Formalizing Results on Directed Sets

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Abstract

Directed sets are of fundamental interest in domain theory and topology. In this paper, we formalize some results on directed sets in Isabelle/HOL, most notably: under the axiom of choice, a poset has a supremum for every directed set if and only if it does so for every chain; and a function between such posets preserves suprema of directed sets if and only if it preserves suprema of chains. The known pen-and-paper proofs of these results crucially use uncountable transfinite sequences, which are not directly implementable in Isabelle/HOL. We show how to emulate such proofs by utilizing Isabelle/HOL's ordinal and cardinal library. Thanks to the formalization, we relax some conditions for the above results.

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1 Introduction

A *directed set* is a set D equipped with a binary relation $\sqsubseteq$ such that any finite subset $X \subseteq D$ has an upper bound in D with respect to $\sqsubseteq$. The property is often equivalently stated that D is non-empty and any two elements $x, y \in D$ have a bound in D, assuming that $\sqsubseteq$ is transitive (as in posets).

Directed sets find uses in various fields of mathematics and computer science. In topology (see for example the textbook [7]), directed sets are used to generalize the set of natural numbers: sequences $\mathbb{N} \to A$ are generalized to *nets* $D \to A$, where D is an arbitrary directed set. For example, the usual result on metric spaces that continuous functions are precisely functions that preserve limits of sequences can be generalized in general topological spaces as: the continuous functions are precisely functions that preserve limits of nets. In domain theory [1], key ingredients are *directed-complete posets*, where every directed subset has a supremum in the poset, and *Scott-continuous functions* between posets, that is, functions that preserve suprema of directed sets. Thanks to their fixed-point properties (which we have formalized in Isabelle/HOL in a previous work [5]), directed-complete posets naturally appear in denotational semantics of languages with loops or fixed-point operators (see for example Scott domains [11, 13]). Directed sets also appear in reachability and coverability analyses of transition systems through the notion of ideals, that is, downward-closed directed sets. They allow effective representations of objects, making forward and backward analysis of well-structured transition systems – such as Petri nets – possible (see e.g., [6]).

Apparently milder generalizations of natural numbers are chains (totally ordered sets) or even well-ordered sets. In the mathematics literature, the following results are known (assuming the axiom of choice):

Theorem 1 ([4]) *A poset is directed-complete if (and only if) it has a supremum for every non-empty well-ordered subset.*

Theorem 2 ([9]) *Let f be a function between posets, each of which has a supremum for every non-empty chain. If f preserves suprema of non-empty chains, then it is Scott-continuous.*

The pen-and-paper proofs of these results use induction on cardinality, where the finite case is merely the base case. The core of the proof is a technical result called Iwamura's Lemma [8], where the countable case is merely an easy case, and the main part heavily uses transfinite sequences indexed by uncountable ordinals.

To formalize these results in Isabelle/HOL we extensively use the existing library for ordinals and cardinals [3], but we needed some delicate work in emulating the pen-and-paper proofs. In Isabelle/HOL, or any proof assistant based on higher-order logic (HOL), it is not possible to have a datatype for arbitrarily large ordinals; hence, it is not possible to directly formalize transfinite sequences. We show how to emulate transfinite sequences using the ordinal and cardinal library [3]. As far as the authors know, our work is the first to mechanize the proof of Theorems 1 and 2, as well as Iwamura's Lemma. We prove the two theorems for quasi-ordered sets, relaxing antisymmetry, and strengthen Theorem 2 so that chains are replaced by well-ordered sets and conditions on the codomain are completely dropped.

Related Work Systems based on Zermelo-Fraenkel set theory, such as Mizar [2] and Isabelle/ZF [10], have more direct support for ordinals and cardinals and should pose less challenge in mechanizing the above results. Nevertheless, a part of our contribution is in demonstrating that the power of (Isabelle/)HOL is strong enough to deal with uncountable transfinite sequences.

