

An Example of a Cofinitary Group in Isabelle/HOL

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Abstract

We formalize the usual proof that the group generated by the function $k \mapsto k + 1$ on the integers gives rise to a cofinitary group.

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```
theory CofGroups  
imports Main HOL-Library.Nat-Bijection  
begin
```

1 Introduction

Cofinitary groups have received a lot of attention in Set Theory. I will start by giving some references, that together give a nice view of the area. See also Kastermans [7] for my view of where the study of these groups (other

than formalization) is headed. Starting work was done by Adeleke [1], Truss [12] and [13], and Koppelberg [10]. Cameron [3] is a very nice survey. There is also work on cardinal invariants related to these groups and other almost disjoint families, see e.g. Brendle, Spinas, and Zhang [2], Hrušák, Steprans, and Zhang [5], and Kastermans and Zhang [9]. Then there is also work on constructions and descriptive complexity of these groups, see e.g. Zhang [14], Gao and Zhang [4], and Kastermans [6] and [8].

In this note we work through formalizing a basic example of a cofinitary group. We want to achieve two things by working through this example. First how to formalize some proofs from basic set-theoretic algebra, and secondly, to do some first steps in the study of formalization of this area of set theory. This is related to the work of Paulson and Grąbczewski [11] on formalizing set theory, our preference however is towards using Isar resulting in a development more readable for “normal” mathematicians.

A *cofinitary group* is a subgroup G of the symmetric group on \mathbb{N} (in Isabelle *nat*) such that all non-identity elements $g \in G$ have finitely many fixed points. A simple example of a cofinitary group is obtained by considering the group G' a subgroup of the symmetric group on \mathbb{Z} (in Isabelle *int* generated by the function $upOne : \mathbb{Z} \rightarrow \mathbb{Z}$ defined by $k \mapsto k + 1$). No element in this group other than the identity has a fixed point. Conjugating this group by any bijection $\mathbb{Z} \rightarrow \mathbb{N}$ gives a cofinitary group.

We will develop a workable definition of a cofinitary group (Section 2) and show that the group as described in the previous paragraph is indeed cofinitary (this takes the whole paper, but is all pulled together in Section 9). Note: formalizing the previous paragraph is all that is completed in this note.

Since this note is also written to be read by the proverbial “normal” mathematician we will sometimes remark on notations as used in Isabelle as they related to common notation. We do expect this proverbial mathematician to be somewhat flexible though. He or she will need to be flexible in reading, this is just like reading any other article; part of reading is reconstructing.

We end this introduction with a quick overview of the paper. In Section 2 we define the notion of cofinitary group. In Section 3 we define the function $upOne$ and give some of its basic properties. In Section 4 we define the set $Ex1$ which is the underlying set of the group generated by $upOne$, there we also derive a normal form theorem for the elements of this set. In Section 5 we show all elements in $Ex1$ are cofinitary bijections (cofinitary here is used in the general meaning of having finitely many fixed points). In Section 6 we show this set is closed under composition and inverse, in effect showing that it is a “cofinitary group” (cofinitary group here is in quotes, since we only define it for sets of permutations on the natural numbers). In Section 7 we show the general theorem that conjugating a permutation by a bijection

does the expected thing to the set of fixed points. In Section 8 we define the function *CONJ* that is conjugation by *ni-bij* (a bijection from *nat* to *int*), show that it acts well with respect to the group operations, use it to define *Ex2* which is the underlying set of the cofinitary group we are constructing, and show the basic properties of *Ex2*. Finally in Section 9 we quickly show that all the work in the section before it combines to show that *Ex2* is a cofinitary group.

2 The Main Notions

First we define the two main notions.

We write *S-inf* for the symmetric group on the natural numbers (we do not define this as a group, only as the set of bijections).

definition *S-inf* :: (*nat* \Rightarrow *nat*) set
where
S-inf = {*f* :: (*nat* \Rightarrow *nat*). *bij f*}

Note here that *bij f* is the predicate that *f* is a bijection. This is common notation in Isabelle, a predicate applied to an object. Related to this *inj f* means *f* is injective, and *surj f* means *f* is surjective.

The same notation is used for function application. Next we define a function *Fix*, applying it to an object is also written by juxtaposition.

Given any function *f* we define *Fix f* to be the set of fixed points for this function.

definition *Fix* :: (*'a* \Rightarrow *'a*) \Rightarrow (*'a* set)
where
Fix f = { *n* . *f*(*n*) = *n* }

We then define a locale *CofinitaryGroup* that represents the notion of a cofinitary group. An interpretation is given by giving a set of functions *nat* \rightarrow *nat* and showing that it satisfies the identities the locale assumes. A locale is a way to collect together some information that can then later be used in a flexible way (we will not make a lot of use of that here).

locale *CofinitaryGroup* =
fixes
dom :: (*nat* \Rightarrow *nat*) set
assumes
type-dom : *dom* \subseteq *S-inf* **and**
id-com : *id* \in *dom* **and**
mult-closed : *f* \in *dom* \wedge *g* \in *dom* \Longrightarrow *f* \circ *g* \in *dom* **and**
inv-closed : *f* \in *dom* \Longrightarrow *inv f* \in *dom* **and**
cofinitary : *f* \in *dom* \wedge *f* \neq *id* \Longrightarrow *finite* (*Fix f*)

3 The Function $upOne$

Here we define the function, $upOne$, translation up by 1 and proof some of its basic properties.

