Propositional logic

Solution 1

(a)

$$false(as(true \Rightarrow false) \Leftrightarrow false)$$

(b)

$$true(as(false \Rightarrow false) \Leftrightarrow true)$$

(c)

$$true(as(false \Rightarrow true) \Leftrightarrow true)$$

(d)

$$true(as(false \Rightarrow false) \Leftrightarrow true)$$

(Assuming that pigs can't fly . . .)

Solution 2

(a)

p	q	$p \wedge q$	$(p \wedge q) \Rightarrow p$
t	t	t	t
t	f	f	t
f	t	f	t
f	f	f	t

(b)

p	q	$p \wedge q$	$\neg\, p$	$\neg\, p \Rightarrow (p \wedge q)$	$(\neg\, p \Rightarrow (p \wedge q)) \Leftrightarrow p$
t	t	t	f	t	t
t	f	f	f	t	t
f	t	f	t	f	t
f	f	f	t	f	t

(c)

p	q	$p \Rightarrow q$	$p \wedge (p \Rightarrow q)$	$(p \wedge (p \Rightarrow q)) \Rightarrow q$
t	t	t	t	t
t	f	f	f	t
f	t	t	f	t
f	f	t	f	t

Solution 3

(a)

$$\begin{aligned}
&p \Rightarrow \neg\, p \\
&\qquad \Leftrightarrow \neg\, p \vee \neg\, p && [\Rightarrow] \\
&\qquad \Leftrightarrow \neg\, p && [\text{idempotence}]
\end{aligned}$$

(b)

$$\begin{aligned}
&\neg\, p \Rightarrow p \\
&\qquad \Leftrightarrow \neg\, \neg\, p \vee p && [\Rightarrow] \\
&\qquad \Leftrightarrow p \vee p && [\neg\ \neg\,] \\
&\qquad \Leftrightarrow p && [\text{idempotence}]
\end{aligned}$$

(c)

$$\begin{aligned}
&p \Rightarrow (q \Rightarrow r) \\
&\qquad \Leftrightarrow \neg\, p \vee (q \Rightarrow r) && [\Rightarrow] \\
&\qquad \Leftrightarrow \neg\, p \vee \neg\, q \vee r && [\Rightarrow] \\
&\qquad \Leftrightarrow \neg\, p \vee \neg\, q \vee r && [\text{associativity}] \\
&\qquad \Leftrightarrow \neg\, (p \wedge q) \vee r && [\text{De Morgan}] \\
&\qquad \Leftrightarrow p \wedge q \Rightarrow r && [\Rightarrow]
\end{aligned}$$

(d)

$$\begin{aligned}
&q \Rightarrow (p \Rightarrow r) \\
&\qquad \Leftrightarrow \neg\, q \vee (p \Rightarrow r) && [\Rightarrow] \\
&\qquad \Leftrightarrow \neg\, q \vee \neg\, p \vee r && [\Rightarrow] \\
&\qquad \Leftrightarrow \neg\, p \vee \neg\, q \vee r && [\text{associativity} \wedge \text{commutativity}] \\
&\qquad \Leftrightarrow \neg\, p \vee (q \Rightarrow r) && [\Rightarrow] \\
&\qquad \Leftrightarrow p \Rightarrow (q \Rightarrow r) && [\Rightarrow]
\end{aligned}$$

(e)

$$
\begin{aligned}
&p \land q \Leftrightarrow p \\
&\qquad \Leftrightarrow (p \land q \Rightarrow p) \land (p \Rightarrow p \land q) && [\Leftrightarrow] \\
&\qquad \Leftrightarrow (\neg\, (p \land q) \lor p) \land (\neg\, p \lor p \land q) && [\Rightarrow] \\
&\qquad \Leftrightarrow (\neg\, p \lor \neg\, q \lor p) \land (\neg\, p \lor p \land q) && [\text{De Morgan}] \\
&\qquad \Leftrightarrow (\neg\, q \lor \neg\, p \lor p) \land (\neg\, p \lor p \land q) && [\text{associativity} \land \text{comm .}] \\
&\qquad \Leftrightarrow (\neg\, q \lor \mathit{true}) \land (\neg\, p \lor p \land q) && [\text{excluded middle}] \\
&\qquad \Leftrightarrow \mathit{true} \land (\neg\, p \lor p \land q) && [\lor \land \text{true}] \\
&\qquad \Leftrightarrow \neg\, p \lor p \land q && [\land \land \text{true}] \\
&\qquad \Leftrightarrow (\neg\, p \lor p) \land (\neg\, p \lor q) && [\text{distribution}] \\
&\qquad \Leftrightarrow \mathit{true} \land (\neg\, p \lor q) && [\text{excluded middle}] \\
&\qquad \Leftrightarrow \neg\, p \lor q && [\land \land \text{true}] \\
&\qquad \Leftrightarrow p \Rightarrow q && [\Rightarrow]
\end{aligned}
$$

