

# Stone Relation Algebras

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## Abstract

We develop Stone relation algebras, which generalise relation algebras by replacing the underlying Boolean algebra structure with a Stone algebra. We show that finite matrices over bounded linear orders form an instance. As a consequence, relation-algebraic concepts and methods can be used for reasoning about weighted graphs. We also develop a fixpoint calculus and apply it to compare different definitions of reflexive-transitive closures in semirings.

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# 1 Synopsis and Motivation

This document describes the following six theory files:

- \* `Fixpoints` develops a fixpoint calculus based on partial orders. We also consider least (pre)fixpoints and greatest (post)fixpoints. The derived rules include `unfold`, `square`, `rolling`, `fusion`, `exchange` and diagonal rules studied in [1]. Our results are based on the existence of fixpoints instead of completeness of the underlying structure.
- \* `Semirings` contains a hierarchy of structures generalising idempotent semirings. In particular, several of these algebras do not assume that multiplication is associative in order to capture models such as multirelations. Even in such a weak setting we can derive several results comparing different definitions of reflexive-transitive closures based on fixpoints.
- \* `Relation Algebras` introduces Stone relation algebras, which weaken the Boolean algebra structure of relation algebras to Stone algebras. This is motivated by the wish to represent weighted graphs (matrices over numbers) in addition to unweighted graphs (Boolean matrices) that form relations. Many results of relation algebras can be derived from the weaker axioms and therefore also apply to weighted graphs. Some results hold in Stone relation algebras after small modifications. This allows us to apply relational concepts and methods also to weighted graphs. In particular, we prove a number of properties that have been used to verify graph algorithms. Tarski's relation algebras [28] arise as a special case by imposing further axioms.
- \* `Subalgebras of Relation Algebras` studies the structures of subsets of elements characterised by a given property. In particular we look at regular elements (which correspond to unweighted graphs), coreflexives (tests), vectors and covectors (which can be used to represent sets). The subsets are turned into Isabelle/HOL types, which are shown to form instances of various algebras.
- \* `Matrix Relation Algebras` lifts the Stone algebra hierarchy, the semiring structure and, finally, Stone relation algebras to finite square matrices. These are mostly standard constructions similar to those in [3, 4] implemented so that they work for many algebraic structures. In particular, they can be instantiated to weighted graphs (see below) and extended to Kleene algebras (not part of this development).
- \* `Matrices over Bounded Linear Orders` studies relational properties. In particular, we characterise univalent, injective, total, surjective, mapping, bijective, vector, covector, point, atom, reflexive, coreflexive,

irreflexive, symmetric, antisymmetric and asymmetric matrices. Definitions of these properties are taken from relation algebras and their meaning for matrices over bounded linear orders (weighted graphs) is explained by logical formulas in terms of matrix entries.

The development is based on a theory of Stone algebras [15] and forms the basis for an extension to Kleene algebras to capture further properties of graphs. We apply Stone relation algebras to verify Prim's minimum spanning tree algorithm in Isabelle/HOL in [14].

Related libraries for semirings and relation algebras in the Archive of Formal Proofs are [3, 4]. The theory `Kleene_Algebra/Dioid.thy` introduces a number of structures that generalise idempotent semirings, but does not cover most of the semiring structures in the present development. The theory `Relation_Algebra/Relation_Algebra.thy` covers Tarski's relation algebras and hence cannot be reused for the present development as most properties need to be derived from the weaker axioms of Stone relation algebras. The matrix constructions in theories `Kleene_Algebra/Inf_Matrix.thy` and `Relation_Algebra/Relation_Algebra_Models.thy` are similar, but have strong restrictions on the matrix entry types not appropriate for many algebraic structures in the present development. We also deviate from these hierarchies by basing idempotent semirings directly on the Isabelle/HOL semilattice structures instead of a separate structure; this results in a somewhat smoother integration with the lattice structure of relation algebras.

## 2 Fixpoints

This theory develops a fixpoint calculus based on partial orders. Besides fixpoints we consider least prefixpoints and greatest postfixpoints of functions on a partial order. We do not assume that the underlying structure is complete or that all functions are continuous or isotone. Assumptions about the existence of fixpoints and necessary properties of the involved functions will be stated explicitly in each theorem. This way, the results can be instantiated by various structures, such as complete lattices and Kleene algebras, which impose different kinds of restriction. See, for example, [1, 10] for fixpoint calculi in complete lattices. Our fixpoint calculus contains similar rules, in particular:

- \* unfold rule,
- \* fixpoint operators preserve isotonicity,
- \* square rule,
- \* rolling rule,
- \* various fusion rules,

- \* exchange rule and
- \* diagonal rule.

All of our rules are based on existence rather than completeness of the underlying structure. We have applied results from this theory in [13] and subsequent papers for unifying and reasoning about the semantics of recursion in various relational and matrix-based computation models.

**theory** *Fixpoints*

**imports** *Stone-Algebras.Lattice-Basics*

**begin**

The whole calculus is based on partial orders only.

**context** *order*

**begin**

We first define when an element  $x$  is a least/greatest (pre/post)fixpoint of a given function  $f$ .

**definition** *is-fixpoint*  $f x \equiv f x = x$   $:: ('a \Rightarrow 'a) \Rightarrow 'a \Rightarrow \text{bool}$  **where** *is-fixpoint*

**definition** *is-prefixpoint*  $f x \equiv f x \leq x$   $:: ('a \Rightarrow 'a) \Rightarrow 'a \Rightarrow \text{bool}$  **where** *is-prefixpoint*

**definition** *is-postfixpoint*  $f x \equiv f x \geq x$   $:: ('a \Rightarrow 'a) \Rightarrow 'a \Rightarrow \text{bool}$  **where** *is-postfixpoint*

**definition** *is-least-fixpoint*  $f x \equiv f x = x \wedge (\forall y . f y = y \longrightarrow x \leq y)$   $:: ('a \Rightarrow 'a) \Rightarrow 'a \Rightarrow \text{bool}$  **where** *is-least-fixpoint*

**definition** *is-greatest-fixpoint*  $f x \equiv f x = x \wedge (\forall y . f y = y \longrightarrow x \geq y)$   $:: ('a \Rightarrow 'a) \Rightarrow 'a \Rightarrow \text{bool}$  **where** *is-greatest-fixpoint*

**definition** *is-least-prefixpoint*  $f x \equiv f x \leq x \wedge (\forall y . f y \leq y \longrightarrow x \leq y)$   $:: ('a \Rightarrow 'a) \Rightarrow 'a \Rightarrow \text{bool}$  **where** *is-least-prefixpoint*

**definition** *is-greatest-postfixpoint*  $f x \equiv f x \geq x \wedge (\forall y . f y \geq y \longrightarrow x \geq y)$   $:: ('a \Rightarrow 'a) \Rightarrow 'a \Rightarrow \text{bool}$  **where** *is-greatest-postfixpoint*

Next follows the existence of the corresponding fixpoints for a given function  $f$ .

**definition** *has-fixpoint*  $f \equiv \exists x . \text{is-fixpoint } f x$   $:: ('a \Rightarrow 'a) \Rightarrow \text{bool}$  **where** *has-fixpoint*

**definition** *has-prefixpoint*  $f \equiv \exists x . \text{is-prefixpoint } f x$   $:: ('a \Rightarrow 'a) \Rightarrow \text{bool}$  **where** *has-prefixpoint*

**definition** *has-postfixpoint*  $f \equiv \exists x . \text{is-postfixpoint } f x$   $:: ('a \Rightarrow 'a) \Rightarrow \text{bool}$  **where** *has-postfixpoint*

**definition** *has-least-fixpoint*  $f \equiv \exists x . \text{is-least-fixpoint } f x$   $:: ('a \Rightarrow 'a) \Rightarrow \text{bool}$  **where** *has-least-fixpoint*

**definition** *has-greatest-fixpoint*  $f \equiv \exists x . \text{is-greatest-fixpoint } f x$   $:: ('a \Rightarrow 'a) \Rightarrow \text{bool}$  **where** *has-greatest-fixpoint*

**definition** *has-least-prefixpoint*  $f \equiv \exists x . \text{is-least-prefixpoint } f x$   $:: ('a \Rightarrow 'a) \Rightarrow \text{bool}$  **where** *has-least-prefixpoint*

**definition** *has-greatest-postfixpoint* :: ('a ⇒ 'a) ⇒ bool **where**  
*has-greatest-postfixpoint* f ≡ ∃ x . *is-greatest-postfixpoint* f x

The actual least/greatest (pre/post)fixpoints of a given function *f* are extracted by the following operators.

**definition** *the-least-fixpoint* :: ('a ⇒ 'a) ⇒ 'a (μ - [201] 200) **where** μ f  
= (THE x . *is-least-fixpoint* f x)  
**definition** *the-greatest-fixpoint* :: ('a ⇒ 'a) ⇒ 'a (ν - [201] 200) **where** ν f  
= (THE x . *is-greatest-fixpoint* f x)  
**definition** *the-least-prefixpoint* :: ('a ⇒ 'a) ⇒ 'a (pμ - [201] 200) **where** pμ f  
= (THE x . *is-least-prefixpoint* f x)  
**definition** *the-greatest-postfixpoint* :: ('a ⇒ 'a) ⇒ 'a (pν - [201] 200) **where** pν f  
= (THE x . *is-greatest-postfixpoint* f x)

We start with basic consequences of the above definitions.

**lemma** *least-fixpoint-unique*:  
*has-least-fixpoint* f ⇒ ∃!x . *is-least-fixpoint* f x  
**using** *has-least-fixpoint-def is-least-fixpoint-def order.antisym* **by** *auto*

**lemma** *greatest-fixpoint-unique*:  
*has-greatest-fixpoint* f ⇒ ∃!x . *is-greatest-fixpoint* f x  
**using** *has-greatest-fixpoint-def is-greatest-fixpoint-def order.antisym* **by** *auto*

**lemma** *least-prefixpoint-unique*:  
*has-least-prefixpoint* f ⇒ ∃!x . *is-least-prefixpoint* f x  
**using** *has-least-prefixpoint-def is-least-prefixpoint-def order.antisym* **by** *auto*

**lemma** *greatest-postfixpoint-unique*:  
*has-greatest-postfixpoint* f ⇒ ∃!x . *is-greatest-postfixpoint* f x  
**using** *has-greatest-postfixpoint-def is-greatest-postfixpoint-def order.antisym* **by**  
*auto*

**lemma** *least-fixpoint*:  
*has-least-fixpoint* f ⇒ *is-least-fixpoint* f (μ f)  
**by** (*simp add: least-fixpoint-unique theI' the-least-fixpoint-def*)

**lemma** *greatest-fixpoint*:  
*has-greatest-fixpoint* f ⇒ *is-greatest-fixpoint* f (ν f)  
**by** (*simp add: greatest-fixpoint-unique theI' the-greatest-fixpoint-def*)

**lemma** *least-prefixpoint*:  
*has-least-prefixpoint* f ⇒ *is-least-prefixpoint* f (pμ f)  
**by** (*simp add: least-prefixpoint-unique theI' the-least-prefixpoint-def*)

**lemma** *greatest-postfixpoint*:  
*has-greatest-postfixpoint* f ⇒ *is-greatest-postfixpoint* f (pν f)  
**by** (*simp add: greatest-postfixpoint-unique theI' the-greatest-postfixpoint-def*)

**lemma** *least-fixpoint-same*:

*is-least-fixpoint*  $f\ x \implies x = \mu f$   
**by** (*simp add: is-least-fixpoint-def order.antisym the-equality the-least-fixpoint-def*)

**lemma** *greatest-fixpoint-same*:  
*is-greatest-fixpoint*  $f\ x \implies x = \nu f$   
**using** *greatest-fixpoint greatest-fixpoint-unique has-greatest-fixpoint-def* **by** *auto*

**lemma** *least-prefixpoint-same*:  
*is-least-prefixpoint*  $f\ x \implies x = p\mu f$   
**using** *has-least-prefixpoint-def least-prefixpoint least-prefixpoint-unique* **by** *blast*

**lemma** *greatest-postfixpoint-same*:  
*is-greatest-postfixpoint*  $f\ x \implies x = p\nu f$   
**using** *greatest-postfixpoint greatest-postfixpoint-unique has-greatest-postfixpoint-def* **by** *auto*

**lemma** *least-fixpoint-char*:  
*is-least-fixpoint*  $f\ x \iff has-least-fixpoint\ f \wedge x = \mu f$   
**using** *has-least-fixpoint-def least-fixpoint-same* **by** *auto*

**lemma** *least-prefixpoint-char*:  
*is-least-prefixpoint*  $f\ x \iff has-least-prefixpoint\ f \wedge x = p\mu f$   
**using** *has-least-prefixpoint-def least-prefixpoint-same* **by** *auto*

**lemma** *greatest-fixpoint-char*:  
*is-greatest-fixpoint*  $f\ x \iff has-greatest-fixpoint\ f \wedge x = \nu f$   
**using** *greatest-fixpoint-same has-greatest-fixpoint-def* **by** *auto*

**lemma** *greatest-postfixpoint-char*:  
*is-greatest-postfixpoint*  $f\ x \iff has-greatest-postfixpoint\ f \wedge x = p\nu f$   
**using** *greatest-postfixpoint-same has-greatest-postfixpoint-def* **by** *auto*

Next come the unfold rules for least/greatest (pre/post)fixpoints.

**lemma** *mu-unfold*:  
*has-least-fixpoint*  $f \implies f\ (\mu f) = \mu f$   
**using** *is-least-fixpoint-def least-fixpoint* **by** *auto*

**lemma** *pmu-unfold*:  
*has-least-prefixpoint*  $f \implies f\ (p\mu f) \leq p\mu f$   
**using** *is-least-prefixpoint-def least-prefixpoint* **by** *blast*

**lemma** *nu-unfold*:  
*has-greatest-fixpoint*  $f \implies \nu f = f\ (\nu f)$   
**by** (*metis is-greatest-fixpoint-def greatest-fixpoint*)

**lemma** *pnu-unfold*:  
*has-greatest-postfixpoint*  $f \implies p\nu f \leq f\ (p\nu f)$   
**using** *greatest-postfixpoint is-greatest-postfixpoint-def* **by** *auto*

Pre-/postfixpoints of isotone functions are fixpoints.

**lemma** *least-prefixpoint-fixpoint*:

*has-least-prefixpoint f  $\implies$  isotone f  $\implies$  is-least-fixpoint f (pμ f)*

**using** *is-least-fixpoint-def is-least-prefixpoint-def least-prefixpoint order.antisym isotone-def* **by** *auto*

**lemma** *pmu-mu*:

*has-least-prefixpoint f  $\implies$  isotone f  $\implies$  pμ f = μ f*

**by** (*simp add: least-fixpoint-same least-prefixpoint-fixpoint*)

**lemma** *greatest-postfixpoint-fixpoint*:

*has-greatest-postfixpoint f  $\implies$  isotone f  $\implies$  is-greatest-fixpoint f (pν f)*

**using** *greatest-postfixpoint is-greatest-fixpoint-def is-greatest-postfixpoint-def order.antisym isotone-def* **by** *auto*

**lemma** *pnu-nu*:

*has-greatest-postfixpoint f  $\implies$  isotone f  $\implies$  pν f = ν f*

**by** (*simp add: greatest-fixpoint-same greatest-postfixpoint-fixpoint*)

The fixpoint operators preserve isotonicity.

**lemma** *pmu-isotone*:

*has-least-prefixpoint f  $\implies$  has-least-prefixpoint g  $\implies$  f  $\leq\leq$  g  $\implies$  pμ f  $\leq$  pμ g*

**by** (*metis is-least-prefixpoint-def least-prefixpoint order-trans lifted-less-eq-def*)

**lemma** *mu-isotone*:

*has-least-prefixpoint f  $\implies$  has-least-prefixpoint g  $\implies$  isotone f  $\implies$  isotone g*

$\implies$  f  $\leq\leq$  g  $\implies$  μ f  $\leq$  μ g

**using** *pmu-isotone pmu-mu* **by** *fastforce*

**lemma** *pnu-isotone*:

*has-greatest-postfixpoint f  $\implies$  has-greatest-postfixpoint g  $\implies$  f  $\leq\leq$  g  $\implies$  pν f*

$\leq$  pν g

**by** (*metis greatest-postfixpoint is-greatest-postfixpoint-def order-trans lifted-less-eq-def*)

**lemma** *nu-isotone*:

*has-greatest-postfixpoint f  $\implies$  has-greatest-postfixpoint g  $\implies$  isotone f  $\implies$*

*isotone g  $\implies$  f  $\leq\leq$  g  $\implies$  ν f  $\leq$  ν g*

**using** *pnu-isotone pnu-nu* **by** *fastforce*

The square rule for fixpoints of a function applied twice.

**lemma** *mu-square*:

*isotone f  $\implies$  has-least-fixpoint f  $\implies$  has-least-fixpoint (f  $\circ$  f)  $\implies$  μ f = μ (f  $\circ$  f)*

**by** (*metis (no-types, opaque-lifting) order.antisym is-least-fixpoint-def isotone-def least-fixpoint-char least-fixpoint-unique o-apply*)

**lemma** *nu-square*:

$isotone\ f \implies has\_greatest\_fixpoint\ f \implies has\_greatest\_fixpoint\ (f \circ f) \implies \nu\ f = \nu\ (f \circ f)$

**by** (*metis* (*no-types*, *opaque-lifting*) *order.antisym is-greatest-fixpoint-def isotone-def greatest-fixpoint-char greatest-fixpoint-unique o-apply*)

The rolling rule for fixpoints of the composition of two functions.

**lemma** *mu-roll*:

**assumes** *isotone g*

**and** *has-least-fixpoint (f o g)*

**and** *has-least-fixpoint (g o f)*

**shows**  $\mu\ (g \circ f) = g\ (\mu\ (f \circ g))$

**proof** (*rule order.antisym*)

**show**  $\mu\ (g \circ f) \leq g\ (\mu\ (f \circ g))$

**by** (*metis* *assms(2-3) comp-apply is-least-fixpoint-def least-fixpoint*)

**next**

**have** *is-least-fixpoint (g o f) (mu (g o f))*

**by** (*simp add: assms(3) least-fixpoint*)

**thus**  $g\ (\mu\ (f \circ g)) \leq \mu\ (g \circ f)$

**by** (*metis* (*no-types*) *assms(1-2) comp-def is-least-fixpoint-def least-fixpoint isotone-def*)

**qed**

**lemma** *nu-roll*:

**assumes** *isotone g*

**and** *has-greatest-fixpoint (f o g)*

**and** *has-greatest-fixpoint (g o f)*

**shows**  $\nu\ (g \circ f) = g\ (\nu\ (f \circ g))$

**proof** (*rule order.antisym*)

**have** *1: is-greatest-fixpoint (f o g) (nu (f o g))*

**by** (*simp add: assms(2) greatest-fixpoint*)

**have** *is-greatest-fixpoint (g o f) (nu (g o f))*

**by** (*simp add: assms(3) greatest-fixpoint*)

**thus**  $\nu\ (g \circ f) \leq g\ (\nu\ (f \circ g))$

**using** *1* **by** (*metis* (*no-types*) *assms(1) comp-def is-greatest-fixpoint-def isotone-def*)

**next**

**show**  $g\ (\nu\ (f \circ g)) \leq \nu\ (g \circ f)$

**by** (*metis* *assms(2-3) comp-apply greatest-fixpoint is-greatest-fixpoint-def*)

**qed**

Least (pre)fixpoints are below greatest (post)fixpoints.

**lemma** *mu-below-nu*:

$has\_least\_fixpoint\ f \implies has\_greatest\_fixpoint\ f \implies \mu\ f \leq \nu\ f$

**using** *greatest-fixpoint is-greatest-fixpoint-def mu-unfold* **by** *auto*

**lemma** *pmu-below-pnu-fix*:

$has\_fixpoint\ f \implies has\_least\_prefixpoint\ f \implies has\_greatest\_postfixpoint\ f \implies p\mu\ f \leq p\nu\ f$

**by** (*metis* *greatest-postfixpoint has-fixpoint-def is-fixpoint-def*)



*is-greatest-postfixpoint-def is-least-prefixpoint-def least-prefixpoint order-refl order-trans*)

**lemma** *pmu-below-pnu-iso*:

*isotone f  $\implies$  has-least-prefixpoint f  $\implies$  has-greatest-postfixpoint f  $\implies$   $p\mu f \leq p\nu f$*

**using** *greatest-postfixpoint-fixpoint is-greatest-fixpoint-def is-least-fixpoint-def least-prefixpoint-fixpoint* **by** *auto*

Several variants of the fusion rule for fixpoints follow.