```
definition  $upOne :: int \Rightarrow int$   
where  
 $upOne\ n = n + 1$ 
```

```
declare  $upOne-def$  [ $simp$ ] — automated tools can use the definition
```

First we show that this function is a bijection. This is done in the usual two parts; we show it is injective by showing from the assumption that outputs on two numbers are equal that these two numbers are equal. Then we show it is surjective by finding the number that maps to a given number.

```
lemma  $inj-upOne: inj\ upOne$   
by ( $rule\ Fun.injI, simp$ )
```

```
lemma  $surj-upOne: surj\ upOne$   
proof ( $unfold\ Fun.surj-def, rule$ )  
  fix  $k::int$   
  show  $\exists m. k = upOne\ m$   
    by ( $rule\ exI[of\ \lambda l. k = upOne\ l\ k - 1], simp$ )  
qed
```

```
theorem  $bij-upOne: bij\ upOne$   
by ( $unfold\ bij-def, rule\ conjI\ [OF\ inj-upOne\ surj-upOne]$ )
```

Now we show that the set of fixed points of $upOne$ is empty. We show this in two steps, first we show that no number is a fixed point, and then derive from this that the set of fixed points is empty.

```
lemma  $no-fix-upOne: upOne\ n \neq n$   
proof ( $rule\ notI$ )  
  assume  $upOne\ n = n$   
  with  $upOne-def$  have  $n+1 = n$  by  $simp$   
  thus  $False$  by  $auto$   
qed
```

```
theorem  $Fix\ upOne = \{\}$   
proof —  
  from  $Fix-def[of\ upOne]$   
  have  $Fix\ upOne = \{n . upOne\ n = n\}$  by  $auto$   
  with  $no-fix-upOne$  have  $Fix\ upOne = \{n . False\}$  by  $auto$   
  with  $Set.empty-def$  show  $Fix\ upOne = \{\}$  by  $auto$   
qed
```

Finally we derive the equation for the inverse of $upOne$. The rule we use references *Hilbert-Choice* since the inv operator, the operator that gives an inverse of a function, is defined using Hilbert's choice operator.

```

lemma inv-upOne-eq: (inv upOne) (n::int) = n - 1
proof -
  fix n :: int
  have ((inv upOne) ∘ upOne) (n - 1) = (inv upOne) n by simp
  with inj-upOne and Hilbert-Choice.inv-o-cancel
  show (inv upOne) n = n - 1 by auto
qed

```

We can also show this quickly using *Hilbert-Choice.inv_f_eq* properly instantiated : $upOne (n - 1) = n \implies inv\ upOne\ n = n - 1$.

```

lemma (inv upOne) n = n - 1
by (rule Hilbert-Choice.inv-f-eq[of upOne n - 1 n, OF inj-upOne], simp)

```

4 The Set of Functions and Normal Forms

We define the set *Ex1* of all powers of *upOne* and study some of its properties, note that this is the group generated by *upOne* (in Section 6 we prove it closed under composition and inverse). In Section 5 we show that all its elements are cofinitary and bijections (bijections with finitely many fixed points). Note that this is not a cofinitary group, since our definition requires the group to be a subset of *S-inf*

```

inductive-set Ex1 :: (int  $\Rightarrow$  int) set where
  base-func: upOne  $\in$  Ex1 |
  comp-func: f  $\in$  Ex1  $\implies$  (upOne ∘ f)  $\in$  Ex1 |
  comp-inv : f  $\in$  Ex1  $\implies$  ((inv upOne) ∘ f)  $\in$  Ex1

```

We start by showing a *normal form* for elements in this set.