Except for the extra care for transfinite sequences, our proof of Iwamura's Lemma is largely based on the original proof from [8]. Markowsky presented a proof of Theorem 1 using Iwamura's Lemma [9, Corollary 1]. While he took a minimal-counterexample approach, we take a more constructive approach to build a well-ordered set of suprema. This construction was crucial to be reused in the proof of Theorem 2, which Markowsky claimed without a proof [9]. Another proof of Theorem 1 can be found in [4], without using Iwamura's Lemma, but still crucially using transfinite sequences.

This work has been published in the conference paper [14].

2 Preliminaries

2.1 Connecting Predicate-Based and Set-Based Relations

theory *Well-Order-Connection*
imports
Main
Complete-Non-Orders.Well-Relations
begin

lemma *refl-on-relation-of*: *refl-on A* (*relation-of r A*) $\longleftrightarrow$ *reflexive A r*
⟨*proof*⟩

lemma *trans-relation-of*: *trans* (*relation-of r A*) $\longleftrightarrow$ *transitive A r*
⟨*proof*⟩

lemma *preorder-on-relation-of*: *preorder-on A* (*relation-of r A*) $\longleftrightarrow$ *quasi-ordered-set A r*
⟨*proof*⟩

lemma *antisym-relation-of*: *antisym* (*relation-of r A*) $\longleftrightarrow$ *antisymmetric A r*
⟨*proof*⟩

lemma *partial-order-on-relation-of*:
partial-order-on A (*relation-of r A*) $\longleftrightarrow$ *partially-ordered-set A r*
⟨*proof*⟩

lemma *total-on-relation-of*: *total-on A* (*relation-of r A*) $\longleftrightarrow$ *semiconnex A r*

⟨*proof*⟩

lemma *linear-order-on-relation-of*:
shows *linear-order-on A* (*relation-of r A*) ⟷ *total-ordered-set A r*
⟨*proof*⟩

lemma *relation-of-sub-Id*: (*relation-of r A* − *Id*) = *relation-of* (λ*x y*. *r x y* ∧ *x* ≠ *y*) *A*
⟨*proof*⟩

lemma (**in** *antisymmetric*) *asympartp-iff-weak-neq*:
shows *x* ∈ *A* ⟹ *y* ∈ *A* ⟹ *asympartp* (⊑) *x y* ⟷ *x* ⊑ *y* ∧ *x* ≠ *y*
⟨*proof*⟩

lemma *wf-relation-of*: *wf* (*relation-of r A*) = *well-founded A r*
⟨*proof*⟩

lemma *well-order-on-relation-of*:
shows *well-order-on A* (*relation-of r A*) ⟷ *well-ordered-set A r*
⟨*proof*⟩

lemma (**in** *connex*) *Field-relation-of*: *Field* (*relation-of* (⊑) *A*) = *A*
⟨*proof*⟩

lemma (**in** *well-ordered-set*) *Well-order-relation-of*:
shows *Well-order* (*relation-of* (⊑) *A*)
⟨*proof*⟩

lemma *in-relation-of*: (*x*,*y*) ∈ *relation-of r A* ⟷ *x* ∈ *A* ∧ *y* ∈ *A* ∧ *r x y*
⟨*proof*⟩

lemma *relation-of-triv*: *relation-of* (λ*x y*. (*x*,*y*) ∈ *r*) *UNIV* = *r*
⟨*proof*⟩

lemma *Restr-eq-relation-of*: *Restr R A* = *relation-of* (λ*x y*. (*x*,*y*) ∈ *R*) *A*
⟨*proof*⟩

theorem *ex-well-order*: ∃ *r*. *well-ordered-set A r*
⟨*proof*⟩

end
theory *Directed-Completeness*
imports
Complete-Non-Orders.Continuity
Well-Order-Connection
HOL−Cardinals.Cardinals
HOL−Library.FuncSet
begin