**lemma** *mu-fusion-1*:

**assumes** *galois l u*

**and** *isotone h*

**and** *has-least-prefixpoint g*

**and** *has-least-fixpoint h*

**and**  *$l (g (u (\mu h))) \leq h (l (u (\mu h)))$*

**shows**  *$l (p\mu g) \leq \mu h$*

**proof** –

**have**  *$l (g (u (\mu h))) \leq \mu h$*

**by** (*metis assms(1,2,4,5) galois-char isotone-def order-lesseq-imp mu-unfold*)

**thus**  *$l (p\mu g) \leq \mu h$*

**using** *assms(1,3) is-least-prefixpoint-def least-prefixpoint galois-def* **by** *auto*

**qed**

**lemma** *mu-fusion-2*:

*galois l u  $\implies$  isotone h  $\implies$  has-least-prefixpoint g  $\implies$  has-least-fixpoint h  $\implies$   $l \circ g \leq h \circ l \implies l (p\mu g) \leq \mu h$*

**by** (*simp add: mu-fusion-1 lifted-less-eq-def*)

**lemma** *mu-fusion-equal-1*:

*galois l u  $\implies$  isotone g  $\implies$  isotone h  $\implies$  has-least-prefixpoint g  $\implies$*

*has-least-fixpoint h  $\implies$   $l (g (u (\mu h))) \leq h(l(u(\mu h))) \implies l (g (p\mu g)) = h (l (p\mu g)) \implies \mu h = l (p\mu g) \wedge \mu h = l (\mu g)$*

**by** (*metis order.antisym least-fixpoint least-prefixpoint-fixpoint is-least-fixpoint-def mu-fusion-1 pmu-mu*)

**lemma** *mu-fusion-equal-2*:

*galois l u  $\implies$  isotone h  $\implies$  has-least-prefixpoint g  $\implies$  has-least-prefixpoint h  $\implies$   $l (g (u (\mu h))) \leq h (l (u (\mu h))) \wedge l (g (p\mu g)) = h (l (p\mu g)) \implies p\mu h = l (p\mu g) \wedge \mu h = l (p\mu g)$*

**by** (*metis is-least-prefixpoint-def least-fixpoint-char least-prefixpoint least-prefixpoint-fixpoint order.antisym galois-char isotone-def mu-fusion-1*)

**lemma** *mu-fusion-equal-3*:

**assumes** *galois l u*

**and** *isotone g*

**and** *isotone h*

**and** *has-least-prefixpoint g*

**and** *has-least-fixpoint h*

and  $l \circ g = h \circ l$   
 shows  $\mu h = l (p\mu g)$   
 and  $\mu h = l (\mu g)$   
**proof** –  
 have  $\forall x . l (g x) = h (l x)$   
 using *assms(6) comp-eq-elim* by *blast*  
 thus  $\mu h = l (p\mu g)$   
 using *assms(1-5) mu-fusion-equal-1* by *auto*  
 thus  $\mu h = l (\mu g)$   
 by (*simp add: assms(2,4) pmu-mu*)  
**qed**

**lemma** *mu-fusion-equal-4*:  
 assumes *galois l u*  
 and *isotone h*  
 and *has-least-prefixpoint g*  
 and *has-least-prefixpoint h*  
 and  $l \circ g = h \circ l$   
 shows  $p\mu h = l (p\mu g)$   
 and  $\mu h = l (p\mu g)$   
**proof** –  
 have  $\forall x . l (g x) = h (l x)$   
 using *assms(5) comp-eq-elim* by *blast*  
 thus  $p\mu h = l (p\mu g)$   
 using *assms(1-4) mu-fusion-equal-2* by *auto*  
 thus  $\mu h = l (p\mu g)$   
 by (*simp add: assms(2,4) pmu-mu*)  
**qed**

**lemma** *nu-fusion-1*:  
 assumes *galois l u*  
 and *isotone h*  
 and *has-greatest-postfixpoint g*  
 and *has-greatest-fixpoint h*  
 and  $h (u (l (\nu h))) \leq u (g (l (\nu h)))$   
 shows  $\nu h \leq u (p\nu g)$   
**proof** –  
 have  $\nu h \leq u (g (l (\nu h)))$   
 by (*metis assms(1,2,4,5) order-trans galois-char isotone-def nu-unfold*)  
 thus  $\nu h \leq u (p\nu g)$   
 by (*metis assms(1,3) greatest-postfixpoint is-greatest-postfixpoint-def ord.galois-def*)  
**qed**

**lemma** *nu-fusion-2*:  
 $galois l u \implies isotone h \implies has-greatest-postfixpoint g \implies has-greatest-fixpoint h \implies h \circ u \leq u \circ g \implies \nu h \leq u (p\nu g)$   
 by (*simp add: nu-fusion-1 lifted-less-eq-def*)

**lemma** *nu-fusion-equal-1:*

*galois l u  $\implies$  isotone g  $\implies$  isotone h  $\implies$  has-greatest-postfixpoint g  $\implies$   
has-greatest-fixpoint h  $\implies$  h (u (l (v h)))  $\leq$  u (g (l (v h)))  $\implies$  h (u (pν g)) = u  
(g (pν g))  $\implies$  v h = u (pν g)  $\wedge$  v h = u (v g)*

**by** (*metis greatest-fixpoint-char greatest-postfixpoint-fixpoint  
is-greatest-fixpoint-def order.antisym nu-fusion-1*)

**lemma** *nu-fusion-equal-2:*

*galois l u  $\implies$  isotone h  $\implies$  has-greatest-postfixpoint g  $\implies$   
has-greatest-postfixpoint h  $\implies$  h (u (l (v h)))  $\leq$  u (g (l (v h)))  $\wedge$  h (u (pν g)) =  
u (g (pν g))  $\implies$  pν h = u (pν g)  $\wedge$  v h = u (pν g)*

**by** (*metis greatest-fixpoint-char greatest-postfixpoint greatest-postfixpoint-fixpoint  
is-greatest-postfixpoint-def order.antisym galois-char nu-fusion-1 isotone-def*)

**lemma** *nu-fusion-equal-3:*

**assumes** *galois l u*  
**and** *isotone g*  
**and** *isotone h*  
**and** *has-greatest-postfixpoint g*  
**and** *has-greatest-fixpoint h*  
**and** *h  $\circ$  u = u  $\circ$  g*  
**shows** *v h = u (pν g)*  
**and** *v h = u (v g)*

**proof** –

**have**  $\forall x . u (g x) = h (u x)$   
**using** *assms(6) comp-eq-dest* **by** *fastforce*  
**thus** *v h = u (pν g)*  
**using** *assms(1–5) nu-fusion-equal-1* **by** *auto*  
**thus** *v h = u (v g)*  
**by** (*simp add: assms(2–4) pnu-nu*)

**qed**

**lemma** *nu-fusion-equal-4:*

**assumes** *galois l u*  
**and** *isotone h*  
**and** *has-greatest-postfixpoint g*  
**and** *has-greatest-postfixpoint h*  
**and** *h  $\circ$  u = u  $\circ$  g*  
**shows** *pν h = u (pν g)*  
**and** *v h = u (pν g)*

**proof** –

**have**  $\forall x . u (g x) = h (u x)$   
**using** *assms(5) comp-eq-dest* **by** *fastforce*  
**thus** *pν h = u (pν g)*  
**using** *assms(1–4) nu-fusion-equal-2* **by** *auto*  
**thus** *v h = u (pν g)*  
**by** (*simp add: assms(2,4) pnu-nu*)

**qed**

Next come the exchange rules for replacing the first/second function in

a composition.

**lemma** *mu-exchange-1*:

**assumes** *galois*  $l\ u$   
**and** *isotone*  $g$   
**and** *isotone*  $h$   
**and** *has-least-prefixpoint*  $(l \circ h)$   
**and** *has-least-prefixpoint*  $(h \circ g)$   
**and** *has-least-fixpoint*  $(g \circ h)$   
**and**  $l \circ h \circ g \leq\leq g \circ h \circ l$   
**shows**  $\mu(l \circ h) \leq \mu(g \circ h)$

**proof** –

**have**  $1: l \circ (h \circ g) \leq\leq (g \circ h) \circ l$   
**by** (*simp add: assms(7) rewriteL-comp-comp*)  
**have**  $(l \circ h) (\mu(g \circ h)) = l (\mu(h \circ g))$   
**by** (*metis assms(2,3,5,6) comp-apply least-fixpoint-char least-prefixpoint-fixpoint isotone-def mu-roll*)  
**also have**  $\dots \leq \mu(g \circ h)$   
**using**  $1$  **by** (*metis assms(1-3,5,6) comp-apply least-fixpoint-char least-prefixpoint-fixpoint isotone-def mu-fusion-2*)  
**finally have**  $p\mu(l \circ h) \leq \mu(g \circ h)$   
**using** *assms(4) is-least-prefixpoint-def least-prefixpoint* **by** *blast*  
**thus**  $\mu(l \circ h) \leq \mu(g \circ h)$   
**by** (*metis assms(1,3,4) galois-char isotone-def least-fixpoint-char least-prefixpoint-fixpoint o-apply*)  
**qed**

**lemma** *mu-exchange-2*:

**assumes** *galois*  $l\ u$   
**and** *isotone*  $g$   
**and** *isotone*  $h$   
**and** *has-least-prefixpoint*  $(l \circ h)$   
**and** *has-least-prefixpoint*  $(h \circ l)$   
**and** *has-least-prefixpoint*  $(h \circ g)$   
**and** *has-least-fixpoint*  $(g \circ h)$   
**and** *has-least-fixpoint*  $(h \circ g)$   
**and**  $l \circ h \circ g \leq\leq g \circ h \circ l$   
**shows**  $\mu(h \circ l) \leq \mu(h \circ g)$

**proof** –

**have**  $\mu(h \circ l) = h(\mu(l \circ h))$   
**by** (*metis (no-types, lifting) assms(1,3-5) galois-char isotone-def least-fixpoint-char least-prefixpoint-fixpoint mu-roll o-apply*)  
**also have**  $\dots \leq h(\mu(g \circ h))$   
**using** *assms(1-4,6,7,9) isotone-def mu-exchange-1* **by** *blast*  
**also have**  $\dots = \mu(h \circ g)$   
**by** (*simp add: assms(3,7,8) mu-roll*)  
**finally show** *?thesis*

**qed**

**lemma** *mu-exchange-equal*:

**assumes** *galois l u*  
**and** *galois k t*  
**and** *isotone h*  
**and** *has-least-prefixpoint (l o h)*  
**and** *has-least-prefixpoint (h o l)*  
**and** *has-least-prefixpoint (k o h)*  
**and** *has-least-prefixpoint (h o k)*  
**and**  $l \circ h \circ k = k \circ h \circ l$   
**shows**  $\mu (l \circ h) = \mu (k \circ h)$   
**and**  $\mu (h \circ l) = \mu (h \circ k)$   
**proof** –  
**have** 1: *has-least-fixpoint (k o h)*  
**using** *assms(2,3,6) least-fixpoint-char least-prefixpoint-fixpoint galois-char isotone-def* **by** *auto*  
**have** 2: *has-least-fixpoint (h o k)*  
**using** *assms(2,3,7) least-fixpoint-char least-prefixpoint-fixpoint galois-char isotone-def* **by** *auto*  
**have** 3: *has-least-fixpoint (l o h)*  
**using** *assms(1,3,4) least-fixpoint-char least-prefixpoint-fixpoint galois-char isotone-def* **by** *auto*  
**have** 4: *has-least-fixpoint (h o l)*  
**using** *assms(1,3,5) least-fixpoint-char least-prefixpoint-fixpoint galois-char isotone-def* **by** *auto*  
**show**  $\mu (h \circ l) = \mu (h \circ k)$   
**using** 1 2 3 4 *assms order.antisym galois-char lifted-reflexive mu-exchange-2*  
**by** *auto*  
**show**  $\mu (l \circ h) = \mu (k \circ h)$   
**using** 1 2 3 4 *assms order.antisym galois-char lifted-reflexive mu-exchange-1*  
**by** *auto*  
**qed**

**lemma** *nu-exchange-1*:

**assumes** *galois l u*  
**and** *isotone g*  
**and** *isotone h*  
**and** *has-greatest-postfixpoint (u o h)*  
**and** *has-greatest-postfixpoint (h o g)*  
**and** *has-greatest-fixpoint (g o h)*  
**and**  $g \circ h \circ u \leq u \circ h \circ g$   
**shows**  $\nu (g \circ h) \leq \nu (u \circ h)$   
**proof** –  
**have**  $(g \circ h) \circ u \leq u \circ (h \circ g)$   
**by** (*simp add: assms(7) o-assoc*)  
**hence**  $\nu (g \circ h) \leq \nu (h \circ g)$   
**by** (*metis assms(1-3,5,6) greatest-fixpoint-char greatest-postfixpoint-fixpoint isotone-def nu-fusion-2 o-apply*)  
**also have**  $\dots = \nu (u \circ h)$   
**by** (*metis assms(2,3,5,6) greatest-fixpoint-char greatest-postfixpoint-fixpoint*)

*isotone-def nu-roll o-apply*  
**finally have**  $\nu (g \circ h) \leq p\nu (u \circ h)$   
**using** *assms(4) greatest-postfixpoint is-greatest-postfixpoint-def* **by** *blast*  
**thus**  $\nu (g \circ h) \leq \nu (u \circ h)$   
**using** *assms(1,3,4) galois-char greatest-fixpoint-char*  
*greatest-postfixpoint-fixpoint isotone-def* **by** *auto*  
**qed**

**lemma** *nu-exchange-2:*

**assumes** *galois l u*  
**and** *isotone g*  
**and** *isotone h*  
**and** *has-greatest-postfixpoint (u o h)*  
**and** *has-greatest-postfixpoint (h o u)*  
**and** *has-greatest-postfixpoint (h o g)*  
**and** *has-greatest-fixpoint (g o h)*  
**and** *has-greatest-fixpoint (h o g)*  
**and**  $g \circ h \circ u \leq u \circ h \circ g$   
**shows**  $\nu (h \circ g) \leq \nu (h \circ u)$   
**proof** –  
**have**  $\nu (h \circ g) = h (\nu (g \circ h))$   
**by** (*simp add: assms(3,7,8) nu-roll*)  
**also have**  $\dots \leq h (\nu (u \circ h))$   
**using** *assms(1-4,6,7,9) isotone-def nu-exchange-1* **by** *blast*  
**also have**  $\dots = \nu (h \circ u)$   
**by** (*metis (no-types, lifting) assms(1,3-5) galois-char greatest-fixpoint-char*  
*greatest-postfixpoint-fixpoint isotone-def nu-roll o-apply*)  
**finally show**  $\nu (h \circ g) \leq \nu (h \circ u)$

**qed**

**lemma** *nu-exchange-equal:*

**assumes** *galois l u*  
**and** *galois k t*  
**and** *isotone h*  
**and** *has-greatest-postfixpoint (u o h)*  
**and** *has-greatest-postfixpoint (h o u)*  
**and** *has-greatest-postfixpoint (t o h)*  
**and** *has-greatest-postfixpoint (h o t)*  
**and**  $u \circ h \circ t = t \circ h \circ u$   
**shows**  $\nu (u \circ h) = \nu (t \circ h)$   
**and**  $\nu (h \circ u) = \nu (h \circ t)$   
**proof** –  
**have** *1: has-greatest-fixpoint (u o h)*  
**using** *assms(1,3,4) greatest-fixpoint-char greatest-postfixpoint-fixpoint*  
*galois-char isotone-def* **by** *auto*  
**have** *2: has-greatest-fixpoint (h o u)*  
**using** *assms(1,3,5) greatest-fixpoint-char greatest-postfixpoint-fixpoint*  
*galois-char isotone-def* **by** *auto*

```

have 3: has-greatest-fixpoint (t ◦ h)
  using assms(2,3,6) greatest-fixpoint-char greatest-postfixpoint-fixpoint
galois-char isotone-def by auto
  have 4: has-greatest-fixpoint (h ◦ t)
    using assms(2,3,7) greatest-fixpoint-char greatest-postfixpoint-fixpoint
galois-char isotone-def by auto
  show  $\nu (u \circ h) = \nu (t \circ h)$ 
    using 1 2 3 4 assms order.antisym galois-char lifted-reflexive nu-exchange-1
by auto
  show  $\nu (h \circ u) = \nu (h \circ t)$ 
    using 1 2 3 4 assms order.antisym galois-char lifted-reflexive nu-exchange-2
by auto
qed

```

The following results generalise parts of [10, Exercise 8.27] from continuous functions on complete partial orders to the present setting.

**lemma** *mu-commute-fixpoint-1*:

```

isotone f  $\implies$  has-least-fixpoint (f ◦ g)  $\implies$  f ◦ g = g ◦ f  $\implies$  is-fixpoint f ( $\mu$  (f ◦ g))
by (metis is-fixpoint-def mu-roll)

```

**lemma** *mu-commute-fixpoint-2*:

```

isotone g  $\implies$  has-least-fixpoint (f ◦ g)  $\implies$  f ◦ g = g ◦ f  $\implies$  is-fixpoint g ( $\mu$  (f ◦ g))
by (simp add: mu-commute-fixpoint-1)

```

**lemma** *mu-commute-least-fixpoint*:

```

isotone f  $\implies$  isotone g  $\implies$  has-least-fixpoint f  $\implies$  has-least-fixpoint g  $\implies$ 
has-least-fixpoint (f ◦ g)  $\implies$  f ◦ g = g ◦ f  $\implies$   $\mu$  (f ◦ g) =  $\mu$  f  $\implies$   $\mu$  g  $\leq$   $\mu$  f
by (metis is-least-fixpoint-def least-fixpoint mu-roll)

```

The converse of the preceding result is claimed for continuous  $f, g$  on a complete partial order; it is unknown whether it holds without these additional assumptions.

**lemma** *nu-commute-fixpoint-1*:

```

isotone f  $\implies$  has-greatest-fixpoint (f ◦ g)  $\implies$  f ◦ g = g ◦ f  $\implies$  is-fixpoint f ( $\nu$ (f ◦ g))
by (metis is-fixpoint-def nu-roll)

```

**lemma** *nu-commute-fixpoint-2*:

```

isotone g  $\implies$  has-greatest-fixpoint (f ◦ g)  $\implies$  f ◦ g = g ◦ f  $\implies$  is-fixpoint g ( $\nu$ (f ◦ g))
by (simp add: nu-commute-fixpoint-1)

```

**lemma** *nu-commute-greatest-fixpoint*:

```

isotone f  $\implies$  isotone g  $\implies$  has-greatest-fixpoint f  $\implies$  has-greatest-fixpoint g
 $\implies$  has-greatest-fixpoint (f ◦ g)  $\implies$  f ◦ g = g ◦ f  $\implies$   $\nu$  (f ◦ g) =  $\nu$  f  $\implies$   $\nu$  f  $\leq$ 
 $\nu$  g
by (metis greatest-fixpoint is-greatest-fixpoint-def nu-roll)

```

Finally, we show a number of versions of the diagonal rule for functions with two arguments.