```

lemma Ex1-Normal-form-part1: f  $\in$  Ex1  $\implies$   $\exists k. \forall n. f(n) = n + k$ 

```

```

proof (rule Ex1.induct [of f], blast)
  - blast takes care of the first goal which is formal noise
  assume f  $\in$  Ex1
  have  $\forall n. upOne\ n = n + 1$  by simp
  with HOL.exI show  $\exists k. \forall n. upOne\ n = n + k$  by auto
next
  fix fa :: int  $\Rightarrow$  int
  assume fa-k:  $\exists k. \forall n. fa\ n = n + k$ 
  thus  $\exists k. \forall n. (upOne \circ fa)\ n = n + k$  by auto
next
  fix fa :: int  $\Rightarrow$  int
  assume fa-k:  $\exists k. \forall n. fa\ n = n + k$ 
  from inv-upOne-eq have  $\forall n. (inv\ upOne)\ n = n - 1$  by auto
  with fa-k show  $\exists k. \forall n. (inv\ upOne \circ fa)\ n = n + k$  by auto
qed

```

Now we'll show the other direction. Then we apply rule *int-induct* which allows us to do the induction by first showing it true for $k = 1$, then showing

that if true for $k = i$ it is also true for $k = i + 1$ and finally showing that if true for $k = i$ then it is also true for $k = i - 1$.

All proofs are fairly straightforward and use extensionality for functions. In the base case we are just dealing with *upOne*. In the other cases we define the function *?h* which satisfies the induction hypothesis. Then *f* is obtained from this by adding or subtracting one pointwise.

In this proof we use some pattern matching to save on writing. In the statement of the theorem, we match the theorem against *?P k* thereby defining the predicate *?P*.

```

lemma Ex1-Normal-form-part2:
  ( $\forall f. ((\forall n. f\ n = n + k) \longrightarrow f \in Ex1)$ ) (is ?P k)
proof (rule int-induct [of ?P 1])
  show  $\forall f. (\forall n. f\ n = n + 1) \longrightarrow f \in Ex1$ 
  proof
    fix f:: int  $\Rightarrow$  int
    show  $(\forall n. f\ n = n + 1) \longrightarrow f \in Ex1$ 
    proof
      assume  $\forall n. f\ n = n + 1$ 
      hence  $\forall n. f\ n = upOne\ n$  by auto
      with fun-eq-iff [of f upOne, THEN sym]
      have f = upOne by auto
      with Ex1.base-func show f  $\in Ex1$  by auto
    qed
  qed
next
  fix i::int
  assume  $1 \leq i$ 
  assume induct-hyp:  $\forall f. (\forall n. f\ n = n + i) \longrightarrow f \in Ex1$ 
  show  $\forall f. (\forall n. f\ n = n + (i + 1)) \longrightarrow f \in Ex1$ 
  proof
    fix f:: int  $\Rightarrow$  int
    show  $(\forall n. f\ n = n + (i + 1)) \longrightarrow f \in Ex1$ 
    proof
      assume f-eq:  $\forall n. f\ n = n + (i + 1)$ 
      let ?h =  $\lambda n. n + i$ 
      from induct-hyp have h-Ex1: ?h  $\in Ex1$  by auto
      from f-eq have  $\forall n. f\ n = upOne\ (?h\ n)$  by (unfold upOne-def, auto)
      hence  $\forall n. f\ n = (upOne \circ ?h)\ n$  by auto
      with fun-eq-iff [THEN sym, of f upOne  $\circ$  ?h]
      have f = upOne  $\circ$  ?h by auto
      with h-Ex1 and Ex1.comp-func [of ?h] show f  $\in Ex1$  by auto
    qed
  qed
next
  fix i::int
  assume  $i \leq 1$ 
  assume induct-hyp:  $\forall f. (\forall n. f\ n = n + i) \longrightarrow f \in Ex1$ 

```

```

show  $\forall f. (\forall n. f\ n = n + (i - 1)) \longrightarrow f \in Ex1$ 
proof
  fix  $f :: int \Rightarrow int$ 
  show  $(\forall n. f\ n = n + (i - 1)) \longrightarrow f \in Ex1$ 
  proof
    assume  $f\text{-eq}: \forall n. f\ n = n + (i - 1)$ 
    let  $?h = \lambda n. n + i$ 
    from induct-hyp have  $h\text{-}Ex1: ?h \in Ex1$  by auto
    from inv-upOne-eq and  $f\text{-eq}$ 
      have  $\forall n. f\ n = (inv\ upOne)\ (?h\ n)$  by auto
    hence  $\forall n. f\ n = (inv\ upOne \circ ?h)\ n$  by auto
    with fun-eq-iff [THEN sym, of f inv upOne  $\circ$  ?h]
      have  $f = inv\ upOne \circ ?h$  by auto
    with  $h\text{-}Ex1$  and  $Ex1.comp\ inv$  [of ?h] show  $f \in Ex1$  by auto
  qed
qed
qed

```

Combining the two directions we get the normal form theorem.

