req.1 Basic Functions are Representable in Q

inc:req:bre: sec

First we have to show that all the basic functions are representable in $\mathbf{Q}$. In the end, we need to show how to assign to each k-ary basic function $f(x_0, \ldots, x_{k-1})$ a formula $\varphi_f(x_0, \ldots, x_{k-1}, y)$ that represents it.

We will be able to represent zero, successor, plus, times, the characteristic function for equality, and projections. In each case, the appropriate representing function is entirely straightforward; for example, zero is represented by the formula $y = \mathsf{o}$, successor is represented by the formula $x_0' = y$, and addition is represented by the formula $(x_0 + x_1) = y$. The work involves showing that $\mathbf{Q}$ can prove the relevant sentences; for example, saying that addition is represented by the formula above involves showing that for every pair of natural numbers m and n, $\mathbf{Q}$ proves

$$\overline{n} + \overline{m} = \overline{n+m} \text{ and}$$
$$\forall y\,((\overline{n} + \overline{m}) = y \rightarrow y = \overline{n+m}).$$

inc:req:bre: prop:rep-zero

Proposition req.1. *The zero function* $\mathrm{zero}(x) = 0$ *is represented in* $\mathbf{Q}$ *by* $\varphi_{\mathrm{zero}}(x, y) \equiv y = \mathsf{o}$.

inc:req:bre: prop:rep-succ

Proposition req.2. *The successor function* $\mathrm{succ}(x) = x + 1$ *is represented in* $\mathbf{Q}$ *by* $\varphi_{\mathrm{succ}}(x, y) \equiv y = x'$.

inc:req:bre: prop:rep-proj

Proposition req.3. *The projection function* $P^n_i(x_0, \ldots, x_{n-1}) = x_i$ *is represented in* $\mathbf{Q}$ *by*

$$\varphi_{P^n_i}(x_0, \ldots, x_{n-1}, y) \equiv y = x_i.$$

Problem req.1. Prove that $y = \mathsf{o}$, $y = x'$, and $y = x_i$ represent zero, succ, and P^n_i, respectively.

inc:req:bre: prop:rep-id

Proposition req.4. *The characteristic function of* $=$,

$$\chi_=(x_0, x_1) = \begin{cases} 1 & \text{if } x_0 = x_1 \\ 0 & \text{otherwise} \end{cases}$$

is represented in $\mathbf{Q}$ *by*

$$\varphi_{\chi_=}(x_0, x_1, y) \equiv (x_0 = x_1 \wedge y = \overline{1}) \vee (x_0 \neq x_1 \wedge y = \overline{0}).$$

The proof requires the following lemma.

inc:req:bre: lem:q-proves-neq

Lemma req.5. *Given natural numbers* n *and* m, *if* $n \neq m$, *then* $\mathbf{Q} \vdash \overline{n} \neq \overline{m}$.

Proof. Use induction on n to show that for every m, if $n \neq m$, then $Q \vdash \overline{n} \neq \overline{m}$.

In the base case, $n = 0$. If m is not equal to 0, then $m = k + 1$ for some natural number k. We have an axiom that says $\forall x\, 0 \neq x'$. By a quantifier axiom, replacing x by $\overline{k}$, we can conclude $0 \neq \overline{k}'$. But $\overline{k}'$ is just $\overline{m}$.

In the induction step, we can assume the claim is true for n, and consider $n+1$. Let m be any natural number. There are two possibilities: either $m = 0$ or for some k we have $m = k+1$. The first case is handled as above. In the second case, suppose $n+1 \neq k+1$. Then $n \neq k$. By the induction hypothesis for n we have $\mathbf{Q} \vdash \overline{n} \neq \overline{k}$. We have an axiom that says $\forall x \, \forall y \, x' = y' \rightarrow x = y$. Using a quantifier axiom, we have $\overline{n}' = \overline{k}' \rightarrow \overline{n} = \overline{k}$. Using propositional logic, we can conclude, in $\mathbf{Q}$, $\overline{n} \neq \overline{k} \rightarrow \overline{n}' \neq \overline{k}'$. Using modus ponens, we can conclude $\overline{n}' \neq \overline{k}'$, which is what we want, since $\overline{k}'$ is $\overline{m}$. □

explanation

Note that the lemma does not say much: in essence it says that $\mathbf{Q}$ can prove that different numerals denote different objects. For example, $\mathbf{Q}$ proves $0'' \neq 0'''$. But showing that this holds in general requires some care. Note also that although we are using induction, it is induction *outside* of $\mathbf{Q}$.

Proof of Proposition req.4. If $n = m$, then $\overline{n}$ and $\overline{m}$ are the same term, and $\chi_=(n, m) = 1$. But $\mathbf{Q} \vdash (\overline{n} = \overline{m} \land \overline{1} = \overline{1})$, so it proves $\varphi_=(\overline{n}, \overline{m}, \overline{1})$. If $n \neq m$, then $\chi_=(n, m) = 0$. By Lemma req.5, $\mathbf{Q} \vdash \overline{n} \neq \overline{m}$ and so also $(\overline{n} \neq \overline{m} \land \mathsf{o} = \mathsf{o})$. Thus $\mathbf{Q} \vdash \varphi_=(\overline{n}, \overline{m}, \overline{0})$.