**lemma** *mu-diagonal-1*:

**assumes** *isotone* ( $\lambda x . \mu (\lambda y . f x y)$ )  
**and**  $\forall x . \text{has-least-fixpoint } (\lambda y . f x y)$   
**and** *has-least-prefixpoint* ( $\lambda x . \mu (\lambda y . f x y)$ )  
**shows**  $\mu (\lambda x . f x x) = \mu (\lambda x . \mu (\lambda y . f x y))$

**proof** –

**let**  $?g = \lambda x . \mu (\lambda y . f x y)$   
**have** 1: *is-least-prefixpoint*  $?g (\mu ?g)$   
**using** *assms(1,3) least-prefixpoint pmu-mu* **by** *fastforce*  
**have**  $f (\mu ?g) (\mu ?g) = \mu ?g$   
**by** (*metis (no-types, lifting) assms is-least-fixpoint-def least-fixpoint-char least-prefixpoint-fixpoint*)  
**hence** *is-least-fixpoint* ( $\lambda x . f x x$ ) ( $\mu ?g$ )  
**using** 1 *assms(2) is-least-fixpoint-def is-least-prefixpoint-def least-fixpoint* **by** *auto*  
**thus** *?thesis*  
**using** *least-fixpoint-same* **by** *simp*  
**qed**

**lemma** *mu-diagonal-2*:

$\forall x . \text{isotone } (\lambda y . f x y) \wedge \text{isotone } (\lambda y . f y x) \wedge \text{has-least-prefixpoint } (\lambda y . f x y) \implies \text{has-least-prefixpoint } (\lambda x . \mu (\lambda y . f x y)) \implies \mu (\lambda x . f x x) = \mu (\lambda x . \mu (\lambda y . f x y))$   
**apply** (*rule mu-diagonal-1*)  
**using** *isotone-def lifted-less-eq-def mu-isotone* **apply** *simp*  
**using** *has-least-fixpoint-def least-prefixpoint-fixpoint* **apply** *blast*  
**by** *simp*

**lemma** *nu-diagonal-1*:

**assumes** *isotone* ( $\lambda x . \nu (\lambda y . f x y)$ )  
**and**  $\forall x . \text{has-greatest-fixpoint } (\lambda y . f x y)$   
**and** *has-greatest-postfixpoint* ( $\lambda x . \nu (\lambda y . f x y)$ )  
**shows**  $\nu (\lambda x . f x x) = \nu (\lambda x . \nu (\lambda y . f x y))$

**proof** –

**let**  $?g = \lambda x . \nu (\lambda y . f x y)$   
**have** 1: *is-greatest-postfixpoint*  $?g (\nu ?g)$   
**using** *assms(1,3) greatest-postfixpoint pnu-nu* **by** *fastforce*  
**have**  $f (\nu ?g) (\nu ?g) = \nu ?g$   
**by** (*metis (no-types, lifting) assms is-greatest-fixpoint-def greatest-fixpoint-char greatest-postfixpoint-fixpoint*)  
**hence** *is-greatest-fixpoint* ( $\lambda x . f x x$ ) ( $\nu ?g$ )  
**using** 1 *assms(2) is-greatest-fixpoint-def is-greatest-postfixpoint-def greatest-fixpoint* **by** *auto*  
**thus** *?thesis*  
**using** *greatest-fixpoint-same* **by** *simp*  
**qed**



**lemma** *nu-diagonal-2*:

$\forall x . \text{isotone } (\lambda y . f x y) \wedge \text{isotone } (\lambda y . f y x) \wedge \text{has-greatest-postfixpoint } (\lambda y . f x y) \implies \text{has-greatest-postfixpoint } (\lambda x . \nu (\lambda y . f x y)) \implies \nu (\lambda x . f x x) = \nu (\lambda x . \nu (\lambda y . f x y))$

**apply** (*rule nu-diagonal-1*)

**using** *isotone-def lifted-less-eq-def nu-isotone* **apply** *simp*

**using** *has-greatest-fixpoint-def greatest-postfixpoint-fixpoint* **apply** *blast*

**by** *simp*

**end**

**end**

### 3 Semirings

This theory develops a hierarchy of idempotent semirings. All kinds of semiring considered here are bounded semilattices, but many lack additional properties typically assumed for semirings. In particular, we consider the variants of semirings, in which

- \* multiplication is not required to be associative;
- \* a right zero and unit of multiplication need not exist;
- \* multiplication has a left residual;
- \* multiplication from the left is not required to distribute over addition;
- \* the semilattice order has a greatest element.

We have applied results from this theory a number of papers for unifying computation models. For example, see [13] for various relational and matrix-based computation models and [6] for multirelational models.

The main results in this theory relate different ways of defining reflexive-transitive closures as discussed in [6].

**theory** *Semirings*

**imports** *Fixpoints*

**begin**

#### 3.1 Idempotent Semirings

The following definitions are standard for relations. Putting them into a general class that depends only on the signature facilitates reuse. Coreflexives are sometimes called partial identities, subidentities, monotypes or tests.

```

class times-one-ord = times + one + ord
begin

abbreviation reflexive :: 'a ⇒ bool where reflexive x ≡ 1 ≤ x
abbreviation coreflexive :: 'a ⇒ bool where coreflexive x ≡ x ≤ 1

abbreviation transitive :: 'a ⇒ bool where transitive x ≡ x * x ≤ x
abbreviation dense-rel :: 'a ⇒ bool where dense-rel x ≡ x ≤ x * x
abbreviation idempotent :: 'a ⇒ bool where idempotent x ≡ x * x = x

abbreviation preorder :: 'a ⇒ bool where preorder x ≡ reflexive x ∧
transitive x

abbreviation coreflexives ≡ { x . coreflexive x }

end

```

The first algebra is a very weak idempotent semiring, in which multiplication is not necessarily associative.

```

class non-associative-left-semiring = bounded-semilattice-sup-bot + times + one
+
  assumes mult-left-sub-dist-sup: x * y ⊔ x * z ≤ x * (y ⊔ z)
  assumes mult-right-dist-sup: (x ⊔ y) * z = x * z ⊔ y * z
  assumes mult-left-zero [simp]: bot * x = bot
  assumes mult-left-one [simp]: 1 * x = x
  assumes mult-sub-right-one: x ≤ x * 1
begin

subclass times-one-ord .

```

We first show basic isotonicity and subdistributivity properties of multiplication.

```

lemma mult-left-isotone:
  x ≤ y ⇒ x * z ≤ y * z
  using mult-right-dist-sup sup-right-divisibility by auto

lemma mult-right-isotone:
  x ≤ y ⇒ z * x ≤ z * y
  using mult-left-sub-dist-sup sup.bounded-iff sup-right-divisibility by auto

lemma mult-isotone:
  w ≤ y ⇒ x ≤ z ⇒ w * x ≤ y * z
  using order-trans mult-left-isotone mult-right-isotone by blast

lemma affine-isotone:
  isotone (λx . y * x ⊔ z)
  using isotone-def mult-right-isotone sup-left-isotone by auto

lemma mult-left-sub-dist-sup-left:

```

$x * y \leq x * (y \sqcup z)$   
**by** (*simp add: mult-right-isotone*)

**lemma** *mult-left-sub-dist-sup-right*:  
 $x * z \leq x * (y \sqcup z)$   
**by** (*simp add: mult-right-isotone*)

**lemma** *mult-right-sub-dist-sup-left*:  
 $x * z \leq (x \sqcup y) * z$   
**by** (*simp add: mult-left-isotone*)

**lemma** *mult-right-sub-dist-sup-right*:  
 $y * z \leq (x \sqcup y) * z$   
**by** (*simp add: mult-left-isotone*)

**lemma** *case-split-left*:  
**assumes**  $1 \leq w \sqcup z$   
**and**  $w * x \leq y$   
**and**  $z * x \leq y$   
**shows**  $x \leq y$   
**proof** –  
**have**  $(w \sqcup z) * x \leq y$   
**by** (*simp add: assms(2-3) mult-right-dist-sup*)  
**thus** *?thesis*  
**by** (*metis assms(1) dual-order.trans mult-left-one mult-left-isotone*)  
**qed**

**lemma** *case-split-left-equal*:  
 $w \sqcup z = 1 \implies w * x = w * y \implies z * x = z * y \implies x = y$   
**by** (*metis mult-left-one mult-right-dist-sup*)

Next we consider under which semiring operations the above properties are closed.

**lemma** *reflexive-one-closed*:  
*reflexive 1*  
**by** *simp*

**lemma** *reflexive-sup-closed*:  
*reflexive x  $\implies$  reflexive (x  $\sqcup$  y)*  
**by** (*simp add: le-supI1*)

**lemma** *reflexive-mult-closed*:  
*reflexive x  $\implies$  reflexive y  $\implies$  reflexive (x \* y)*  
**using** *mult-isotone* **by** *fastforce*

**lemma** *coreflexive-bot-closed*:  
*coreflexive bot*  
**by** *simp*

**lemma** *coreflexive-one-closed*:

*coreflexive 1*

**by** *simp*

**lemma** *coreflexive-sup-closed*:

*coreflexive x  $\implies$  coreflexive y  $\implies$  coreflexive (x  $\sqcup$  y)*

**by** *simp*

**lemma** *coreflexive-mult-closed*:

*coreflexive x  $\implies$  coreflexive y  $\implies$  coreflexive (x \* y)*

**using** *mult-isotone* **by** *fastforce*

**lemma** *transitive-bot-closed*:

*transitive bot*

**by** *simp*

**lemma** *transitive-one-closed*:

*transitive 1*

**by** *simp*

**lemma** *dense-bot-closed*:

*dense-rel bot*

**by** *simp*

**lemma** *dense-one-closed*:

*dense-rel 1*

**by** *simp*

**lemma** *dense-sup-closed*:

*dense-rel x  $\implies$  dense-rel y  $\implies$  dense-rel (x  $\sqcup$  y)*

**by** (*metis mult-right-dist-sup order-lesseq-imp sup.mono  
mult-left-sub-dist-sup-left mult-left-sub-dist-sup-right*)

**lemma** *idempotent-bot-closed*:

*idempotent bot*

**by** *simp*

**lemma** *idempotent-one-closed*:

*idempotent 1*

**by** *simp*

**lemma** *preorder-one-closed*:

*preorder 1*

**by** *simp*

**lemma** *coreflexive-transitive*:

*coreflexive x  $\implies$  transitive x*

**using** *mult-left-isotone* **by** *fastforce*

**lemma** *preorder-idempotent*:  
*preorder*  $x \implies$  *idempotent*  $x$   
**using** *order.antisym mult-isotone* **by** *fastforce*

We study the following three ways of defining reflexive-transitive closures. Each of them is given as a least prefixpoint, but the underlying functions are different. They implement left recursion, right recursion and symmetric recursion, respectively.

**abbreviation**  $Lf :: 'a \Rightarrow ('a \Rightarrow 'a)$  **where**  $Lf\ y \equiv (\lambda x . 1 \sqcup x * y)$   
**abbreviation**  $Rf :: 'a \Rightarrow ('a \Rightarrow 'a)$  **where**  $Rf\ y \equiv (\lambda x . 1 \sqcup y * x)$   
**abbreviation**  $Sf :: 'a \Rightarrow ('a \Rightarrow 'a)$  **where**  $Sf\ y \equiv (\lambda x . 1 \sqcup y \sqcup x * x)$

**abbreviation**  $lstar :: 'a \Rightarrow 'a$  **where**  $lstar\ y \equiv p\mu\ (Lf\ y)$   
**abbreviation**  $rstar :: 'a \Rightarrow 'a$  **where**  $rstar\ y \equiv p\mu\ (Rf\ y)$   
**abbreviation**  $sstar :: 'a \Rightarrow 'a$  **where**  $sstar\ y \equiv p\mu\ (Sf\ y)$

All functions are isotone and, therefore, if the prefixpoints exist they are also fixpoints.

**lemma** *lstar-rec-isotone*:  
*isotone*  $(Lf\ y)$   
**using** *isotone-def sup-right-divisibility sup-right-isotone*  
*mult-right-sub-dist-sup-right* **by** *auto*

**lemma** *rstar-rec-isotone*:  
*isotone*  $(Rf\ y)$   
**using** *isotone-def sup-right-divisibility sup-right-isotone*  
*mult-left-sub-dist-sup-right* **by** *auto*

**lemma** *sstar-rec-isotone*:  
*isotone*  $(Sf\ y)$   
**using** *isotone-def sup-right-isotone mult-isotone* **by** *auto*

**lemma** *lstar-fixpoint*:  
*has-least-prefixpoint*  $(Lf\ y) \implies lstar\ y = \mu\ (Lf\ y)$   
**by** *(simp add: pmu-mu lstar-rec-isotone)*

**lemma** *rstar-fixpoint*:  
*has-least-prefixpoint*  $(Rf\ y) \implies rstar\ y = \mu\ (Rf\ y)$   
**by** *(simp add: pmu-mu rstar-rec-isotone)*

**lemma** *sstar-fixpoint*:  
*has-least-prefixpoint*  $(Sf\ y) \implies sstar\ y = \mu\ (Sf\ y)$   
**by** *(simp add: pmu-mu sstar-rec-isotone)*

**lemma** *sstar-increasing*:  
*has-least-prefixpoint*  $(Sf\ y) \implies y \leq sstar\ y$   
**using** *order-trans pmu-unfold sup-ge1 sup-ge2* **by** *blast*

The fixpoint given by right recursion is always below the one given by symmetric recursion.

```

lemma rstar-below-sstar:
  assumes has-least-prefixpoint (Rf y)
    and has-least-prefixpoint (Sf y)
    shows  $rstar\ y \leq sstar\ y$ 
proof –
  have  $y \leq sstar\ y$ 
    using assms(2) pmu-unfold by force
  hence  $Rf\ y\ (sstar\ y) \leq Sf\ y\ (sstar\ y)$ 
    by (meson sup.cobounded1 sup.mono mult-left-isotone)
  also have  $\dots \leq sstar\ y$ 
    using assms(2) pmu-unfold by blast
  finally show ?thesis
    using assms(1) is-least-prefixpoint-def least-prefixpoint by auto
qed

```

**end**

Our next structure adds one half of the associativity property. This inequality holds, for example, for multirelations under the compositions defined by Parikh and Peleg [23, 25]. The converse inequality requires up-closed multirelations for Parikh’s composition.

```

class pre-left-semiring = non-associative-left-semiring +
  assumes mult-semi-associative:  $(x * y) * z \leq x * (y * z)$ 
begin

```

```

lemma mult-one-associative [simp]:
   $x * 1 * y = x * y$ 
  by (metis dual-order.antisym mult-left-isotone mult-left-one
mult-semi-associative mult-sub-right-one)

```

```

lemma mult-sup-associative-one:
   $(x * (y * 1)) * z \leq x * (y * z)$ 
  by (metis mult-semi-associative mult-one-associative)

```

```

lemma rstar-increasing:
  assumes has-least-prefixpoint (Rf y)
    shows  $y \leq rstar\ y$ 
proof –
  have  $Rf\ y\ (rstar\ y) \leq rstar\ y$ 
    using assms pmu-unfold by blast
  thus ?thesis
    by (metis le-supE mult-right-isotone mult-sub-right-one sup.absorb-iff2)
qed

```

**end**

For the next structure we add a left residual operation. Such a residual is available, for example, for multirelations.

The operator notation for binary division is introduced in a class that

requires a unary inverse. This is appropriate for fields, but too strong in the present context of semirings. We therefore reintroduce it without requiring a unary inverse.

**no-notation**

*inverse-divide* (**infixl**  $'/$  70)

**notation**

*divide* (**infixl**  $'/$  70)

**class** *residuated-pre-left-semiring* = *pre-left-semiring* + *divide* +

**assumes** *lres-galois*:  $x * y \leq z \iff x \leq z / y$

**begin**

We first derive basic properties of left residuals from the Galois connection.

**lemma** *lres-left-isotone*:

$x \leq y \implies x / z \leq y / z$

**using** *dual-order.trans lres-galois* **by** *blast*

**lemma** *lres-right-antitone*:

$x \leq y \implies z / y \leq z / x$

**using** *dual-order.trans lres-galois mult-right-isotone* **by** *blast*

**lemma** *lres-inverse*:

$(x / y) * y \leq x$

**by** (*simp add: lres-galois*)

**lemma** *lres-one*:

$x / 1 \leq x$

**using** *mult-sub-right-one order-trans lres-inverse* **by** *blast*

**lemma** *lres-mult-sub-lres-lres*:

$x / (z * y) \leq (x / y) / z$

**using** *lres-galois mult-semi-associative order.trans* **by** *blast*

**lemma** *mult-lres-sub-assoc*:

$x * (y / z) \leq (x * y) / z$

**by** (*meson dual-order.trans lres-galois mult-right-isotone lres-inverse lres-mult-sub-lres-lres*)

With the help of a left residual, it follows that left recursion is below right recursion.

**lemma** *lstar-below-rstar*:

**assumes** *has-least-prefixpoint* (*Lf* *y*)

**and** *has-least-prefixpoint* (*Rf* *y*)

**shows**  $lstar\ y \leq rstar\ y$

**proof** –

**have**  $y * (rstar\ y / y) * y \leq y * rstar\ y$

```

    using lres-galois mult-lres-sub-assoc by auto
  also have ... ≤ rstar y
    using assms(2) le-supE pmu-unfold by blast
  finally have y * (rstar y / y) ≤ rstar y / y
    by (simp add: lres-galois)
  hence Rf y (rstar y / y) ≤ rstar y / y
    using assms(2) lres-galois rstar-increasing by fastforce
  hence rstar y ≤ rstar y / y
    using assms(2) is-least-prefixpoint-def least-prefixpoint by auto
  hence Lf y (rstar y) ≤ rstar y
    using assms(2) lres-galois pmu-unfold by fastforce
  thus ?thesis
    using assms(1) is-least-prefixpoint-def least-prefixpoint by auto
qed

```

Moreover, right recursion gives the same result as symmetric recursion. The next proof follows an argument of [5, Satz 10.1.5].

```

lemma rstar-sstar:
  assumes has-least-prefixpoint (Rf y)
    and has-least-prefixpoint (Sf y)
  shows rstar y = sstar y
proof -
  have Rf y (rstar y / rstar y) * rstar y ≤ rstar y ⊔ y * ((rstar y / rstar y) *
rstar y)
    using mult-right-dist-sup mult-semi-associative sup-right-isotone by auto
  also have ... ≤ rstar y ⊔ y * rstar y
    using mult-right-isotone sup-right-isotone lres-inverse by blast
  also have ... ≤ rstar y
    using assms(1) pmu-unfold by fastforce
  finally have Rf y (rstar y / rstar y) ≤ rstar y / rstar y
    by (simp add: lres-galois)
  hence rstar y * rstar y ≤ rstar y
    using assms(1) is-least-prefixpoint-def least-prefixpoint lres-galois by auto
  hence y ⊔ rstar y * rstar y ≤ rstar y
    by (simp add: assms(1) rstar-increasing)
  hence Sf y (rstar y) ≤ rstar y
    using assms(1) pmu-unfold by force
  hence sstar y ≤ rstar y
    using assms(2) is-least-prefixpoint-def least-prefixpoint by auto
  thus ?thesis
    by (simp add: assms order.antisym rstar-below-sstar)
qed
end

```

In the next structure we add full associativity of multiplication, as well as a right unit. Still, multiplication does not need to have a right zero and does not need to distribute over addition from the left.

```

class idempotent-left-semiring = non-associative-left-semiring + monoid-mult

```



**begin**

**subclass** *pre-left-semiring*  
  **by** *unfold-locales (simp add: mult-assoc)*

**lemma** *zero-right-mult-decreasing*:  
   $x * \text{bot} \leq x$   
  **by** (*metis bot-least mult-1-right mult-right-isotone*)

The following result shows that for dense coreflexives there are two equivalent ways to express that a property is preserved. In the setting of Kleene algebras, this is well known for tests, which form a Boolean subalgebra. The point here is that only very few properties of tests are needed to show the equivalence.

**lemma** *test-preserves-equation*:  
  **assumes** *dense-rel p*  
    **and** *coreflexive p*  
  **shows**  $p * x \leq x * p \longleftrightarrow p * x = p * x * p$   
**proof**  
  **assume**  $1: p * x \leq x * p$   
  **have**  $p * x \leq p * p * x$   
    **by** (*simp add: assms(1) mult-left-isotone*)  
  **also have**  $\dots \leq p * x * p$   
    **using**  $1$  **by** (*simp add: mult-right-isotone mult-assoc*)  
  **finally show**  $p * x = p * x * p$   
    **using** *assms(2) order.antisym mult-right-isotone* **by** *fastforce*  
**next**  
  **assume**  $p * x = p * x * p$   
  **thus**  $p * x \leq x * p$   
    **by** (*metis assms(2) mult-left-isotone mult-left-one*)  
**qed**  
**end**

The next structure has both distributivity properties of multiplication. Only a right zero is missing from full semirings. This is important as many computation models do not have a right zero of sequential composition.

**class** *idempotent-left-zero-semiring* = *idempotent-left-semiring* +  
  **assumes** *mult-left-dist-sup:  $x * (y \sqcup z) = x * y \sqcup x * z$*   
**begin**

**lemma** *case-split-right*:  
  **assumes**  $1 \leq w \sqcup z$   
    **and**  $x * w \leq y$   
    **and**  $x * z \leq y$   
  **shows**  $x \leq y$   
**proof** –  
  **have**  $x * (w \sqcup z) \leq y$   
    **by** (*simp add: assms(2–3) mult-left-dist-sup*)

**thus** *?thesis*  
**by** (*metis assms(1) dual-order.trans mult-1-right mult-right-isotone*)  
**qed**

**lemma** *case-split-right-equal*:  
 $w \sqcup z = 1 \implies x * w = y * w \implies x * z = y * z \implies x = y$   
**by** (*metis mult-1-right mult-left-dist-sup*)

This is the first structure we can connect to the semirings provided by Isabelle/HOL.