(f)

$$
\begin{aligned}
&p \lor q \Leftrightarrow p \\
&\qquad \Leftrightarrow (p \lor q \Rightarrow p) \land (p \Rightarrow p \lor q) && [\Leftrightarrow] \\
&\qquad \Leftrightarrow (\neg\, (p \lor q) \lor p) \land (\neg\, p \lor p \lor q) && [\Rightarrow] \\
&\qquad \Leftrightarrow (\neg\, p \land \neg\, q \lor p) \land (\neg\, p \lor p \lor q) && [\text{De Morgan}] \\
&\qquad \Leftrightarrow (\neg\, p \lor p) \land (\neg\, q \lor p) \land (\neg\, p \lor p \lor q) && [\text{distribution}] \\
&\qquad \Leftrightarrow \mathit{true} \land (\neg\, q \lor p) \land (\neg\, p \lor p \lor q) && [\text{excluded middle}] \\
&\qquad \Leftrightarrow (\neg\, q \lor p) \land (\neg\, p \lor p \lor q) && [\land \land \text{true}] \\
&\qquad \Leftrightarrow (\neg\, q \lor p) \land (\neg\, p \lor p \lor q) && [\text{associativity}] \\
&\qquad \Leftrightarrow (\neg\, q \lor p) \land (\mathit{true} \lor q) && [\text{excluded middle}] \\
&\qquad \Leftrightarrow (\neg\, q \lor p) \land \mathit{true} && [\lor \land \text{true}] \\
&\qquad \Leftrightarrow \neg\, q \lor p && [\land \land \text{true}] \\
&\qquad \Leftrightarrow q \Rightarrow p && [\Rightarrow]
\end{aligned}
$$

Solution 4

(a) (p or q) $\Leftrightarrow$ ((not p or not q) and q) is not a tautology. You might illustrate this via a truth table or via a chain of equivalences, showing that the proposition is not equivalent to true. Alternatively, you might try and find a combination of values for which the proposition is false. (In this case, the proposition is false when p and q are both true.)

(b) (p or q) $\Leftrightarrow$ ((not p and not q) or q) is not a tautology. In this case, the proposition is false when p is true and q is false.

Solution 5

(a)

$$\exists\, d : \mathit{Dog} \bullet \mathit{gentle}(d) \land \mathit{well\_trained}(d)$$

(b)

$$\forall d : Dog \bullet neat(d) \land well\_trained(d) \Rightarrow attractive(d)$$

(c) (Requires nested quantifier in implication - parser limitation)

Solution 6

(a) This is a true *proposition* : $whatever the value of x, the expression x^2$ - x + 1 denotes a natural number. If we choose y to be this natural number, we will find that p is true.

(b) This is a false proposition. We cannot choose a large enough value for y such that p will hold for any value of x.

(c) This is a false proposition. It is an implication whose antecedent part is true and whose consequent part is false.

(d) This is a true proposition. It is an implication whose antecedent part is false and whose consequent part is true.

Solution 7

(a) We must define a predicate p that is false for at least one value of x, and is true for at least one other value. A suitable solution would be $p \Leftrightarrow x > 1$.

(b) With the above choice of p, we require only that q is sometimes false when p is true (for else the universal quantification would hold). A suitable solution would be $q \Leftrightarrow x > 3$.

Solution 8

(a)

$$\forall x : N \bullet x \geq z$$

Equality

Solution 9

(d)

$$\begin{aligned}
&\exists x : N \bullet x = 1 \land x > y \lor x = 2 \land x > z \\
&\qquad \Leftrightarrow \exists x : N \bullet x = 1 \land x > y \lor \exists x : N \bullet x = 2 \land x > z \\
&\qquad \Leftrightarrow 1 \in N \land 1 > y \lor \exists x : N \bullet x = 2 \land x > z \\
&\qquad \Leftrightarrow 1 \in N \land 1 > y \lor 2 \in N \land 2 > z \\
&\qquad \Leftrightarrow 1 > y \lor 2 > z
\end{aligned}$$

Solution 10

As discussed, the quantifier $\exists_1$ can help give rise to a 'test' or 'precondition' to ensure that an application of mu will work.

So, as a simple example, as the proposition

$$\exists_1\, n\colon N \bullet \forall\, m\colon N \bullet n \leq m$$

is equivalent to true, we can be certain that the statement

$$\mu\, n\colon N \bullet \forall\, m\colon N \bullet n \leq m$$

will return a result (which happens to be 0).

Solution 11

(a) (mu a : N | a= a) = 0 is a provable statement, since 0 is the only natural number with the specified property.

(b) $(\mu\, b\colon N \bullet b = b) = 1$ is not provable. The specified property is true of both 0 and 1, and thus the value of the mu-expression is undefined.

(c) $(\mu\, c\colon N \bullet c > c) = (\mu\, c\colon N \bullet c > c)$ is a provable statement. Neither expression is properly defined, but we may conclude that they are equal; there is little else that we can prove about them.

(d) $(\mu\, d\colon N \bullet d = d) = 1$ is not a provable statement. We cannot confirm that 1 is the only natural number with the specified property; we do not know what value is taken by undefined operations.

Solution 12

(Requires mu-operator with expression part - not yet implemented)

(a)

$$\mu\, m\colon \mathit{Mountain} \mid \forall\, n\colon \mathit{Mountain} \bullet \mathit{height}(n) \leq \mathit{height}(m) \bullet \mathit{height}(m)$$

(b)

$$\mu\, c\colon \mathit{Chapter} \mid \exists_1\, d\colon \mathit{Chapter} \bullet \mathit{length}(d) > \mathit{length}(c) \bullet \mathit{length}(c)$$

(c) Assuming the existence of a suitable function, max: $(\mu\, n\colon N \bullet n = \mathit{max}(\{m\colon N \mid 8 * m < 100.8 * m\})$. 100 - n)

Deductive proofs

Solution 13

$$\dfrac{\ulcorner p \wedge (p \Rightarrow q)\urcorner^{[1]} \qquad \dfrac{\dfrac{p \wedge (p \Rightarrow q)}{p}\,[\wedge\text{-elim}^{[1]}] \qquad \dfrac{\dfrac{p \wedge (p \Rightarrow q)}{p \Rightarrow q}\,[\wedge\text{-elim}^{[1]}] \quad \dfrac{p \wedge (p \Rightarrow q)}{p}\,[\wedge\text{-elim}^{[1]}]}{q}\,[\Rightarrow \text{elim}]}{p \wedge q}\,[\wedge \text{ intro}]}{p \wedge (p \Rightarrow q) \Rightarrow p \wedge q}\,[\Rightarrow\text{-intro}^{[1]}]$$

