).

I.4.19 We can compute \( f(x) \) by running the machine until it halts. This is the computation with \( x = 0 \).
Here is the computation with input $x = 1$.

<table>
<thead>
<tr>
<th>Step</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>$q_0$</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>$q_0$</td>
</tr>
<tr>
<td>2</td>
<td>1 1</td>
</tr>
<tr>
<td></td>
<td>$q_1$</td>
</tr>
</tbody>
</table>

The same for $x = 2$.

<table>
<thead>
<tr>
<th>Step</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1 1</td>
</tr>
<tr>
<td></td>
<td>$q_0$</td>
</tr>
<tr>
<td>1</td>
<td>1 1</td>
</tr>
<tr>
<td></td>
<td>$q_0$</td>
</tr>
<tr>
<td>2</td>
<td>1 1 1</td>
</tr>
<tr>
<td></td>
<td>$q_0$</td>
</tr>
</tbody>
</table>

This is 3.

<table>
<thead>
<tr>
<th>Step</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1 1 1</td>
</tr>
<tr>
<td></td>
<td>$q_0$</td>
</tr>
<tr>
<td>1</td>
<td>1 1 1</td>
</tr>
<tr>
<td></td>
<td>$q_0$</td>
</tr>
<tr>
<td>2</td>
<td>1 1 1 1</td>
</tr>
<tr>
<td></td>
<td>$q_0$</td>
</tr>
</tbody>
</table>

This is 4.

<table>
<thead>
<tr>
<th>Step</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1 1 1 1</td>
</tr>
<tr>
<td></td>
<td>$q_0$</td>
</tr>
<tr>
<td>1</td>
<td>1 1 1 1</td>
</tr>
<tr>
<td></td>
<td>$q_0$</td>
</tr>
<tr>
<td>2</td>
<td>1 1 1 1 1</td>
</tr>
<tr>
<td></td>
<td>$q_0$</td>
</tr>
</tbody>
</table>

Finally, this is the computation for $f(5)$.
This table summarizes.

<table>
<thead>
<tr>
<th>Step</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1 1 1 1 1 q₀</td>
</tr>
<tr>
<td>1</td>
<td>1 1 1 1 1 q₀</td>
</tr>
<tr>
<td>2</td>
<td>1 1 1 1 1 q₀</td>
</tr>
<tr>
<td>3</td>
<td>1 1 1 1 1 q₀</td>
</tr>
<tr>
<td>4</td>
<td>1 1 1 1 1 q₀</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1 1 1 1 1 q₀</td>
</tr>
<tr>
<td>6</td>
<td>1 1 1 1 1 q₁</td>
</tr>
<tr>
<td>7</td>
<td>1 1 1 1 1 q₁</td>
</tr>
<tr>
<td>8</td>
<td>1 1 1 1 1 q₁</td>
</tr>
<tr>
<td>9</td>
<td>1 1 1 1 1 q₁</td>
</tr>
</tbody>
</table>

This is the same for $x = 2$.

<table>
<thead>
<tr>
<th>Step</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1 1 1 1 1 q₀</td>
</tr>
<tr>
<td>1</td>
<td>1 1 1 1 1 q₁</td>
</tr>
<tr>
<td>2</td>
<td>1 1 1 1 1 q₂</td>
</tr>
</tbody>
</table>

To compute $f(x)$ we can run the machine until it halts. This is the computation with $x = 0$,

<table>
<thead>
<tr>
<th>Step</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1 1 1 1 1 q₀</td>
</tr>
<tr>
<td>1</td>
<td>1 1 1 1 1 q₂</td>
</tr>
</tbody>
</table>

and this is the computation with input $x = 1$.

This is the same for $x = 2$.

<table>
<thead>
<tr>
<th>Step</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1 1 1 1 1 q₀</td>
</tr>
<tr>
<td>1</td>
<td>1 1 1 1 1 q₁</td>
</tr>
<tr>
<td>2</td>
<td>1 1 1 1 1 q₂</td>
</tr>
</tbody>
</table>

The $x = 3$ computation does this.
This is $x = 4$.

Finally, this is the computation for $f(5)$.

The table below summarizes.

<table>
<thead>
<tr>
<th>$x$</th>
<th>$0$</th>
<th>$1$</th>
<th>$2$</th>
<th>$3$</th>
<th>$4$</th>
<th>$5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f(x)$</td>
<td>$2$</td>
<td>$3$</td>
<td>$3$</td>
<td>$3$</td>
<td>$3$</td>
<td>$3$</td>
</tr>
</tbody>
</table>

For this machine the running time is constant. The machine in the prior exercise does the same job but its running time is a linear function of the input size.

**I.4.21** One way to compute $f(x)$ is to run the machine until it halts.

(A) This is the computation with $x = 0$.

(b) This is $x = 1$.  

(A) This is the computation with $x = 0$.

(b) This is $x = 1$.  

(A) This is the computation with $x = 0$.

(b) This is $x = 1$.  

(A) This is the computation with $x = 0$.

(b) This is $x = 1$.  

(A) This is the computation with $x = 0$.

(b) This is $x = 1$.  

(A) This is the computation with $x = 0$.

(b) This is $x = 1$.  

(A) This is the computation with $x = 0$.

(b) This is $x = 1$.  

(A) This is the computation with $x = 0$.

(b) This is $x = 1$.  

(A) This is the computation with $x = 0$.

(b) This is $x = 1$.  

(A) This is the computation with $x = 0$.

(b) This is $x = 1$.  

(A) This is the computation with $x = 0$.

(b) This is $x = 1$.  

(A) This is the computation with $x = 0$.

(b) This is $x = 1$.  

(A) This is the computation with $x = 0$.

(b) This is $x = 1$.  

(A) This is the computation with $x = 0$.

(b) This is $x = 1$.  

(A) This is the computation with $x = 0$.
Step Configuration

<table>
<thead>
<tr>
<th>Step</th>
<th>Configuration</th>
</tr>
</thead>
</table>
| 0    | 1 1
|      | q0           |
| 1    | 1 1
|      | q1           |
| 2    | 1 1          |
|      | q2           |

(c) This is the same for \( x = 2 \).

Step Configuration

<table>
<thead>
<tr>
<th>Step</th>
<th>Configuration</th>
</tr>
</thead>
</table>
| 3    | 1 1
|      | q3           |
| 4    | 1 1
|      | q4           |

(d) The table summarizes.

\[
\begin{array}{c|ccc}
 x & 0 & 1 & 2 \\
 \hline
 f(x) & 4 & 4 & 4 \\
\end{array}
\]

This machine ignores its input, moves right two squares and back left two, and then halts. So its running time is constant, \( f(x) = 4 \).

I.2 These are not too hard to compute by hand, but a small program is also handy.

(a) The script gives this.

\[
\begin{align*}
> & \ (H \ 4) \\
> & \ (H \ (H \ 4)) \\
> & \ (H \ (H \ (H \ 4)))
\end{align*}
\]

So \( H(4, 1) = 2, H(4, 2) = 1, H(4, 3) = 4 \).

(b) The script says this.

\[
\begin{align*}
> & \ (C \ 4) \\
> & \ 2
\end{align*}
\]

So \( C(4) = 2 \), which matches the result of the prior item.

(c) Here are the successive values.

\[
\begin{align*}
> & \ (H \ 5) \\
> & \ (H \ (H \ 5)) \\
> & \ (H \ (H \ (H \ 5)))
\end{align*}
\]
Thus \( C(5) = 5 \), which agrees with the program’s result.

\[
\begin{array}{l}
> \ (0 5) \\
5
\end{array}
\]

(d) The successive values are 11, 34, 17, 52, 26, 13, 40, 20, 10, 5, 16, 8, 4, 2, and 1, so \( C(11) = 14 \).

(e) Here are the values.

<table>
<thead>
<tr>
<th>( n )</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C(n) )</td>
<td></td>
<td>0</td>
<td>1</td>
<td>7</td>
<td>2</td>
<td>5</td>
<td>8</td>
<td>16</td>
<td>3</td>
<td>19</td>
<td>6</td>
<td>14</td>
<td>9</td>
<td>9</td>
<td>17</td>
<td>15</td>
<td>4</td>
<td>12</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

Figure 1 on page 28 shows that XKCD has something to say about the Collatz conjecture.

I.A.1 This command line run starts with five 1’s.

```
$ ./turing-machine.rkt -f machines/pred.tm -c "1" -r "1111"
step 0: q0: *11111
step 1: q0: 1*1111
step 2: q0: 11*111
step 3: q0: 111*11
step 4: q0: 1111*1
step 5: q0: 11111*B
step 6: q1: 11111*B
step 7: q1: 1111*B
step 8: q2: 11*11BB
step 9: q2: 111*1BB
step 10: q2: 1111*BB
step 11: q2: 11111*BB
step 12: q2: *B*1111BB
step 13: q3: B*1111BB
step 14: HALT
```

Here it is looking like the tape.
This is the command line invocation for an empty tape,

```
$ ./turing-machine.rkt -f machines/pred.tm -c ""
step 0: q0: *B*
step 1: q1: *B*B
step 2: q2: *B*BB
step 3: q3: B*B*B
step 4: HALT
```

and the matching sequence of tape diagrams.

```
<table>
<thead>
<tr>
<th>Step</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<tr>
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</tr>
<tr>
<td>3</td>
<td>q0</td>
</tr>
<tr>
<td>4</td>
<td>q0</td>
</tr>
</tbody>
</table>
```

I.A.2  This simulates $1 + 2$.

```
$ ./turing-machine.rkt -f machines/pred.tm -c "1" -r "11"
step 0: q0: *1* 11
step 1: q0: 1*B *11
step 2: q1: 1*B *11
step 3: q1: 1*1*11
step 4: q2: 1*1*11
step 5: q2: *1*11
step 6: q2: *B*11
step 7: q3: *B*11
step 8: q3: B*1*11
step 9: q4: B*1*11
step 10: q5: B*B*1*11
step 11: HALT
```

and this is the matching tape diagram.
### Step Configuration

<table>
<thead>
<tr>
<th>Step</th>
<th>Configuration</th>
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</thead>
<tbody>
<tr>
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<tr>
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<tbody>
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<td>9</td>
<td>1 1 1 1 1 q4</td>
</tr>
<tr>
<td>10</td>
<td>1 1 1 1 1 q5</td>
</tr>
</tbody>
</table>

The command line for $0 + 2$

```bash
$ ./turing-machine.rkt -f machines/pred.tm -c "" -f "11"
```
gives these tape diagrams.

<table>
<thead>
<tr>
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<th>Configuration</th>
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</thead>
<tbody>
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<td>0</td>
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<tr>
<td>3</td>
<td>1 1 1 1 1 q1</td>
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<th>Configuration</th>
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</thead>
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<td>1 1 1 1 1 q2</td>
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<td>7</td>
<td>1 1 1 1 1 q2</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Step</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>1 1 1 1 1 q3</td>
</tr>
<tr>
<td>9</td>
<td>1 1 1 1 1 q4</td>
</tr>
<tr>
<td>10</td>
<td>1 1 1 1 1 q5</td>
</tr>
</tbody>
</table>

The command line for $0 + 0$

```bash
$ ./turing-machine.rkt -f machines/pred.tm -c ""
```
gives this sequence of tape diagrams.

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<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>1 1 1 1 1 q1</td>
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<td>2</td>
<td>1 1 1 1 1 q1</td>
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<table>
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<tr>
<th>Step</th>
<th>Configuration</th>
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<td>3</td>
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<td>1 1 1 1 1 q2</td>
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<td>5</td>
<td>1 1 1 1 1 q2</td>
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<table>
<thead>
<tr>
<th>Step</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>1 1 1 1 1 q3</td>
</tr>
<tr>
<td>7</td>
<td>1 1 1 1 1 q4</td>
</tr>
<tr>
<td>8</td>
<td>1 1 1 1 1 q5</td>
</tr>
</tbody>
</table>

### I.A.3 This ten-instruction machine

\[ \mathcal{P}_{\text{addthree}} = \{ q_0 1 R q_0, q_0 B B q_1, q_1 B 1 q_1, q_1 1 R q_2, q_2 B 1 q_2, q_2 1 R q_3, q_3 B 1 q_3, q_3 1 L q_4, q_4 1 L q_4, q_4 B R q_5 \} \]

matches the source for the simulator.
This command line for input 4

\[ ./turing-machine.rkt -f machines/addthree.tm -c "1" -r "111" \]

gives these tape diagrams.

The command line for 0

\[ ./turing-machine.rkt -f machines/addthree.tm -c " " \]

gives this sequence of tape diagrams.

I.A.4

(a) Something like this will do.

\[ P_0 = \{ q_{10}\emptyset q_{10}, q_{10}1q_{10}, q_{10}\emptyset\emptyset q_{100} \} \]

(b) This will back up, blanking out cells.

\[ P_1 = \{ q_{20}\emptyset Bq_{21}, q_{20}1Bq_{21}, q_{20}\emptyset\emptyset Bq_{100}, q_{21}\emptyset Lq_{20}, q_{21}1Lq_{20}, q_{21}\emptyset Lq_{20} \} \]

(c) Here, roughly \( q_0 \) is where none of the substring is matched, \( q_1 \) is where \( \emptyset \) has been seen and the machine is looking for the 1, and \( q_2 \) is where \( \emptyset 1 \) has been seen and the machine is looking for the 0. Then the four states \( q_3, q_4, q_5, \) and \( q_6 \) mark a failure (they end with \( q_6 \) writing \( \emptyset \) on a blank tape). The four states \( q_7, q_8, \)
\(q_9\), and \(q_{10}\) mark a success.

\[P_{\text{decide}010} = \{q_00Rq_1, q_01Rq_0, q_00BBq_3, q_10Rq_1, q_11Rq_2, q_20Rq_7, q_211q_0, q_22BBq_3, q_30Rq_3, q_31Rq_3, q_33BLq_4, q_40BBq_5, q_41Bq_5, q_42BBq_6, q_50Lq_4, q_51Lq_4, q_52BLq_4, q_60Rq_{100}, q_610q_{100}, q_620q_{100}, q_70Rq_7, q_71lq_7, q_72BLq_8, q_80BBq_9, q_81Bq_9, q_82BBq_{10}, q_90Lq_8, q_91Lq_8, q_92BLq_8, q_{10}01q_{100}, q_{10}11q_{100}, q_{10}B1q_{100}\}

I.B.1

(a) This is a table for \((P \land Q) \land R\).

<table>
<thead>
<tr>
<th>(P)</th>
<th>(Q)</th>
<th>(R)</th>
<th>(P \land Q)</th>
<th>((P \land Q) \land R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
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</tbody>
</table>

(b) And this is a table for \(P \land (Q \land R)\). It has the same final column as the one from the prior item.

<table>
<thead>
<tr>
<th>(P)</th>
<th>(Q)</th>
<th>(R)</th>
<th>(Q \land R)</th>
<th>(P \land (Q \land R))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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</table>

(c) This is a table for \(P \land (Q \lor R)\).

<table>
<thead>
<tr>
<th>(P)</th>
<th>(Q)</th>
<th>(R)</th>
<th>(Q \lor R)</th>
<th>(P \land (Q \lor R))</th>
</tr>
</thead>
<tbody>
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</tr>
</tbody>
</table>

(d) And this is a table for \((P \land Q) \lor (P \land R)\). It has the same final column as the prior item.

<table>
<thead>
<tr>
<th>(P)</th>
<th>(Q)</th>
<th>(R)</th>
<th>(P \land Q)</th>
<th>(P \land R)</th>
<th>((P \land Q) \lor (P \land R))</th>
</tr>
</thead>
<tbody>
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</tbody>
</table>
I.B.2

(a) This is a table for $\neg(P \lor Q)$.

<table>
<thead>
<tr>
<th>P</th>
<th>Q</th>
<th>P $\lor$ Q</th>
<th>$\neg(P \lor Q)$</th>
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</thead>
<tbody>
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</table>

(b) The same for $\neg P \land \neg Q$.

<table>
<thead>
<tr>
<th>P</th>
<th>Q</th>
<th>$\neg P$</th>
<th>$\neg Q$</th>
<th>$\neg P \land \neg Q$</th>
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<tbody>
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<td>0</td>
</tr>
</tbody>
</table>

It has the same final column as the prior item.

(c) This is a table for $\neg (P \land Q)$.

<table>
<thead>
<tr>
<th>P</th>
<th>Q</th>
<th>P $\land$ Q</th>
<th>$\neg (P \land Q)$</th>
</tr>
</thead>
<tbody>
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</tbody>
</table>

(d) This is the one for $\neg P \lor \neg Q$.

<table>
<thead>
<tr>
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<th>Q</th>
<th>$\neg P$</th>
<th>$\neg Q$</th>
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</tbody>
</table>

The final column is the same as the final column of the prior item.

I.C.4 It takes 17331 turns to stabilize.

I.D.8 From two arguments $k$ and $y$, either $k$ decreases or $k$ is fixed and $y$ decreases. When $y$ reaches zero then $k$ decreases, so it eventually reaches zero as well, and $A(0, y)$ obviously terminates.

I.D.11 *All the parts of $A$ are primitive recursive but as a whole it is not?* Yes. It is a question of uniformity. Imagine that we have an enumeration of the primitive recursive functions $f_0, f_1, \ldots$. Perhaps $A_0 = f_0$, and $A_1 = f_{121}$, and $A_2 = f_{800}$. But the function associating the subscript on the $A$ with the subscript on the $f$ is not primitive recursive.
Chapter II: Background

II.1.19 To show that the map is one-to-one we will show that $g(n) = g(\hat{n})$ can only happen if $n = \hat{n}$. So let $g(n) = g(\hat{n})$, giving $3n = 3\hat{n}$. Divide by three to get $n = \hat{n}$.
   To show the map is onto we will show that every member of the codomain $y \in \{3k \mid k \in \mathbb{N}\}$ is mapped-to by some member of the domain. Because $y$ is a multiple of three, $y/3$ is a natural number. Of course, $y = g(y/3)$, so $y$ is indeed the image of some member of the domain.

II.1.20 This is a type error. It is not the sets that are one-to-one or onto; rather, it is a function $f$ between the sets. (For $D = \{n^2 \mid n \in \mathbb{N}\}$ and $C = \{n^3 \mid n \in \mathbb{N}\}$ the natural such function $f : D \to C$ is $f(n) = n^{3/2}$.)

II.1.21
   (a) The function $f : \mathbb{Z} \to \mathbb{Z}$ given by $f(x) = 2x$ is one-to-one but not onto. Verifying that it is one-to-one is routine: assume that $f(x) = f(\hat{x})$ for $x, \hat{x} \in \mathbb{Z}$, so that $2x = 2\hat{x}$, and then cancel the 2’s to get that $x = \hat{x}$.
   To show that it is not onto we need only name one codomain element $y \in \mathbb{Z}$ that is not the image of any domain element. One such is $y = 1$, since the image of every domain element is even.
   (b) The function $g : \mathbb{Z} \to \mathbb{Z}$ given by $g(x) = 2x - 1$ is also one-to-one but not onto. The one-to-one argument works just as it did in the prior item: assume that $g(x) = g(\hat{x})$ for $x, \hat{x} \in \mathbb{Z}$ so that $2x - 1 = 2\hat{x} - 1$. Add 1 to both sides and cancel the 2’s to get $x = \hat{x}$. This function is not onto because the codomain element $y = 2$ is not the image of any domain element, since it is even but the number $2x - 1$ is odd for any input integer $x$.
   (c) They are not inverse. For instance, $f \circ g(1) = f(g(1)) = f(1) = 2$.

II.1.22
   (a) The function $f : \mathbb{N} \to \mathbb{N}$ given by $f(n) = n + 1$ is one-to-one but not onto. To check that it is one-to-one suppose that $f(n_0) = f(n_1)$ for $n_0, n_1 \in \mathbb{N}$, so that $n_0 + 1 = n_1 + 1$, and then subtract 1 from both sides to get $n_0 = n_1$. It is not onto because the codomain element 0 $\in \mathbb{N}$ is not the image of any domain element.
   (b) The map $f : \mathbb{Z} \to \mathbb{Z}$ given by $f(n) = n + 1$ is a correspondence — it is both one-to-one and onto. The verification that it is one-to-one goes: assume that $f(n_0) = f(n_1)$ so that $n_0 + 1 = n_1 + 1$, and subtract 1 to conclude that $n_0 = n_1$. The verification that it is onto goes: fix some codomain element $y \in \mathbb{Z}$ and note that $x = y - 1$ is a domain element which satisfies that $f(x) = y$.
   (c) The function $f : \mathbb{N} \to \mathbb{N}$ defined by $f(n) = 2n$ is one-to-one but not onto. For one-to-one, assume that $n_0, n_1 \in \mathbb{N}$ are such that $f(n_0) = f(n_1)$. Then $2n_0 = 2n_1$ and cancelling the 2’s gives that $n_0 = n_1$. It is not onto because the codomain element $y = 1$ is not the image of any domain element, since all such images are even.
   (d) The function $f : \mathbb{Z} \to \mathbb{Z}$ defined by $f(n) = 2n$ is one-to-one but not onto. The one-to-one verification is as in the prior item: suppose that $f(n_0) = f(n_1)$ for some $n_0, n_1 \in \mathbb{Z}$, so that $2n_0 = 2n_1$, and cancel the 2’s to conclude that $n_0 = n_1$. Also as in the prior item, this map is not onto because the codomain element $y = 1$ is not in the range of the function, as all of the range elements are even.
   (e) The function $f : \mathbb{Z} \to \mathbb{N}$ given by $f(n) = |n|$ is not one-to-one but it is onto. It is not one-to-one because the two domain elements $n_0 = -1$ and $n_1 = 1$ map to the same output, $f(n_0) = 2 = f(n_1)$. To show that $f$ is an onto map consider a codomain element $y \in \mathbb{N}$, and observe that if we take the domain element $x \in \mathbb{Z}$ such that $x = y$ then $f(x) = y$.

II.1.23
   (a) This function is a correspondence. To verify that it is one-to-one suppose that $f(q_0) = f(q_1)$ for $q_0, q_1 \in \mathbb{Q}$, so that $q_0 + 3 = q_1 + 3$, and subtract 3 from both sides to get that $q_0 = q_1$. For onto, consider a codomain element $y \in \mathbb{Q}$ and observe that the domain element $q \in \mathbb{Q}$ given by $q = y - 3$ satisfies that $f(q) = y$.
   (b) This function is not a correspondence. It is not onto because the codomain element $1/2 \in \mathbb{Q}$ is not the image of any domain element $z \in \mathbb{Z}$, since each such image $f(z) = z + 3$ is an integer. (This function is
one-to-one: suppose that \( f(z_0) = f(z_1) \), so that \( z_0 + 3 = z_1 + 3 \), and subtract 3 from both sides to conclude that \( z_0 = z_1 \). But because it is not onto, it is not a correspondence.

(c) This is not a correspondence. It is not even a function, because it is not well-defined—the two \( q_0 = 1/2 \) and \( q_1 = 2/4 \) are equal, \( q_0 = q_1 \), but they are not associated with the same \( |a \cdot b|'s \) since \( |1 \cdot 2| = 2 \) and \( |2 \cdot 4| = 8 \).

\[ \text{Verified II.1.24} \]

(a) This set is finite. It has the same cardinality as \( I = \{0, 1, 2\} \), as witnessed by the function \( f: I \to \{0, 1, 2, 3\} \) given by \( f(x) = x + 1 \), which is one-to-one and onto by inspection.

(b) The set \( S = \{0, 1, 2, 3, 4, 5, 16, \ldots\} \) of perfect squares is infinite. There is no correspondence between some \( I = \{0, 1, \ldots n - 1\} \) and \( S \) since there is no onto function— for any \( f: I \to S \) the set \( \{f(0), f(1), \ldots f(n - 1)\} \) cannot equal \( S \) because it has a largest element but \( S \) has no largest element.

(c) The set of primes is infinite. The argument from the prior item applies.

(b) By the Fundamental Theorem of Arithmetic, a fifth degree polynomial has at most five real number roots. Thus this set has cardinality at most five, and so is finite.

\[ \text{Verified II.1.25} \]

(a) The map \( f: \{0, 1, 2\} \to \{3, 4, 5\} \) given by \( f(0) = 3, f(1) = 4, \) and \( f(2) = 5 \), that is, \( f(x) = x + 3 \), is a correspondence. By inspection each element of the codomain is associated with one and only one element of the domain.

(b) The function \( f(x) = x^3 \) is a correspondence between these sets. For each perfect cube there is one and only one associated integer cube root.

\[ \text{Verified II.1.26} \]

(a) The function \( f \) given by \( 0 \mapsto \pi, 1 \mapsto \pi + 1, 3 \mapsto \pi + 2, \) and \( 7 \mapsto \pi + 3 \) is both one-to-one and onto, by inspection.

(b) Let \( E = \{2n \mid n \in \mathbb{N}\} \) and \( S = \{n^2 \mid n \in \mathbb{N}\} \). Consider the map \( f: E \to S \) given by \( f(x) = (x/2)^2 \). To show that \( f \) is one-to-one, suppose that \( f(x_0) = f(x_1) \). Then \( (x_0/2)^2 = (x_1/2)^2 \) and because these are natural numbers their square roots are equal, \( x_0/2 = x_1/2 \). Thus \( x_0 = x_1 \) and the map is one-to-one.

For onto, consider \( y \in S \). Because \( y \) is a perfect square there is a natural number \( n \in \mathbb{N} \) so that \( y = n^2 \). Let \( x = 2n \). Clearly \( x \) is even and \( f(x) = y \).

(c) The second interval is \( 2/3 \)-ths of the width of the first, so consider the function \( f(x) = (2/3) \cdot x - (5/3) \). It is one-to-one because \( f(x_0) = f(x_1) \) implies that \( (2/3) \cdot x_0 - (5/3) = (2/3) \cdot x_1 - (5/3) \), and straightforward algebra gives that \( x_0 = x_1 \). To show that \( f \) is onto, fix \( y \in (-1..1) \). Let \( x = (y + (5/3)) / (2/3) \) (this came from solving \( y = (2/3)x - (5/3) \) for \( x \)). When \( y \) is an element of the codomain \((-1..1)\) then this \( x \) is an element of the domain \((1..4)\), and more algebra shows that \( f(x) = y \).

\[ \text{Verified II.1.27} \]

The problem statement is ambiguous as to which set is the domain and which is the codomain. We will prove that \( f: (0..1) \to (1..\infty) \) given by \( f(x) = 1/x \) is one-to-one and onto.

For one-to-one assume that \( f(x_0) = f(x_1) \), where \( x_0, x_1 \in (0..1) \). Then \( 1/x_0 = 1/x_1 \) and cross-multiplication gives \( x_1 = x_0 \). For onto suppose that \( y \in (1..\infty) \) and note that if \( x = 1/y \) then \( f(x) = y \) and also \( x \in (0..1) \).

\[ \text{Verified II.1.28} \]

Call the sets \( D = \{1, 2, 3, 4, \ldots\} \) and \( C = \{7, 10, 13, 16, \ldots\} \). We will show that the function \( f: D \to C \) described by the formula \( f(x) = 3(x - 1) + 7 \) gives a correspondence between the sets. This function is one-to-one since \( f(x_0) = f(x_1) \) implies that \( 3(x_0 - 1) + 7 = 3(x_1 - 1) + 7 \), and subtracting 7, dividing by 3, and adding 1 gives that \( x_0 = x_1 \). It is onto because if \( y \) is an element of the codomain \( C \) then it has the form \( y = 3n + 4 \) for \( n \in \mathbb{N}^+ \). That equation gives \( y = 3(n - 1) + 7 \). Some algebra gives \( (y - 7)/3 = n - 1 \) for \( n \in \mathbb{N}^+ \) and we have that \( n = ((y - 7)/3) + 1 \) is an element of \( \mathbb{N}^+ = D \) with \( f(n) = y \).

\[ \text{Verified II.1.29} \]

(a) The obvious map is this.

<table>
<thead>
<tr>
<th>( x )</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f(x) )</td>
<td>48</td>
<td>49</td>
<td>50</td>
<td>51</td>
<td>52</td>
<td>53</td>
<td>54</td>
<td>55</td>
<td>56</td>
<td>57</td>
</tr>
</tbody>
</table>

It is one-to-one by inspection, meaning that looking over the association shows that never do two different domain elements map to the same codomain element. Similarly, it is also onto by inspection.
(b) The inverse map associates the same pairs of elements in the prior item’s table, but the domain and codomain swap places so here $A$ is the domain and $C$ is the codomain.

<table>
<thead>
<tr>
<th>$x$</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y$</td>
<td>48</td>
<td>49</td>
<td>50</td>
<td>51</td>
<td>52</td>
<td>53</td>
<td>54</td>
<td>55</td>
<td>56</td>
<td>57</td>
</tr>
</tbody>
</table>

As in the prior item, this map is one-to-one and onto by inspection.

**Verified II.1.30** For each pair of sets we could define a function whose domain is the first set, or a function whose domain is the second set. We choose whichever is convenient.

(a) Write the even numbers as $E = \{2n \mid n \in \mathbb{N}\}$. Consider the function $f : \mathbb{N} \to E$ defined by $f(m) = 2m$. To verify that $f$ is one-to-one, assume that two inputs yield the same output $f(m) = f(\hat{m})$, giving $2m = 2\hat{m}$, and divide by 2 to get that therefore the two inputs are the same, $m = \hat{m}$.

To verify that $f$ is onto, consider a member of the codomain $y \in E$, so that $y = 2n$ for some $n \in \mathbb{N}$. Now, $n = y/2$ has the property that $f(n) = y$. Note that $n$ is an element of the domain $\mathbb{N}$ because as a member of the codomain, $y$ is even, and thus dividing by two yields a natural number.

(b) Write the odd numbers as $M = \{2n + 1 \mid n \in \mathbb{N}\}$. Consider $g : \mathbb{N} \to M$ given by $n \mapsto 2n + 1$. To verify that $g$ is one-to-one, assume that $g(m_0) = g(m_1)$, so that $2m_0 + 1 = 2m_1 + 1$, subtract 1, and divide by 2, to conclude that $m_0 = m_1$.

To verify that $g$ is onto, start with an element of the codomain $y \in M$. Then it has the form $y = 2k + 1$ for some natural number $k$. That means there is a natural number $k$ that maps under $g$ to $y$, namely $k = (y-1)/2$.

(c) One answer is to cite the two prior exercise parts and that the inverse of a correspondence is also a correspondence, to get that the composition $g \circ f^{-1}$ is a correspondence from the even numbers to the odds.

A direct answer is to consider the map $p : E \to M$ given by $p(n) = n + 1$. Verify that $p$ is one-to-one and onto as in the prior two items.

**Verified II.1.31** The natural correspondence $f_0 : (0..1) \to (0..2)$ is $f_0(x) = 2x$. For the other two there are many choices but two more correspondences $f_0, f_1, f_2 : (0..1) \to (0..2)$ are $f_1(x) = 2 - 2x$ and $f_2(x) = 2x^2$. Figure 2 on page 37 shows the three graphs. They are different functions because they return different values on the input $x = 1/3$.

Each function is one-to-one and onto because the figure shows that every horizontal line at $y \in (0..2)$ intercepts its graph in one and only one point.

For an algebraic verification that they are correspondences we can use $f_1$ as a model. It is one-to-one because if $f(x_0) = f(x_1)$ then $2 - 2x_0 = 2 - 2x_1$, and then subtracting 2 and dividing by $-2$ yields that $x_0 = x_1$. It is onto because if $y \in (0..2)$ then the number $x = (y - 2)/(-2)$ is an element of $(0..1)$ and has the property that $f(x) = 2 - 2 \cdot ((y - 2)/-2) = y$.

**Verified II.1.32** The function

$$
\hat{f}(n) = \begin{cases} 
1 & \text{if } n = 0 \\
0 & \text{if } n = 1 \\
n^2 & \text{if } n > 1 
\end{cases}
$$

is different than Example 1.8’s function $f$ because they give different outputs for the input 0. That $\hat{f}$ is onto is clear, as every perfect square is the output associated with some input. That $\hat{f}$ is a one-to-one function is also

\[\text{Figure 2, for question II.1.31: The correspondences } f_0, f_1, f_2 : (0..1) \to (0..2) \text{ given by } f_0(x) = 2x, f_1(x) = 2 - 2x, \text{ and } f_2(x) = 2x^2.\]
clear, although it is a little messier to write down. Assume \( \hat{f}(x_0) = \hat{f}(x_1) \) and then there are four cases: both \( x_0 \) and \( x_1 \) are members of the set \( \{0, 1\} \), only the first one is a member, only the second is a member, or neither is a member. All four cases are easy.

**Verified II.1.33** To check that \( f \) is one-to-one suppose that \( f(x_0) = f(x_1) \), so that \( c^{x_0} = c^{x_1} \). Take the logarithm base \( c \) of \( \mathbb{R} \), of the domain of \( f \). Of course, \( f(x) = f(y) = y \).

For onto, consider a codomain element \( y \in (0, \infty) \). The number \( x = \log_c(y) \) is defined and is an element of \( \mathbb{R} \), of the domain of \( f \). Hence, \( f(x) = y \).

**Verified II.1.34** The two \( \mathbb{P}_2 = \{2^k \mid k \in \mathbb{N}\} = \{1, 2, 4, 8, \ldots\} \) and \( \mathbb{P}_3 = \{3^k \mid k \in \mathbb{N}\} = \{1, 3, 9, \ldots\} \) are subsets of \( \mathbb{N} \).

The natural correspondence \( g : \mathbb{P}_2 \to \mathbb{P}_3 \) is to associate elements having the same exponent, \( g(2^k) = 3^k \). This function is one-to-one because if \( g(2^{k_0}) = g(2^{k_1}) \) then \( 3^{k_0} = 3^{k_1} \), and taking the logarithm base 3 of both sides shows that the inputs are the same, \( k_0 = k_1 \). This function is onto because if \( y \in \mathbb{P}_3 \) then it has the form \( y = 3^k \), and is the image of \( 2^k \in \mathbb{P}_2 \).

The obvious generalization is that if two natural numbers \( a, b \in \mathbb{N} \) are greater than 1 then \( \mathbb{P}_a = \{a^k \mid k \in \mathbb{N}\} \) and \( \mathbb{P}_b = \{b^k \mid k \in \mathbb{N}\} \) are sets of natural numbers that have the same cardinality. The argument is as in the prior paragraph.

**Verified II.1.35** Of course, for each item there are many possible answers.

(a) One is \( f_0 : N \to N \) given by \( f_0(n) = n + 1 \). It is one-to-one because if \( f_0(n) = f_0(\hat{n}) \) then \( n + 1 = \hat{n} + 1 \) and \( n = \hat{n} \). It is not onto because no \( n \in \mathbb{N} \) maps to 0.

A second one is \( f_1 : N \to N \) given by \( f_1(n) = n^2 \). It is one-to-one because if \( f_1(n) = f_1(\hat{n}) \) then \( n^2 = \hat{n}^2 \), and because these are natural numbers they are nonnegative, so \( n = \hat{n} \). This function is not onto because no natural number maps to 2.

(b) This function

\[
\begin{align*}
\hat{f}_0(x) &= \begin{cases} x/2 & \text{if } x \text{ is even} \\ (x - 1)/2 & \text{if } x \text{ is odd} \end{cases} \\
\hat{f}_0(x) &= \begin{pmatrix} 0 & 1 & 2 & 3 & 4 & 5 & \ldots \\ 0 & 0 & 1 & 2 & 2 & 2 & \ldots \end{pmatrix}
\end{align*}
\]

is onto because every \( y \in \mathbb{N} \) is the image of \( x = 2y \). It is not one-to-one because \( f_0(1) = f_0(0) \).

A second one is \( f_1(x) = \lfloor \sqrt{x} \rfloor \) (recall that the floor operation, \( \lfloor n \rfloor \), gives the largest integer less than or equal to \( n \)).

\[
\begin{array}{c|cccccccccc}
 x & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & \ldots \\
f_1(x) & 0 & 1 & 1 & 2 & 2 & 2 & 2 & 2 & 3 & 3 & \ldots \\
\end{array}
\]

It is onto because every \( y \in \mathbb{N} \) is the image of \( x = y^2 \). It is not one-to-one because \( f_1(1) = f_1(2) \).

(c) One such map is \( f_0(x) = 0 \). It is not one-to-one because \( f_0(0) = f_0(1) \). It is not onto because no natural number input maps to 1.

A non-constant such function is the square of the prior item’s second one, \( f_1(x) = (\lfloor \sqrt{x} \rfloor)^2 \).

\[
\begin{array}{c|cccccccccc}
 x & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & \ldots \\
f_1(x) & 0 & 1 & 1 & 4 & 4 & 4 & 4 & 4 & 9 & 9 & \ldots \\
\end{array}
\]

It is not one-to-one because \( f_1(1) = f_1(2) \). It is not onto because no number maps to 2, as 2 is not a square.

(d) The natural function that is both one-to-one and onto is the identity function, \( f_0(x) = x \). It is one-to-one because if \( f_0(n) = f_0(\hat{n}) \) then \( n = \hat{n} \), just straight from the definition of \( f_0 \). It is onto because any codomain element \( y \in \mathbb{N} \) is the image under \( f_0 \) of itself, \( f_0(y) = y \).

Another correspondence swaps even and odd numbers.

\[
\begin{align*}
f_1(x) &= \begin{cases} x + 1 & \text{if } x \text{ is even} \\ x - 1 & \text{if } x \text{ is odd} \end{cases} \\
f_1(x) &= \begin{pmatrix} 0 & 1 & 2 & 3 & 4 & 5 & \ldots \\ 1 & 0 & 3 & 2 & 5 & 4 & \ldots \end{pmatrix}
\end{align*}
\]

Observe first that \( f_1 : N \to N \); that is, if \( x \in \mathbb{N} \) then \( f_1(x) \in \mathbb{N} \). To check that \( f_1 \) is one-to-one suppose that \( f_1(n) = f_1(\hat{n}) \). There are two cases. If \( n \) is odd then \( f_1(n) = n - 1 \) is even, and so \( f_1(\hat{n}) \) is even also, implying that \( \hat{n} \) is odd, and therefore \( n - 1 = \hat{n} - 1 \), giving that \( n = \hat{n} \). The even case is similar. To check
that $f_1$ is onto consider a codomain point $y \in \mathbb{N}$. Here also there are two cases and we will only do the odd one, so suppose that $y$ is odd. Then $y = f_1(x)$ where $x = y - 1$, and $x$ is an element of the domain $\mathbb{N}$ because if $y$ is odd then $y - 1 \geq 0$.

**Verified II.1.36** Let $D = (3..5)$ and $C = (-1..10)$.

One correspondence is $f_0(x) = (11/2)(x - 3) - 1$. Whether $f_0 : D \to C$ is not obvious so we start with that: if $3 < x < 5$ then subtracting 3, multiplying by 11/2, and subtracting 1 from all terms gives $-1 < f_0(x) < 10$. Next we show that this map is onto. If $y \in C$ then $y = f_0(x)$ where $x = (2/11)(y + 1) + 3$. To verify that this input $x$ is an element of the domain $D$, start with $-1 < y < 10$, add 1 to all terms, multiply by 2/11, and add 3, ending with $3 < x < 5$. Finally, we show that the map $f_0$ is one-to-one. If $f_0(x) = f_0(\hat{x})$ then $(11/2)(x - 3) - 1 = (11/2)(\hat{x} - 3) - 1$ and adding 1 to both sides, multiplying by 2/11, and finally adding 3, gives that $x = \hat{x}$.

Another correspondence is $f_1(x) = (11/4)(x - 3)^2 - 1$. As with $f_0$ we start by verifying that $f_1 : D \to C$: if $3 < x < 5$ then subtracting 3, squaring, multiplying by 11/4, and subtracting 1 from all terms gives $-1 < f_1(x) < 10$. To show that $f_1$ is onto assume that $y \in C$. Then $y = f_1(x)$ where $x = \sqrt{(4/11)(y + 1) + 3}$. To check that $x \in D$, start with $-1 < y < 10$ and add 1 to all terms, multiply by 4/11, square (this doesn’t change the direction of the <’s because all numbers are nonnegative), and add 3, ending with $3 < x < 5$. To show that this map is one-to-one, assume $f_1(x) = f_1(\hat{x})$ so that $(11/4)(x - 3)^2 - 1 = (11/4)(\hat{x} - 3)^2 - 1$. To both sides add 1, multiply by 4/11, take the square root (which is unambiguous because the x’s are all greater than zero) and then add 3, giving that $x = \hat{x}$.

Figure 3 on page 39 shows that the two functions are unequal. It also gives an alternative demonstration that each is a correspondence because for each, every horizontal line at $y \in (-1..10)$ intersects the graph one and only one point.

**Verified II.1.37** In each case we produce a function from one set to the other and verify that it is both one-to-one and onto. For the third item, note that just because a set appears first in the question does not mean that it must be the domain of the correspondence.

(a) Where $S_4 = \{ 4k \mid k \in \mathbb{N} \}$ and $S_5 = \{ 5k \mid k \in \mathbb{N} \}$, let $f : S_4 \to S_5$ be $f(x) = (5/4)x$. It is one-to-one because $f(x_0) = f(x_1)$ implies that $(5/4)x_0 = (5/4)x_1$, so $x_0 = x_1$. It is onto because if we consider a codomain element $y = 5k$ for some $k \in \mathbb{N}$ then clearly $y = f(4k)$.

(b) These two sets are the same set, that is, the contain the same numbers. They correspond via the identity function.

(c) Write $T = \{ 0, 1, 3, 6, \ldots \} = \{ n(n + 1)/2 \mid n \in \mathbb{N} \}$ (these are called the triangular numbers). Consider the function $f : \mathbb{N} \to T$ defined by $f(n) = n(n + 1)/2$. This map is one-to-one because the continuous function $\hat{f} : \mathbb{R} \to \mathbb{R}$ given by $\hat{f}(x) = x(x + 1)/2$ is a parabola with roots at 0 and −1 and so the part in the positive numbers, with $x \geq 0$, has that a horizontal line at $y$ will intersect the graph in at most one point. The fact that $\hat{f}$ is one-to-one gives that its restriction $f$ is also one-to-one. The function $f$ is onto by definition, since $T$ is defined as the range of that function.

**Verified II.1.38**
One is \( f(x) = 2x \). This map is one-to-one because if \( f(x) = f(\hat{x}) \) then \( 2x = 2\hat{x} \) and so \( x = \hat{x} \). This map is onto because where \( 0 < y < 2 \), the number \( x = y/2 \) has the properties that \( f(x) = y \) and \( 0 < x < 1 \).

(b) One is \( f(x) = (b - a) \cdot x + a \). Note that \( f: (0..1) \to (a..b) \) since if \( 0 < x < 1 \) then multiplying by \( b - a \) gives \( 0 < x < (b - a) \) (the \(<\)'s maintain their direction because \( a < b \)), and adding \( a \) gives \( a < x < b \). Further, this function is one-to-one: because \( b - a \neq 0 \) this line does not have slope 0 and so the function passes the horizontal line test (for an algebraic argument, start with \( f(x) = f(\hat{x}) \), subtract \( a \) and divide by \( b - a \), and conclude that \( x = \hat{x} \)). Finally, to show that this function is onto, fix \( y \in (a..b) \). Note that \( f(x) = y \) where \( x = (y - a)/(b - a) \). What remains is to check that \( x \in (0..1) \): starting from \( a < y < b \), subtract \( a \) and divide by \( b - a \) to get \( 0 < (y - a)/(b - a) < 1 \) (as earlier, note that the \(<\)'s maintain their direction because \( b - a > 0 \)).

(c) One is \( f(x) = x + a \). This function is one-to-one because \( f(x) = f(\hat{x}) \) implies that \( x + a = \hat{x} + a \) and so \( x = \hat{x} \). It is onto because if \( y \in (a..\infty) \) then \( y = f(x) \) where \( x = y - a \) (and \( x \in (0..\infty) \)).

Similar triangles gives \( x/(x + 1) = f(x)/1 \). Figure 4 on page 40 shows that it is a correspondence because for each \( y \in (0..1) \), the horizontal line at that height intercepts the function's graph in exactly one point.

Consider the function \( f: \mathbb{N} \to S \) given by \( f(m) = \frac{m + \sqrt{2}}{\sqrt{2}} = 2^{1/(m+2)} \). It is one-to-one because if \( f(m) = f(n) \) then \( 2^{1/(m+2)} = 2^{1/(n+2)} \). Take the logarithm of both sides \( \log(2^{1/(m+2)}) = \log(2^{1/(n+2)}) \) to get \( (1/(m + 2)) \cdot \log(2) = (1/(n + 2)) \cdot \log(2), \) and so \( 1/(m + 2) = 1/(n + 2) \). Thus \( m = n \).

This function is onto because if \( y \in S \) then \( y = 2^{1/n} \) for some \( n \in \mathbb{N} \) with \( n \geq 2 \). Thus, \( y = 2^{1/(x+2)} = f(x) \) for \( x \in \mathbb{N} \).

Recall that just as every natural number has a finite decimal representation, and that this representation is unique, so also every natural number has a unique binary representation.

(a) View each string of bits \( \sigma \) starting with 1 as the binary representation of a natural number \( n \). Then \( f: B \to \mathbb{N} \) given by \( \sigma \mapsto n - 1 \) is clearly a correspondence.

(b) Prefix each string \( \tau \in B^* \) with 1, so \( \sigma = 1^\tau \). Now the prior argument applies.

The tangent function is a correspondence from \((-\pi/2..\pi/2)\) to \( \mathbb{R} \) so its inverse, arctangent, is a correspondence in the other direction. Thus, \( g(x) = (\arctan(x) + (\pi/2))/\pi \) gives a correspondence from \( \mathbb{R} \) to \((0..1)\). See Figure 5 on page 40, which shows that \( g \) is one-to-one and onto because for each element \( y \) of the codomain \((0..1)\), the horizontal line at \( y \) intercepts the function's graph in exactly one point.

(a) The map \( g: I_0 \to I_1 \) given by \( g(x) = x \cdot (r_1/r_0) \) is onto because if \( y \in I_1 = [0..2\pi r_1] \) then \( y = g(x) \) where \( x = y \cdot (r_0/r_1) \), and \( 0 \leq y < 2\pi r_1 \) implies that \( 0 \leq y \cdot (r_0/r_1) < 2\pi r_0 \). To show that this map is one-to-one suppose \( g(x) = g(\hat{x}) \). Then \( x \cdot (r_1/r_0) = \hat{x} \cdot (r_1/r_0) \) and so \( x = \hat{x} \).

(b) The map \( g(x) = a + x \cdot (b - a) \) is a correspondence. To verify that it is one-to-one, suppose that \( g(x) = g(\hat{x}) \) so that \( a + x \cdot (b - a) = a + \hat{x} \cdot (b - a) \). Subtract \( a \) and divide by \( b - a \) to conclude that \( x = \hat{x} \). This map is also
onto because \( y \in [a..b] \) is the image of \( x = (y - a)/(b - a) \), and \( a \leq y < b \) implies that \( 0 \leq y - a < b - a \), and so \( 0 \leq (y - a)/(b - a) < 1 \).

(c) By the prior item there are correspondences \( f : [0..1) \rightarrow [a..b) \) and \( g : [0..1) \rightarrow [c..d) \). Then the composition \( g \circ f^{-1} \) has domain \([a..b)\), codomain \([c..d)\), and is a correspondence.

(This is also easy to check by considering the map \( f : [a..b) \rightarrow [c..d) \) given by \( f(x) = c + (x - a) \cdot (d - c)/(b - a) \).

**Verified II.1.43** Suppose for contradiction that \( f \) is not one-to-one. Then there are \( x, \hat{x} \in D \) such that \( f(x) = f(\hat{x}) \) but \( x \neq \hat{x} \). But one or the other of these two is smaller; without loss of generality suppose that \( x < \hat{x} \). Then \( x < \hat{x} \) but \( f(x) = f(\hat{x}) \), which contradicts that the function is strictly increasing.

Yes, the same argument works for \( D \subseteq \mathbb{N} \).

**Verified II.1.44**

(a) Let \( \mathcal{E} = \{2n \mid n \in \mathbb{N}\} \). The natural correspondence is \( f : \mathbb{N} \rightarrow \mathcal{E} \) given by \( n \mapsto 2n \). This map is one-to-one because if \( f(n) = f(\hat{n}) \) then \( 2n = 2\hat{n} \) and so \( n = \hat{n} \). This map is onto because if \( y \in \mathcal{E} \) then \( y = 2k \) for some \( k \in \mathbb{N} \) and setting \( n = k \) gives that \( y = f(n) \).

(b) Let \( T = \{n \in \mathbb{N} \mid n > 4\} \). Consider \( f : \mathbb{N} \rightarrow T \) given by \( n \mapsto n + 5 \). This is one-to-one because if \( f(n) = f(\hat{n}) \) then \( n + 5 = \hat{n} + 5 \) and \( n = \hat{n} \). It is onto because if \( y \in T \) then \( y = f(x) \) where \( x = y - 5 \), and observe that \( y \in T \) implies that \( y - 5 \in \mathbb{N} \). So \( f \) is a correspondence.

**Verified II.1.45** We will show that no matter what is the cardinality of the finite set \( S \subseteq \mathbb{N} \), there is a correspondence \( f : \mathbb{N} \rightarrow \mathbb{N} - S \). We will use induction, at each step taking the finite set to have one element more than at the prior step.

Before the proof we give an illustration. Suppose that we have a five-element set \( S_5 = \{2, 5, 8, 10, 11\} \) and this correspondence \( f_5 : \mathbb{N} \rightarrow \mathbb{N} - S_5 \).

\[
\begin{array}{c|cccccccc}
\quad & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & \ldots \\
\hline
f_5(n) & 0 & 1 & 3 & 4 & 6 & 7 & 9 & 12 & \ldots \\
\end{array}
\]

Now we add a sixth element, so let \( S = S_5 \cup \{9\} \). We want a correspondence \( f : \mathbb{N} \rightarrow \mathbb{N} - S \). The natural approach is find that \( 9 = f_5(6) \) and define \( f \) in this way.

\[
f(n) = \begin{cases} f_5(n) & - \text{if } n < 6 \\ f_5(n + 1) & - \text{if } n > 6 \end{cases}
\]

The induction argument's base case is \( S = \emptyset \) and here the identity function \( f(n) = n \) is clearly a one-to-one and onto map from \( \mathbb{N} \) to \( \mathbb{N} - S \).