**sublocale** *semiring: ordered-semiring sup bot less-eq less times*  
**apply** *unfold-locales*  
**using** *sup-right-isotone* **apply** *blast*  
**apply** (*simp add: mult-right-dist-sup*)  
**apply** (*simp add: mult-left-dist-sup*)  
**apply** (*simp add: mult-right-isotone*)  
**by** (*simp add: mult-left-isotone*)

**sublocale** *semiring: semiring-numeral 1 times sup ..*

**end**

Completing this part of the hierarchy, we obtain idempotent semirings by adding a right zero of multiplication.

**class** *idempotent-semiring = idempotent-left-zero-semiring +*  
**assumes** *mult-right-zero [simp]: x \* bot = bot*  
**begin**

**sublocale** *semiring: semiring-0 sup bot times*  
**by** *unfold-locales simp-all*

**end**

### 3.2 Bounded Idempotent Semirings

All of the following semirings have a greatest element in the underlying semi-lattice order. With this element, we can express further standard properties of relations. We extend each class in the above hierarchy in turn.

**class** *times-top = times + top*  
**begin**

**abbreviation** *vector*  $:: 'a \Rightarrow \text{bool}$  **where** *vector*  $x \equiv x * \text{top} = x$   
**abbreviation** *covector*  $:: 'a \Rightarrow \text{bool}$  **where** *covector*  $x \equiv \text{top} * x = x$   
**abbreviation** *total*  $:: 'a \Rightarrow \text{bool}$  **where** *total*  $x \equiv x * \text{top} = \text{top}$   
**abbreviation** *surjective*  $:: 'a \Rightarrow \text{bool}$  **where** *surjective*  $x \equiv \text{top} * x = \text{top}$

**abbreviation** *vectors*  $\equiv \{ x . \text{vector } x \}$   
**abbreviation** *covectors*  $\equiv \{ x . \text{covector } x \}$

**end**

```
class bounded-non-associative-left-semiring = non-associative-left-semiring + top
+
  assumes sup-right-top [simp]:  $x \sqcup \text{top} = \text{top}$ 
begin
```

```
subclass times-top .
```

We first give basic properties of the greatest element.

```
lemma sup-left-top [simp]:
   $\text{top} \sqcup x = \text{top}$ 
using sup-right-top sup commute by fastforce
```

```
lemma top-greatest [simp]:
   $x \leq \text{top}$ 
by (simp add: le-iff-sup)
```

```
lemma top-left-mult-increasing:
   $x \leq \text{top} * x$ 
by (metis mult-left-isotone mult-left-one top-greatest)
```

```
lemma top-right-mult-increasing:
   $x \leq x * \text{top}$ 
using mult-right-isotone mult-sub-right-one order-trans top-greatest by blast
```

```
lemma top-mult-top [simp]:
   $\text{top} * \text{top} = \text{top}$ 
by (simp add: order.antisym top-left-mult-increasing)
```

Closure of the above properties under the semiring operations is considered next.

```
lemma vector-bot-closed:
  vector bot
by simp
```

```
lemma vector-top-closed:
  vector top
by simp
```

```
lemma vector-sup-closed:
  vector  $x \implies \text{vector } y \implies \text{vector } (x \sqcup y)$ 
by (simp add: mult-right-dist-sup)
```

```
lemma covector-top-closed:
  covector top
by simp
```

**lemma** *total-one-closed*:

*total 1*

**by** *simp*

**lemma** *total-top-closed*:

*total top*

**by** *simp*

**lemma** *total-sup-closed*:

*total x  $\implies$  total (x  $\sqcup$  y)*

**by** (*simp add: mult-right-dist-sup*)

**lemma** *surjective-one-closed*:

*surjective 1*

**by** (*simp add: order.antisym mult-sub-right-one*)

**lemma** *surjective-top-closed*:

*surjective top*

**by** *simp*

**lemma** *surjective-sup-closed*:

*surjective x  $\implies$  surjective (x  $\sqcup$  y)*

**by** (*metis le-iff-sup mult-left-sub-dist-sup-left sup-left-top*)

**lemma** *reflexive-top-closed*:

*reflexive top*

**by** *simp*

**lemma** *transitive-top-closed*:

*transitive top*

**by** *simp*

**lemma** *dense-top-closed*:

*dense-rel top*

**by** *simp*

**lemma** *idempotent-top-closed*:

*idempotent top*

**by** *simp*

**lemma** *preorder-top-closed*:

*preorder top*

**by** *simp*

**end**

Some closure properties require at least half of associativity.

**class** *bounded-pre-left-semiring* = *pre-left-semiring* +  
*bounded-non-associative-left-semiring*

**begin**

**lemma** *vector-mult-closed*:

*vector*  $y \implies \text{vector } (x * y)$

**by** (*metis order.antisym mult-semi-associative top-right-mult-increasing*)

**lemma** *surjective-mult-closed*:

*surjective*  $x \implies \text{surjective } y \implies \text{surjective } (x * y)$

**by** (*metis order.antisym mult-semi-associative top-greatest*)

**end**

We next consider residuals with the greatest element.

**class** *bounded-residuated-pre-left-semiring* = *residuated-pre-left-semiring* +

*bounded-pre-left-semiring*

**begin**

**lemma** *lres-top-decreasing*:

$x / \text{top} \leq x$

**using** *lres-inverse order.trans top-right-mult-increasing by blast*

**lemma** *top-lres-absorb [simp]*:

$\text{top} / x = \text{top}$

**using** *order.antisym lres-galois top-greatest by blast*

**lemma** *covector-lres-closed*:

*covector*  $x \implies \text{covector } (x / y)$

**by** (*metis order.antisym mult-lres-sub-assoc top-left-mult-increasing*)

**end**

Some closure properties require full associativity.

**class** *bounded-idempotent-left-semiring* = *bounded-pre-left-semiring* +

*idempotent-left-semiring*

**begin**

**lemma** *covector-mult-closed*:

*covector*  $x \implies \text{covector } (x * y)$

**by** (*metis mult-assoc*)

**lemma** *total-mult-closed*:

*total*  $x \implies \text{total } y \implies \text{total } (x * y)$

**by** (*simp add: mult-assoc*)

**end**

Some closure properties require distributivity from the left.

**class** *bounded-idempotent-left-zero-semiring* = *bounded-idempotent-left-semiring*

+ *idempotent-left-zero-semiring*

**begin**

**lemma** *covector-sup-closed*:

*covector*  $x \implies$  *covector*  $y \implies$  *covector*  $(x \sqcup y)$

**by** (*simp add: mult-left-dist-sup*)

**end**

Our final structure is an idempotent semiring with a greatest element.

**class** *bounded-idempotent-semiring* = *bounded-idempotent-left-zero-semiring* +  
*idempotent-semiring*

**begin**

**lemma** *covector-bot-closed*:

*covector* *bot*

**by** *simp*

**end**

**end**

## 4 Relation Algebras

The main structures introduced in this theory are Stone relation algebras. They generalise Tarski's relation algebras [28] by weakening the Boolean algebra lattice structure to a Stone algebra. Our motivation is to generalise relation-algebraic methods from unweighted graphs to weighted graphs. Unlike unweighted graphs, weighted graphs do not form a Boolean algebra because there is no complement operation on the edge weights. However, edge weights form a Stone algebra, and matrices over edge weights (that is, weighted graphs) form a Stone relation algebra.

The development in this theory is described in our papers [14, 16]. Our main application there is the verification of Prim's minimum spanning tree algorithm. Related work about fuzzy relations [12, 29], Dedekind categories [18] and rough relations [9, 24] is also discussed in these papers. In particular, Stone relation algebras do not assume that the underlying lattice is complete or a Heyting algebra, and they do not assume that composition has residuals.

We proceed in two steps. First, we study the positive fragment in the form of single-object bounded distributive allegories [11]. Second, we extend these structures by a pseudocomplement operation with additional axioms to obtain Stone relation algebras.

Tarski's relation algebras are then obtained by a simple extension that imposes a Boolean algebra. See, for example, [7, 17, 20, 21, 26, 27] for further details about relations and relation algebras, and [2, 8] for algebras of relations with a smaller signature.

**theory** *Relation-Algebras*

**imports** *Stone-Algebras.P-Algebras Semirings*

**begin**

## 4.1 Single-Object Bounded Distributive Allegories

We start with developing bounded distributive allegories. The following definitions concern properties of relations that require converse in addition to lattice and semiring operations.

**class** *conv* =

**fixes** *conv* :: 'a  $\Rightarrow$  'a ( $-^T$  [100] 100)

**class** *bounded-distrib-allegory-signature* = *inf* + *sup* + *times* + *conv* + *bot* + *top* + *one* + *ord*

**begin**

**subclass** *times-one-ord* .

**subclass** *times-top* .

**abbreviation** *total-var* :: 'a  $\Rightarrow$  bool **where** *total-var*  $x \equiv 1 \leq x * x^T$

**abbreviation** *surjective-var* :: 'a  $\Rightarrow$  bool **where** *surjective-var*  $x \equiv 1 \leq x^T * x$

**abbreviation** *univalent* :: 'a  $\Rightarrow$  bool **where** *univalent*  $x \equiv x^T * x \leq 1$

**abbreviation** *injective* :: 'a  $\Rightarrow$  bool **where** *injective*  $x \equiv x * x^T \leq 1$

**abbreviation** *mapping* :: 'a  $\Rightarrow$  bool **where** *mapping*  $x \equiv$  *univalent*  $x$   
 $\wedge$  *total*  $x$

**abbreviation** *bijective* :: 'a  $\Rightarrow$  bool **where** *bijective*  $x \equiv$  *injective*  $x \wedge$   
*surjective*  $x$

**abbreviation** *point* :: 'a  $\Rightarrow$  bool **where** *point*  $x \equiv$  *vector*  $x \wedge$   
*bijective*  $x$

**abbreviation** *arc* :: 'a  $\Rightarrow$  bool **where** *arc*  $x \equiv$  *bijective*  $(x * top)$   
 $\wedge$  *bijective*  $(x^T * top)$

**abbreviation** *symmetric* :: 'a  $\Rightarrow$  bool **where** *symmetric*  $x \equiv x^T = x$

**abbreviation** *antisymmetric* :: 'a  $\Rightarrow$  bool **where** *antisymmetric*  $x \equiv x \sqcap x^T \leq 1$

**abbreviation** *asymmetric* :: 'a  $\Rightarrow$  bool **where** *asymmetric*  $x \equiv x \sqcap x^T =$   
*bot*

**abbreviation** *linear* :: 'a  $\Rightarrow$  bool **where** *linear*  $x \equiv x \sqcup x^T = top$

**abbreviation** *equivalence* :: 'a  $\Rightarrow$  bool **where** *equivalence*  $x \equiv$  *preorder*  $x \wedge$   
*symmetric*  $x$

**abbreviation** *order* :: 'a  $\Rightarrow$  bool **where** *order*  $x \equiv$  *preorder*  $x \wedge$   
*antisymmetric*  $x$

**abbreviation** *linear-order* :: 'a  $\Rightarrow$  bool **where** *linear-order*  $x \equiv$  *order*  $x \wedge$   
*linear*  $x$

**end**

We reuse the relation algebra axioms given in [20] except for one – see lemma *conv-complement-sub* below – which we replace with the Dedekind rule (or modular law) *dedekind-1*. The Dedekind rule or variants of it are known from [7, 11, 19, 27]. We add *conv-left-zero*, which follows in relation algebras but not in the present setting. The main change is that only a bounded distributive lattice is required, not a Boolean algebra.

```

class bounded-distrib-allegory = bounded-distrib-lattice + times + one + conv +
assumes conv-associative      : (x * y) * z = x * (y * z)
assumes conv-right-dist-sup  : (x  $\sqcup$  y) * z = (x * z)  $\sqcup$  (y * z)
assumes conv-left-zero [simp]: bot * x = bot
assumes conv-left-one [simp]: 1 * x = x
assumes conv-involutive [simp]: xTT = x
assumes conv-dist-sup       : (x  $\sqcup$  y)T = xT  $\sqcup$  yT
assumes conv-dist-comp      : (x * y)T = yT * xT
assumes dedekind-1         : x * y  $\sqcap$  z  $\leq$  x * (y  $\sqcap$  (xT * z))
begin

subclass bounded-distrib-allegory-signature .

```

Many properties of relation algebras already follow in bounded distributive allegories.

```

lemma conv-isotone:
  x  $\leq$  y  $\implies$  xT  $\leq$  yT
by (metis conv-dist-sup le-iff-sup)

```

```

lemma conv-order:
  x  $\leq$  y  $\longleftrightarrow$  xT  $\leq$  yT
using conv-isotone by fastforce

```

```

lemma conv-bot [simp]:
  botT = bot
using conv-order bot-unique by force

```

```

lemma conv-top [simp]:
  topT = top
by (metis conv-involutive conv-order order.eq-iff top-greatest)

```

```

lemma conv-dist-inf:
  (x  $\sqcap$  y)T = xT  $\sqcap$  yT
apply (rule order.antisym)
using conv-order apply simp
by (metis conv-order conv-involutive inf.boundedI inf.cobounded1
inf.cobounded2)

```

```

lemma conv-inf-bot-iff:
  bot = xT  $\sqcap$  y  $\longleftrightarrow$  bot = x  $\sqcap$  yT
using conv-dist-inf conv-bot by fastforce

```



**lemma** *conv-one* [*simp*]:

$$1^T = 1$$

**by** (*metis comp-left-one conv-dist-comp conv-involutive*)

**lemma** *comp-left-dist-sup*:

$$(x * y) \sqcup (x * z) = x * (y \sqcup z)$$

**by** (*metis comp-right-dist-sup conv-involutive conv-dist-sup conv-dist-comp*)

**lemma** *comp-right-isotone*:

$$x \leq y \implies z * x \leq z * y$$

**by** (*simp add: comp-left-dist-sup sup.absorb-iff1*)

**lemma** *comp-left-isotone*:

$$x \leq y \implies x * z \leq y * z$$

**by** (*metis comp-right-dist-sup le-iff-sup*)

**lemma** *comp-isotone*:

$$x \leq y \implies w \leq z \implies x * w \leq y * z$$

**using** *comp-left-isotone comp-right-isotone order.trans* **by** *blast*

**lemma** *comp-left-subdist-inf*:

$$(x \sqcap y) * z \leq x * z \sqcap y * z$$

**by** (*simp add: comp-left-isotone*)

**lemma** *comp-left-increasing-sup*:

$$x * y \leq (x \sqcup z) * y$$

**by** (*simp add: comp-left-isotone*)

**lemma** *comp-right-subdist-inf*:

$$x * (y \sqcap z) \leq x * y \sqcap x * z$$

**by** (*simp add: comp-right-isotone*)

**lemma** *comp-right-increasing-sup*:

$$x * y \leq x * (y \sqcup z)$$

**by** (*simp add: comp-right-isotone*)

**lemma** *comp-right-zero* [*simp*]:

$$x * \text{bot} = \text{bot}$$

**by** (*metis comp-left-zero conv-dist-comp conv-involutive*)

**lemma** *comp-right-one* [*simp*]:

$$x * 1 = x$$

**by** (*metis comp-left-one conv-dist-comp conv-involutive*)

**lemma** *comp-left-conjugate*:

$$\text{conjugate } (\lambda y . x * y) (\lambda y . x^T * y)$$

**apply** (*unfold conjugate-def, intro allI*)

**by** (*metis comp-right-zero bot.extremum-unique conv-involutive dedekind-1*)

*inf.commute*)

**lemma** *comp-right-conjugate*:

*conjugate* ( $\lambda y . y * x$ ) ( $\lambda y . y * x^T$ )

**apply** (*unfold conjugate-def*, *intro allI*)

**by** (*metis comp-left-conjugate[unfolded conjugate-def] conv-inf-bot-iff*  
*conv-dist-comp conv-involutive*)

We still obtain a semiring structure.

**subclass** *bounded-idempotent-semiring*

**by** (*unfold-locales*)

(*auto simp: comp-right-isotone comp-right-dist-sup comp-associative*  
*comp-left-dist-sup*)

**sublocale** *inf: semiring-0 sup bot inf*

**by** (*unfold-locales, auto simp: inf-sup-distrib2 inf-sup-distrib1 inf-assoc*)

**lemma** *schroeder-1*:

$x * y \sqcap z = \text{bot} \iff x^T * z \sqcap y = \text{bot}$

**using** *abel-semigroup.commute comp-left-conjugate conjugate-def*

*inf.abel-semigroup-axioms* **by** *fastforce*

**lemma** *schroeder-2*:

$x * y \sqcap z = \text{bot} \iff z * y^T \sqcap x = \text{bot}$

**by** (*metis comp-right-conjugate conjugate-def inf-commute*)

**lemma** *comp-additive*:

*additive* ( $\lambda y . x * y$ )  $\wedge$  *additive* ( $\lambda y . x^T * y$ )  $\wedge$  *additive* ( $\lambda y . y * x$ )  $\wedge$  *additive*  
( $\lambda y . y * x^T$ )

**by** (*simp add: comp-left-dist-sup additive-def comp-right-dist-sup*)

**lemma** *dedekind-2*:

$y * x \sqcap z \leq (y \sqcap (z * x^T)) * x$

**by** (*metis conv-dist-inf conv-order conv-dist-comp dedekind-1*)

The intersection with a vector can still be exported from the first argument of a composition, and many other properties of vectors and covectors continue to hold.

**lemma** *vector-inf-comp*:

*vector*  $x \implies (x \sqcap y) * z = x \sqcap (y * z)$

**apply** (*rule order.antisym*)

**apply** (*metis comp-left-subdist-inf comp-right-isotone inf.sup-left-isotone*  
*order-lesseq-imp top-greatest*)

**by** (*metis comp-left-isotone comp-right-isotone dedekind-2 inf-commute*  
*inf-mono order-refl order-trans top-greatest*)

**lemma** *vector-inf-closed*:

*vector*  $x \implies \text{vector } y \implies \text{vector } (x \sqcap y)$

**by** (*simp add: vector-inf-comp*)

**lemma** *vector-inf-one-comp*:

*vector*  $x \implies (x \sqcap 1) * y = x \sqcap y$   
**by** (*simp add: vector-inf-comp*)

**lemma** *covector-inf-comp-1*:

**assumes** *vector*  $x$   
**shows**  $(y \sqcap x^T) * z = (y \sqcap x^T) * (x \sqcap z)$

**proof** –

**have**  $(y \sqcap x^T) * z \leq (y \sqcap x^T) * (z \sqcap ((y^T \sqcap x) * top))$   
**by** (*metis inf-top-right dedekind-1 conv-dist-inf conv-involutive*)  
**also have**  $\dots \leq (y \sqcap x^T) * (x \sqcap z)$

**by** (*metis assms comp-left-isotone comp-right-isotone inf-le2 inf-mono order-refl inf-commute*)

**finally show** *?thesis*

**by** (*simp add: comp-right-isotone order.antisym*)

**qed**

**lemma** *covector-inf-comp-2*:

**assumes** *vector*  $x$   
**shows**  $y * (x \sqcap z) = (y \sqcap x^T) * (x \sqcap z)$

**proof** –

**have**  $y * (x \sqcap z) \leq (y \sqcap (top * (x \sqcap z)^T)) * (x \sqcap z)$   
**by** (*metis dedekind-2 inf-top-right*)  
**also have**  $\dots \leq (y \sqcap x^T) * (x \sqcap z)$

**by** (*metis assms comp-left-isotone conv-dist-comp conv-order conv-top eq-refl inf-le1 inf-mono*)

**finally show** *?thesis*

**using** *comp-left-subdist-inf order.antisym* **by** *auto*

**qed**

**lemma** *covector-inf-comp-3*:

*vector*  $x \implies (y \sqcap x^T) * z = y * (x \sqcap z)$   
**by** (*metis covector-inf-comp-1 covector-inf-comp-2*)

**lemma** *covector-inf-closed*:

*covector*  $x \implies \text{covector } y \implies \text{covector } (x \sqcap y)$   
**by** (*metis comp-right-subdist-inf order.antisym top-left-mult-increasing*)

**lemma** *vector-conv-covector*:

*vector*  $v \iff \text{covector } (v^T)$   
**by** (*metis conv-dist-comp conv-involutive conv-top*)

**lemma** *covector-conv-vector*:

*covector*  $v \iff \text{vector } (v^T)$   
**by** (*simp add: vector-conv-covector*)

**lemma** *covector-comp-inf*:

*covector*  $z \implies x * (y \sqcap z) = x * y \sqcap z$

**apply** (*rule order.antisym*)  
**apply** (*metis comp-isotone comp-right-subdist-inf inf.boundedE inf.boundedI inf.cobounded2 top.extremum*)  
**by** (*metis comp-left-isotone comp-right-isotone dedekind-1 inf-commute inf-mono order-refl order-trans top-greatest*)

**lemma** *vector-restrict-comp-conv*:

*vector*  $x \implies x \sqcap y \leq x^T * y$

**by** (*metis covector-inf-comp-3 eq-refl inf.sup-monoid.add-commute inf-top-right le-supE sup.orderE top-left-mult-increasing*)

**lemma** *covector-restrict-comp-conv*:

*covector*  $x \implies y \sqcap x \leq y * x^T$

**by** (*metis conv-dist-comp conv-dist-inf conv-order conv-top inf.sup-monoid.add-commute vector-restrict-comp-conv*)

**lemma** *covector-comp-inf-1*:

*covector*  $x \implies (y \sqcap x) * z = y * (x^T \sqcap z)$

**using** *covector-conv-vector covector-inf-comp-3* **by** *fastforce*

We still have two ways to represent surjectivity and totality.