2.2 Missing Lemmas

no-notation *disj* (**infixr** | *30*)

lemma *Sup-funpow-mono*:
  fixes f :: *'a* :: *complete-lattice* ⇒ *'a*
  assumes *mono*: *mono f*
  shows *mono* ($\bigsqcup$ *i*. *f* ^^ *i*)
  ⟨*proof*⟩

lemma *iso-imp-compat*:
  assumes *iso*: *iso r r' f* **shows** *compat r r' f*
  ⟨*proof*⟩

lemma *iso-inv-into*:
  assumes *ISO*: *iso r r' f*
  shows *iso r' r* (*inv-into* (*Field r*) *f*)
  ⟨*proof*⟩

lemmas *iso-imp-compat-inv-into* = *iso-imp-compat*[*OF iso-inv-into*]

lemma *infinite-iff-natLeq*: *infinite A* ⟷ *natLeq* ≤*o* |*A*|
  ⟨*proof*⟩

As we cannot formalize transfinite sequences directly, we take the following approach: We just use A as the index set, and instead of the ordering on ordinals, we take the well-order that is chosen by the cardinality library to denote $|A|$.

definition *well-order-of* (('(⪯-')) [*0*]*1000*) **where** ($\preceq_A$) *x y* ≡ (*x*,*y*) ∈ |*A*|

abbreviation *well-order-le* (- ⪯- - [*51*,*0*,*51*]*50*) **where** *x* $\preceq_A$ *y* ≡ ($\preceq_A$) *x y*

abbreviation *well-order-less* (- ≺- - [*51*,*0*,*51*]*50*) **where** *x* $\prec_A$ *y* ≡ *asympartp* ($\preceq_A$) *x y*

lemmas *well-order-ofI* = *well-order-of-def*[*unfolded atomize-eq*, *THEN iffD2*]
lemmas *well-order-ofD* = *well-order-of-def*[*unfolded atomize-eq*, *THEN iffD1*]

lemma *carrier*: **assumes** *x* $\preceq_A$ *y* **shows** *x* ∈ *A* **and** *y* ∈ *A*
  ⟨*proof*⟩

lemma *relation-of*[*simp*]: *relation-of* ($\preceq_A$) *A* = |*A*|
  ⟨*proof*⟩

interpretation *well-order-of*: *well-ordered-set A* ($\preceq_A$)
  ⟨*proof*⟩

Thanks to the well-order theorem, one can have a sequence $\{A_\alpha\}_{\alpha<|A|}$ of subsets of A that satisfies the following three conditions:

- cardinality: $|A_\alpha| < |A|$ for every $\alpha < |A|$,
- monotonicity: $A_\alpha \subseteq A_\beta$ whenever $\alpha \leq \beta < |A|$, and
- range: if A is infinite, $A = \bigcup_{\alpha<|A|} A_\alpha$.

The following serves the purpose.

definition *Pre* ($-_{\prec}$ *[1000]1000*) **where** $A_{\prec}\ a \equiv \{b \in A.\ b \prec_A\ a\}$

lemma *Pre-eq-underS*: $A_{\prec}\ a = underS\ |A|\ a$
⟨*proof*⟩

lemma *Pre-card*: **assumes** *aA*: $a \in A$ **shows** $|A_{\prec}\ a| <o\ |A|$
⟨*proof*⟩

lemma *Pre-carrier*: $A_{\prec}\ a \subseteq A$ ⟨*proof*⟩

lemma *Pre-mono*: *monotone-on* A $(\preceq_A)$ $(\subseteq)$ $(A_{\prec})$
⟨*proof*⟩

lemma *extreme-imp-finite*:
assumes *e*: *extreme* A $(\preceq_A)$ e **shows** *finite* A
⟨*proof*⟩

lemma *infinite-imp-ex-Pre*:
assumes *inf*: *infinite* A **and** *xA*: $x \in A$ **shows** $\exists\, y \in A.\ x \in A_{\prec}\ y$
⟨*proof*⟩

lemma *infinite-imp-Un-Pre*: **assumes** *inf*: *infinite* A **shows** $\bigcup (A_{\prec}\ `\ A) = A$
⟨*proof*⟩