Solution 14

In one direction:

$$\dfrac{\ulcorner p \wedge q \Leftrightarrow p\urcorner^{[1]} \qquad \dfrac{\ulcorner p\urcorner^{[2]} \qquad \dfrac{\dfrac{\dfrac{}{p \wedge q}\,[\text{derived}]}{p \wedge q}\,[\Rightarrow \text{elim from } 1 \wedge 2]}{q}\,[\wedge\text{-elim}^{[3]}]}{p \Rightarrow q}\,[\Rightarrow\text{-intro}^{[2]}]}{(p \wedge q \Leftrightarrow p) \Rightarrow (p \Rightarrow q)}\,[\Rightarrow\text{-intro}^{[1]}]$$

and the other:

$$\dfrac{\ulcorner p \Rightarrow q\urcorner^{[1]} \qquad \dfrac{\dfrac{\ulcorner p \wedge q\urcorner^{[2]} \quad \ulcorner p\urcorner^{[2]}}{p \wedge q \Rightarrow p}\,[\Rightarrow\text{-intro}^{[2]}] \qquad \dfrac{\ulcorner p\urcorner^{[3]} \quad \ulcorner p \wedge q\urcorner^{[1]}}{p \Rightarrow p \wedge q}\,[\Rightarrow\text{-intro}^{[3]}]}{p \wedge q \Leftrightarrow p}\,[\Leftrightarrow \text{intro}]}{(p \Rightarrow q) \Rightarrow (p \wedge q \Leftrightarrow p)}\,[\Rightarrow\text{-intro}^{[1]}]$$

We can then combine these two proofs *with* $\Leftrightarrow$ *intro*.

Solution 15

$$\dfrac{\ulcorner (p \Rightarrow q) \wedge \neg\, q\urcorner^{[1]} \qquad \dfrac{\ulcorner p\urcorner^{[2]} \qquad \dfrac{\dfrac{\ulcorner p \Rightarrow q\urcorner^{[1]} \quad \ulcorner p\urcorner^{[2]}}{q}\,[\Rightarrow \text{elim}] \qquad \ulcorner \neg\, q\urcorner^{[1]}}{\mathit{false}}\,[\text{false intro}]}{\neg\, p}\,[\text{false-elim}^{[2]}]}{(p \Rightarrow q) \wedge \neg\, q \Rightarrow \neg\, p}\,[\Rightarrow\text{-intro}^{[1]}]$$

Solution 16

In one direction:

$$\dfrac{\ulcorner p \wedge (q \vee r) \urcorner^{[1]} \qquad \dfrac{\ulcorner q \vee r \urcorner^{[1]} \qquad \begin{array}{c} \dfrac{\dfrac{\ulcorner p \urcorner^{[1]} \quad \dfrac{}{q}\,[\text{case assumption}]}{p \wedge q}\,[\wedge \text{ intro}]}{p \wedge q \vee p \wedge r}\,[\vee \text{ intro}] \\ \vdots \end{array} \qquad \begin{array}{c} \dfrac{\dfrac{\ulcorner p \urcorner^{[1]} \quad \dfrac{}{r}\,[\text{case assumption}]}{p \wedge r}\,[\wedge \text{ intro}]}{p \wedge q \vee p \wedge r}\,[\vee \text{ intro}] \\ \vdots \end{array}}{p \wedge q \vee p \wedge r}\,[\vee\text{-elim}^{[2]}]}{p \wedge (q \vee r) \Rightarrow p \wedge q \vee p \wedge r}\,[\Rightarrow\text{-intro}^{[1]}]$$

In the other:

$$\dfrac{\ulcorner p \wedge q \vee p \wedge r \urcorner^{[3]} \qquad \dfrac{\ulcorner case1 \vee case2 \urcorner^{[3]} \qquad \begin{array}{c} \dfrac{\dfrac{\dfrac{}{p}\,[\wedge \text{ elim}]}{q \vee r}\,[\vee \text{ intro}]}{p \wedge (q \vee r)}\,[\wedge \text{ intro}] \\ \vdots \end{array} \qquad \begin{array}{c} \dfrac{\dfrac{\dfrac{}{p}\,[\wedge \text{ elim}]}{q \vee r}\,[\vee \text{ intro}]}{p \wedge (q \vee r)}\,[\wedge \text{ intro}] \\ \vdots \end{array}}{p \wedge (q \vee r)}\,[\vee\text{-elim}^{[4]}]}{p \wedge q \vee p \wedge r \Rightarrow p \wedge (q \vee r)}\,[\Rightarrow\text{-intro}^{[3]}]$$

Solution 17

In one direction:

$$\dfrac{\ulcorner p \vee q \wedge r \urcorner^{[3]} \qquad \dfrac{}{(p \vee q) \wedge (p \vee r)}\,[\vee \text{ elim } \wedge \wedge \text{ intro}]}{p \vee q \wedge r \Rightarrow (p \vee q) \wedge (p \vee r)}\,[\Rightarrow\text{-intro}^{[3]}]$$

and the other:

$$\dfrac{\ulcorner (p \vee q) \wedge (p \vee r) \urcorner^{[1]} \qquad \ulcorner p \vee q \wedge r \urcorner^{[2]}}{(p \vee q) \wedge (p \vee r) \Rightarrow p \vee q \wedge r}\,[\Rightarrow\text{-intro}^{[1]}]$$

Solution 18

In one direction:

$$\dfrac{\ulcorner p \Rightarrow q \urcorner^{[1]} \quad \neg\, p \vee q}{(p \Rightarrow q) \Rightarrow \neg\, p \vee q}\ [\Rightarrow\text{-intro}^{[1]}]$$

and the other:

$$\dfrac{\ulcorner \neg\, p \vee q \urcorner^{[3]} \qquad \dfrac{\ulcorner p \urcorner^{[4]} \quad \ulcorner q \urcorner^{[3]}}{p \Rightarrow q}\ [\Rightarrow\text{-intro}^{[4]}]}{\neg\, p \vee q \Rightarrow (p \Rightarrow q)}\ [\Rightarrow\text{-intro}^{[3]}]$$

Sets and types

Solution 19

(a) 1 in $\{4, 3, 2, 1\}$ is true.

