1 Basic construction

Proposition 1. *For all types A, the type $S^2 \to A$ is equal to*

$$\sum_{x:A} \mathrm{refl}_x = \mathrm{refl}_x.$$

Proposition 2. *Suppose that A is a type, B a family of types over A and P a family of mere propositions over A, such that we have a family of functions $B(x) \to P(x)$ for all $x : A$. We then have an equality of types*

$$\sum_{x:A} B(x) = \sum\Big(t : \sum_{x:A} P(x)\Big) B(\mathrm{pr}_1 t).$$

A function f is said to be *invertible* if it admits a two-sided inverse. We define the type of invertibility proofs of f to be the type

$$\mathrm{inverse}(f) :\equiv \sum_{g:B\to A} (f \circ g = \mathrm{id}) \times (g \circ f = \mathrm{id})$$

and denote the type of all invertible maps between two types A and B by $\mathrm{Inv}(A, B) :\equiv \sum_{f:A\to B} \mathrm{inverse}(f)$.

A function f is said to be an *equivalence* if it admits both a left and a right sided inverse. We define the type of equivalence proofs of f to be the type

$$\mathrm{equiv}(f) :\equiv \sum_{g:B\to A} (f \circ g = \mathrm{id}) \times \sum_{h:B\to A} (h \circ f = \mathrm{id})$$

and similarly denote the type of all equivalences between two types A and B by $A \simeq B$.

We recall the following two important facts:

Proposition 3. *For all functions f, the type of equivalence proofs of f is a mere proposition.*

Proposition 4. *For all functions f, the types of invertibility and equivalence proofs of f are logically equivalent. In other words, a function is invertible if and only if it is an equivalence.*

Lemma 5. *Suppose A is a type. The type of invertibility proofs of id_A is equal to $\mathrm{id}_A = \mathrm{id}_A$.*

Proof. By reassociating the dependent sum type, we see that the type of invertibility proofs of id_A is equal to

$$\sum\Big(G : \sum_{g:A\to A} (g = \mathrm{id}_A)\Big) (\mathrm{pr}_1 G = \mathrm{id}_A).$$

Since the type $\sum_{g:A\to A} (g = \mathrm{id}_A)$ is contractible onto $(\mathrm{id}_A, \mathrm{refl})$, we see the whole type is equal to $\mathrm{pr}_1 (\mathrm{id}_A, \mathrm{refl}) = \mathrm{id}_A$, which is itself equal to $\mathrm{id}_A = \mathrm{id}_A$. $\square$

Proposition 6. *The type* $\mathrm{Inv}(A,B)$ *is equal to the type* $\sum_{e:A=B} e = e$ *for all types* A *and* B.

Proof. We view inverse and equiv as two families of types over $A \to B$. Proposition 3 then tells us that equiv is a family of mere propositions over $A \to B$, whereas proposition 4 in particular tells us that we have a family of functions $\mathrm{inverse}(f) \to \mathrm{equiv}(f)$ for all functions $f : A \to B$. By proposition 2, it then follows that the type $\mathrm{Inv}(A,B)$ is equal to the type $\sum_{e:A\simeq B} \mathrm{inverse}(\mathrm{pr}_1 e)$.

On the other hand, we first observe that the type $\sum_{e:A=B} e = e$ is equal to the type $\sum_{e:A\simeq B} e = e$ by univalence. Now, since equiv is a family of mere propositions, $A \simeq B$ is a subtype of $A \to B$. By the subtype identity principle, it follows that the type $e = e$ is equal to the type $\mathrm{pr}_1 e = \mathrm{pr}_1 e$ for all equivalences $e : A \simeq B$.

To construct the desired equality, it thus suffices to construct an equality between the types $\sum_{e:A\simeq B} \mathrm{inverse}(\mathrm{pr}_1 e)$ and $\sum_{e:A\simeq B} \mathrm{pr}_1 e = \mathrm{pr}_1 e$. By the fiberwise equivalence construction, it further suffices to construct an equality between $\mathrm{inverse}(\mathrm{pr}_1 e)$ and $\mathrm{pr}_1 e = \mathrm{pr}_1 e$ for all equivalences $e : A \simeq B$. The result then follows by equivalence induction and Lemma 5. $\square$

Theorem 7. *The type* $\sum_{A,B:\mathcal{U}} \mathrm{Inv}(A,B)$ *is equal to the type* $S^2 \to \mathcal{U}$.