For the second part, we also have two cases. If $n = m$, we have to show that $\mathbf{Q} \vdash \forall y \, (\varphi_=(\overline{n}, \overline{m}, y) \rightarrow y = \overline{1})$. Arguing informally, suppose $\varphi_=(\overline{n}, \overline{m}, y)$, i.e.,

$$(\overline{n} = \overline{n} \land y = \overline{1}) \lor (\overline{n} \neq \overline{n} \land y = \overline{0})$$

The left disjunct implies $y = \overline{1}$ by logic; the right contradicts $\overline{n} = \overline{n}$ which is provable by logic.

Suppose, on the other hand, that $n \neq m$. Then $\varphi_=(\overline{n}, \overline{m}, y)$ is

$$(\overline{n} = \overline{m} \land y = \overline{1}) \lor (\overline{n} \neq \overline{m} \land y = \overline{0})$$

Here, the left disjunct contradicts $\overline{n} \neq \overline{m}$, which is provable in $\mathbf{Q}$ by Lemma req.5; the right disjunct entails $y = \overline{0}$. □

Proposition req.6. *The addition function* $\mathrm{add}(x_0, x_1) = x_0 + x_1$ *is represented in* $\mathbf{Q}$ *by* *inc:req:bre: prop:rep-add*

$$\varphi_{\mathrm{add}}(x_0, x_1, y) \equiv y = (x_0 + x_1).$$

Lemma req.7. $\mathbf{Q} \vdash (\overline{n} + \overline{m}) = \overline{n + m}$ *inc:req:bre: lem:q-proves-add*

Proof. We prove this by induction on m. If $m = 0$, the claim is that $\mathbf{Q} \vdash (\overline{n} + \mathsf{o}) = \overline{n}$. This follows by axiom Q_4. Now suppose the claim for m; let's prove the claim for $m+1$, i.e., prove that $\mathbf{Q} \vdash (\overline{n} + \overline{m+1}) = \overline{n+m+1}$. Note that $\overline{m+1}$ is just $\overline{m}'$, and $\overline{n+m+1}$ is just $\overline{n+m}'$. By axiom Q_5, $\mathbf{Q} \vdash (\overline{n} + \overline{m}') = (\overline{n} + \overline{m})'$. By induction hypothesis, $\mathbf{Q} \vdash (\overline{n} + \overline{m}) = \overline{n+m}$. So $\mathbf{Q} \vdash (\overline{n} + \overline{m}') = \overline{n+m}'$. □

Proof of Proposition req.6. The formula $\varphi_{\mathrm{add}}(x_0, x_1, y)$ representing add is $y = (x_0 + x_1)$. First we show that if $\mathrm{add}(n, m) = k$, then $\mathbf{Q} \vdash \varphi_{\mathrm{add}}(\overline{n}, \overline{m}, \overline{k})$, i.e.,

$\mathbf{Q} \vdash \overline{k} = (\overline{n} + \overline{m})$. But since $k = n + m$, $\overline{k}$ just is $\overline{n+m}$, and we've shown in Lemma req.7 that $\mathbf{Q} \vdash (\overline{n} + \overline{m}) = \overline{n+m}$.

We also have to show that if $\mathrm{add}(n, m) = k$, then

$$\mathbf{Q} \vdash \forall y\, (\varphi_{\mathrm{add}}(\overline{n}, \overline{m}, y) \to y = \overline{k}).$$

Suppose we have $(\overline{n} + \overline{m}) = y$. Since

$$\mathbf{Q} \vdash (\overline{n} + \overline{m}) = \overline{n+m},$$

we can replace the left side with $\overline{n+m}$ and get $\overline{n+m} = y$, for arbitrary y. □

inc:req:bre: prop:rep-mult **Proposition req.8.** *The multiplication function* $\mathrm{mult}(x_0, x_1) = x_0 \cdot x_1$ *is represented in* $\mathbf{Q}$ *by*

$$\varphi_{\mathrm{mult}}(x_0, x_1, y) \equiv y = (x_0 \times x_1).$$

Proof. Exercise. □

inc:req:bre: lem:q-proves-mult **Lemma req.9.** $\mathbf{Q} \vdash (\overline{n} \times \overline{m}) = \overline{n \cdot m}$

Proof. Exercise. □

Problem req.2. Prove Lemma req.9.

Problem req.3. Use Lemma req.9 to prove Proposition req.8.

Recall that we use $\times$ for the function symbol of the language of arithmetic, and $\cdot$ for the ordinary multiplication operation on numbers. So $\cdot$ can appear between expressions for numbers (such as in $m \cdot n$) while $\times$ appears only between terms of the language of arithmetic (such as in $(\overline{m} \times \overline{n})$). Even more confusingly, $+$ is used for both the function symbol and the addition operation. When it appears between terms—e.g., in $(\overline{n} + \overline{m})$—it is the 2-place function symbol of the language of arithmetic, and when it appears between numbers—e.g., in $n + m$—it is the addition operation. This includes the case $\overline{n+m}$: this is the standard numeral corresponding to the number $n + m$. explanation

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Bibliography