(b) $\{1\}$ in $\{1, 2, 3, 4\}$ is undefined.

(c) $\{1\}$ in $\{\{1\}, \{2\}, \{3\}, \{4\}\}$ is true.

(d) The empty set in $\{1, 2, 3, 4\}$ is undefined.

Solution 20

(a)

$$\{1\} \times \{2, 3\}$$

is the set $\{(1, 2), (1, 3)\}$

(b) The empty set cross $\{2, 3\}$ is the empty set

(c)

$$\mathbb{P}\, \emptyset \times \{1\}$$

is the set $\{(\emptyset, 1)\}$

(d) $\{(1, 2)\}$ cross $\{3, 4\}$ is the set $\{((1, 2), 3), ((1, 2), 4)\}$

Solution 21

There are various ways of describing these sets via set comprehensions. Examples are given below.

(a)

$$\{z \colon Z \mid 0 \leq z \wedge z \leq 100\}$$

(b)

$$\{z \colon Z \mid z = 10\}$$

(c)

$$\{z \colon Z \mid z \bmod 2 = 0 \vee z \bmod 3 = 0 \vee z \bmod 5 = 0\}$$

Solution 22

(a)

$$\{n \colon N \mid n \leq 4 \bullet n^2\}$$

(b)

$$\{n \colon N \mid n \leq 4 \bullet (n, n^2)\}$$

(c) $n : P0, 1$

(d) $\{n \colon \mathbb{P}\{0,1\} \mid \mathit{true} \bullet (n, \#n)\}$

Solution 23

(a)

$$\begin{aligned} & x \in a \cap a \\ & \qquad \Leftrightarrow x \in a \wedge x \in a \\ & \qquad \Leftrightarrow x \in a \end{aligned}$$

(b)

$$\begin{aligned} & x \in a \cup a \\ & \qquad \Leftrightarrow x \in a \vee x \in a \\ & \qquad \Leftrightarrow x \in a \end{aligned}$$

Solution 24

(a)

The set of all pairs of integers is Z cross Z. To give it a name, we could write:

Pairs == Z $\times Z$

(b)

The set of all integer pairs in which each element is strictly greater than zero could be defined by:

StrictlyPositivePairs == { m, n : $Z \mid m > 0 \wedge n > 0 \bullet (m, n)\}$

(c)

It is intuitive to use a singular noun for the name of a basic type; we define the set of all people by writing:

$[Person]$

(d)

The set of all couples could be defined by:

Couples == { s : $\mathbb{P}$ $Person \mid \#s = 2\}$

Solution 25

(Requires generic set notation and Cartesian product)

Solution 26

(Requires generic parameters and relation type notation)

Relations

Solution 27

(a)

The power set of $\{(0,0),(0,1),(1,0),(1,1)\}$ is:

$\{\emptyset,\{(0,0)\},\{(0,1)\},\{(1,0)\},\{(1,1)\},\{(1,0),(1,1)\},\{(0,0),(0,1)\},\{(0,1),(1,1)\},\{(0,1),(1,0)\},\{(0,0),(1,1)\},\{(0,0$

(b)

$$\{\emptyset, \{(0,0)\}, \{(0,1)\}, \{(0,0),(0,1)\}\}$$

(c)

$$\{\emptyset\}$$

(d)

$$\{\emptyset\}$$

Solution 28

(a)

$$\operatorname{dom} R = \{0,1,2\}$$

(b)

$$\operatorname{ran} R = \{1,2,3\}$$

(c)

$$\{1,2\} \lhd R = \{1 \mapsto 2, 1 \mapsto 3, 2 \mapsto 3\}$$

Solution 29

(a)

$$\{2 \mapsto 4, 3 \mapsto 3, 3 \mapsto 4, 4 \mapsto 2\}$$

(b)

$$\{1 \mapsto 3, 2 \mapsto 2, 2 \mapsto 3, 3 \mapsto 1\}$$

(c)

$$\{1 \mapsto 1, 2 \mapsto 2, 2 \mapsto 3, 3 \mapsto 2, 3 \mapsto 3, 4 \mapsto 4\}$$

(d)

$$\{1 \mapsto 4, 2 \mapsto 2, 2 \mapsto 3, 3 \mapsto 2, 3 \mapsto 3, 4 \mapsto 1\}$$

Solution 30

$$\begin{array}{|l} childOf : Person \leftrightarrow Person \end{array}$$

(a)

parentOf == childOf^{-1}

This is a good example of how there are many different ways of writing the same thing. An alternative abbreviation is:

parentOf == { x, y : $Person \mid x \mapsto y \in childOf \bullet y \mapsto x\}$

Or, via an axiomatic definition:

$$\begin{array}{|l} parentOf : Person \leftrightarrow Person \\ \hline parentOf = childOf^{-1} \end{array}$$

(b)

siblingOf == (childOf $\circ parentOf) \setminus id$

(c)

cousinOf == childOf $\circ siblingOf \circ parentOf$

(d)

ancestorOf == parentOf^{+}

Solution 31

(Requires compound identifiers with operators - R+, R*)

(a)

R == { a, b : $N \mid b = a \vee b = a\}$

(b)