For the inductive step take \( k \in \mathbb{N} \), assume that the statement is true for any subset of \( \mathbb{N} \) whose cardinality is less than or equal to \( k \), and consider \( S \subseteq \mathbb{N} \) with \( |S| = k + 1 \). Fix any \( s \in S \) and let \( S_k = S - \{s\} \). By the inductive hypothesis there is a correspondence \( f_k : \mathbb{N} \rightarrow \mathbb{N} - S_k \). Set \( \hat{n} \) to be such that \( f_k(\hat{n}) = s \) and define \( f : \mathbb{N} \rightarrow \mathbb{N} - S \) in this way:

\[
f(n) = \begin{cases} f_k(n) & - \text{if } n < \hat{n} \\ f_k(n + 1) & - \text{if } n > \hat{n} \end{cases}
\]

The function \( f : \mathbb{N} \rightarrow \mathbb{N} - S \) is one-to-one because it is a restriction of \( f_k \), which is a one-to-one map from \( \mathbb{N} \) to \( \mathbb{N} - \hat{S} \). Similarly, \( f \) is onto because \( f_k \) is onto, from \( \mathbb{N} \) to \( \mathbb{N} - S_k \). Thus \( f \) is a correspondence between \( \mathbb{N} \) and \( \mathbb{N} - S \), and so the two have the same cardinality.

**Verified II.1.46**

(a) The inverse function \( f^{-1} : C \rightarrow D \) is given by \( f^{-1}(\text{Spades}) = 0 \), \( f^{-1}(\text{Hearts}) = 1 \), \( f^{-1}(\text{Clubs}) = 2 \), and \( f^{-1}(\text{Diamonds}) = 3 \). By inspection it is both one-to-one and onto.

(b) Suppose that \( f : D \rightarrow C \) is a correspondence. Consider the binary relation, the set of ordered pairs, \( f^{-1} = \{(y, x) \mid f(x) = y \} \). We will show that \( f^{-1} \) is a function, which means that we will show that it is well-defined, that each input \( y \in C \) is associated with one and only one output \( x \in D \).

Each \( y \in C \) is associated with at least one \( x \) because the function \( f \) is onto. Each \( y \in C \) is associated with at most one \( x \) because \( f \) is one-to-one.
(c) To show that \( f^{-1} : C \rightarrow D \) is one-to-one suppose that \( f^{-1}(y) = f^{-1}(\hat{y}) \). Then there is a \( x \in D \) such that \( f(x) = y \) and \( f(x) = \hat{y} \). This contradicts that \( f \) is a function, because a function must be well-defined.

To show that \( f^{-1} \) is onto consider a member of its codomain, \( \hat{x} \in D \). By the definition of a function there is a \( \hat{y} \in C \) with \( f(\hat{x}) = \hat{y} \), and then \( \hat{x} = f^{-1}(\hat{y}) \).

**Verified** II.1.47 One direction is straightforward: no finite set has the same cardinality as a proper subset of itself, by Lemma 1.5.

For the other direction, fix an infinite set \( S \), to show that it has the same cardinality as a proper subset of itself. (Remark: as elsewhere, we feel free here to use the Axiom of Choice.) Choose any element \( s_0 \in S \). Then \( S - \{s_0\} \) is not empty (or else \( S \) is not infinite) so choose \( s_1 \in S - \{s_0\} \). Continuing in this way gives \( \{s_0, s_1, s_2 \ldots \} \). Then this is a correspondence from \( S \) to \( S - \{s_0\} \).

\[
f(x) = \begin{cases} 
  s_{i+1} & \text{if } x = s_i \text{ for some } i \in \mathbb{N} \\
  x & \text{otherwise}
\end{cases}
\]

**Verified** II.1.48 Denote the function \( f : D \rightarrow C \), and assume that \( D \) is finite.

(a) We will argue that the statement \( |\text{dom}(f)| \geq |\text{ran}(f)| \) holds for all functions on finite domains by induction on the number of elements in \( D \).

The base step is that the domain has no elements at all, \( \text{dom}(f) = \emptyset \). The only function with an empty domain is the empty function. The empty function’s range is empty, \( \text{ran}(f) = \emptyset \), and thus \( |\text{dom}(f)| \geq |\text{ran}(f)| \).

For the inductive step, fix \( k \in \mathbb{N} \), assume that the statement is true for any function with a domain having \( 0 \) elements, or \( 1 \) elements, \( \ldots \) or \( k \) elements, and consider the \( |D| = k + 1 \) case.

Because \( k + 1 > 0 \) there is a \( d \in D \). Let \( \hat{D} = D - \{d\} \) and consider the restriction \( f \upharpoonright \hat{D} : \hat{D} \rightarrow C \). Its domain has \( k \) many elements, so the induction hypothesis applies, giving \( |\text{dom}(f) \upharpoonright \hat{D}| \geq |\text{ran}(f) \upharpoonright \hat{D}| \).

To add back the element \( d \) there are two cases; see Figure 6 on page 42. The first case, on the left in the figure, is that the range of \( f \) is the same as the range of the restriction \( f \upharpoonright \hat{D} \). The other case is that the range of \( f \) has one additional element. In either case, adding 1 to both sides ends the argument.

\[
|\text{dom}(f)| = |\text{dom}(f) \upharpoonright \hat{D}| + 1 \geq |\text{ran}(f) \upharpoonright \hat{D}| + 1 \geq |\text{ran}(f)|
\]

(b) Assume that the function is one-to-one. We will show that the domain and range have the same size by induction on the number of elements in the domain. This argument is like the prior item’s except that it has only the single case shown on the right of Figure 6 on page 42.

The base step is that the function’s domain has no elements at all, \( \text{dom}(f) = \emptyset \). This function’s range is empty and \( |\text{dom}(f)| = |\text{ran}(f)| \).

For the inductive step, fix \( k \in \mathbb{N} \), assume that the domain and range have the same size for any one-to-one function where the domain \( D \) has \( 0 \) elements, or \( 1 \) element, \( \ldots \) or \( k \) elements, and suppose that \( |D| = k + 1 \).

Because \( k + 1 > 0 \) there is a \( d \in D \). Let \( \hat{D} = D - \{d\} \). Consider the restriction function \( f \upharpoonright \hat{D} : \hat{D} \rightarrow C \). The function \( f \) is one-to-one so the restriction is also one-to-one. The induction hypothesis applies, giving \( |\text{dom}(f) \upharpoonright \hat{D}| = |\text{ran}(f) \upharpoonright \hat{D}| \). Adding 1 to both sides gives \( |\text{dom}(f)| = |\text{dom}(f) \upharpoonright \hat{D}| + 1 = |\text{ran}(f) \upharpoonright \hat{D}| + 1 = |\text{ran}(f)| \).

(c) Figure 7 on page 43 illustrates the argument.

For the proof, let \( f \) be a function with a finite domain that is not one-to-one. Fix some numbering of its
domain, \( D = \{d_0, d_1, \ldots, d_n\} \). Consider
\[
\hat{D} = \{d_i \in D \mid i \text{ is minimal among the indices } j \text{ where } f(d_j) = f(d_i)\}
\]
(in the illustration, \( f(d_0) = f(d_1) \) and \( f(d_2) = f(d_3) \) so this is the set \( \{d_0, d_2\} \)).

Because \( f \) is not one-to-one, \( \hat{D} \) is a proper subset of \( D \). The restriction \( f \upharpoonright \hat{D} : \hat{D} \to C \) is one-to-one. By the prior item, its range has the same number of elements as its domain. The range of \( f \) is the same as the range of \( f \upharpoonright \hat{D} \). But the domain of \( f \) has more elements than the domain of \( f \upharpoonright \hat{D} \). Thus the domain of \( f \) contains more elements than its range.

(b) Let \( D \) and \( C \) be finite sets. If there is a correspondence \( f : D \to C \) then the prior items show that the sets have the same number of elements.

For the other direction assume that the two have the same number of elements. Fix a numbering of each, \( D = \{d_0, \ldots, d_k\} \) and \( C = \{c_0, \ldots, c_k\} \). Then the map \( f : D \to C \) defined by \( f(d_i) = c_i \) is clearly a correspondence.

**Verified II.2.17** The table alternates between column 0 and column 1.

\[
\begin{array}{cccccccc}
 n \in \mathbb{N} & 6 & 7 & 8 & 9 & 10 & 11 & 12 \\
 f(n) \in \{0, 1\} \times \mathbb{N} & \langle 0, 3 \rangle & \langle 1, 3 \rangle & \langle 0, 4 \rangle & \langle 1, 4 \rangle & \langle 0, 5 \rangle & \langle 1, 5 \rangle & \langle 0, 6 \rangle \\
\end{array}
\]

The formulas are \( x(n) = (1 + (-1)^{n+1})/2 \) and \( y(n) = \lfloor n/2 \rfloor \).

**Verified II.2.18**

(a) The pair before \( \langle 50, 50 \rangle \) is \( \langle 49, 51 \rangle \) and the pair after is \( \langle 51, 49 \rangle \). As a check they correspond to cantor(50, 50) = 5 100, cantor(49, 51) = 5 099, and cantor(51, 49) = 5 101.

(b) The pair before \( \langle 100, 4 \rangle \) is \( \langle 99, 5 \rangle \) and the pair after is \( \langle 101, 3 \rangle \). As a check, the three correspond to cantor(100, 4) = 5 560, cantor(99, 5) = 5 559, and cantor(101, 3) = 5 561.

(c) The pair before \( \langle 4, 100 \rangle \) is \( \langle 3, 101 \rangle \) and the pair after is \( \langle 5, 99 \rangle \). The three give cantor(100, 4) = 5 465, cantor(99, 5) = 5 463, and cantor(5, 99) = 5 465.

(d) Before \( \langle 0, 200 \rangle \) is \( \langle 199, 0 \rangle \) while after is \( \langle 1, 199 \rangle \). These three correspond to cantor(0, 200) = 20 100, cantor(199, 0) = 20 099, and cantor(1, 199) = 20 101.

(e) Before \( \langle 200, 0 \rangle \) is \( \langle 199, 1 \rangle \) while after is \( \langle 0, 201 \rangle \). They correspond to cantor(200, 0) = 20 300, cantor(199, 1) = 20 299, and cantor(0, 201) = 20 301.

**Verified II.2.19**

(a) The correspondence \( f_T : \mathbb{N} \to T \) is given by \( f_T(n) = 2n \). The correspondence \( f_F : \mathbb{N} \to T \) is given by \( f_F(m) = 5m \). Checking that each is one-to-one and onto is easy.

\[
\begin{array}{cccccccc}
 n \in \mathbb{N} & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\
 f_T(n) \in T & 0 & 2 & 4 & 6 & 8 & 10 & 12 & 14 & 16 & 18 \\
 f_F(n) \in F & 0 & 5 & 10 & 15 & 20 & 25 & 30 & 35 & 40 & 45 \\
\end{array}
\]

(b) This correspondence gives outputs in ascending order.

\[
\begin{array}{cccccccc}
 n \in \mathbb{N} & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\
 f(n) \in T \cup F & 0 & 2 & 4 & 5 & 6 & 8 & 10 & 12 & 14 & 15 \\
\end{array}
\]

**Verified II.2.20** This gives the first few associations for a function \( f : \mathbb{N} \to \mathbb{N} \times \{0, 1\} \).

\[
\begin{array}{c|cccccccc}
 n & 0 & 1 & 2 & 3 & 4 & 5 & \ldots & \\
 f(n) & \langle 0, 0 \rangle & \langle 0, 1 \rangle & \langle 1, 0 \rangle & \langle 1, 1 \rangle & \langle 2, 0 \rangle & \langle 2, 1 \rangle & \ldots \\
\end{array}
\]
From that table a description sufficient for computing \( f \) is easy.

\[
\begin{align*}
f(n) &= \begin{cases} 
\langle \lfloor n/2 \rfloor, 0 \rangle & \text{if } n \text{ is even} \\
\langle \lfloor n/2 \rfloor, 1 \rangle & \text{if } n \text{ is odd}
\end{cases}
\end{align*}
\]

That gives \( f(0) = \langle 0, 0 \rangle \), \( f(10) = \langle 5, 0 \rangle \), \( f(100) = \langle 50, 0 \rangle \), and \( f(101) = \langle 50, 1 \rangle \).

To go from the pair to the number we need the inverse, \( f^{-1}(i,j) = 2i + j \). Then \( f^{-1}(2,1) = 5 \), \( f^{-1}(20,1) = 41 \), and \( f^{-1}(200,1) = 401 \).

**Verified** II.2.21 This gives the first few of the associations.

<table>
<thead>
<tr>
<th>Number</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pair</td>
<td>\langle 0, 0 \rangle</td>
<td>\langle 1, 0 \rangle</td>
<td>\langle 2, 0 \rangle</td>
<td>\langle 0, 1 \rangle</td>
<td>\langle 1, 1 \rangle</td>
<td>\langle 2, 1 \rangle</td>
<td>\langle 0, 2 \rangle</td>
<td>\langle 1, 2 \rangle</td>
<td>\langle 2, 2 \rangle</td>
<td>...</td>
</tr>
</tbody>
</table>

The formula for the top to bottom association is

\[
\begin{align*}
f(n) &= \begin{cases} 
\langle 0, \lfloor n/3 \rfloor \rangle & \text{if } 3 \text{ divides } n \\
\langle 1, \lfloor n/3 \rfloor \rangle & \text{if } n \text{ mod } 3 = 1 \\
\langle 2, \lfloor n/3 \rfloor \rangle & \text{if } n \text{ mod } 3 = 2
\end{cases}
\end{align*}
\]

(in short: \( f(n) = \langle n \text{ mod } 3, \lfloor n/3 \rfloor \rangle \)). Thus \( f(0) = \langle 0, 0 \rangle \), \( f(10) = \langle 1, 3 \rangle \), \( f(100) = \langle 1, 33 \rangle \), and \( f(1,000) = \langle 1, 333 \rangle \). The formula for the bottom to top function \( f^{-1}: \{0,1,2\} \times \mathbb{N} \rightarrow \mathbb{N} \) is also easy, \( f^{-1}(x,y) = x + 3y \).

With that, \( f^{-1}(1,2) = 7 \), \( f^{-1}(1,20) = 61 \), and \( f^{-1}(1,200) = 601 \).

**Verified** II.2.22 This is the initial part of an enumeration \( f \) of \( \{0,1,2,3\} \times \mathbb{N} \).

<table>
<thead>
<tr>
<th>Number</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pair</td>
<td>\langle 0, 0 \rangle</td>
<td>\langle 1, 0 \rangle</td>
<td>\langle 2, 0 \rangle</td>
<td>\langle 3, 0 \rangle</td>
<td>\langle 0, 1 \rangle</td>
<td>\langle 1, 1 \rangle</td>
<td>\langle 2, 1 \rangle</td>
<td>\langle 3, 1 \rangle</td>
<td>\langle 0, 2 \rangle</td>
<td>...</td>
</tr>
</tbody>
</table>

The formula for the top to bottom association is \( f(n) = \langle n \text{ mod } 4, \lfloor n/4 \rfloor \rangle \), so \( x(n) = n \text{ mod } 4 \) and \( y(n) = \lfloor n/4 \rfloor \).

In general, for \( k \in \mathbb{N} \) an enumeration \( f \) of \( \{0,1,2,\ldots,k\} \times \mathbb{N} \) is \( f(n) = \langle n \text{ mod } (k+1), \lfloor n/(k+1) \rfloor \rangle \).

**Verified** II.2.23 Example 2.4’s table shows up to \( n = 6 \).

<table>
<thead>
<tr>
<th>Number</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pair</td>
<td>\langle 1, 2 \rangle</td>
<td>\langle 2, 1 \rangle</td>
<td>\langle 3, 0 \rangle</td>
<td>\langle 0, 4 \rangle</td>
<td>\langle 1, 3 \rangle</td>
<td>\langle 2, 2 \rangle</td>
<td>\langle 3, 1 \rangle</td>
<td>\langle 4, 0 \rangle</td>
<td>\langle 0, 5 \rangle</td>
<td>\langle 1, 4 \rangle</td>
</tr>
</tbody>
</table>

**Verified** II.2.24 One way to compute this function is by brute force. Given \( n \), a program can generate the pairs in ascending order \( \{0,0\}, \langle 0,1 \rangle, \langle 1,0 \rangle, \langle 0,2 \rangle, \ldots \), keeping count, until it generates the matching one. Figure 8 on page 44 has a routine that from an input pair, gives the next one.

**Verified** II.2.25 Corollary 2.12 gives that, because the set \( A - B \) is a subset of \( A \), it is countable. Similarly \( B - A \subseteq B \) is countable. Then, by the same result, their union is also countable.

**Verified** II.2.26 Where \( S = \{a+bi \mid a,b \in \mathbb{Z}\} \), obviously the map \( g: \mathbb{Z} \times \mathbb{Z} \rightarrow S \) given by \( g(a,b) = a + bi \) is a correspondence. Lemma 2.8 says that \( \mathbb{Z} \times \mathbb{Z} \) is countable so there is a correspondence \( f: \mathbb{N} \rightarrow \mathbb{Z} \times \mathbb{Z} \). Then the composition \( g \circ f: \mathbb{N} \rightarrow S \) is a correspondence.

**Verified** II.2.27 Below are the pairs in ascending order along with the resulting associated rational number.
\begin{center}
<table>
<thead>
<tr>
<th>( n )</th>
<th>( \text{pairs} )</th>
<th>( f(n) \in \mathbb{Q} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>( \langle 0, 0 \rangle, \langle 0, 1 \rangle )</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>( \langle 1, 0 \rangle, \langle 0, 2 \rangle, \langle 1, 1 \rangle )</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>( \langle 2, 0 \rangle, \langle 0, 3 \rangle, \langle 1, 2 \rangle )</td>
<td>1/2</td>
</tr>
<tr>
<td>3</td>
<td>( \langle 2, 1 \rangle )</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>( \langle 3, 0 \rangle, \langle 0, 4 \rangle, \langle 1, 3 \rangle )</td>
<td>1/3</td>
</tr>
<tr>
<td>5</td>
<td>( \langle 2, 2 \rangle, \langle 3, 1 \rangle )</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>( \langle 4, 0 \rangle, \langle 0, 5 \rangle, \langle 1, 4 \rangle )</td>
<td>1/4</td>
</tr>
<tr>
<td>7</td>
<td>( \langle 2, 3 \rangle )</td>
<td>2/3</td>
</tr>
<tr>
<td>8</td>
<td>( \langle 3, 2 \rangle )</td>
<td>3/2</td>
</tr>
<tr>
<td>9</td>
<td>( \langle 4, 1 \rangle )</td>
<td>4</td>
</tr>
<tr>
<td>10</td>
<td>( \langle 5, 0 \rangle, \langle 0, 6 \rangle, \langle 1, 5 \rangle )</td>
<td>1/5</td>
</tr>
<tr>
<td>11</td>
<td>( \langle 2, 4 \rangle, \langle 3, 3 \rangle, \langle 4, 2 \rangle, \langle 5, 1 \rangle )</td>
<td>5</td>
</tr>
</tbody>
</table>
\end{center}

Verified II.2.28

(a) The map \( f : \mathbb{Z}^{n+1} \to \mathbb{Z}_n[x] \) given by \( f(a_0, \ldots, a_n) = a_n x^n + \cdots + a_1 x + a_0 \) is clearly a correspondence. Since Corollary 2.9 says that there is a correspondence \( g : \mathbb{N} \to \mathbb{Z}^{n+1} \), we have a correspondence \( f \circ g \) from \( \mathbb{N} \) to \( \mathbb{Z}_n[x] \).

(b) The set \( \mathbb{Z}[x] \) is the union of the \( \mathbb{Z}_i[x] \) over all \( i \in \mathbb{N} \), and the union of countably many countable sets is countable.

Verified II.2.29 We will use that the function \( \text{cantor} : \mathbb{N}^2 \to \mathbb{N} \) is a correspondence.

To verify that \( \text{cantor}_3 \) is onto, fix a codomain element \( n \in \mathbb{N} \). Because \( \text{cantor} \) is onto there is a pair \( \langle w, z \rangle \in \mathbb{N}^2 \) such that \( \text{cantor}(w, z) = n \). Also because \( \text{cantor} \) is onto, there is a pair \( \langle x, y \rangle \in \mathbb{N}^2 \) so that \( \text{cantor}(x, y) = w \). Then \( \text{cantor}_3(x, y, z) = \text{cantor}(\text{cantor}(x, y), z) = n \).

What’s left is to verify that \( \text{cantor}_3 \) is one-to-one. Suppose that \( \text{cantor}_3(a_0, b_0, c_0) = \text{cantor}_3(a_1, b_1, c_1) \). Then \( \text{cantor}(a_0, b_0, c_0) = \text{cantor}(a_1, b_1, c_1) \). The function \( \text{cantor} \) is one-to-one so the prior sentence implies that \( \text{cantor}(a_0, b_0) = \text{cantor}(a_1, b_1) \) and \( c_0 = c_1 \). Again applying that \( \text{cantor} \) is one-to-one gives that \( a_0 = a_1, b_0 = b_1 \), along with the \( c_0 = c_1 \).

Verified II.2.30 A way to be confident about these is to write a small script.

(a) \( c_3(0, 0, 0) = 0, c_3(1, 2, 3) = 172, c_3(3, 3, 3) = 381 \)

(b) \( c_3(0, 0, 0) = 0, c_3(0, 0, 1) = 1, c_3(1, 0, 0) = 2, c_3(0, 1, 0) = 3, c_3(1, 0, 1) = 4 \)

(c) \( c_3(x, y, z) = x + [(y + z + 1)(y + z) + 2x + 2y + 2] \cdot [y + z + 1)(y + z) + 2x + 2y]/8 \)

Verified II.2.31 Plug \( x = y = i \) into \( \text{cantor}(x, y) = x + (x + y)(x + y + 1)/2 \) to get \( \text{cantor}(i, i) = i + (2i)(2i + 1)/2 = 2i^2 + 2i \).

That’s \( 2i(i + 1) \). It is obviously a multiple of 2 but because the numbers \( i \) and \( i + 1 \) are consecutive, one of them contributes another factor of 2. Hence the entire expression is a multiple of 4.

Verified II.2.32 Let \( S_0, S_1 \), and \( S_2 \) be countably infinite and suppose that \( f_0 : \mathbb{N} \to S_0, f_1 : \mathbb{N} \to S_1 \) and \( f_2 : \mathbb{N} \to S_2 \) are onto. Then \( \hat{f} : \mathbb{N} \to S_0 \cup S_1 \cup S_2 \) given by

\[
\hat{f}(n) = \begin{cases} 
    f_0(n/3) & \text{if } n \text{ is a multiple of } 3, \text{ that is, } n \text{ mod } 3 = 0 \\
    f_1((n - 1)/3) & \text{if } n \text{ leaves a remainder of } 1 \text{ on division by } 3, \text{ so } n \text{ mod } 3 = 1 \\
    f_2((n - 2)/3) & \text{if } n \text{ leaves a remainder of } 2 \text{ on division by } 3, \text{ so } n \text{ mod } 3 = 2 
\end{cases}
\]

(briefly, \( \hat{f}(n) = f_{n \text{ mod } 3}(\lfloor n/3 \rfloor) \)) and illustrated by

\[
\begin{array}{cccccccc}
    n & 0 & 1 & 2 & 3 & 4 & 5 & 6 & \ldots \\
    \hat{f}(n) & f_0(0) & f_1(0) & f_2(0) & f_0(1) & f_1(1) & f_2(1) & f_3(0) & \ldots \\
\end{array}
\]

is clearly onto. Lemma 2.11 applies, and so the union is countable.

Verified II.2.33 Think of a function \( f : \{0, 1\} \to \mathbb{N} \) as a pair \( \langle f(0), f(1) \rangle \). That is, there is a natural correspondence between \( \{0, 1\} \) and \( \mathbb{N} \times \mathbb{N} \), which is countable.

Verified II.2.34 Because \( S \) is countable, Lemma 2.11 says that either it is empty or there is an onto function \( g : \mathbb{N} \to S \). If \( S \) is empty then the range set is empty, so it is countable. Otherwise, the function \( f \circ g : \mathbb{N} \to \text{ran}(f) \) is onto.
II.2.35  The cross product of two finites sets is finite because the number of elements in the cross product equals the product of the number of elements in the sets.

Next we do a finite set, \( S = \{ s_0, \ldots, s_{m-1} \} \), and a countably infinite set, \( T = \{ t_0, t_1, \ldots \} \). Consider \( S \times T \) (the \( T \times S \) argument is similar). Enumerate it row-wise, so that where \( n = d \cdot m + r \) is the usual quotient-remainder relationship then \( f(n) = \langle s_r, t_d \rangle \). (This initial portion of the \( m = 3 \) case

| \( n \) | 0 | 1 | 2 | 3 | 4 | 5 | 6 | ...
|-------|---|---|---|---|---|---|---|-----|
| \( f(n) \) | \( (0,0) \) | \( (1,0) \) | \( (2,0) \) | \( (0,1) \) | \( (1,1) \) | \( (2,1) \) | \( (0,2) \) | ...

illustrates that an equivalent formula is \( f(n) = \langle s_{n \mod m}, t_{\lfloor n/m \rfloor} \rangle \). Clearly this function is a correspondence.

II.2.36

(a) The set of length 5 strings \( \Sigma^5 = \{ \langle s_0, \ldots, s_4 \rangle \mid s_i \in \Sigma \} \) is the cross product of five finite sets, each with 40 characters. So \( \Sigma^5 \) has 40^5 many members. (By the way, 40^5 = 102400000.) Thus it is countable.
(b) The set \( \Sigma^0 \cup \Sigma^1 \cup \cdots \cup \Sigma^8 \) is the union of finitely many finite sets. So it is finite and therefore countable.
(c) The set \( \Sigma^* = \Sigma^0 \cup \Sigma^1 \cup \cdots \) is the union of countably many finite sets. By Corollary 2.12 it is countable.
(d) A program is a finite string. So the set of all programs is a subset of \( \Sigma^* \). Corollary 2.12 says that this set is countable.

II.2.37

(a) These are easy to calculate by hand or with a script.

<table>
<thead>
<tr>
<th>( m = 0 )</th>
<th>( m = 1 )</th>
<th>( m = 2 )</th>
<th>( m = 3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n = 0 )</td>
<td>0</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>( n = 1 )</td>
<td>1</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>( n = 2 )</td>
<td>3</td>
<td>11</td>
<td>19</td>
</tr>
<tr>
<td>( n = 3 )</td>
<td>7</td>
<td>23</td>
<td>39</td>
</tr>
</tbody>
</table>

(b) Every natural number greater than zero is a unique product of primes, \( 2^{e_2}3^{e_3} \cdots p^{e_p} \). So every such number is the product of a power of two, \( 2^n \), with an odd number, \( 2m + 1 \), and so corresponds to the pair \( \langle n, m \rangle \).
(c) This table shows that under the box enumeration \( \langle 3, 4 \rangle \) corresponds with 19.

\[
\begin{array}{ccccccc}
\hline
y & 4 & 3 & 2 & 1 & 0 \\
\hline
x & 0 & 1 & 2 & 3 & 4 \\
\hline
16 & 17 & 18 & 19 & 20 \\
9 & 10 & 11 & 12 & 21 \\
4 & 5 & 6 & 13 & 22 \\
1 & 2 & 7 & 14 & 23 \\
0 & 3 & 8 & 15 & 24 \\
\hline
\end{array}
\]

II.2.38

(a)\( \text{cantor}(2, 1) = 8 \)

(b) Solving \( 8 = 1 + [(1 + y)(1 + y + 1)]/2 \) leads to the quadratic equation \( 0 = y^2 - 3x - 12 \). The quadratic formula gives \((-3 \pm \sqrt{57})/2\), two different solutions, \( y \approx 2.27 \) and \( y \approx -5.27 \). Figure 9 on page 47 shows the graph.

II.2.39

(a) Let \( f_0: \mathbb{N} \to S_0 \) and \( f_1: \mathbb{N} \to S_1 \) be correspondences. Then this map is onto the set \( S_0 \cup S_1 \)

\[
f(n) = \begin{cases} 
    f_0(g_0^{-1}(n)) & \text{if } n \in C_0 \\
    f_1(g_1^{-1}(n)) & \text{if } n \in C_1 
\end{cases}
\]

because the range of \( g_0^{-1} \) is \( \mathbb{N} \) and the image of \( \mathbb{N} \) under \( f_0 \) is \( S_0 \), and likewise for \( S_1 \).

(b) Let \( f_0: \mathbb{N} \to S_0 \), \( f_1: \mathbb{N} \to S_1 \), and \( f_2: \mathbb{N} \to S_2 \) be correspondences. Then this map is onto.

\[
f(n) = \begin{cases} 
    f_0(g_0^{-1}(n)) & \text{if } n \in C_0 \\
    f_1(g_1^{-1}(n)) & \text{if } n \in C_1 \\
    f_2(g_2^{-1}(n)) & \text{if } n \in C_2 
\end{cases}
\]
(c) Begin with countably infinitely many sets \( S_j \), each of which is countable. Let \( f_j : \mathbb{N} \to S_j \) be correspondences. Write \( C_k \) for the set of natural numbers whose binary representation ends in \( k \)-many 0's but not \( k + 1 \)-many. Each \( C_k \) is countably infinite so there are correspondences \( g_k : \mathbb{N} \to C_k \) for all \( k \in \mathbb{N} \). Then where \( n \in C_j \) the map given by \( f_j = f_j(g_j^{-1}(n)) \) has domain \( \mathbb{N} \) and codomain \( \bigcup_j S_j \), and is clearly onto.

Verified **II.3.9** Infinite is different than exhaustive. The list \( 0, 2, 4, \ldots \) is infinite but does not exhaust all of the natural numbers.

Verified **II.3.10** The union is not the whole real numbers. It does not include irrational numbers. For instance, \( \pi = 3.14 \ldots \) is not in any of the sets and so is not in the union.

Verified **II.3.11** Cantor’s Theorem says that the power set has more elements than the set.

(a) The set \( \{0, 1, 2\} \) has three elements. Its power set has eight.

\[
\mathcal{P}(\{0, 1, 2\}) = \{\{0, 1, 2\}, \{0, 1\}, \{0, 2\}, \{1, 2\}, \{0\}, \{1\}, \{2\}, \emptyset\}
\]

(b) The set \( \{0, 1\} \) has two elements while its power set \( \mathcal{P}(\{0, 1\}) = \{\{0, 1\}, \{0\}, \{1\}, \emptyset\} \) has four.

(c) The set \( \{0\} \) only has one element but its power set \( \mathcal{P}(\{0\}) = \{\{0\}, \emptyset\} \) has two.

(d) The empty set has zero elements, while its power set \( \mathcal{P}\emptyset = \{\emptyset\} \) has one.

Verified **II.3.12** The definition of ‘\( \leq \)' for cardinality is that \( |S| \leq |T| \) if there is a one-to-one function from \( S \) to \( T \).

(a) The function \( f : S \to S \) given by \( f(1) = 11 \), \( f(2) = 12 \), and \( f(3) = 13 \) is one-to-one by inspection.

(b) The function \( f : T \to T \) given by \( f(1) = 11 \), \( f(2) = 12 \), and \( f(3) = 13 \) is one-to-one by inspection.

(c) Again by inspection, the function \( f : S \to S \) given by \( f(1) = 1 \), \( f(2) = 3 \), and \( f(3) = 5 \) is one-to-one.

(d) The function \( f : E \to \mathcal{O} \) given by \( f(x) = x + 1 \) is a one-to-one function. The verification is easy: \( f(x_0) = f(x_1) \) implies that \( x_0 + 1 = x_1 + 1 \), and so \( x_0 = x_1 \).

**II.3.13** The two differ on the set from which the elements are drawn.

(a) Countable; this is the set \( \{\ldots, -2, -1, 0, 1\} \), which is a subset of the natural numbers.

(b) Uncountable; it is the set of real numbers \( (-\infty, 2) \). (This set corresponds to \( \mathbb{R} \) under the map \( x \mapsto \ln(1 - (x - 2)) \).)

Verified **II.3.14**

(a) This set is uncountable. (It has at least the same cardinality as \( (1, 4) \subset \mathbb{R} \) since the injection map is one-to-one. This interval has the same cardinality as \( \mathbb{R} \) because \( x \mapsto \tan((\pi/3) \cdot (x - 1) - (\pi/2)) \) is a correspondence.)

(b) Countable. (Because it is given as a subset of the naturals, this set is \( \{1, 2, 3\} \), which is finite.)

(c) Uncountable. (The function \( x \mapsto \ln(x - 5) \) is a correspondence with \( \mathbb{R} \).)
(d) Countable. (Any subset of \( \mathbb{N} \) is countable.)

**Verified** II.3.15 For the two element set \( A_2 = \{0, 1\} \), the power set, \( \mathcal{P}(A_2) = \{\{0, 1\}, \{0\}, \{1\}, \{\}\} \), has four elements. Making a function from \( A_2 \) to \( \mathcal{P}(A_2) \) involves picking where to send 0 and where to send 1. So there are \( 4 \cdot 4 = 16 \) different functions.

<table>
<thead>
<tr>
<th>function ( f_i )</th>
<th>( f_i(0) )</th>
<th>( f_i(1) )</th>
<th>function ( f_i )</th>
<th>( f_i(0) )</th>
<th>( f_i(1) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_0 )</td>
<td>{}</td>
<td>{}</td>
<td>( f_6 )</td>
<td>{1}</td>
<td>{}</td>
</tr>
<tr>
<td>( f_1 )</td>
<td>{}</td>
<td>{0}</td>
<td>( f_9 )</td>
<td>{1}</td>
<td>{0}</td>
</tr>
<tr>
<td>( f_2 )</td>
<td>{}</td>
<td>{1}</td>
<td>( f_{10} )</td>
<td>{1}</td>
<td>{1}</td>
</tr>
<tr>
<td>( f_3 )</td>
<td>{0, 1}</td>
<td></td>
<td>( f_{11} )</td>
<td>{1}</td>
<td>{0, 1}</td>
</tr>
<tr>
<td>( f_4 )</td>
<td>{0}</td>
<td></td>
<td>( f_{12} )</td>
<td>{0, 1}</td>
<td>{}</td>
</tr>
<tr>
<td>( f_5 )</td>
<td>{0}</td>
<td>{0}</td>
<td>( f_{13} )</td>
<td>{0, 1}</td>
<td>{0}</td>
</tr>
<tr>
<td>( f_6 )</td>
<td>{0}</td>
<td>{1}</td>
<td>( f_{14} )</td>
<td>{0, 1}</td>
<td>{1}</td>
</tr>
<tr>
<td>( f_7 )</td>
<td>{0}</td>
<td>{0, 1}</td>
<td>( f_{15} )</td>
<td>{0, 1}</td>
<td>{0, 1}</td>
</tr>
</tbody>
</table>

The three element set \( A_3 \) has \( |\mathcal{P}(A_3)| = 8 \). The number of functions from \( A_3 \) to \( \mathcal{P}(A_3) \) is \( 8^3 = 512 \). In general, where \( |A| = n \) the power set has \( |\mathcal{P}(A)| = 2^n \)-many elements. The number of functions is \( (2^n)^n = 2^{n^2} \). (As a check, \( n = 2 \) gives \( 2^4 = 16 \) and \( n = 3 \) gives \( 2^9 = 512 \).)

**Verified** II.3.16

(a) These are the functions from \( S \) to \( T \).

<table>
<thead>
<tr>
<th>function ( f_i )</th>
<th>( f_i(0) )</th>
<th>( f_i(1) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_0 )</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>( f_1 )</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>( f_2 )</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>( f_3 )</td>
<td>11</td>
<td>11</td>
</tr>
</tbody>
</table>

The functions that are one-to-one are \( f_1 \) and \( f_2 \).

(b) These are the functions from \( S \) to \( T \).

<table>
<thead>
<tr>
<th>function ( f_i )</th>
<th>( f_i(0) )</th>
<th>( f_i(1) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_0 )</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>( f_1 )</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>( f_2 )</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>( f_3 )</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>( f_4 )</td>
<td>11</td>
<td>11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>function ( f_i )</th>
<th>( f_i(0) )</th>
<th>( f_i(1) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_5 )</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>( f_6 )</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>( f_7 )</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td>( f_8 )</td>
<td>12</td>
<td>12</td>
</tr>
</tbody>
</table>

The functions that are one-to-one are \( f_1, f_2, f_3, f_5, f_6, \) and \( f_7 \).

**Verified** II.3.17

(a) The answer is (iii) since the union of two finite sets is finite. (All of these apply: (ii) countable or uncountable, (iii) finite, (iv) countably infinite, or uncountable. The sharpest one, the one that is most specific, is (iii).)

(b) The sharpest is (iv).

(c) The sharpest is (i).

(d) The sharpest is (iv). (The intersection could be finite but there are cases where it is countable, such as \( A = \mathbb{N} \) and \( B = \mathbb{R} \). So that is the sharpest statement.)

**Verified** II.3.18 The question doesn’t require a proof but here the parenthetical comments give a justification.

(a) They are all possible except for the last one. (An example of (i) and (ii) is \( \text{id}: \{0, 1\} \to \{0, 1\} \). An example of (iii) and (iv) is \( \text{id}: \mathbb{N} \to \mathbb{N} \). Lemma 2.11 rules out (v).)

(b) They are all possible. (An example of (i) and (ii) is \( \text{id}: \{0, 1\} \to \{0, 1\} \). An example of (iii) and (iv) is \( \text{id}: \mathbb{N} \to \mathbb{N} \). An example of (v) is \( i: \mathbb{N} \to \mathbb{R} \) given by \( i(x) = x \).)

**Verified** II.3.19 Theorem 3.6 says that a set’s cardinality is strictly less than that of its power set. So one set with a cardinality larger than \( \mathbb{R} \) is \( \mathcal{P}(\mathbb{R}) \).

**Verified** II.3.20
(A) The set of finite bit strings, \( \mathbb{B}^* \), is the union of the sets \( \mathbb{B}^k = \{ (b_0b_1 \ldots b_{k-1}) \mid k \in \mathbb{N} \} \). The set \( \mathbb{B}^k \) is finite, it has \( 2^k \) many elements, and so this is a countable union of countable sets.

(b) Suppose that the set of infinite bit strings has an exhaustive enumeration \( f_0, f_1, \ldots \). Let \( g : \mathbb{B} \to \mathbb{B} \) be given by \( g(0) = 1 \) and \( g(1) = 0 \). Then the infinite bit string \( F : \mathbb{N} \to \mathbb{B} \) defined by \( F(i) = g(f_i(i)) \) is not equal to any of the \( f_i \), which contradicts that the enumeration is exhaustive.

**Verified** II.3.21 Let \( S \) and \( T \) be such that \( S \subseteq T \). Then the identity function, the map \( \text{id} : S \to T \) given by \( \text{id}(s) = s \), is clearly one to one. Then \( |S| \leq |T| \) by Definition 3.3.

**Verified** II.3.22 Let the collection of all such functions be \( S = \{ f : \mathbb{N} \to \mathbb{N} \mid \text{ran}(f) \text{ is finite} \} \). Assume that it is countable so that there is a correspondence \( h : \mathbb{N} \to S \). For all natural numbers \( i \), the value of \( h(i) \) is a function, which we will denote \( f_i \).

Define \( g : \mathbb{N} \to \mathbb{N} \) by \( g(x) = 0 \) if \( x \neq 0 \) and \( g(x) = 1 \) otherwise. Consider the function \( k : \mathbb{N} \to \mathbb{N} \) given by \( k(i) = g(f_i(i)) \). This map has a finite range, namely \( \text{ran}(k) = \{ 0, 1 \} \), but \( k \) is not equal to any \( f_i \in S \) because they differ on the input \( i \).

**Verified** II.3.24 As stated in the question, the set of rational numbers is countable. Suppose that the irrational numbers were also countable. Then, because the union of two countable sets is countable, the real numbers would be countable. But the reals are not countable and so the irrationals are not countable either.

**Verified** II.3.25 (a) Write the decimal expansion of \( z \) as \( z = 0.z_0z_1z_2 \ldots \). It does not end in 9’s as the output of \( g \) is never a 9. So \( z \) has a unique decimal expansion. For each \( q_i \), the decimal expansion of \( z \) differs from \( q_i \)’s in that \( z_1 \cdot 10^{-(i+1)} \neq q_i_1 \cdot 10^{-(i+1)} \), by the definition of \( g \). Because their decimal expansions differ, and because neither ends in 9’s, the two are different numbers.

Since \( z \) does not equal any rational number, it is irrational.

(b) If \( d = \sum_{n \in \mathbb{N}} d_{n,n} \cdot 10^{-(n+1)} \) is rational then its decimal expansion repeats. That is, there is a decimal place such that place the expansion consists of a sequence of digits \( d_j,d_{j+1} \ldots d_{j+k} \) repeated again and again. But then the prior item’s \( z \) would also repeat, in that past that same decimal place its expansion would consist of a sequence of digits \( g(d_j)g(d_{j+1}) \ldots g(d_{j+k}) \) repeated again and again. That would make \( z \) rational, which it isn’t.

(c) Why should it be a contradiction? In Theorem 3.1 we start with what purported to be a list of all reals and then produce a real that is not on that list. Here we start with what is a list of all rationals and produce something that is not a rational. Entirely different.

**Verified** II.3.26 Before we do the proof, consider \( S = \{ 0, 1, 2, 3 \} \). These are the elements of \( \mathcal{P}(S) \).

\[
\{ \}, \{ 0 \}, \{ 1 \}, \{ 2 \}, \{ 0, 1 \}, \{ 0, 2 \}, \{ 1, 2 \}, \{ 0, 1, 2 \} \\
\{ 3 \}, \{ 0, 3 \}, \{ 1, 3 \}, \{ 2, 3 \}, \{ 0, 1, 3 \}, \{ 0, 2, 3 \}, \{ 1, 2, 3 \}, \{ 0, 1, 2, 3 \}
\]

So, fixing \( \hat{s} = 3 \in S \) gives two classes of subsets, those sets containing \( \hat{s} \) and those not containing \( \hat{s} \), and the two have the same number of members.

Our proof uses induction on \( |S| \). The base case is that \( |S| = 0 \), so \( S \) is empty. Then \( \mathcal{P}(S) = \{ \varnothing \} \) and \( |\mathcal{P}(S)| = 1 \), as required.

For the inductive step fix \( k \in \mathbb{N}^+ \), assume that the statement is true for \( n = 0, 1, \ldots, n = k \), and consider a set \( S \) where \( |S| = k + 1 \). Because \( |S| = k + 1 \), the set has an element, \( \hat{s} \in S \). The inductive hypothesis applies to \( S - \{ \hat{s} \} \), so \( \mathcal{P}(S - \{ \hat{s} \}) \) has \( 2^k \)-many elements. As illustrated in the example above, the elements of \( \mathcal{P}(S - \{ \hat{s} \}) \), which do not contain \( \hat{s} \), are in correspondence with the elements of \( \mathcal{P}(S) \) that do contain \( \hat{s} \). Thus the total number of elements of \( \mathcal{P}(S) \) is \( 2 \cdot 2^k \), which equals \( 2^{k+1} \).

**Verified** II.3.27 Suppose that \( f(s_i) = H \). There are two possibilities, either \( s_i \in H \) or else \( s_i \notin H \). If \( s_i \in H \) then student \( s_i \) is a member of their own list, so \( s_i \) is not humbl, so this violates its case assumption. On the other hand, if \( s_i \notin H \) then \( s_i \) is not a member of their own list, so \( s_i \) is humbl, which also violates this case assumption.

**Verified** II.3.28 One way is to take the diagonal bits two at a time; for instance changing 01 to 10, and changing any other two-bit sequence to 01.

**Verified** II.3.29 (a) In \( a + ar + ar^2 + ar^3 + \cdots = a \cdot 1/(1 - r) \), take \( a = 9 \) and \( r = 0.1 \). The left side is \( 9 + 0.9 + 0.09 + 0.009 + \cdots = 9.99999 \ldots \). The right side is \( 9 \cdot 1/(1 - (0.1)) = 9/0.9 = 10 \). Subtract 9 from both
(b) Consider a real number with two representations. Write the representations as \( \bar{x} = (x_N, x_{N-1}, \ldots) \) and \( \bar{y} = (y_N, y_{N-1}, \ldots) \), subject to \( x_i, y_i \in \{0, 1, \ldots, 9\} \) and to this condition.

\[
\sum_{N \geq i} x_i \cdot 10^i = \sum_{N \geq i} y_i \cdot 10^i
\]

(*)

(The number \( N \in \mathbb{Z} \) is the furthest left nonzero decimal place among the two representations.) For instance, for \( 1.000 \ldots = 0.999 \ldots \) we have \( x_0 = 1, x_{-1} = 0, x_{-2} = 0, \ldots \), giving \( 1 \cdot 10^0 + 0 \cdot 10^{-1} + 0 \cdot 10^{-2} + \cdots \), and \( y_0 = 0, y_{-1} = 9, y_{-2} = 9, \ldots \), giving \( 0 \cdot 10^0 + 9 \cdot 10^{-1} + 9 \cdot 10^{-2} + \cdots \).

Let the leftmost decimal place where the two differ be \( M \), so that \( x_M \neq y_M \) and \( x_i = y_i \) for \( i \in \{N, N-1, \ldots, M\} \). One of \( x_M \) or \( y_M \) is larger; without loss of generality suppose that \( x_M > y_M \). We must show that \( x_M = y_M + 1 \) (as it does for the example \( \langle 1, 0, 0 \ldots \rangle \) and \( \langle 0, 9, 9 \ldots \rangle \)).

The reason is that the remaining digits can add to a number no larger than \( \sum_{M+1} 9 \cdot 10^i \). This adds to \( 10^M \) by the geometric series formula. If \( x_M - y_M > 1 \) then \( \sum_{N \leq i \leq M} x_i 10^i - \sum_{N \leq i \leq M} y_i 10^i = (x_M - y_M) \cdot 10^M \) is at least \( 2 \cdot 10^M \), and the remaining digits cannot make up the difference to satisfy condition (*).

(c) Continuing with the notation from the prior item, we want to show that \( x_j = 0 \) and \( y_j = 9 \) for \( j \in \{M - 1, M - 2, \ldots\} \). The argument is similar to the prior one and we will do only \( j = M - 1 \). We have that the representations differ by one in decimal place \( M \).

\[
\left( \sum_{N \leq i \leq M} x_i 10^i \right) - \left( \sum_{N \leq i \leq M} y_i 10^i \right) = 10^M
\]

Suppose that \( y_{M-1} - x_{M-1} \leq 8 \). Then

\[
\left( \sum_{N \leq i \leq M-1} x_i 10^i \right) - \left( \sum_{N \leq i \leq M-1} y_i 10^i \right) \geq 10^M - 8 \cdot 10^{M-1}
\]

and the remaining digits can add to a number no larger than \( \sum_{M+1} 9 \cdot 10^i = 1 \cdot 10^{M-1} \), again by the geometric series formula. Adding that into the prior equation is not enough to satisfy (*). (The cases of \( j = M - 2, j = M - 3 \), etc. are similar.)

**Verified II.3.30** Suppose otherwise, that \( C \) is the set of all sets. Then \( \mathcal{P}(C) \) would be a collection of sets so we would have \( \mathcal{P}(C) \subseteq C \). That would give \( |\mathcal{P}(C)| \leq |C| \), which would contradict Cantor’s Theorem.

**Verified II.3.31**

(a) These are the chains for \( S \).

<table>
<thead>
<tr>
<th>( s \in S )</th>
<th>( \text{Chain} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0, a, 0, a ...</td>
</tr>
<tr>
<td>1</td>
<td>1, b, 1, b ...</td>
</tr>
<tr>
<td>2</td>
<td>2, d, 3, c, 2, d ...</td>
</tr>
<tr>
<td>3</td>
<td>same as the chain for 2 -</td>
</tr>
</tbody>
</table>

These are the chains for \( T \).

<table>
<thead>
<tr>
<th>( t \in T )</th>
<th>( \text{Chain} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>a, 0, a, 0 ...</td>
</tr>
<tr>
<td>b</td>
<td>b, 1, b, 1 ...</td>
</tr>
<tr>
<td>c</td>
<td>c, 2, d, 3, c, 2 ...</td>
</tr>
<tr>
<td>d</td>
<td>same as the chain for c -</td>
</tr>
</tbody>
</table>

(b) Let \( S = \{0, 2, 4, 6, \ldots\} \), let \( T = \{1, 3, 5, \ldots\} \), and take \( f: S \to T \) to be \( f(s) = s + 1 \), and \( g: T \to S \) to be \( g(t) = t + 1 \). The function \( f \) is one-to-one because if \( f(s) = f(\hat{s}) \) then \( s + 1 = \hat{s} + 1 \), and so \( s = \hat{s} \). The function \( g \) is one-to-one in the same way.

The chain associated with \( 0 \in S \) is 0, 1, 2, 3 ... It contains all the elements of both sets, and so the chain is unique. It also has a first element, that is, there is no element of \( T \) that is \( g^{-1}(0) \).
(c) If they are not already disjoint, if \( S \cap T \neq \emptyset \), then we can just color all the elements of \( S \) purple and all the elements of \( T \) gold and that will make them disjoint for sure. More precisely, consider the set \( \{0\} \times S \) of pairs \((0,s)\) along with the set \( \{1\} \times T \) of pairs \((1,t)\). These are disjoint sets because any two elements differ in the first entry. Obviously they correspond to the original sets \( S \) and \( T \).

(d) First we show that every element is in a unique chain. Fix some \( x \in S \cup T \). Because we assume that the two sets are disjoint, the function operation that applies to \( x \) is determined, meaning that if \( x \in S \) then for the chain we next consider \( f(x) \) while if \( x \in T \) then we are next doing \( g \). With that, all the elements of the chain to the right of \( x \) are determined. And, because the two functions are one-to-one, all of the element to the left are likewise determined also.