**lemma** *surjective-var*:

*surjective*  $x \iff \text{surjective-var } x$

**proof**

**assume** *surjective*  $x$

**thus** *surjective-var*  $x$

**by** (*metis dedekind-2 comp-left-one inf-absorb2 top-greatest*)

**next**

**assume** *surjective-var*  $x$

**hence**  $x^T * (x * \text{top}) = \text{top}$

**by** (*metis comp-left-isotone comp-associative comp-left-one top-le*)

**thus** *surjective*  $x$

**by** (*metis comp-right-isotone conv-top conv-dist-comp conv-involutive top-greatest top-le*)

**qed**

**lemma** *total-var*:

*total*  $x \iff \text{total-var } x$

**by** (*metis conv-top conv-dist-comp conv-involutive surjective-var*)

**lemma** *surjective-conv-total*:

*surjective*  $x \iff \text{total } (x^T)$

**by** (*metis conv-top conv-dist-comp conv-involutive*)

**lemma** *total-conv-surjective*:

*total*  $x \iff \text{surjective } (x^T)$

**by** (*simp add: surjective-conv-total*)

**lemma** *injective-conv-univalent*:

*injective*  $x \iff$  *univalent*  $(x^T)$   
**by** *simp*

**lemma** *univalent-conv-injective*:  
*univalent*  $x \iff$  *injective*  $(x^T)$   
**by** *simp*

We continue with studying further closure properties.

**lemma** *univalent-bot-closed*:  
*univalent* *bot*  
**by** *simp*

**lemma** *univalent-one-closed*:  
*univalent* *1*  
**by** *simp*

**lemma** *univalent-inf-closed*:  
*univalent*  $x \implies$  *univalent*  $(x \sqcap y)$   
**by** (*metis comp-left-subdist-inf comp-right-subdist-inf conv-dist-inf*  
*inf.cobounded1 order-lesseq-imp*)

**lemma** *univalent-mult-closed*:  
**assumes** *univalent*  $x$   
**and** *univalent*  $y$   
**shows** *univalent*  $(x * y)$   
**proof** –  
**have**  $(x * y)^T * x \leq y^T$   
**by** (*metis assms(1) comp-left-isotone comp-right-one conv-one conv-order*  
*comp-associative conv-dist-comp conv-involutive*)  
**thus** *?thesis*  
**by** (*metis assms(2) comp-left-isotone comp-associative dual-order.trans*)  
**qed**

**lemma** *injective-bot-closed*:  
*injective* *bot*  
**by** *simp*

**lemma** *injective-one-closed*:  
*injective* *1*  
**by** *simp*

**lemma** *injective-inf-closed*:  
*injective*  $x \implies$  *injective*  $(x \sqcap y)$   
**by** (*metis conv-dist-inf injective-conv-univalent univalent-inf-closed*)

**lemma** *injective-mult-closed*:  
*injective*  $x \implies$  *injective*  $y \implies$  *injective*  $(x * y)$   
**by** (*metis injective-conv-univalent conv-dist-comp univalent-mult-closed*)

**lemma** *mapping-one-closed*:

*mapping 1*

**by** *simp*

**lemma** *mapping-mult-closed*:

*mapping x  $\implies$  mapping y  $\implies$  mapping (x \* y)*

**by** (*simp add: comp-associative univalent-mult-closed*)

**lemma** *bijection-one-closed*:

*bijection 1*

**by** *simp*

**lemma** *bijection-mult-closed*:

*bijection x  $\implies$  bijection y  $\implies$  bijection (x \* y)*

**by** (*metis injective-mult-closed comp-associative*)

**lemma** *bijection-conv-mapping*:

*bijection x  $\longleftrightarrow$  mapping (x<sup>T</sup>)*

**by** (*simp add: surjective-conv-total*)

**lemma** *mapping-conv-bijection*:

*mapping x  $\longleftrightarrow$  bijection (x<sup>T</sup>)*

**by** (*simp add: total-conv-surjective*)

**lemma** *reflexive-inf-closed*:

*reflexive x  $\implies$  reflexive y  $\implies$  reflexive (x  $\sqcap$  y)*

**by** *simp*

**lemma** *reflexive-conv-closed*:

*reflexive x  $\implies$  reflexive (x<sup>T</sup>)*

**using** *conv-isotone* **by** *force*

**lemma** *coreflexive-inf-closed*:

*coreflexive x  $\implies$  coreflexive (x  $\sqcap$  y)*

**by** (*simp add: le-infI1*)

**lemma** *coreflexive-conv-closed*:

*coreflexive x  $\implies$  coreflexive (x<sup>T</sup>)*

**using** *conv-order* **by** *force*

**lemma** *coreflexive-symmetric*:

*coreflexive x  $\implies$  symmetric x*

**by** (*metis comp-right-one comp-right-subdist-inf conv-dist-inf conv-dist-comp conv-involutive dedekind-1 inf.absorb1 inf.absorb2*)

**lemma** *transitive-inf-closed*:

*transitive x  $\implies$  transitive y  $\implies$  transitive (x  $\sqcap$  y)*

**by** (*meson comp-left-subdist-inf inf.cobounded1 inf.sup-mono inf-le2 mult-right-isotone order.trans*)

**lemma** *transitive-conv-closed*:  
*transitive*  $x \implies \text{transitive } (x^T)$   
**using** *conv-order conv-dist-comp* **by** *fastforce*

**lemma** *dense-conv-closed*:  
*dense-rel*  $x \implies \text{dense-rel } (x^T)$   
**using** *conv-order conv-dist-comp* **by** *fastforce*

**lemma** *idempotent-conv-closed*:  
*idempotent*  $x \implies \text{idempotent } (x^T)$   
**by** (*metis conv-dist-comp*)

**lemma** *preorder-inf-closed*:  
*preorder*  $x \implies \text{preorder } y \implies \text{preorder } (x \sqcap y)$   
**using** *transitive-inf-closed* **by** *auto*

**lemma** *preorder-conv-closed*:  
*preorder*  $x \implies \text{preorder } (x^T)$   
**by** (*simp add: reflexive-conv-closed transitive-conv-closed*)

**lemma** *symmetric-bot-closed*:  
*symmetric bot*  
**by** *simp*

**lemma** *symmetric-one-closed*:  
*symmetric 1*  
**by** *simp*

**lemma** *symmetric-top-closed*:  
*symmetric top*  
**by** *simp*

**lemma** *symmetric-inf-closed*:  
*symmetric*  $x \implies \text{symmetric } y \implies \text{symmetric } (x \sqcap y)$   
**by** (*simp add: conv-dist-inf*)

**lemma** *symmetric-sup-closed*:  
*symmetric*  $x \implies \text{symmetric } y \implies \text{symmetric } (x \sqcup y)$   
**by** (*simp add: conv-dist-sup*)

**lemma** *symmetric-conv-closed*:  
*symmetric*  $x \implies \text{symmetric } (x^T)$   
**by** *simp*

**lemma** *one-inf-conv*:  
 $1 \sqcap x = 1 \sqcap x^T$   
**by** (*metis conv-dist-inf coreflexive-symmetric inf.cobounded1 symmetric-one-closed*)

**lemma** *antisymmetric-bot-closed*:

*antisymmetric bot*

**by** *simp*

**lemma** *antisymmetric-one-closed*:

*antisymmetric 1*

**by** *simp*

**lemma** *antisymmetric-inf-closed*:

*antisymmetric  $x \implies$  antisymmetric  $(x \sqcap y)$*

**by** (*rule order-trans[where  $y=x \sqcap x^T$ ]*) (*simp-all add: conv-isotone inf.coboundedI2 inf.sup-assoc*)

**lemma** *antisymmetric-conv-closed*:

*antisymmetric  $x \implies$  antisymmetric  $(x^T)$*

**by** (*simp add: inf-commute*)

**lemma** *asymmetric-bot-closed*:

*asymmetric bot*

**by** *simp*

**lemma** *asymmetric-inf-closed*:

*asymmetric  $x \implies$  asymmetric  $(x \sqcap y)$*

**by** (*metis conv-dist-inf inf.mult-zero-left inf.left-commute inf-assoc*)

**lemma** *asymmetric-conv-closed*:

*asymmetric  $x \implies$  asymmetric  $(x^T)$*

**by** (*simp add: inf-commute*)

**lemma** *linear-top-closed*:

*linear top*

**by** *simp*

**lemma** *linear-sup-closed*:

*linear  $x \implies$  linear  $(x \sqcup y)$*

**by** (*metis conv-dist-sup sup-assoc sup-commute sup-top-right*)

**lemma** *linear-reflexive*:

*linear  $x \implies$  reflexive  $x$*

**by** (*metis one-inf-conv inf.distrib-left inf.cobounded2 inf.orderE reflexive-top-closed sup.idem*)

**lemma** *linear-conv-closed*:

*linear  $x \implies$  linear  $(x^T)$*

**by** (*simp add: sup-commute*)

**lemma** *linear-comp-closed*:

**assumes** *linear  $x$*



**and** *linear y*  
**shows** *linear (x \* y)*  
**proof** –  
**have** *reflexive y*  
**by** (*simp add: assms(2) linear-reflexive*)  
**hence**  $x \sqcup x^T \leq x * y \sqcup y^T * x^T$   
**by** (*metis case-split-left case-split-right le-supI sup.cobounded1 sup.cobounded2 sup.idem reflexive-conv-closed*)  
**thus** *?thesis*  
**by** (*simp add: assms(1) conv-dist-comp top-le*)  
**qed**

**lemma** *equivalence-one-closed:*  
*equivalence 1*  
**by** *simp*

**lemma** *equivalence-top-closed:*  
*equivalence top*  
**by** *simp*

**lemma** *equivalence-inf-closed:*  
*equivalence x  $\implies$  equivalence y  $\implies$  equivalence (x  $\sqcap$  y)*  
**using** *conv-dist-inf preorder-inf-closed by auto*

**lemma** *equivalence-conv-closed:*  
*equivalence x  $\implies$  equivalence (x<sup>T</sup>)*  
**by** *simp*

**lemma** *order-one-closed:*  
*order 1*  
**by** *simp*

**lemma** *order-inf-closed:*  
*order x  $\implies$  order y  $\implies$  order (x  $\sqcap$  y)*  
**using** *antisymmetric-inf-closed transitive-inf-closed by auto*

**lemma** *order-conv-closed:*  
*order x  $\implies$  order (x<sup>T</sup>)*  
**by** (*simp add: inf-commute reflexive-conv-closed transitive-conv-closed*)

**lemma** *linear-order-conv-closed:*  
*linear-order x  $\implies$  linear-order (x<sup>T</sup>)*  
**using** *equivalence-top-closed conv-dist-sup inf-commute reflexive-conv-closed transitive-conv-closed by force*

We show a fact about equivalences.

**lemma** *equivalence-comp-dist-inf:*  
*equivalence x  $\implies$  x \* y  $\sqcap$  x \* z = x \* (y  $\sqcap$  x \* z)*  
**by** (*metis order.antisym comp-right-subdist-inf dedekind-1 order.eq-iff*)

*inf.absorb1 inf.absorb2 mult-1-right mult-assoc*)

The following result generalises the fact that composition with a test amounts to intersection with the corresponding vector. Both tests and vectors can be used to represent sets as relations.

**lemma** *coreflexive-comp-top-inf:*

*coreflexive x  $\implies$  x \* top  $\sqcap$  y = x \* y*

**apply** (*rule order.antisym*)

**apply** (*metis comp-left-isotone comp-left-one coreflexive-symmetric dedekind-1 inf-top-left order-trans*)

**using** *comp-left-isotone comp-right-isotone* **by** *fastforce*

**lemma** *coreflexive-comp-top-inf-one:*

*coreflexive x  $\implies$  x \* top  $\sqcap$  1 = x*

**by** (*simp add: coreflexive-comp-top-inf*)

**lemma** *coreflexive-comp-inf:*

*coreflexive x  $\implies$  coreflexive y  $\implies$  x \* y = x  $\sqcap$  y*

**by** (*metis (full-types) coreflexive-comp-top-inf coreflexive-comp-top-inf-one inf.mult-assoc inf.absorb2*)

**lemma** *coreflexive-comp-inf-comp:*

**assumes** *coreflexive x*

**and** *coreflexive y*

**shows**  $(x * z) \sqcap (y * z) = (x \sqcap y) * z$

**proof** –

**have**  $(x * z) \sqcap (y * z) = x * top \sqcap z \sqcap y * top \sqcap z$

**using** *assms coreflexive-comp-top-inf inf-assoc* **by** *auto*

**also have**  $\dots = x * top \sqcap y * top \sqcap z$

**by** (*simp add: inf.commute inf.left-commute*)

**also have**  $\dots = (x \sqcap y) * top \sqcap z$

**by** (*metis assms coreflexive-comp-inf coreflexive-comp-top-inf mult-assoc*)

**also have**  $\dots = (x \sqcap y) * z$

**by** (*simp add: assms(1) coreflexive-comp-top-inf coreflexive-inf-closed*)

**finally show** *?thesis*

**qed**

**lemma** *test-comp-test-inf:*

$(x \sqcap 1) * y * (z \sqcap 1) = (x \sqcap 1) * y \sqcap y * (z \sqcap 1)$

**by** (*smt comp-right-one comp-right-subdist-inf coreflexive-comp-top-inf inf.left-commute inf.orderE inf-le2 mult-assoc*)

**lemma** *test-comp-test-top:*

$y \sqcap (x \sqcap 1) * top * (z \sqcap 1) = (x \sqcap 1) * y * (z \sqcap 1)$

**proof** –

**have**  $\forall u v . (v \sqcap u^T)^T = v^T \sqcap u$

**using** *conv-dist-inf* **by** *auto*

**thus** *?thesis*

by (*smt conv-dist-comp conv-involutive coreflexive-comp-top-inf  
inf.cobounded2 inf.left-commute inf.sup-monoid.add-commute  
symmetric-one-closed mult-assoc symmetric-top-closed*)  
qed

**lemma** *coreflexive-idempotent*:  
coreflexive  $x \implies$  idempotent  $x$   
by (*simp add: coreflexive-comp-inf*)

**lemma** *coreflexive-univalent*:  
coreflexive  $x \implies$  univalent  $x$   
by (*simp add: coreflexive-idempotent coreflexive-symmetric*)

**lemma** *coreflexive-injective*:  
coreflexive  $x \implies$  injective  $x$   
by (*simp add: coreflexive-idempotent coreflexive-symmetric*)

**lemma** *coreflexive-commutative*:  
coreflexive  $x \implies$  coreflexive  $y \implies x * y = y * x$   
by (*simp add: coreflexive-comp-inf inf.commute*)

**lemma** *coreflexive-dedekind*:  
coreflexive  $x \implies$  coreflexive  $y \implies$  coreflexive  $z \implies x * y \sqcap z \leq x * (y \sqcap x * z)$   
by (*simp add: coreflexive-comp-inf inf.coboundedI1 inf.left-commute*)

Also the equational version of the Dedekind rule continues to hold.

**lemma** *dedekind-eq*:  
 $x * y \sqcap z = (x \sqcap (z * y^T)) * (y \sqcap (x^T * z)) \sqcap z$   
**proof** (*rule order.antisym*)  
have  $x * y \sqcap z \leq x * (y \sqcap (x^T * z)) \sqcap z$   
by (*simp add: dedekind-1*)  
also have  $\dots \leq (x \sqcap (z * (y \sqcap (x^T * z))^T)) * (y \sqcap (x^T * z)) \sqcap z$   
by (*simp add: dedekind-2*)  
also have  $\dots \leq (x \sqcap (z * y^T)) * (y \sqcap (x^T * z)) \sqcap z$   
by (*metis comp-left-isotone comp-right-isotone inf-mono conv-order  
inf.cobounded1 order-refl*)  
finally show  $x * y \sqcap z \leq (x \sqcap (z * y^T)) * (y \sqcap (x^T * z)) \sqcap z$   
.  
next  
show  $(x \sqcap (z * y^T)) * (y \sqcap (x^T * z)) \sqcap z \leq x * y \sqcap z$   
using *comp-isotone inf.sup-left-isotone* by auto  
qed

**lemma** *dedekind*:  
 $x * y \sqcap z \leq (x \sqcap (z * y^T)) * (y \sqcap (x^T * z))$   
by (*metis dedekind-eq inf.cobounded1*)

**lemma** *vector-export-comp*:  
 $(x * top \sqcap y) * z = x * top \sqcap y * z$

**proof** –

**have**  $vector (x * top)$   
**by** (*simp add: comp-associative*)  
**thus** *?thesis*  
**by** (*simp add: vector-inf-comp*)  
**qed**

**lemma** *vector-export-comp-unit*:  
 $(x * top \sqcap 1) * y = x * top \sqcap y$   
**by** (*simp add: vector-export-comp*)

We solve a few exercises from [27].