S == { a, b : $N \mid b = a \vee b = a\}$

(c) R+ == $\{a, b \colon N \mid b > a\}$

(d) R* == $\{a, b \colon N \mid b \geq a\}$

Solution 32

(a)

$$\begin{aligned} & x \mapsto y \in A \lhd B \lhd R \\ & \qquad \Leftrightarrow x \in A \wedge x \mapsto y \in (B \lhd R) \\ & \qquad \Leftrightarrow x \in A \wedge x \in B \wedge x \mapsto y \in R \\ & \qquad \Leftrightarrow x \in A \cap B \wedge x \mapsto y \in R \\ & \qquad \Leftrightarrow x \mapsto y \in A \cap B \lhd R \end{aligned}$$

(b)

$$
\begin{aligned}
& x \mapsto y \in R \cup S \rhd C \\
& \qquad \Leftrightarrow x \mapsto y \in R \cup S \wedge y \in C \\
& \qquad \Leftrightarrow (x \mapsto y \in R \vee x \mapsto y \in S) \wedge y \in C \\
& \qquad \Leftrightarrow x \mapsto y \in R \wedge y \in C \vee x \mapsto y \in S \wedge y \in C \\
& \qquad \Leftrightarrow x \mapsto y \in R \rhd C \vee x \mapsto y \in S \rhd C \\
& \qquad \Leftrightarrow x \mapsto y \in (R \rhd C) \cup (S \rhd C)
\end{aligned}
$$

Functions

Solution 33

The set of 9 functions:

$$\{\emptyset, \{(0,0)\}, \{(0,1)\}, \{(1,1)\}, \{(1,0)\}, \{(0,0),(1,1)\}, \{(0,1),(1,1)\}, \{(1,0),(0,0)\}, \{(0,1),(1,0)\}\}$$

(a)

The set of total functions:

$$\{\{(0,0),(1,1)\}, \{(0,1),(1,1)\}, \{(1,0),(0,0)\}, \{(0,1),(1,0)\}\}$$

(b)

The set of functions which are neither injective nor surjective:

$$\{\{(0,1),(1,1)\}, \{(0,0),(1,0)\}\}$$

(c)

The set of functions which are injective but not surjective:

$$\{\emptyset, \{(0,0)\}, \{(0,1)\}, \{(1,0)\}, \{(1,1)\}\}$$

(d) There are no functions (of this type) which are surjective but not injective.

(e)

The set of bijective functions:

$$\{\{(0,0),(1,1)\},\{(0,1),(1,0)\}\}$$

Solution 34

(a)

$$\{1 \mapsto a, 2 \mapsto b, 3 \mapsto c, 4 \mapsto b\}$$

(b)

$$\{1 \mapsto c, 2 \mapsto b, 3 \mapsto c, 4 \mapsto d\}$$

(c)

$$\{1 \mapsto c, 2 \mapsto b, 3 \mapsto c, 4 \mapsto b\}$$

(d)

$$\{1 \mapsto c, 2 \mapsto b, 3 \mapsto c, 4 \mapsto b\}$$

Solution 35

(Requires power set notation P and relational image)

(a)

$$\begin{array}{|l}
children : Person \to \mathbb{P}\ Person \\
\hline
children = \{p\colon Person \bullet p \mapsto parentOf(\!|\ \{p\}\ |\!)\}
\end{array}$$

(b)

$$\begin{array}{|l}
number_of_grandchildren : Person \to N \\
\hline
number_of_grandchildren = \{p\colon Person \bullet p \mapsto \#parentOf \circ parentOf(\!|\ \{p\}\ |\!)\}
\end{array}$$

Solution 36

(Note: This solution demonstrates relation types in quantifier domains)

$$\begin{array}{|l}
number_of_drivers : Drivers \leftrightarrow Cars \to (Cars \to N) \\
\hline
number_of_drivers = \lambda\, r : Drivers \leftrightarrow Cars \bullet \{c\colon \operatorname{ran} r \bullet c \mapsto \#\{d\colon Drivers \mid d \mapsto c \in r\}\}
\end{array}$$

Sequences

Solution 37

(a)

$$\langle a \rangle$$

(b)

$$\{1 \mapsto a, 2 \mapsto b, 2 \mapsto a, 3 \mapsto c, 3 \mapsto b, 4 \mapsto d\}$$

(c)

$$\{2 \mapsto b, 3 \mapsto c, 4 \mapsto d\}$$

(d)

$$\{1, 2, 3, 4\}$$

(e)

$$\{a, b\}$$

(f)

$$\{a \mapsto 1, b \mapsto 2, c \mapsto 3, d \mapsto 4\}$$

(g)

$$\langle a, b \rangle$$

(h)

$$\{3 \mapsto b\}$$

(i)

$$\{a\}$$

(j)

$$c$$

Solution 38

(a)

$$\begin{array}{|l} f : Place \rightarrow \mathbb{P}\ Place \\ \hline \forall\, p\colon Place \bullet f(p) = \{q\colon Place \mid p \mapsto q \in \operatorname{ran} trains\} \end{array}$$

(b)

$$\{p\colon Place \mid \exists_1\, x\colon \operatorname{dom} trains \bullet trains(x).2 = p\}$$

(c)

$$\mu\, p\colon Place \bullet \forall\, q\colon Place \bullet p \neq q \land \#\{x\colon \operatorname{dom} trains \mid trains(x).2 = p\} > \#\{x\colon \operatorname{dom} trains \mid trains(x).2 = q\}$$

Solution 39

(a)

$large\_coins : Collection \rightarrow N$

$\forall\, c\colon Collection \bullet large\_coins(c) = c(large)$

(Blocked $by : underscoreinidentifierforfuzzcompatibility$)

(b)

$add\_coin : Collection * Coin \rightarrow Collection$

$\forall\, c\colon Collection \bullet \forall\, d\colon Coin \bullet add\_coin(c, d) = c \cup [\![d]\!]$

(Blocked $by : underscoreinidentifierandbagunion$)

Modelling

Solutions 40-52 are work in progress - many require features not yet implemented

Solution 40

(Work in progress - requires semicolon-separated bindings in set comprehensions)

(a)

$hd : seq(Title * Length * Viewed)$

$cumulative\_total(hd) \leq 12000$

$\forall p\colon \operatorname{ran} hd \bullet p.2 \leq 360$

Note that cumulative$_t otalisdefinedinpart(d)$.