```

theorem Ex1-Normal-form:  $(f \in Ex1) = (\exists k. \forall n. f(n) = n + k)$ 
proof
  assume  $f \in Ex1$ 
  with Ex1-Normal-form-part1 [of f]
    show  $(\exists k. \forall n. f(n) = n + k)$  by auto
  next
  assume  $\exists k. \forall n. f(n) = n + k$ 
  with Ex1-Normal-form-part2
    show  $f \in Ex1$  by auto
qed

```

5 All Elements Cofinitary Bijections.

We now show all elements in *CofGroups.Ex1* are bijections, Theorem *all-bij*, and have no fixed points, Theorem *no-fixed-pt*.

```

theorem all-bij:  $f \in Ex1 \implies bij\ f$ 
proof (unfold bij-def)
  assume  $f \in Ex1$ 
  with Ex1-Normal-form
    obtain  $k$  where  $f\text{-eq}: \forall n. f\ n = n + k$  by auto

  show  $inj\ f \wedge surj\ f$ 
  proof (rule conjI)
    show INJ:  $inj\ f$ 
    proof (rule injI)
      fix  $n\ m$ 
      assume  $f\ n = f\ m$ 
      with  $f\text{-eq}$  have  $n + k = m + k$  by auto
      thus  $n = m$  by auto

```

```

qed
next

show SURJ: surj f
proof (unfold Fun.surj-def, rule allI)
  fix n
  from f-eq have n = f (n - k) by auto
  thus  $\exists m. n = f m$  by (rule exI)
qed
qed
qed

theorem no-fixed-pt:
  assumes f-Ex1:  $f \in Ex1$ 
  and f-not-id:  $f \neq id$ 
  shows Fix f = {}
proof -
  — we start by proving an easy general fact
  have f-eq-then-id:  $(\forall n. f(n) = n) \implies f = id$ 
  proof -
    assume f-prop :  $\forall n. f(n) = n$ 
    have (f x = id x) = (f x = x) by simp
    hence  $(\forall x. (f x = id x)) = (\forall x. (f x = x))$  by simp
    with fun-eq-iff[THEN sym, of f id] and f-prop show f = id by auto
  qed
  from f-Ex1 and Ex1-Normal-form have  $\exists k. \forall n. f(n) = n + k$  by auto
  then obtain k where k-prop:  $\forall n. f(n) = n + k$  ..
  hence  $k = 0 \implies \forall n. f(n) = n$  by auto
  with f-eq-then-id and f-not-id have  $k \neq 0$  by auto
  with k-prop have  $\forall n. f(n) \neq n$  by auto
  moreover
  from Fix-def[of f] have Fix f = {n . f(n) = n} by auto
  ultimately have Fix f = {n. False} by auto
  with Set.empty-def show Fix f = {} by auto
qed

```

6 Closed under Composition and Inverse

We start by showing that this set is closed under composition. These facts can later be conjugated to easily obtain the corresponding results for the group on the natural numbers.

```

theorem closed-comp:  $f \in Ex1 \wedge g \in Ex1 \implies f \circ g \in Ex1$ 
proof (rule Ex1.induct [of f], blast)
  assume f  $\in Ex1 \wedge g \in Ex1$ 
  with Ex1.comp-func[of g] show  $upOne \circ g \in Ex1$  by auto
next
  fix fa
  assume fa  $\circ g \in Ex1$ 

```



```

with Ex1.comp-func [of  $fa \circ g$ ]
  and Fun.o-assoc [of  $upOne\ fa\ g$ ]
  show  $upOne \circ fa \circ g \in Ex1$  by auto
next
  fix fa
  assume  $fa \circ g \in Ex1$ 
  with Ex1.comp-inv [of  $fa \circ g$ ]
    and Fun.o-assoc [of  $inv\ upOne\ fa\ g$ ]
    show  $(inv\ upOne) \circ fa \circ g \in Ex1$  by auto
qed

```

Now we show the set is closed under inverses. This is done by an induction on the definition of *CofGroups.Ex1* only using the normal form theorem and rewriting of expressions.

theorem *closed-inv*: $f \in Ex1 \implies inv\ f \in Ex1$

proof (*rule Ex1.induct* [of *f*], *blast*)

assume $f \in Ex1$

show $inv\ upOne \in Ex1$ (**is** $?right \in Ex1$)

proof –

let $?left = inv\ upOne \circ (inv\ upOne \circ upOne)$

```

{
  from Ex1.comp-inv and Ex1.base-func have  $?left \in Ex1$  by auto
}

```

moreover