3 Iwamura's lemma

As the proof involves a number of (inductive) definitions, we build a locale for collecting those definitions and lemmas.

locale *Iwamura-proof* = *related-set* +
assumes *dir*: *directed-set* A $(\sqsubseteq)$
begin

Inside this locale, a related set $(A, \sqsubseteq)$ is fixed and assumed to be directed. The proof starts with declaring, using the axiom of choice, a function f that chooses a bound $f\ X \in A$ for every finite subset $X \subseteq A$. This function can be formalized using the SOME construction:

definition *f* **where** $f\ X \equiv SOME\ z.\ z \in A \wedge bound\ X\ (\sqsubseteq)\ z$

lemma assumes *XA*: $X \subseteq A$ **and** *Xfin*: *finite* X
shows *f-carrier*: $f\ X \in A$ **and** *f-bound*: *bound* X $(\sqsubseteq)$ $(f\ X)$
⟨*proof*⟩

3.1 Uncountable Case

Actually, the main part of the proof of Iwamura's Lemma is about monotonically expanding an infinite subset (in particular A_α) of A into a directed one, without changing the cardinality. To this end, Iwamura's original proof introduces a function $F\colon PowA \to PowA$ that expands a set with upper bounds of *all finite subsets*. This approach is different from Markowsky's reproof (based on [12]) which uses nested transfinite induction to extend a set one element after another.

definition F **where** $F\ X \equiv X \cup f\ \text{`}\ Fpow\ X$

lemma *F-carrier*: $X \subseteq A \Longrightarrow F\ X \subseteq A$
  and *F-infl*: $X \subseteq F\ X$
  and *F-fin*: $\mathit{finite}\ X \Longrightarrow \mathit{finite}\ (F\ X)$
  ⟨*proof*⟩

lemma *F-card*: **assumes** *inf*: $\mathit{infinite}\ X$ **shows** $|F\ X| =o\ |X|$
⟨*proof*⟩

lemma *F-mono*: $\mathit{mono}\ F$
⟨*proof*⟩

lemma *Fn-carrier*: $X \subseteq A \Longrightarrow (F\ \widehat{}\widehat{}\ n)\ X \subseteq A$
  and *Fn-infl*: $X \subseteq (F\ \widehat{}\widehat{}\ n)\ X$
  and *Fn-fin*: $\mathit{finite}\ X \Longrightarrow \mathit{finite}\ ((F\ \widehat{}\widehat{}\ n)\ X)$
  and *Fn-card*: $\mathit{infinite}\ X \Longrightarrow |(F\ \widehat{}\widehat{}\ n)\ X| =o\ |X|$
⟨*proof*⟩

lemma *Fn-mono1*: $i \le j \Longrightarrow (F\ \widehat{}\widehat{}\ i)\ X \subseteq (F\ \widehat{}\widehat{}\ j)\ X$ **for** $i\ j$
  ⟨*proof*⟩

We take the ω-iteration of the monotone function F, namely:

definition *Flim* (F^ω) **where** $F^\omega\ X \equiv \bigcup i.\ (F\ \widehat{}\widehat{}\ i)\ X$

lemma *Flim-mono*: $\mathit{mono}\ F^\omega$
⟨*proof*⟩

lemma *Flim-infl*: $X \subseteq F^\omega\ X$
  ⟨*proof*⟩

lemma *Flim-carrier*: **assumes** $X \subseteq A$ **shows** $F^\omega\ X \subseteq A$
  ⟨*proof*⟩

lemma *Flim-directed*: **assumes** $X \subseteq A$ **shows** *directed-set* $(F^\omega\ X)\ (\sqsubseteq)$
⟨*proof*⟩

lemma *Flim-card*: **assumes** $\mathit{infinite}\ X$ **shows** $|F^\omega\ X| =o\ |X|$
⟨*proof*⟩

lemma *Flim-fin*: **assumes** *finite* X **shows** $|F^\omega\ X| \le o$ *natLeq*
⟨*proof*⟩