(b)

$$\{p\colon \operatorname{ran} hd \mid p.2 > 120 \bullet p.1\}$$

(c)

These can be defined recursively:

$viewed : \text{seq } Programme \rightarrow \text{seq } Programme$

$viewed(\langle\rangle) = \langle\rangle \land \forall x\colon Programme \bullet \forall s\colon \text{ seq } Programme \bullet viewed(\langle x\rangle \frown s) = (\text{if } x.3 = yes \text{ then } \langle x\rangle \frown viewe$

or otherwise (omitted - requires semicolon-separated bindings in set comprehension)

(d)

$cumulative\_total : \text{seq } Title * Length * Viewed \rightarrow N$

$cumulative\_total(\langle\rangle) = 0 \, \forall x\colon Title * Length * Viewed \bullet \forall s\colon \text{ seq } Title * Length * Viewed \bullet cumulative\_total$

(e)

(mu $p : ranhd \, |\forall q\colon \operatorname{ran} hd \bullet p \neq q \land p.2 > q.2|$ p.1)

(This, of course, assumes that there is a unique element with this property.)

(f)

(f) Omitted - requires semicolon-separated bindings in nested set comprehension

(g)

axdef

$g : seq(Title * Length * Viewed) \to seq(Title * Length * Viewed)$

where

$\forall s: \text{seq } Title * Length * Viewed \bullet g(s) = s \rhd \{x: \text{ran } s \mid x \neq longest\_viewed(s)\}$

end

Where longest$_v iewedisdefinedas$

axdef

$longest\_viewed : seq(Title * Length * Viewed)+ \to Title * Length * Viewed$

where

$\forall s: \text{seq } Title * Length * Viewed \bullet longest_viewed(s) = (\mu p: \text{ran } s \bullet p.3 = yes$and $\forall q: \text{ran } s \bullet p \neq q \land q.3 = yes \land p.2 > q.2)$

end

This, of course, assumes that there is at least one viewed programme (and one of a unique maximum length).

(h)

$s : \text{seq } Title * Length * Viewed \to \text{seq } Title * Length * Viewed$

$\forall x: \text{seq } Title * Length * Viewed \bullet items(s(x)) = items(x) \land \forall i, j: \text{dom } s(x) \bullet i < j \Rightarrow s(x)(i).2 \geq s(x)(j).2$

Solution 41

(a)

axdef

$records : Year \rightarrowtail\!\!\!\!\!\!\!\rightarrow \text{Table}$

where

dom(records) = 1993..current

$\forall\, y\colon\ \mathrm{dom}\, \mathit{records} \bullet \#\mathit{records}(y) \leq 50$

$\forall\ y : \mathit{dom}(\mathit{records})\ |\forall\, e\colon\ \mathrm{ran}\, \mathit{records}(y) \bullet \mathit{year}(e.1) = y$

$\forall\ r : \mathit{ran}(\mathit{records})\ |\forall\, i1, i2\colon\ \mathrm{dom}\, r \bullet i1 \neq i2 \land r(i1).1 = r(i2).1 \Rightarrow r(i1).3 \neq r(i2).3$

end

(b)

(i)

$$\{e\colon \mathit{Entry} \mid \exists\, r\colon\ \mathrm{ran}\, \mathit{records} \bullet e \in \mathrm{ran}\, r \land e.3 = 479\}$$

$$ii$$

$$\{e\colon \mathit{Entry} \mid \exists\, r\colon\ \mathrm{ran}\, \mathit{records} \bullet e \in \mathrm{ran}\, r \land e.6 > e.5\}$$

$$iii$$

$$\{e\colon \mathit{Entry} \mid \exists\, r\colon\ \mathrm{ran}\, \mathit{records} \bullet e \in \mathrm{ran}\, r \land e.7 \geq 70\}$$

$$iv$$

$$\{c\colon \mathit{Course} \mid \forall\, r\colon\ \mathrm{ran}\, \mathit{records} \bullet \forall\, e\colon\ \mathrm{ran}\, r \bullet e.2 = c \Rightarrow e.7 \geq 70\}$$

$$v$$

$\{y\colon\ \mathit{Year} \mid y \in \mathrm{dom}\, \mathit{records} \bullet y \mapsto \{l\colon \mathit{Lecturer} \mid \#\{c\colon\ \mathrm{ran}\, \mathit{records}(y) \mid c.4 = l\} > 6\}\}$

(c)

axdef

where

$\forall\, x\colon \mathit{Entry} \bullet \forall\, s\colon\ \mathrm{seq}\ \mathit{Entry} \bullet 479\_courses(\langle\rangle) = \langle\rangle$ and $479_c ourses(\langle x\rangle\ ^s) = if x.3 = 479 then \langle x\rangle\ ^479_c ourses(s) else 479_c ourses(s)$

end

(Blocked $by : underscoreinidentifier - usecamelCaseforfuzzcompatibility$)

(d)

$$\forall x\colon Entry \bullet \forall s\colon \mathrm{seq}\ Entry \bullet total(\langle\rangle) = 0 \land total(\langle x\rangle \frown s) = x.5 + total(s)$$