As to the four possibilities, either a chain is finite, that is, it repeats, or it is infinite. If it repeats then it is case (i). If it is infinite then it either does not have an initial element, and so is case (ii), or else it does. If it does have an initial element then either that element is from the set \( S \), as in case (iii), or else that element is from the set \( T \), as in case (iv).

(e) We will consider the correspondence for each chain type below. But first note that because each case is a restriction of a function, each is well-defined. That is, never does any of these maps associate two different outputs with the same input.

A type (i) chain repeats after some number of elements \( s_0, t_0, s_1, t_1, \ldots, s_{n-1}, t_{n-1}, s_n = s_0 \) (because the sets are disjoint it cannot repeat after a single element, and we can thus take the first element to be a member of \( S \)). The function \( f \) makes these associations.

\[
s_0 \mapsto t_0 \quad s_1 \mapsto t_1, \quad \ldots \quad s_{n-1} \mapsto t_{n-1}
\]

This is clearly a correspondence among the elements of the chain. It is manifestly onto the set \( \{t_0, t_1, \ldots, t_{n-1}\} \) and it is one-to-one because the \( t_j \)'s are distinct, or else the chain would be shorter.

For a type (ii) chain

\[
\ldots f^{-1}(g^{-1}(s)), g^{-1}(s), s, f(s), g(f(s)), f(g(f(s))), \ldots
\]

the function \( f \) associates these.

\[
\ldots f^{-1}(g^{-1}(s)) \mapsto g^{-1}(s), s \mapsto f(s), g(f(s)) \mapsto f(g(f(s))), \ldots
\]

This also is clearly a correspondence.

A type (iii) chain

\[
s, f(s), g(f(s)), f(g(f(s))), \ldots
\]

has these associations.

\[
s \mapsto f(s), \quad g(f(s)) \mapsto f(g(f(s))), \ldots
\]

Again, clearly a correspondence.

The one that takes some thought is a chain of type (iv).

\[
t, g(t), f(g(t)), g(f(g(t))), \ldots
\]

We want a correspondence function from \( S \) to \( T \). Consider these associations.

\[
g(t) \mapsto t \quad g(f(t)) \mapsto f(t), \quad \ldots
\]

Because the function \( g \) is one-to-one its inverse is defined, over its range. So this association is a well-defined function. Like the chain types above, this also is clearly a correspondence.

Verified II.4.5 A Universal Turing machine is a regular machine, in that it is just another machine in the list \( P_0, P_1, \ldots \) Perhaps your friend meant something more like, “What does a Universal Turing machine do that a non-universal machine does not do?” Every machine does a job. Some machines expect a single input and
then double it, some interpret their input as two numbers and then add them. A Universal Turing machine expects two inputs, \( e \) and \( x \), and the output of this machine is the same as the output of the machine \( P_e \) on input \( x \), including failing to halt if that machine fails to halt. It is universal in that any input/output behavior that can be mechanically produced can be produced by this one device.

**II.4.6** Every general purpose computer, including any standard laptop or cell phone, is equivalent in computable power to a Universal Turing machine.

A person can object that a standard laptop for instance does not come from the store with unboundedly much memory. That's true. But such a machine can store things in the cloud and so is not restricted to the installed memory, and in this sense its memory is unbounded.

A person can go on to worry that there are only so many bits available in the physical universe and thus memory is not in the end unbounded. Perhaps that is true — although we could worry back that we have not got enough time to exhaust what bits that there are before the Big Bang becomes a Big Crunch, or whatever it will become — but at least we can take general purpose devices to be so very close to Universal Turing machines that it is quite hard to tell them apart.

**II.4.7** Yes. If \( P_{e_0} \) and \( P_{e_1} \) are universal then giving the first one the inputs \( e_1 \) and \( x \) will result in an input/output behavior exactly like the second. Likewise, giving \( P_{e_0} \) the inputs \( e_0 \) and \( x \) will result in the machine behaving just like itself.

**II.4.8** The answer is that it does those things in software. A laptop uses the binary alphabet but simulates working with any language with any alphabet. For instance, it may simulate the symbol \( \hat{a} \) just like itself. Likewise, the universal machine does not use its states to simulate the states of the simulated machine. Rather, it has codes for those states that it manipulates on the tape.

**II.4.9** Yes, every computable function has infinitely many indices by Lemma 2.15. So if \( P_e \) is universal, then the associated function \( \phi_e \) has infinitely many unequal indices so that \( \phi_e = \phi_{e_0} = \phi_{e_1} = \cdots \). The machines \( P_{e_0}, P_{e_1}, \ldots \) are all universal.

**II.4.10** We know that 5 equals cantor\((2, 0)\), that is, \( \text{pair}(5) = \langle 2, 0 \rangle \). So in \( \phi_{e_0}(e_0, 5) \) the argument to \( \phi_{e_0} \) is the value of \( \phi_2(0) \). So, where \( \text{pair}(\phi_2(0)) = \langle a, b \rangle \), the value of \( \phi_{e_0}(e_0, 5) \) is \( \phi_a(b) \).

**II.4.11** We write \( f_{i,a} \) for the function produced by freezing \( x_i \) to the value \( a \).

(a) The resulting one-variable function is \( f_{0,4}(x_1) = 12 + 4x_1 \).

(b) The one-variable function is \( f_{0,5}(x_1) = 15 + 5x_1 \).

(c) The one-variable function is \( f_{1,0}(x_0) = 3x_0 \).

**II.4.12** We use \( \hat{f} \) for the name of each function.

(a) The resulting two-variable function is \( \hat{f}(x_1, x_2) = 1 + 2x_1 + 3x_2 \).

(b) The result is the two-variable function \( \hat{f}(x_1, x_2) = 2 + 2x_1 + 3x_2 \).

(c) This gives \( \hat{f}(x_1, x_2) = a + 2x_1 + 3x_2 \).

(d) This results in the one-variable function \( \hat{f}(x_2) = 11 + 3x_2 \).

(e) The result is \( \hat{f}(x_2) = a + 2b + 3x_2 \).

**II.4.13**

(a) The two subscripts on \( s_{1,1} \) mean that we will freeze the first input and leaves the second one as a variable. So \( \hat{\phi}_{s_{1,1}(e,1)} \) will be a one-input function. The arguments \( e \) and 1 indicate that we are working on Turing machine \( e \), the one whose flow chart is given in the problem statement, and that the input is frozen to be \( x_0 = 1 \). This flowchart gives a sense of the result.

```
<table>
<thead>
<tr>
<th>Start</th>
</tr>
</thead>
<tbody>
<tr>
<td>Read x_1</td>
</tr>
<tr>
<td>Print 1 + x_1</td>
</tr>
<tr>
<td>↓</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>↓</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>End</td>
</tr>
</tbody>
</table>
```

The function is \( \phi_{s_{1,1}(e,1)}(x_1) = 1 + x_1 \).
(b) The values are $\phi_{s_1}(e,1)(0) = 1$, $\phi_{s_1}(e,1)(1) = 2$, and $\phi_{s_1}(e,1)(2) = 3$.
(c) The notation $s_1(e,0)$ indicates that we work on Turing machine $e$, that we freeze the first input to $x_0 = 0$, and that we leave the second input as a variable. This flowchart gives the idea.

```
Start
Read x1
Print 0 + x1
End
```

The function is $\phi_{s_1}(e,1)(x_1) = 0 + x_1 = x_1$.
(d) We have $\phi_{s_1}(e,0)(0) = 0$, $\phi_{s_1}(e,0)(1) = 1$, and $\phi_{s_1}(e,0)(2) = 2$.

**Verified II.4.14**

(A) The notation $s_2(e,1)$ indicates that we work on $P_e$, that we freeze the first input to $x_0 = 1$, and that we leave the second and third inputs as variables. This flowchart sketches the behavior.

```
Start
Read x1, x2
Print 1 + x1 $\cdot$ x2
End
```

The function is $\phi_{s_1}(e,1)(x_1, x_2) = 1 + x_1 \cdot x_2$.
(b) We have $\phi_{s_1}(e,1)(0,1) = 1$, $\phi_{s_1}(e,1)(1,0) = 1$, and $\phi_{s_1}(e,1)(2,3) = 7$.
(c) The $s_2(e,1,2)$ says that we start with $P_e$, that we freeze the first input to $x_0 = 1$ and the second input to $x_1 = 2$, and leave the third input as a variable. This sketches the result.

```
Start
Read x2
Print 1 + 2 $\cdot$ x2
End
```

The function is $\phi_{s_2}(e,1,2)(x_2) = 1 + 2 \cdot x_2$.
(d) The values are $\phi_{s_2}(e,1,2)(0) = 1$, $\phi_{s_2}(e,1,2)(1) = 3$, and $\phi_{s_2}(e,1,2)(2) = 5$.

**Verified II.4.15**

(A) $\phi_{s_1}(e,0)(x_1) = x_1$
(B) $\phi_{s_1}(e,0)(5) = 5$
(C) $\phi_{s_1}(e,1)(x_1) = x_1$
(D) $\phi_{s_1}(e,1)(5) = 5$
(E) $\phi_{s_1}(e,2)(x_1)$
(F) $\phi_{s_1}(e,2)(5)$

**II.4.16**

(A) This flowchart sketches $P_{s(e,0,3)}$.

```
Start
Read y
Print 3 $\cdot$ y
0 even?
Y
Print 3 + y
N
End
```

The function is $\phi_{s(e,0,3)}(y) = 3y$. Consequently, $\phi_{s(e,0,3)}(5) = 15$.
(b) This is the flowchart sketching $P_{s(e,1,3)}$.

![Flowchart](image1)

The computed function is $\phi_{s(e,1,3)}(y) = 3 + y$, and consequently $\phi_{s(e,1,3)}(5) = 8$.

(c) This is the flowchart sketching $P_{s(e,a,b)}$.

![Flowchart](image2)

The distinction between this and the flowchart in the question statement is that here the machine does not read in $x_0$ or $x_1$. Those two are hard-coded, as $a$ and $b$, into the program body. This is a family of functions parametrized by $a$ and $b$, and the indices of these functions are uniformly computable from $e$, $a$, and $b$, using the $s$-$m$-$n$ function $s$.

**Verified II.4.17**

(A) The function $\psi(x, y) = 3x + y$ is computable by Church’s Thesis, as sketched in this flowchart.

![Flowchart](image3)

(b) By the prior item there is a Turing machine that computes the function $\psi$. Suppose that it is $P_e$. The $s$-$m$-$n$ theorem gives that $P_{s_{1,1}(e,n)}$ computes the function $y \mapsto 3n + y$. Take $\psi_n = \phi_{s_{1,1}(e,n)}$.

**Verified II.4.18** Start with the function $\psi : \mathbb{N}^2 \to \mathbb{N}$ defined by $\psi(x, y) = y + x^2$. By Church’s Thesis it is computable, since it is computed by the machine sketched by this flowchart.

![Flowchart](image4)

Suppose that machine has index $e$, that is, suppose that $\psi(x, y) = \phi_e(x, y)$.

By the $s$-$m$-$n$ theorem there is a family of computable functions parametrized by $n$, $\phi_{s_{1,1}(n)}$, with the desired behavior, $\phi_{s_{1,1}(n)}(y) = y + n^2$. Take $g(n)$ to be $s_{1,1}(n)$.

**Verified II.4.19** Start with the function $\psi(u, v, x) = ux + v$. Church’s Thesis gives that it is computable, by the machine sketched by this flowchart.
Let that machine have index \( e \), that is, suppose that \( \psi(u, v, x) = \phi_e(u, v, x) \).

The s-m-n theorem gives a family of computable functions \( \phi_{s,1}(m, b) \) parametrized by \( m \) and \( b \) with the desired behavior, \( \phi_{s,1}(m, b)(x) = m \cdot x + b \). Take \( g(m, b) \) to be \( s_{2,1}(m, b) \).

**Verified II.4.20**

(a) This gives the same result as \( \phi_{e_1}(5) \), that is, it converges and gives 20.

(b) This returns 4 times the the value of \( \text{cantor}(e_0, 5) \).

(c) This returns \( \phi_{e_1}(5) = 20 \).

**Verified II.4.21**

(a) This gives the same result as \( \phi_{e_1}(4) \), that is, it gives 6.

(b) This returns the value of \( \phi_4(e_1) \), whatever that is.

(c) This returns \( \phi_{e_2}(3) \) plus 2, which is 11.

(d) Because \( \text{pair}(4) = \langle 1, 1 \rangle \), this returns the same as \( \phi_1(1) \), whatever that is.

**Verified II.5.16** False. There is such a function. But it is not computable; there is no Turing machine whose behavior is that function.

**Verified II.5.17** The unsolvability results do not say that you cannot prove that a particular machine does a particular thing. The given machine does indeed fail to halt on all inputs and it is indeed obvious. Instead the results say that no machine can take in the index \( x \) and correctly determine whether \( \mathcal{P}_x \) does that thing.

**Verified II.5.18**

(a) False. The function exists. We say that the problem is unsolvable because that function is not mechanically computable.

(b) False. Church’s Thesis asserts that Turing machines are a maximally-powerful model of computation. The existence of unsolvable problems is inherent in effective computation.

**Verified II.5.19** Any finite set is computable.

**Verified II.5.20** Briefly, we have to distinguish between a machine and the function that it computes. Many different machines compute the same function. Rice’s theorem is about those properties of the machine that extend to be properties of the computed functions. For instance, “Does this code compute the squaring function?” is unsolvable, but “Does this code contain the letter K?” is not.

A more sophisticated answer is that two machines ‘extensionally equal’ if they compute the same function, so that for every input either both machines run forever on that input, or they both terminate and output the same value. An ‘extensional property’ of programs is a property that respects extensional equality, i.e., if two machines are extensionally equal then they either both have the property or both not have it. Then Rice’s Theorem says that a computable extensional property of machines either holds of all machines or of none.

Here are some non-extensional properties, to which Rice’s Theorem does not apply: (i) the machine halts within 100 steps (we can always modify a machine to an extensionally equal one that runs longer), (ii) the machine uses fewer than \( n \) memory cells within the first \( m \) steps of execution (we can always modify a machine to an extensionally equal one so that it uses extra memory), and (iii) the machine source contains state \( q_{10} \) (we can add extra states).

**Verified II.5.21** Yes, any finite set is computable. You could, for example, compute membership in a finite set with a sequence of if-then-else statements.

**Verified II.5.22**

(a) The function \( f(x, y) = 3x + y \) is intuitively computable, as sketched on the left of Figure 10 on page 56.

Church’s Thesis gives that there is a Turing machine with that behavior; let that machine have index \( e \), so that \( f(x, y) = \phi_e(x, y) \) for all \( x, y \in \mathbb{N} \). Applying the s-m-n Theorem to parametrize \( x \) gives this computable family of one-input computable functions: \( \phi_{s(e,x)}(y) = 3x + y \). Flowcharts sketching some associated machines are on the right side of Figure 10 on page 56.
(b) The function \( f(x, y) = xy^2 \) is intuitively computable, as in Figure 11 on page 56. Church’s Thesis gives that there is a Turing machine \( P_e \) with that behavior, so that \( f(x, y) = \phi_e(x, y) \) for all \( x, y \in \mathbb{N} \). Applying the \( s\mbox{-}m\mbox{-}n \) Theorem to parametrize \( x \) gives \( \phi_{s(e,x)}(y) = xy^2 \), which is a family of one-input functions. Flowcharts sketching some associated machines are on the right side of Figure 11 on page 56.

(c) The function \( f \) is intuitively computable, as sketched on the left of Figure 12 on page 57. Church’s Thesis gives that there is a Turing machine \( P_e \) with that behavior, so that \( f(x, y) = \phi_e(x, y) \) for all \( x, y \in \mathbb{N} \). Apply the \( s\mbox{-}m\mbox{-}n \) Theorem to parametrize \( x \). The resulting family of one-input functions is this.

\[
\phi_{s(e,x)}(y) = \begin{cases} 
x & \text{if } x \text{ is odd} \\
0 & \text{otherwise}
\end{cases}
\]

Flowcharts sketching associated machines are on the right side of Figure 12 on page 57.

Verified II.5.23 We will show that this function is not mechanically computable.

\[
\text{total\_decider}(e) = \begin{cases} 
1 & \text{if } \phi_e(y) \downarrow \text{ for all } y \\
0 & \text{otherwise}
\end{cases}
\]

The function

\[
\psi(x, y) = \begin{cases} 
42 & \text{if } \phi_x(x) \downarrow \\
\uparrow & \text{otherwise}
\end{cases}
\]

is intuitively computable by the flowchart on the left of Figure 13 on page 57. Thus Church’s Thesis says that there is a Turing machine that computes it; let that machine have index \( e \), so that \( \psi(x, y) = \phi_e(x, y) \). The \( s\mbox{-}m\mbox{-}n \) Theorem gives a family of functions parametrized by \( x \), whose machines are sketched on the right of Figure 13 on page 57. Notice that \( \phi_x(x) \downarrow \) if and only if \( \text{total\_decider}(s(e,x)) = 1 \).

Since \( s \) is computable, if we can mechanically compute \( \text{total\_decider} \) then we can mechanically solve the Halting problem. We cannot mechanically solve the Halting problem, so we cannot mechanically compute \( \text{total\_decider} \).

Verified II.5.24

(a) We will show that this function is not mechanically computable.

\[
\text{square\_decider}(e) = \begin{cases} 
1 & \text{if } \phi_e(y) = y^2 \text{ for all } y \\
0 & \text{otherwise}
\end{cases}
\]
Consider this function.

$$\psi(x, y) = \begin{cases} y^2 & \text{if } \phi_x(x) \downarrow \\ \uparrow & \text{otherwise} \end{cases}$$

The flowchart on the left of Figure 14 on page 58 shows that $\psi$ is intuitively computable so by Church’s Thesis there is a Turing machine that computes it. Let that machine have index $e$. Apply the $s$-$m$-$n$ Theorem to get a family of functions parametrized by $x$, whose machines are sketched on the right of Figure 14 on page 58. Then $\phi_x(x) \downarrow$ if and only if $\text{square_decider}(s(e, x)) = 1$.

So, since the function $s$ is computable, if we can mechanically compute $\text{square_decider}$ then we can mechanically solve the Halting problem. But we can’t mechanically solve the Halting problem so we cannot mechanically compute $\text{square_decider}$.

(b) We will show that this function is not computable.

$$\text{same_value_decider}(e) = \begin{cases} 1 & \text{if } \phi_e(y) = \phi_e(y + 1) \text{ for some } y \\ 0 & \text{otherwise} \end{cases}$$

This function

$$\psi(x, y) = \begin{cases} 42 & \text{if } \phi_x(x) \downarrow \\ \uparrow & \text{otherwise} \end{cases}$$

is intuitively computable by the flowchart on the left of Figure 15 on page 58. So, by Church’s Thesis there is a Turing machine that computes it; let that machine have index $e$. Apply the $s$-$m$-$n$ Theorem to get a family of functions parametrized by $x$, whose machines are sketched on the right of Figure 15 on page 58. Observe that these machines produce the function with constant output 42 if and only if the machine gets through the middle box. More precisely stated, $\phi_x(x) \downarrow$ if and only if $\text{same_value_decider}(s(e, x)) = 1$.

Since the function $s$ is computable, if we can mechanically compute $\text{same_value_decider}$ then we can mechanically solve the Halting problem, which we cannot do.
Figure 14, for question II.5.24: The machine associated with the function $\psi = \phi_e$ and the machine associated with $\phi_{s(e,x)}$.

Figure 15, for question II.5.24: The machine associated with the function $\psi = \phi_e$ and the machine for $\phi_{s(e,x)}$.

\[ \text{(A) We will show that this function is not computable; no Turing machine has this input-output behavior.} \]

\[
\text{diverges_on_five}\_\text{decider}(e) =
\begin{cases}
1 & \text{if } \phi_e(5) \uparrow \\
0 & \text{otherwise}
\end{cases}
\]

The function
\[
\psi(x, y) =
\begin{cases}
42 & \text{if } \phi_x(x) \downarrow \\
\uparrow & \text{otherwise}
\end{cases}
\]

is intuitively computable by the flowchart on the left of Figure 16 on page 59. So Church’s Thesis says that there is a Turing machine that computes it. Let that machine have index $e$, so that $\psi(x, y) = \phi_e(x, y)$. The s-m-n Theorem gives a family of functions parametrized by $x$, whose machines are sketched on the right of Figure 16 on page 59. Then $\phi_x(x) \downarrow$ if and only if $\text{diverges_on_five}\_\text{decider}(s(e, x)) = 1$. Because the function $s$ is mechanically computable, this means that if we could mechanically compute $\text{diverges_on_five}\_\text{decider}$ then we could mechanically solve the Halting problem. But we cannot mechanically solve the Halting problem, so we cannot mechanically compute $\text{diverges_on_five}\_\text{decider}$.

\[ \text{(b) We want to show that this function is not computable.} \]

\[
\text{diverge_on_odds}\_\text{decider}(e) =
\begin{cases}
1 & \text{if } \phi_e(y) \uparrow \text{ for all odd } y \in \mathbb{N} \\
0 & \text{otherwise}
\end{cases}
\]

The argument given in the prior item will do again here.

II.5.26

\[ \text{(A) We will show that no Turing machine has this input-output behavior.} \]

\[
\text{successor}\_\text{decider}(e) =
\begin{cases}
1 & \text{if } \phi_e(x) = x + 1 \text{ for all } x \in \mathbb{N} \\
0 & \text{otherwise}
\end{cases}
\]

The function
\[
\psi(x, y) =
\begin{cases}
y + 1 & \text{if } \phi_x(x) \downarrow \\
\uparrow & \text{otherwise}
\end{cases}
\]
is intuitively computable by the flowchart on the left of Figure 17 on page 59. So Church’s Thesis says that there is a Turing machine that computes it. Let that machine have index \( e \), so that \( \psi(x, y) = \phi_e(x, y) \).

The \( s\text{-}m\text{-}n \) Theorem gives a family of functions parametrized by \( x \), whose machines are sketched on the right of Figure 17 on page 59. Then \( \phi_s(x) \downarrow \) if and only if \( \text{successor\_decider}(s(e, x)) = 1 \). The function \( s \) is mechanically computable, so if we could mechanically compute \( \text{successor\_decider} \) then we could mechanically solve the Halting problem. But we can't do that, so we cannot mechanically compute \( \text{successor\_decider} \).

(b) We will show that this function is not mechanically computable.

\[
\text{converges\_on\_twice\_input\_decider}(e) = \begin{cases} 
1 & \text{if there is } x \in \mathbb{N} \text{ so that } \phi_e(x) \downarrow \text{ and } \phi_e(2x) \downarrow \\
0 & \text{otherwise}
\end{cases}
\]

The function

\[
\psi(x, y) = \begin{cases} 
42 & \text{if } \phi_s(x) \downarrow \\
\uparrow & \text{otherwise}
\end{cases}
\]

is intuitively computable by the flowchart on the left of Figure 18 on page 60. So Church’s Thesis says that there is a Turing machine that computes it. Let that machine have index \( e \). Apply the \( s\text{-}m\text{-}n \) Theorem to get a family of functions parametrized by \( x \), whose machines are sketched on the right of Figure 18 on page 60. Then \( \phi_s(x) \downarrow \) if and only if \( \text{converges\_on\_twice\_input\_decider}(s(e, x)) = 1 \). So if we could mechanically compute \( \text{converges\_on\_twice\_input\_decider} \) then we could mechanically solve the Halting problem. But we cannot mechanically solve the Halting problem, so we cannot mechanically compute \( \text{converges\_on\_twice\_input\_decider} \).

II.5.27

(a) This is solvable. Given the index \( e \), start by translating it to the set of Turing machine instructions, \( P_e \) (remember that we are using numberings that are acceptable in the sense defined on page 72). Now count the number of states that appear in that Turing machine.

(b) This is not solvable; \( \text{halts\_on\_empty} \) is not mechanically computable. For, consider this function.

\[
\psi(x) = \begin{cases} 
42 & \text{if } \phi_s(x) \downarrow \\
\uparrow & \text{otherwise}
\end{cases}
\]
It is intuitively mechanically computable, and so by Church’s Thesis there is a Turing machine that computes it. Let the index of that machine be \( e \). Apply the \( s\)-\( m\)-\( n\) theorem to parametrize \( x \), giving a uniformly computable family of functions \( \Phi_{s(e,x)} \). (The \( \Phi_{s(e,x)}' \)'s are functions of no input; that’s fine as the associated Turing machine simply does not read any input from the tape.)

Then \( \Phi_x(x) \downarrow \) if and only if \( \text{halts}_x(s(e,x)) = 1 \). If \( \text{halts}_x(s(e,x)) \) were mechanically computable then we could mechanically solve the Halting problem, so \( \text{halts}_x(s(e,x)) \) is not mechanically computable.

(c) This is solvable. From the index \( e \), use a Universal Turing machine to run \( P_e \) on input \( e \) for one hundred steps. By the end either it has halted or it hasn’t.

II.5.28 No, it is not an index set. We can write two Turing machines with the same behavior, say, on input \( x \) they return output \( y \). But one of them takes only a few steps to do this while the other takes 101 steps. The index of the second set is a member of \( I \) but the index of the first set is not a member.

II.5.29

(A) Recall the first problem: given an index \( x \), decide if the Turing machine \( P_x \) squares its input so that \( \Phi_x(y) = y^2 \) for all \( y \in \mathbb{N} \). To apply Rice’s Theorem we must show that \( I = \{ x \in \mathbb{N} | \Phi_x(y) = y^2 \text{ for all } y \in \mathbb{N} \} \) is a nontrivial index set. First, it is not empty because clearly we can write a program that squares its input, and then by Church’s Thesis there is a Turing machine with that behavior. That machine’s index is a member of \( I \).

Second, \( I \) is not equal to \( \mathbb{N} \) because we can write a program that does not square its input, for instance because it does not halt on any input. By Church’s Thesis there is a Turing machine with that behavior, and the machine’s index is not a member of \( I \).

To finish we verify that \( I \) is an index set. Suppose that \( x \in I \) and that \( \hat{x} \) is such that \( \Phi_x(y) \approx \Phi_{\hat{x}} \). Because \( x \in I \) we must have that \( \Phi_x(y) = y^2 \) for all \( y \in \mathbb{N} \). But then because the two have the same behavior, \( \Phi_{\hat{x}}(y) = y^2 \) for all \( y \) also, and therefore \( \hat{x} \in I \). Thus, \( I \) is an index set.

(b) The problem is: given \( x \), determine if \( \Phi_x \) is such that there is a \( y \in \mathbb{N} \) where \( \Phi_x(y) = \Phi_x(y+1) \). For Rice’s Theorem we will show that \( I = \{ x \in \mathbb{N} | \Phi_x(y) = \Phi_x(y+1) \text{ for some } y \in \mathbb{N} \} \) is a nontrivial index set. First, \( I \) is not empty because we can write a program that outputs 1 for all input, and then by Church’s Thesis there is a Turing machine with that behavior. That machine’s index is a member of \( I \).

Second, \( I \) is not all of \( \mathbb{N} \) because we can write a program that does not halt on any input. By Church’s Thesis there is a Turing machine with that behavior, and the machine’s index is not a member of \( I \).

We finish by verifying that \( I \) is an index set. Suppose that \( x \in I \) and that \( \hat{x} \) is such that \( \Phi_x \approx \Phi_{\hat{x}} \). Because \( x \in I \) there must exist a \( y \in \mathbb{N} \) such that \( \Phi_x(y) = \Phi_x(y+1) \). Because the two have the same behavior, \( \Phi_{\hat{x}}(y) = \Phi_{\hat{x}}(y+1) \) also, and therefore \( \hat{x} \in I \). Thus, \( I \) is an index set.

II.5.30

(A) We first state the problem precisely: given an index \( x \), decide if \( \Phi_x(y) \downarrow \) for all \( y \in \mathbb{N} \). To show that this problem is unsolvable we will verify that \( I = \{ x \in \mathbb{N} | \Phi_x(y) \downarrow \text{ for all } y \in \mathbb{N} \} \) is a nontrivial index set.

It is not empty because we can write a program that returns its input, and then by Church’s Thesis there is a Turing machine with that behavior. That machine’s index is a member of \( I \).

It is not equal to \( \mathbb{N} \) because we can write a program that does not halt on any input. By Church’s Thesis there is a Turing machine with that behavior and the machine’s index is not a member of \( I \).

We finish verifying that \( I \) is an index set. Suppose that \( x \in I \) and that \( \hat{x} \) is such that \( \Phi_x \approx \Phi_{\hat{x}} \). Because
II.5.31 For both items we will use Rice’s Theorem.

II.5.32 We will use Rice’s Theorem so consider $I = \{ e \mid P_e \text{ accepts } 101 \}$ is a nontrivial index set. First, $I$ is nonempty because we can write a Turing machine to output 1 on all inputs, which accepts the string 101. The index of that Turing machine is an element of $I$. Second, $I$ does not equal $\mathbb{N}$ because we can write a Turing machine to output 0 on all inputs, which accepts the empty subset of $\mathcal{B}$, which is not infinite. The index of that Turing machine is not an element of $I$. Therefore $\hat{x} \in I$, and $I$ is an index set.

II.5.33 This problem is solvable. We can write a program that inputs cantor($x$, $y$), applies the unpairing function to get $x$ and $y$, and then plugs them into $ax + by$, to see if the result equals $c$.

II.5.34 Briefly, we cannot tell anything by whether the machine ‘goes on’. It can go on to do quite complex things.

For more, we can reduce this problem to the Halting problem. Consider this $\psi : \mathbb{N}^2 \to \mathbb{N}$.

\[
\psi(x, y) = \begin{cases} 
42 & \text{if machine } P_x \text{ halts on } x \text{ and } y = \epsilon \\
\uparrow & \text{otherwise}
\end{cases}
\]

(We can take this machine to have tape alphabet $\Sigma = \{B, 1\}$.) This is intuitively computable so Church’s Thesis gives that there is a Turing machine with this behavior, and we can assume it has index $e$. Apply the $s-m-n$ Theorem to parametrize $x$, giving a family of machines and associated computable
functions as here.

\[ \phi_{s(e, x)}(y) = \begin{cases} 42 & \text{if machine } P_x \text{ halts on } x \text{ and } y = \varepsilon \\ \uparrow & \text{otherwise} \end{cases} \]

Then \( \phi_e(x) \uparrow \) if and only if the function \( \phi_{s(e, x)} \) halts only on \( y = \varepsilon \). So if we could check the latter mechanically then we could mechanically solve the Halting problem, which of course we cannot.

II.5.35 There are of course many answers; one is \( I_0 = \{ e \mid P_e \text{ solves the Halting problem} \} \).

II.5.36 We will call each set \( I \).

(a) Suppose that \( e \in I \) and suppose that \( \hat{e} \) is such that \( \phi_e \equiv \phi_{\hat{e}} \). Because \( e \in I \) the machine \( P_e \) halts on at least five inputs, that is, the function \( \phi_e \) converges on at least five inputs. Because \( \phi_e \equiv \phi_{\hat{e}} \), the function \( \phi_{\hat{e}} \) also halts on at least five inputs, namely, the same five. Thus \( \hat{e} \in I \) also.

(b) Suppose that \( e \in I \) and suppose also that \( \hat{e} \in \mathbb{N} \) is such that \( \phi_e \equiv \phi_{\hat{e}} \). Because \( e \in I \) the function \( \phi_e \) is one-to-one. Because \( \phi_e \equiv \phi_{\hat{e}} \), the function \( \phi_{\hat{e}} \) is also one-to-one. Thus \( \hat{e} \in I \).

(c) Suppose that \( e \in I \) and also that \( \hat{e} \in \mathbb{N} \) is such that \( \phi_e \equiv \phi_{\hat{e}} \). Because \( e \in I \) the function \( \phi_e \) is either total or else \( \phi_e(3) \uparrow \). In the first case, that \( \phi_e \) is total, because \( \phi_e \equiv \phi_{\hat{e}} \), the function \( \phi_{\hat{e}} \) is also total. In the case that \( \phi_e(3) \uparrow \), because they have the same behavior, \( \phi_{\hat{e}}(3) \uparrow \) also. In either case, \( \hat{e} \in I \).

II.5.37

(a) The relation \( \equiv \) is reflexive because a Turing machine \( P_e \) has the same behavior as itself: \( \phi_e \equiv \phi_e \). It is symmetric because if \( P_e \) has the same behavior as \( P_{\hat{e}} \) then the converse also holds. Transitivity is just as clear.

(b) Each equivalence class is a set of integers \( e \in \mathbb{N} \). Two integers are together in a class, \( e, \hat{e} \in C \) if the input-output behaviors of the associated Turing machines \( P_e \) and \( P_{\hat{e}} \) are the same, \( \phi_e \equiv \phi_{\hat{e}} \). (As an example, one class contains the indices of all Turing machines that double the input, \( C = \{ e \in \mathbb{N} \mid \phi_e(x) = 2x \text{ for all } x \} \).

(c) We follow the hint. Suppose that \( I \) is an index set and that \( e \in C \) is an element of \( I \). If \( \hat{e} \in C \) then \( \phi_{\hat{e}} \equiv \phi_e \) because \( C \) is an equivalence class for the relation \( \equiv \). But \( I \) is an index set so \( \hat{e} \in I \) also.

II.5.38

(a) Let \( I \) be an index set and consider the complement, \( I^c \). Suppose that \( e \in I^c \) and suppose also that \( \hat{e} \in \mathbb{N} \) is such that \( \phi_e \equiv \phi_{\hat{e}} \). We will show that \( \hat{e} \in I^c \).

By the definition of set complement, either \( \hat{e} \in I \) or \( \hat{e} \in I^c \). If \( \hat{e} \in I \) then because \( \phi_e \equiv \phi_{\hat{e}} \) and because \( I \) is an index set, we have that \( \hat{e} \in I \) also. This contradicts that \( e \in I \) and therefore \( \hat{e} \in I^c \).

(b) Fix a collection \( I_j \) of index sets and consider the union \( I = \bigcup \{ I_j \} \). Suppose that \( e \in I \) and suppose also that \( \hat{e} \in \mathbb{N} \) is such that \( \phi_e \equiv \phi_{\hat{e}} \). We will show that \( \hat{e} \in I \).

The number \( e \) is an element of the union \( \bigcup \{ I_j \} = \mathbb{N} \) so it is an element of some \( I_{j_0} \). Because \( \phi_e \equiv \phi_{\hat{e}} \) and because \( I_{j_0} \) is an index set, the number \( \hat{e} \) is an element of \( I_{j_0} \), and is therefore an element of the union \( I \). Thus \( I \) is an index set.

(c) Let \( I_j \) be a collection of index sets and let \( I = \bigcap \{ I_j \} \). Suppose that \( e \in I \), and also that \( \hat{e} \in \mathbb{N} \) is such that \( \phi_e \equiv \phi_{\hat{e}} \). We will show that \( \hat{e} \in I \).

Since \( e \) is an element of the intersection \( \bigcap \{ I_j \} = I \), it is an element of each set \( I_j \). Because \( \phi_e \equiv \phi_{\hat{e}} \) and because \( I_j \) is an index set, the number \( \hat{e} \) is an element of \( I_j \) also. As \( \hat{e} \) is an element of each \( I_j \), it is an element of the intersection \( I \). Thus \( I \) is an index set.

II.5.39 The differences between this case and the one in the section are very small. The proof there starts by considering an index set \( I \). It fixes an index \( e_0 \in \mathbb{N} \) so that \( \phi_{e_0}(y) \uparrow \) for all inputs \( y \in \mathbb{N} \). It then does the \( e_0 \notin I \) case. So what's left is to do \( e_0 \in I \). Here's a difference: because \( I \) is nontrivial, it does not equal \( \mathbb{N} \) so there is some \( e_1 \notin I \). Because \( I \) is an index set, \( \phi_{e_0} \neq \phi_{e_1} \). Thus there is an input \( y \) such that \( \phi_{e_1}(y) \downarrow \).

Consider the flowchart on the left of Figure 19 on page 63. By Church's Thesis there is a Turing machine with that behavior; call it \( P_c \). Apply the s-m-n theorem to parametrize \( x \), resulting in the uniformly computable family of functions \( \phi_{s(e, x)} \), whose computation is outlined on the right of Figure 19 on page 63. We've constructed the machines so that if \( \phi_e(x) \uparrow \) then \( \phi_{s(e, x)} \equiv \phi_{e_0} \) and thus \( s(e, x) \in \mathbb{N} \). Further, if \( \phi_e(x) \downarrow \) then \( \phi_{s(e, x)} \equiv \phi_{e_1} \) and thus \( s(e, x) \notin \mathbb{N} \). Therefore if \( I \) were mechanically computable, so that we could effectively check whether \( s(e, x) \in \mathbb{N} \), then we could mechanically solve the Halting problem. (This part of the argument is like the one in the section, but with the cases of \( s(e, x) \in \mathbb{N} \) and \( s(e, x) \notin \mathbb{N} \) reversed.)
II.5.40 The set of functions \( f : \mathbb{N} \rightarrow \mathbb{N} \) is the disjoint union of two subsets: the functions that are computable and the functions that are not. We know that the set of computable functions is countable. Because the union of two countable sets is countable, if the set of non-computable functions were also countable then there would be countably many functions overall, which there are not. Thus the set of non-computable functions is not countable.

II.5.41 Fix an element \( k \in K \). The range of this function is \( K \).

\[
    f(x, n) = \begin{cases} 
    x & \text{if } \mathcal{P}_x \text{ with input } x \text{ halts in } n \text{ steps} \\
    k & \text{otherwise}
    \end{cases}
\]

Clearly the function is computable and converges on all inputs.

II.5.42 Start with decidable languages \( L_0 \) and \( L_1 \) and consider the union \( L = L_0 \cup L_1 \). Because they are decidable, there are Turing machines \( \mathcal{P}_{e_0} \) and \( \mathcal{P}_{e_1} \) that decide membership.

\[
    \phi_{e_0}(x) = \begin{cases} 
    1 & \text{if } x \in L_0 \\
    0 & \text{if } x \notin L_0
    \end{cases} \quad \phi_{e_1}(x) = \begin{cases} 
    1 & \text{if } x \in L_1 \\
    0 & \text{if } x \notin L_1
    \end{cases}
\]

Note that because they decide membership, these machines halt on all inputs.

(a) A sketch of the machine that decides membership in \( L_0 \cup L_1 \) is in Figure 20 on page 63. A number is an element of the union if it is a member of either set. So, given \( x \), this machine first runs \( \mathcal{P}_{e_0} \) on \( x \). If that returns 1 then \( x \) is a member of the union, so the new machine outputs 1. Otherwise the new machine runs \( \mathcal{P}_{e_1} \) on \( x \) and returns the result.

(b) A sketch of the machine that decides membership in \( L_0 \cap L_1 \) is in Figure 20 on page 63. A number is an element of the union if it is a member of both sets. So, given \( x \), this machine first runs \( \mathcal{P}_{e_0} \) on \( x \). If that returns 0 then \( x \) is not a member of the intersection, so the new machine outputs 0. Otherwise the new machine runs \( \mathcal{P}_{e_1} \) on \( x \) and returns the result.

(c) Complement is straightforward. For the complement of \( L_0 \) the new machine just runs \( \mathcal{P}_{e_0} \) and subtracts the result from 1.
II.6.7 Not completely right. It is right that a set is computably enumerable if it can be enumerated by a Turing machine. That is, a Turing machine exists that, when started on a blank tape, will print all of the sets members on the tape. (This machine just outputs \( f(0), f(1), \ldots \) It may run forever if there are infinitely many elements in the set.) However, the “but is not computable” is wrong. Any computable set is computably enumerable (although there are computably enumerable sets that are not computable). For instance, the set of even numbers is computably enumerable and also computable.

II.6.8 For each part we will produce a function \( f : \mathbb{N} \to \mathbb{N} \) that is effective.

(a) The identity function, \( f(x) = x \), works.

(b) The function \( f(x) = 2x \) comes to mind.

(c) \( f(x) = x^2 \)

(d) This will do.

\[
\begin{aligned}
f(x) &= 5 \quad \text{if } x = 0 \\
 &\quad \text{7 otherwise.}
\end{aligned}
\]

II.6.9 For each item we produce an effective function \( f : \mathbb{N} \to \mathbb{N} \).

(a) The association \( n \mapsto n\text{-th prime} \) is a function. Clearly we can write a program that computes it, so by Church’s Thesis it is effective.

(b) To compute this function one approach is brute force: generate the \( n\text{-th} \) one by searching through the natural numbers, 0, 1, \ldots, checking each to see if its digits appear in non-increasing order. Output the \( n\text{-th} \) such number.

II.6.10 The first is computable, since to decide if a number \( e \) is a member of this set we can run a simulation for twenty steps. The second is computably enumerable but not computable. It is computably enumerable because we can dovetail computations for the indices \( e \in \mathbb{N} \). It is not computable because clearly if we could solve it then we could solve the problem of deciding membership in \( \{ e \mid \phi_e(y) \downarrow \} \), but we cannot solve that problem by Rice’s Theorem.

II.6.11

(a) Decidable. Indices are source-equivalent: there is a program that takes in the index \( e \) and puts out the set of instructions for \( P_e \). With that set of instructions, just scan it for \( q_4 \).

(b) Semidecidable but not decidable. To show it is computably enumerable, use dovetailing on the indices \( e \in \mathbb{N} \) to run \( P_e \) on input 3. When a the machines halts, enumerate its \( e \) into the set. As to being not computable, we know from the prior section that this is not a computable set.

(c) Computable. Given \( e \), decide if it is in the set by running \( P_e \) on 3 for the hundred steps.

II.6.12 The function is an enumeration but unless it is computable, it is not a computable enumeration. This can happen; an example of a countable set that is not computably enumerable is \( K^c \).

II.6.13 Briefly, we dovetail. First run \( P_0 \) on input 5 for one step. Then run \( P_0 \) on input 5 for a second step and \( P_1 \) on input 5 for one step. Then run \( P_0 \) for a third step, along with \( P_1 \) for its second step and \( P_2 \) on input 5 for one step. Continue in this way. The enumerating function \( f : \mathbb{N} \to \mathbb{N} \) is: \( f(0) \) is the index of the first such computation to halt, \( f(1) \) is the index of the second, etc. (Note that \( A_5 \) is infinite since any finite set is computable, so computation of any \( f(i) \) will halt in a finite number of steps.)

II.6.14 Dovetail. Start by running \( P_0 \) on input 2 for one step. Then run \( P_0 \) on input 2 for a second step and \( P_1 \) on input 2 for one step. Next, run \( P_0 \) for a third step, along with \( P_1 \) for its second step and \( P_2 \) on input 2 for one step. Continue in this way. Then \( f(0) \) is the index of the first such computation to halt and output 4, \( f(1) \) is the index of the second, etc. (This set is infinite since any finite set is computable and this set is clearly not computable. Thus computation of any \( f(i) \) will halt in a finite number of steps.)

II.6.15 The complement of the Halting problem set, \( K^c \), is countable since it is a subset of \( \mathbb{N} \). Thus it has an enumeration, a function with domain \( \mathbb{N} \) whose range is this set. But Corollary 6.6 shows that it has no computable enumeration.

II.6.16 There are of course many correct answers. One answer is to take \( K \) as the first set. For the second, take \( K \) with its smallest element omitted and for the third, take \( K \) with the smallest two elements omitted.
A perhaps less wiseguy-ish answer is to take $K$ along with some sets that we used as examples in the prior section, such as \{ $e \in \mathbb{N} \mid \phi_e(3) \downarrow$ \} and \{ $e \in \mathbb{N} \mid$ there is $x \in \mathbb{N}$ so that $\phi_e(x) = 7$ \}.

Verified **II.6.17**

(a) Enumerate it by dovetailing. The difference from some of the dovetail examples is that here there are two numbers, $e$ and $x$. So recall Cantor’s pairing function.

<table>
<thead>
<tr>
<th>Pair</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>\ldots</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,0</td>
<td>0,1</td>
<td>1,0</td>
<td>0,2</td>
<td>1,1</td>
<td>2,0</td>
<td>0,3</td>
<td>\ldots</td>
<td></td>
</tr>
</tbody>
</table>

To dovetail, first run $P_0$ on input 0 for one step. Then run $P_0$ on input 0 for a second step along with $P_0$ on input 1 for one step. Next, run $P_0$ on input 0 for its third step, and $P_0$ on input 1 for its second step, and $P_1$ on input 0 for one step. The enumerating function outputs $\langle e, x \rangle$ when $P_e$ halts on $x$.

(b) This is immediate from the second item of Lemma 6.3.

Verified **II.6.18** The two collections are not disjoint. Rather, the collection of computable sets is a subset of the collection of computably enumerable sets.

Further, clearly the collection \{ $W_e \mid e \in \mathbb{N}$ \} is countable. Since there are uncountably many subsets of $\mathbb{N}$ (because the power set of $\mathbb{N}$ has cardinality greater than $\mathbb{N}$), the computably enumerable sets do not include every subset of $\mathbb{N}$.

Verified **II.6.19** The computable sets are also computably enumerable so we will have shown that $\text{Tot}$ is neither computable nor computably enumerable if we have shown that it is not computably enumerable.

So, assume that $\text{Tot} = \{ e \mid \phi_e(y) \downarrow \text{ for all } y \}$ is computably enumerable, enumerated by $f: \mathbb{N} \to \mathbb{N}$. Following the hint, that gives a table like the one starting Section 5 on unsolvability, because the $i, j$ entry $\phi_i(j)$ is sure to halt. Diagonalize: consider $h: \mathbb{N} \to \mathbb{N}$ given by $h(e) = 1 + \phi_e(e)$. It is clearly effective, total, and unequal to any member of $\text{Tot}$, which is a contradiction.

Verified **II.6.20** Yes, the Halting problem set $K$ fits both criteria. Three other examples are the set \{ $e \in \mathbb{N} \mid \phi_e(3) \downarrow$ \}, the set \{ $e \in \mathbb{N} \mid$ there is $x \in \mathbb{N}$ so that $\phi_e(x) = 7$ \}, and \{ $e \in \mathbb{N} \mid \phi_e(x) = 2x$ for all $x \in \mathbb{N}$ \}.

Verified **II.6.21** The answer to the second effectively answers the first, but we will do both items anyway.

(a) Let $S = \{ s_0, \ldots s_{k-1} \}$ for $k \in \mathbb{N}$. Then this function enumerates $S$.

$$f(x) = \begin{cases} 
1 & \text{if } x = s_0 \text{ or } \ldots \text{ or } x = s_{k-1} \\
0 & \text{otherwise}
\end{cases}$$

It is clearly computable.

(b) The algorithm inputs a set of numbers $S = \{ s_0, \ldots s_{k-1} \}$. It returns a function, the one in the prior item. This function is clearly computable.

Another approach is to start with the number $k = |S|$. Define a function with $k + 1$ inputs, $x_0, \ldots x_{k-1}, y$ that tests whether $y$ equals any of the $x_i$’s, and returns 1 if it does or 0 if it does not. Where $S = \{ s_0, \ldots s_{k-1} \}$, apply the s-m-n Theorem to freeze the value of each $x_i$ to be $s_i$. That’s the desired function.

Verified **II.6.22** Let the computably enumerable set be $W$ and fix a computable enumeration $\phi(0), \phi(1), \ldots$. We will define an $S \subseteq W$ that is computable. The first element of $S$ is $s_0 = \phi(0)$. The second element $s_1$ is the first member of the enumeration that is larger than $s_0$; such a number must eventually appear because $W$ is infinite.

In general $s_i$ is the first element of the enumeration that is larger than $s_{i-1}$ (as with $s_1$, one must eventually appear).

The set $S$ is computably enumerable because we have just described a mechanical procedure to enumerate it. It is computable because given a number $n \in \mathbb{N}$, to determine whether it is an element of $S$ just wait until either it is enumerated into $S$ or a number larger than it is enumerated into $S$, which shows $n \notin S$.

Verified **II.6.23** Fix an $\hat{r} \in R$. Then this function

$$g(i) = \begin{cases} 
\frac{f(i)}{\hat{r}} & \text{if } f(i) \downarrow \\
\hat{r} & \text{otherwise}
\end{cases}$$

is total, computable, and enumerates $R$. 
II.6.24 Suppose that $S$ is computable, so that its characteristic function

$$
\mathbb{I}_S(x) = \begin{cases} 
1 & \text{if } x \in S \\
0 & \text{if not}
\end{cases}
$$

is a computable function. To enumerate $S$ in increasing order the idea is to run $\mathbb{I}_S(0)$, $\mathbb{I}_S(1)$, $\ldots$, each of which must converge because the function is computable, and then the first element of $S$ is the smallest, the second element is the second smallest, etc.

More formally, we define the enumerating function by: where $s_0$ is the smallest element of $S$ then $f(0) = s_0$, and where we have values for $f(0)$, $\ldots$, $f(k)$ then the value for $f(k + 1)$ is the smallest number $x$ such that $x > f(k)$ and $\mathbb{I}_S(x) = 1$. Because $S$ is infinite, there is always such an $x$.

For the other direction, assume that $S$ is an infinite set that is enumerable in increasing order, by the computable function $h$. Given $x$, to decide whether $x \in S$, compute $h(0)$, $h(1)$, $\ldots$ until one of the outputs is $x$ (in which case $x \in S$) or one of the outputs is a number larger than $x$ (in which case $x \notin S$).

II.6.25 One direction is easy. If a set is computably enumerable without repetition then it must be infinite, simply because if it were finite then the enumeration would run out of new elements to output.

The other direction is about memoizing. Let the set $S$ be infinite and computably enumerable with enumerating function $f$. We will produce an enumerating function $g$ that is one-to-one. Define $g(0) = f(0)$. For each $i \in \mathbb{N}$ define $g(i + 1)$ to be the first element of $S$ enumerated by $f$ after it enumerates $g(i)$ that is not an element of $\{g(0), \ldots, g(i)\}$.

II.6.26 The set of ordered pairs $\{(a, b) \mid a \in K \text{ and } b \in K^c\}$ is not computably enumerable, or else $K^c$ would be computably enumerable. Similarly it is not co-computably enumerable.

II.6.27

(a) No. The set $\mathbb{N}$ is obviously computable. Its subset $K$ is not.

(b) Yes. Let $S_0 \subseteq \mathbb{N}$ and $S_1 \subseteq \mathbb{N}$ be computable via the functions $\phi_{S_0}$ and $\phi_{S_1}$. A sketch of the machine to compute the union is in Figure 21 on page 66.