```

{
  from bij-upOne and bij-is-inj have  $inj\ upOne$  by auto
  hence  $inv\ upOne \circ upOne = id$  by auto
  hence  $?left = ?right$  by auto
}

```

ultimately

show $?thesis$ **by** *auto*

qed

next

fix *f*

assume $f \in Ex1$

from *f-Ex1* **and** *Ex1-Normal-form*

obtain *k* **where** $f\text{-eq}: \forall n. f\ n = n + k$ **by** *auto*

show $inv\ (upOne \circ f) \in Ex1$

proof –

let $?ic = inv\ (upOne \circ f)$

let $?ci = inv\ f \circ inv\ upOne$

```

{
  — first we get an expression for  $inv\ f \circ inv\ upOne$ 
  {
    from all-bij and f-Ex1 have  $bij\ f$  by auto
    with bij-is-inj have  $inj\ f$  by auto
    have  $\forall n. inv\ f\ n = n - k$ 
    proof

```

```

    fix n
    from f-eq have f (n - k) = n by auto
    with inv-f-eq[of f n-k n] and inj-f
    show inv f n = n-k by auto
  qed
  with inv-upOne-eq
  have  $\forall n. ?ci\ n = n - k - 1$  by auto
  hence  $\forall n. ?ci\ n = n + (-1 - k)$  by arith
}
moreover
— then we check that this implies  $inv\ f \circ inv\ upOne$  is
— a member of CofGroups.Ex1
{
  from Ex1-Normal-form-part2[of -1 - k]
  have  $(\forall f. ((\forall n. f\ n = n + (-1 - k)) \longrightarrow f \in Ex1))$  by auto
}
ultimately
have  $?ci \in Ex1$  by auto
}
moreover
{
  from f-Ex1 all-bij have bij f by auto
  with bij-upOne and o-inv-distrib[THEN sym]
  have  $?ci = ?ic$  by auto
}
ultimately show ?thesis by auto
qed
next
fix f
assume f-Ex1: f  $\in Ex1$ 
with Ex1-Normal-form
  obtain k where f-eq:  $\forall n. f\ n = n + k$  by auto

show inv (inv upOne  $\circ$  f)  $\in Ex1$ 
proof —
  let ?ic = inv (inv upOne  $\circ$  f)
  let ?c = inv f  $\circ$  upOne
  {
    from all-bij and f-Ex1 have bij f by auto
    with bij-is-inj have inj-f: inj f by auto
    have  $\forall n. inv\ f\ n = n - k$ 
    proof
      fix n
      from f-eq have f (n - k) = n by auto
      with inv-f-eq[of f n-k n] and inj-f
      show inv f n = n-k by auto
    qed
    with upOne-def
    have  $\forall n. (inv\ f \circ upOne)\ n = n - k + 1$  by auto
  }

```

```

    hence  $\forall n. (inv\ f \circ upOne)\ n = n + (1 - k)$  by arith
  moreover
  from Ex1-Normal-form-part2[of 1 - k]
  have  $(\forall f. ((\forall n. f\ n = n + (1 - k)) \longrightarrow f \in Ex1))$  by auto
  ultimately
  have  $?c \in Ex1$  by auto
}
moreover
{
  from f-Ex1 all-bij and bij-is-inj have bij f by auto
  moreover
  from bij-upOne and bij-imp-bij-inv have bij (inv upOne) by auto
  moreover
  note o-inv-distrib[THEN sym]
  ultimately
  have  $inv\ f \circ inv\ (inv\ upOne) = inv\ (inv\ upOne \circ f)$  by auto
  moreover
  from bij-upOne and inv-inv-eq
  have  $inv\ (inv\ upOne) = upOne$  by auto
  ultimately
  have  $?c = ?ic$  by auto
}
ultimately
show ?thesis by auto
qed
qed

```

7 Conjugation with a Bijection

An abbreviation of the bijection from the natural numbers to the integers defined in the library. This will be used to coerce the functions above to be on the natural numbers.

abbreviation *ni-bij* == *int-decode*

lemma *bij-f-o-inf-f*: *bij f* $\implies f \circ inv\ f = id$

unfolding *bij-def surj-iff* by *simp*

The following theorem is a key theorem in showing that the group we are interested in is cofinitary. It states that when you conjugate a function with a bijection the fixed points get mapped over.

theorem *conj-fix-pt*: $\bigwedge f::'a \Rightarrow 'b. \bigwedge g::'b \Rightarrow 'b. (bij\ f)$

$\implies ((inv\ f)'(Fix\ g)) = Fix\ ((inv\ f) \circ g \circ f)$

proof –

fix *f::'a \Rightarrow 'b*

assume *bij-f: bij f*

with *bij-def* **have** *inj-f: inj f* by *auto*

fix *g::'b \Rightarrow 'b*