**lemma** *ex231a* [*simp*]:  
 $(1 \sqcap x * x^T) * x = x$   
**by** (*metis inf.cobounded1 inf.idem inf-right-idem comp-left-one conv-one coreflexive-comp-top-inf dedekind-eq*)

**lemma** *ex231b* [*simp*]:  
 $x * (1 \sqcap x^T * x) = x$   
**by** (*metis conv-dist-comp conv-dist-inf conv-involutive conv-one ex231a*)

**lemma** *ex231c*:  
 $x \leq x * x^T * x$   
**by** (*metis comp-left-isotone ex231a inf-le2*)

**lemma** *ex231d*:  
 $x \leq x * top * x$   
**by** (*metis comp-left-isotone comp-right-isotone top-greatest order-trans ex231c*)

**lemma** *ex231e* [*simp*]:  
 $x * top * x * top = x * top$   
**by** (*metis ex231d order.antisym comp-associative mult-right-isotone top.extremum*)

**lemma** *arc-injective*:  
 $arc x \implies injective x$   
**by** (*metis conv-dist-inf conv-involutive inf.absorb2 top-right-mult-increasing univalent-inf-closed*)

**lemma** *arc-conv-closed*:  
 $arc x \implies arc (x^T)$   
**by** *simp*

**lemma** *arc-univalent*:  
 $arc x \implies univalent x$   
**using** *arc-conv-closed arc-injective univalent-conv-injective* **by** *blast*

**lemma** *injective-codomain*:  
**assumes** *injective x*

```

shows  $x * (x \sqcap 1) = x \sqcap 1$ 
proof (rule order.antisym)
  show  $x * (x \sqcap 1) \leq x \sqcap 1$ 
    by (metis assms comp-right-one dual-order.trans inf.boundedI inf.cobounded1
inf.sup-monoid.add-commute mult-right-isotone one-inf-conv)
  next
    show  $x \sqcap 1 \leq x * (x \sqcap 1)$ 
      by (metis coreflexive-idempotent inf.cobounded1 inf.cobounded2
mult-left-isotone)
qed

```

The following result generalises [22, Exercise 2]. It is used to show that the while-loop preserves injectivity of the constructed tree.

```

lemma injective-sup:
  assumes injective t
    and  $e * t^T \leq 1$ 
    and injective e
  shows injective (t  $\sqcup$  e)
proof -
  have (t  $\sqcup$  e) * (t  $\sqcup$  e)^T = t * t^T  $\sqcup$  t * e^T  $\sqcup$  e * t^T  $\sqcup$  e * e^T
    by (simp add: comp-left-dist-sup conv-dist-sup semiring.distrib-right sup.assoc)
  thus ?thesis
    using assms coreflexive-symmetric conv-dist-comp by fastforce
qed

```

```

lemma injective-inv:
   $injective\ t \implies e * t^T = bot \implies arc\ e \implies injective\ (t \sqcup e)$ 
  using arc-injective injective-sup bot-least by blast

```

```

lemma univalent-sup:
   $univalent\ t \implies e^T * t \leq 1 \implies univalent\ e \implies univalent\ (t \sqcup e)$ 
  by (metis injective-sup conv-dist-sup conv-involutive)

```

```

lemma point-injective:
   $arc\ x \implies x^T * top * x \leq 1$ 
  by (metis conv-top comp-associative conv-dist-comp conv-involutive
vector-top-closed)

```

```

lemma vv-transitive:
   $vector\ v \implies (v * v^T) * (v * v^T) \leq v * v^T$ 
  by (metis comp-associative comp-left-isotone comp-right-isotone top-greatest)

```

```

lemma epm-3:
  assumes  $e \leq w$ 
    and injective w
  shows  $e = w \sqcap top * e$ 
proof -
  have  $w \sqcap top * e \leq w * e^T * e$ 
    by (metis (no-types, lifting) inf.absorb2 top.extremum dedekind-2)

```

*inf.commute*)  
**also have**  $\dots \leq w * w^T * e$   
**by** (*simp add: assms(1) conv-isotone mult-left-isotone mult-right-isotone*)  
**also have**  $\dots \leq e$   
**using** *assms(2) coreflexive-comp-top-inf inf.sup-right-divisibility* **by** *blast*  
**finally show** *?thesis*  
**by** (*simp add: assms(1) top-left-mult-increasing order.antisym*)  
**qed**

**lemma** *comp-inf-vector*:  
 $x * (y \sqcap z * top) = (x \sqcap top * z^T) * y$   
**by** (*metis conv-top covector-inf-comp-3 comp-associative conv-dist-comp inf.commute vector-top-closed*)

**lemma** *inf-vector-comp*:  
 $(x \sqcap y * top) * z = y * top \sqcap x * z$   
**using** *inf.commute vector-export-comp* **by** *auto*

**lemma** *comp-inf-covector*:  
 $x * (y \sqcap top * z) = x * y \sqcap top * z$   
**by** (*simp add: covector-comp-inf covector-mult-closed*)

Well-known distributivity properties of univalent and injective relations over meet continue to hold.

**lemma** *univalent-comp-left-dist-inf*:  
**assumes** *univalent x*  
**shows**  $x * (y \sqcap z) = x * y \sqcap x * z$   
**proof** (*rule order.antisym*)  
**show**  $x * (y \sqcap z) \leq x * y \sqcap x * z$   
**by** (*simp add: comp-right-isotone*)  
**next**  
**have**  $x * y \sqcap x * z \leq (x \sqcap x * z * y^T) * (y \sqcap x^T * x * z)$   
**by** (*metis comp-associative dedekind*)  
**also have**  $\dots \leq x * (y \sqcap x^T * x * z)$   
**by** (*simp add: comp-left-isotone*)  
**also have**  $\dots \leq x * (y \sqcap 1 * z)$   
**using** *assms comp-left-isotone comp-right-isotone inf.sup-right-isotone* **by** *blast*  
**finally show**  $x * y \sqcap x * z \leq x * (y \sqcap z)$   
**by** *simp*  
**qed**

**lemma** *injective-comp-right-dist-inf*:  
 $injective z \implies (x \sqcap y) * z = x * z \sqcap y * z$   
**by** (*metis univalent-comp-left-dist-inf conv-dist-comp conv-involutive conv-dist-inf*)

**lemma** *vector-covector*:  
 $vector v \implies vector w \implies v \sqcap w^T = v * w^T$

by (*metis covector-comp-inf inf-top-left vector-conv-covector*)

**lemma** *comp-inf-vector-1*:

$(x \sqcap \text{top} * y) * z = x * (z \sqcap (\text{top} * y)^T)$

by (*simp add: comp-inf-vector conv-dist-comp*)

The shunting properties for bijective relations and mappings continue to hold.

**lemma** *shunt-bijective*:

assumes *bijective*  $z$

shows  $x \leq y * z \iff x * z^T \leq y$

**proof**

assume  $x \leq y * z$

hence  $x * z^T \leq y * z * z^T$

by (*simp add: mult-left-isotone*)

also have  $\dots \leq y$

using *assms comp-associative mult-right-isotone* by *fastforce*

finally show  $x * z^T \leq y$

.

**next**

assume  $1: x * z^T \leq y$

have  $x = x \sqcap \text{top} * z$

by (*simp add: assms*)

also have  $\dots \leq x * z^T * z$

by (*metis dedekind-2 inf-commute inf-top.right-neutral*)

also have  $\dots \leq y * z$

using  $1$  by (*simp add: mult-left-isotone*)

finally show  $x \leq y * z$

.

**qed**

**lemma** *shunt-mapping*:

*mapping*  $z \implies x \leq z * y \iff z^T * x \leq y$

by (*metis shunt-bijective mapping-conv-bijective conv-order conv-dist-comp conv-involutive*)

**lemma** *bijective-reverse*:

assumes *bijective*  $p$

and *bijective*  $q$

shows  $p \leq r * q \iff q \leq r^T * p$

**proof** –

have  $p \leq r * q \iff p * q^T \leq r$

by (*simp add: assms(2) shunt-bijective*)

also have  $\dots \iff q^T \leq p^T * r$

by (*metis assms(1) conv-dist-comp conv-involutive conv-order shunt-bijective*)

also have  $\dots \iff q \leq r^T * p$

using *conv-dist-comp conv-isotone* by *fastforce*

finally show *?thesis*

by *simp*

**qed**

**lemma** *arc-expanded*:

$arc\ x \longleftrightarrow x * top * x^T \leq 1 \wedge x^T * top * x \leq 1 \wedge top * x * top = top$   
**by** (*metis conv-top comp-associative conv-dist-comp conv-involutive vector-top-closed*)

**lemma** *arc-top-arc*:

**assumes** *arc x*  
**shows**  $x * top * x = x$   
**by** (*metis assms epm-3 top-right-mult-increasing vector-inf-comp vector-mult-closed vector-top-closed*)

**lemma** *arc-top-edge*:

**assumes** *arc x*  
**shows**  $x^T * top * x = x^T * x$   
**proof** –  
**have**  $x^T = x^T * top \sqcap top * x^T$   
**using** *assms epm-3 top-right-mult-increasing* **by** *simp*  
**thus** *?thesis*  
**by** (*metis comp-inf-vector-1 conv-dist-comp conv-involutive conv-top inf.absorb1 top-right-mult-increasing*)  
**qed**

Lemmas *arc-eq-1* and *arc-eq-2* were contributed by Nicolas Robinson-O'Brien.

**lemma** *arc-eq-1*:

**assumes** *arc x*  
**shows**  $x = x * x^T * x$   
**proof** –  
**have**  $x * x^T * x \leq x * top * x$   
**by** (*simp add: mult-left-isotone mult-right-isotone*)  
**also have**  $\dots \leq x$   
**by** (*simp add: assms arc-top-arc*)  
**finally have**  $x * x^T * x \leq x$   
**by** *simp*  
**thus** *?thesis*  
**by** (*simp add: order.antisym ex231c*)  
**qed**

**lemma** *arc-eq-2*:

**assumes** *arc x*  
**shows**  $x^T = x^T * x * x^T$   
**using** *arc-eq-1 assms conv-involutive* **by** *fastforce*

**lemma** *points-arc*:

$point\ x \implies point\ y \implies arc\ (x * y^T)$   
**by** (*metis comp-associative conv-dist-comp conv-involutive equivalence-top-closed*)



**lemma** *point-arc*:  
*point*  $x \implies \text{arc } (x * x^T)$   
**by** (*simp add: points-arc*)

**lemma** *arc-expanded-1*:  
 $\text{arc } e \implies e * x * e^T \leq 1$   
**by** (*meson arc-expanded order-trans top-greatest mult-left-isotone mult-right-isotone*)

**lemma** *arc-expanded-2*:  
 $\text{arc } e \implies e^T * x * e \leq 1$   
**by** (*meson arc-expanded order-trans top-greatest mult-left-isotone mult-right-isotone*)

**lemma** *point-conv-comp*:  
*point*  $x \implies x^T * x = \text{top}$   
**using** *order-eq-iff shunt-bijective top-greatest vector-conv-covector* **by** *blast*

**lemma** *point-antisymmetric*:  
*point*  $x \implies \text{antisymmetric } x$   
**by** (*simp add: vector-covector*)

**lemma** *mapping-inf-point-arc*:  
**assumes** *mapping*  $x$   
**and** *point*  $y$   
**shows**  $\text{arc } (x \sqcap y)$   
**proof** (*unfold arc-expanded, intro conjI*)  
**show**  $(x \sqcap y) * \text{top} * (x \sqcap y)^T \leq 1$   
**by** (*metis assms conv-dist-comp covector-conv-vector inf.orderE inf.sup-monoid.add-commute surjective-conv-total top.extremum top-right-mult-increasing vector-export-comp*)  
**have**  $(x \sqcap y)^T * \text{top} * (x \sqcap y) = x^T * y * (x \sqcap y)$   
**by** (*simp add: assms(2) conv-dist-inf covector-inf-comp-3*)  
**also have**  $\dots = x^T * (y \sqcap y^T) * x$   
**by** (*simp add: assms(2) comp-associative covector-inf-comp-3 inf.sup-monoid.add-commute*)  
**also have**  $\dots \leq x^T * x$   
**by** (*metis assms(2) comp-right-one mult-left-isotone mult-right-isotone vector-covector*)  
**also have**  $\dots \leq 1$   
**by** (*simp add: assms(1)*)  
**finally show**  $(x \sqcap y)^T * \text{top} * (x \sqcap y) \leq 1$   
**show**  $\text{top} * (x \sqcap y) * \text{top} = \text{top}$   
**by** (*metis assms inf-top-right inf-vector-comp mult-assoc*)  
**qed**

**end**

## 4.2 Single-Object Pseudocomplemented Distributive Allegories

We extend single-object bounded distributive allegories by a pseudocomplement operation. The following definitions concern properties of relations that require a pseudocomplement.

```
class relation-algebra-signature = bounded-distrib-allegory-signature + uminus
begin
```

```
abbreviation irreflexive      :: 'a ⇒ bool where irreflexive x      ≡ x ≤ -1
abbreviation strict-linear    :: 'a ⇒ bool where strict-linear x    ≡ x ⊔ xT
= -1
```

```
abbreviation strict-order     :: 'a ⇒ bool where strict-order x     ≡
irreflexive x ∧ transitive x
```

```
abbreviation linear-strict-order :: 'a ⇒ bool where linear-strict-order x ≡
strict-order x ∧ strict-linear x
```

The following variants are useful for the graph model.

```
abbreviation pp-mapping       :: 'a ⇒ bool where pp-mapping x       ≡
univalent x ∧ total (−x)
```

```
abbreviation pp-bijective     :: 'a ⇒ bool where pp-bijective x     ≡
injective x ∧ surjective (−x)
```

```
abbreviation pp-point        :: 'a ⇒ bool where pp-point x        ≡ vector
x ∧ pp-bijective x
```

```
abbreviation pp-arc          :: 'a ⇒ bool where pp-arc x          ≡
pp-bijective (x * top) ∧ pp-bijective (xT * top)
```

```
end
```

```
class pd-allegory = bounded-distrib-allegory + p-algebra
begin
```

```
subclass relation-algebra-signature .
```

```
subclass pd-algebra ..
```

```
lemma conv-complement-1:
```

$$-(x^T) \sqcup (-x)^T = (-x)^T$$

```
by (metis conv-dist-inf conv-order bot-least conv-involutive pseudo-complement
sup.absorb2 sup.cobounded2)
```

```
lemma conv-complement:
```

$$(-x)^T = -(x^T)$$

```
by (metis conv-complement-1 conv-dist-sup conv-involutive sup-commute)
```

```
lemma conv-complement-sub-inf [simp]:
```

$$x^T * -(x * y) \sqcap y = \text{bot}$$

**by** (*metis comp-left-zero conv-dist-comp conv-involutive dedekind-1 inf-import-p inf-p inf-right-idem ppp pseudo-complement regular-closed-bot*)

**lemma** *conv-complement-sub-leq*:

$$x^T * -(x * y) \leq -y$$

**using** *pseudo-complement conv-complement-sub-inf* **by** *blast*

**lemma** *conv-complement-sub [simp]*:

$$x^T * -(x * y) \sqcup -y = -y$$

**by** (*simp add: conv-complement-sub-leq sup.absorb2*)

**lemma** *complement-conv-sub*:

$$-(y * x) * x^T \leq -y$$

**by** (*metis conv-complement conv-complement-sub-leq conv-order conv-dist-comp*)

The following so-called Schröder equivalences, or De Morgan's Theorem K, hold only with a pseudocomplemented element on both right-hand sides.

**lemma** *schröder-3-p*:

$$x * y \leq -z \iff x^T * z \leq -y$$

**using** *pseudo-complement schröder-1* **by** *auto*

**lemma** *schröder-4-p*:

$$x * y \leq -z \iff z * y^T \leq -x$$

**using** *pseudo-complement schröder-2* **by** *auto*

**lemma** *comp-pp-semi-commute*:

$$x * --y \leq --(x * y)$$

**using** *conv-complement-sub-leq schröder-3-p* **by** *fastforce*

The following result looks similar to a property of (anti)domain.

**lemma** *p-comp-pp [simp]*:

$$-(x * --y) = -(x * y)$$

**using** *comp-pp-semi-commute comp-right-isotone order.eq-iff p-antitone pp-increasing* **by** *fastforce*

**lemma** *pp-comp-semi-commute*:

$$--x * y \leq --(x * y)$$

**using** *complement-conv-sub schröder-4-p* **by** *fastforce*

**lemma** *p-pp-comp [simp]*:

$$-(-x * y) = -(x * y)$$

**using** *pp-comp-semi-commute comp-left-isotone order.eq-iff p-antitone pp-increasing* **by** *fastforce*

**lemma** *pp-comp-subdist*:

$$--x * --y \leq --(x * y)$$

**by** (*simp add: p-antitone-iff*)

**lemma** *theorem24xxiii*:

$x * y \sqcap -(x * z) = x * (y \sqcap -z) \sqcap -(x * z)$   
**proof** –  
**have**  $x * y \sqcap -(x * z) \leq x * (y \sqcap (x^T * -(x * z)))$   
**by** (*simp add: dedekind-1*)  
**also have**  $\dots \leq x * (y \sqcap -z)$   
**using** *comp-right-isotone conv-complement-sub-leq inf.sup-right-isotone* **by**  
*auto*  
**finally show** *?thesis*  
**using** *comp-right-subdist-inf order.antisym inf.coboundedI2 inf commute* **by**  
*auto*  
**qed**

Even in Stone relation algebras, we do not obtain the backward implication in the following result.

**lemma** *vector-complement-closed:*

*vector*  $x \implies \text{vector } (-x)$

**by** (*metis complement-conv-sub conv-top order.eq-iff top-right-mult-increasing*)

**lemma** *covector-complement-closed:*

*covector*  $x \implies \text{covector } (-x)$

**by** (*metis conv-complement-sub-leq conv-top order.eq-iff top-left-mult-increasing*)

**lemma** *covector-vector-comp:*

*vector*  $v \implies -v^T * v = \text{bot}$

**by** (*metis conv-bot conv-complement conv-complement-sub-inf conv-dist-comp conv-involutive inf-top.right-neutral*)

**lemma** *irreflexive-bot-closed:*

*irreflexive* *bot*

**by** *simp*

**lemma** *irreflexive-inf-closed:*

*irreflexive*  $x \implies \text{irreflexive } (x \sqcap y)$

**by** (*simp add: le-infI1*)

**lemma** *irreflexive-sup-closed:*

*irreflexive*  $x \implies \text{irreflexive } y \implies \text{irreflexive } (x \sqcup y)$

**by** *simp*

**lemma** *irreflexive-conv-closed:*

*irreflexive*  $x \implies \text{irreflexive } (x^T)$

**using** *conv-complement conv-isotone* **by** *fastforce*

**lemma** *reflexive-complement-irreflexive:*

*reflexive*  $x \implies \text{irreflexive } (-x)$

**by** (*simp add: p-antitone*)

**lemma** *irreflexive-complement-reflexive:*

*irreflexive*  $x \iff \text{reflexive } (-x)$

**by** (*simp add: p-antitone-iff*)

**lemma** *symmetric-complement-closed*:  
*symmetric*  $x \implies$  *symmetric*  $(-x)$   
**by** (*simp add: conv-complement*)

**lemma** *asymmetric-irreflexive*:  
*asymmetric*  $x \implies$  *irreflexive*  $x$   
**by** (*metis inf.mult-not-zero inf.left-commute inf.right-idem*  
*inf.sup-monoid.add-commute pseudo-complement one-inf-conv*)

**lemma** *linear-asymmetric*:  
*linear*  $x \implies$  *asymmetric*  $(-x)$   
**using** *conv-complement p-top* **by force**

**lemma** *strict-linear-sup-closed*:  
*strict-linear*  $x \implies$  *strict-linear*  $y \implies$  *strict-linear*  $(x \sqcup y)$   
**by** (*metis (mono-tags, opaque-lifting) conv-dist-sup sup.right-idem sup-assoc*  
*sup-commute*)

**lemma** *strict-linear-irreflexive*:  
*strict-linear*  $x \implies$  *irreflexive*  $x$   
**using** *sup-left-divisibility* **by blast**

**lemma** *strict-linear-conv-closed*:  
*strict-linear*  $x \implies$  *strict-linear*  $(x^T)$   
**by** (*simp add: sup-commute*)

**lemma** *strict-order-var*:  
*strict-order*  $x \iff$  *asymmetric*  $x \wedge$  *transitive*  $x$   
**by** (*metis asymmetric-irreflexive comp-right-one irreflexive-conv-closed*  
*conv-dist-comp dual-order.trans pseudo-complement schroeder-3-p*)

**lemma** *strict-order-bot-closed*:  
*strict-order* *bot*  
**by** *simp*

**lemma** *strict-order-inf-closed*:  
*strict-order*  $x \implies$  *strict-order*  $y \implies$  *strict-order*  $(x \sqcap y)$   
**using** *inf.coboundedI1 transitive-inf-closed* **by auto**

**lemma** *strict-order-conv-closed*:  
*strict-order*  $x \implies$  *strict-order*  $(x^T)$   
**using** *irreflexive-conv-closed transitive-conv-closed* **by blast**

**lemma** *order-strict-order*:  
**assumes** *order*  $x$   
**shows** *strict-order*  $(x \sqcap -1)$   
**proof** (*rule conjI*)

```

show 1: irreflexive (x  $\sqcap$  -1)
  by simp
have antisymmetric (x  $\sqcap$  -1)
  using antisymmetric-inf-closed assms by blast
hence (x  $\sqcap$  -1) * (x  $\sqcap$  -1)  $\sqcap$  1  $\leq$  (x  $\sqcap$  -1  $\sqcap$  (x  $\sqcap$  -1)T) * (x  $\sqcap$  -1  $\sqcap$  (x  $\sqcap$ 
-1)T)
  using 1 by (metis (no-types) coreflexive-symmetric irreflexive-inf-closed
coreflexive-transitive dedekind-1 inf-idem mult-1-right semiring.mult-not-zero
strict-order-var)
  also have ... = (x  $\sqcap$  xT  $\sqcap$  -1) * (x  $\sqcap$  xT  $\sqcap$  -1)
  by (simp add: conv-complement conv-dist-inf inf.absorb2
inf.sup-monoid.add-assoc)
  also have ... = bot
  using assms order.antisym reflexive-conv-closed by fastforce
finally have (x  $\sqcap$  -1) * (x  $\sqcap$  -1)  $\leq$  -1
  using le-bot pseudo-complement by blast
thus transitive (x  $\sqcap$  -1)
  by (meson assms comp-isotone inf.boundedI inf.cobounded1
inf.order-lesseq-imp)
qed

```

```

lemma strict-order-order:
  strict-order x  $\implies$  order (x  $\sqcup$  1)
  apply (unfold strict-order-var, intro conjI)
  apply simp
  apply (simp add: mult-left-dist-sup mult-right-dist-sup sup.absorb2)
  using conv-dist-sup coreflexive-bot-closed sup.absorb2 sup-inf-distrib2 by
fastforce

```

```

lemma linear-strict-order-conv-closed:
  linear-strict-order x  $\implies$  linear-strict-order (xT)
  by (simp add: irreflexive-conv-closed sup-monoid.add-commute
transitive-conv-closed)

```

```

lemma linear-order-strict-order:
  linear-order x  $\implies$  linear-strict-order (x  $\sqcap$  -1)
  apply (rule conjI)
  using order-strict-order apply simp
  by (metis conv-complement conv-dist-inf coreflexive-symmetric order.eq-iff
inf.absorb2 inf.distrib-left inf.sup-monoid.add-commute top.extremum)

```

```

lemma regular-conv-closed:
  regular x  $\implies$  regular (xT)
  by (metis conv-complement)

```

We show a number of facts about equivalences.

```

lemma equivalence-comp-left-complement:
  equivalence x  $\implies$  x * -x = -x
  apply (rule order.antisym)

```

**apply** (*metis conv-complement-sub-leq preorder-idempotent*)  
**using** *mult-left-isotone* **by** *fastforce*

**lemma** *equivalence-comp-right-complement*:  
*equivalence*  $x \Longrightarrow -x * x = -x$   
**by** (*metis equivalence-comp-left-complement conv-complement conv-dist-comp*)

The pseudocomplement of tests is given by the following operation.