Proof. We first quantify the equality in Proposition 6 over $B : \mathcal{U}$, obtaining an equality between $\sum_{B:\mathcal{U}} \mathrm{Inv}(A,B)$ and $\sum_{B:\mathcal{U}} \sum_{e:A=B} e = e$. Since the type $\sum_{B:\mathcal{U}} A = B$ is contractible onto (A, refl_A), the second type is equal to $\mathrm{refl}_A = \mathrm{refl}_A$. Now quantifying over $A : \mathcal{U}$, we obtain an equality between $\sum_{A,B:\mathcal{U}} \mathrm{Inv}(A,B)$ and $\sum_{A:\mathcal{U}} \mathrm{refl}_A = \mathrm{refl}_A$, which is equal to $S^2 \to \mathcal{U}$ by the universal property of the sphere. $\square$

2 n-invertible functions

Definition 8. We define a notion of n-invertibility on $A \to B$ by induction on n. Let $f : A \to B$ be a function. We say that f is 0-invertible if there exists a function $g : B \to A$. We say that f is $(n+1)$-invertible if there exist functions $g : B \to A$ and

$$r : \prod_{x:A} \prod_{y:B} (fx = y) \to (x = gy),$$

such that $r(x,y)$ is n-invertible for all x and y.

We thus define the type of $(n+1)$-inverses to be

$$\mathrm{inverse}_{n+1}(f) = \sum_{g:B\to A} \sum_{r:\mathrm{Adj}(f,g)} \prod_{x:A} \prod_{y:B} \mathrm{inverse}_n(r(x,y)),$$

where $\mathrm{Adj}(f,g) = \prod_{x:A} \prod_{y:B} (fx = y) \to (x = gy)$.

Remark 9. We note that 1-invertibility coincides with the ordinary notion of invertibility. By path induction, the data of a 1-invertible function $f : A \to B$ consists exactly of a function $g : B \to A$, together with homotopies of type $\prod_{x:A} x = g(fx)$ and $\prod_{y:B} f(gy) = y$, witnessing that f is invertible.

Lemma 10. *The type* $\mathrm{inverse}_{n+1}(\mathrm{id}_A)$ *is equal to*

$$\prod_{x,y:A} \mathrm{inverse}_n(\mathrm{id}_{x=y})$$

for all $n : \mathbb{N}$.

Proposition 11. *The type* $\mathrm{inverse}_{n+1}(\mathrm{id}_A)$ *is equal to* $\prod_{x:A} \Omega^{n+1}(A,x)$ *for all* $n : \mathbb{N}$.

Proof. We prove the result by induction on n. We make use of the previous lemma in both cases. For the base case, we have

$$\begin{aligned}\mathrm{inverse}_1(\mathrm{id}_A) = \prod_{x,y:A} \mathrm{inverse}_0(\mathrm{id}_{x=y}) = \prod_{x,y:A} (x=y) \to (x=y) = \\ = \prod_{x:A}(x=x) = \prod_{x:A} \Omega^1(A,x).\end{aligned}$$

For the inductive step, we have

$$\begin{aligned}\mathrm{inverse}_{n+2}\,(\mathrm{id}_A) = \prod_{x,y:A} \mathrm{inverse}_{n+1}(\mathrm{id}_{x=y}) = \prod_{x,y:A} \prod_{p:x=y} \Omega^{n+1}(x=y,p) \\ = \prod_{x:A} \Omega^{n+1}(x=x, \mathrm{refl}_x) = \prod_{x:A} \Omega^{n+2}(A,x).\end{aligned}$$

□

Proposition 12. *Let* $n : \mathbb{N}$ *and suppose* $f : A \to B$ *is* $(n+1)$*-invertible. Then* f *is* n*-invertible.*

Proof. We again prove the result by induction on n. For the base case, suppose $f : A \to B$ is 1-invertible. We then have a function $g : B \to A$ together with some data, but g itself is enough to show that f is 0-invertible.

For the inductive step, suppose $f : A \to B$ is $(n+2)$-invertible. We then have a function $g : B \to A$ and a certain dependent function r, such that $r(x,y)$ is $(n+1)$-invertible for all $x, y : A$. By the inductive hypothesis, $r(x,y)$ is n-invertible for all $x, y : A$, showing that f is $(n+1)$-invertible. □

Corollary 13. *Let* $n : \mathbb{N}$ *and suppose* $f : A \to B$ *is* $(n+1)$*-invertible. Then* f *is an equivalence.*

Proof. Using the previous proposition, we can show that every $(n+1)$-invertible function is 1-invertible. Since 1-invertibility coincides with invertibility, this shows that it is also an equivalence. □

Theorem 14. *Let* $\mathcal{U}$ *be a universe and* $A : \mathcal{U}$ *a type. The type*

$$\sum_{B:\mathcal{U}} \sum_{f:A\to B} \mathrm{inverse}_{n+1}(f)$$

of all $(n+1)$*-invertible maps with domain* A *is equal to* $\Omega^{n+2}(\mathcal{U}, A)$.