Solution 42

$[Person]$

axdef

$State : P(seq(iseq(Person)))$

where

$\forall\ s : State\ |\forall\, i, j\colon\ \mathrm{dom}\, s \bullet i \neq j \land \mathrm{ran}\, s(i) \cap \mathrm{ran}\, s(j) = \{\}$

end

(b)

axdef

$add : N * Person * State \rightarrowtail\!\!\!\!\rightarrow$ State

where

$\forall\, n\colon N \bullet \forall\, p\colon Person \bullet \forall\, s\colon State \bullet n \in \mathrm{dom}\, s \land p \notin \bigcup \mathrm{ran}\, \mathrm{ran}\, s|$

add(n, p, s) = s ++ n $\mapsto$ s(n) $\langle p\rangle$

end

(Blocked by: $\rightarrowtail\!\!\!\!\rightarrow$ operator not implemented)

Solution 43

(a)

(i) $\forall\ i : dombookings\ |\forall\, x, y\colon bookings(i) \bullet x \neq y \wedge x.2 \mathrel{..} x.3 \cap y.2 \mathrel{..} y.3 = \{\}$

(ii) $\forall\ i : dombookings\ |\forall$ x : $bookings(i)|$ $\{x.2, x.3\}$ subseteq 1..max(i.1)

(iii) $\forall\ i : dombookings\ |\forall\, b\colon bookings(i) \bullet b.2 \leq b.3$

(iv) This is enforced by the constraint for part (i).

(b)

(i) $\{i\colon \operatorname{dom} bookings \mid i.1 = Banbury \bullet i.2\}$

(ii) $\{i\colon \operatorname{dom} bookings \mid i.1 = Banbury \wedge \exists\, b\colon bookings(i) \bullet 50 \in b.2 \mathrel{..} b.3\}$

(iii) $r : Room;\ s : N\ |\exists\, i\colon \operatorname{dom} bookings \bullet i.1 = r \wedge i.2 = s.$ (r, s)

(iv) $r : Room\ |\exists\, i\colon \operatorname{dom} bookings \bullet i.1 = r \wedge \#bookings(i) \geq 10$

Free types and induction

$[N]$

$Tree ::= stalk \mid leaf\langle\langle N\rangle\rangle \mid branch\langle\langle Tree \times Tree\rangle\rangle$

Solution 44

The two cases of the proof are established by equational $reasoning : thefirstby$

reverse $(\langle\rangle\ ^{t}) = reverset[cat.1a] = (reverset)\langle\rangle$ [cat.1b]

where cat.1a is $\langle\rangle$ s = s$andcat.1biss\langle\rangle$ = s

and the second by

reverse $((\langle x\rangle\ ^{u})^{t}) = reverse(\langle x\rangle\ ^{(}u^{t}))[cat.2]$

= reverse (u $^{t})\langle x\rangle$ [reverse.2]

= (reverse t $^{r}everseu)\langle x\rangle$ [anti-distributive]

= reverse t $^{(}reverseu\langle x\rangle)$ [cat.2]

= reverse t $^{r}everse(\langle x\rangle\ ^{u})[reverse.2]$

Solution 45

The base case:

reverse (reverse $\langle\rangle$) = reverse $\langle\rangle$ [reverse.1] = $\langle\rangle$ [reverse.1]

The inductive step:

reverse (reverse ($\langle x \rangle$ ^{t}))

= reverse ((reverse t) $\langle x \rangle$) [reverse.2]

= reverse ($\langle x \rangle$) $^{r}everse(reverset)[anti - distributive]$

= reverse ($\langle x \rangle$ $\langle\rangle$) $^{r}everse(reverset)[cat.1]$

= ((reverse $\langle\rangle$) $\langle x \rangle$) $^{r}everse(reverset)[reverse.2]$

= ($\langle\rangle$ $\langle x \rangle$) $^{r}everse(reverset)[reverse.1]$

= $\langle x \rangle$ $^{r}everse(reverset)[cat.1]$

= $\langle x \rangle$ $^{t}[reverse(reverset) = t]$

Solution 46

(a)

$count : Tree \to N$

count $stalk = 0$

$\forall\, n \colon N \bullet count(leaf(n)) = 1$

$\forall\, t1, t2 \colon Tree \bullet count(branch(t1, t2)) = count(t1) + count(t2)$

(Blocked $by : recursivefreetypesandpatternmatching$)

(b)

$flatten : Tree \to seqN$

flatten stalk = $\langle\rangle$

$\forall n: N \bullet \mathit{flatten}(\mathit{leaf}(n)) = \langle n \rangle$

$\forall t1, t2: \mathit{Tree} \bullet \mathit{flatten}(\mathit{branch}(t1, t2)) = \mathit{flatten}(t1^{\mathit{flatten}})(t2)$

(Blocked $\mathit{by} : \mathit{recursivefreetypesandpatternmatching}$)

Solution 47

First, exhibit the induction principle for the free type:

P stalk and ($\forall n: N \bullet \mathbb{P}\ \mathit{leaf}(n)$) and ($\forall t1, t2: \mathit{Tree} \bullet \mathbb{P}\ t1 \land \mathbb{P}\ t2 \Rightarrow \mathbb{P}\ \mathit{branch}(t1, t2)$)

implies $\forall t: \mathit{Tree} \bullet \mathbb{P}\ t$

This gives three cases for the proof:

(flatten stalk) = $\langle\rangle$ [flatten] = 0 [] = count stalk [count]

(Remaining cases omitted - require equational reasoning with recursive functions)