```

show  $((\text{inv } f)'(\text{Fix } g)) = \text{Fix } ((\text{inv } f) \circ g \circ f)$ 
thm set-eq-subset[of  $(\text{inv } f)'(\text{Fix } g) \text{Fix}((\text{inv } f) \circ g \circ f)$ ]
proof
  show  $(\text{inv } f)'(\text{Fix } g) \subseteq \text{Fix } ((\text{inv } f) \circ g \circ f)$ 
  proof
    fix  $x$ 
    assume  $x \in (\text{inv } f)'(\text{Fix } g)$ 
    with image-def have  $\exists y \in \text{Fix } g. x = (\text{inv } f) y$  by auto
    from this obtain  $y$  where y-prop:  $y \in \text{Fix } g \wedge x = (\text{inv } f) y$  by auto
    hence  $x = (\text{inv } f) y$  ..
    hence  $f x = (f \circ \text{inv } f) y$  by auto
    with bij-f and bij-f-o-inf-f[of f] have f-x-y:  $f x = y$  by auto
    from y-prop have  $y \in \text{Fix } g$  ..
    with Fix-def[of g] have  $g y = y$  by auto
    with f-x-y have  $g (f x) = f x$  by auto
    hence  $(\text{inv } f) (g (f x)) = \text{inv } f (f x)$  by auto
    with inv-f-f and inj-f have  $(\text{inv } f) (g (f x)) = x$  by auto
    hence  $((\text{inv } f) \circ g \circ f) x = x$  by auto
    with Fix-def[of inv f o g o f]
    show  $x \in \text{Fix } ((\text{inv } f) \circ g \circ f)$  by auto
  qed
next
show  $\text{Fix } ((\text{inv } f) \circ g \circ f) \subseteq (\text{inv } f)'(\text{Fix } g)$ 
proof
  fix  $x$ 
  assume  $x \in \text{Fix } ((\text{inv } f) \circ g \circ f)$ 
  with Fix-def[of inv f o g o f]
  have x-fix:  $(\text{inv } f \circ g \circ f) x = x$  by auto
  hence  $(\text{inv } f) (g(f(x))) = x$  by auto
  hence  $\exists y. (\text{inv } f) y = x$  by auto
  from this obtain  $y$  where x-inf-f-y:  $x = (\text{inv } f) y$  by auto
  with x-fix have  $(\text{inv } f \circ g \circ f)((\text{inv } f) y) = (\text{inv } f) y$  by auto
  hence  $(f \circ \text{inv } f \circ g \circ f \circ \text{inv } f) (y) = (f \circ \text{inv } f)(y)$  by auto
  with o-assoc
  have  $((f \circ \text{inv } f) \circ g \circ (f \circ \text{inv } f)) y = (f \circ \text{inv } f) y$  by auto
  with bij-f and bij-f-o-inf-f[of f]
  have  $g y = y$  by auto
  with Fix-def[of g] have  $y \in \text{Fix } g$  by auto
  with x-inf-f-y show  $x \in (\text{inv } f)'(\text{Fix } g)$  by auto
  qed
qed
qed

```

8 Bijections on \mathbb{N}

In this section we define the subset *Ex2* of *S-inf* that is the conjugate of *CofGroups.Ex1* *bij ni-bij*, and show its basic properties.

CONJ is the function that will conjugate *CofGroups.Ex1* to *Ex2*.

definition *CONJ* :: (int ⇒ int) ⇒ (nat ⇒ nat)

where

CONJ f = (inv ni-bij) ◦ f ◦ ni-bij

declare *CONJ-def* [*simp*] — automated tools can use the definition

We quickly check that this function is of the right type, and then show three of its properties that are very useful in showing *Ex2* is a group.

lemma *type-CONJ*: f ∈ *Ex1* ⇒ (inv ni-bij) ◦ f ◦ ni-bij ∈ *S-inf*

proof —

assume *f-Ex1*: f ∈ *Ex1*

with *all-bij* have *bij f* by *auto*

with *bij-int-decode* and *bij-comp*

have *bij-f-nibij*: *bij* (f ◦ ni-bij) by *auto*

with *bij-int-decode* and *bij-imp-bij-inv* have *bij* (inv ni-bij) by *auto*

with *bij-f-nibij* and *bij-comp*[of f ◦ ni-bij inv ni-bij]

and *o-assoc*[of inv ni-bij f ni-bij]

have *bij* ((inv ni-bij) ◦ f ◦ ni-bij) by *auto*