lemma *mono-uncountable*: *monotone-on* A $(\preceq_A)$ $(\subseteq)$ $(F^\omega \circ A_\prec)$
⟨*proof*⟩

lemma *card-uncountable*:
assumes *aA*: $a \in A$ **and** *unc*: *natLeq* $<o$ $|A|$
shows $|F^\omega\ (A_\prec\ a)| <o\ |A|$
⟨*proof*⟩

lemma *in-I-uncountable*:
assumes *aA*: $a \in A$ **and** *inf*: *infinite* A
shows $\exists\, a' \in A.\ a \in F^\omega\ (A_\prec\ a')$
⟨*proof*⟩

lemma *carrier-uncountable*:
shows $F^\omega\ (A_\prec\ a) \subseteq A$
⟨*proof*⟩

lemma *range-uncountable*: **assumes** *inf*: *infinite* A **shows** $\bigcup ((F^\omega \circ A_\prec)\ `\ A) = A$
⟨*proof*⟩

lemma *infl-uncountable*:
assumes *aA*: $a \in A$ **and** *bA*: $b \in A$ **and** *ab*: $a \prec_A b$
shows $a \in F^\omega\ (A_\prec\ b)$
⟨*proof*⟩

3.2 Countable Case

context
assumes *countable*: $|A| =o$ *natLeq*
begin

The assumption above means that there exists an order-isomorphism between $(\mathbb{N}, \le)$ and $(A, \preceq_A)$.

definition *seq* :: *nat* $\Rightarrow$ *'a* **where** *seq* $\equiv$ *SOME* f. *iso natLeq* $|A|$ f

lemma *seq-iso*: *iso natLeq* $|A|$ *seq*
⟨*proof*⟩

lemma *seq-bij-betw*: *bij-betw seq UNIV A*
⟨*proof*⟩

This means that A has been indexed by $\mathbb{N}$.

lemma *range-seq*: *range seq* $= A$
⟨*proof*⟩

lemma *seq-mono*: *monotone* (≤) ($\preceq_A$) *seq*
⟨*proof*⟩

lemma *inv-seq-mono*: *monotone-on A* ($\preceq_A$) (≤) (*inv seq*)
⟨*proof*⟩

We turn the sequence into a sequence of directed subsets of A:

fun *Seq* :: *nat* ⇒ *'a set* **where**
Seq 0 = {*f* {}}
| *Seq* (*Suc n*) = *Seq n* ∪ {*seq n*, *f* (*Seq n* ∪ {*seq n*})}

lemma *seq-n-in-Seq-n*: *seq n* ∈ *Seq* (*Suc n*) ⟨*proof*⟩

lemma *Seq-finite*: *finite* (*Seq n*)
⟨*proof*⟩

lemma *Seq-card*: |*Seq n*| <*o* |*A*|
⟨*proof*⟩

lemma *Seq-carrier*: *Seq n* ⊆ *A*
⟨*proof*⟩

lemma *Seq-range*: ⋃(*range Seq*) = *A*
⟨*proof*⟩

lemma *Seq-extremed*:
assumes *refl*: *reflexive A* (⊑) **shows** *extremed* (*Seq n*) (⊑)
⟨*proof*⟩

lemma *Seq-directed*: **assumes** *refl*: *reflexive A* (⊑) **shows** *directed-set* (*Seq n*) (⊑)
⟨*proof*⟩

lemma *range-countable*: ⋃((*Seq* ∘ *inv seq*) ‘ *A*) = *A*
⟨*proof*⟩

lemma *Seq-mono*: *mono Seq*
⟨*proof*⟩

lemma *mono-countable*: *monotone-on A* ($\preceq_A$) (⊆) (*Seq* ∘ *inv seq*)
⟨*proof*⟩

lemma *infl-countable*:
assumes *aA*: *a* ∈ *A* **and** *bA*: *b* ∈ *A* **and** *ab*: $a \prec_A b$
shows *a* ∈ *Seq* (*inv seq b*)
⟨*proof*⟩