Supplementary material : assignment practice

Solution 48

$[\mathit{SongId}, \mathit{UserId}, \mathit{PlaylistId}, \mathit{Playlist}]$

$\mathit{songs} : \mathbb{F}\ \mathit{SongIdusers} : \mathbb{F}\ \mathit{UserIdplaylists} : \mathit{PlaylistId} \nrightarrow \mathit{PlaylistplaylistOwner} : \mathit{PlaylistId} \nrightarrow \mathit{UserIdplaylistS}$

$\forall i: \operatorname{dom} \mathit{playlists} \bullet \operatorname{ran} \mathit{playlists}(i)(\mathit{subseteq})(\mathit{songs}) \operatorname{dom} \mathit{playlistOwner}(\mathit{subseteq})(\operatorname{dom} \mathit{playlists}) \operatorname{ran} \mathit{playlistO}$

Solution 49

$\mathit{hated} : \mathit{UserId} \nrightarrow \mathbb{F}\ \mathit{SongIdloved} : \mathit{UserId} \nrightarrow \mathbb{F}\ \mathit{SongId}$

$\operatorname{dom} \mathit{hated}(\mathit{subseteq})(\mathit{users}) \forall i: \operatorname{dom} \mathit{hated} \bullet \mathit{hated}(i)(\mathit{subseteq})(\mathit{songs}) \operatorname{dom} \mathit{loved}(\mathit{subseteq})(\mathit{users}) \forall i: \operatorname{dom}$

Solution 50

(a)

A == users $\setminus \bigcup \operatorname{ran} \mathit{playlistSubscribers}$

(b)

B == { p : dom $\mathit{playlistSubscribers} \mid \#\mathit{playlistSubscribers}(p) \geq 100\}$

(c)

C == $\mu\, u\colon \operatorname{dom} \mathit{loved} \bullet \forall\, v\colon \operatorname{dom} \mathit{loved} \bullet u \neq v \wedge \#\mathit{loved}(u) > \#\mathit{loved}(v)$

(d)

D == $\mu\, s\colon \mathit{songs} \bullet \forall\, t\colon \mathit{songs} \bullet s \neq t \wedge \#\{u\colon \mathit{UserId} \mid s \in \mathit{loved}(u)\} > \#\{u\colon \mathit{UserId} \mid t \in \mathit{loved}(u)\}$

Solution 51

(a)

Let's first define two helper functions:

$\mathit{loveHateScore} : \mathit{SongId}+ \rightarrow N$

$\forall\ i : \mathit{songs} \mid \{u\colon \mathit{UserId} \mid i \in \mathit{loved}(u)\} \geq\ \{u\colon \mathit{UserId} \mid i \in \mathit{hated}(u)\} \Rightarrow$

loveHateScore(i) = $\{u\colon \mathit{UserId} \mid i \in \mathit{loved}(u)\}$ - $\{u\colon \mathit{UserId} \mid i \in \mathit{hated}(u)\}$

and

$\forall\ i : \mathit{songs} \mid \{u\colon \mathit{UserId} \mid i \in \mathit{loved}(u)\} <\ \{u\colon \mathit{UserId} \mid i \in \mathit{hated}(u)\} \Rightarrow$

loveHateScore(i) = 0

$\mathit{playlistCount} : \mathit{SongId} \nrightarrow N$

$\forall\, i\colon \mathit{songs} \bullet \mathit{playlistCount}(i) = \#\{p\colon \operatorname{dom} \mathit{playlist} \mid i \in \operatorname{ran} \mathit{playlist}(p)\}$

We then have:

$$\begin{array}{|l} length : SongId \rightarrow\!\!\!\!\!\!+ \; Npopularity : SongId \rightarrow\!\!\!\!\!\!+ \; N \\ \hline \mathrm{dom}\, length(subseteq)(songs)\, \mathrm{dom}\, popularity(subseteq)(songs) \,\forall\, i : songs \bullet popularity(i) = loveHateScore(i) + \end{array}$$

(b)

$mostPopular : SongId$

$(\exists_1 \; i : songs \; |\forall\, j : songs \bullet i \neq j \wedge popularity(i) > popularity(j)) \Rightarrow$

mostPopular = (mu i : $songs$ $|\forall\, j : songs \bullet i \neq j \wedge popularity(i) > popularity(j))$

and

$\neg \; \exists_1 \, i : songs \bullet \forall\, j : songs \bullet i \neq j \wedge popularity(i) > popularity(j) \Rightarrow mostPopular = nullSong$

(c) playlistsContainingMostPopularSong == $\{i : \; \mathrm{dom}\, playlists \mid mostPopular \in \mathrm{ran}\, playlists(i)\}$

Solution 52

(a)

$premiumPlays : seq(Play) \rightarrow seq(Play)$

premiumPlays($\langle\rangle$) = $\langle\rangle$

$\forall \; x : Play; \; s : seq(Play) \; |$

premiumPlays($\langle x \rangle \; ^s$) =$\langle x \rangle \; ^p remiumPlays(s) if userStatus(x.2) = premium$

premiumPlays(s) if userStatus(x.2) = standard

(Note: Uses camelCase for fuzz compatibility)

(b)

$standardPlays : seq(Play) \rightarrow seq(Play)$

standardPlays($\langle\rangle$) = $\langle\rangle$

$\forall\ x : Play;\ s : seq(Play) \mid$

standardPlays($\langle x \rangle\ ^s$) =$\langle x \rangle\ ^s tandardPlays(s) if userStatus(x.2) = standard$

standardPlays(s) if userStatus(x.2) = premium

(Note: Uses camelCase for fuzz compatibility)

(c)

$cumulativeLength : seq(Play) \rightarrow N$

cumulativeLength($\langle\rangle$) = 0

$\forall\ x : Play;\ s : seq(Play) \mid$

cumulativeLength($\langle x \rangle\ ^s$) = $length(x.1) + cumulativeLength(s)$

(Note: Uses camelCase for fuzz compatibility)