(c) Yes. A sketch of the machine to compute the intersection is in Figure 21 on page 66.

(d) Yes. A sketch of the machine to compute the complement is in Figure 21 on page 66.

II.6.28

(a) Yes. Let $W_{e_0}, W_{e_1} \subseteq \mathbb{N}$ be computably enumerable, via $\phi_{e_0}, \phi_{e_1} : \mathbb{N} \to \mathbb{N}$. Dovetail enumerations of the two sets. That is, run $P_{e_0}$ and $P_{e_1}$ on input 0 for a step each. Then, run $P_{e_0}$ and $P_{e_1}$ on input 0 for a second step, and also run $P_{e_0}$ and $P_{e_1}$ on input 1 for a step each. Continue in this way, and when a number is enumerated into either of $W_{e_0}$ or $W_{e_1}$, enumerate it into their union.

(b) Yes. As in the prior item, dovetail enumerations of the two sets. When a number has been enumerated into both of $W_{e_0}$ or $W_{e_1}$, enumerate it into their intersection.

(c) No. The Halting problem set $K$ is computably enumerable but its complement is not.

II.6.29 Let $S$ be the domain of a partial computable function $f$. We will produce a partial computable function $g$
First run the computation of \( f(0) \) for a step. Then run the computation of \( f(0) \) for a second step and the computation of \( f(1) \) for a step. Next run the computation of \( f(0) \) for its third step, run the computation of \( f(1) \) for its second step, and run the computation of \( f(2) \) for a step. Continue in this way. Define \( g(0) \) to be the first number \( i \) where the computation of \( f(i) \) halts, define \( g(1) \) to be the next number \( j \) where the computation of \( f(j) \) halts, etc. Clearly \( g \) is partial computable and has range \( S \).

The other direction works much the same way. We are given a partial computable \( g \) whose range is \( S \) and we will produce a partial computable \( f \) whose domain is \( S \) by dovetailing computations of \( g \). First run \( g(0) \) for a step. Then run the computation of \( g(0) \) for a second step and the computation of \( g(1) \) for a step. Next run \( g(0) \) for its third step, \( g(1) \) for its second step, and \( g(2) \) for a step. Continue in this way. When a computation halts, \( g(i) = k \), define \( f(k) \) to have some nominal value, such as 42. Clearly \( f \) is partial computable and has domain \( S \).

**Verified II.7.13**

(a) This is wrong. For instance, the empty set is reducible to the Halting problem set, \( \emptyset \leq_T K \), but while a decider for \( \emptyset \) is trivial, there is no computable decider for \( K \).

The correct statement is the opposite: if \( A \leq_T B \) then a decider for \( B \) can be used to decide the set \( A \).

(b) This is wrong. As in the prior item, if \( A \) is the empty set then it is computable. Then \( A \leq_T B \) where \( B \) equals the Halting problem set \( K \), but \( B \) is not decidable. The other way around is right: if \( B \) is decidable then \( A \) is decidable also.

(c) True. If \( A \leq_T B \) then \( \phi_e^B = \mathbb{1}_A \) for some index \( e \in \mathbb{N} \). If we could compute \( B \) then we could use that ability to compute \( A \). So if \( A \) is uncomputable then \( B \) is also uncomputable.

**Verified II.7.14** A decider is a Turing machine (whose computed function is the characteristic function of some set). An oracle is an addition to a Turing machine, a set that the machine can query.

**Verified II.7.15** First of all, they are fascinating and fun. Is that not enough?

Beyond that, they help us understand the relationships among problems. In the Complexity chapter we will expand on the idea to help understand how many everyday, practical, problems are related. This will include trying to understand which are easy and which are hard.

**Verified II.7.16** Their answer captures the spirit of the reason for considering oracle computations. But it is lacking in two ways. The first is a technicality: there are oracles such as the empty set, where computations relative to that oracle can only solve problems that you could solve already.

The second lack is that their answer doesn’t refer to the mechanism at all. That is, the oracle set doesn’t solve the problems. We might informally speak of an oracle as solving problems but for a definition we should say that we give a machine access to answers about membership in the set and then the input-output behavior of the machine is the solution to those problems.

**Verified II.7.17** We take the first question to ask: is there a most-powerful oracle, one that solves every problem? The answer is no. Given an oracle \( X \subseteq \mathbb{N} \), the problem of deciding membership in \( K^X \), the Halting problem in that oracle, is not solvable from \( X \).

The second question asks whether, given a set \( S \subseteq \mathbb{N} \), there is an oracle that suffices to determine membership in \( S \). The answer is yes; the oracle \( S \) will do.

**Verified II.7.18** Each oracle can only compute answers to some problems. But for each oracle there are problems that it cannot solve.

**Verified II.7.19** Any subset of \( \mathbb{N} \) can be an oracle, so there are uncountably many oracles.

**Verified II.7.20** Consider a machine with oracle \( X \) that takes input \( x \), accesses the oracle to determine if \( x \in X \), and then prints out the opposite. So if it finds that \( x \in X \) then it prints 0, while if it finds that \( x \notin X \) then it prints 1. This machine will, given oracle \( A \), compute the characteristic function of \( A^c \).

**Verified II.7.21** In an oracle computation that halts, there are indeed only finitely many calls to the oracle. But the calls when the computation’s input is 0 may well differ from the calls when the computation’s input is 1.

**Verified II.7.22** The computation will proceed in exactly the same way, so it will come to the same result.

**Verified II.7.23** If \( K \leq_T \emptyset \) were true then there would be an oracle machine whose computed function \( \phi^\emptyset \) is the characteristic function of \( K \). But because membership in \( \emptyset \) is itself computable we could replace oracle calls with the computation itself, so that any time the machine asks if \( x \) is an element of the oracle, we replace that
II.7.24 Verified We can do these just like the ones in the Halting problem section.
(a) Let \( A = \{ x \mid P_x \text{ outputs a 7 for some input } \} \). Consider this function.
\[
\psi(x, y) = \begin{cases} 
7 & \text{if } P_x \text{ halts on input } x \\
\uparrow & \text{otherwise}
\end{cases}
\]

We can produce this behavior with a program that takes two inputs, \( x, y \in \mathbb{N} \), simulates running \( P_x \) on input \( x \), prints 7, and then stops. See Figure 22 on page 68. Then by Church’s Thesis there is a Turing machine that does that, so fix an index \( e \) where \( \phi_e = \psi \).

Apply the s-m-n Theorem to get a family of functions \( \phi_{s(e,x)} \), each of which takes in one input \( y \) and outputs 7 if \( \phi_x(x) \downarrow \), or diverges otherwise. Then \( x \in K \) if and only if \( s(e,x) \in A \), and so \( K \leq_T A \).

(b) Let \( D = \{ x \mid \phi_x(y) = 2y \text{ for all inputs } y \} \). Consider this function.
\[
\psi(x, y) = \begin{cases} 
2y & \text{if } P_x \text{ halts on input } x \\
\uparrow & \text{otherwise}
\end{cases}
\]

We can produce this behavior with a program that takes two inputs, \( x, y \in \mathbb{N} \), simulates running \( P_x \) on input \( x \), prints \( 2y \), and then stops. See Figure 23 on page 68. So Church’s Thesis gives that there is a Turing machine, with an index \( e \), so that \( \phi_e = \psi \).

Apply the s-m-n Theorem to get a family of functions \( \phi_{s(e,x)} \) that take in one input \( y \) and output \( 2y \) if \( \phi_x(x) \downarrow \), or diverges otherwise. Then \( x \in K \) if and only if \( s(e,x) \in D \), and so \( K \leq_T D \).

Verified II.7.25 One is \( C = \{ \text{cantor}(0, a) \mid a \in A \} \cup \{ \text{cantor}(1, b) \mid b \in B \} \). Clearly from this set we can answer questions about membership in each of \( A \) and \( B \).

Verified II.7.26 There are only countably many programs that can involve an oracle call. That is, there are only countably many oracle-enhanced Turing machines.

Verified II.7.27
(a) No. The Halting problem set \( K \) is a subset of the natural numbers \( \mathbb{N} \) but \( K \not\leq_T \mathbb{N} \), because the Halting problem is unsolvable.
(b) No. The Halting problem set \( K \) is not Turing reducible to \( \mathbb{N} \), but \( \mathbb{N} = K \cup K^c \).
II.7.28
(a) The natural definition is that a set $B$ is computably enumerable in the set $A$ if $B$ is the range of a total $A$-computable function, or if $B$ is empty. That is, $B$ is c.e. in $A$ if $B = \{ \phi^A_e(x) \mid x \in \mathbb{N} \}$ for some index $e$ where the function is total, or if $B = \emptyset$.

(b) As in Lemma 7.5, we can output the elements of $\mathbb{N}$ without even referring to the oracle. The function $\phi^A_e(x) = x$ is computable, and does not need to ever refer to the oracle.

(c) Dovetail. First run the computation of $P^A_0$ on input 0 for one step. Then run the computation of $P^A_0$ on input 0 for a second step, and the computation of $P^A_1$ on input 1 for one step. Next run the computation of $P^A_0$ on input 0 for its third step, the computation of $P^A_1$ on input 1 for its second step, and the computation of $P^A_2$ on input 2 for one step. As computations halt, enumerate the index into $K^A$.

II.8.7 Saying that the two are the same function, that $\phi_{g(v)} = \phi_{\phi^A_e(v)}$, is very different than saying that the indices are the same, that $g(v) = \phi^A_e(v)$. (That is, we can easily write two different programs to compute the same function.) In particular, the Padding Lemma, Lemma 2.15 on page 73, says that every computable function (including the partial functions) has many indices.

II.8.8
(a) Apply the Fixed Point Theorem to the computable function $f(x) = x + 7$.
(b) Apply the Fixed Point Theorem to $f(x) = 2x$.

II.8.9
(a) No matter what numbering scheme we use for Turing machines, if it is acceptable then there is a Turing machine that computes the same function as the machine with twice its index; that is, there exists a $k \in \mathbb{N}$ so that $\phi_k = \phi_{3k}$.

(b) For any acceptable numbering scheme, there is a Turing machine that computes the same function as the machine whose index is the square. That is, there exists a $k \in \mathbb{N}$ so that $\phi_k = \phi_{k^2}$.

(c) Consider this $f : \mathbb{N} \rightarrow \mathbb{N}$.

$$f(x) = \begin{cases} 1 & \text{if } x = 5 \\ 0 & \text{otherwise} \end{cases}$$

For any acceptable numbering for Turing machines there will be a $k \in \mathbb{N}$ so that $\phi_k = \phi_{f(k)}$.

(d) If the function is $f(x) = 42$ then the Fixed Point Theorem gives that for any acceptable numbering there is a $k \in \mathbb{N}$ so that $\phi_k = \phi_{f(k)} = \phi_{42}$. The number $k = 42$ comes to mind, but the Padding Lemma shows that there are infinitely many such indices $k$.

II.8.10
(a) Consider the function on the left and observe that it is computed by the program sketched on the left of Figure 24 on page 70. Church’s Thesis gives there is a Turing machine with this behavior. Let that machine’s index be $e$.

$$\psi(x, y) = \begin{cases} 42 & \text{if } y = x^2 \\ \uparrow & \text{otherwise} \end{cases} \phi_{s(e, x)}(y) = \begin{cases} 42 & \text{if } y = x^2 \\ \uparrow & \text{otherwise} \end{cases}$$

Apply the $s$-$m$-$n$ Theorem to get the family of functions on the right.

(b) The number $e$ is fixed because it is the index of the Turing machine that we chose to compute $\psi$. So, define $g : \mathbb{N} \rightarrow \mathbb{N}$ by $g(x) = s(e, x)$.

(c) The Fixed Point Theorem gives a $m \in \mathbb{N}$ with $\phi_m = \phi_{g(m)} = \phi_{s(e, m)}$. Thus $W_m = \{ m^2 \}$.

II.8.11
(a) The function $p : \mathbb{N} \rightarrow \mathbb{N}$ such that $p(x)$ is the $x$-th prime number is computable by Church’s Thesis.

(b) We want to get the family of functions on the right side below, computed by the machines sketched on the right of Figure 25 on page 70, as a uniformly computable family. By now this is a familiar situation. Consider
the function on the left, observe that it is computed by the machine sketched on the left of the figure, cite Church’s Thesis to get that it has an index, and let that index be $e$.

The number $e$ is fixed so $s(e, x)$ is a function only of the variable $x$. To emphasize that, define $g: \mathbb{N} \rightarrow \mathbb{N}$ by $g(x) = s(e, x)$. The Fixed Point Theorem gives a $m \in \mathbb{N}$ with $\phi_m = \phi g(m) = \phi s(e, m)$, which halts only when the input is the $m$-th prime.

**Verified II.8.12** Consider the function on the left. By Church’s Thesis it is computable and so has an index; let that index be $e$.

\[
ψ(x, y) = \begin{cases} 
42 & \text{if } y = p(x) \\
\uparrow & \text{otherwise}
\end{cases} \\
\phiₘ(x, y) = \begin{cases} 
42 & \text{if } y = p(x) \\
\uparrow & \text{otherwise}
\end{cases}
\]

Apply the $s$-$m$-$n$ Theorem to get the uniformly computable family of functions on the right. The number $e$ is fixed so define $g: \mathbb{N} \rightarrow \mathbb{N}$ by $g(x) = s(e, x)$. The Fixed Point Theorem gives $m \in \mathbb{N}$ with $\phi_m = \phi g(m) = \phi s(e, m)$, which halts only when the input is the $m$-th prime.

**Verified II.8.13** We use Corollary 8.3 as a guide. Consider the function on the left below. It is computed by the machine sketched on the left in Figure 26 on page 71, so Church’s Thesis gives that there is a Turing machine index for this machine; let it be $e$.

\[
ψ(x, y) = \begin{cases} 
42 & \text{if } y \leq x \\
\uparrow & \text{otherwise}
\end{cases} \\
\phiₘ(x, y) = \begin{cases} 
42 & \text{if } y \leq x \\
\uparrow & \text{otherwise}
\end{cases}
\]

Apply the $s$-$m$-$n$ Theorem to get the family of machines sketched on the right, which compute the family of functions given on the right of (*).

Because $e$ is the index of the machine on the left, it is fixed. So $s(e, x)$ is a function of the single variable $x$. Let $g: \mathbb{N} \rightarrow \mathbb{N}$ be defined by $g(x) = s(e, x)$. By the Fixed Point Theorem Theorem 8.1, the function $g$ has a fixed point so that there is a $k \in \mathbb{N}$ with $\phi_k = \phi g(k) = \phi s(e, k)$. Observe that $W_k = \{0, 1, \ldots, k\}$.

**Verified II.8.14** Yes, we can take $f(x) = x$. Or, if we want $f(n) \neq n$ then this is the Padding Lemma.

**Verified II.8.15**
(a) The function on the left below is computed by the machine sketched on the left of Figure 27 on page 71. Church’s Thesis gives that it has an index; let that index be $e$.

$$
\psi(x, y) = \begin{cases} 
42 & \text{if } y \neq x \\
\uparrow & \text{otherwise} 
\end{cases} \quad \phi_{s(e,x)}(y) = \begin{cases} 
42 & \text{if } y \neq x \\
\uparrow & \text{otherwise} 
\end{cases}
$$

The $s$-$m$-$n$ Theorem parametrizes $x$ to get the family of functions on the right. The number $e$ is fixed so define $g: \mathbb{N} \to \mathbb{N}$ by $g(x) = s(e, x)$. Apply the Fixed Point Theorem to get a $k \in \mathbb{N}$ with $\phi_k = \phi_{g(k)} = \phi_{s(e,k)}$, and so $W_k = \mathbb{N} - \{k\}$.

(b) No such computably enumerable $W_m$ exists. The set $M = \{m \mid \phi_m(x)\text{converges}\}$ is computably enumerable, by dovetailing. It is the complement of the given set, so if the given set were computably enumerable then the two would be computable. But showing that they are not computable is routine, for instance with Rice’s Theorem.

**Verified II.8.16**

(a) Consider the function $\psi(x, y) = x$. By Church’s Thesis there is a Turing machine with that behavior — it is computed by the machine on the left of Figure 28 on page 72 — so let that be machine $T_e$. Apply the $s$-$m$-$n$ Theorem to get the machine on the right, which computes the family of functions $\phi_{s(e,x)}(y) = x$. There, $e$ is fixed since it is just the index of the Turing machine on the left, so let $g: \mathbb{N} \to \mathbb{N}$ be given by $g(x) = s(e, x)$.

By the Fixed Point Theorem there is an $m \in \mathbb{N}$ where $\phi_m = \phi_{g(m)} = \phi_{s(e,m)}$, which has range $\{m\}$.

(b) This is the same as the prior answer, but starting with $\psi(x, y) = 2x$.

**II.8.17** By Corollary 8.3 there is an index $e$ satisfying this.

$$
\phi_e(y) = \begin{cases} 
\downarrow & \text{if } y = e \\
\uparrow & \text{otherwise} 
\end{cases}
$$

Then $e \in K$.

By the Pumping Lemma there exists $\hat{e} \neq e$ such that $\phi_{\hat{e}} = \phi_e$. Then $\hat{e} \neq e$ implies that $\phi_e(\hat{e}) \uparrow$, which implies that $\phi_{\hat{e}}(\hat{e}) \uparrow$, and so $\hat{e} \notin K$. Thus $K$ is not an index set.

**Verified II.A.1** Put the passengers from bus $B_0$ in rooms 0, 100, 200, etc. Put the passengers from $B_1$ in rooms 1, 101, 201, etc. In general, put $b_{i,j}$ in room $i + 100j$.

**Verified II.A.2** Person $j$ from bus $B_i$ goes into $f(b_{i,j}) = 2 \cdot \text{cantor}(i, j) + 1$. 
**II.A.3** Each person is a triple. \(\langle i, j, k \rangle = \langle \text{floor number}, \text{space number for the bus}, \text{person number on that bus} \rangle\). One way to assign them rooms is to use \(\text{cantor}(\text{cantor}(i, j), k)\).

**II.A.4** No, the power set \(\mathcal{P}(\mathbb{R})\) has more members than does \(\mathbb{R}\).

**II.C.2** Here is a classic.

\[
\text{self} = \lambda (x) \left( (\lambda (y) y) x \right)
\]

**II.C.3** The code

```python
# quine.py
s = r"print 's = \n' + s + '\n'' + 'exec(s)''
exec(s)
```

gives this command line output.

```
$ python quine.py
s = 'print 's = \n' + s + '\n'' + 'exec(s)''
exec(s)
```

Here is another, using Python's string substitution operator \%.

```
s = 's = %r\nprint(s%s)'
print(s%s)
```

**II.C.4**

\[
\text{diag} s = \text{ regexp-replace #rx"x" s s})
\]

**II.D.5** \((2(c + 1)(n + 2))^{(c+1)n}\)

**II.E.1** I got these. (If you get different numbers because your machine is much faster than mine, don’t email me. I don’t give a damn.)

<table>
<thead>
<tr>
<th>0</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>0.577</td>
<td>3.178</td>
<td>9.366</td>
<td>19.569</td>
<td>36.004</td>
<td>59.118</td>
<td>91.427</td>
</tr>
</tbody>
</table>

**II.E.2** Turing machine number 666 proves to be \((\tau \ 0 \ 1 \ 0) \ (2 \ 0 \ 1)\).

**II.E.3**
(a) The new way gives an index without having to enumerate all Turing machines with intermediate Cantor numbers. The new way has the disadvantage that there are natural numbers for which there is no associated Turing machine (such as the number $2^1$).

(b) Sage gives this.

```
sage: 2*3*5^5*7*11*13*4*17*5*19*2
1265294248968750
```
Chapter III: Languages

Verified III.1.16
(A) Five are 000, 001, 010, 011, and 100.
(B) These five work: 0, 1, 00, 11, and 000. (Is the empty string in that language? It is an arguable point.)

Verified III.1.17 No. By definition, a language is a set of strings and also by definition, a string is of finite length. For some real numbers the decimal representation does not make a finite string; one is $\pi = 3.14\ldots$ and another is $1/3 = 0.33\ldots$

Verified III.1.18 If $\beta = \langle b_0, \ldots, b_{i-1} \rangle$ is a string then $\beta \hookrightarrow \beta^R = \langle b_{i-1}, \ldots, b_0 \rangle$ is clearly a palindrome.

There are palindromes not of that form. One is $\gamma = 010$, which cannot be decomposed into $\gamma = \beta \hookrightarrow \beta^R$.

Verified III.1.19
(A) These are the members of $\mathcal{L}_0 \sim \mathcal{L}_1$.
\[
\epsilon, b, bb, bbb,
\quad a, ab, abb, abbb
\quad aa, aab, aabb, aabbb
\quad aaa, aaab, aaabb, aaabbb
\]
(B) These are the members of $\mathcal{L}_1 \sim \mathcal{L}_0$.
\[
\epsilon, a, aa, aaa,
\quad b, ba, baa, baaa
\quad bb, bba, bbaa, bbaaa
\quad bbb, bbb, bbb, bbbaaa
\]
(c) We have this.
\[
\mathcal{L}_2^0 = \mathcal{L}_1 \sim \mathcal{L}_0 = \{ \emptyset, a, aa, aaa, aaaaa, aaaaaa, aaaaaaa \}
\]
(d) There are many different correct answers, but a natural ten are $\epsilon, a, aa, \ldots, a^9$.

Verified III.1.20
(A) The language consists of any number of a’s followed by a single b. Thus five members are b, ab, aab, aab, and aaaaab.
(B) The language consists of a number of a’s followed by the same number of b’s. Thus five members are $\epsilon, ab, aab, aabbb$, and aaaaabbb.
(C) The language is a set of strings of 1’s followed by 0’s, where there is one more 0 than 1. Five members are $\emptyset, 100, 11000, 1110000, 111100000$.
(D) The language consists of strings from $\mathbb{B}^*$ where there is a string of 1’s, then a string of 0’s, then a single 1. The number of 0’s is twice the number of leading 1’s. Five members are $1, 1001, 110001, 1^3\theta^61, 1^4\theta^81$.

Verified III.1.21
(A) $\mathcal{L}_2 = \{ aa, aab, aba, abab \}$
(B) $\mathcal{L}_3 = \{ aaa, aaab, aaba, aabab, abaa, ababa, ababab \}$
(c) $\mathcal{L}_1 = \mathcal{L} = \{ a, ab \}$
(d) $\mathcal{L}_0 = \{ \epsilon \}$

III.1.22
(A) $L_0 \ominus L_1 = \{ \text{ab, abb, abbb, abbb}\}$
(b) $L_1 \ominus L_0 = \{ \text{ba, bab, bba, bbab}\}$
(c) $L_0^2 = \{ \text{aa, aab, aba, abab}\}$
(d) $L_1^2 = \{ \text{bb, bbb, bbab}\}$
(e) $L_0^3 \ominus L_1^3 = \{ \text{aabb, aabbb, aabbbb, ababbb, ababbb, ababbb}\}$

Verified III.1.23 The concatenation of $0$-many strings is $\epsilon$. That is, if $\sigma \in L$ then $\sigma^0$ is defined to be the empty string.

III.1.24 It is the empty set, $\emptyset^* = \emptyset$. By definition, $L^* = \{\sigma_0 \cdots \sigma_{k-1} \mid k \in \mathbb{N} \text{ and } \sigma_0, \ldots, \sigma_{k-1} \in L\}$. If the language is empty then the condition $\sigma_0, \ldots, \sigma_{k-1} \in L$ is never met.

Verified III.1.25 No. Let $L = \{a, b\}$ and let $k = 2$. Then the $k$-th power of the language is $L^k = \{aa, ab, ba, bb\}$, while the language of $k$-th powers is $\{\sigma^2 \mid \sigma \in L\} = \{aa, bb\}$.

III.1.26 Yes, but only in an edge case. If $L = \emptyset$ then $L^* = \emptyset$ while $(L \cup \{\epsilon\})^* = \{\epsilon\}$.

We will show that if $L \neq \emptyset$ then the two sets are equal, $L^* = (L \cup \{\epsilon\})^*$. The containment $L^* \subseteq (L \cup \{\epsilon\})^*$ is clear.

For the other direction, $(L \cup \{\epsilon\})^* \subseteq L^*$, assume that $\sigma \in (L \cup \{\epsilon\})^*$. Then $\sigma = \sigma_0 \cdots \sigma_{k-1}$ for some $n \in \mathbb{N}$ and $\sigma_i \in L \cup \{\epsilon\}$. If for all $i \in \{0, \ldots, n-1\}$ the string $\sigma_i$ equals $\epsilon$ then $\sigma = \epsilon$, and is an element of $L^*$ because $L \neq \emptyset$ and $\epsilon = \rho^0$ for any $\rho \in L$. Otherwise there is at least one $i \in \{0, \ldots, n-1\}$ such that $\sigma_i \neq \epsilon$. In this case, omitting from the string $\sigma$ those $\sigma_j$ that equal the empty string gives that $\sigma \in L^k$ for some $k \leq n$, and so $\sigma \in L^*$.

III.1.27 Let the alphabet be $\Sigma$.

(a) Consider unequal strings $\sigma_0 \neq \sigma_1$. They can’t both be the empty string, and if one of them is the empty string but the other is not then they $\sigma_0^2 \neq \sigma_1^2$ because one of those two is empty while the other is not. So now suppose that neither of the two strings $\sigma_0$ and $\sigma_1$ is empty. If they are different lengths then their squares are also different lengths. The case remaining is that they are nonempty equal-length strings, $\sigma_0 = \langle s_{0,0}, s_{0,1}, \ldots, s_{0,n}\rangle$ and $\sigma_1 = \langle s_{1,0}, s_{1,1}, \ldots, s_{1,n}\rangle$ for some $n \in \mathbb{N}$. Fix the smallest index $i$ where $s_{0,i} \neq s_{1,i}$. For that same $i$ we have that $\sigma_0^2$ and $\sigma_1^2$ differ on index $i$, and are therefore unequal.

The prior paragraph implies that if $L$ has $k$-many different elements $L = \{\sigma_0, \ldots, \sigma_{k-1}\}$ then the elements of the set $\{\sigma_0^2, \ldots, \sigma_{k-1}^2\} \subseteq L^2$ are different.

(b) The language $L = \{\epsilon\}$ has $L^2 = \{\epsilon\}$.

(c) Let $L = \{\sigma_0, \sigma_1, \ldots, \sigma_{k-1}\}$ for $k \in \mathbb{N}^+$ (we take these strings to all be different from each other). Then the list $\sigma_0 \cdots \sigma_0, \sigma_0 \cdots \sigma_1, \ldots, \sigma_0 \cdots \sigma_{k-1}$ has length $k^2$. Hence the largest number of elements that $L^2$ can have is $k^2$.

(d) Consider the language $L = \{\sigma_0, \sigma_1, \ldots, \sigma_{k-1}\}$ where the $k$-many strings have length one and are unequal, so each consists of a single symbol that is different from the symbols used in any of the others. Clearly all of the members of the list $\sigma_0 \sigma_0, \sigma_0 \sigma_1, \ldots, \sigma_0 \sigma_{k-1}$ are unequal, and so $L^2$ has $k^2$-many elements.

III.1.28 Recall that $L^k = \{\sigma_0 \cdots \sigma_{k-1} \mid \sigma_i \in L\}$ and that $L^* = \{\sigma_0 \cdots \sigma_{k-1} \mid k \in \mathbb{N} \text{ and } \sigma_0, \ldots, \sigma_{k-1} \in L\}$.

We first show that $L^k \subseteq L^*$. If $k = 0$ then we are assuming $L \neq \emptyset$, we can take some $\sigma \in L$ and find $\sigma^0 = \epsilon$. Thus $L^0 = \{\epsilon\}$ and $\epsilon \in L^*$. Now suppose that $k > 0$ and fix $\sigma \in L^k$, so that $\sigma = \sigma_0 \cdots \sigma_{k-1}$.

Then the definition of $L^*$ gives that $\sigma \in L^*$. We finish by showing that $L^* \subseteq L^0 \cup L^1 \cup \cdots$. Fix $\sigma \in L^*$ (recall that $L \neq \emptyset$), so that $\sigma = \sigma_0 \cdots \sigma_{k-1}$ for some $k \in \mathbb{N}$. Note that $\sigma \in L^k$ (even if $k = 0$). Thus $L^* \subseteq L^0 \cup L^1 \cup \cdots$.

III.1.29 The set of concatenations $\sigma_1 \cdots \sigma_0$ where $\sigma_1 \in L_1$ and $\sigma_0 \in L_0$ is empty, because there are no $\sigma_0$ members of $L_0$.

Verified III.1.30

(a) An alphabet is finite by definition. (Appendix A has a review.)

(b) Because the language is finite, there is a longest string and for $B$ we can take the length of that string (or else the language is empty and we can take $B = 0$).

(c) Let $L_0, \ldots, L_k$ be finite languages over $\Sigma^*$ for some $k \in \mathbb{N}$. Then the union is also finite because it contains at most $|L_0| + \cdots + |L_k|$ elements.

(d) Let $L_0, \ldots, L_k$ be finite languages over $\Sigma^*$. Then the intersection contains at most $\min(|L_0|, \ldots, |L_k|)$ elements, so it is finite also. The number of strings in the concatenation $L_0 \cdots L_1 \cdots L_k$ is at most the product $|L_0| \cdots |L_1| \cdots |L_k|$.
III.1.31 In $\hat{L}$ all strings are of even length. The language $L$ contains all palindromes, of any length.

Verified

III.1.32 The prefixes are $\varepsilon$, a, b, ab, ab, aba, abaa, abaab, and abaaba.

Verified

III.1.33

(a) Concatenating $\sigma_0 \cdots \sigma_{m-1} \in \Sigma^m$ with $\tau_0 \cdots \tau_{n-1} \in \Sigma^n$ gives $\sigma_0 \cdots \sigma_{m-1} \tau_0 \cdots \tau_{n-1} \in \Sigma^{m+n}$.

(b) By definition $L_0^* L_1 = \{ \sigma_0 \sigma_1 \mid \sigma_0 \in L_0 \text{ and } \sigma_1 \in L_1 \}$. If one of the two is the empty set then the condition is never satisfied, so the result is the empty set.

(c) For any string $\sigma \in L^*$ we have $\sigma^0 = \varepsilon$. Thus, if there are any strings in the language then when raised to the zero power they all give the empty string, so the result is $L^0 = \{ \varepsilon \}$.

(d) By the second item, if $L = \emptyset$ gave that $L^0 = \emptyset$ for $L = \emptyset$, then for any language $\hat{L}$, extending the formula for the prior item results in $\hat{L} = \hat{L}^1 = \hat{L}^1 \hat{L}^0 = \hat{L} \emptyset = \emptyset$, which is nonsense.

III.1.34

(a) Consider the set $S = \Sigma \times \cdots \times \Sigma$ (we are avoiding calling this $\Sigma^n$ because the two differ, in that the cross product is set of $n$-tuples while $\Sigma^n$ is a subset of $\Sigma^*$). It is the cross product of countably many countable sets and so is countable by Chapter Two’s Corollary 2.9. There is a one-to-one and onto function $g : \mathbb{N} \rightarrow S$.

The function $\text{concat} : S \rightarrow \Sigma^n$ that concatenates its arguments together $f(\sigma_0, \ldots, \sigma_{n-1}) = \sigma_0 \cdots \sigma_{n-1}$ is clearly onto. So the composition $f \circ g : \mathbb{N} \rightarrow \Sigma^n$ is onto. Then by Chapter Two’s Lemma 2.11, $\Sigma^n$ is countable.

(b) The set $\Sigma^* = \Sigma^0 \cup \Sigma^1 \cup \cdots$ is the countable union of countable sets and so by Chapter Two’s Corollary 2.12 is a countable set.

III.1.35 To prevent confusion between the two forms, denote $\{ \sigma_0 \cdots \sigma_{k-1} \mid \sigma_i \in L \}$ as $kL$, for the purpose of this argument.

We first show that any element of $kL$ is an element of $\ell k$. We do a simple induction argument. The base cases are that $0L$ and $L^0$ both equal to $\{ \varepsilon \}$ by definition, and that $\sigma_0 \in L^1$ and $\sigma_i \in L^1$ for any $\sigma_0 \in L$. The inductive step is that from the hypothesis that $\sigma_0 \cdots \sigma_{i-1} \in L^1$ implies that $\sigma_0 \cdots \sigma_i \in L^1$ we get that $\sigma_0 \cdots \sigma_i \in L^{i+1}$, because it is $(\sigma_0 \cdots \sigma_{i-1}) \sigma_i$.

The other direction is that any element of $\ell k$ is an element of $kL$. Again we do this by a simple induction. Again the base cases are that $0L$ and $L^0$ both equal to $\{ \varepsilon \}$ by definition, and that $\sigma_0 \in L^1$ and $\sigma_i \in L^1$ for any $\sigma_i \in L$. The inductive step is that if $\sigma \in L^k$ then $\sigma \tau \in L^k$ and so $\sigma = \sigma_0 \cdots \sigma_{k-1} \sigma_k$. Then $\sigma \tau$ has the form $\sigma_0 \cdots \sigma_{i-1} \tau$ and so is an element of $i \tau L$.

Verified

III.1.36 The statement is true. As motivation for the argument, the natural language to try for a counterexample is $L = \{ a, aa, \ldots \}$. However, $L^\perp$ is a proper subset of $L$ since it does not contain $a$.

With that, suppose $L \neq \emptyset$. Then there is a string $\sigma \in \Sigma^*$ such that $\sigma \in L$. From among all language members, take $\sigma$ to have minimal length. If $\varepsilon \neq L$ then $\sigma \tau \in L^\perp$ is strictly longer than $\sigma$ for any $\tau \in L$, and by the minimality of $\sigma$, it is not an element of $L^\perp$. This means that $L^\perp$ is not equal to $L$.

III.1.37

(a) For any sets, languages or not, union and intersection are commutative.

(b) We have $L^\perp \{ \varepsilon \} = \{ \sigma \varepsilon \mid \sigma \in L \} = \{ \sigma \mid \sigma \in L \} = L$.

(c) Where $\Sigma = \{ a, b \}$ take $L_0 = \{ a \}$ and $L_1 = \{ b \}$. Then $L_0^\perp L_1 = \{ ab \}$ while $L_1^\perp L_0 = \{ ba \}$.

(d) This is immediate from the fact that string concatenation is associative: the $i$-th entry of $(\sigma_0 \cdots \sigma_3) \sigma_2$ is the same as the $i$-th entry of $\sigma_0 \cdots \sigma_3 \sigma_2$.

(e) This is immediate from the fact that for strings $\sigma_0^R$ equals $\sigma_1^R \sigma_0$.

(f) A string is an element of $(L_0 \cup L_1)^\perp L_2$ if and only if it has the form $\sigma \tau$ where $\tau \in L_2$, and $\sigma \in L_0$ or $\sigma \in L_1$. That’s true if and only if both $\tau \in L_2$ and $\sigma \in L_0$, or both $\tau \in L_2$ and $\sigma \in L_1$. In turn that holds if and only if $\sigma \in (L_0 \cup L_1)^\perp L_2$. The right-distributive argument goes the same way.

(g) For any language $L$ the definition gives $\hat{L} = \{ \sigma_0 \sigma_1 \mid \sigma_0 \in \emptyset \text{ and } \sigma_1 \in L \}$. The condition $\sigma_0 \in \emptyset$ is never satisfied so this set is empty. The same goes for $L^\perp$.

(h) For any strings, no matter how the concatenation is parenthesized we can remove the parentheses. For instance, $(\sigma_0 \sigma_1 \sigma_2)^R = (\sigma_0 \sigma_1 \sigma_2)$ because the $i$-th elements of the two are equal. (We can easily show this statement by induction.) From this, the result is immediate.
III.2.12
(a) We've adopted the convention that the start symbol is the head of the first listed rule so it is \(\langle\text{expr}\rangle\).
(b) The terminals are \(a, b, \text{etc.}\)
(c) The nonterminals are \(\langle\text{expr}\rangle, \langle\text{term}\rangle, \text{and } \langle\text{factor}\rangle\).
(d) There are twenty seven rewrite rules on the final line. The other two lines have a total of four, so that makes thirty one.
(e) Two are \(a+b\) and \(j\cdot h+k\cdot m\).
(f) Three are \(a^+, \text{and } +, \text{and } **\).

III.2.13
(a) The start symbol, by our convention that it is the head of the first listed rule, is \(\langle\text{sentence}\rangle\).
(b) The terminals are the, young, caught, man, and ball.
(c) The nonterminals are \(\langle\text{sentence}\rangle, \langle\text{noun phrase}\rangle, \langle\text{verb phrase}\rangle, \langle\text{article}\rangle, \langle\text{noun}\rangle, \langle\text{adjective}\rangle, \text{and } \langle\text{verb}\rangle\).
(d) Three are the ball caught the young man, the ball caught the man, and the man caught the man.
(e) Three are ball, man man man, and \(\epsilon\).

III.2.14
(a) Here is a derivation of 'the car hit a wall'.
\[
\langle\text{sentence}\rangle \Rightarrow \langle\text{subject}\rangle \langle\text{predicate}\rangle \Rightarrow \langle\text{article}\rangle \langle\text{noun}\rangle \langle\text{predicate}\rangle
\]
\[
\Rightarrow \langle\text{article}\rangle \langle\text{noun}\rangle \langle\text{verb}\rangle \langle\text{direct object}\rangle \Rightarrow \langle\text{article}\rangle \langle\text{noun}\rangle \langle\text{verb}\rangle \langle\text{article}\rangle \langle\text{noun}\rangle
\]
\[
\Rightarrow \text{the } \langle\text{noun}\rangle \langle\text{verb}\rangle \langle\text{article}\rangle \langle\text{noun}\rangle \Rightarrow \text{the car } \langle\text{verb}\rangle \langle\text{article}\rangle \langle\text{noun}\rangle
\]
\[
\Rightarrow \text{the car hit } \langle\text{article}\rangle \langle\text{noun}\rangle \Rightarrow \text{the car hit a } \langle\text{noun}\rangle
\]
\[
\Rightarrow \text{the car hit a wall}
\]
(b) Here is a derivation of 'the car hit the wall'.
\[
\langle\text{sentence}\rangle \Rightarrow \langle\text{subject}\rangle \langle\text{predicate}\rangle \Rightarrow \langle\text{article}\rangle \langle\text{noun}\rangle \langle\text{predicate}\rangle
\]
\[
\Rightarrow \text{the } \langle\text{noun}\rangle \langle\text{predicate}\rangle \Rightarrow \text{the car } \langle\text{predicate}\rangle
\]
\[
\Rightarrow \text{the car } \langle\text{verb}\rangle \langle\text{direct object}\rangle \Rightarrow \text{the car hit } \langle\text{direct object}\rangle
\]
\[
\Rightarrow \text{the car hit } \langle\text{article}\rangle \langle\text{noun}\rangle \Rightarrow \text{the car hit the } \langle\text{noun}\rangle
\]
\[
\Rightarrow \text{the car hit the wall}
\]
(c) This is one for 'the wall hit a car'.
\[
\langle\text{sentence}\rangle \Rightarrow \langle\text{subject}\rangle \langle\text{predicate}\rangle \Rightarrow \langle\text{article}\rangle \langle\text{noun}\rangle \langle\text{predicate}\rangle
\]
\[
\Rightarrow \langle\text{article}\rangle \langle\text{noun}\rangle \langle\text{verb}\rangle \langle\text{direct object}\rangle \Rightarrow \langle\text{article}\rangle \langle\text{noun}\rangle \langle\text{verb}\rangle \langle\text{article}\rangle \langle\text{noun}\rangle
\]
\[
\Rightarrow \langle\text{article}\rangle \langle\text{noun} \text{ hit }\rangle \langle\text{article}\rangle \langle\text{noun}\rangle \Rightarrow \langle\text{article}\rangle \langle\text{wall hit}\rangle \langle\text{article}\rangle \langle\text{noun}\rangle
\]
\[
\Rightarrow \langle\text{article}\rangle \langle\text{wall hit }\rangle \langle\text{article}\rangle \langle\text{car}\rangle \Rightarrow \langle\text{article}\rangle \langle\text{wall hit}\rangle \langle\text{article}\rangle \langle\text{car}\rangle
\]
\[
\Rightarrow \text{the wall hit a car}
\]

III.2.15
(a) This is a derivation for 'dog bites man'.
\[
\langle\text{sentence}\rangle \Rightarrow \langle\text{subject}\rangle \langle\text{predicate}\rangle \Rightarrow \langle\text{article}\rangle \langle\text{noun1}\rangle \langle\text{predicate}\rangle
\]
\[
\Rightarrow \langle\text{article}\rangle \langle\text{noun1}\rangle \langle\text{verb}\rangle \langle\text{direct object}\rangle \Rightarrow \langle\text{article}\rangle \langle\text{noun1}\rangle \langle\text{verb}\rangle \langle\text{article}\rangle \langle\text{noun2}\rangle
\]
\[
\Rightarrow \epsilon \langle\text{noun1}\rangle \langle\text{verb}\rangle \langle\text{article}\rangle \langle\text{noun2}\rangle \Rightarrow \epsilon \text{ dog } \langle\text{verb}\rangle \langle\text{article}\rangle \langle\text{noun2}\rangle
\]
\[
\Rightarrow \epsilon \text{ dog bites } \langle\text{article}\rangle \langle\text{noun2}\rangle \Rightarrow \epsilon \text{ dog bites } \epsilon \langle\text{noun2}\rangle
\]
\[
\Rightarrow \epsilon \text{ dog bites } \epsilon \text{ man } = \epsilon \text{ dog bites man}
\]
(b) The start symbol \(\langle\text{subject}\rangle\) expands to \(\langle\text{article}\rangle \langle\text{noun1}\rangle\), but man is derived only from \(\langle\text{noun2}\rangle\). So man cannot be the first word of the sentence.

III.2.16 There is no nonterminal \(\langle\text{dog|flea}\rangle\) or \(\langle\text{man|dog}\rangle\). This is confusing nonterminals with terminals.

III.2.17
(a) First the leftmost derivation.
\[
S \Rightarrow T \cdot B \cdot U \Rightarrow a \cdot T \cdot b \cdot U \Rightarrow a \cdot a \cdot e \cdot b \cdot U = a \cdot a \cdot b
\]
\[
\Rightarrow a \cdot a \cdot a \cdot U \Rightarrow a \cdot a \cdot a \cdot b \cdot U \Rightarrow a \cdot a \cdot b \cdot b \cdot b = a \cdot a \cdot a \cdot b
\]
Next the rightmost derivation.
III.2.18 Figure 29 on page 79 shows the tree.

III.2.19 We will use induction to show that in the course of a derivation all of the results are of either the form either $a^k S b^k$ or of the form $a^k b^k$. By the definition of the language generated by a grammar, only strings without any nonterminals are in the language so that will give the verification.

The induction is on the number of derivation steps, that is, on the number of rule applications. The base step is that there are zero-many rule applications. In this case the string is ‘S’, which is the $k = 0$ instance of the desired form.

For the inductive step assume that the statement is true where the number of rule applications is $n = 0$, $n = 1, \ldots n = k$ and consider the $n = k + 1$ case. We get the string for the $k + 1$ case by applying a rule to a string after the $k$ case. The inductive hypothesis is that such a string has one of two forms, $a^k S b^k$ or $a^k b^k$. The rules don’t apply to the latter string so consider the former one.

Applied to $a^k S b^k$ the first rule gives $a^{k+1} S b^k$, which has the right form. The second rule gives $a^{k+1} b^{k+1}$, again of the right form.

III.2.20 Bit of a trick question: this grammar has no terminating derivations so it generates the empty language $L = \emptyset$.

III.2.21 Here is one.

\[
\langle \text{identifier} \rangle \rightarrow \langle \text{letter} \rangle \mid \langle \text{letter-or-digit-string} \rangle \\
\langle \text{letter-or-digit-string} \rangle \rightarrow \langle \text{letter} \rangle \langle \text{letter-or-digit-string} \rangle \\
\quad \mid \langle \text{digit} \rangle \langle \text{letter-or-digit-string} \rangle \\
\quad \mid \varepsilon \\
\langle \text{letter} \rangle \rightarrow a \mid \ldots \mid z \mid A \mid \ldots \mid Z \\
\langle \text{digit} \rangle \rightarrow 0 \mid \ldots \mid 9
\]

III.2.22

\[
\langle \text{identifier} \rangle \rightarrow \langle \text{letter} \rangle \langle \text{second} \rangle \\
\langle \text{second} \rangle \rightarrow \langle \text{letter-or-digit} \rangle \langle \text{third} \rangle \mid \varepsilon \\
\langle \text{third} \rangle \rightarrow \langle \text{letter-or-digit} \rangle \langle \text{fourth} \rangle \mid \varepsilon \\
\langle \text{fourth} \rangle \rightarrow \langle \text{letter-or-digit} \rangle
\]
\[ \langle \text{letter-or-digit} \rangle \rightarrow \langle \text{letter} \rangle | \langle \text{digit} \rangle \]
\[ \langle \text{letter} \rangle \rightarrow a \ | \ldots \ | z \ | A \ | \ldots \ | Z \]
\[ \langle \text{digit} \rangle \rightarrow 0 \ | \ldots \ | 9 \]

**III.2.23** It is the empty language, \( \mathcal{L} = \emptyset \).

**III.2.24**

(a) \[ \langle \text{string} \rangle \rightarrow \langle \text{letter} \rangle \langle \text{string} \rangle | \epsilon \]
\[ \langle \text{letter} \rangle \rightarrow a \ | \ldots \ | z \]

(b) \[ \langle \text{string} \rangle \rightarrow \langle \text{digit} \rangle \langle \text{string} \rangle \]
\[ \langle \text{digit} \rangle \rightarrow 0 \ | \ldots \ | 9 \]

**III.2.25** Here is the start of a derivation.

\[ \langle \text{postal address} \rangle \Rightarrow \langle \text{name} \rangle \langle \text{EOL} \rangle \langle \text{street address} \rangle \langle \text{EOL} \rangle \langle \text{town} \rangle \]
\[ \Rightarrow \langle \text{personal part} \rangle \langle \text{last name} \rangle \langle \text{opt suffix} \rangle \langle \text{EOL} \rangle \langle \text{street address} \rangle \langle \text{EOL} \rangle \langle \text{town} \rangle \]
\[ \Rightarrow \langle \text{first name} \rangle \langle \text{last name} \rangle \langle \text{opt suffix} \rangle \langle \text{EOL} \rangle \langle \text{street address} \rangle \langle \text{EOL} \rangle \langle \text{town} \rangle \]
\[ \Rightarrow \langle \text{char string} \rangle \langle \text{last name} \rangle \langle \text{opt suffix} \rangle \langle \text{EOL} \rangle \langle \text{street address} \rangle \langle \text{EOL} \rangle \langle \text{town} \rangle \]
\[ \Rightarrow \langle \text{char string} \rangle \langle \text{char string} \rangle \langle \text{opt suffix} \rangle \langle \text{EOL} \rangle \langle \text{street address} \rangle \langle \text{EOL} \rangle \langle \text{town} \rangle \]
\[ \Rightarrow \langle \text{char string} \rangle \langle \text{char string} \rangle \langle \epsilon \rangle \langle \text{EOL} \rangle \langle \text{street address} \rangle \langle \text{EOL} \rangle \langle \text{town} \rangle \]
\[ = \langle \text{char string} \rangle \langle \text{char string} \rangle \langle \text{EOL} \rangle \langle \text{house num} \rangle \langle \text{street name} \rangle \langle \text{apt num} \rangle \langle \text{EOL} \rangle \langle \text{town} \rangle \]
\[ \Rightarrow \langle \text{char string} \rangle \langle \text{char string} \rangle \langle \text{EOL} \rangle \langle \text{digit string} \rangle \langle \text{street name} \rangle \langle \text{apt num} \rangle \langle \text{EOL} \rangle \langle \text{town} \rangle \]
\[ \Rightarrow \langle \text{char string} \rangle \langle \text{char string} \rangle \langle \text{EOL} \rangle \langle \text{digit string} \rangle \langle \text{street name} \rangle \langle \text{char string} \rangle \langle \text{EOL} \rangle \langle \text{town} \rangle \]
\[ \Rightarrow \langle \text{char string} \rangle \langle \text{char string} \rangle \langle \text{EOL} \rangle \langle \text{digit string} \rangle \langle \text{char string} \rangle \langle \text{EOL} \rangle \langle \text{town} \rangle \]
\[ = \langle \text{char string} \rangle \langle \text{char string} \rangle \langle \text{EOL} \rangle \langle \text{digit string} \rangle \langle \text{char string} \rangle \langle \text{EOL} \rangle \langle \text{town} \rangle \]
\[ \Rightarrow \langle \text{char string} \rangle \langle \text{char string} \rangle \langle \text{EOL} \rangle \langle \text{digit string} \rangle \langle \text{char string} \rangle \langle \text{EOL} \rangle \langle \text{town} \rangle \langle \text{state or region} \rangle \]
\[ \Rightarrow \langle \text{char string} \rangle \langle \text{char string} \rangle \langle \text{EOL} \rangle \langle \text{digit string} \rangle \langle \text{char string} \rangle \langle \text{EOL} \rangle \langle \text{char string} \rangle \langle \text{state or region} \rangle \]
\[ \Rightarrow \langle \text{char string} \rangle \langle \text{char string} \rangle \langle \text{EOL} \rangle \langle \text{digit string} \rangle \langle \text{char string} \rangle \langle \text{EOL} \rangle \langle \text{char string} \rangle \langle \text{char string} \rangle \langle \text{char string} \rangle \langle \text{state or region} \rangle \]

(a) From the above derivation steps we can easily get to the address.

(b) The above derivation steps get us most of the way there. The problem is the ‘B’ in 221B; it is not part of a digit string.

(c) Some are that you may need more than one line for the address, that some addresses do not have a house number, and that some names or addresses require non-ASCII letters.

**Verified** **III.2.26**

(a) These two rules suffice: \( S \rightarrow 11S | \epsilon \).

(b) As with the prior item, this is straightforward: \( S \rightarrow 111S | \epsilon \).