with *S-inf-def* show ((inv ni-bij) ◦ f ◦ ni-bij) ∈ *S-inf* by *auto*

qed

lemma *inv-CONJ*:

assumes *bij-f*: *bij* f

shows inv (*CONJ* f) = *CONJ* (inv f) (is ?left = ?right)

proof —

have *st1*: ?left = inv ((inv ni-bij) ◦ f ◦ ni-bij)

using *CONJ-def* by *auto*

from *bij-int-decode* and *bij-imp-bij-inv*

have *inv-ni-bij-bij*: *bij* (inv ni-bij) by *auto*

with *bij-f* and *bij-comp* have *bij* (inv ni-bij ◦ f) by *auto*

with *o-inv-distrib*[of inv ni-bij ◦ f ni-bij] and *bij-int-decode*

have inv ((inv ni-bij) ◦ f ◦ ni-bij) =

(inv ni-bij) ◦ (inv ((inv ni-bij) ◦ f)) by *auto*

with *st1* have *st2*: ?left =

(inv ni-bij) ◦ (inv ((inv ni-bij) ◦ f)) by *auto*

from *inv-ni-bij-bij* and ⟨*bij f*⟩ and *o-inv-distrib*

have *h1*: inv (inv ni-bij ◦ f) = inv f ◦ inv (inv (ni-bij)) by *auto*

from *bij-int-decode* and *inv-inv-eq*[of ni-bij]

have inv (inv ni-bij) = ni-bij by *auto*

with *st2* and *h1* have ?left = (inv ni-bij ◦ (inv f ◦ (ni-bij))) by *auto*

with *o-assoc* have ?left = inv ni-bij ◦ inv f ◦ ni-bij by *auto*

with *CONJ-def*[of inv f] show ?thesis by *auto*

qed

lemma *comp-CONJ*:

CONJ (f ◦ g) = (*CONJ* f) ◦ (*CONJ* g) (is ?left = ?right)

proof —

from *bij-int-decode* have *surj ni-bij* unfolding *bij-def* by *auto*

then have $ni\text{-bij} \circ (inv\ ni\text{-bij}) = id$ **unfolding surj-iff by auto**
moreover
have $?left = (inv\ ni\text{-bij}) \circ (f \circ g) \circ ni\text{-bij}$ **by simp**
hence $?left = (inv\ ni\text{-bij}) \circ ((f \circ id) \circ g) \circ ni\text{-bij}$ **by simp**
ultimately
have $?left =$
 $(inv\ ni\text{-bij}) \circ ((f \circ (ni\text{-bij} \circ (inv\ ni\text{-bij}))) \circ g) \circ ni\text{-bij}$
by auto
 — a simple computation using only associativity
 — completes the proof
thus $?left = ?right$ **by (auto simp add: o-assoc)**
qed

lemma $id\text{-CONJ}$: $CONJ\ id = id$
proof (*unfold CONJ-def*)
from $bij\text{-int-decode}$ **have** $inj\ ni\text{-bij}$ **using** $bij\text{-def}$ **by auto**
hence $inv\ ni\text{-bij} \circ ni\text{-bij} = id$ **by auto**
thus $(inv\ ni\text{-bij} \circ id) \circ ni\text{-bij} = id$ **by auto**
qed

We now define the group we are interested in, and show the basic facts that together will show this is a cofinitary group.

definition $Ex2$:: $(nat \Rightarrow nat)$ *set*
where
 $Ex2 = CONJ'Ex1$

theorem $mem\text{-}Ex2\text{-rule}$: $f \in Ex2 = (\exists g. (g \in Ex1 \wedge f = CONJ\ g))$
proof
assume $f \in Ex2$
hence $f \in CONJ'Ex1$ **using** $Ex2\text{-def}$ **by auto**
from *this* **obtain** g **where** $g \in Ex1 \wedge f = CONJ\ g$ **by blast**
thus $\exists g. (g \in Ex1 \wedge f = CONJ\ g)$ **by auto**
next
assume $\exists g. (g \in Ex1 \wedge f = CONJ\ g)$
with $Ex2\text{-def}$ **show** $f \in Ex2$ **by auto**
qed

theorem $Ex2\text{-cofinitary}$:
assumes $f\text{-}Ex2$: $f \in Ex2$
and $f\text{-}nid$: $f \neq id$
shows $Fix\ f = \{\}$
proof —
from $f\text{-}Ex2$ **and** $mem\text{-}Ex2\text{-rule}$
obtain g **where** $g\text{-}Ex1$: $g \in Ex1$ **and** $f\text{-}cg$: $f = CONJ\ g$ **by auto**
with $id\text{-CONJ}$ **and** $f\text{-}nid$ **have** $g \neq id$ **by auto**
with $g\text{-}Ex1$ **and** $no\text{-fixed-pt}[of\ g]$ **have** $fg\text{-empty}$: $Fix\ g = \{\}$ **by auto**