**abbreviation** *coreflexive-complement* ::  $'a \Rightarrow 'a (-'' [80] 80)$   
**where**  $x' \equiv -x \sqcap 1$

**lemma** *coreflexive-comp-top-coreflexive-complement*:  
*coreflexive*  $x \Longrightarrow (x * top)' = x'$   
**by** (*metis coreflexive-comp-top-inf-one inf commute inf-import-p*)

**lemma** *coreflexive-comp-inf-complement*:  
*coreflexive*  $x \Longrightarrow (x * y) \sqcap -z = (x * y) \sqcap -(x * z)$   
**by** (*metis coreflexive-comp-top-inf inf.sup-relative-same-increasing inf-import-p inf-le1*)

**lemma** *double-coreflexive-complement*:  
 $x'' = (-x)'$   
**using** *inf.sup-monoid.add-commute inf-import-p* **by** *auto*

**lemma** *coreflexive-pp-dist-comp*:  
**assumes** *coreflexive*  $x$   
**and** *coreflexive*  $y$   
**shows**  $(x * y)'' = x'' * y''$   
**proof** –  
**have**  $(x * y)'' = --(x * y) \sqcap 1$   
**by** (*simp add: double-coreflexive-complement*)  
**also have**  $\dots = --x \sqcap --y \sqcap 1$   
**by** (*simp add: assms coreflexive-comp-inf*)  
**also have**  $\dots = (--x \sqcap 1) * (--y \sqcap 1)$   
**by** (*simp add: coreflexive-comp-inf inf.left-commute inf.sup-monoid.add-assoc*)  
**also have**  $\dots = x'' * y''$   
**by** (*simp add: double-coreflexive-complement*)  
**finally show** *?thesis*

**qed**

**lemma** *coreflexive-pseudo-complement*:  
*coreflexive*  $x \Longrightarrow x \sqcap y = bot \iff x \leq y'$   
**by** (*simp add: pseudo-complement*)

**lemma** *pp-bijective-conv-mapping*:  
*pp-bijective*  $x \iff pp\text{-mapping } (x^T)$   
**by** (*simp add: conv-complement surjective-conv-total*)

**lemma** *pp-arc-expanded*:

$pp\text{-arc } x \longleftrightarrow x * top * x^T \leq 1 \wedge x^T * top * x \leq 1 \wedge top * \neg\neg x * top = top$

**proof**

**assume** 1: *pp-arc*  $x$

**have** 2:  $x * top * x^T \leq 1$

**using** 1 **by** (*metis comp-associative conv-dist-comp equivalence-top-closed vector-top-closed*)

**have** 3:  $x^T * top * x \leq 1$

**using** 1 **by** (*metis conv-dist-comp conv-involutive equivalence-top-closed vector-top-closed mult-assoc*)

**have** 4:  $x^T \leq x^T * x * x^T$

**by** (*metis conv-involutive ex231c*)

**have**  $top = \neg\neg(top * x) * top$

**using** 1 **by** (*metis conv-complement conv-dist-comp conv-involutive equivalence-top-closed*)

**also have**  $\dots \leq \neg\neg(top * x^T * top * x) * top$

**using** 1 **by** (*metis eq-refl mult-assoc p-comp-pp p-pp-comp*)

**also have**  $\dots = (top * \neg\neg(x * top) \sqcap \neg\neg(top * x^T * top * x)) * top$

**using** 1 **by** *simp*

**also have**  $\dots = top * (\neg\neg(x * top) \sqcap \neg\neg(top * x^T * top * x)) * top$

**by** (*simp add: covector-complement-closed covector-comp-inf covector-mult-closed*)

**also have**  $\dots = top * \neg\neg(x * top \sqcap top * x^T * top * x) * top$

**by** *simp*

**also have**  $\dots = top * \neg\neg(x * top * x^T * top * x) * top$

**by** (*metis comp-associative comp-inf-covector inf-top.left-neutral*)

**also have**  $\dots \leq top * \neg\neg(x * top * x^T * x * x^T * top * x) * top$

**using** 4 **by** (*metis comp-associative comp-left-isotone comp-right-isotone pp-isotone*)

**also have**  $\dots \leq top * \neg\neg(x * x^T * top * x) * top$

**using** 2 **by** (*metis comp-associative comp-left-isotone comp-right-isotone pp-isotone comp-left-one*)

**also have**  $\dots \leq top * \neg\neg x * top$

**using** 3 **by** (*metis comp-associative comp-left-isotone comp-right-isotone pp-isotone comp-right-one*)

**finally show**  $x * top * x^T \leq 1 \wedge x^T * top * x \leq 1 \wedge top * \neg\neg x * top = top$

**using** 2 3 *top-le* **by** *blast*

**next**

**assume**  $x * top * x^T \leq 1 \wedge x^T * top * x \leq 1 \wedge top * \neg\neg x * top = top$

**thus** *pp-arc*  $x$

**apply** (*intro conjI*)

**apply** (*metis comp-associative conv-dist-comp equivalence-top-closed vector-top-closed*)

**apply** (*metis comp-associative mult-right-isotone top-le pp-comp-semi-commute*)

**apply** (*metis conv-dist-comp coreflexive-symmetric vector-conv-covector vector-top-closed mult-assoc*)

**by** (*metis conv-complement conv-dist-comp equivalence-top-closed inf.orderE inf-top.left-neutral mult-right-isotone pp-comp-semi-commute*)



qed

The following operation represents states with infinite executions of non-strict computations.

**abbreviation**  $N :: 'a \Rightarrow 'a$   
**where**  $N x \equiv -(-x * top) \sqcap 1$

**lemma** *N-comp*:  
 $N x * y = -(-x * top) \sqcap y$   
**by** (*simp add: vector-mult-closed vector-complement-closed vector-inf-one-comp*)

**lemma** *N-comp-top [simp]*:  
 $N x * top = -(-x * top)$   
**by** (*simp add: N-comp*)

**lemma** *vector-N-pp*:  
 $vector\ x \Longrightarrow N x = --x \sqcap 1$   
**by** (*simp add: vector-complement-closed*)

**lemma** *N-vector-pp [simp]*:  
 $N (x * top) = --(x * top) \sqcap 1$   
**by** (*simp add: comp-associative vector-complement-closed*)

**lemma** *N-vector-top-pp [simp]*:  
 $N (x * top) * top = --(x * top)$   
**by** (*metis N-comp-top comp-associative vector-top-closed vector-complement-closed*)

**lemma** *N-below-inf-one-pp*:  
 $N x \leq --x \sqcap 1$   
**using** *inf.sup-left-isotone p-antitone top-right-mult-increasing* **by auto**

**lemma** *N-below-pp*:  
 $N x \leq --x$   
**using** *N-below-inf-one-pp* **by auto**

**lemma** *N-comp-N*:  
 $N x * N y = -(-x * top) \sqcap -(-y * top) \sqcap 1$   
**by** (*simp add: N-comp inf.mult-assoc*)

**lemma** *N-bot [simp]*:  
 $N bot = bot$   
**by** *simp*

**lemma** *N-top [simp]*:  
 $N top = 1$   
**by** *simp*

**lemma** *n-split-omega-mult-pp*:

$xs * --xo = xo \implies \text{vector } xo \implies N \text{ top} * xo = xs * N xo * \text{top}$   
**by** (*metis N-top N-vector-top-pp comp-associative comp-left-one*)

Many of the following results have been derived for verifying Prim's minimum spanning tree algorithm.

**lemma ee:**

**assumes** *vector v*  
**and**  $e \leq v * -v^T$   
**shows**  $e * e = \text{bot}$

**proof** –

**have**  $e * v \leq \text{bot}$   
**by** (*metis assms covector-vector-comp comp-associative mult-left-isotone mult-right-zero*)  
**thus** *?thesis*  
**by** (*metis assms(2) bot-unique comp-associative mult-right-isotone semiring.mult-not-zero*)

**qed**

**lemma et:**

**assumes** *vector v*  
**and**  $e \leq v * -v^T$   
**and**  $t \leq v * v^T$   
**shows**  $e * t = \text{bot}$   
**and**  $e * t^T = \text{bot}$

**proof** –

**have**  $e * t \leq v * -v^T * v * v^T$   
**using** *assms(2-3) comp-isotone mult-assoc* **by** *fastforce*  
**thus**  $e * t = \text{bot}$   
**by** (*simp add: assms(1) covector-vector-comp le-bot mult-assoc*)

**next**

**have**  $t^T \leq v * v^T$   
**using** *assms(3) conv-order conv-dist-comp* **by** *fastforce*  
**hence**  $e * t^T \leq v * -v^T * v * v^T$   
**by** (*metis assms(2) comp-associative comp-isotone*)  
**thus**  $e * t^T = \text{bot}$   
**by** (*simp add: assms(1) covector-vector-comp le-bot mult-assoc*)

**qed**

**lemma ve-dist:**

**assumes**  $e \leq v * -v^T$   
**and** *vector v*  
**and** *arc e*  
**shows**  $(v \sqcup e^T * \text{top}) * (v \sqcup e^T * \text{top})^T = v * v^T \sqcup v * v^T * e \sqcup e^T * v * v^T \sqcup e^T * e$

**proof** –

**have**  $e \leq v * \text{top}$   
**using** *assms(1) comp-right-isotone dual-order.trans top-greatest* **by** *blast*  
**hence**  $v * \text{top} * e = v * \text{top} * (v * \text{top} \sqcap e)$   
**by** (*simp add: inf.absorb2*)

**also have**  $\dots = (v * top \sqcap top * v^T) * e$   
**using** *assms(2) covector-inf-comp-3 vector-conv-covector* **by force**  
**also have**  $\dots = v * top * v^T * e$   
**by** (*metis assms(2) inf-top-right vector-inf-comp*)  
**also have**  $\dots = v * v^T * e$   
**by** (*simp add: assms(2)*)  
**finally have 1:**  $v * top * e = v * v^T * e$   
 .  
**have**  $e^T * top * e \leq e^T * top * e * e^T * e$   
**using** *ex231c comp-associative mult-right-isotone* **by auto**  
**also have**  $\dots \leq e^T * e$   
**by** (*metis assms(3) coreflexive-comp-top-inf le-infE mult-semi-associative point-injective*)  
**finally have 2:**  $e^T * top * e = e^T * e$   
**by** (*simp add: order.antisym mult-left-isotone top-right-mult-increasing*)  
**have**  $(v \sqcup e^T * top) * (v \sqcup e^T * top)^T = (v \sqcup e^T * top) * (v^T \sqcup top * e)$   
**by** (*simp add: conv-dist-comp conv-dist-sup*)  
**also have**  $\dots = v * v^T \sqcup v * top * e \sqcup e^T * top * v^T \sqcup e^T * top * top * e$   
**by** (*metis semiring.distrib-left semiring.distrib-right sup-assoc mult-assoc*)  
**also have**  $\dots = v * v^T \sqcup v * top * e \sqcup (v * top * e)^T \sqcup e^T * top * e$   
**by** (*simp add: comp-associative conv-dist-comp*)  
**also have**  $\dots = v * v^T \sqcup v * v^T * e \sqcup (v * v^T * e)^T \sqcup e^T * e$   
**using 1 2 by simp**  
**finally show ?thesis**  
**by** (*simp add: comp-associative conv-dist-comp*)  
**qed**

**lemma** *ev:*

*vector v*  $\implies e \leq v * -v^T \implies e * v = bot$   
**by** (*metis covector-vector-comp order.antisym bot-least comp-associative mult-left-isotone mult-right-zero*)

**lemma** *vTeT:*

*vector v*  $\implies e \leq v * -v^T \implies v^T * e^T = bot$   
**using** *conv-bot ev conv-dist-comp* **by fastforce**

The following result is used to show that the while-loop of Prim's algorithm preserves that the constructed tree is a subgraph of  $g$ .

**lemma** *prim-subgraph-inv:*

**assumes**  $e \leq v * -v^T \sqcap g$   
**and**  $t \leq v * v^T \sqcap g$   
**shows**  $t \sqcup e \leq ((v \sqcup e^T * top) * (v \sqcup e^T * top)^T) \sqcap g$

**proof** (*rule sup-least*)

**have**  $t \leq ((v \sqcup e^T * top) * v^T) \sqcap g$   
**using** *assms(2) le-supI1 mult-right-dist-sup* **by auto**  
**also have**  $\dots \leq ((v \sqcup e^T * top) * (v \sqcup e^T * top)^T) \sqcap g$   
**using** *comp-right-isotone conv-dist-sup inf.sup-left-isotone* **by auto**  
**finally show**  $t \leq ((v \sqcup e^T * top) * (v \sqcup e^T * top)^T) \sqcap g$   
 .

**next**  
**have**  $e \leq v * top$   
**by** (*meson assms(1) inf.boundedE mult-right-isotone order.trans top.extremum*)  
**hence**  $e \leq v * top \sqcap top * e$   
**by** (*simp add: top-left-mult-increasing*)  
**also have**  $\dots = v * top * e$   
**by** (*metis inf-top-right vector-export-comp*)  
**finally have**  $e \leq v * top * e \sqcap g$   
**using** *assms(1)* **by** *auto*  
**also have**  $\dots = v * (e^T * top)^T \sqcap g$   
**by** (*simp add: comp-associative conv-dist-comp*)  
**also have**  $\dots \leq v * (v \sqcup e^T * top)^T \sqcap g$   
**by** (*simp add: conv-dist-sup mult-left-dist-sup sup.assoc sup.orderI*)  
**also have**  $\dots \leq (v \sqcup e^T * top) * (v \sqcup e^T * top)^T \sqcap g$   
**using** *inf.sup-left-isotone mult-right-sub-dist-sup-left* **by** *auto*  
**finally show**  $e \leq ((v \sqcup e^T * top) * (v \sqcup e^T * top)^T) \sqcap g$   
**qed**

The following result shows how to apply the Schröder equivalence to the middle factor in a composition of three relations. Again the elements on the right-hand side need to be pseudocomplemented.

**lemma** *triple-schroeder-p*:  
 $x * y * z \leq -w \iff x^T * w * z^T \leq -y$   
**using** *mult-assoc p-antitone-iff schroeder-3-p schroeder-4-p* **by** *auto*

The rotation versions of the Schröder equivalences continue to hold, again with pseudocomplemented elements on the right-hand side.

**lemma** *schroeder-5-p*:  
 $x * y \leq -z \iff y * z^T \leq -x^T$   
**using** *schroeder-3-p schroeder-4-p* **by** *auto*

**lemma** *schroeder-6-p*:  
 $x * y \leq -z \iff z^T * x \leq -y^T$   
**using** *schroeder-3-p schroeder-4-p* **by** *auto*

**lemma** *vector-conv-compl*:  
*vector*  $v \implies top * -v^T = -v^T$   
**by** (*simp add: covector-complement-closed vector-conv-covector*)

Composition commutes, relative to the diversity relation.

**lemma** *comp-commute-below-diversity*:  
 $x * y \leq -1 \iff y * x \leq -1$   
**by** (*metis comp-right-one conv-dist-comp conv-one schroeder-3-p schroeder-4-p*)

**lemma** *comp-injective-below-complement*:  
*injective*  $y \implies -x * y \leq -(x * y)$

**by** (*metis p-antitone-iff comp-associative comp-right-isotone comp-right-one schroeder-4-p*)

**lemma** *comp-univalent-below-complement*:

*univalent*  $x \implies x * -y \leq -(x * y)$

**by** (*metis p-inf pseudo-complement semiring.mult-zero-right univalent-comp-left-dist-inf*)

Bijjective relations and mappings can be exported from a pseudocomplement.

**lemma** *comp-bijjective-complement*:

*bijjective*  $y \implies -x * y = -(x * y)$

**using** *comp-injective-below-complement complement-conv-sub order.antisym shunt-bijjective* **by** *blast*

**lemma** *comp-mapping-complement*:

*mapping*  $x \implies x * -y = -(x * y)$

**by** (*metis (full-types) comp-bijjective-complement conv-complement conv-dist-comp conv-involutive total-conv-surjective*)

The following facts are used in the correctness proof of Kruskal's minimum spanning tree algorithm.