**III.2.27**

(a) This is a sentence of length one.

\[ \langle \text{sentence} \rangle \Rightarrow \text{buffalo} \langle \text{sentence} \rangle \Rightarrow \text{buffalo} \epsilon = \text{buffalo} \]

Here is a sentence of length one.

\[ \langle \text{sentence} \rangle \Rightarrow \text{buffalo} \langle \text{sentence} \rangle \Rightarrow \text{buffalo buffalo} \langle \text{sentence} \rangle \]
\[ \Rightarrow \text{buffalo buffalo} \epsilon = \text{buffalo buffalo} \]

And, a sentence of length three.

\[ \langle \text{sentence} \rangle \Rightarrow \text{buffalo} \langle \text{sentence} \rangle \Rightarrow \text{buffalo buffalo} \langle \text{sentence} \rangle \]
\[ \Rightarrow \text{buffalo buffalo} \text{buffalo} \langle \text{sentence} \rangle \Rightarrow \text{buffalo buffalo buffalo} \epsilon \]
\[ = \text{buffalo buffalo buffalo} \]

(b) In English ‘buffalo’ is a noun referring to the American bison, or to a city in New York State, and it is a verb referring to fooling or confusing someone. So, the sentence of length one could be a command instructing the listener to fool someone. The sentence of length two could be a command instructing that same listener
to fool all of a city in upstate New York. The length three sentence could exhort American bison in particular to confuse that entire city.

**III.2.28**

(A) This is a derivation of (a . b).

\[
\langle s \text{ expression} \rangle \Rightarrow ( \langle s \text{ expression} \rangle . \langle s \text{ expression} \rangle ) \Rightarrow ( \langle \text{atomic symbol} \rangle . \langle s \text{ expression} \rangle ) \\
\Rightarrow ( \langle \text{letter} \rangle . \langle \text{atomic symbol} \rangle ) \Rightarrow ( \langle \text{letter} \rangle . \langle \text{atomic symbol} \rangle ) \\
\Rightarrow ( \langle \text{letter} \rangle \varepsilon . \langle \text{atomic symbol} \rangle ) = ( \langle \text{letter} \rangle . \langle \text{atomic symbol} \rangle ) \\
\Rightarrow ( \langle \text{letter} \rangle \varepsilon ) = ( \langle \text{letter} \rangle ) \Rightarrow ( a . b )
\]

(b) This is a derivation of (a . (b . c)).

\[
\langle s \text{ expression} \rangle \Rightarrow ( \langle s \text{ expression} \rangle . \langle s \text{ expression} \rangle ) \\
\Rightarrow ( \langle s \text{ expression} \rangle . ( \langle s \text{ expression} \rangle . \langle s \text{ expression} \rangle ) ) \\
\Rightarrow ( \langle s \text{ expression} \rangle . \langle s \text{ expression} \rangle ) \\
\Rightarrow ( \langle \text{atomic symbol} \rangle . \langle s \text{ expression} \rangle ) \\
\Rightarrow ( \langle \text{letter} \rangle . \langle \text{atomic symbol} \rangle . \langle s \text{ expression} \rangle ) \\
\Rightarrow ( a \langle \text{atomic part} \rangle . \langle s \text{ expression} \rangle ) \\
\Rightarrow ( a \varepsilon . ( \langle s \text{ expression} \rangle . \langle s \text{ expression} \rangle ) ) = ( a . ( \langle s \text{ expression} \rangle . \langle s \text{ expression} \rangle ) ) \\
\Rightarrow ( a . ( \langle \text{atomic symbol} \rangle . \langle s \text{ expression} \rangle ) ) \Rightarrow ( a . ( \langle \text{atomic symbol} \rangle . \langle \text{atomic symbol} \rangle ) ) \\
\Rightarrow ( a . ( \langle \text{letter} \rangle . \langle \text{atomic part} \rangle . \langle \text{atomic symbol} \rangle ) ) \\
\Rightarrow ( a . ( \langle \text{letter} \rangle . \langle \text{letter} \rangle \varepsilon . \langle \text{letter} \rangle . \langle \text{atomic part} \rangle ) ) = ( a . ( \langle \text{letter} \rangle . \langle \text{letter} \rangle . \langle \text{atomic part} \rangle ) ) \\
\Rightarrow ( a . ( \langle \text{letter} \rangle . \langle \text{letter} \rangle \varepsilon ) ) = ( a . ( \langle \text{letter} \rangle . \langle \text{letter} \rangle ) ) \\
\Rightarrow ( a . ( b . \langle \text{letter} \rangle ) ) \Rightarrow ( a . ( b . c ) )
\]

(c) This is the first few steps of a derivation of ((a . b) . c).

\[
\langle s \text{ expression} \rangle \Rightarrow ( \langle s \text{ expression} \rangle . \langle s \text{ expression} \rangle ) \\
\Rightarrow ( \langle s \text{ expression} \rangle . \langle s \text{ expression} \rangle ) \\
\Rightarrow ( \langle \text{atomic symbol} \rangle . \langle s \text{ expression} \rangle ) \\
\Rightarrow ( \langle \text{letter} \rangle . \langle \text{atomic symbol} \rangle . \langle s \text{ expression} \rangle ) \\
\Rightarrow ( a \langle \text{atomic part} \rangle . \langle s \text{ expression} \rangle ) \\
\Rightarrow ( a \varepsilon . ( \langle s \text{ expression} \rangle . \langle s \text{ expression} \rangle ) ) = ( a . ( \langle s \text{ expression} \rangle . \langle s \text{ expression} \rangle ) ) \\
\Rightarrow ( a . ( \langle \text{atomic symbol} \rangle . \langle s \text{ expression} \rangle ) ) \Rightarrow ( a . ( \langle \text{atomic symbol} \rangle . \langle \text{atomic symbol} \rangle ) ) \\
\Rightarrow ( a . ( \langle \text{letter} \rangle . \langle \text{atomic part} \rangle . \langle \text{atomic symbol} \rangle ) ) \\
\Rightarrow ( a . ( \langle \text{letter} \rangle . \langle \text{letter} \rangle \varepsilon . \langle \text{letter} \rangle . \langle \text{atomic part} \rangle ) ) = ( a . ( \langle \text{letter} \rangle . \langle \text{letter} \rangle . \langle \text{atomic part} \rangle ) ) \\
\Rightarrow ( a . ( \langle \text{letter} \rangle . \langle \text{letter} \rangle \varepsilon ) ) = ( a . ( \langle \text{letter} \rangle . \langle \text{letter} \rangle ) ) \\
\Rightarrow ( a . ( b . \langle \text{letter} \rangle ) ) \Rightarrow ( a . ( b . c ) )
\]

The rest proceeds as does the prior answer.

**III.2.29** The steps are tedious but routine.

\[
\langle \text{expr} \rangle \Rightarrow \langle \text{expr} \rangle + \langle \text{term} \rangle \Rightarrow \langle \text{expr} \rangle + \langle \text{factor} \rangle \\
\Rightarrow \langle \text{expr} \rangle + ( \langle \text{expr} \rangle ) \Rightarrow \langle \text{expr} \rangle + ( \langle \text{term} \rangle ) \\
\Rightarrow \langle \text{expr} \rangle + ( \langle \text{term} \rangle \ast \langle \text{factor} \rangle ) \Rightarrow \langle \text{expr} \rangle + ( \langle \text{factor} \rangle \ast \langle \text{factor} \rangle ) \\
\Rightarrow \langle \text{term} \rangle + ( \langle \text{factor} \rangle \ast \langle \text{factor} \rangle ) \Rightarrow \langle \text{factor} \rangle + ( \langle \text{factor} \rangle \ast \langle \text{factor} \rangle ) \\
\Rightarrow a + ( \langle \text{factor} \rangle \ast \langle \text{factor} \rangle ) \Rightarrow a + ( \langle b \ast \langle \text{factor} \rangle \rangle ) \\
\Rightarrow a + ( b \ast \langle \text{factor} \rangle )
\]

**III.2.30**

(A) It is \( \mathcal{L} = \{ \varepsilon \} \).

(b) This is one leftmost derivation.

\[
S \Rightarrow \varepsilon
\]

and here is another.

\[
S \Rightarrow S \Rightarrow \varepsilon
\]

**III.2.31** One leftmost derivation is this.

\[
\langle \text{bit-string} \rangle \Rightarrow \langle \text{bit-string} \rangle \langle \text{bit-string} \rangle \Rightarrow \emptyset \langle \text{bit-string} \rangle \\
\Rightarrow \emptyset \langle \text{bit-string} \rangle \langle \text{bit-string} \rangle \Rightarrow \emptyset \emptyset \langle \text{bit-string} \rangle \\
\Rightarrow \emptyset \emptyset \emptyset
\]

Here is another.
Figure 30, for question III.3.15: Adjacency relation among the New England states.

Figure 31, for question III.3.15: Relation of ‘beats’ among Rock, Paper, and Scissors.

\[
\langle \text{bit-string} \rangle \Rightarrow \langle \text{bit-string} \rangle \langle \text{bit-string} \rangle \Rightarrow \langle \text{bit-string} \rangle \emptyset \\
\Rightarrow \langle \text{bit-string} \rangle \langle \text{bit-string} \rangle \emptyset \Rightarrow \emptyset \langle \text{bit-string} \rangle \emptyset \\
\Rightarrow \emptyset \emptyset \emptyset
\]

### III.2.32

(a) One leftmost derivation is \( E \Rightarrow E - E \Rightarrow a - E \Rightarrow a - E - E \Rightarrow a - b - E \Rightarrow a - b - a \). A second one is \( E \Rightarrow E - E \Rightarrow E - E - E \Rightarrow a - E - E \Rightarrow a - b - E \Rightarrow a - b - a \).

(b) Here we go: \( E \Rightarrow E - T \Rightarrow E - T - T \Rightarrow T - T - T \Rightarrow a - T - T \Rightarrow a - b - T \Rightarrow a - b - a \).

### III.2.33

\( S \Rightarrow aBS \Rightarrow aBaBScc \Rightarrow aBaBabccc \Rightarrow aaBBabccc \Rightarrow aaBBbccc \Rightarrow aabbbccc \Rightarrow aaabbbccc \)

### III.3.15

(a) Figure 30 on page 82 shows the graph.

(b) The graph is a loop, Figure 31 on page 82.

(c) The graph is Figure 32 on page 83.

(d) This graph is Figure 33 on page 83.

(e) This prerequisite structure is Figure 34 on page 83.

### III.3.16

(a) One possible picture is Figure 35 on page 83.

(b) Here is the matrix.

\[
\mathcal{M}(G) = \begin{pmatrix}
0 & 1 & 0 & 1 & 0 & 1 \\
1 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 1 & 0 & 0 & 0 \\
0 & 1 & 0 & 1 & 0 & 1 \\
1 & 0 & 0 & 0 & 1 & 0 \\
\end{pmatrix}
\]

(c) From the picture, Figure 35 on page 83, there are clearly only two: \( G_0 = \{ v_0, v_1, v_4, v_5 \} \) and \( G_1 = \{ v_0, v_2, v_4, v_5 \} \).

(d) It is the same two as in the prior item.

### III.3.17
Figure 32, for question III.3.15: Divisibility relation among small numbers.

Figure 33, for question III.3.15: Bridge connection relation between land masses.

Figure 34, for question III.3.15: Prerequisite structure among courses.

Figure 35, for question III.3.16: A graph with some edges.
**III.3.18** See Figure 36 on page 84.

**III.3.19** The minimal number of frequencies is three. Figure 37 on page 84 gives a three-coloring. Starting with \( v_6 \) and tracing around shows that no two-coloring will suffice.

**III.3.20** The directed graph is Figure 38 on page 85. Every type is compatible with itself so every vertex is shown with a loop. The type \( O^- \) can donate to everyone, as we see from its row below, so it is a universal donor. The type \( AB^+ \) is a universal receptor, as we see from its column.

Here is the graph’s adjacency matrix.

\[
\begin{array}{cccccccc}
O^- & O^+ & A^- & A^+ & B^- & B^+ & AB^- & AB^+ \\
O^- & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
O^+ & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\
A^- & 0 & 0 & 1 & 1 & 0 & 1 & 1 \\
A^+ & 0 & 0 & 0 & 1 & 0 & 0 & 1 \\
B^- & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
B^+ & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\
AB^- & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\
AB^+ & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
\end{array}
\]

**Verified**  **III.3.21** The graph in Example 3.2 has this degree sequence: \( \langle 4, 4, 3, 3, 2 \rangle \). The vertices \( v_1 \) and \( v_2 \) have degree 4, the vertices \( v_3 \) and \( v_4 \) have degree 3, and the vertex \( v_0 \) has degree 2.

In Example 3.4 the graph on the left has degree sequence \( \langle 3, 3, 3, 3 \rangle \). The graph on the right has \( \langle 3, 3, 3, 3, 3, 3 \rangle \) (there are eight 3’s, one for each corner of the cube).

**III.3.22** Both of these graphs are complete in the sense that every possible node-to-node connection is there.
Figure 38, for question III.3.20: Compatibility for blood types.

(Except that there are no loops). Here is the adjacency matrix for the graph on the left.

\[
\begin{pmatrix}
0 & 1 & 1 & 1 \\
1 & 0 & 1 & 1 \\
1 & 1 & 0 & 1 \\
1 & 1 & 1 & 0
\end{pmatrix}
\]

And this is the adjacency matrix for the cube graph on the right.

\[
\begin{pmatrix}
0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 0
\end{pmatrix}
\]

III.3.23 The simple graph is Figure 39 on page 85.

III.3.24
(a) The function is suggested by the names of the vertices: $a \mapsto A$, $b \mapsto B$, etc. It is one-to-one and onto by inspection so it is a correspondence.

(b) The edges on the left are: $ax, ay, az$, $bx, by, bz$, $cx, cy$, and $cz$. The edges on the right are: $AX, AY, AZ$, $BX, BY, BZ, CX, CY$, and $CZ$. Under the mapping the edge $ax$ is associated with $AX$, the edge $ay$ is associated with $AY$, etc., and this exhausts the edges on the right.

III.3.25

(a) A path is a trail with distinct vertices (except that possibly the starting vertex equals the ending vertex). This trail meets that criteria.

(b) The vertex $B$ appears twice, not both at the start and end.

(c) Figure 40 on page 86 illustrates. By definition every tree is connected, so there is a path. Suppose for contradiction that there are two unequal paths from $v_0$ to $v_n$. Then there is some vertex $v_i$ where the paths diverge and also a vertex $v_k$ where they come together again. But that makes a cycle from $v_i$, around the one path to $v_k$, and back by the other path to return to $v_i$. The contradiction is that trees do not have cycles.

III.3.26

(a) For each edge we choose two vertices. Thus the number of potential edges is $\binom{n}{2} = n \cdot (n-1)/2$.

(b) For each edge, we either include it or leave it out. So with $n$ vertices there are $2^{n(n-1)/2}$ graphs. (Some of these may be isomorphic, but they are different in that they involve different vertices connected.)

III.3.27

(a) By the definition of graph isomorphism, Definition 3.14, if two graphs $\mathcal{G}$ and $\mathcal{G}'$ are isomorphic then there is a correspondence among their vertices. They therefore have the same number of vertices.

(b) As in the prior item, the definition of graph isomorphism states that the edges correspond.

(c) Suppose that $\mathcal{G} = \langle V, E \rangle$ and $\mathcal{G}' = \langle \hat{V}, \hat{E} \rangle$ are isomorphic via the function $f$. Let vertex $v \in V$ have degree $k$. Then in the set $E$ the vertex $v$ occurs $k$ times (counting once for edges in which the vertex occurs once, and twice for loops on $v$).

Apply the correspondence. That is, consider the vertex $f(v)$ and the set $\hat{E}$. Because $f$ gives a correspondence among edges, the vertex must occur $k$ times in the set. So $f(v)$ has degree $k$.

(d) This is the same as the prior item, but instead of a single vertex $v$ there is a sequence of vertices $v_0, \ldots, v_n$.

(e) Clearly they have the same degree sequence, $(3, 1, 1, 1, 1, 1)$. Suppose that the two are isomorphic via the correspondence $f$. Then $f$ must associate the two degree-3 vertices. The graph on the left has two unequal length 2 paths that start with its degree 3 vertex. The graph on the right does not have two.

(f) The degree sequences differ. On the left the degree sequence is $(3, 3, 3, 3)$ while on the right it is $(4, 4, 4, 4, 4, 4, 4, 4)$.

III.3.28

(a) There is a length 2 walk from $v_i$ to $v_j$ if and only if there is some $v_k$ where both $v_i v_k$ and $v_k v_j$ are edges. Thus the number of such walks is $m_{i,1}m_{1,j} + m_{i,2}m_{2,j} + \cdots + m_{i,n}m_{n,j}$, where each $m_{a,b}$ is an entry from $M(\mathcal{G})$. But that is the the $i,j$ entry of $(M(\mathcal{G}))^2$.

(b) For induction assume the hypothesis that the statement is true for $n = 2, \ldots, n = p$ and consider $n = p + 1$. There is a length $p + 1$ walk from $v_i$ to $v_j$ if and only if there is some $v_k$ where there is a length $p$ walk from $v_i$ to $v_k$, and also $v_k v_j$ is an edge. By the inductive hypothesis the number of such walks is $q_{i,1}m_{1,j} + q_{i,2}m_{2,j} + \cdots + q_{i,n}m_{n,j}$, where each $q_{i,b}$ is an entry from $(M(\mathcal{G}))^p$ and $m_{b,j}$ is an entry from $M(\mathcal{G})$. We recognize that as the $i,j$ entry of $(M(\mathcal{G}))^{p+1}$.

III.3.29

(a) We will keep track of a set $R$ of reachable vertices. To start, put $q_0$ into a set $R_0$. For the first step find all vertices connected to $q_0$, and enter them into the set $R_1 \supseteq R_0$. At step $k + 1$ put all vertices connected to
any vertex in \( R_k \) into a set \( R_{k+1} \supseteq R_k \). When there are no new vertices then we are done (this must happen after finitely many steps because there are finitely many vertices, by our definition of a graph). The result is the set \( R \). The unreachable vertices are those that are not members of \( R \).

(b) For the graph on the left these are the steps.

<table>
<thead>
<tr>
<th>step ( k )</th>
<th>( R_k )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>{ ( w_0 ) }</td>
</tr>
<tr>
<td>1</td>
<td>{ ( w_0, w_1 ) }</td>
</tr>
<tr>
<td>2</td>
<td>{ ( w_0, w_1, w_2 ) } = R</td>
</tr>
</tbody>
</table>

Here are the steps for the graph on the right.

<table>
<thead>
<tr>
<th>step ( k )</th>
<th>( R_k )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>{ ( w_0 ) }</td>
</tr>
<tr>
<td>1</td>
<td>{ ( w_0, w_1 ) }</td>
</tr>
<tr>
<td>2</td>
<td>{ ( w_0, w_1, w_3 ) } = R</td>
</tr>
</tbody>
</table>

III.A.5

\( \langle \text{zip} \rangle ::= \langle \text{digit} \rangle \langle \text{digit} \rangle \langle \text{digit} \rangle \langle \text{digit} \rangle \langle \text{digit} \rangle | [-\langle \text{digit} \rangle \langle \text{digit} \rangle \langle \text{digit} \rangle \langle \text{digit} \rangle] \)

\( \langle \text{digit} \rangle ::= 0 \mid 1 \ldots \mid 9 \)

III.A.6 Here we stick to lower-case ASCII letters.

\( \langle \text{palindrome} \rangle ::= a \langle \text{palindrome} \rangle a \mid b \langle \text{palindrome} \rangle b \mid \ldots z \langle \text{palindrome} \rangle z \mid \langle \text{letter} \rangle \mid \varepsilon \)

\( \langle \text{letter} \rangle ::= a \mid b \mid \ldots z \)

You could omit \( \varepsilon \) if you don’t like it as a palindrome.

III.A.7 Here is one way to do it.

\( \langle \text{course code} \rangle ::= \langle \text{dept} \rangle \langle \text{space} \rangle \langle \text{course-number} \rangle \)

\( \langle \text{dept} \rangle ::= \langle \text{two-letter} \rangle \mid \langle \text{three-letter} \rangle \)

\( \langle \text{two-letter} \rangle ::= \langle \text{letter} \rangle \langle \text{letter} \rangle \)

\( \langle \text{three-letter} \rangle ::= \langle \text{two-letter} \rangle \langle \text{letter} \rangle \)

\( \langle \text{course-number} \rangle ::= \langle \text{digit} \rangle \langle \text{digit} \rangle \langle \text{digit} \rangle \)

\( \langle \text{digit} \rangle ::= 0 \mid \ldots 9 \)

The \( \langle \text{space} \rangle \) produces a hard-to-show blank space.

You could also put the department names in on a case-by-case basis, as here.

\( \langle \text{dept} \rangle ::= \text{MA} \mid \text{PSY} \mid \ldots \)

This has the disadvantage that if a department code changes then this part of the description also changes. It has the advantage of being more correct, of not allowing department names that are nonsensical.

III.A.8

(A) This will do.

\( \langle \text{pointfloat} \rangle ::= \langle \text{intpart} \rangle \langle \text{fraction} \rangle \mid \langle \text{intpart} \rangle . \mid \langle \text{fraction} \rangle \)

(B) \n
\( \langle \text{intpart} \rangle ::= \langle \text{intpart} \rangle \langle \text{digit} \rangle \mid \langle \text{digit} \rangle \)

(c) This is just a list of cases

\( \langle \text{exponent} \rangle ::= e \langle \text{intpart} \rangle \mid e+ \langle \text{intpart} \rangle \mid e- \langle \text{intpart} \rangle \mid E \langle \text{intpart} \rangle \mid E+ \langle \text{intpart} \rangle \mid E- \langle \text{intpart} \rangle \)

III.A.9

(A) This is a grammar for standard notation.
Here is a derivation. We feel free to use the BNF notation to, for instance, put in multiple

This is a grammar for subtractive notation.

Yes, because all derivations must go from

(b) This is a grammar for subtractive notation.

(a) Here is a derivation. We feel free to use the BNF notation to, for instance, put in multiple \( \langle \text{statement} \rangle \)'s on the third line instead of putting them in one at a time.

\[
\begin{align*}
\langle \text{start} \rangle & := \langle \text{thousands} \rangle \langle \text{hundreds} \rangle \langle \text{tens} \rangle \langle \text{ones} \rangle \\
\langle \text{thousands} \rangle & := M^* \\
\langle \text{hundreds} \rangle & := C | CC | CCC | CCCC | D | DC | DCC | DCCC | DCCCC | \varepsilon \\
\langle \text{tens} \rangle & := X | XX | XXX | XXXX | L | LX | LXX | LXXX | LXXXX | \varepsilon \\
\langle \text{ones} \rangle & := I | II | III | IIII | V | VII | VIII | VIII | \varepsilon
\end{align*}
\]

(b) Yes, because all derivations must go from \( \langle \text{program} \rangle \) through \( \langle \text{statement-list} \rangle \), which forces them to have curly braces.

III.A.11 In this partial derivation we feel free to leverage the BNF notation to, for instance, put in multiple \( \langle \text{s-expression} \rangle \)'s for a \( \langle \text{list} \rangle \) at one time, instead of putting them in one at a time.
\(\langle s\text{-expression} \rangle \Rightarrow \langle \text{list} \rangle\)
\(\Rightarrow (\langle s\text{-expression} \rangle \langle s\text{-expression} \rangle \langle s\text{-expression} \rangle)\)
\(\Rightarrow (\langle s\text{-expression} \rangle \langle \text{list} \rangle \langle s\text{-expression} \rangle)\)
\(\Rightarrow (\langle s\text{-expression} \rangle \langle s\text{-expression} \rangle \langle s\text{-expression} \rangle)\)
\(\Rightarrow (\langle \text{atomic-symbol} \rangle \langle s\text{-expression} \rangle \langle s\text{-expression} \rangle)\)
\(\Rightarrow (\langle \text{letter} \rangle \langle \text{atomic-part} \rangle \langle s\text{-expression} \rangle \langle s\text{-expression} \rangle)\)
\(\Rightarrow (\langle \text{letter} \rangle \langle \text{letter} \rangle \langle \text{atomic-part} \rangle \langle s\text{-expression} \rangle \langle s\text{-expression} \rangle)\)
\(\Rightarrow (\langle \text{letter} \rangle \langle \text{letter} \rangle \langle \text{letter} \rangle \langle \text{letter} \rangle \langle s\text{-expression} \rangle \langle s\text{-expression} \rangle \langle s\text{-expression} \rangle)\)
\(\Rightarrow (\langle \text{letter} \rangle \langle \text{letter} \rangle \langle \text{letter} \rangle \langle \text{letter} \rangle \langle \text{letter} \rangle \langle s\text{-expression} \rangle \langle s\text{-expression} \rangle \langle s\text{-expression} \rangle)\)

Expanding the remaining nonterminals to letters is tedious, so we will stop here.

III.A.12

(A) Here we will leverage the BNF notation to, for instance, substitute for multiple nonterminals, instead of putting them in one at a time.

\(\langle \text{format-spec} \rangle \Rightarrow 0 \langle \text{width} \rangle \langle \text{type} \rangle\)
\(\Rightarrow 0 \langle \text{integer} \rangle \langle \text{type} \rangle\)
\(\Rightarrow 0 \langle \text{digit} \rangle \langle \text{type} \rangle\)
\(\Rightarrow 0 \ 3 \langle \text{type} \rangle\)
\(\Rightarrow 0 \ 3 \ f\)

(B) \(\langle \text{format-spec} \rangle \Rightarrow \langle \text{sign} \rangle \ # 0 \langle \text{width} \rangle \langle \text{type} \rangle\)
\(\Rightarrow + \ # 0 \langle \text{width} \rangle \langle \text{type} \rangle\)
\(\Rightarrow + \ # 0 \langle \text{integer} \rangle \langle \text{type} \rangle\)
\(\Rightarrow + \ # 0 \langle \text{digit} \rangle \langle \text{type} \rangle\)
\(\Rightarrow + \ # 0 \ 2 \langle \text{type} \rangle\)
\(\Rightarrow + \ # 0 \ 2 \ X\)
Chapter IV: Automata

IV.1.16

(A) Step Configuration

<table>
<thead>
<tr>
<th>Step</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>a b a</td>
</tr>
<tr>
<td></td>
<td>q0</td>
</tr>
<tr>
<td>1</td>
<td>b a</td>
</tr>
<tr>
<td></td>
<td>q1</td>
</tr>
<tr>
<td>2</td>
<td>b</td>
</tr>
</tbody>
</table>

(B) Step Configuration

<table>
<thead>
<tr>
<th>Step</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>b a</td>
</tr>
<tr>
<td></td>
<td>q0</td>
</tr>
<tr>
<td>1</td>
<td>a</td>
</tr>
</tbody>
</table>

(C) Step Configuration

<table>
<thead>
<tr>
<th>Step</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>b a a b a</td>
</tr>
<tr>
<td></td>
<td>q0</td>
</tr>
<tr>
<td>1</td>
<td>b a b a</td>
</tr>
<tr>
<td></td>
<td>q0</td>
</tr>
<tr>
<td>2</td>
<td>a b a</td>
</tr>
</tbody>
</table>

IV.1.17 Verified False. An example is that Example 1.7’s machine accepts the set containing each of these: 0, 1, 2, …

IV.1.18 Verified A language can contain the empty string. A machine can accept the empty string. But we have no definition for a language accepting a string.

IV.1.19 Verified Each input character consumed causes one transition. So an input string of length \( n \) causes the machine to undergo \( n \) transitions. (This includes that the empty string \( \epsilon \) causes no transitions.) With \( n \) transitions, the machine will have visited \( n + 1 \) many not necessarily distinct states, including the start state.

IV.1.20 Verified First, “\( n \) is infinite” is wrong. That set is a language \( \{ b, ab, a^2b, \ldots \} \) and in each string from that language the number of a’s is finite.

Second, this Finite State machine accepts the language.

IV.1.21 Verified

(a) A string is in this language if and only if it has some number of a’s, followed by a single b, followed by the same number of a’s. That is, the two strings of a’s have the same length. Five elements of the language are aba, aabaa, b, aaabaaa, and aaaaabaaa. Five non-elements are ba, aaba, a, abba, and bbabb.

(b) The strings in this language have some number of a’s followed by a single b, followed by a number of a’s. The two numbers of a’s need not be the same, and may be zero. Five language elements are abaa, aabaa,
ab, baaaa, and b. Five non-elements are bab, aabb, bb, aabaab, and a. 

(c) The criteria for a string to be in this language is that it must start with b and be followed by some number of a’s. That could be zero-many a’s. Five elements of the language are baa, ba, ba^3, and ba^4. Five non-elements are a, ε, abaaa, baaaab, and bb.

(d) A string is in this language if and only if it consists of some number of a’s followed by a b, followed by some number of a’s, where the second string of a’s has two more than the first string. Five members of the language are abaa, bbaaaa, a^3ba^5, a^4ba^6, and baa. Five non-members are aba, abaaaa, ba, b, and bab.

(e) This language has members that are doubles in that a member consists of the concatenation of two copies of some string. Five members of the language are aaabaaab, babbab, aa, bbbabbbba, and abbaabba. Five non-members are aba, b, aaabaab, babaa, and bbb.

IV.1.22

(a) The language consists of strings with some number of a’s (that number may be zero), followed by a single c, followed by some number of b’s.

(b) The language consists of strings of at least one a.

(c) Strings in this language start with an a, followed by any number of characters, and end with two b’s.

Verified IV.1.23

(a) For Example 1.6 the only accepting state is q_2. In Example 1.7 also, the only accepting state is q_2. For Example 1.8 the accepting states are q_3, q_6, and q_8. For Example 1.9 it is q_0.

(b) Only Example 1.9 accepts the empty string ε because only in this machine is q_0 an accepting state.

(c) For Example 1.6 the shortest accepted string is the length two string 00. For Example 1.7 it is any single-digit length one string, such as 9. For Example 1.8 any of the length three strings jpg, png, and pdf. For Example 1.9 it is the empty string ε.

Verified IV.1.24 Modify the machine so that its initial state is not an accepting state. Here there are two states whose intuitive meaning is that the sum of the digits seen so far is congruent to 0 modulo 3.

Verified IV.1.25 This is the graph picture.

The language is \{ σ ∈ \{ a, b \}^* | σ = b(ab)^n for n ∈ N \}.

Verified IV.1.26 The language is the set of strings over Σ = \{ a, b \} the contain exactly one b.

Verified IV.1.27 To accept strings containing the substring abc the machine must have a state whose intuitive meaning is “have just seen a, next looking for bc.” That state is q_1. The state q_2 means that the machine has just processed a substring ab and is looking for c. And q_3 means the machine has seen the substring abc. Finally, q_0 is the state the machine is in if it has so far not seen even the first character in a potential substring abc. Here is the machine.
Note that if the machine processes ab followed by b then it returns to q₀, but if it processes ab followed by a then it does not return to q₀, it passes to q₁. This follows from the intuitive meaning of q₁.

**Verified IV.1.28** Five elements of the language are aabb, bbab, abab, aababb, and a³b⁴. Five nonelements are ε, a, b, aab, and bbbaabb. Here is the machine.

The intuitive meaning of the states in the first row, q₀, q₁, and q₂, is that when the machine is in those states it has so far seen zero-many b’s. States in the second row are where the machine has so far seen one b. The third row contains the states where the machine has seen two b’s. Similarly, the first column contains the states where the machine has so far seen no a’s, in the second column are states where the machine has seen a single a, and in the final column the machine has see two a’s.

**Verified IV.1.29**

(a) Five strings that are elements of the language are aa, aab, aba, and baa. Five that are not are ε, a, b, ab, and ba. This machine accepts only strings in that language.

(b) Five elements of the language are aa, aab, aba, baa, and aabb. Five that are not in the language are ε, a, ba, aaa, and baaa.

(c) Five strings that are elements of the language are ε, a, b, aa, and ab. Five that are not are aaa, aab, aaba, abaa, and baaa.

(d) Five from the language are ab, aab, aba, abb, and bab. Five that are not in the language are ε, a, b, ba, and bbbbaaaa.

**Verified IV.1.30** The first machine accepts only 911 while the second accepts anything but 911. Note that in the two machines the sets of accepting states are complementary.
Verified IV.1.31 Here are the length three strings.

\[
\begin{array}{c|cccccccc}
\text{Input } \sigma & \text{aaa} & \text{aab} & \text{aba} & \text{abb} & \text{baa} & \text{bab} & \text{bba} & \text{bbb} \\
\hat{\Delta}(\sigma) & q_1 & q_2 & q_1 & q_2 & q_1 & q_2 & q_1 & q_0
\end{array}
\]

And here are the length four strings.

\[
\begin{array}{c|cccccccc}
\text{Input } \sigma & \text{aaaa} & \text{aab} & \text{aba} & \text{abb} & \text{aaab} & \text{aab} & \text{abab} & \text{abbb} \\
\hat{\Delta}(\sigma) & q_1 & q_2 & q_1 & q_2 & q_1 & q_2 & q_1 & q_0 \\
 & \text{bbaa} & \text{baab} & \text{baba} & \text{bbab} & \text{bbab} & \text{bbba} & \text{bbbb}
\end{array}
\]

Verified IV.1.32

IV.1.33

(a) Five that are in the language are aa, aaa, baa, aaaa, and abaa. Five that are not are \( \varepsilon \), a, b, ab ba, and aba. Here is the machine.

(b) The only string in the language is \( \varepsilon \). That is, \( L = \{ \varepsilon \} \). Five not in the language are a, b, aa, ab, and ba. The machine is this.

(c) There are only two strings in the language: \( L = \{ \text{aaab}, \text{baaa} \} \). Five strings not in the language are \( \varepsilon \), a, b, aa, and ab. The machine is this.

(d) Five strings in the language are \( \varepsilon \), a, b, aa, and bb. Five not in the language are ab, ba, aab, aba, and baa. This is the machine.
Note that $q_0$ is an accepting state.

**Verified** IV.1.34 It outputs the length one string containing the start state, $\hat{\Lambda}(\varepsilon) = q_0$.

**Verified** IV.1.35

(A) 

\[ \begin{align*}
q_0 &\quad a \quad q_1 \\
&\quad b \quad a \\
&\quad \text{any} \quad b
\end{align*} \]

(B) 

\[ \begin{align*}
q_0 &\quad 0,2 \\
&\quad 1,2,3,4,6,7,8,9 \\
&\quad q_1 0,5
\end{align*} \]

**Verified** IV.1.36 Note that although the string $\sigma = \text{AEAIAOAUA}$ has an $A$ that occurs after an $E$, nonetheless the machine should accept it because there exists a subsequence of string elements consisting of the ordered vowels.

**Verified** IV.1.37

(A) Five that are: $+1$, $123$, $-123.45$, $-0.0$, and $0$. Five that are not: $+,-,..$, $12.3.4$, and $2+3$

(B) No, before the period must come at least one digit.

(C) It is the set of representations of real numbers with integer part, a decimal point, and a decimal part.

**Verified** IV.1.38

(A) Five that are in the language are $010$, $0010$, $0$, $0101000$, and $\varepsilon$. Five that are not are $10, 0110, 0101, 01001, 1$, and $1$.

(b) A string is a binary representation of a multiple of 4 if and only if it ends in two zero's, $00$, or it is $0$. Five in the language are $100, 0100, 1000, 10100$, and $0$. Five not in the language are $10, 1, 1001, 001$, and $\varepsilon$.

(c) Five strings in the language are $0, 20, 12, 88$, and $08$. Five that are not are $1, 01, 2221, 17$, and $\varepsilon$. 
(d) This is basically the same as the second item. A string is a decimal representation of a multiple of 100 if and only if it ends in two zero's, 00, or it is 0. Five in the language are 100, 0100, 2000, 60300, and 0. Five not in the language are 10, 8, 1009, 001, and ε.

IV.1.39 A number is divisible by four if and only if its representation ends in 00, 04, ... 96, or the single-digit cases where the representation is 0, 4, or 8. That's 28 cases. A picture would be cluttered but this is a finite language and for any finite language there is a Finite State machines that accepts that language. (We shall see an alternative approach that makes a clearer picture in the section on nondeterminism.)

IV.1.40 This is the computation.

\[ \langle q_0, 2332 \rangle \vdash \langle q_2, 332 \rangle \vdash \langle q_2, 32 \rangle \vdash \langle q_2, 2 \rangle \vdash \langle 1, \varepsilon \rangle \]

The state \( q_1 \) is not an accepting state so the machine rejects 2332.

IV.1.41 Verified Recall the transition function for that example.

\[ \Delta \]

<table>
<thead>
<tr>
<th>( \Delta )</th>
<th>0</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>( q_0 )</td>
<td>( q_1 )</td>
<td>( q_3 )</td>
</tr>
<tr>
<td>( q_1 )</td>
<td>( q_2 )</td>
<td>( q_4 )</td>
</tr>
<tr>
<td>+ ( q_2 )</td>
<td>( q_2 )</td>
<td>( q_5 )</td>
</tr>
<tr>
<td>( q_3 )</td>
<td>( q_4 )</td>
<td>( q_0 )</td>
</tr>
<tr>
<td>( q_4 )</td>
<td>( q_5 )</td>
<td>( q_1 )</td>
</tr>
<tr>
<td>( q_5 )</td>
<td>( q_5 )</td>
<td>( q_2 )</td>
</tr>
</tbody>
</table>

(a) If the input string is \( \sigma = \theta \) then peel off the final character with \( \sigma = \sigma_0 \sim \theta = \varepsilon \sim \theta \) and the definition gives this.

\[ \hat{\Delta}(\theta) = \Delta(\hat{\Delta}(\varepsilon), \theta) = \Delta(q_0, \theta) = q_1 \]

(Note that in the left-most expression \( \theta \) is a length one string, while in the rest of the above equation \( \theta \) is a character, and we are ignoring this uninteresting point.) Similarly, \( \hat{\Delta}(1) = q_3 \).

(b) For \( \sigma = \emptyset \theta \) use the prior item's computation of \( \hat{\Delta}(\theta) \).

\[ \hat{\Delta}(\emptyset \theta) = \Delta(\hat{\Delta}(\emptyset), \theta) = \Delta(q_1, \theta) = q_2 \]

The other three are similar.

\[ \hat{\Delta}(\emptyset 0) = q_4 \quad \hat{\Delta}(\emptyset 1) = q_4 \quad \hat{\Delta}(\emptyset 1) = q_0 \]

(c) For each of these use the prior item's computation. Here is the first.

\[ \hat{\Delta}(\emptyset 0 0) = \Delta(\hat{\Delta}(\emptyset 0), \theta) = \Delta(q_2, \theta) = q_2 \]

The others are computed in the same way.

IV.1.42

IV.1.43 Verified
(A) There is one such machine.

\[
\begin{array}{c|c|c|c|c}
\text{state} & \text{meaning} & \text{with wolf} & \text{with goat} & \text{with cabbage} & \text{with nothing} \\
\hline
s_0 & n: mwgc, f: – & s_{12} & s_{10} & s_9 & s_8 \\
s_1 & n: mwg, f: c & s_{13} & s_{11} & e & s_9 \\
s_2 & n: mwc, f: g & s_{14} & e & s_{11} & s_{10} \\
s_3 & n: mw, f: gc & e & e & e & e \\
s_4 & n: mge, f: w & e & s_{14} & s_{13} & s_{12} \\
s_5 & n: mg, f: wc & e & s_{15} & e & s_{13} \\
s_6 & n: mc, f: wg & e & e & e & e \\
s_7 & n: m, f: wgc & e & e & e & e \\
s_8 & n: wgc, f: m– & e & e & e & e \\
s_9 & n: wg, f: mc & e & e & e & e \\
s_{10} & n: wc, f: mg & e & s_0 & e & s_2 \\
s_{11} & n: w, f: mgc & e & s_1 & s_{10} & s_3 \\
s_{12} & n: gc, f: mw & e & e & e & e \\
s_{13} & n: g, f: mwc & s_1 & e & s_4 & s_5 \\
s_{14} & n: c, f: mwg & s_2 & s_4 & e & s_6 \\
s_{15} & n: –, f: mwgc & s_{15} & s_{15} & s_{15} & s_{15} \\
e & \text{error} & e & e & e & e \\
\end{array}
\]

Figure 42, for question IV.1.44: Finite state machine for Wolf-Goat-Cabbage.

(A) There are three ways for the first player to win.

(B) This list has 16 machines.

\[
\begin{array}{c|c|c} \Delta_0 & 0 & 1 \\
q_0 & q_0 & q_0 \end{array}
\]

\[
\begin{array}{c|c|c} \Delta_1 & 0 & 1 \\
q_0 & q_0 & q_0 \end{array}
\]

\[
\begin{array}{c|c|c} \Delta_2 & 0 & 1 \\
q_0 & q_0 & q_0 \end{array}
\]

\[
\begin{array}{c|c|c} \Delta_15 & 0 & 1 \\
q_0 & q_1 & q_1 \end{array}
\]

(c) Fix \( n \) states, \( Q = \{ q_0, \ldots, q_{n-1} \} \). Each line of the transition table has two columns so the number of distinct lines is \( n \cdot n = n^2 \). An overall table chooses \( n \) such lines. There are \( n^2 \cdot n^2 \cdot \ldots \cdot n^2 = n^{2n} \) many ways to do that.

(d) For each of the \( n \) states, either it is final or it is not. The additional factor of \( 2^n \) makes the total number of distinct tables equal to \( 2^n \cdot n^{2n} \).

Verified **IV.1.44** We can have the man, the wolf, the goat, and the cabbage, on the near or far side. The allowed transitions are: man crosses with wolf, man crosses with goat, man crosses with cabbage, and man crosses by himself. Here are the states; some of them lead to an error state, as readers of the 700’s would have understood.

In the Finite State machine shown in Figure 42 on page 97 the start state is \( s_0 \) and the only accepting state is \( s_{15} \). In words: *The man first brings the goat to the far side and leaves it there. He goes back and brings the wolf with him, leaving it on the far side, and brings back the goat. He leaves the goat on the initial side, takes the cabbage and brings it to the far side. Finally, he goes back to the original shore, and takes the goat to bring it to the far side.*

Verified **IV.1.45**

(A) There are three ways for the first player to win.
(b) Encode the ending position as a length nine string.

\[
\begin{array}{c|c|c}
q_0 & q_1 & q_2 \\
q_3 & q_4 & q_5 \\
q_6 & q_7 & q_8 \\
q_9 & \end{array}
\]

\[
a_{i,j} \in \Sigma = \{ X, E \}
\]

Here, E means 'else' — either player 0 marked that square or it is blank because the game ended before that square was filled. There are eight ways for X to win.

The machine takes the shape of a binary tree of depth nine. It has \( 2^9 \) branches and \( 2^{10} \) total state nodes, too many to show here so this picture just shows ellipses.

Put double-circle states for the terminal node in each of the eight branches described above, such as XXXEEEEEE.

**IV.1.46** This is based on Example 1.8.

We will prove this by induction on the number of strings in the language. If the language is empty then we use any Finite State machine with the right alphabet and no accepting states. If the language has one string \( \sigma \) then we write a Finite State machine whose state transitions track the characters of \( \sigma \) as does the top line in the example. That is, we have this.

As the diagram shows, the last state in that sequence is an accepting state. Also as shown, all transitions for characters not in the sequence go to e. (If \( \sigma = \epsilon \) then there are two states, with the initial state \( q_0 \) an accepting state and all transitions going to the error state \( e \) that is not an accepting state.)
For the inductive case, assume that there is a machine for any language of size \( n = 1, \ldots, n = k \) and consider a language \( L \) with \( k + 1 \)-many strings. Order the alphabet \( \Sigma \); in the example we use the grade school alphabetical ordering. This character ordering gives rise to an ordering of the strings, called lexicographic ordering. List \( L \)'s strings lexicographically:

\[ \sigma_0, \ldots, \sigma_k, \sigma_{k+1} \]

The induction assumption gives a machine for the language consisting of the strings \( \sigma_0, \ldots, \sigma_k \). The example shows what to do next; it has the two final strings png and pdf and the machine splits where the two strings split, after the p. Following that model, find the longest common substring for \( \sigma_k \) and \( \sigma_{k+1} \), so that \( \sigma_k = \alpha \dashv \beta \), and \( \sigma_{k+1} = \alpha \dashv \gamma \), and the initial character of \( \beta \) is not equal to the initial character of \( \gamma \). (It could be that \( \beta = \varepsilon \). It could also be that \( \alpha = \varepsilon \).) As in the example, split the machine after it has traversed the common string.

\[ \alpha[0] \alpha[-1] \sigma_k[i] \sigma_k[-1] \sigma_{k+1}[i] \sigma_{k+1}[-1] \]

(To be more readable this figure omits all the transitions involving \( \varepsilon \).)

**IV.1.47** Recall that an alphabet is finite, by definition.

(A) We will show that there are infinitely many different Finite State machines. Fix any \( \Sigma \) and suppose \( s \in \Sigma \). The machines below differ in the number of states, and in that they accept different languages. (If \( \Sigma \) contains characters other than \( s \) then use the second column.)

\[
\begin{array}{c|c|c}
\Delta & s & \text{other} \\
\hline
+ q_0 & q_0 & q_0 \\
\end{array}
\begin{array}{c|c|c}
\Delta & s & \text{other} \\
\hline
+ q_0 & q_1 & q_0 \\
\end{array}
\begin{array}{c|c|c}
\Delta & s & \text{other} \\
\hline
+ q_0 & q_0 & q_0 \\
\end{array}
\]

That shows, under a reasonable interpretation of what it means for machines to differ, that there are at least countably many Finite State machines. (The technical wording is that these machines are not isomorphic.)

(B) The argument that there are no more than countably many machines also requires an interpretation. Assume that the set of possible states is countable, \( Q = \{ q_0, q_1, \ldots \} \), so as to not get uncountably many machines by virtue of there being uncountably many possible states. With that, the argument that we can count the Finite State machines is straightforward since for any collection of finitely many states \( q_0, \ldots, q_k \) there are finitely many transition tables. Thus the number of Finite State machines using those states is countable. And then the union of countably many countable sets is countable, so the number of machines over all collections of finitely many states is countable.

(C) Because \( \Sigma \) has at least two members, the usual diagonalization construction shows that the power set of \( \Sigma \) is not countable.

**IV.2.23** The main point is that entries in the table are sets of states. This is the machine in Example 2.7.

\[
\begin{array}{c|c|c|c}
\Delta & a & b \\
\hline
q_0 & \{q_0, q_1\} & \{q_0, q_2\} \\
q_1 & \{q_3\} & \{} \\
q_2 & \{} & \{q_3\} \\
+ q_3 & \{q_3\} & \{q_3\} \\
\end{array}
\]

This is Example 2.8's machine.

\[
\begin{array}{c|c|c|c}
\Delta & a & b & c \\
\hline
+ q_0 & \{q_1\} & \{} & \{} \\
q_1 & \{} & \{} & \{q_0\} \\
\end{array}
\]

**IV.2.24**

(A) Yes. From \( q_0 \) a \( \varepsilon \) transition goes to \( q_2 \), which is an accepting state.
(b) No. From \( q_0 \) the machine can either read the \( \emptyset \) and go to \( q_1 \), or take the \( \epsilon \) transition to \( q_2 \) and then read the \( \emptyset \), which sends the machine to no-state. Neither \( q_2 \) nor no-state is an accepting state.

Said more formally, the \( \epsilon \) closure of \( q_0 \) is \{ \( q_0, q_2 \) \}. Neither state, on reading the character \( \emptyset \), transitions to a state whose \( \epsilon \) closure includes an accepting state.

(c) Yes. With that input the machine can go from \( q_0 \) to \( q_1 \), then to \( q_2 \), and then around the loop to \( q_2 \) again. More formally, this is a sequence of allowed transitions that ends in an accepting state.

\[
\langle q_0, \emptyset \rangle \vdash \langle q_1, 1 \rangle \vdash \langle q_2, 1 \rangle \vdash \langle q_2, \epsilon \rangle
\]

(d) No. Starting at \( q_0 \) with the character \( \emptyset \) first on the tape the machine can do two things. If it takes the \( \epsilon \) transition then when it reads the \( \emptyset \) it goes to no-state, which is not an accepting state.

Otherwise, the \( \emptyset \) moves the machine to \( q_1 \). Next, on the following tape character \( 1 \), the machine moves to \{ \( q_2 \) \}. Finally, on the third character \( \emptyset \), the machine moves to no-state.

(e) There are two: \( \emptyset 1111 \) and \( 1111 \).

**IV.2.25** In this class saying something is “just mathematical abstraction” is like objecting in an electrodynamics class that this is all “just electricity.” That’s what we are doing here.

Said another way, if someone compares what we are thinking about here with data structures, and holds the latter up as a model of “real” then that is a stretch. “Real” is things like changing diapers and grafting fruit trees. All of what we are doing, in the entire programs of computer science and mathematics, is abstraction of one kind of another.

If a person responds, “OK, but abstraction can go too far, and get away from what brought me into the program” then the answer is that people in a program need to take as the default assumption that the people who put together this program, and such programs across the world, put in steps that lead somewhere. Nondeterminism is here because it is necessary to understand the material of the fifth chapter, which describes the most important problem in the field today, one that will directly impact all practitioners, the \( P \) versus \( NP \) question.

Besides, it is interesting, and fun. Those are respectable criteria for at least some consideration.

**Verified IV.2.26** The machine accepts the input string if there is a sequence of legal transitions that allows the machine to process the string and that ends in an accepting state. It does not say there must not be any wrong ways to go, only that there must be a right way.

For instance, the given machine can accept \( aab \) by starting in \( q_0 \), transitioning to \( q_1 \) on the first \( a \), taking the \( \epsilon \) transition to \( q_0 \), then going to \( q_1 \) on the second \( a \), then going to \( q_2 \), which is accepting, with the \( b \).

\[
\langle q_0, aab \rangle \vdash \langle q_1, ab \rangle \vdash \langle q_0, ab \rangle \vdash \langle q_1, b \rangle \vdash \langle q_2, \epsilon \rangle
\]

This machine accepts the language \( L = \{ a^n b \mid n \in \mathbb{N} \} \).