end

To match the types, we use the inverse *inv seq* of the isomorphism isaseq. We define the final I as follows:

definition I **where** $I \equiv if\ |A| =o\ natLeq\ then\ Seq \circ inv\ seq\ else\ F^{\omega} \circ A_{\prec}$

lemma *I-carrier*: $I\ a \subseteq A$
⟨*proof*⟩

lemma *I-directed*: **assumes** *reflexive* A $(\sqsubseteq)$ **shows** *directed-set* $(I\ a)$ $(\sqsubseteq)$
⟨*proof*⟩

lemma *I-mono*: *monotone-on* A $(\preceq_A)$ $(\subseteq)$ I
⟨*proof*⟩

lemma *I-card*:
assumes *inf*: *infinite* A **and** *aA*: $a \in A$
shows $|I\ a| <o\ |A|$
⟨*proof*⟩

lemma *I-range*: **assumes** *inf*: *infinite* A **shows** $\bigcup (I`A) = A$
⟨*proof*⟩

lemma *I-infl*: **assumes** $a \in A$ $b \in A$ $a \prec_A b$ **shows** $a \in I\ b$
⟨*proof*⟩

end

Now we close the locale *Iwamura-proof* and state the final result in the global scope.

theorem (**in** *reflexive*) *Iwamura*:
assumes *dir*: *directed-set* A $(\sqsubseteq)$ **and** *inf*: *infinite* A
shows $\exists I.\ (\forall a \in A.\ directed\text{-}set\ (I\ a)\ (\sqsubseteq) \wedge |I\ a| <o\ |A|\ ) \wedge$
monotone-on A $(\preceq_A)$ $(\subseteq)$ $I \wedge \bigcup (I`A) = A$
⟨*proof*⟩

4 Directed Completeness and Scott-Continuity

abbreviation *nonempty* $A \equiv if\ A = \{\}\ then\ \bot\ else\ \top$

lemma (**in** *quasi-ordered-set*) *directed-completeness-lemma*:
fixes *leB* (**infix** $\trianglelefteq$ *50*)
assumes *comp*: (*nonempty* $\sqcap$ *well-related-set*)$-$*complete* A $(\sqsubseteq)$ **and** *dir*: *directed-set* D $(\sqsubseteq)$ **and** *DA*: $D \subseteq A$
shows $\exists s.$ *extreme-bound* A $(\sqsubseteq)$ D s
and *well-related-set*$-$*continuous* A $(\sqsubseteq)$ B $(\trianglelefteq)$ $f \Longrightarrow$
$D \neq \{\} \Longrightarrow$ *extreme-bound* A $(\sqsubseteq)$ D $t \Longrightarrow$ *extreme-bound* B $(\trianglelefteq)$ $(f\ `\ D)$ $(f\ t)$
⟨*proof*⟩

The next Theorem corresponds to Proposition 5.9 of [4], without antisymmetry on A.

theorem (**in** *quasi-ordered-set*) *well-complete-iff-directed-complete*:

$(nonempty \sqcap well\text{-}related\text{-}set)-complete\ A\ (\sqsubseteq) \longleftrightarrow directed\text{-}set-complete\ A\ (\sqsubseteq)$
(**is** $?l \longleftrightarrow ?r$)
⟨*proof*⟩

The next Theorem corresponds to Corollary 3 of [9] without any assumptions on the codomain B and without antisymmetry on the domain A.

theorem (**in** *quasi-ordered-set*)
fixes *leB* (**infix** $\trianglelefteq$ *50*)
assumes *comp*: $(nonempty \sqcap well\text{-}related\text{-}set)-complete\ A\ (\sqsubseteq)$
shows $well\text{-}related\text{-}set-continuous\ A\ (\sqsubseteq)\ B\ (\trianglelefteq)\ f \longleftrightarrow directed\text{-}set-continuous\ A\ (\sqsubseteq)\ B\ (\trianglelefteq)\ f$
(**is** $?l \longleftrightarrow ?r$)
⟨*proof*⟩

end

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