from $conj\text{-fix-pt}[of\ ni\text{-bij}\ g]$ **and** $bij\text{-int-decode}$
have $(inv\ ni\text{-bij})'(Fix\ g) = Fix\ (CONJ\ g)$ **by auto**
with $fg\text{-empty}$ **have** $\{\} = Fix\ (CONJ\ g)$ **by auto**

with $f\text{-cg}$ **show** $\text{Fix } f = \{\}$ **by** *auto*
qed

lemma $id\text{-}Ex2$: $id \in Ex2$

proof –

from $Ex1\text{-Normal-form-part2}$ [of 0] **have** $id \in Ex1$ **by** *auto*
with $id\text{-}CONJ$ **and** $Ex2\text{-def}$ **and** $mem\text{-}Ex2\text{-rule}$ **show** *?thesis* **by** *auto*
qed

lemma $inv\text{-}Ex2$: $f \in Ex2 \implies (inv\ f) \in Ex2$

proof –

assume $f \in Ex2$
with $mem\text{-}Ex2\text{-rule}$ **obtain** g **where** $g \in Ex1$ **and** $f = CONJ\ g$ **by** *auto*
with $closed\text{-}inv$ **have** $inv\ g \in Ex1$ **by** *auto*
from $\langle f = CONJ\ g \rangle$ **have** $if\text{-}iCg$: $inv\ f = inv\ (CONJ\ g)$ **by** *auto*
from $all\text{-}bij$ **and** $\langle g \in Ex1 \rangle$ **have** $bij\ g$ **by** *auto*
with $if\text{-}iCg$ **and** $inv\text{-}CONJ$ **have** $inv\ f = CONJ\ (inv\ g)$ **by** *auto*
from $\langle g \in Ex1 \rangle$ **and** $closed\text{-}inv$ **have** $inv\ g \in Ex1$ **by** *auto*
with $\langle inv\ f = CONJ\ (inv\ g) \rangle$ **and** $mem\text{-}Ex2\text{-rule}$ **show** $inv\ f \in Ex2$ **by** *auto*
qed

lemma $comp\text{-}Ex2$:

assumes $f\text{-}Ex2$: $f \in Ex2$ **and**

$g\text{-}Ex2$: $g \in Ex2$

shows $f \circ g \in Ex2$

proof –

from $f\text{-}Ex2$ **obtain** $f\text{-}1$
where $f\text{-}1\text{-}Ex1$: $f\text{-}1 \in Ex1$ **and** $f = CONJ\ f\text{-}1$
using $mem\text{-}Ex2\text{-rule}$ **by** *auto*
moreover
from $g\text{-}Ex2$ **obtain** $g\text{-}1$
where $g\text{-}1\text{-}Ex1$: $g\text{-}1 \in Ex1$ **and** $g = CONJ\ g\text{-}1$
using $mem\text{-}Ex2\text{-rule}$ **by** *auto*
ultimately
have $f \circ g = (CONJ\ f\text{-}1) \circ (CONJ\ g\text{-}1)$ **by** *auto*
hence $f \circ g = CONJ\ (f\text{-}1 \circ g\text{-}1)$ **using** $comp\text{-}CONJ$ **by** *auto*
moreover
have $f\text{-}1 \circ g\text{-}1 \in Ex1$ **using** $closed\text{-}comp$ **and** $f\text{-}1\text{-}Ex1$ **and** $g\text{-}1\text{-}Ex1$ **by** *auto*
ultimately
show $f \circ g \in Ex2$ **using** $mem\text{-}Ex2\text{-rule}$ **by** *auto*
qed

9 The Conclusion

With all that we have shown we have already clearly shown $Ex2$ to be a cofinitary group. The formalization also shows this, we just have to refer to

the correct theorems proved above.

interpretation *CofinitaryGroup Ex2*

proof

show $Ex2 \subseteq S\text{-inf}$

proof

fix f

assume $f \in Ex2$

with *mem-Ex2-rule* **obtain** g **where** $g \in Ex1$ **and** $f = CONJ\ g$ **by** *auto*

with *type-CONJ* **show** $f \in S\text{-inf}$ **by** *auto*

qed

next

from *id-Ex2* **show** $id \in Ex2$.

next

fix $f\ g$

assume $f \in Ex2 \wedge g \in Ex2$

with *comp-Ex2* **show** $f \circ g \in Ex2$ **by** *auto*

next

fix f

assume $f \in Ex2$

with *inv-Ex2* **show** $inv\ f \in Ex2$ **by** *auto*

next

fix f

assume $f \in Ex2 \wedge f \neq id$

with *Ex2-cofinitary* **have** $Fix\ f = \{\}$ **by** *auto*

thus *finite* ($Fix\ f$) **using** *finite-def* **by** *auto*

qed

end

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