**Verified IV.2.27** This is the graph of the nondeterministic machine. (It is nondeterministic in that the edges don’t list every element of the alphabet \{ \( \sim, \emptyset, \ldots, 9 \) \}.)

**Verified IV.2.28**

**Verified IV.2.29**

(a) It does not accept the empty string because the \( \epsilon \) closure of \( q_0 \) does not contain any final states, since the \( \epsilon \) closure equals \{ \( q_0 \) \}.

(b) It accepts both of the one-character strings \( a \) and \( b \). For instance, on the string \( a \) the machine can transition from \( q_0 \) to \( q_1 \), and then it can make an \( \epsilon \) transition to \( q_2 \), which is an accepting state.

(c) The given machine can accept \( aab \) by starting in \( q_0 \), transitioning to \( q_0 \) on the first \( a \), then going to \( q_1 \) on the second \( a \), taking the \( \epsilon \) transition to \( q_2 \), then going to \( q_2 \) with the \( b \), thereby ending in an accepting state.

\[
\langle q_0, aab \rangle \vdash \langle q_0, ab \rangle \vdash \langle q_1, b \rangle \vdash \langle q_2, b \rangle \vdash \langle q_2, \epsilon \rangle
\]
(d) Five of the shortest strings are: a, b, aa, ab, and aab.
(e) Five that it does not accept are: the empty string ε, ba, baa, bab, and baaa.

Verified IV.2.30

<table>
<thead>
<tr>
<th>Δ</th>
<th>ε</th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>q₀</td>
<td>{ q₁ }</td>
<td>{ q₁ }</td>
<td>{ }</td>
</tr>
<tr>
<td>q₁</td>
<td>{ q₀ }</td>
<td>{ }</td>
<td>{ q₂ }</td>
</tr>
<tr>
<td>+ q₂</td>
<td>{ }</td>
<td>{ }</td>
<td>{ }</td>
</tr>
</tbody>
</table>

Verified IV.2.31

(A)

(B)

(C)

(D)

IV.2.32

(A)

(B) A string is in the language if it consists of, first, some number of repetitions of: either a number of repetitions of a or ba. Then it has either bb, or a b followed by an a or b. Finally, the suffix consists of some number of characters, either a or b.

(c) This is the transition function for the associated deterministic machine.
\( \Delta_D \) | \( a \) | \( b \)  
---|---|---  
\( s_0 = \{ \} \) | \( s_0 \) | \( s_0 \)  
\( s_1 = \{ q_0 \} \) | \( s_1 \) | \( s_0 \)  
\( s_2 = \{ q_1 \} \) | \( s_2 \) | \( s_0 \)  
\( + s_3 = \{ q_2 \} \) | \( s_3 \) | \( s_0 \)  
\( s_4 = \{ q_3 \} \) | \( s_4 \) | \( s_0 \)  
\( s_5 = \{ q_0, q_1 \} \) | \( s_5 \) | \( s_1 \)  
\( + s_6 = \{ q_0, q_2 \} \) | \( s_6 \) | \( s_1 \)  
\( s_7 = \{ q_0, q_3 \} \) | \( s_7 \) | \( s_1 \)  
\( + s_8 = \{ q_1, q_2 \} \) | \( s_8 \) | \( s_0 \)  
\( s_9 = \{ q_1, q_3 \} \) | \( s_9 \) | \( s_0 \)  
\( + s_{10} = \{ q_2, q_3 \} \) | \( s_{10} \) | \( s_0 \)  
\( + s_{11} = \{ q_0, q_1, q_2 \} \) | \( s_{11} \) | \( s_1 \)  
\( s_{12} = \{ q_0, q_1, q_3 \} \) | \( s_{12} \) | \( s_1 \)  
\( + s_{13} = \{ q_0, q_2, q_3 \} \) | \( s_{13} \) | \( s_1 \)  
\( + s_{14} = \{ q_1, q_2, q_3 \} \) | \( s_{14} \) | \( s_0 \)  
\( + s_{15} = \{ q_0, q_1, q_2, q_3 \} \) | \( s_{15} \) | \( s_1 \)

**Verified IV.2.33**

**Verified IV.2.34**

(A)

(B)

**Verified IV.2.35** That machine has seven states.

<table>
<thead>
<tr>
<th>state ( q )</th>
<th>( q_0 )</th>
<th>( q_1 )</th>
<th>( q_2 )</th>
<th>( q_3 )</th>
<th>( q_4 )</th>
<th>( q_5 )</th>
<th>( q_6 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varepsilon ) closure ( \hat{E}(q) )</td>
<td>{ ( q_0, q_2, q_3, q_5 ) }</td>
<td>{ ( q_1 ) }</td>
<td>{ ( q_2, q_3, q_5 ) }</td>
<td>{ ( q_3 ) }</td>
<td>{ ( q_4 ) }</td>
<td>{ ( q_5 ) }</td>
<td>{ ( q_6 ) }</td>
</tr>
</tbody>
</table>

**Verified IV.2.36**

The associated deterministic machine has eight states. Its accepting states are the ones containing \( q_2 \).
\[ \Delta_D \]

<table>
<thead>
<tr>
<th></th>
<th>( \emptyset )</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>( s_0 ) = {}</td>
<td>( s_0 )</td>
<td>( s_0 )</td>
</tr>
<tr>
<td>( s_1 ) = { ( q_0 ) }</td>
<td>( s_0 )</td>
<td>( s_2 )</td>
</tr>
<tr>
<td>( s_2 ) = { ( q_1 ) }</td>
<td>( s_3 )</td>
<td>( s_0 )</td>
</tr>
<tr>
<td>+ ( s_3 ) = { ( q_2 ) }</td>
<td>( s_3 )</td>
<td>( s_3 )</td>
</tr>
<tr>
<td>( s_4 ) = { ( q_0, q_1 ) }</td>
<td>( s_3 )</td>
<td>( s_2 )</td>
</tr>
<tr>
<td>+ ( s_5 ) = { ( q_0, q_2 ) }</td>
<td>( s_3 )</td>
<td>( s_6 )</td>
</tr>
<tr>
<td>+ ( s_6 ) = { ( q_1, q_2 ) }</td>
<td>( s_3 )</td>
<td>( s_3 )</td>
</tr>
<tr>
<td>+ ( s_7 ) = { ( q_0, q_1, q_2 ) }</td>
<td>( s_3 )</td>
<td>( s_6 )</td>
</tr>
</tbody>
</table>

**Verified IV.2.37** There are a number of ways to go. This is one

![Diagram 1](image1)

and this is another.

![Diagram 2](image2)

**Verified IV.2.38**

![Diagram 3](image3)

**Verified IV.2.39** One description is \( \mathcal{L} = \{ \sigma \in \{a, b\}^* \mid \sigma = \varepsilon \text{ or } \sigma = \varepsilon q^j \varepsilon^i \text{ for } i \geq 1 \text{ and } j \geq 0 \} \).

**Verified IV.2.40** It is \( \mathcal{L} = \{ \sigma \in \{a, b\}^* \mid \sigma \text{ has no substring \textit{bba}} \} \).

**IV.2.41** Here is the nondeterministic machine

![Diagram 4](image4)

and this is a deterministic version.

![Diagram 5](image5)

**IV.2.42** This is for the machine on the left.
\[ \Delta_D \begin{array}{c|cc} & 0 & 1 \\ \hline s_0 = \{ \} & s_0 & s_0 \\ s_1 = \{ q_0 \} & s_4 & s_0 \\ s_2 = \{ q_1 \} & s_3 & s_3 \\ + s_3 = \{ q_2 \} & s_0 & s_1 \\ s_4 = \{ q_0, q_1 \} & s_7 & s_3 \\ + s_5 = \{ q_0, q_2 \} & s_4 & s_1 \\ + s_6 = \{ q_1, q_2 \} & s_3 & s_5 \\ + s_7 = \{ q_0, q_1, q_2 \} & s_7 & s_5 \end{array} \]

And, this is for the machine on the right.

\[ \Delta_D \begin{array}{c|cc} & 0 & 1 \\ \hline s_0 = \{ \} & s_0 & s_0 \\ s_1 = \{ q_0 \} & s_4 & s_1 \\ s_2 = \{ q_1 \} & s_3 & s_3 \\ + s_3 = \{ q_2 \} & s_0 & s_5 \\ s_4 = \{ q_0, q_1 \} & s_7 & s_1 \\ + s_5 = \{ q_0, q_2 \} & s_4 & s_1 \\ + s_6 = \{ q_1, q_2 \} & s_3 & s_5 \\ + s_7 = \{ q_0, q_1, q_2 \} & s_7 & s_5 \end{array} \]

**Verified** IV.2.43

(A)

(B)

IV.2.44

(A)

(B)
IV.2.45 Here are the graphs.

The machine on the left, the one that accepts only the empty string, has this table.

\[
\begin{array}{ccc}
\Delta & a & b & c \\
+ q_0 & \{ \} & \{ \} & \{ \}
\end{array}
\]

The machine on the right has this.

\[
\begin{array}{ccc}
\Delta & a & b & c \\
q_0 & \{ q_1 \} & \{ q_1 \} & \{ q_1 \} \\
+ q_1 & \{ q_1 \} & \{ q_1 \} & \{ q_1 \}
\end{array}
\]

**Verified**

IV.2.46

(a) This is a derivation of \(aabb\).

\[
S \Rightarrow aA \Rightarrow abB \Rightarrow abb
\]

This is a derivation of \(aabb\).

\[
S \Rightarrow aA \Rightarrow aaA \Rightarrow aabB \Rightarrow aabb
\]

And, this is a derivation of \(abbb\).

\[
S \Rightarrow aA \Rightarrow abB \Rightarrow abbB \Rightarrow abbb
\]

Verifying that they are accepted by the machine is routine.

(b) The language of the machine and the grammar is \(L = \{a^ib^j \mid i > 0, j > 1\}\).

**Verified**

IV.2.47 Each of these is solvable. For each we will sketch an algorithm.

(a) Clearly we can write a simulator for deterministic Finite State machines. By Church’s Thesis since we can write it on a modern computer, we can write one for a Turing machine. When given an input \(\sigma\), the machine will consume it in no more than \(|\sigma|\) steps, and so the simulation is sure to halt. Then just check whether the ending state is an accepting state.

(b) The section body discusses how to simulate a nondeterministic computation, by dovetailing (that is, time-slicing). With that we can answer questions about whether this machine accepts a given input \(\sigma\) just as in the prior item.

IV.2.48

(a) Here is the list.
Figure 43, for question IV.3.17: String matching test.

| $\varepsilon$ | $a^*b$ | $a^*$ | $\emptyset$ | $\varepsilon$ | $b(a|b)a$ | $(a|b)(\varepsilon|a)a$ |
|--------------|---------|--------|--------------|--------------|----------------|-------------------|
| $\varepsilon$ | F       | T      | F            | T            | F             | F                 |
| a            | F       | T      | F            | F            | F             | F                 |
| b            | T       | F      | F            | F            | F             | F                 |
| aa           | F       | T      | F            | F            | F             | T                 |
| ab           | T       | F      | F            | F            | F             | F                 |
| ba           | F       | F      | F            | F            | F             | T                 |
| bb           | F       | F      | F            | F            | F             | F                 |
| aaa          | F       | T      | F            | F            | F             | F                 |
| aab          | T       | F      | F            | F            | F             | F                 |
| aba          | F       | F      | F            | F            | F             | T                 |
| abb          | F       | F      | F            | F            | F             | F                 |
| baa          | F       | F      | F            | T            | T             | T                 |
| bab          | F       | F      | F            | F            | F             | F                 |
| bba          | F       | F      | F            | T            | F             | F                 |
| bbb          | F       | F      | F            | F            | F             | F                 |

So, $\hat{E}(q_0) = \{q_0, q_3\}$, $\hat{E}(q_1) = \{q_0, q_1\}$, $\hat{E}(q_2) = \{q_2\}$, and $\hat{E}(q_3) = \{q_3\}$.

This is similar.

So, $\hat{E}(q_0) = \{q_0\}$, $\hat{E}(q_1) = \{q_1, q_2\}$, and $\hat{E}(q_2) = \{q_2\}$.

IV.3.15

(a) Yes. One match is $\emptyset \in \emptyset$.

(b) Yes. This works: $\emptyset \in \emptyset$.

(c) No. To match, the $\emptyset$ must be a final character.

(d) Yes. A match is $\emptyset \in \emptyset$.

(e) Yes. Here is a match: $\emptyset \in \emptyset$.

IV.3.16

(a) Five that match are $\emptyset, \emptyset, \emptyset, \emptyset, \emptyset$, and $\emptyset \emptyset = \emptyset \emptyset \emptyset$. Five that do not are $\varepsilon, 1, 10, 11, \text{ and } 100$.

(b) Five matching strings are $\varepsilon, \emptyset, \emptyset \emptyset, \emptyset \emptyset \emptyset, \emptyset \emptyset \emptyset \emptyset, \text{ and } (\emptyset \emptyset)$.

(c) Matches are $101$ and $111$. Five that do not match are $\varepsilon, \emptyset, \emptyset, \emptyset, \emptyset, \text{ and } 10$.

(d) Five matches are $\emptyset, \emptyset, \emptyset, \emptyset, \emptyset, \text{ and } \emptyset$. Five that don't match are $\varepsilon, \emptyset \emptyset, \emptyset \emptyset \emptyset \emptyset, \emptyset \emptyset \emptyset \emptyset \emptyset, \text{ and } \emptyset \emptyset \emptyset \emptyset \emptyset \emptyset$.

(e) Matches: none. Non-matches: $\varepsilon, \emptyset, \emptyset, \emptyset, \emptyset, \text{ and } 10$.

Verified IV.3.17 Figure 43 on page 106 shows the table. Observe that the regular expression $\emptyset$ never matches.

Verified IV.3.18 Figure 44 on page 107 shows the table. Note that the regular expression $\emptyset$ never matches.
### Table 44, for question IV.3.18: String matching test.

| 0*1 | 1*0 | ∅ | ε | 0(0|1)* | (100)(ε|1)0* |
|-----|-----|---|----|---------|----------------|
| ε   | F   | F | F  | F       | F              |
| 0   | F   | T | F  | F       | T              |
| 1   | T   | F | F  | F       | F              |
| 00  | F   | F | F  | F       | T              |
| 01  | T   | F | F  | F       | T              |
| 10  | F   | T | F  | F       | F              |
| 11  | F   | F | F  | F       | F              |
| 000 | F   | F | F  | F       | T              |
| 001 | T   | F | F  | F       | T              |
| 010 | F   | F | F  | F       | T              |
| 011 | F   | F | F  | F       | T              |
| 100 | F   | F | F  | F       | T              |
| 101 | F   | F | F  | F       | F              |
| 110 | F   | T | F  | F       | F              |
| 111 | F   | F | F  | F       | F              |

**Figure 44, for question IV.3.18: String matching test.**

**Verified IV.3.19** The definition is \( L(R)^* = \{ \sigma_0 \cdots \sigma_{k-1} \mid k \in \mathbb{N} \text{ and } \sigma_0, \ldots, \sigma_{k-1} \in L(R) \} \). That is, the language of the star is the star of the language: \( L(R)^* = (L(R))^* \).

As an example, \((0*1)^*\) matches 01001 because 01001 = 01 001, and both of 01 and 001 matches \((0*1)\).

Thus, Kleene star means something more like “repeatedly match the inside.”

**Verified IV.3.20** One is \((0|1)^*0110(0|1)^*\).

**IV.3.21** Regular expressions are not unique. For instance, here are two regular expressions for the language of strings over \( \Sigma = \{a, b\} \) that have a substring with at least three \(a\)'s: \((a|b)^*aaa(a|b)^*\) and \((a|b)^*aaaa^*(a|b)^*\).

**IV.3.22** \(((a|b)^*|((a|c)^*)|((b|c)^*))\)

**IV.3.23**

(a) \(b(a|b)^*\)

(b) \((a|b)^*a(a|b)\)

(c) The two characters could come in the order \(a \ldots b \ldots \) or the order \(a \ldots b \ldots \). So this works: \((a|b)^*(((a(a|b)^*b))|(b(a|b)^*a)))(a|b)^*\).

(d) The \(a\)'s must come in triplets: \((b*ab*ab*ab^*)^*b^*\).

**Verified IV.3.24**

(a) \(aba(a|b)^*\)

(b) \((a|b)^*aba\)

(c) \((a|b)^*aba(a|b)^*\)

**IV.3.25**

(a) There must be at least one 1, and more 1's must come in pairs: \((0*10*1)^*0*10^*\).

(b) The regular expression \((\epsilon|1)(01)^*(\epsilon|0)\) will do. Note that it matches the empty string, as well as the string 0 and the string 1.

(c) A multiple of eight in binary ends in three \(0\)'s: \((0|1)^*000\). That expression matches binary numbers with leading \(0\)'s and won't match \(0\). If you don’t like that then instead use \((1(0|1)^*000)^*0\).

**IV.3.26**

(a) This is an answer: \(((ba)^*bb^*\)*. Notice that it matches the empty string, and that it matches babab.

(b) \((a|b)^*(((bba*bb)|bbb))(a|b)^*\)

**IV.3.27**

(a) Here the \(0\)'s come in pairs: \((1*01*01)^*1^*\).
(b) Here two of the 1’s have no Kleene star’s: $0^*10^*10^*1^*(0|1)^*$. 
(c) One that will do is to start with the expression from the prior item and replace all the 0’s with the expression from the first item.

\[((1*01*01*)*1*)*1((1*01*01*)*1*)*1((1*01*01*)*1*)*1*(((1*01*01*)*1*)|1)*\]

### IV.3.28

(A) $(a(a|b)*a)| (b(a|b)*b)$  
(B) $((aaa)*b(aaa)*|(a(aaa)*ba(aaa)*)|(aa(aaa)*baa(aaa))*$  

### IV.3.29

(A) $1(0|1)^*000$  
(B) $1(01)^*00(10)^*1$  
(C) $\varepsilon|0|1(01)^* (1|\varepsilon) |1(01)^* (0|\varepsilon)$

### IV.3.30

(A) Transform the machine $M$ to a new machine $\hat{M}$ by making the set of final states of $\hat{M}$ be $S$.  
(B) Transform the machine $M$ to $\hat{M}$ by making the start state be the given first single state, and also make the set $S$ of the prior item contain only the ending state. Then apply the argument given for the prior item.  

### IV.3.31

We will construct the reachable states, and then the unreachable ones are the others.  
(A) The set of reachable states is $S_2 = S_3 = \cdots = \{q_0, q_1, q_2\}$. So the set of unreachable states is $\{q_3\}$.

<table>
<thead>
<tr>
<th>$i$</th>
<th>$S_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>${q_0}$</td>
</tr>
<tr>
<td>1</td>
<td>${q_0, q_1}$</td>
</tr>
<tr>
<td>2</td>
<td>${q_0, q_1, q_2}$</td>
</tr>
<tr>
<td>3</td>
<td>${q_0, q_1, q_2}$</td>
</tr>
</tbody>
</table>

(b) The set of reachable states is $S_2 = S_3 = \cdots = \{q_0, q_1, q_2\}$. Thus the set of unreachable states is $\{q_2, q_4\}$.

<table>
<thead>
<tr>
<th>$i$</th>
<th>$S_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>${q_0}$</td>
</tr>
<tr>
<td>1</td>
<td>${q_0, q_1}$</td>
</tr>
<tr>
<td>2</td>
<td>${q_0, q_1, q_2}$</td>
</tr>
<tr>
<td>3</td>
<td>${q_0, q_1, q_3}$</td>
</tr>
</tbody>
</table>

### IV.3.32

Alphabets are finite, as defined in Appendix A. So the set of length $n$ strings over $\Sigma$ is finite, and therefore countable. Chapter II’s Corollary 2.12 shows that the countable union of countable sets is countable, and so the union over all $n$ of length $n$ strings is countable.

### IV.3.33

Figure 45 on page 109 shows the two trees.

### IV.3.34

Figure 46 on page 109 shows the two trees.

### IV.3.35

(A) This is $\hat{M}$.

(b) This is the before half of the diagram from Lemma 3.13’s proof, with $\hat{M}$ repeated for convenience.
Figure 45, for question IV.3.33: Parse trees for $a(b|c)$ and $ab^*(a|c)$.

Figure 46, for question IV.3.34: Parse trees for $a(b|c)^*$ and $a(b^*|c^*)$. 
The state $q_0$ has two states that originate arrows into it, and two that receive arrows from it. So we get this translation of the diagram's notation.

$$
\begin{array}{cccccccc}
q & q_{i0} & q_{i1} & q_{o0} & q_{o1} & R_{i_0} & R_{i_1} & R_{i_0,\alpha_0} & R_{i_0,\alpha_1} & R_{i_1,\alpha_0} & R_{i_1,\alpha_1} & R_\ell & R_{\alpha_0} & R_{\alpha_1} \\
q_0 & e & q_1 & q & f & \varepsilon & b & \varepsilon & b & \varepsilon & a & \varepsilon & b & a & \varepsilon \\
\end{array}
$$

(c) This is the after half diagram of Lemma 3.13's proof, along with the machine $\hat{M}$ after $q_0$ is eliminated.

IV.3.36

(A) This is $\hat{M}$ along with the before half of the diagram from Lemma 3.13's proof.

The state $q_0$ has one state that originates arrows into it, and one that receives arrows from it. So we get this translation of the diagram's notation.

$$
\begin{array}{ccccccc}
q & q_{i0} & q_{i1} & q_{o0} & R_{i_0} & R_{i_0,\alpha_0} & R_\ell & R_{\alpha_0} \\
q_0 & e & q_1 & q_1 & \varepsilon & \varepsilon & 0|1 & 1 \\
\end{array}
$$

This is the after half diagram of Lemma 3.13's proof, along with the machine $\hat{M}$ after $q_0$ is eliminated.
(b) This is the machine from the prior answer, along with the before half of the diagram from Lemma 3.13’s proof.

The state $q_1$ has one state that originates arrows into it, and one that receives arrows from it. So we get this translation of the diagram’s notation.

<table>
<thead>
<tr>
<th>$q$</th>
<th>$q_{i0}$</th>
<th>$q_{o0}$</th>
<th>$R_{i0}$</th>
<th>$R_{b_{i0}0}$</th>
<th>$R_f$</th>
<th>$R_{o0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q_1$</td>
<td>$e$</td>
<td>$q_2$</td>
<td>$e$</td>
<td>(0</td>
<td>1)*1</td>
<td></td>
</tr>
</tbody>
</table>

This is the after half diagram of Lemma 3.13’s proof, along with the machine $\hat{M}$ after $q_1$ is eliminated.

(c) This is the machine from the prior answer, along with the before half diagram.
The state $q_2$ has one state that originates arrows into it, and one that receives arrows from it. So we get this translation of the diagram's notation.

$$
\begin{array}{c|ccc}
q & q_{i0} & q_{o0} & R_{i0} & R_{i0,0} & R_f & R_{o0} \\
q_2 & e & f & \epsilon(\emptyset|1)^*11 & - & - & \epsilon \\
\end{array}
$$

This is the after half diagram along with the machine after $q_2$ is gone.

(d) The regular expression is $\epsilon(\emptyset|1)^*11\epsilon$.

**IV.3.37** This is $\hat{M}$ along with the before half of the diagram from Lemma 3.13’s proof.

The state $q_1$ has two states that originate arrows into it, and two that receive arrows from it. So we get this translation of the diagram’s notation.

$$
\begin{array}{c|ccccc}
q & q_{i0} & q_{i1} & q_{o0} & q_{o1} & q_{i1} \\
q_1 & q_0 & q_2 & q_0 & q_2 & q_1 \\
\end{array}
$$

Here is the after diagram, along with the machine $\hat{M}$ after the elimination of $q_1$.

**IV.3.38** Each of these gives the progression of steps.

(A)

$$
\begin{array}{c|c}
e & a|b \\
e & f \\
\end{array}
$$
(b) First concatenation and then Kleene star.

\[ \text{First concatenation and then Kleene star.} \]

\[ (a|b)c^*(a|b)c^* \]

\[ (a|b) c^* e q_0 q_1 f \]

\[ a \]

\[ b \]

\[ b^* \]

IV.4.6

Verified

(A) False. For example, the language \( \{ a^n \mid n \in \mathbb{N} \} = \{ \epsilon, a, aa, \ldots \} \) is regular and infinite.

(b) False, the empty language is accepted by any Finite State machine that has no accepting states. It is also
the language described by the regular expression \( \emptyset \).

(c) False. The language \( B^* \) is the set of all strings is accepted by any Finite State machine whose states are all
accepting states. It is also the language described by the regular expression \( (\emptyset | 1)^* \).

(d) False, a Finite State machine with no accepting states does not accept any strings.

(e) False, a minimal machine cannot be further reduced. For instance, a machine with only one state, and that
state accepting, is the smallest machine that accepts \( L = B^* \).

IV.4.7

Verified

(A) False. This is not necessary if the two languages are not regular. For example, where \( L \) is not regular, the
union \( \emptyset \cup L \) is not regular.

(b) This is like the last one, \( L \cap B^* = L \).

IV.4.8

Verified

The first is true and the second is false.

(A) If the language consists of the strings \( \sigma_0, \ldots, \sigma_{n-1} \) then a regular expression is \( \sigma_0 | \cdots | \sigma_{n-1} \).

(b) The language over \( \Sigma = \{ a, b \} \) described by the regular expression \( a^* \) is \( \{ \epsilon, a, aa, \ldots \} \), and is infinite.

IV.4.9

Verified

One way to show this is to give a regular expression for each.

(A) \( a(a|b)^*a \)

(b) \( b^*(ab+a)^*b^* \)

IV.4.10

Each is false. The same example suffices for all three. For \( L_0 \) use the set of all bitstrings, \( B^* \). For \( L_1 \) use
any non-regular subset of it, the existence of which is guaranteed by Lemma 4.2.

IV.4.11

This is not really a sensible question.

If we assert that no English sentence has more than a million words (see (Wikipedia contributors 2020))
then we might claim that English is a regular language because we can enumerate the allowed sentences, and
there are finitely many of them.
Otherwise we must choose a grammar. But which one? Is “Colourless green ideas sleep furiously” a legal sentence even though it is not sensible? Is “My god, it is her” allowed even though some would say it should be “My god, it is she”?

Really, the whole thing is a problem. (See https://cs.stackexchange.com/a/116178/67754.)

**IV.4.12** Because the language is regular it is described by a regular expression, $R$. Then the regular expression $1R$ describes $\hat{L}$.

**IV.4.13** Let $\Sigma$ be the alphabet of the language $L$. The collection of even length strings over $\Sigma$ is regular since there is clearly a Finite State machine that accepts only those strings. The intersection of $L$ with this collection is an intersection of two regular languages, so it is regular.

**IV.4.14** The graphical representation of a Finite State machine is a directed graph. So we can naturally extend the definition of one vertex being reachable from another to one state $q$ being reachable from another state $\hat{q}$, if there is a sequence of directed edges that go from the first node to the second.

(a) Fix a Finite State machine $M$ that accepts $L$. From it derive a new Finite State machine by making an accepting state every state $q$ from which an accepting state of $M$ is reachable. Clearly that machine accepts $\text{pref}(L)$.

(b) Again, fix a Finite State machine $M$ that accepts $L$. Let $S$ be the set of states reachable from $q_0$. Get $\hat{M}$ by introducing a new state $r$ and defining an $\epsilon$ transition to each state in $S$. Here also, clearly this machine accepts $\text{suff}(L)$.

(c) We have $\text{allprefs}(L) = (L^c - \Sigma^*)^c$, so it is regular.

**IV.4.15** Over $B$ the language of all strings $L = B^*$ is regular, and is uncountable.

**IV.4.16** The result is a nondeterministic Finite State machine.

(a) $\hat{L}$

(b) $\hat{M}$

(c) $\hat{N}$

(d) $\hat{O}$

**IV.4.17** For one direction suppose that the machine accepts at least one string, $\sigma$, of length $k$ where $n \leq k < 2n$. In processing $\sigma$ the machine must go through at least $n$-many transitions. But the machine has $n$ states and starting at $q_0$ and visiting all the other states exactly once would require only $n - 1$ many transitions. Thus, by the Pigeonhole principle, in processing the string $\sigma$ the machine visits some state $q$ twice. That is, in processing $\sigma$ the machine makes a loop.

Said another way, the accepted string $\sigma$ decomposes as $\sigma = \alpha \beta \gamma$ where processing the $\alpha$ portion takes the machine from the start to the loop (from state $q_0$ to $q$), the $\beta$ portion takes the machine around the nontrivial loop (so that $\beta \neq \epsilon$ brings the machine from $q$ to $q$ again) and the $\gamma$ portion brings the machine to some final state. But then the accepted language is infinite, since clearly the machine also accepts $\alpha \beta \beta \gamma$, etc. (Note that we can take $\beta$ to be of length less than $n$ because otherwise the size of the machine would imply it has a subloop.)

Conversely, suppose the language of accepted strings is infinite. At least one of them is longer than $n$; fix one that is longer but of minimal length. As in the prior paragraph, because the machine only has $n$ states, by the Pigeonhole principle the accepted string $\sigma$ decomposes as $\sigma = \alpha \beta \gamma$ where the $\beta$ portion is a nontrivial loop so processing $\beta$ brings the machine from $q_0$ to some $q$, then processing $\beta \neq \epsilon$ brings the machine from $q$ to $q$ again, and then processing the $\gamma$ portion brings the machine to some final state. Because the string is of minimal length, $|\beta| < n$. In total then, $|\sigma| < 2n$.

**IV.4.18**

(a) $\hat{h}(01) = aba, \hat{h}(10) = baa, \hat{h}(101) = baaba$

(b) A regular expression to describe $\hat{L} = \{ \sigma \in B^* \}$ is $(0|1)*1$. A regular expression to describe $\hat{h}(\hat{L})$ is $(a|ba)*ba$. 
(c) Let $\mathcal{L}$ be described by the regular expression $R$. Apply the function $h$ to each non-meta symbol in $R$. The result is a regular expression that describes $h(\mathcal{L})$.

**IV.4.19** For this machine the language of accepted strings contains 1.

![State machine diagram]

If we complement the set of accepting states then the language of the resulting machine also contains 1.

**IV.4.20**

(a) We prove this by induction on the length of $\sigma_1$. For the base case consider both $\sigma_1 = \epsilon$ and $\sigma_1 = a$ for some $a \in \Sigma$. With both, the statement obviously holds.

For the inductive case assume that the statement is true when $|\sigma_1| = 0$, $|\sigma_1| = 1$, ..., $|\sigma_1| = k$ and consider the $|\sigma_1| = k + 1$ case. In this case $\sigma_1 = \alpha \cdot a$ for some character $\alpha \in \Sigma$ and string $\alpha \in \Sigma^{*}$ of length $k$.

Then $(\sigma_0 \cdot \sigma_1)^R = (\sigma_0 \cdot \alpha \cdot a)^R$. Apply the base case to get $= a^R \cdot (\sigma_0 \cdot \alpha)^R$. The inductive hypothesis gives $= a^R \cdot \sigma_0^R$, and finish by recognizing that as $\sigma_1^R = \sigma_0^R$.

(b) We prove this by induction on the length of the regular expression. The base case is that $|R| = 1$. If $R = \emptyset$ then by condition (i) $R^R$ is the regular expression $\emptyset$, and $L(R) = L(R^R)$ because both equal the empty set, as required. If $R = \epsilon$ then by condition (ii) $R^R = \epsilon$, and $L(R) = \{\epsilon\} = L(R^R)$, again as required. And, similarly, if $R = x$ for some $x \in \Sigma$ then by condition (iii) $R^R = x$ and $L(R) = \{x\} = L(R^R)$.

Now for the inductive step. Assume that the statement is true for regular expressions $R$ of length $n = 1$, $n = 2$, ..., $n = k$, and consider an expression of length $n = k + 1$. We handled the case that it is a concatenation, $R = R_0 \cdot R_1$, in this question's first item.

If $R = R_0 \cdot R_1$ then $L(R^R) = L((R_0 \cdot R_1)^R) = L(R_0^R \cdot R_1^R)$ by condition (v). By the definition of the language associated with a pipe regular expression following Definition 3.4 that gives $= L(R_0^R) \cup L(R_1^R)$. The inductive hypothesis gives $L(R_0^R) \cup L(R_1^R)$, which equals $\{\sigma_0^R \mid \sigma_0 \in L(R_0)\} \cup \{\sigma_1^R \mid \sigma_1 \in L(R_1)\}$ and again applying the material following Definition 3.4 that equals $L(R^R)$.

The final form is similar. If $R = R_0^*$ then $L(R^R) = L((R_0^*)^R)$. By the definition following Definition 3.4 that equals $\{\sigma_0 \cdot \cdots \cdot \sigma_m \mid \sigma_j \in L(R_0)\}$. Rewriting gives $\{\tau_0 \cdot \cdots \cdot \tau_m \mid \tau_j \in L(R_0)\}$. By this exercise’s first item that equals $\{\tau_0 \cdot \cdots \cdot \tau_0 \mid \tau_j \in L(R_0)\}$, which is the set $(L(R_0^R))^R$.

**Verified**  
**IV.5.8** There is no such regular expression. Definition 3.4 just does not have the capacity for that construct.

**Verified**  
**IV.5.9** Compared with $\sigma = \alpha \beta \gamma$, the string $\alpha \gamma$ has had $\beta$ omitted. By definition $\sigma$ has balanced parentheses. Because $\beta$ consists of at least one open parentheses, $\gamma$, its omission of $\beta$ means that in $\alpha \gamma$ the number of open parentheses is at least one fewer than the number of closed parentheses.

**Verified**  
**IV.5.10** If a language is finite, $\mathcal{L} = \{\sigma_0, \ldots, \sigma_n\}$, then the conclusion of the Pumping Lemma holds by taking the pumping length to be $p > \max(|\sigma_0|, \ldots, |\sigma_n|)$.

**IV.5.11** It is not correct.

The first problem is that it is not sensible. Strings don’t have states.

Even if you figure that they meant to introduce a machine and say something like, “if a language has a string where the Finite State machine that accepts the language has fewer states then the length of the string then it cannot be a regular language” then it still isn’t sensible because if there is a Finite State machine then the language is regular.

And, even if we stretch figuring out what they meant all the way to making things up for them and assume they meant something like this, “If in an argument where we assumed the language is accepted by a Finite State machine we show that the language has a string that is longer than the number of states in the machine, then we have the desired contradiction” then the statement, while now technically sensible, is wrong. For example, there is a Finite State machine that accepts strings described by $a^3 \cdot b^3$, and there certainly are strings of that form whose length is greater than the number of states in the machine.

**IV.5.12**

(a) Five elements of $\mathcal{L}_0$ are $bb$, $abbb$, $aabb$, $a^3b^5$, and $a^4b^6$. Five strings that are not elements are $\epsilon$, $a$, $ab$,
aabbb, and baabbbb.

Assume for contradiction that $L_0$ is regular. By the Pumping Lemma it has a pumping length, $p$. Consider $\sigma = a^p b^{p+2}$. This string is a member of the language that is of length greater than or equal to $p$ so the Pumping Lemma gives a decomposition $\sigma = \alpha^\gamma \beta^\gamma \gamma$ subject to the three conditions. Condition (1) is that $|\alpha \beta| \leq p$, so these two substrings contain only $a$'s. Condition (2) is that $\beta$ is nonempty, so it consists of at least one $a$.

Consider the list $\alpha \gamma, \alpha \beta^2 \gamma, \ldots$. Its second element $\alpha \beta^2 \gamma$ has more $a$'s, but no more $b$'s, than does $\sigma = \alpha \beta \gamma$. That means $\alpha \beta^2 \gamma$ is not an element of the language $L_0$, a contradiction to the Pumping Lemma's condition (3).

(b) In prose, this language consists of $a$'s followed by $b$'s and then followed by $c$'s, with only the restriction that the number of $a$'s equals the number of $c$'s. Thus five elements of $L_1$ are: $\varepsilon$, $ac$, $b$, $aabbcc$, and $bb$. Five that are not are: $aac$, $acc$, $ab$, $bbc$, and $ca$.

Assume for contradiction that $L_1$ is regular. Then it has a pumping length $p$. Consider $\sigma = a^p c^p$. Because $\sigma \in L_1$ and $|\sigma| \geq p$, the Pumping Lemma says that it decomposes, $\sigma = \alpha^\gamma \beta^\gamma \gamma$, in a way that satisfies the three conditions. By condition (1) the first two substrings together are short, $|\alpha \beta| \leq p$. Thus these two consist entirely of $a$'s. By condition (2) the second substring $\beta$ is nonempty, so it consists of at least one $a$. Finally, condition (3) gives that the strings $\alpha \gamma, \alpha \beta^2 \gamma, \ldots$ are all members of the language $L_1$. But the string $\alpha \gamma$, when compared with $\sigma = \alpha \beta \gamma$, has at least one fewer $a$ but the same number of $c$'s. That means it does not have the same number of the two characters, so it is not a member of the language, which is a contradiction.

(c) A prose description is that in $L_2$ the strings have $a$'s followed by $b$'s, with the number of $a$'s less than the number of $b$'s. So five strings that are members of $L_2$ are $abb$, $abbb$, $ab^5$, and $a^5 b^5$. Five strings that are not elements are $\varepsilon$, $a$, $ab$, $aabb$, and $baabbb$.

For contradiction suppose that $L_2$ is regular and fix a pumping length, $p$. The string $\sigma = a^p b^{p+1}$ is an element of the language whose length is greater than or equal to the pumping length. So the Pumping Lemma gives a decomposition $\sigma = \alpha^\gamma \beta^\gamma \gamma$, subject to the three conditions. Condition (1), that $|\alpha \beta| \leq p$, says that these two substrings contain only $a$'s. Condition (2), that $\beta$ is nonempty, says that it consists of at least one $a$.

Consider the strings $\alpha \gamma, \alpha \beta^2 \gamma, \ldots$. Compared with $\sigma = \alpha \beta \gamma$, the string $\alpha \beta^2 \gamma$ has more $a$'s, but no more $b$'s. Thus the number of $a$'s is at least $p+1$ while the number of $b$'s is fixed at $p+1$. That means that $\alpha \beta^2 \gamma$ is not a member of the language $L_2$, which contradicts the Pumping Lemma's condition (3).

Verified IV.5.13 The Pumping Lemma only allows us to conclude that $\alpha \beta$ consists of $\langle$'s, not that this substring got all the $\langle$'s. The substring $\gamma$ indeed got all of the close parentheses, the $\rangle$'s, but that we know, it may have gotten some of the open parentheses as well.

IV.5.14 Yes, that is right.

IV.5.15 Let $\mathcal{L} = \{ \sigma \in \{a, b\}^* \mid \text{the number of } a\text{'s is greater than the number of } b\text{'s} \}$. Assume for contradiction that it is regular. Then the Pumping Lemma applies and this language has a pumping length, $p$. The string $\sigma = a^{p+1} b^p$ is an element of the language whose length is greater than or equal to $p$. So there is a decomposition $\sigma = \alpha \beta \gamma$ that satisfies the three conditions. Condition (i) gives that $|\alpha \beta| \leq p$ and so these two substrings contain only $a$'s. Condition (2) gives that $\beta$ is nonempty and thus it consists of at least one $a$.

The contradiction comes on considering condition (3)'s list $\alpha \gamma, \alpha \beta^2 \gamma, \ldots$. The first entry in that list, $\alpha \gamma$, when compared with $\sigma = \alpha \beta \gamma$ will have at least one a fewer, and the same number of $b$'s. It is therefore not a member of the language $\mathcal{L}$, contradicting condition (3). This contradiction shows that $\mathcal{L}$ is not regular.

IV.5.16

(A) Five strings that are members are $aaa$, $aaba$, $aaab$, and $aaaabbb$. This languages is regular, and a regular expression that describes it is $aaab\ast$.

(b) Five strings in this language are $bbb$, $abbb$, $aabb$, and $a^3 b^5$. This language is not regular.

To get a contradiction assume that it is regular. The Pumping Lemma says that the language has a pumping length, $p$. The string $\sigma = a^p b^{p+3}$ is a member of the language and has length greater than or equal to the pumping length. So it decomposes, $\sigma = \alpha \beta \gamma$, in a way that is subject to the three conditions. The first condition is that $|\alpha \beta| \leq p$ and so the two substrings $\alpha$ and $\beta$ consist only of $a$'s. The second condition
is that $|\beta| > 0$ and so the substring $\beta$ consists of at least one $a$.

Finally, consider the list $\alpha \gamma$, $\alpha \beta^2 \gamma$, . . . . Condition (3) says that any element of that list is a member of the language. However, the list's first element has fewer $a$'s than $\sigma$ but the same number of $b$'s, and therefore the number of $a$'s is not three less than the number of $b$'s. This is a contradiction.

(c) Five members of this language are $\epsilon$, abab, babbab, aaaa, and aaabaaab. It is not regular.

Suppose otherwise, that it is regular. By the Pumping Lemma the language has a pumping length, $p$. Consider $\sigma = a^p b^p - a^p b$. It is a member of the language whose length is greater than or equal to $p$ and so it has a decomposition $\sigma = \alpha \beta \gamma$ that satisfies the three conditions. The first condition, $|\alpha \beta| \leq p$, gives that the two substrings contain only $a$'s. The second condition, $|\beta| > 0$, gives that the second substring consists of at least one $a$.

Now consider the list from the third condition, $\alpha \gamma$, $\alpha \beta^2 \gamma$, . . . . Compare $\alpha \gamma$ to $\sigma = \alpha \beta \gamma$. Because the $\beta$ is omitted in $\alpha \gamma$, before its first $b$ it has fewer $a$'s than $\sigma$ has before its first $b$. But before the second $b$ the two strings have the same number of $a$'s. So $\alpha \gamma$ is not a member of the language, which contradicts the third condition.

(d) Five strings in this language are $\epsilon$, aab, b, aaaaabb, and aabbb. This language is regular. A regular expression that describes it is $a^*b^*$.

(e) Five strings in this language are $b^{13}$, $ab^{14}$, $b^{14}$, $a^2b^{15}$, and $ab^{15}$. This language is not regular.

Assume that it is regular, for contradiction. Then the language has a pumping length, $p$. Let $\sigma = a^p b^{p+13}$. By the Pumping Lemma it has a decomposition into $\sigma = \alpha \beta \gamma$ that satisfies the three conditions. As a consequence of the first condition the first two substrings consist only of $a$'s. A consequence of the second condition is that $\beta$ consists of at least one $a$.

Consider $\alpha \gamma$, $\alpha \beta^2 \gamma$, . . . . Its second element, $\alpha \beta^2 \gamma$, has at least one more $a$ than does $\sigma$. Thus its number of $a$'s is not more than 12 less than its number of $b$'s, which means that it is not a member of the language. That contradicts the Pumping Lemma's third condition.

IV.5.17 The first is not regular while the second is regular.

(a) For contradiction suppose that this language is regular. Then it has a pumping length, $p$. Consider the string $\sigma = a^p b^p$. It is a member of the language whose length is greater than or equal to $p$ so it decomposes into $\sigma = \alpha \beta \gamma$ in a way that satisfies the three conditions. Condition (1) implies that both $\alpha$ and $\beta$ consist of at least one $a$.

Now consider condition (3)'s list, $\alpha \gamma$, $\alpha \beta^2 \gamma$, . . . . Compared to $\sigma = \alpha \beta \gamma$, the entry $\alpha \gamma$ has at least one fewer $a$ but the same number of $b$'s. Therefore the number of $a$'s is not the square of the number of $b$'s, and so $\alpha \gamma$ is not in the language. That contradicts condition (3).

(b) A regular expression that describes this language is $aaa^*bbb^*$.

IV.5.18 Five strings from the language are cb, abcb, aaacbb, aaacbbbb, and aaacbbbbbb.

To show that this language is not regular, assume for contradiction that it is. Then the language has a pumping length, $p$. Consider $\sigma = a^p cb b^{p+1}$. Because this string is a member of the language and has length at least $p$, the Pumping Lemma gives that it decomposes into $\sigma = \alpha \beta \gamma$, subject to the three conditions.

The first condition, $|\alpha \beta| \leq p$, implies that the two substrings $\alpha$ and $\beta$ contain only $a$'s. The second condition, $|\beta| > 0$, implies that $\beta$ consists of at least one $a$.

Now, in the list $\alpha \gamma$, $\alpha \beta^2 \gamma$, . . . consider the first one, $\alpha \gamma$. By the prior paragraph, compared with $\sigma = \alpha \beta \gamma$ this string has at least one fewer $a$ but the same number of $b$'s. So the number of $a$'s is not one less than the number of $b$'s, and this string is not in the language, which is a contradiction to the third condition.

IV.5.19 The language is regular. It is a trick question: take $\alpha = \epsilon$ to get that the set equals $b^*$.

IV.5.20 Assume that it is regular and let the pumping length be $p$. Take $\sigma = 1^p$. This string is a member of $L$ and has length at least $p$, so the Pumping Lemma says it decomposes as $\sigma = \alpha \beta \gamma$ subject to the three conditions. The second condition implies that $|\beta| > 0$. Consider the list $\alpha \gamma$, $\alpha \beta^2 \gamma$, $\alpha \beta^3 \gamma$, . . . . After the first, the difference between the lengths of successive list elements is always $|\beta|$. But, as the hint notes, the difference between successive factorials is not fixed, instead it grows without bound. So there is a list element that is not in the language, which contradicts the third condition. So the language is not regular.

IV.5.21 The first is regular, and is described by the regular expression $\theta * 10^*$. The second is not regular. To prove that assume for contradiction that it is regular. Then it has a pumping length, $p$. Consider $\sigma = \theta^p 10^p$, which
IV.5.26 Let this language be called \( L \).

The proof of the Pumping Lemma uses the Pigeonhole Principle to show that there is at least one loop in any machine that accepts the language. So set \( p = 9 \). If \( \sigma = \text{aabbabbaba} \) then because \( |\sigma| \geq p \) and \( \sigma \in \mathcal{L} \), we know there is a decomposition satisfying the three conditions. One such is \( \alpha = \text{a}, \beta = \text{abbab}, \) and \( \gamma = \text{aba} \).

Checking that (1) \( |\alpha\beta| \leq p \), that (2) \( \beta \neq \epsilon \), and (3) the strings \( \alpha\gamma, \alpha\beta^2\gamma, \ldots \) are all members of \( \mathcal{L} \).

Consider \( \alpha = \text{a(ab)^200 aba} \) then again because \( |\sigma| \geq p \) and \( \sigma \in \mathcal{L} \), we know there is a decomposition satisfying the three conditions. One such is \( \alpha = \text{a}, \beta = \text{abb}, \) and \( \gamma = (\text{abb})^{199}\text{aba} \). Checking the three conditions is routine.

Finally, if \( \sigma = \text{aabbababaa} \) then we can take \( \alpha = \text{aab}, \beta = \text{babbab}, \) and \( \gamma = \text{a} \). Or, we could instead take \( \alpha = \text{aab}, \beta = \text{bba}, \) and \( \gamma = \text{bbaa} \). Again, checking the three conditions is routine.

IV.5.27 (a) The number of \( \gamma \)'s is the product of the number of \( \alpha \)'s and the number of \( \beta \)'s. Five such strings are \( \text{abc}, \text{abbbcc}, \text{aabcc}, \) and \( \text{aabbbccc} \).

(b) For contradiction assume that this language, \( \mathcal{L} \), is regular. The Pumping Lemma says that \( \mathcal{L} \) has a pumping length, \( p \). Consider \( \sigma = \alpha \beta^n \gamma \). That string has more than \( p \) characters so it decomposes as \( \sigma = \alpha \beta \gamma \),
subject to the three conditions. Condition (1) is that \(|\alpha \beta| \leq p\) and so both substrings \(\alpha\) and \(\beta\) are composed entirely of \(a\)'s. Condition (2) is that \(\beta\) is not the empty string and so \(\beta\) consists of at least one \(a\).

Condition (3) is that the strings in the list \(a\gamma, a\beta^2\gamma, a\beta^3\gamma, \ldots\) are also members of the language. We will get the contradiction from the first one, \(a\gamma\). Compared to \(\sigma = a\beta^r\gamma\), in the first one the \(\beta\) is gone. So the number of \(a\)'s in \(a\gamma\) is less than the number in \(\sigma = a\beta^r\gamma\), But the number of \(b\)'s and the number of \(c\)'s is the same. Thus in \(a\gamma\) the number of \(a\)'s times the number of \(b\)'s does not equal the number of \(c\)'s.

**IV.5.28** We need that \(|\alpha \beta| \leq 4\), that \(|\beta| > 0\), and that the strings \(a\gamma, a\beta^2\gamma, a\beta^3\gamma, \ldots\) are members of \(L\).

(a) \(\alpha = \epsilon, \beta = a, \) and \(\gamma = bbb\)

(b) \(\alpha = \epsilon, \beta = b, \) and \(\gamma = b^{14}\)

**IV.5.29**

(a) This works.

(b) The prior item shows that there is a Finite State machine accepting this language that has three states. So, any non-empty word of the language must cause it to repeat a state, and therefore can be pumped. The minimum length of a non-empty word of the language is 2 so the minimum pumping length is at most 2. However the language contains no word of length 1 so if \(\sigma \in L\) and \(|\sigma| \geq 1\) then automatically \(|\sigma \geq 2|\), and so \(\sigma\) can be pumped. Therefore the minimum pumping length for the language is 1.

**IV.5.30**

(a) Because it accepts the input \(\epsilon\) the initial state \(q_0\) must be an accepting state. If \(q_0\) were the only accepting state then this machine accepts \(a\) by virtue of a loop from \(q_0\) to itself, which would make the machine accept \(aa\). That is not in the language \(L\), so there must be at least one other accepting state.

(b) Because it accepts the input \(\epsilon\) the initial state \(q_0\) must be an accepting state. If \(q_0\) were the only accepting state then this machine accepts \(a\) by virtue of a loop from \(q_0\) to itself, which would make the machine accept \(aa\). That string is not a member of the language \(L_2\) so there must be at least one accepting state other than \(q_0\).

If the machine accepts \(aa\) by being in state \(q_0\) then that involves a loop, so the string \(aaa\) would also be accepted by this machine. But that string is not in the language \(L_2\), so the extended transition function on this input, \(\hat{E}(aa)\), is not equal to the state \(q_0\). Similarly, if \(\hat{E}(aa)\) were equal to \(\hat{E}(a)\) then there would be a loop from this state to itself on input \(a\), and so the machine would also accept \(aaa\). But the machine does not accept \(aaa\) because that string is not in the language \(L_2\), so there must be a third accepting state.

(c) This is the natural extension of the prior two items. Consider \(L_n = \{ \epsilon, a, \ldots, a^n \}\). If \(\hat{E}(a^n)\) were equal to \(\hat{E}(a^i)\) for any \(i < n\) then there would be a loop and so the machine would accept additional strings.

**IV.6.8** Pairs that are not 1-distinguishable are: \(q_0, q_1,\) and \(q_2, q_2,\) and \(q_1, q_2,\) so one class is \(\mathcal{E}_{i,0} = \{ q_0, q_1, q_2 \}\). Besides that, another pair of states that are not 1-distinguishable is \(q_3, q_5\) so another class is \(\mathcal{E}_{i,1} = \{ q_3, q_5 \}\). The last class is \(\mathcal{E}_{i,2} = \{ q_4 \}\).

**IV.6.9**

(a) The given classes say that we can \(i\)-distinguish \(q_0\) from \(q_2, q_3,\) and \(q_4\). So looking down the column headed by 0 we see checkmarks in rows labelled 2, 3, and 4. The other columns work the same way.
IV.6.10

(A) These are the checkmarks.

\[
\begin{array}{ccc|cc}
\checkmark q_0, q_1 & q_1, q_1 & q_2, q_3 & \checkmark, \checkmark, \checkmark & \checkmark, \checkmark, \checkmark \\
\checkmark q_0, q_2 & q_1, q_2 & q_2, q_4 & \checkmark, \checkmark, \checkmark & \checkmark, \checkmark, \checkmark \\
q_0, q_5 & q_1, q_5 & q_2, q_5 & \checkmark, \checkmark, \checkmark & \checkmark, \checkmark, \checkmark \\
q_1, q_2 & q_1, q_2 & q_3, q_4 & \checkmark, \checkmark, \checkmark & \checkmark, \checkmark, \checkmark \\
q_1, q_5 & q_1, q_5 & q_3, q_5 & \checkmark, \checkmark, \checkmark & \checkmark, \checkmark, \checkmark \\
q_2, q_5 & q_2, q_5 & q_4, q_5 & \checkmark, \checkmark, \checkmark & \checkmark, \checkmark, \checkmark \\
q_3, q_4 & q_3, q_4 & q_5, q_5 & \checkmark, \checkmark, \checkmark & \checkmark, \checkmark, \checkmark \\
\end{array}
\]

For example, the first row is checkmarked because on the right side the second entry, the b entry, has two classes that differ, \(\varepsilon_{0,0} \neq \varepsilon_{0,1}\).

(b) The checkmarks show that we can 1-distinguish \(q_0\) from \(q_1\) and \(q_2\) but not from \(q_5\). And, we can tell \(q_1\) and \(q_2\) from \(q_5\) but not from each other. The matching \(\sim_1\) classes are \(\varepsilon_{1,0} = \{q_0, q_5\}\), \(\varepsilon_{1,1} = \{q_1, q_2\}\), and \(\varepsilon_{1,2} = \{q_3, q_4\}\).

IV.6.11 First, all the states are reachable, by inspection.

Start by checkmarking the \(i, j\) entries where one of \(q_i\) and \(q_j\) is accepting while the other is not.

\[
\begin{array}{c|c|c}
0 & 1 & 1 \\
\end{array}
\]

The checkmark denote a pair of states that are 0-distinguishable and the blanks denote pairs of states that are 0-indistinguishable. Here are the two \(\sim_0\)-equivalence classes.

\(\varepsilon_{0,0} = \{q_0, q_2\}\)

\(\varepsilon_{0,1} = \{q_1\}\)

Next we see if any of these classes split.

\[
\begin{array}{c|c|c|c|c}
0 & 1 & 0 & 1 \\
q_0, q_2 & q_0, q_2 & q_1, q_1 & \checkmark, \checkmark, \checkmark \\
\end{array}
\]

The answer is that they don’t split. The process stops and here are the two \(\sim\)-equivalence classes.

\(\varepsilon_{1,0} = \{q_0, q_2\} = R_0\)

\(\varepsilon_{1,1} = \{q_1\} = R_1\)

Incorporating the arrow information from the original machine gives this minimized one.

IV.6.12

(A) These are the sets.

\[
\begin{array}{c|c}
Step n & R_n \\
0 & \{q_0\} \\
1 & \{q_0, q_1\} \\
2 & \{q_0, q_1, q_2\} \\
3 & \{q_0, q_1, q_2\} \\
\end{array}
\]

Thus the set of reachable states is \(R = \{q_0, q_1, q_2\}\). The set of unreachable states is \(Q - R = \{q_3\}\). Here is the machine with only the reachable states.
(b) These are the sets.

<table>
<thead>
<tr>
<th>Step $n$</th>
<th>$R_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>${q_0}$</td>
</tr>
<tr>
<td>1</td>
<td>${q_0, q_1, q_3}$</td>
</tr>
<tr>
<td>2</td>
<td>${q_0, q_1, q_3, q_4}$</td>
</tr>
<tr>
<td>3</td>
<td>${q_0, q_1, q_3, q_4}$</td>
</tr>
</tbody>
</table>

The set of reachable states is $R = R_2 = \{q_0, q_1, q_3, q_4\}$. The set of unreachable states is $Q - R = \{q_2, q_5\}$.

IV.6.13 For convenience, here is that machine.

Every state is reachable, by inspection.

Start by checkmarking the $i, j$ entries where one of $q_i$ and $q_j$ is accepting while the other is not.

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>0</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\checkmark$ $q_0, q_1$</td>
<td>$q_1, q_3$</td>
<td>$q_2, q_3$</td>
<td>$\varepsilon_{0,0}, \varepsilon_{0,0}$</td>
<td>$\varepsilon_{0,0}, \varepsilon_{0,1}$</td>
</tr>
<tr>
<td>$\checkmark$ $q_0, q_2$</td>
<td>$q_1, q_3$</td>
<td>$q_3, q_4$</td>
<td>$\varepsilon_{0,0}, \varepsilon_{0,1}$</td>
<td>$\varepsilon_{0,0}, \varepsilon_{0,0}$</td>
</tr>
<tr>
<td>$\checkmark$ $q_0, q_4$</td>
<td>$q_1, q_5$</td>
<td>$q_2, q_4$</td>
<td>$\varepsilon_{0,0}, \varepsilon_{0,1}$</td>
<td>$\varepsilon_{0,0}, \varepsilon_{0,0}$</td>
</tr>
<tr>
<td>$\checkmark$ $q_1, q_2$</td>
<td>$q_1, q_3$</td>
<td>$q_3, q_4$</td>
<td>$\varepsilon_{0,0}, \varepsilon_{1,0}$</td>
<td>$\varepsilon_{1,0}, \varepsilon_{0,0}$</td>
</tr>
<tr>
<td>$\checkmark$ $q_1, q_4$</td>
<td>$q_1, q_5$</td>
<td>$q_3, q_4$</td>
<td>$\varepsilon_{0,0}, \varepsilon_{0,1}$</td>
<td>$\varepsilon_{0,1}, \varepsilon_{0,0}$</td>
</tr>
<tr>
<td>$\checkmark$ $q_2, q_4$</td>
<td>$q_3, q_5$</td>
<td>$q_4, q_4$</td>
<td>$\varepsilon_{0,1}, \varepsilon_{0,1}$</td>
<td>$\varepsilon_{0,0}, \varepsilon_{0,0}$</td>
</tr>
<tr>
<td>$\checkmark$ $q_3, q_5$</td>
<td>$q_3, q_5$</td>
<td>$q_5, q_5$</td>
<td>$\varepsilon_{0,1}, \varepsilon_{0,1}$</td>
<td>$\varepsilon_{0,1}, \varepsilon_{0,1}$</td>
</tr>
</tbody>
</table>

There is a checkmark in box $i, j$ if the states $q_i$ and $q_j$ are 0-distiguishable. The blanks denote pairs that are 0-indistinguishable. There are two $\sim_0$ equivalence classes.

$\varepsilon_{0,0} = \{q_0, q_1, q_2, q_4\}$ \hspace{1cm} $\varepsilon_{0,1} = \{q_3, q_5\}$

The next step is to see if any of these classes split.

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>0</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\checkmark$ $q_2, q_4$</td>
<td>$q_3, q_5$</td>
<td>$q_4, q_4$</td>
<td>$\varepsilon_{1,3}, \varepsilon_{1,3}$</td>
<td>$\varepsilon_{1,2}, \varepsilon_{1,2}$</td>
</tr>
<tr>
<td>$\checkmark$ $q_3, q_5$</td>
<td>$q_3, q_5$</td>
<td>$q_5, q_5$</td>
<td>$\varepsilon_{1,3}, \varepsilon_{1,3}$</td>
<td>$\varepsilon_{1,3}, \varepsilon_{1,3}$</td>
</tr>
</tbody>
</table>

The only pairs of states that are 1-distiguishable are $q_2, q_4$ and $q_3, q_5$. These are the $\sim_1$ classes.

$\varepsilon_{1,0} = \{q_0, q_2\}$ \hspace{1cm} $\varepsilon_{1,1} = \{q_1\}$ \hspace{1cm} $\varepsilon_{1,2} = \{q_2, q_4\}$ \hspace{1cm} $\varepsilon_{1,3} = \{q_3, q_5\}$

Now try it again to see if any of these classes split.
The only pairs of states that are 1-distinguishable are $q_2, q_4$ and $q_3, q_5$. These are the $\sim_1$ classes.

$$\mathcal{E}_{1,0} = \{q_0, q_2\} \quad \mathcal{E}_{1,1} = \{q_1\} \quad \mathcal{E}_{1,2} = \{q_2, q_4\} \quad \mathcal{E}_{1,3} = \{q_3, q_5\}$$

There is no splitting; these are the $\sim$ classes.

$$r_0 = \mathcal{E}_{2,0} = \{q_0, q_2\} \quad r_1 = \mathcal{E}_{2,1} = \{q_1\} \quad r_2 = \mathcal{E}_{2,2} = \{q_2, q_4\} \quad r_3 = \mathcal{E}_{2,3} = \{q_3, q_5\}$$

Bringing in the transition information from the original machine gives this minimized version.

![Diagram](image)

**Verified** IV.6.14 Not a hell of a lot. You get back the original machine in that you get $r_0 = \mathcal{E}_{n,0} = \{q_0\}, r_1 = \mathcal{E}_{n,1} = \{q_1\}$, etc.

**IV.6.15** By inspection the states $q_6$ and $q_7$ are unreachable, so drop them.

With that, start by checkmarking the $i, j$ entries where one of $q_i$ and $q_j$ is accepting while the other is not.

$$
\begin{array}{ccc}
\checkmark & \checkmark & 1 \\
\checkmark & \checkmark & \checkmark & 2 \\
\checkmark & \checkmark & \checkmark & \checkmark & 3 \\
\checkmark & \checkmark & \checkmark & \checkmark & \checkmark & 4 \\
\checkmark & \checkmark & \checkmark & \checkmark & \checkmark & \checkmark & 5 \\
\end{array}
$$

The checkmarks are for pairs of states that are 0-distinguishable, and the blanks denote pairs that are 0-indistinguishable. There are two $\sim_0$-equivalence classes.

$$\mathcal{E}_{0,0} = \{q_0, q_2\} \quad \mathcal{E}_{0,1} = \{q_1, q_3, q_4, q_5\}$$

Next we see if any of these classes split.

<table>
<thead>
<tr>
<th></th>
<th>a</th>
<th>b</th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\checkmark$ q1, q3</td>
<td>44, 40</td>
<td>42, 44</td>
<td>40, 0, 0</td>
<td>0, 0, 0</td>
</tr>
<tr>
<td>$\checkmark$ q1, q4</td>
<td>44, 40</td>
<td>42, 44</td>
<td>40, 0, 0</td>
<td>0, 0, 0</td>
</tr>
<tr>
<td>$\checkmark$ q1, 5</td>
<td>44, 40</td>
<td>42, 44</td>
<td>40, 0, 0</td>
<td>0, 0, 0</td>
</tr>
<tr>
<td>$\checkmark$ q3, q4</td>
<td>40, 0, 0</td>
<td>0, 0, 0</td>
<td>0, 0, 0</td>
<td>0, 0, 0</td>
</tr>
<tr>
<td>$\checkmark$ q3, q5</td>
<td>40, 0, 0</td>
<td>0, 0, 0</td>
<td>0, 0, 0</td>
<td>0, 0, 0</td>
</tr>
<tr>
<td>$\checkmark$ q4, q5</td>
<td>40, 0, 0</td>
<td>0, 0, 0</td>
<td>0, 0, 0</td>
<td>0, 0, 0</td>
</tr>
<tr>
<td>q0, q2</td>
<td>q1, q1</td>
<td>q3, q5</td>
<td>0, 0, 0</td>
<td>0, 0, 0</td>
</tr>
</tbody>
</table>

So, $q_0$ and $q_2$ are not 1-distinguishable. On the other hand, as shown in the triangular table, $q_1$ is 1-distinguishable from $q_3$, $q_4$, and $q_5$. And, $q_3$ is 1-distinguishable from $q_4$ but not from $q_5$. Finally, $q_4$ is 1-distinguishable from $q_5$. These are the $\sim_1$ classes.

$$\mathcal{E}_{1,0} = \{q_0, q_2\} \quad \mathcal{E}_{1,1} = \{q_1\} \quad \mathcal{E}_{1,2} = \{q_3, q_5\} \quad \mathcal{E}_{1,3} = \{q_4\}$$

Determine which states are 2-distinguishable by computing whether any of those classes split.
There is no splitting so the minimal machine has four states.

\[ r_0 = \mathcal{E}_{2,0} = \{ q_0, q_2 \} \quad r_1 = \mathcal{E}_{2,1} = \{ q_1 \} \quad r_2 = \mathcal{E}_{2,2} = \{ q_3, q_5 \} \quad r_3 = \mathcal{E}_{2,3} = \{ q_4 \} \]

The transitions from the input machine give this minimized one.

**Verified** IV.6.16 The answer is “yes.” The initial state of the minimal machine, \( r_0 \), is the one that contains \( q_0 \). In the minimized machine a state is accepting if and only if it contains any final states in the original machine. So if \( q_0 \) is accepting then \( r_0 \) is also accepting.

IV.6.17 By inspection all of the states are reachable. So start by checkmarking the \( i, j \) entries where one of \( q_i \) and \( q_j \) is accepting while the other is not.

There are two \( \sim_0 \)-equivalence classes.

\[ \mathcal{E}_{0,0} = \{ q_0, q_1, q_3 \} \quad \mathcal{E}_{0,1} = \{ q_2, q_4 \} \]

Next we see if any of these classes split.

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>0</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>( q_0, q_1 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( q_0, q_3 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( q_1, q_3 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( q_2, q_4 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

So, \( q_1 \) and \( q_3 \) are not 1-distinguishable but all the others are 1-distinguishable. These are the \( \sim_1 \) classes.

\[ \mathcal{E}_{1,0} = \{ q_0 \} \quad \mathcal{E}_{1,1} = \{ q_1, q_3 \} \quad \mathcal{E}_{1,2} = \{ q_2 \} \quad \mathcal{E}_{1,3} = \{ q_4 \} \]

Step 2 is to decide of any of the \( \sim_1 \) classes split.

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>0</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>( q_1, q_3 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

So, \( q_1 \) and \( q_3 \) are 2-distinguishable. These are the \( \sim_2 \) classes.

\[ \mathcal{E}_{1,0} = \{ q_0 \} \quad \mathcal{E}_{1,1} = \{ q_1 \} \quad \mathcal{E}_{1,2} = \{ q_2 \} \quad \mathcal{E}_{1,3} = \{ q_3 \} \quad \mathcal{E}_{1,4} = \{ q_4 \} \]

The starting machine is minimal.

**Verified** IV.6.18 By eye, all of the states are reachable. So start with the triangular table, checkmarking the \( i, j \) entries where one of \( q_i \) and \( q_j \) is accepting while the other is not.
There are two \( \sim_0 \)-equivalence classes.

\[
\mathcal{E}_{0,0} = \{ q_0, q_1, q_2, q_5 \} \quad \mathcal{E}_{0,1} = \{ q_3, q_4 \}
\]

Next we see if we can 1-distinguish any of these states that cannot be 0-distinguished.

\[
\begin{array}{cccc}
\checkmark q_0, q_1 & q_1, q_2 & q_2, q_3 \quad \mathcal{E}_{0,0}, \mathcal{E}_{0,0} & \mathcal{E}_{0,0}, \mathcal{E}_{0,0} \\
\checkmark q_0, q_2 & q_1, q_2 & q_2, q_4 \quad \mathcal{E}_{0,0}, \mathcal{E}_{0,0} & \mathcal{E}_{0,0}, \mathcal{E}_{0,0} \\
q_0, q_5 & q_1, q_5 & q_2, q_5 \quad \mathcal{E}_{0,0}, \mathcal{E}_{0,0} & \mathcal{E}_{0,0}, \mathcal{E}_{0,0} \\
q_1, q_2 & q_1, q_2 & q_3, q_4 \quad \mathcal{E}_{0,0}, \mathcal{E}_{0,0} & \mathcal{E}_{0,0}, \mathcal{E}_{0,0} \\
\checkmark q_1, q_5 & q_1, q_5 & q_3, q_5 \quad \mathcal{E}_{0,0}, \mathcal{E}_{0,0} & \mathcal{E}_{0,0}, \mathcal{E}_{0,0} \\
\checkmark q_2, q_5 & q_2, q_5 & q_4, q_5 \quad \mathcal{E}_{0,0}, \mathcal{E}_{0,0} & \mathcal{E}_{0,0}, \mathcal{E}_{0,0} \\
q_3, q_4 & q_3, q_4 & q_5, q_5 \quad \mathcal{E}_{0,1}, \mathcal{E}_{1,1} & \mathcal{E}_{0,0}, \mathcal{E}_{0,0} \\
\end{array}
\]

These are the \( \sim_1 \) classes.

\[
\mathcal{E}_{1,0} = \{ q_0, q_3 \} \quad \mathcal{E}_{1,1} = \{ q_1, q_2 \} \quad \mathcal{E}_{1,2} = \{ q_3, q_4 \}
\]

Iterate. See if any of these classes split.

\[
\begin{array}{cccc}
\checkmark q_0, q_5 & q_1, q_5 & q_2, q_5 \quad \mathcal{E}_{1,1}, \mathcal{E}_{1,0} & \mathcal{E}_{1,1}, \mathcal{E}_{1,0} \\
q_1, q_2 & q_1, q_2 & q_3, q_4 \quad \mathcal{E}_{1,1}, \mathcal{E}_{1,1} & \mathcal{E}_{1,2}, \mathcal{E}_{1,2} \\
q_3, q_4 & q_3, q_4 & q_5, q_5 \quad \mathcal{E}_{1,2}, \mathcal{E}_{1,2} & \mathcal{E}_{1,0}, \mathcal{E}_{1,0} \\
\end{array}
\]

The class \( \mathcal{E}_{1,0} \) splits in two. The pairs that are not 2-distinguishable are: \( q_1, q_2 \), and \( q_3, q_4 \). These are the \( \sim_2 \) classes.

\[
\mathcal{E}_{2,0} = \{ q_0 \} \quad \mathcal{E}_{2,1} = \{ q_1, q_2 \} \quad \mathcal{E}_{2,2} = \{ q_3, q_4 \} \quad \mathcal{E}_{2,3} = \{ q_5 \}
\]

Again.

\[
\begin{array}{cccc}
q_1, q_2 & q_1, q_2 & q_3, q_4 \quad \mathcal{E}_{2,1}, \mathcal{E}_{2,1} & \mathcal{E}_{2,2}, \mathcal{E}_{2,2} \\
q_3, q_4 & q_3, q_4 & q_5, q_5 \quad \mathcal{E}_{2,2}, \mathcal{E}_{2,2} & \mathcal{E}_{2,3}, \mathcal{E}_{2,3} \\
\end{array}
\]

There is no splitting. These are the \( \sim \) classes.

\[
r_0 = \mathcal{E}_{3,0} = \{ q_0 \} \quad r_1 = \mathcal{E}_{3,1} = \{ q_1, q_2 \} \quad r_2 = \mathcal{E}_{3,2} = \{ q_3, q_4 \} \quad r_3 = \mathcal{E}_{3,3} = \{ q_5 \}
\]

Here is the minimized machine.

IV.6.19 We will go through the algorithm but before we do, observe that the answer must be that a machine with a minimal number of states and that accepts no string has one state, namely the initial state, and all arrows are loops.

By inspection all of the states are reachable. So start by checkmarking the \( i, j \) entries where one of \( q_i \) and \( q_j \) is accepting while the other is not.
There is one \( \sim_0 \)-equivalence class.

\[
\mathcal{E}_{0,0} = \{ q_0, q_1, q_2, q_3 \}
\]

Next we see if any of these classes split.

<table>
<thead>
<tr>
<th>( q_0 \rightarrow q_1 )</th>
<th>( q_1 \rightarrow q_1 )</th>
<th>( q_1 \rightarrow q_2 )</th>
<th>( q_2 \rightarrow q_2 )</th>
<th>( q_2 \rightarrow q_3 )</th>
<th>( q_3 \rightarrow q_3 )</th>
<th>( q_3 \rightarrow q_2 )</th>
<th>( q_2 \rightarrow q_2 )</th>
<th>( q_2 \rightarrow q_3 )</th>
<th>( q_3 \rightarrow q_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 0 \rightarrow 0 )</td>
<td>( 0 \rightarrow 0 )</td>
<td>( 0 \rightarrow 0 )</td>
<td>( 0 \rightarrow 0 )</td>
<td>( 0 \rightarrow 0 )</td>
<td>( 0 \rightarrow 0 )</td>
<td>( 0 \rightarrow 0 )</td>
<td>( 0 \rightarrow 0 )</td>
<td>( 0 \rightarrow 0 )</td>
<td>( 0 \rightarrow 0 )</td>
</tr>
<tr>
<td>( 1 \rightarrow 1 )</td>
<td>( 1 \rightarrow 1 )</td>
<td>( 1 \rightarrow 1 )</td>
<td>( 1 \rightarrow 1 )</td>
<td>( 1 \rightarrow 1 )</td>
<td>( 1 \rightarrow 1 )</td>
<td>( 1 \rightarrow 1 )</td>
<td>( 1 \rightarrow 1 )</td>
<td>( 1 \rightarrow 1 )</td>
<td>( 1 \rightarrow 1 )</td>
</tr>
</tbody>
</table>

Of course, if there is only one class then it cannot split, so there is only one \( \sim_1 \) class.

\[
\mathcal{E}_{0,0} = \{ q_0, q_1, q_2, q_3 \}
\]

This is the resulting minimized machine, as predicted.

If a machine has that all states are accepting then a similar thing happens. It accepts the language \( \Sigma^* \) and the minimal such machine has one state, which is both initial and accepting.

**IV.6.20** By inspection all of the states are reachable. So start by checkmarking the \( i, j \) entries where one of \( q_i \) and \( q_j \) is accepting while the other is not.

There are two \( \sim_0 \)-equivalence classes.

\[
\mathcal{E}_{0,0} = \{ q_0, q_2, q_3, q_5 \} \quad \mathcal{E}_{0,1} = \{ q_1, q_4 \}
\]

Next we see if any of these classes split.

<table>
<thead>
<tr>
<th>( q_0 \rightarrow q_2 )</th>
<th>( q_1 \rightarrow q_1 )</th>
<th>( q_1 \rightarrow q_4 )</th>
<th>( q_2 \rightarrow q_4 )</th>
<th>( q_2 \rightarrow q_3 )</th>
<th>( q_3 \rightarrow q_4 )</th>
<th>( q_3 \rightarrow q_2 )</th>
<th>( q_2 \rightarrow q_3 )</th>
<th>( q_3 \rightarrow q_2 )</th>
<th>( q_3 \rightarrow q_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a \rightarrow a )</td>
<td>( a \rightarrow a )</td>
<td>( a \rightarrow a )</td>
<td>( a \rightarrow a )</td>
<td>( a \rightarrow a )</td>
<td>( a \rightarrow a )</td>
<td>( a \rightarrow a )</td>
<td>( a \rightarrow a )</td>
<td>( a \rightarrow a )</td>
<td>( a \rightarrow a )</td>
</tr>
<tr>
<td>( b \rightarrow b )</td>
<td>( b \rightarrow b )</td>
<td>( b \rightarrow b )</td>
<td>( b \rightarrow b )</td>
<td>( b \rightarrow b )</td>
<td>( b \rightarrow b )</td>
<td>( b \rightarrow b )</td>
<td>( b \rightarrow b )</td>
<td>( b \rightarrow b )</td>
<td>( b \rightarrow b )</td>
</tr>
</tbody>
</table>

So, \( q_2 \) and \( q_5 \) are not 1-distinguishable but all the other pairs are 1-distinguishable. These are the \( \sim_1 \) classes.

\[
\mathcal{E}_{1,0} = \{ q_0 \} \quad \mathcal{E}_{1,1} = \{ q_1 \} \quad \mathcal{E}_{1,2} = \{ q_2, q_3 \} \quad \mathcal{E}_{1,3} = \{ q_3 \} \quad \mathcal{E}_{1,4} = \{ q_4 \}
\]

Finally we see if the one remaining multi-state classes splits.

<table>
<thead>
<tr>
<th>( q_2 \rightarrow q_5 )</th>
<th>( q_1 \rightarrow q_4 )</th>
<th>( q_4 \rightarrow q_1 )</th>
<th>( q_1 \rightarrow q_4 )</th>
<th>( q_4 \rightarrow q_1 )</th>
<th>( q_1 \rightarrow q_4 )</th>
<th>( q_4 \rightarrow q_1 )</th>
<th>( q_1 \rightarrow q_4 )</th>
<th>( q_4 \rightarrow q_1 )</th>
<th>( q_1 \rightarrow q_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a \rightarrow a )</td>
<td>( a \rightarrow a )</td>
<td>( a \rightarrow a )</td>
<td>( a \rightarrow a )</td>
<td>( a \rightarrow a )</td>
<td>( a \rightarrow a )</td>
<td>( a \rightarrow a )</td>
<td>( a \rightarrow a )</td>
<td>( a \rightarrow a )</td>
<td>( a \rightarrow a )</td>
</tr>
<tr>
<td>( b \rightarrow b )</td>
<td>( b \rightarrow b )</td>
<td>( b \rightarrow b )</td>
<td>( b \rightarrow b )</td>
<td>( b \rightarrow b )</td>
<td>( b \rightarrow b )</td>
<td>( b \rightarrow b )</td>
<td>( b \rightarrow b )</td>
<td>( b \rightarrow b )</td>
<td>( b \rightarrow b )</td>
</tr>
</tbody>
</table>
Thus all of the states are not 2-distinguishable. These are the \( \sim_2 \) classes.

\[
\mathcal{E}_{2,0} = \{ q_0 \} \quad \mathcal{E}_{2,1} = \{ q_1 \} \quad \mathcal{E}_{2,2} = \{ q_2 \} \quad \mathcal{E}_{2,3} = \{ q_3 \} \quad \mathcal{E}_{2,4} = \{ q_4 \} \quad \mathcal{E}_{2,5} = \{ q_5 \}
\]

The original machine is minimal.

**IV.6.21** You will get a machine that accepts the same language. The reachable states of this machine will form a minimal set. But there will still be unreachable states (although perhaps fewer of them.)

**IV.6.22** By inspection all of the states are reachable. So start by checkmarking the \( i, j \) entries where one of \( q_i \) and \( q_j \) is accepting while the other is not.

There are two \( \sim_0 \)-equivalence classes.

\[
\mathcal{E}_{0,0} = \{ 0, 1, 2, 3 \} \quad \mathcal{E}_{0,1} = \{ 4 \}
\]

Next we see if any of these classes split.

So, \( q_3 \) is 1-distinguishable from all the other states, but no other pairs are 1-distinguishable. These are the \( \sim_1 \) classes.

\[
\mathcal{E}_{1,0} = \{ q_0, q_1, q_2 \} \quad \mathcal{E}_{1,1} = \{ q_3 \} \quad \mathcal{E}_{1,2} = \{ q_4 \}
\]

Next time through.

So, \( q_2 \) is 2-distinguishable from \( q_0 \) and \( q_1 \), giving these \( \sim_2 \) classes.

\[
\mathcal{E}_{2,0} = \{ q_0, q_1 \} \quad \mathcal{E}_{2,1} = \{ q_2 \} \quad \mathcal{E}_{2,2} = \{ q_3 \} \quad \mathcal{E}_{2,3} = \{ q_4 \}
\]

Once more through.

So, \( q_1 \) is 3-distinguishable from \( q_0 \) and these are the giving these \( \sim_3 \) classes.

\[
\mathcal{E}_{3,0} = \{ q_0 \} \quad \mathcal{E}_{3,1} = \{ q_1 \} \quad \mathcal{E}_{3,2} = \{ q_2 \} \quad \mathcal{E}_{3,3} = \{ q_3 \} \quad \mathcal{E}_{3,4} = \{ q_4 \}
\]

No additional splitting happens on the next iteration; indeed, there is nothing left to split. The process stops. The minimized machine has five states; it is the machine we started with.

**IV.6.23**
(A) We must show that it is reflexive, symmetric, and transitive. Fix some \( n \). Obviously any state is \( n \)-indistinguishable from itself, for any \( n \). Symmetry is also clear. So suppose \( q_0 \sim_n q_1 \) and \( q_1 \sim_n q_2 \). Let \( \sigma \) be a string of length less than or equal to \( n \). If \( \sigma \) takes the machine from \( q_0 \) to an accepting state then because of \( q_0 \sim_n q_1 \) it also takes the machine from \( q_1 \) to an accepting state. Because of \( q_1 \sim_n q_2 \) it also takes the machine from \( q_2 \) to an accepting state. The same holds for non-accepting states.

(b) It is an equivalence because it is \( \sim_k \) for some \( k \).

IV.6.24

(A) By inspection all of the states are reachable. So start by checkmarking the \( i, j \) entries where one of \( q_i \) and \( q_j \) is accepting while the other is not.

There are two \( \sim_0 \)-equivalence classes.

\[ E_{0,0} = \{ q_0, q_2 \} \quad E_{0,1} = \{ q_1 \} \]

Next we see if any of these classes split.

So the class \( E_{0,0} \) does not split. These are the \( \sim_1 \) classes.

\[ r_0 = E_{0,0} = \{ q_0, q_2 \} \quad r_1 = E_{0,1} = \{ q_1 \} \]

Here is the minimized machine.

(b) Here is the machine with the arrows reversed, the nodes renamed, and the start node made final, and the final one made a start.

(c) This is the table to convert that nondeterministic Finite State machine to a deterministic one.

<table>
<thead>
<tr>
<th>Node name</th>
<th>Set of nodes</th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>( u_0 )</td>
<td>( \emptyset )</td>
<td>( u_0 )</td>
<td>( u_0 )</td>
</tr>
<tr>
<td>( + \ u_1 )</td>
<td>( { t_0 } )</td>
<td>( u_0 )</td>
<td>( u_0 )</td>
</tr>
<tr>
<td>( u_2 )</td>
<td>( { t_1 } )</td>
<td>( u_7 )</td>
<td>( u_2 )</td>
</tr>
<tr>
<td>( u_3 )</td>
<td>( { t_2 } )</td>
<td>( u_0 )</td>
<td>( u_1 )</td>
</tr>
<tr>
<td>( + \ u_4 )</td>
<td>( { t_0, t_1 } )</td>
<td>( u_7 )</td>
<td>( u_2 )</td>
</tr>
<tr>
<td>( + \ u_5 )</td>
<td>( { t_0, t_2 } )</td>
<td>( u_0 )</td>
<td>( u_3 )</td>
</tr>
<tr>
<td>( u_6 )</td>
<td>( { t_1, t_2 } )</td>
<td>( u_7 )</td>
<td>( u_7 )</td>
</tr>
<tr>
<td>( + \ u_7 )</td>
<td>( { t_0, t_1, t_2 } )</td>
<td>( u_7 )</td>
<td>( u_7 )</td>
</tr>
</tbody>
</table>

Here is the arrow diagram.
The only reachable states are $u_2$ and $u_7$.

(d) Here is the picture.

(e) Convert that nondeterministic Finite State machine to a deterministic one.

<table>
<thead>
<tr>
<th>Node name</th>
<th>Set of nodes</th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w_0$</td>
<td>$\emptyset$</td>
<td>$w_0$</td>
<td>$w_0$</td>
</tr>
<tr>
<td>$+ w_1$</td>
<td>${v_2}$</td>
<td>$w_0$</td>
<td>$w_1$</td>
</tr>
<tr>
<td>$w_2$</td>
<td>${v_7}$</td>
<td>$w_3$</td>
<td>$w_2$</td>
</tr>
<tr>
<td>$+ w_3$</td>
<td>${v_2, v_7}$</td>
<td>$w_3$</td>
<td>$w_3$</td>
</tr>
</tbody>
</table>

Here is the arrow diagram.

Once we omit unreachable states, this machine is the same (except for state renaming) as the one in the first item.

IV.6.25 The machine of Exercise 6.22

has five states and is minimal for the language described by $b^*ab^*ab^*a(a|b)^*$. Using induction to generalize this observation is straightforward.

IV.7.8 This is a regular language so you don't need the stack.

IV.7.12 It is the language of even-length palindromes, $\{\tau \tau^R | \tau \in B^* \}$. 

IV.7.13

$X \rightarrow aXc | b$

IV.7.14

$T \rightarrow aTa | bTb | b$

IV.7.16

$S \rightarrow aS a | bS b | cTc | a | b | c | \varepsilon$

$T \rightarrow aTa | bTb | a | b | c | \varepsilon$

IV.7.18 One direction is that if a string $\sigma \in B^*$ is generated by the grammar then it is a palindrome $\sigma = \sigma^R$. We do induction on the grammar's structure. The basis step is that the string is either empty $\sigma = \varepsilon$, or of
length one \( \sigma = 0 \) or \( \sigma = 1 \). All three cases are evidently palindromes. For the inductive step we assume the length of the string \(|\sigma|\) is greater than one and that the statement is true for all shorter strings, all \( \tau \in \mathbb{B}^* \) with \(|\tau| < |\sigma|\). In the case that \( \sigma = \emptyset \), the string \( \sigma \) is a palindrome by the inductive hypothesis that \( \tau \) is a palindrome. The case that \( \sigma = 1 \) \( \tau \) is similar.

The other direction is that if the string is a palindrome \( \sigma = \sigma^R \) then it is generated by the grammar. We can use induction on the length \(|\sigma|\). If the length of \( \sigma \in \mathbb{B}^* \) is 0 then the string is empty, \( \sigma = \varepsilon \). In this case it is a palindrome and is also derived from the grammar since \( P \rightarrow \varepsilon \) is one of the listed production rules. If the length of \( \sigma \) is 1 then either \( \sigma = 0 \) or \( \sigma = 1 \), and these two are both palindromes and also derived from the grammar. Finally, assume that \(|\sigma| > 1 \) and that the statement is true for all strings \( \tau \in \mathbb{B}^* \) of length less than \( \sigma \). There are two cases. If \( \sigma \)'s first character is \( 0 \) then because \( \sigma \) is a palindrome it has the form \( \sigma = 0\tau 0 \), where \( \tau \) is a palindrome. The induction hypothesis applies to give that \( \tau \) is derived from the grammar. But then so is \( \sigma \), using the production \( P \rightarrow 0P0 \). The case that \( \sigma \)'s first character is \( 1 \) works the same way.

**IV.A.20**

(a) \( .*abc.* \)
(b) \( .*abc+.\) *
(c) \( .*abc2.* \)
(d) \( .*abc2,5.* \)
(e) \( .*abc2,. \)
(f) \( .*a(b|c).\) * or \( .*a[bc].\)

**IV.A.21**

(a) \( .*abe.* \) Note that in practice you often can just write \( abe \); see your language’s regular expression documentation.
(b) \( [a-zA-Z0-9]* \)
(c) \[ \]

**IV.A.22**

(a) \( (a|e|i|o|u).*bc.* \)
(b) \( (a|e|i|o|u)(bc|.*bc).\)
(c) \( .*a.*e.*i.*o.*u.* \)
(d) \( (.a.*e.*i.*o.*u.*|.*a.*e.*i.*o.*u.*|.*a.*e.*i.*o.*u.*|.*a.*e.*i.*o.*u.*) \)

There are \( 5! = 120 \) clauses.

You might use a program to write this regex.

**IV.A.23**

\( .*[\[\].]* \)

**IV.A.24**

\( \backslash d[10] \)

**IV.A.25**

(a) \( (\backslash d(3)\|\backslash(\backslash d(3))\) \backslash d(3)\|\backslash d(4) \)
(b) We must factor out the space as well as the area code: \( (\backslash d(3) \| (\backslash d(3)) )?\backslash d(3)\|\backslash d(4). \)

**IV.A.27 \**

\( \backslash d(2):\backslash d(2):\backslash d(2):(\backslash d(+)\|\backslash d(2):(\backslash d(2))? \)

**IV.A.28** One is \([-+]?(\backslash d)+\?\|\backslash d)*\|\backslash d+ \)

**IV.A.29**

(a) \( 4(\backslash d15\|\backslash d12) \)
(b) \( (5[1-5]\|\backslash d2[22][1-9]\|22[3-9]\|\backslash d2[3-6]\|\backslash d2[2701]\|\backslash d2[2720])\|\backslash d12 \)
(c) \( 3[47][0-9]13 \)

**IV.A.30**

(a) We can do the six as alternatives.

\( [A-Z]\|\backslash d2 \|\backslash d[A-Z]2\|\backslash d[A-Z]\|\backslash d[A-Z][A-Z]\|\backslash d[A-Z]2\|\backslash d[A-Z][A-Z]\|\backslash d[A-Z]2\|\backslash d[A-Z]2\|\backslash d[A-Z][A-Z]\) \backslash d[A-Z]2 \)

(b) We can factor out the ending of \( [A-Z]2 \).

\( [A-Z]\|\backslash d2\|\backslash d[A-Z]\|\backslash d[A-Z][A-Z]\|\backslash d[A-Z]2\|\backslash d[A-Z][A-Z]\|\backslash d[A-Z]2\|\backslash d[A-Z][A-Z]\) \backslash d[A-Z]2 \)

**Verified IV.A.31** A suitable regex is textasciicircum g.n.{3}i.$ and a match is 'gynaecia', meaning the aggregate of carpels or pistils in a flower.
IV.A.32 Factoring out the whitespace would mean that times without an or pm must have a trailing whitespace.

IV.A.33 This tries to match a character after the end of the string: $. (In practice, in a regular expression multiline mode the dollar sign matches a newline character and so this can match. But that lies outside our scope.)

IV.A.34 \^[M0,4(CM|CD|D?C0,3)(XC|XL|L?X0,3)(IX|IV|V?I0,3)$

IV.A.35 Assume it is a regular language and let its pumping length be $p$. Consider $\sigma = a^p b a^p b$ It is an element of $L$ whose length is greater than $p$ so By the Pumping Lemma it decomposes as $\sigma = \alpha \beta \gamma$ subject to the three conditions. By the first condition the length of $\alpha \beta$ is less than $p$, and so these two substrings consist solely of $a$'s. The second condition is that $\beta$ is not the empty string. The third condition says that the strings $\alpha \gamma$, $\alpha \beta^2 \gamma$, ... are all members of $L$. Note that the first is not a square because in omitting $\beta$ it omits at least one a from the prefix but not from the suffix. That's a contradiction.

IV.A.36

(a) We take the alphabet to be $\Sigma = \mathbb{B}$. Assume that it is regular and let its pumping length be $p$. Consider $\sigma = \theta^p \theta^p$, which is a member of the language. By the Pumping Lemma it therefore decomposes into $\sigma = \alpha \beta \gamma$ subject to the three conditions. By the first and second conditions $\alpha \beta$ consists solely of $\theta$'s, and is therefore part of the prefix before the 1, and $\beta$ is nonempty. By the third condition the string $\alpha \gamma$ is also a member of $L$. But this is a contradiction because the omission of $\beta$ means that $\alpha \gamma$ has fewer $\theta$'s before the 1 than after.

(b) $(a*)b\1$

IV.A.37

(a) .*$r$

(b) .*$t.*$t.*$

(c) .*$foo.*$

IV.A

(A) HELP

(B) "(A|B)<(C|\1)($AB|OE|SK)"

IV.B.15 If $k \neq n$ then $a^k b^k \in L$ but $a^m b^k \notin L$, so there are infinitely many classes.
Chapter V: Computational Complexity

**V.1.27** True. Remember that Big $O$ means something like “grows at a rate less than or equal to.” Growing at a rate less than or equal to $n^2$ implies growing at a rate less than or equal to $n^3$.

**V.1.28** First, the assertion, “I have an algorithm with running time $O(x^2)$” does not mean the time is quadratic, since if $f(x) = x$ then $f$ is $O(n^2)$.

Also, even if the running time is quadratic, it may involve constants and lower order terms. Thus, $1000 \cdot x^2$ is $O(n^2)$, as is $x^2 + 3x + 42$. All of the things that impact performance on a particular platform are not part of the algorithm analysis, which only applies to a computing model.

(Another issue is that the the runtime behavior is quadratic only for sufficiently large inputs. So unless you know that 5 is greater than the $N$ of the definition, there is no reason to think quadratic at all.)

**V.1.29** No doubt they mean that for their problem they have an algorithm that is $O(n^3)$.

**V.1.30**

(a) Because 5 in binary is 101, it takes three bits.
(b) The number 50 in binary is 110010, so it takes six bits.
(c) In binary the number 500 is 1 1111 0100, so it take nine bits.
(d) The binary equivalent of 5 000 is 1 0011 1000 1000, which is thirteen bits.

This table verifies these using the formula bits$(n) = 1 + \lfloor \lg(n) \rfloor$.

<table>
<thead>
<tr>
<th>integer $n$</th>
<th>5</th>
<th>50</th>
<th>500</th>
<th>5 000</th>
</tr>
</thead>
<tbody>
<tr>
<td>binary</td>
<td>101</td>
<td>11010</td>
<td>1 1111 0100</td>
<td>1 0011 1000 1000</td>
</tr>
<tr>
<td>$\lg(n)$</td>
<td>2.322</td>
<td>5.644</td>
<td>8.966</td>
<td>12.288</td>
</tr>
<tr>
<td>$1 + \lg(n)$</td>
<td>3</td>
<td>6</td>
<td>9</td>
<td>13</td>
</tr>
</tbody>
</table>

**V.1.31** The second is true, the first is not.
Recall the intuition that ‘$f$ is $O(g)$’ means something like “$f$’s growth rate is less than or equal to $g$’s,” while ‘$f$ is $\Theta(g)$’ means something like “$f$’s growth rate is roughly the same as $g$’s.” With this in mind, the second one makes sense since if $f$ and $g$ grow at roughly the same rate then that certainly implies $f$’s that rate is less than or equal to $g$’s. More precisely, by definition, if $f$ is $\Theta(g)$ then both $f$ is $O(g)$ and $g$ is $O(f)$.

Again with the intuition in mind, assuming that $f$’s growth is less than or equal to $g$’s does not give that the two rates are equal. That is, there are functions $f$, $g$ so that $f$ is $O(g)$ but $f$ is not $\Theta(g)$. One such pair is $f(n) = n$ and $g(n) = n^2$.

**V.1.32** We use the principles for simplifying Big $O$ expressions from page 254.

(a) $O(n^2)$
(b) $O(2^n)$
(c) $O(n^4)$
(d) $O(\lg n)$

**V.1.33**

(a) For sufficiently large input arguments $n$, this function is $f(n) = 0$. So it is $O(1)$.
(b) For sufficiently large arguments $n$, this function is $f(n) = n^2$. So it is $O(n^2)$.
(c) For sufficiently large $n$, this function is $f(n) = \lg(n)$. So it is $O(\lg(n))$.

**V.1.34** We follow the principles for simplifying Big $O$ expressions, and use ?? 1.24.

(a) Both of these are $O(n^2)$. So both $f$ is $O(g)$ and also $g$ is $O(f)$, that is, $f$ is $\Theta(g)$.
(b) Here, $g$ is a logarithmic function and $f$ is a cubic, so $g$ is $O(f)$ but it is not the case that $f$ is $O(g)$.
(c) The function $f$ is quadratic, while $g$ is a square root, so $g$ is $O(f)$ but $f$ is not $O(g)$.
(d) The function \( f \) is \( \Theta(n^{1.2}) \) while the function \( g \) is \( \Theta(n^{\sqrt{2}}) \), which is approximately \( \Theta(n^{1.414}) \). Consequently, \( f \) is \( \Theta(g) \) but \( g \) is not \( \Theta(f) \).

(e) The exponential function \( 2^{11/6}n \) grows faster than the polynomial function \( n^6 \). So \( f \) is \( \Theta(g) \) but it is not the case the \( g \) is \( \Theta(f) \).

(f) As is shown in ?? 1.24, the function \( 2^n \) is \( \Theta(3^n) \), while \( 3^n \) is not \( \Theta(2^n) \). Thus, \( g \) is \( \Theta(f) \) but \( f \) is not \( \Theta(g) \).

(g) Recall the logarithm rule that \( \lg(3n) = \lg(3) + \lg(n) \). From this it follows that the two have equivalent growth rates, so \( f \) is \( \Theta(g) \).

V.1.35 Observe that \( \cos(t) \) varies between \(-1 \) and \( 1 \). Observe also that by the rules of logarithms \( \lg(5^n) = n \cdot \lg(5) \).

Thus, the ones with a growth rate that is less than or equal to \( n^3 \)'s are the first, second, fourth, and fifth. The third one has a growth rate that is \( \Theta(n^3) \).

V.1.36

(a) True. By the simplifying principles from page 254, its growth rate is dominated by the quadratic term, so \( 5n^2 + 2n \) is \( \Theta(n^2) \), which on the Hardy hierarchy lies below \( n^3 \).

(b) True. As discussed in the section, all logarithmic functions grow at the same rate. So \( \ln n \) is \( \Theta(\lg n) \), and hence \( \ln n \) is \( \Theta(\lg n) \).

(c) True. Where \( f(n) = n^3 + n^2 + n \), by the simplifying principles from page 254, \( f \) is \( \Theta(n^3) \).

(d) True. For any polynomial function \( p \), we have that \( p \) is \( \Theta(2^n) \), by Lemma 1.22.

V.1.37 For each we use the simplifying principles.

(a) \( k = 4 \)

(b) \( k = 4 \)

(c) \( k = 3 \) (The cosine function is bounded between \(-1 \) and \( 1 \).)

(d) \( k = 12 \)

(e) This is \( \Theta(n^{7/2}) \) but since the question specifies that \( k \in \mathbb{N} \), the answer is \( k = 4 \).

Verified V.1.38

<table>
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<th>( n )</th>
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<td>(1.05 \times 10^{-14})</td>
<td>(1.05 \times 10^{-13})</td>
</tr>
</tbody>
</table>

Verified V.1.39 The number of seconds in a year is \( 60 \cdot 60 \cdot 24 \cdot 365.25 = 31,557,600 \). At 10,000 ticks per second, that is about \( 3.16 \times 10^{11} \) ticks in a year (as also described in ?? 1.25). (a) With \( \lg(n) = 3.16 \times 10^{11} \), we have \( n = 2^{3.16 \times 10^{11}} = 4.53 \times 10^{94,997,841,911} \).

(b) \( 3.16 \times 10^{11} \)^2 = \( 9.69 \times 10^{22} \)

(c) \( 3.16 \times 10^{11} \)

(d) Because \( 3.16 \times 10^{11} \)^{1/2} \approx 561,761.52 \), the answer is 561,761.

(e) Because \( 3.16 \times 10^{11} \)^{1/3} \approx 6,808.24 \), the answer is 6,808.

(f) We have \( \lg(3.16 \times 10^{11}) \approx 38.20 \) so the answer is 38.

Verified V.1.40 Solving \( 100,000 \cdot n^2 = n \), gives \( n = 100,000 \). So the first number \( n \) where \( f(n) = 100 \cdot n^2 \) is less than \( g(n) = n^3 \) is \( n = 100,001 \).

Verified V.1.41 Linear. Finite State machines consume one character at each step. So they run in time equal to the length of the input. In the notation of Definition 1.26, \( t_M(\sigma) = |\sigma| \).
Verified V.1.42 Let \( g \) be the function \( g(x) = 1 \).

(a) Directly apply the definition of Big \( O \), Definition 1.6, by taking \( N = 1 \) and \( C = 8 \). If \( x > N = 1 \) then
\[
C \cdot g(x) = 8 \cdot 1 \geq f(x) = 7.
\]

(b) Recall that \( \sin(x) \) is bounded between \(-1\) and \(1\). Take \( N = 1 \) and \( C = 9 \). If \( x > N \) then \( C \cdot g(x) = 9 \geq 7 + \sin(x) = f(x) \).

(c) Fix \( N = 1 \) and \( C = 8 \). If \( x \geq N = 1 \) then \( C \cdot g(x) = 2 \) is greater than \( f(x) = 7 + (1/x) \).

(d) We first show that if it is bounded then it is \( O(1) \). Suppose that \( f \) is bounded by \( K \in \mathbb{R}^+ \). Take \( N = 1 \) and \( C = K \). If \( x \geq N = 1 \) then \( C \cdot g(x) = K \geq f(x) \), so \( f \) is \( O(g) \).

For the converse, suppose that \( f \) is \( O(g) \). Then there exists constants \( N, C \in \mathbb{R}^+ \) so that \( x \geq N \) implies that \( C \cdot g(x) = C \geq f(x) \). Let \( K = \max(C, f(0), \ldots, f(N - 1)) \). If \( x \in \mathbb{R} \) then \( f(x) \leq K \), so \( f \) is bounded by \( K \).

Verified V.1.43 A function \( f : \mathbb{R} \to \mathbb{R} \) is \( O(1) \) if it is bounded by a constant. So \( g(x) \leq x^{O(1)} \) says that the function \( g \) has at most a polynomial growth rate.

Verified V.1.44 The first half, that \( f \) is \( O(g) \), is straightforward. Fix \( N = 1 \) and \( C = 2 \). If \( x \geq N = 1 \) then
\[
C \cdot g(x) = 2x^2 \geq 2x = f(x) \text{ (because } 2x^2 - 2x = 0 \text{ gives } 2 \cdot (x(x - 1)) = 0 \text{ and so the largest } x \text{ for which they are equal is } x = 1).
\]

For the second half, that \( g \) is not \( O(f) \), we will show that for every \( C \) there is no \( N \) that will work. So fix a \( C \), aiming to prove that for any \( N \) it is not the case that \( x \geq N \) implies that \( C \cdot f(x) \geq g(x) \). For any \( N \), consider \( x = \max(N, C + 1) \), which is greater than or equal to \( N \). Because \( x > C \), we have that \( g(x) = x^2 > C \cdot x = C \cdot f(x) \).

Verified V.1.45 Let \( N = 4 \) and \( C = 1 \). If \( n \geq N = 4 \) then \( C \cdot n! = n! = 4! \cdot 5 \cdot 6 \cdot \ldots \cdot (n - 1) \cdot n \geq 2^4 \cdot 2^{n-4} = 2^n \) (note that \( 4! = 24 > 2^4 = 16 \)).

Verified V.1.46 (a) This limit equals 0
\[
\lim_{x \to \infty} \frac{(\log_b(x))^2}{x^d} = \frac{2 \log_b(x) \cdot \frac{1}{x \ln(b)}}{dx^{d-1}} = \frac{2}{d \ln(b)} \cdot \lim_{x \to \infty} \frac{\log_b(x)}{x^d}
\]
by the calculation in Example 1.20.

(b) This limit equals 0
\[
\lim_{x \to \infty} \frac{(\log_b(x))^3}{x^d} = \frac{3(\log_b(x))^2 \cdot \frac{1}{x \ln(b)}}{dx^{d-1}} = \frac{3}{d \ln(b)} \cdot \lim_{x \to \infty} \frac{(\log_b(x))^2}{x^d}
\]
by the calculation in the prior item.

(c) The prior item suggests an argument by induction. So assume that the statement holds for the powers \( n = 1, n = 2, \ldots, n = k \) and consider the \( n = k + 1 \) case.
\[
\lim_{x \to \infty} \frac{(\log_b(x))^{k+1}}{x^d} = \lim_{x \to \infty} \frac{(k + 1)(\log_b(x))^k \cdot \frac{1}{x \ln(b)}}{dx^{d-1}} = \frac{k + 1}{d \ln(b)} \cdot \lim_{x \to \infty} \frac{(\log_b(x))^k}{x^d}
\]
Finish by applying the \( n = k \) inductive hypothesis.

Verified V.1.47 The empty Turing machine ignores its input and halts immediately. So \( t_M(n) = 0 \).

Verified V.1.48 Fix \( N = 1 \) and find \( C \in \mathbb{R} \) large enough that \( C \cdot g(1) \geq f(1) \). Because \( g \) is increasing, if \( x > N = 1 \) then \( C \cdot g(x) \geq C \cdot g(1) \geq f(1) = f(x) \).

Verified V.1.49 (a) The function \( f_0(x) = 0 \) is clearly computable and has output values that grow at a rate that is \( O(1) \). Similarly, the output values of \( f_1(x) = x \) grow at a rate that is \( O() \), and \( f_2(x) = x^2 \) is \( O(x^2) \), etc.

(b) The function
\[
K(x) = \begin{cases} 
0 & \text{if } \phi(x) \uparrow \\
1 & \text{if } \phi(x) \downarrow 
\end{cases}
\]
is clearly \( O(1) \).
(c) Let $M(n)$ be the maximum value of $\phi_i(j)$ where $0 \leq i, j \leq n$ and $\phi_i(j) \downarrow$ (if there is no such maximum because none of the $\phi_i(j)$ converge then define $M(n) = 0$). This is not a computable function, but it is a function. Then the function $\hat{M}(n) = M(n) + 1$ has the property that for any computable function $\phi_e$, for all $n > e$ if $\phi_e(n) \downarrow$ then $\hat{M}(n) > \phi_e(n)$.

**Verified V.1.50** Consider the number $n \in \mathbb{N}$. The hint says that we can check whether a number divides $n$ in quadratic time. Wrapping a loop around that to do all numbers $m$ with $2 < m < n$ adds one to the exponent. So the naive algorithm is $O(n^3)$ in the value of $n$.

However, in terms of bits, the number $n$ is represented by about $\log(n)$-many bits. That is, this expresses the runtime as a function of the size of the input.

runtime $= n^3 = (2^{\text{size}})^3 = 2^3 \cdot \text{size}$

So the relationship between the size of the input and the runtime is exponential.

**Verified V.1.51** Use Theorem 1.17.

$$\lim_{x \to \infty} \frac{2^x}{3^x} = \lim_{x \to \infty} \left(\frac{2}{3}\right)^x = 0$$

**Verified V.1.52**

(A) With an eye toward Theorem 1.17, consider the ratio.

$$\frac{n!}{n^n} = \frac{1 \cdot 2 \cdots n}{n \cdot n \cdots n} \leq \frac{1}{n} \cdot 1 \cdots 1$$

Clearly the limit of the ratio $n!/n^n$ is 0.

(b) No, don’t overlook the $e^{-n}$.

**Verified V.1.53**

(A) Apply L'Hôpital's Rule twice.

$$\lim_{x \to \infty} \frac{x^2 + 5x + 1}{x^2} = \lim_{x \to \infty} \frac{2x + 5}{2x} = \lim_{x \to \infty} \frac{2}{2} = 1$$

(b) Apply L'Hôpital's Rule, remembering to use the Chain Rule for the numerator.

$$\lim_{x \to \infty} \frac{\log(x + 1)}{\log(x)} = \lim_{x \to \infty} \frac{(1/x \log(2)) \cdot 1}{1/x \log(2)} = 1$$

**Verified V.1.54** No. If $O(f)$ is the set of polynomials then $f$ must be a polynomial. However, then $f$ has some degree, and no polynomial of higher degree is a member of $O(f)$.

**Verified V.1.55** Recall the logarithm rules that $\log_b(x^a) = a \cdot \log_b(x)$ and $b^{\log_b(x)} = x$.

(A) L'Hôpital's Rule gives

$$\lim_{x \to \infty} \frac{\log(x)}{(\log(x))^2} = \lim_{x \to \infty} \frac{1/x \log(2)}{2 \log(x) \cdot 1/x \log(2)} = \lim_{x \to \infty} \frac{1}{2 \log(x)} = 0$$

and so Theorem 1.17 gives the required conclusion.

(B) By Theorem 1.17, it suffices to show that this is 0.

$$\lim_{x \to \infty} \frac{x^k}{x^{\log(x)}} = \lim_{x \to \infty} x^{k-\log(x)}$$

Rewrite.

$$x^{k-\log(x)} = 2^{\log(x)^{k-\log(x)}} = 2^{k \log(x)-\log(x) \log(x)} = 2^{k \log(x)-\log(x)^2}$$

Apply the prior item to conclude that the limit of the exponent is $-\infty$, and so the limit of the entire expression is 0.
(c) Taking \( \lg \) of \( x^{\lg(x)} \) gives \( \lg(x^{\lg(x)}) = \lg(x) \cdot \lg(x) \). Taking \( \lg \) of the other expression gives \( \lg(2^{(\lg(x))^2}) = (\lg(x))^2 \cdot \lg(2) \). Since the logarithm and exponential are inverse functions, that is \((\lg(x))^2\).

(d) Rewrite \( x^{\lg(x)} \) as \( 2^{(\lg(x))^2} \). Theorem 1.17

\[
\lim_{x \to \infty} \frac{2^{(\lg(x))^2}}{2^x} = \lim_{x \to \infty} 2^{(\lg(x))^2 - x} = 0
\]
gives the desired conclusion.

Verified V.1.56 We will use the notation from the lemma statement.

(a) The assumption is that \( f \) is \( \mathcal{O}(g) \). So there are constants \( N, C \in \mathbb{R}^+ \) such that \( x \geq N \) implies that \( C \cdot g(x) \geq f(x) \). For the function \( a \cdot f \), use the constants \( \hat{N} = N \) and \( \hat{C} = a \cdot C \). Then \( x \geq \hat{C} \) implies that \( \hat{C} \cdot g(x) \geq f(x) \).

(b) The function \( f_0 \) is \( \mathcal{O}(g_0) \) and the function \( f_1 \) is \( \mathcal{O}(g_1) \). So there are constants \( N_0, C_0, N_1, C_1 \in \mathbb{R}^+ \) such that \( x \geq N_0 \) implies that \( C_0 g_0(x) \geq f_0(x) \), and \( x \geq N_1 \) implies that \( C_1 g_1(x) \geq f_1(x) \). Take \( \hat{N} = \max(N_0, N_1) \) and \( \hat{C} = \max(C_0, C_1) \). Then \( x \geq \hat{N} \) implies that \( \hat{C} \cdot (g_0(x) + g_1(x)) = \hat{C} g_0(x) + \hat{C} g_1(x) \geq f_0(x) + f_1(x) \).

(c) As in the prior item, there are constants \( N_0, C_0, N_1, C_1 \in \mathbb{R}^+ \) such that \( x \geq N_0 \) implies that \( C_0(x) \geq f_0(x) \), and \( x \geq N_1 \) implies that \( C_1(x) \geq f_1(x) \). Take \( \hat{N} = \max(N_0, N_1) \) and \( \hat{C} = C_0 \cdot C_1 \). Then \( x \geq \hat{N} \) implies that \( \hat{C} \cdot (g_0(x) \cdot g_1(x)) = C_0 g_0(x) \cdot C_1 g_1(x) \geq f_0(x) \cdot f_1(x) \).

Verified V.1.57

(a) We must show that \( f \) in \( \mathcal{O}(f) \). Take \( N = 1 \) and \( C = 1 \).

(b) Suppose that \( f_0 \) is \( \mathcal{O}(f_1) \) and that \( f_1 \) is \( \mathcal{O}(f_2) \). Then there exists \( N_0, N_1, C_0, C_1 \in \mathbb{R}^+ \) such that if \( x \geq N_0 \) then \( C_0 \cdot f_1(x) \geq f_0(x) \), and if \( x \geq N_1 \) then \( C_1 \cdot f_2(x) \geq f_1(x) \). Take \( \hat{N} = \max(N_0, N_1) \) and \( \hat{C} = C_0 \cdot C_1 \). Then \( x \geq \hat{N} \) implies that \( \hat{C} \cdot f_2(x) \geq C_0 \cdot f_1(x) \geq f_0(x) \).

Verified V.1.58

(a) If \( \lim_{x \to \infty} f(x)/g(x) \) exists and equals 0 then for any \( \varepsilon > 0 \) there is an \( N \in \mathbb{R} \) such that \( x \geq N \) implies that \( f(x)/g(x) < \varepsilon \). That gives \( f(x) < \varepsilon \cdot g(x) \). Fix \( \varepsilon = 1/2 \) and \( C = 2 \). Take inverses to get that \( x \geq \hat{N} \) implies \( C \cdot g(x) = 2g(x) \geq f(x) \).

(b) To show that \( f \) is \( \mathcal{O}(g) \), take \( N = 1 \) and \( C = 4 \). On the other hand, the limit doesn’t exist, as the ratio oscillates between 1 and 2.

Verified V.1.59 First use L'Hôpital's Rule to get that if \( g(x) = a_m x^m + \cdots + a_0 \) then \( g \) is \( \Theta(x^m) \). Then Example 1.20 shows that any logarithmic function is \( \mathcal{O}(g) \).

For the other half, fix a base \( b > 1 \) and consider the exponential function \( h(x) = b^x \). L'Hôpital's Rule gives this

\[
\lim_{x \to \infty} \frac{x^m}{b^x} = \frac{m}{\ln(b)} \cdot \lim_{x \to \infty} \frac{x^{m-1}}{b^x} = \frac{m(m-1)}{(\ln(b))^2} \cdot \lim_{x \to \infty} \frac{x^{m-2}}{b^x} = \cdots = \frac{m!}{(\ln(b))^m} \cdot \lim_{x \to \infty} \frac{1}{b^x} = 0
\]

and Theorem 1.17 gives the desired conclusion.

V.2.37

(a) One is 3.
(b) One is 2 and another is 4.
(c) One is 5 and another is 10

V.2.38 There are twenty five: 2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41, 43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, and 97.

V.2.39

(a) This formula is satisfiable.
(b) This formula is not satisfiable.

\[
\begin{array}{c|c|c|c|c|c|c}
P & Q & R & P \land Q & \neg Q & \neg Q \land R & (P \land Q) \lor (\neg Q \land R) \\
F & F & F & F & T & F & F \\
F & F & T & F & T & T & T \\
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T & F & T & F & T & T & T \\
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T & T & T & T & F & F & T \\
\end{array}
\]

V.2.41 This is the natural one.

V.2.42

(A) This part of a map shows five countries. Obviously, country A must be a different color than any of the others.

Now add to that map a part where the large country is B and the other four countries have small circles, one where the large country is C, and one each for D and E. In doing this we are allowing countries to consist of non-contiguous regions. The result is five countries where each must be a different color than the others.

(b) Make a circle and split it into five wedges.

V.2.43 The answer is 'yes' since 22 + 986 + 165 = 1173.

V.2.44

(A) AT&T connects to Citigroup, which connects to Ford Motor.
(b) Haliburton connects to Citigroup, which connects to Ford Motor.
(c) There is no connection between Caterpillar and Ford Motor.
(d) Again, as shown, no connection.

V.2.45

(A) 2
(b) 2
(c) 0
(d) 4 (Really, this is not true. I was only in the deleted scenes.)

V.2.46 Here are the packings, with their total weights and values.
### V.2.48
We can do these by eye.

(a) The shortest is $q_2$ to $q_1$ to $q_7$, which has length 14.
(b) The shortest is $q_0$ to $q_3$ to $q_4$ to $q_6$, of length 23.
(c) There is no path between these two vertices.

### V.2.49
Let the probability of success be one minus the probability of failure. Recall that logarithms turn multiplication into addition: \( \log(p_0 \cdot p_1 \cdots p_k) = \log(p_0) + \cdots + \log(p_k) \). Label each edge with the negative of the logarithm (any base) of the probability of success. Minimizing the negative of the sum of the logarithms is maximizing the positive sum. That's the same as maximizing the product of the probabilities of success, which is the overall probability of success.

### V.2.50
Here is a check of every possibility.

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V.2.51 No three-coloring suffices. The three vertices $A$, $C$, and $D$ form a triangle, so they must be different colors. Since $CDF$ is also a triangle, we conclude that $A$ and $F$ are the same colors. So far we have: $C_0 = \{A, F\}$, $C_1 = \{C\}$, $C_2 = \{D\}$.

Next consider triangle $DFI$. Its presence gives that $C$ and $I$ are the same colors. So we have $C_0 = \{A, F\}$, $C_1 = \{C, I\}$, $C_2 = \{D\}$. Then triangle $EFI$ leads to $C_0 = \{A, F\}$, $C_1 = \{C, I\}$, $C_2 = \{D, E\}$.

Finally, triangle $CFG$ gives that $D$ and $G$ are the same color, giving $C_0 = \{A, F\}$, $C_1 = \{C, I\}$, $C_2 = \{D, E, G\}$. But the contradicts the presence of triangle $GEF$.

This is a four-coloring.

V.2.52 A finite set of propositional logic statements $\{S_0, \ldots S_{k-1}\}$ is satisfiable if and only if the single statement $S_0 \land S_1 \ldots \land S_{k-1}$ is satisfiable.

V.2.53 A 3-clique is a triangle. A 2-clique is an edge.

V.2.54 A $k$-clique has $k(k-1)/2$ edges, one for each combination of two vertices.

V.2.56 It has a 4-clique, and thus necessarily a 3-clique
Imagine that we have a routine

\begin{align*}
S &= \{ q_1, q_3 \}.
\end{align*}

An independent set with \( k = 4 \) elements is

\begin{align*}
\hat{S} &= \{ q_0, q_2, q_4, q_5 \}.
\end{align*}

(b) A vertex cover with \( k = 3 \) elements is

\begin{align*}
S &= \{ q_1, q_2, q_4d \}.
\end{align*}

An independent set with \( k = 3 \) elements is

\begin{align*}
\hat{S} &= \{ q_0, q_3, q_5 \}.
\end{align*}

(c) A vertex cover with \( k = 4 \) elements is

\begin{align*}
S &= \{ q_2, q_5, q_8, q_9 \}.
\end{align*}

An independent set with \( k = 6 \) elements is

\begin{align*}
\hat{S} &= \{ q_0, q_1, q_3, q_4, q_6, q_7 \}.
\end{align*}

(d) For any edge, if it has at least one endpoint in \( S \) then it has at most one endpoint in the complement

\begin{align*}
\hat{S} &= V - S.
\end{align*}

Conversely, If an edge has at most one endpoint in \( \hat{S} \) then it has at least one endpoint in the complement

\begin{align*}
S &= V - \hat{S}.
\end{align*}

The set \( M = X \times Y \times Z \) contains these triples \( \langle x, y, z \rangle \).

\[
\begin{array}{cccc}
\text{z = a} & \text{z = d} & \text{z = e} \\
\langle a, b, a \rangle & \langle a, b, d \rangle & \langle a, b, e \rangle \\
\langle b, b, a \rangle & \langle b, b, d \rangle & \langle b, b, e \rangle \\
\langle c, b, a \rangle & \langle c, b, d \rangle & \langle c, b, e \rangle \\
\end{array}
\]

A heuristic is a method that, while it may be used in practice, is not guaranteed to be optimal, perfect, or even rational.

An algorithm for a problem is guaranteed to solve the problem.

A Turing machine is more like a program than an algorithm, in that it is an implementation on a specific hardware platform of an algorithm.

A flowchart is a graphical representation of an algorithm. It might suppress more details than a written representation does.

A process, such as an operating system shell or a web server, might be designed to run forever (or it might not). An algorithm is guaranteed to halt. (Another common use of ‘process’ is that it is an instance of a program that has been loaded into the machine for execution.)

It is true that two programs that implement the same algorithm must compute the same function. It is false that two programs computing the same function must implement the same algorithm.

(a) The algorithm to solve this language decision problem is to, for all input, return 0.

(b) The algorithm here is to always return 1.

The smell of a baby’s head. Baby’s heads have a great smell. But we don’t compute it.

Imagine that we have a routine short_test_path that takes in a weighted graph and two vertices, and returns the shortest path between them. That also solves the decision problem of whether there is any path at all.

If the graph is not weighted, convert it to a weighted graph by taking each edge to be of weight 1.

A function problem version would be to input a graph and output a circuit. An optimization problem would return a circuit that is best by some criterion; for instance could, in a weighted graph, return the circuit of least weight (this is Travelling Salesman).

By taking the numbers in the set \( S = \{ s_0, \ldots, s_{n-1} \} \) one at a time: \( S_0 = \{ s_0 \} \), then \( S_1 = \{ s_0, s_1 \} \), \ldots, you
can figure out from the decision problem solver what is the largest number \( s_j \) in the sum. Subtract that from the goal and then iterate using \( S - \{ s_j \} \).

V.3.19 Ever list of numbers has a maximum, but finding it means at least looking through the list.

V.3.23

(a) See if the input string starts with a 1 bit.
(b) See if the input string has length less than or equal to ten. If the length equals ten then there are some cases to do but that doesn’t change that the algorithm is \( O(1) \).

V.3.24 Check all pairs of vertices.

V.4.9 True. Such problems have algorithms that are \( O(1) \).

V.4.10 Algorithms are not in \( P \), rather, problems are in \( P \) if from among all the algorithms that solve them at least one algorithm is \( O(n^c) \) for some constant \( c \).

V.4.11 An order of growth is a set of functions, subject to some conditions. A complexity class is a set of problems.

V.4.12 The Halting problem is not decidable, so it is not in \( P \).

V.4.15 Give two natural numbers, use Euclid’s algorithm to find if their greatest common divisor is 1. This is a polynomial time algorithm.

V.4.17

(a) By Dijkstra’s algorithm, this can be done in polynomial time. So the problem is in \( P \).
(b) Knapsack is believed to be quite hard. No one knows of a polynomial algorithm.
(c) Euler Path is easy; we just need to check whether each node has even degree. There are algorithms that are linear.
(d) No one knows of a polynomial algorithm for Hamiltonian Circuit.

V.4.18 Pick a vertex and mark it. For the set of vertices connected to that one, mark them. At each step thereafter, mark all vertices connected to any in the set of already-marked vertices.

This algorithm is polynomial in the size of the graph. Specifically, it will take \( O(|V|^2 \cdot |E|) \). But since every edge consists of two vertices, \(|E| \leq |V|^2 \). Thus this algorithm is \( O(|V|^4) \)

V.4.21 Assume that \( L \in P \). Then there is a deterministic Turing machine \( P \) that, given \( \sigma \in \mathbb{B}^* \), accepts it if and only if \( \sigma \in L \), and does so in polynomial time. Then the Turing machine \( \tilde{P} \) that is the same as \( P \) except that the accepting and non-accepting states are swapped will accept \( L^c \), also in polynomial time.

V.4.23

(a) Because the size of the clique is fixed.
(b) Given \( G \), enumerate all triples \( \langle v_0, v_1, v_2 \rangle \in V \) and check whether all three of \( v_0v_1, v_0v_2, and v_1v_2 \) are members of \( E \).

This is a polynomial algorithm. Specifically, it is \( O(|V|^3|E|) \). Because \( |E| \leq |V|^2 \), the algorithm is \( O(|V|^5) \)

V.5.14 It matters that the verifier is both deterministic and runs in time polynomial in the length of the input.

V.5.15

(a) This formula is satisfiable.

(b) This formula is not satisfiable.
That lemma requires that there be a verifier with the property that if $\sigma \in \mathcal{L}$ then there is a witness leading to acceptance, and if $\sigma \notin \mathcal{L}$ then there exists no witness leading to acceptance. Consider the problem $\mathcal{L} = \{ n \in \mathbb{N} \mid n \text{ is even} \}$. Your proposed verifier inputs a pair $\langle \sigma, \omega \rangle$, where $\sigma$ is a number and $\omega$ is a bit, and then accepts the pair if $\omega = 1$. Absolutely, if you give your verifier the pair $\langle 5, 1 \rangle$ then it will not accept. However, give it $\langle 5, 1 \rangle$ and your verifier will accept. That is, for $\sigma = 5$ there exists an $\omega$ leading to acceptance, so your verifier is wrong. Rather, for a correct verifier you need that there exists no $\omega$ that causes it to accept $\sigma = 5$.

The natural way to describe it as a decision problem for a language is with $\{ \sigma \in \mathbb{B}^* \mid \sigma \text{ ends in a } 1 \}$ To show it is in $\text{NP}$, we can have a deterministic Turing machine that uses an empty witness $\omega = \epsilon$, and accepts such strings in polynomial time.

We recast it as a language decision problem by setting a bound $B \in \mathbb{N}$ and considering this set of bitstrings.

$$\mathcal{T}_B = \{ \vec{G} \in \mathbb{B}^* \mid G \text{ is a weighted graph with a circuit of length less than } B \}$$

To show that this problem is in $\text{NP}$ we must produce a verifier. For a witness we can use a circuit $\omega = \langle \ell_0, \ell_1, \ldots, \ell_k \rangle$ that is of total cost less than the bound. The verifier gets an input pair $\langle \sigma, \omega \rangle$ where $\sigma$ is a weighted graph, and checks that $\omega$ is indeed a Hamiltonian circuit of the graph, and that it costs less than the bound. A verifier can do those checks in time polynomial in $|\sigma|$. If the graph $\sigma$ is indeed an element of $\mathcal{T}_B$ then there is such an $\omega$, so the verifier can accept a pair. If $\sigma$ is not an element of $\mathcal{T}_B$ then there is no such $\omega$, and so the verifier will never accept such a pair.

Given the propositional logic statement $F$, a suitable witness is the pair $\omega(\ell_0, \ell_1)$ consisting of two lines of the table. That is, each $\ell_i$ is a substitution, a map from the propositional variables $P, Q, R, \ldots$ to the set $\{ T, F \}$.

Let the given set be $S = \{ s_0, \ldots, s_{k-1} \}$. Then there is a $k$-bit witness $\omega_i$ where $\omega_i[i] = 1$ if $s_i$ is in the knapsack, and $\omega_i[i] = 0$ if not. Clearly that's polynomial in the length of the input, the bitstring representing $k$.

What remains is to check that the witness can be verified in polynomial time. This is just a matter of adding the weights associated with those $i$ such that $\omega_i[i] = 1$ to see that the total is below the weight bound, and of adding the values to see that the total exceeds the value target. Clearly this can be done in polytime.

To recast it as a language decision problem we produce a matching language.

$$\{ \langle n, k \rangle \mid \text{there is a partition of } \{ 1, 2, \ldots, n \} \text{ into at most } k \text{ boxes where no two members add to a third} \}$$

The witness $\omega$ is the partition, the set of boxes. Checking that each box satisfies that no two members add to a third is clearly polytime.

(a) Here is the recasting, as the decision problem for this language.

$$\{ \langle a, b \rangle \in \mathbb{N}^2 \mid \text{there exists } x \in \mathbb{N} \text{ with } ax + 1 = b \}$$

It is a member of $\text{NP}$ because we can take the witness to be $\omega = x$. Checking that $ax + 1 = b$ is clearly polynomial.

(b) This is the equivalent language.

$$\{ M \mid M \text{ is a multiset with } n(n+1)/2 \text{ distances} \}$$

The witness $\omega$ is a set of suitable positions.
The Halting problem is not decidable so it is not in NP.

A vertex cover with \( k = 4 \) elements is \( S = \{ q_2, q_5, q_8, q_9 \} \).

An independent set with \( k = 6 \) elements is \( \hat{S} = \{ q_0, q_1, q_3, q_4, q_6, q_7 \} \).

For any edge, if it has at least one endpoint in \( S \) then it has at most one endpoint in the complement \( \hat{S} = V - S \). Conversely, if an edge has at most one endpoint in \( \hat{S} \) then it has at least one endpoint in the complement \( S = V - \hat{S} \).

We will do Independent Set \( \leq_p \) Vertex Cover; the other reduction is similar. The definition requires that we produce a polytime computable function \( f \). Given an instance of Independent Set \( \sigma = \langle G, \hat{k} \rangle \), then we convert that to an instance of Vertex Cover \( f(\sigma) = \langle G, |G| - \hat{k} \rangle \).

The sum of elements in \( \hat{S} = \{ 6, 7, 19 \} \) equals the sum of elements in \( S - \hat{S} = \{ 3, 4, 12, 13 \} \).

The sum of the elements of \( \hat{T} = \{ 4, 6, 7, 13 \} \) is \( B = 30 \).

If we can partition a set \( S \subset \mathbb{N} \) into \( \hat{S} \subset S \) and \( S - \hat{S} \) with equal sums, then the total of the elements of \( S \) is twice the sum of the elements of \( \hat{S} \), and so is even.
This is the Subset Sum problem.
\[ L_0 = \{ \langle T, B \rangle \mid \text{a subset } \hat{T} \subseteq T \text{ has } \sum_{t \in \hat{T}} t = B \} \]

This is the Partition problem.
\[ L_1 = \{ \langle S \rangle \mid \text{there is } \hat{S} \subset S \text{ with } \sum_{s \in \hat{S}} s = \sum_{s \in S - \hat{S}} s \} \]

We must produce a polytime computable function that takes in \( \sigma = \langle S \rangle \) and outputs \( f(\sigma) = \langle T, B \rangle \), such that \( \sigma \in L_0 \) if and only if \( f(\sigma) \in L_1 \). Given \( \sigma = \langle S \rangle \), consider the sum of its elements \( x = \sum_{s \in S} s \). Where
\[
f(\sigma) = \begin{cases} 
\langle S, x/2 \rangle & \text{if } x \text{ is even} \\
\langle S, x + 1 \rangle & \text{otherwise}
\end{cases}
\]

we have that \( \sigma \in L_1 \) if and only if \( f(\sigma) \in L_0 \), as required (and \( f \) is clearly computable in polytime).

\textbf{(f)} \text{Partition} is one of the \textit{NP} complete sets listed in the section. So \textit{Subset Sum} is \textit{NP}-hard. But \textit{Subset Sum} is clearly \textit{NP}, as a witness \( \omega \) we can use the subset.

\textbf{V.6.27} Nothing. For instance, it could be that \( L \) is in \( P \) and so is \( \hat{L} \). It could also be that \( \hat{L} \) is in some higher-up class. There is not enough information to conclude anything.

\textbf{V.6.28} No, if we knew of a problem in \( \text{NP} - P \) then we’d know that \( P \neq \text{NP} \). We don’t know that.

\textbf{V.6.29} Let \( L_0 \leq_p L_1 \) via the function \( f \), and let \( L_1 \leq_p L_2 \) via the function \( g \), which are polytime computable.

Then for all \( \sigma \in \mathbb{B}^* \) we have \( \sigma \in L_0 \) if and only if \( f(\sigma) \in L_1 \), and \( f(\sigma) \in L_1 \) if and only if \( g \circ f(\sigma) \in L_2 \).

Because \( f, g \) are polytime, \( g \circ f \) is polytime also.

\textbf{V.6.31}
\begin{enumerate}
\item Googling around gives the number \( 10^{86} \).
\item \( \lg(10^{86}) = 86 \cdot \lg(10) \approx 86 \cdot 3.32 = 285.52 \)
\item The average chess game is about 40 moves (see (SE author babou and various others 2013)). The longest game in the cited database is 277 moves, so 286 is a long chess game, but not completely out of range.
\end{enumerate}

\textbf{V.6.32}
\begin{enumerate}
\item False; for example, the brute force algorithm solves all instances.
\item True, where we use Cobham’s Thesis to take ‘quickly’ to mean polytime.
\item False.
\item False.
\end{enumerate}

\textbf{V.6.33}
\begin{enumerate}
\item No.
\item No. It might not be a member of \textit{NP}.
\item No.
\item Yes.
\item No.
\item No.
\item Yes.
\end{enumerate}

\textbf{V.6.34} This is a trick question. Computational classes such as \textit{NP} do not contain algorithms, they contain problems.

\textbf{V.6.39} Assume \( L \leq_p \overline{C}L \). Then there is a polytime \( f \) so that \( \sigma \in L \) if and only if \( f(\sigma) \in \overline{C}L \). That's equivalent to \( \sigma \notin L \) if and only if \( f(\sigma) \notin \overline{C}L \), which holds when \( \sigma \in \overline{C}L \) if and only if \( f(\sigma) \in L \).

\textbf{V.6.40}
\begin{enumerate}
\item It is not a member of \textit{NP} because it is not decidable.
\end{enumerate}
(b) Since $L \in \text{NP}$ there is an associated nondeterministic machine $P$ that decides membership. Consider the Turing machine $\hat{P}_L$ that, given an input $\tau$, constructs the computation tree of $P_L$ on input $\tau$ and halts if and only if $P_L$ accepts $\tau$.

The reduction $L \leq_P \mathcal{H}P$ will be done by a function $f_L$. This function will, given $\sigma$, return the pair $\hat{P}, \sigma$ where $\hat{P}$. (Note that this function is polynomial since, while running $\hat{P}_L$ may not be polynomial, constructing it from $P$ is polynomial.)

V.6.41 A problem $L_0$ is $P$ complete if it is a member of the class $P$ and $L_1 \leq_P L_0$ for every $L_1 \in P$.


V.A.12
(a) $n = pq = 134, (p - 1) \cdot (q - 1) = 120$
(b) Use $e = 7$ (the three 2, 3, and 5 are not relatively prime).
(c) The multiplicative inverse of $e = 7$ modulo $n = 134$ is $d = 103$.
(d) The encryption is $m^e \mod n = 9^7 \mod 143 = 48$. The decryption is $48^{103} \mod 143 = 9$.

V.A.13
(a) With two factors $n = k_0 \cdot k_1$ if one is greater than $\sqrt{n}$ then the other must be less.
(b) If $n$ is a perfect square $n = k \cdot k$ then its first nontrivial factor is $k = \sqrt{n}$.
(c) The square root of $10^{12}$ is $10^6 = 1,000,000$, a million.
(d) The input $n$ has size about $\lg(n)$ bits. Thus $\sqrt{n} \approx 2^{\frac{1}{2} \cdot \text{size of } n} \approx (1/2) \cdot \text{size of } n$.

V.A.1
(a) $\sigma^\tau = 10110^\tau 1101111 = 101101101111$
(b) $\sigma^\tau \sigma = 10110^\tau 1101111^\tau 10110 = 1011011011110110$
(c) $\sigma^R = 10110^R = 01101$
(d) $\sigma^3 = 10110^\tau 10110^\tau 10110 = 101101011010110$
(e) $\theta^3 \sigma = 000^\tau 10110 = 00010110$

V.A.2
(a) abbc
(b) abbbcabca
(c) baacab
(d) abab

V.A.3 There are $2^4 = 16$ bit strings of length 4 and half of them start with 0, so there are 8 strings in the language.

V.A.4
(a) Yes.
(b) Yes.
(c) No.
(d) Yes.

V.A.5 Show that the length of a concatenation is the sum of the two lengths: $|\sigma^\tau| = |(s_0, s_{t-1}, t_0, \ldots, t_{j-1})| = i + j = |\sigma| + |\tau|$. Proving this by induction is routine.

V.A.7 One example using $B\text{i}$ is $\sigma = (0)$ and $\tau = (1)$. Then $\sigma^\tau = (0, 1)$ while $\tau^\sigma = (1, 0)$.

V.B.1
(a) For one-to-one, suppose that $f(x_0) = f(x_1)$ for $x_0, x_1 \in \mathbb{R}$. Then $3x_0 + 1 = 3x_1 + 1$. Subtract the 1’s and divide by 3 to conclude that $x_0 = x_1$. Thus $f$ is one-to-one.

For onto, fix a member of the codomain $c \in \mathbb{R}$. Observe that $d = (c - 1)/3$ is a member of the domain and that $f(d) = 3 \cdot ((c - 1)/3) + 1 = (c - 1) + 1 = c$. Thus $f$ is onto.

(b) The function $g$ is not one-to-one because $g(2) = g(-2)$. It is not onto because no element of the domain $\mathbb{R}$ is mapped by $g$ to the element 0 of the codomain.

V.B.2
(a) It is a left inverse because $g \circ f$ has the action $(x, y) \mapsto (x, y, 0) \mapsto (x, y)$ for all $x$ and $y$. It is not a right inverse because there is an input on which the composition $f \circ g$ is not the identity, namely the action is $(1, 2, 3) \mapsto (1, 2) \mapsto (1, 2, 0)$.

(b) Observe that $f(2) = f(-2) = 4$. Any left inverse would have to map 4 to 2 and also to map 4 to $-2$. That
would be not well-defined, so no function is the left inverse.
(c) One right inverse is \( g_0 : C \to D \) given by \( 10 \mapsto 0, \quad 11 \mapsto 1 \). A second is \( g_1 : C \to D \) given by \( 10 \mapsto 2, \quad 11 \mapsto 3 \).

V.B.3

(a) First, the domain of each equals the codomain of the other so their composition is defined in both ways. Next, \( g \circ f (a) = g(f(a)) = g(a + 3) = (a + 3) - 3 = a \) is the identity map. Similarly, \( f \circ g (a) = (a - 3) + 3 \) is also the identity map. Thus they are inverse.
(b) The inverse of \( h \) is itself. The domain and codomain are equal, as required. If \( n \) is odd then \( h \circ h(n) = h(n - 1) + 1 = n \) (the second equality holds because \( n - 1 \) is even in this case). Similarly if \( n \) is even then \( h \circ h(n) = (n + 1) - 1 = n \).
(c) The inverse of \( s \) is the map \( r : \mathbb{R}^+ \to \mathbb{R}^+ \) given my \( r(x) = \sqrt{x} \). The domain of each is the codomain of the other, and each of \( s \circ r \) and \( r \circ s \) is the identity function.

V.B.4 This is a bean diagram of the function \( f \)

\[
\begin{array}{cccc}
2 & 1 & 0 & 11 \to 12 \\
3 & 1 & 2 & 10 \to 12 \\
4 & 0 & 1 & 0 \to 10 \\
5 & 0 & 2 & 0 \to 10 \\
6 & 0 & 3 & 0 \to 10 \\
\end{array}
\]

and this is a diagram of \( g \).

(a) By inspection \( f \) is both one-to-one and onto.
(b) Reverse the association made by \( f \) so that \( f^{-1}(10) = 0, f^{-1}(11) = 1, \) and \( f^{-1}(12) = 2 \).
(c) The map \( g \) is not one-to-one since \( g(0) = g(1) \). (In addition, \( g \) is not onto since no input is sent to \( 11 \in C \).)
(d) If \( a \) were the inverse of \( g \) then both \( a(10) = 0 \) and \( a(10) = 1 \), which would violate the definition of a function.

V.B.5

(a) Let \( f : D \to C \) and \( g : C \to B \) be one-to-one. Suppose that \( g \circ f (x_0) = g \circ f (x_1) \) for some \( x_0, x_1 \in D \). Then \( g(f(x_0)) = g(f(x_1)) \). The function \( g \) is one-to-one and so, since the two values \( g(f(x_0)) \) and \( g(f(x_1)) \) are equal, the arguments \( f(x_0) \) and \( f(x_1) \) are also equal. The function \( f \) is one-to-one and so \( x_0 = x_1 \). Because \( g \circ f (x_0) = g \circ f (x_1) \) implies that \( x_0 = x_1 \), the composition is one-to-one.
(b) Let \( f : D \to C \) and \( g : C \to B \) be onto. If \( B \) is the empty set then the composition is onto, vacuously.
Otherwise, fix an element of the codomain of the composition, \( b \in B \). The function \( g \) is onto so there is a \( c \in C \) such that \( g(c) = b \). The function \( f \) is onto so there is a \( d \in D \) such that \( f(d) = c \). Then \( g \circ f (d) = b \), and so the composition is onto.
(c) Let \( f : D \to C \) and \( g : C \to B \) be such that the composition \( g \circ f \) is one-to-one. Suppose that \( f \) is not one-to-one. Then there are \( d_0, d_1 \in D \) with \( d_0 \neq d_1 \) such that \( f(d_0) = f(d_1) \). But this implies that \( g(f(d_0)) = g(f(d_1)) \), contradicting that the composition is one-to-one.
(d) Let \( f : D \to C \) and \( g : C \to B \) be such that the composition \( g \circ f \) is onto. Suppose for a contradiction that \( g \) is not onto. Then for some \( b \in B \) there is no \( c \in C \) with \( g(c) = b \). But this means that there is no \( d \in D \) such that \( b = g(f(d)) \), contradicting that the composition is onto. So \( g \) must be onto.
(e) The answer to both questions is “no.”

Let \( D = \{0, 1\}, C = \{10, 11, 12\}, \) and \( B = \{20, 21\} \). Let \( f \) map \( 0 \mapsto 11 \) and \( 1 \mapsto 12 \). Let \( g \) map \( 10 \mapsto 20, 11 \mapsto 20, \) and \( 12 \mapsto 21 \). Then \( g \circ f \) is onto because \( g \circ f (0) = 20 \) and \( g \circ f (1) = 21 \). But \( f \) is not onto because no element of its domain \( D \) is mapped to the element 10 of its codomain \( C \).
The same function is an example of a composition \( g \circ f \) that is one-to-one but where the function performed second, \( g \), is not one-to-one.

**V.B.6**

(a) We first prove that if the function \( f : D \to C \) has an inverse \( f^{-1} : C \to D \) then it must be a correspondence. To verify that \( f \) is one-to-one, suppose that \( d_0, d_1 \in D \) are such that \( f(d_0) = f(d_1) = c \) for some \( c \in C \). Consider \( f^{-1}(c) \). Because \( f^{-1} \circ f \) is the identity map on \( D \) we have both that \( f^{-1}(c) = f^{-1}(f(d_0)) = d_0 \) and that \( f^{-1}(c) = f^{-1}(f(d_1)) = d_1 \). Thus \( d_0 = d_1 \) and so \( f \) is one-to-one.

Next we verify that \( f \) is onto. Suppose otherwise, so that there is a \( c \in C \) that is not associated with any \( d \in D \). The map \( f \circ f^{-1} \) cannot give \( c = f \circ f^{-1}(c) = f(f^{-1}(c)) \) because \( c \not\in \text{ran}(f) \), so this is impossible. Therefore \( f \) is onto.

To finish, we prove that if a map \( f : D \to C \) is a correspondence then it has an inverse. We will define an association \( q : D \to C \) and show that it is well-defined. For each \( c \in C \), let \( g(c) \) be the element \( d \in D \) such that \( f(d) = c \); note that there is such an element because \( f \) is onto, and that there is a unique such element because \( f \) is one-to-one. So \( g \) is well-defined. That \( g \circ f \) and \( f \circ g \) are identity maps is clear.

(b) Suppose that \( f : D \to C \) has two inverses \( g_0, g_1 : C \to D \). We will show that the two make the same associations, that is, we will show that they have the same graph and thus are the same function.

Let \( c \) be an element of the domain \( C \) of the two. The prior item shows that \( f \) is onto so there exists \( d \in D \) such that \( f(d) = c \). The prior item also shows that \( f \) is one-to-one, so there is only one \( d \) with that property: \( d = g_0(c) \) and \( d = g_1(c) \). Therefore \( g_0(c) = g_1(c) \).

(c) An inverse is a function that has an inverse: the inverse of \( f^{-1} \) is \( f \). By the first item then, \( f^{-1} \) is a correspondence.

(d) Here is the verification that one order gives the identity function \((f^{-1} \circ g^{-1}) \circ (g \circ f)(x) = (f^{-1} \circ g^{-1})(g(f(x))) = f^{-1}(g^{-1}(g(f(x)))) = f^{-1}(f(x)) = x \). Verification of the other order is similar.

**V.B.7**

(a) We will will prove this by induction on the number of elements in the codomain \( C \). The base step is that the codomain is empty, \(|C| = 0\). The only function with an empty codomain is the empty function. The definition of function requires that every element of the domain is mapped somewhere, so the domain must not have any members, \(|D| = 0\). Thus \(|C| \geq |D|\).

For the inductive step assume the statement is true for all one-to-one functions between finite sets where the codomains satisfy \(|C| = 0, \ldots, |C| = k\). Consider the next case, \(|C| = k + 1\). Because the codomain does not have zero elements, we can fix some \( \hat{c} \in C \). Let \( \hat{C} = C - \{ \hat{c} \} \). There are two cases: (1) there is a domain element \( d \in D \) with \( f(d) = \hat{c} \), and (2) there isn’t any such \( d \).

Case (2) is easier. Consider the restriction map \( \hat{f} : D \to \hat{C} \) given by \( \hat{f}(d) = f(d) \). Because \( f \) is one-to-one, the map \( \hat{f} \) is also one-to-one. The inductive hypothesis give \(|\hat{C}| \geq |D|\), and therefore \(|C| > |\hat{C}| + 1 \geq |D|\).

In Case (1), where there is a domain element \( \hat{d} \in D \) so that \( f(\hat{d}) = \hat{c} \), observe that because \( f \) is one-to-one there is only one such domain element. Let \( \hat{D} = D - \{ \hat{d} \} \). Consider the restriction \( \hat{f} : \hat{D} \to \hat{C} \) given by \( \hat{f}(d) = f(d) \) for \( d \in \hat{D} \). Because \( f \) is one-to-one, this map is also one-to-one. By the inductive hypothesis \(|\hat{C}| \geq |\hat{D}|\) and adding 1 gives \(|C| = |\hat{C}| + 1 \geq |\hat{D}| + 1 = |D|\).

Alternate proof. We can instead do induction on the number of elements in the domain \( D \). The base step is that the domain is empty, \(|D| = 0\). The only map with an empty domain is the empty function but in any event, the codomain cannot have fewer than zero elements so \(|C| \geq |D|\).

For the inductive step assume that the statement is true for any one-to-one function between finite sets with \(|D| = 0, \ldots, |D| = k\). Consider \(|D| = k + 1\). Fix some \( \hat{d} \in D \) and let \( \hat{D} = D - \{ \hat{d} \} \); such an element exists because \(|D| = k + 1\). Observe that because \( f \) is one-to-one the image of \( \hat{d}, \hat{c} = f(\hat{d}), \) is not the image of any other element of the domain. That is, for \( d \neq \hat{d} \) we have \( f(d) \neq \hat{c} \). Set \( \hat{C} = C - \{ \hat{c} \} \).

The restriction \( \hat{f} : \hat{D} \to \hat{C} \) given by \( \hat{f}(d) = f(d) \) for \( d \in \hat{D} \) is one-to-one because \( f \) is one-to-one. The
inductive hypothesis applies so $|\hat{C}| \geq |\hat{D}|$. Add 1 to get $|C| = |\hat{C}| + 1 \geq |\hat{D}| + 1 = |D|$. 

(b) The proof will be by induction on the number of elements in the codomain. Before we start, here is an illustration. Take $D = \{d_0, d_1, d_2, d_3\}$ and $C = \{c_0, c_1, c_2\}$. Consider the function $f : D \rightarrow C$ given here.

$$d_0 \mapsto c_0 \quad d_1 \mapsto c_1 \quad d_2 \mapsto c_2 \quad d_3 \mapsto c_2$$

That map is onto. To make the induction work we pick an element of the codomain and omit it; suppose we omit $c_2$, along with all of the the elements of the domain that map to it, $f^{-1}(c_2) = \{d_2, d_3\}$. We are left with the function $\hat{f}$ with domain $\hat{D} = \{d_0, d_1\}$ and codomain $\hat{C} = \{c_0, c_1\}$ given here.

$$d_0 \mapsto c_0 \quad d_1 \mapsto c_1$$

This map, the restriction of $f$ to the set $\hat{D}$, is onto. With that, the inductive hypothesis gives that the restricted domain $\hat{D}$ has at least as many elements as $\hat{f}$'s codomain $\hat{C}$. Add back the omitted elements to get the function $f$, and we conclude that its domain $D$ has at least as many elements as its codomain $C$.

Now for the proof. The base step is that there are no elements in the codomain, that $C = \emptyset$. This implies that the domain is also empty because the definition of function requires that every element of the domain is mapped somewhere. Hence $|C| \leq |D|$.

For the inductive step assume that the statement holds for all functions between finite sets that are onto some codomain $C$, where $|C| = 0$, $|C| = 1$, \ldots $|C| = k$. Consider an onto map where $|C| = k + 1$.

The codomain has $k + 1$ elements so it is not empty; fix some $c \in C$. Let $\hat{C} = C - \{c\}$. Because $f$ is onto, the set $f^{-1}(c) = \{d \in D \mid f(d) = c\}$ has at least one element, that is, $|\hat{D}| + 1 \leq |D|$. Finally, observe that the map $\hat{f} : \hat{D} \rightarrow \hat{C}$ is onto. Therefore the inductive hypothesis gives that $|\hat{D}| \geq |\hat{C}|$. Finish by adding one, $|C| = |\hat{C}| + 1 \leq |\hat{D}| + 1 \leq |D|$, Alternate proof. We can instead induction on the number of elements in the domain $D$. As above, before the proof we first give an illustration. There are two cases. In both cases the domain is $D = \{d_0, d_1, d_2, d_3\}$, and to do induction on the number of elements in $D$ we will omit $d_3$, and consider $\hat{D} = D - \{d_3\}$. In the first case the codomain is $C = \{c_0, c_1, c_2\}$ and this is the function $f : D \rightarrow C$.

$$d_0 \mapsto c_0 \quad d_1 \mapsto c_1 \quad d_2 \mapsto c_2 \quad d_3 \mapsto c_2$$

In this case, we consider the map $f : \hat{D} \rightarrow C$. It is onto, so the inductive hypothesis applies and we get that $|\hat{D}| \geq |C|$. Then we get the desired conclusion $|D| > |\hat{D}| \geq |C|$.

The second illustrative case is that the codomain is $C = \{c_0, c_1, c_2, c_3\}$ with this function $f : D \rightarrow C$.

$$d_0 \mapsto c_0 \quad d_1 \mapsto c_1 \quad d_2 \mapsto c_2 \quad d_3 \mapsto c_3$$

Since we are omitting $d_3$ we will also omit $c_3$, giving $\hat{C} = C - \{c_3\}$. Consider the restriction map $\hat{f} : \hat{D} \rightarrow \hat{C}$ given by $\hat{f}(d) = f(d)$ for $d \in \hat{D}$. This map is onto, so the inductive hypothesis applies and we get that $|\hat{D}| \geq |\hat{C}|$. Then $|D| = |\hat{D}| + 1 \geq |\hat{C}| + 1 = |C|$. 

Now for the proof. The base step is that $D$ has no elements at all, $D = \emptyset$. The only function with an empty domain is the empty function. Its range is empty and because it is onto, its codomain equals its range, so $C = \emptyset$. Thus $|C| \leq |D|$ in this case.

For the inductive step assume that the statement is true for onto functions between finite sets for the cases $|D| = 0$, $|D| = 1$, \ldots $|D| = k$. Consider an onto function where $|D| = k + 1$. Because $|D| > 0$ we can fix some $\hat{d} \in D$. Let $\hat{D} = D - \{\hat{d}\}$.

There are two cases: either (1) the codomain element $\hat{c} = f(\hat{d})$ is also the image of another domain element, some $d \in \hat{D}$ with $d \neq \hat{d}$, or else (2) it is not. In case (1) the restriction $\hat{f} : \hat{D} \rightarrow C$ is onto. The inductive hypothesis applies, giving that $|C| \leq |\hat{D}| < |D|$. 

Case (2) is that $\hat{d}$ is the only element of $D$ associated by $f$ with the codomain element $\hat{c}$. Let $\hat{C} = C - \{\hat{c}\}$. Then the the restriction $\hat{f} : \hat{D} \rightarrow \hat{C}$ is onto. The inductive hypothesis gives $|\hat{C}| \leq |\hat{D}|$. Consequently, $|C| = |\hat{C}| + 1 \leq |\hat{D}| + 1 = |D|$.