**lemma** *kruskal-injective-inv*:

**assumes** *injective*  $f$

**and** *covector*  $q$

**and**  $q * f^T \leq q$

**and**  $e \leq q$

**and**  $q * f^T \leq -e$

**and** *injective*  $e$

**and**  $q^T * q \sqcap f^T * f \leq 1$

**shows** *injective*  $((f \sqcap -q) \sqcup (f \sqcap q)^T \sqcup e)$

**proof** –

**have**  $1: (f \sqcap -q) * (f \sqcap -q)^T \leq 1$

**by** (*simp add: assms(1) injective-inf-closed*)

**have**  $2: (f \sqcap -q) * (f \sqcap q) \leq 1$

**proof** –

**have**  $21: bot = q * f^T \sqcap -q$

**by** (*metis assms(3) inf.sup-monoid.add-assoc inf.sup-right-divisibility inf-import-p inf-p*)

**have**  $(f \sqcap -q) * (f \sqcap q) \leq -q * f \sqcap q$

**by** (*metis assms(2) comp-inf-covector comp-isotone inf.cobounded2 inf.left-idem*)

**also have**  $\dots = bot$

**using**  $21$  *schroeder-2* **by** *auto*

**finally show** *?thesis*

**by** (*simp add: bot-unique*)

**qed**

**have**  $3: (f \sqcap -q) * e^T \leq 1$

**proof** –

**have**  $(f \sqcap -q) * e^T \leq -q * e^T$   
**by** (*simp add: mult-left-isotone*)  
**also have**  $\dots = \text{bot}$   
**by** (*metis assms(2,4) bot-unique conv-bot conv-complement*  
*covector-complement-closed p-antitone p-bot regular-closed-bot schroeder-5-p*)  
**finally show** *?thesis*  
**by** (*simp add: bot-unique*)  
**qed**  
**have** 4:  $(f \sqcap q)^T * (f \sqcap -q)^T \leq 1$   
**using** 2 *conv-dist-comp conv-isotone* **by force**  
**have** 5:  $(f \sqcap q)^T * (f \sqcap q) \leq 1$   
**proof** –  
**have**  $(f \sqcap q)^T * (f \sqcap q) \leq q^T * q \sqcap f^T * f$   
**by** (*simp add: conv-isotone mult-isotone*)  
**also have**  $\dots \leq 1$   
**by** (*simp add: assms(7)*)  
**finally show** *?thesis*  
**by** *simp*  
**qed**  
**have** 6:  $(f \sqcap q)^T * e^T \leq 1$   
**proof** –  
**have**  $f^T * e^T \leq -q^T$   
**using** *assms(5) schroeder-5-p* **by** *simp*  
**hence**  $(f \sqcap q)^T * e^T = \text{bot}$   
**by** (*metis assms(2,5) conv-bot conv-dist-comp covector-comp-inf inf.absorb1*  
*inf.cobounded2 inf.sup-monoid.add-commute inf-left-commute inf-p schroeder-4-p*)  
**thus** *?thesis*  
**by** (*simp add: bot-unique*)  
**qed**  
**have** 7:  $e * (f \sqcap -q)^T \leq 1$   
**using** 3 *conv-dist-comp coreflexive-symmetric* **by** *fastforce*  
**have** 8:  $e * (f \sqcap q) \leq 1$   
**using** 6 *conv-dist-comp coreflexive-symmetric* **by** *fastforce*  
**have** 9:  $e * e^T \leq 1$   
**by** (*simp add: assms(6)*)  
**have**  $((f \sqcap -q) \sqcup (f \sqcap q)^T \sqcup e) * ((f \sqcap -q) \sqcup (f \sqcap q)^T \sqcup e)^T = (f \sqcap -q) * (f$   
 $\sqcap -q)^T \sqcup (f \sqcap -q) * (f \sqcap q) \sqcup (f \sqcap -q) * e^T \sqcup (f \sqcap q)^T * (f \sqcap -q)^T \sqcup (f \sqcap$   
 $q)^T * (f \sqcap q) \sqcup (f \sqcap q)^T * e^T \sqcup e * (f \sqcap -q)^T \sqcup e * (f \sqcap q) \sqcup e * e^T$   
**using** *comp-left-dist-sup comp-right-dist-sup conv-dist-sup sup.assoc* **by** *simp*  
**also have**  $\dots \leq 1$   
**using** 1 2 3 4 5 6 7 8 9 **by** *simp*  
**finally show** *?thesis*  
**by** *simp*  
**qed**  
**lemma** *kruskal-exchange-injective-inv-1*:  
**assumes** *injective f*  
**and** *covector q*  
**and**  $q * f^T \leq q$

**and**  $q^T * q \sqcap f^T * f \leq 1$   
**shows** *injective*  $((f \sqcap -q) \sqcup (f \sqcap q)^T)$   
**using** *kruskal-injective-inv* [**where**  $e = \text{bot}$ ] **by** (*simp add: assms*)

**lemma** *kruskal-exchange-acyclic-inv-3*:

**assumes** *injective w*  
**and**  $d \leq w$   
**shows**  $(w \sqcap -d) * d^T * \text{top} = \text{bot}$

**proof** –

**have**  $(w \sqcap -d) * d^T * \text{top} = (w \sqcap -d \sqcap (d^T * \text{top})^T) * \text{top}$   
**by** (*simp add: comp-associative comp-inf-vector-1 conv-dist-comp*)  
**also have**  $\dots = (w \sqcap \text{top} * d \sqcap -d) * \text{top}$   
**by** (*simp add: conv-dist-comp inf-commute inf-left-commute*)  
**finally show** *?thesis*  
**using** *assms epm-3* **by** *simp*

**qed**

**lemma** *kruskal-subgraph-inv*:

**assumes**  $f \leq --(-h \sqcap g)$   
**and**  $e \leq --g$   
**and** *symmetric h*  
**and** *symmetric g*  
**shows**  $(f \sqcap -q) \sqcup (f \sqcap q)^T \sqcup e \leq --(-h \sqcap -e \sqcap -e^T) \sqcap g$

**proof** –

**let**  $?f = (f \sqcap -q) \sqcup (f \sqcap q)^T \sqcup e$   
**let**  $?h = h \sqcap -e \sqcap -e^T$   
**have**  $1: f \sqcap -q \leq -h \sqcap --g$   
**using** *assms(1) inf.coboundedI1* **by** *simp*  
**have**  $(f \sqcap q)^T \leq (-h \sqcap --g)^T$   
**using** *assms(1) inf.coboundedI1 conv-isotone* **by** *simp*  
**also have**  $\dots = -h \sqcap --g$   
**using** *assms(3,4) conv-complement conv-dist-inf* **by** *simp*  
**finally have**  $?f \leq (-h \sqcap --g) \sqcup (e \sqcap --g)$   
**using**  $1$  *assms(2) inf.absorb1 semiring.add-right-mono* **by** *simp*  
**also have**  $\dots \leq (-h \sqcup --e) \sqcap --g$   
**by** (*simp add: inf.coboundedI1 le-supI2 pp-increasing*)  
**also have**  $\dots \leq -?h \sqcap --g$   
**using** *inf.sup-left-isotone order-trans p-antitone-inf p-supdist-inf* **by** *blast*  
**finally show**  $?f \leq --(-?h \sqcap g)$   
**using** *inf-pp-semi-commute order-lesseq-imp* **by** *blast*

**qed**

**lemma** *antisymmetric-inf-diversity*:

*antisymmetric x*  $\implies x \sqcap -1 = x \sqcap -x^T$   
**by** (*smt (verit, del-insts) inf.orderE inf.sup-monoid.add-assoc*  
*inf.sup-monoid.add-commute inf-import-p one-inf-conv*)

**end**

### 4.3 Stone Relation Algebras

We add *pp-dist-comp* and *pp-one*, which follow in relation algebras but not in the present setting. The main change is that only a Stone algebra is required, not a Boolean algebra.

```

class stone-relation-algebra = pd-allegory + stone-algebra +
  assumes pp-dist-comp :  $---(x * y) = ---x * ---y$ 
  assumes pp-one [simp]:  $---1 = 1$ 
begin

```

The following property is a simple consequence of the Stone axiom. We cannot hope to remove the double complement in it.

```

lemma conv-complement-0-p [simp]:
   $(-x)^T \sqcup (---x)^T = top$ 
by (metis conv-top conv-dist-sup stone)

```

```

lemma theorem24xxiv-pp:
   $-(x * y) \sqcup ---(x * z) = -(x * (y \sqcap -z)) \sqcup ---(x * z)$ 
by (metis p-dist-inf theorem24xxiii)

```

```

lemma asymmetric-linear:
  asymmetric  $x \iff$  linear  $(-x)$ 
by (metis conv-complement inf.distrib-left inf-p maddux-3-11-pp p-bot
p-dist-inf)

```

```

lemma strict-linear-asymmetric:
  strict-linear  $x \implies$  antisymmetric  $(-x)$ 
by (metis conv-complement eq-refl p-dist-sup pp-one)

```

```

lemma regular-complement-top:
  regular  $x \implies x \sqcup -x = top$ 
by (metis stone)

```

```

lemma regular-mult-closed:
  regular  $x \implies$  regular  $y \implies$  regular  $(x * y)$ 
by (simp add: pp-dist-comp)

```

```

lemma regular-one-closed:
  regular 1
by simp

```

The following variants of total and surjective are useful for graphs.

```

lemma pp-total:
  total  $(---x) \iff -(x * top) = bot$ 
by (simp add: dense-pp pp-dist-comp)

```

```

lemma pp-surjective:
  surjective  $(---x) \iff -(top * x) = bot$ 
by (metis p-bot p-comp-pp p-top pp-dist-comp)

```



Bijjective elements and mappings are necessarily regular, that is, invariant under double-complement. This implies that points are regular. Moreover, also arcs are regular.

**lemma** *bijjective-regular:*

*bijjective*  $x \implies$  *regular*  $x$

**by** (*metis comp-bijjective-complement mult-left-one regular-one-closed*)

**lemma** *mapping-regular:*

*mapping*  $x \implies$  *regular*  $x$

**by** (*metis bijjective-regular conv-complement conv-involutive total-conv-surjective*)

**lemma** *arc-regular:*

**assumes** *arc*  $x$

**shows** *regular*  $x$

**proof** –

**have**  $--x \leq --(x * top \sqcap top * x)$

**by** (*simp add: pp-isotone top-left-mult-increasing top-right-mult-increasing*)

**also have**  $... = --(x * top) \sqcap --(top * x)$

**by** *simp*

**also have**  $... = x * top \sqcap top * x$

**by** (*metis assms bijjective-regular conv-top conv-dist-comp conv-involutive mapping-regular*)

**also have**  $... \leq x * x^T * top * x$

**by** (*metis comp-associative dedekind-1 inf-commute inf-top.right-neutral*)

**also have**  $... \leq x$

**by** (*metis assms comp-right-one conv-top comp-associative conv-dist-comp conv-involutive mult-right-isotone vector-top-closed*)

**finally show** *?thesis*

**by** (*simp add: order.antisym pp-increasing*)

**qed**

**end**

Every Stone algebra can be expanded to a Stone relation algebra by identifying the semiring and lattice structures and taking identity as converse.

**sublocale** *stone-algebra*  $<$  *comp-inf: stone-relation-algebra* **where** *one* = *top*

**and** *times* = *inf* **and** *conv* = *id*

**proof** (*unfold-locales, goal-cases*)

**case** 7

**show** *?case* **by** (*simp add: inf-commute*)

**qed** (*auto simp: inf.assoc inf-sup-distrib2 inf-left-commute*)

Every bounded linear order can be expanded to a Stone algebra, which can be expanded to a Stone relation algebra by reusing some of the operations. In particular, composition is meet, its identity is *top* and converse is the identity function.

```

class linorder-stone-relation-algebra-expansion = linorder-stone-algebra-expansion
+ times + conv + one +
  assumes times-def [simp]:  $x * y = \min x y$ 
  assumes conv-def [simp]:  $x^T = x$ 
  assumes one-def [simp]:  $1 = \text{top}$ 
begin

lemma times-inf [simp]:
   $x * y = x \sqcap y$ 
  by simp

subclass stone-relation-algebra
  apply unfold-locales
  using comp-inf.mult-right-dist-sup inf-commute inf-assoc inf-left-commute
pp-dist-inf min-def by simp-all

lemma times-dense:
   $x \neq \text{bot} \implies y \neq \text{bot} \implies x * y \neq \text{bot}$ 
  using inf-dense min-inf times-def by presburger

end

```

#### 4.4 Relation Algebras

For a relation algebra, we only require that the underlying lattice is a Boolean algebra. In fact, the only missing axiom is that double-complement is the identity.

```

class relation-algebra = boolean-algebra + stone-relation-algebra
begin

```

```

lemma conv-complement-0 [simp]:
   $x^T \sqcup (-x)^T = \text{top}$ 
  by (simp add: conv-complement)

```

We now obtain the original formulations of the Schröder equivalences.

```

lemma schroeder-3:
   $x * y \leq z \iff x^T * -z \leq -y$ 
  by (simp add: schroeder-3-p)

```

```

lemma schroeder-4:
   $x * y \leq z \iff -z * y^T \leq -x$ 
  by (simp add: schroeder-4-p)

```

```

lemma theorem24xxiv:
   $-(x * y) \sqcup (x * z) = -(x * (y \sqcap -z)) \sqcup (x * z)$ 
  using theorem24xxiv-pp by auto

```

```

lemma vector-N:
  vector  $x \implies N(x) = x \sqcap 1$ 

```

**by** (*simp add: vector-N-pp*)

**lemma** *N-vector* [*simp*]:  
 $N(x * top) = x * top \sqcap 1$   
**by** *simp*

**lemma** *N-vector-top* [*simp*]:  
 $N(x * top) * top = x * top$   
**using** *N-vector-top-pp* **by** *simp*

**lemma** *N-below-inf-one*:  
 $N(x) \leq x \sqcap 1$   
**using** *N-below-inf-one-pp* **by** *simp*

**lemma** *N-below*:  
 $N(x) \leq x$   
**using** *N-below-pp* **by** *simp*

**lemma** *n-split-omega-mult*:  
 $xs * xo = xo \implies xo * top = xo \implies N(top) * xo = xs * N(xo) * top$   
**using** *n-split-omega-mult-pp* **by** *simp*

**lemma** *complement-vector*:  
 $vector\ v \longleftrightarrow vector\ (-v)$   
**using** *vector-complement-closed* **by** *fastforce*

**lemma** *complement-covector*:  
 $covector\ v \longleftrightarrow covector\ (-v)$   
**using** *covector-complement-closed* **by** *force*

**lemma** *triple-schroeder*:  
 $x * y * z \leq w \longleftrightarrow x^T * -w * z^T \leq -y$   
**by** (*simp add: triple-schroeder-p*)

**lemma** *schroeder-5*:  
 $x * y \leq z \longleftrightarrow y * -z^T \leq -x^T$   
**by** (*simp add: conv-complement schroeder-5-p*)

**lemma** *schroeder-6*:  
 $x * y \leq z \longleftrightarrow -z^T * x \leq -y^T$   
**by** (*simp add: conv-complement schroeder-5-p*)

**end**

We briefly look at the so-called Tarski rule. In some models of Stone relation algebras it only holds for regular elements, so we add this as an assumption.

**class** *stone-relation-algebra-tarski* = *stone-relation-algebra* +  
**assumes** *tarski*:  $regular\ x \implies x \neq bot \implies top * x * top = top$

begin

We can then show, for example, that every arc is contained in a pseudo-complemented relation or its pseudocomplement.

**lemma** *arc-in-partition:*

**assumes** *arc*  $x$

**shows**  $x \leq -y \vee x \leq --y$

**proof** –

**have**  $1: x * top * x^T \leq 1 \wedge x^T * top * x \leq 1$

**using** *assms arc-expanded* **by** *auto*

**have**  $\neg x \leq --y \longrightarrow x \leq -y$

**proof**

**assume**  $\neg x \leq --y$

**hence**  $x \sqcap -y \neq bot$

**using** *pseudo-complement* **by** *simp*

**hence**  $top * (x \sqcap -y) * top = top$

**using** *assms arc-regular tarski* **by** *auto*

**hence**  $x = x \sqcap top * (x \sqcap -y) * top$

**by** *simp*

**also have**  $\dots \leq x \sqcap x * ((x \sqcap -y) * top)^T * (x \sqcap -y) * top$

**by** (*metis dedekind-2 inf.cobounded1 inf.boundedI inf-commute mult-assoc inf.absorb2 top.extremum*)

**also have**  $\dots = x \sqcap x * top * (x^T \sqcap -y^T) * (x \sqcap -y) * top$

**by** (*simp add: comp-associative conv-complement conv-dist-comp conv-dist-inf*)

**also have**  $\dots \leq x \sqcap x * top * x^T * (x \sqcap -y) * top$

**using** *inf.sup-right-isotone mult-left-isotone mult-right-isotone* **by** *auto*

**also have**  $\dots \leq x \sqcap 1 * (x \sqcap -y) * top$

**using**  $1$  **by** (*metis comp-associative comp-isotone inf.sup-right-isotone mult-1-left mult-semi-associative*)

**also have**  $\dots = x \sqcap (x \sqcap -y) * top$

**by** *simp*

**also have**  $\dots \leq (x \sqcap -y) * ((x \sqcap -y)^T * x)$

**by** (*metis dedekind-1 inf-commute inf-top-right*)

**also have**  $\dots \leq (x \sqcap -y) * (x^T * x)$

**by** (*simp add: conv-dist-inf mult-left-isotone mult-right-isotone*)

**also have**  $\dots \leq (x \sqcap -y) * (x^T * top * x)$

**by** (*simp add: mult-assoc mult-right-isotone top-left-mult-increasing*)

**also have**  $\dots \leq x \sqcap -y$

**using**  $1$  **by** (*metis mult-right-isotone mult-1-right*)

**finally show**  $x \leq -y$

**by** *simp*

**qed**

**thus** *?thesis*

**by** *auto*

**qed**

**lemma** *non-bot-arc-in-partition-xor:*

**assumes** *arc*  $x$

**and**  $x \neq \text{bot}$   
**shows**  $(x \leq -y \wedge \neg x \leq --y) \vee (\neg x \leq -y \wedge x \leq --y)$   
**proof** –  
**have**  $x \leq -y \wedge x \leq --y \longrightarrow \text{False}$   
**by** (*simp add: assms(2) inf-absorb1 shunting-1-pp*)  
**thus** *?thesis*  
**using** *assms(1) arc-in-partition* **by** *auto*  
**qed**

**lemma** *point-in-vector-or-pseudo-complement:*

**assumes** *point p*  
**and** *vector v*  
**shows**  $p \leq --v \vee p \leq -v$   
**proof** (*rule disjCI*)  
**assume**  $\neg(p \leq -v)$   
**hence**  $\text{top} * (p \sqcap --v) = \text{top}$   
**by** (*smt assms bijective-regular regular-closed-inf regular-closed-p shunting-1-pp tarski vector-complement-closed vector-inf-closed vector-mult-closed*)  
**thus**  $p \leq --v$   
**by** (*metis assms(1) epm-3 inf.absorb-iff1 inf.cobounded1 inf-top.right-neutral*)  
**qed**

**lemma** *distinct-points:*

**assumes** *point x*  
**and** *point y*  
**and**  $x \neq y$   
**shows**  $x \sqcap y = \text{bot}$   
**by** (*metis assms order.antisym comp-bijective-complement inf.sup-monoid.add-commute mult-left-one pseudo-complement regular-one-closed point-in-vector-or-pseudo-complement*)

**lemma** *point-in-vector-or-complement:*

**assumes** *point p*  
**and** *vector v*  
**and** *regular v*  
**shows**  $p \leq v \vee p \leq -v$   
**using** *assms point-in-vector-or-pseudo-complement* **by** *fastforce*

**lemma** *point-in-vector-sup:*

**assumes** *point p*  
**and** *vector v*  
**and** *regular v*  
**and**  $p \leq v \sqcup w$   
**shows**  $p \leq v \vee p \leq w$   
**by** (*metis assms inf.absorb1 shunting-var-p sup-commute point-in-vector-or-complement*)

**lemma** *point-atomic-vector:*

**assumes** *point x*

```

    and vector y
    and regular y
    and  $y \leq x$ 
  shows  $y = x \vee y = \text{bot}$ 
proof (cases  $x \leq -y$ )
  case True
  thus ?thesis
    using assms(4) inf.absorb2 pseudo-complement by force
next
  case False
  thus ?thesis
    using assms point-in-vector-or-pseudo-complement by fastforce
qed

```

lemma *point-in-vector-or-complement-2*:

```

  assumes point x
    and vector y
    and regular y
    and  $\neg y \leq -x$ 
  shows  $x \leq y$ 
  using assms point-in-vector-or-pseudo-complement p-antitone-iff by fastforce

```

The next three lemmas *arc-in-arc-or-complement*, *arc-in-sup-arc* and *different-arc-in-sup-arc* were contributed by Nicolas Robinson-O'Brien.

lemma *arc-in-arc-or-complement*:

```

  assumes arc x
    and arc y
    and  $\neg x \leq y$ 
  shows  $x \leq -y$ 
  using assms arc-in-partition arc-regular by force

```

lemma *arc-in-sup-arc*:

```

  assumes arc x
    and arc y
    and  $x \leq z \sqcup y$ 
  shows  $x \leq z \vee x \leq y$ 
proof (cases  $x \leq y$ )
  case True
  thus ?thesis
    by simp
next
  case False
  hence  $x \leq -y$ 
    using assms(1,2) arc-in-arc-or-complement by blast
  hence  $x \leq -y \sqcap (z \sqcup y)$ 
    using assms(3) by simp
  hence  $x \leq z$ 
    by (metis inf.boundedE inf.sup-monoid.add-commute maddux-3-13
sup-commute)

```

```

thus ?thesis
  by simp
qed

lemma different-arc-in-sup-arc:
  assumes arc x
    and arc y
    and  $x \leq z \sqcup y$ 
    and  $x \neq y$ 
  shows  $x \leq z$ 
proof -
  have  $x \leq -y$ 
    using arc-in-arc-or-complement assms(1,2,4) order.eq-iff p-antitone-iff by
blast
  hence  $x \leq -y \sqcap (z \sqcup y)$ 
    using assms arc-in-sup-arc by simp
  thus ?thesis
    by (metis order-lesseq-imp p-inf-sup-below sup-commute)
qed

end

class relation-algebra-tarski = relation-algebra + stone-relation-algebra-tarski

  Finally, the above axioms of relation algebras do not imply that they
  contain at least two elements. This is necessary, for example, to show that
  arcs are not empty.

class stone-relation-algebra-consistent = stone-relation-algebra +
  assumes consistent: bot  $\neq$  top
begin

lemma arc-not-bot:
  arc x  $\implies$   $x \neq$  bot
  using consistent mult-right-zero by auto

lemma point-not-bot:
  point p  $\implies$   $p \neq$  bot
  using consistent by force

end

class relation-algebra-consistent = relation-algebra +
stone-relation-algebra-consistent

class stone-relation-algebra-tarski-consistent = stone-relation-algebra-tarski +
stone-relation-algebra-consistent
begin

lemma arc-in-partition-xor:

```

$arc\ x \implies (x \leq -y \wedge \neg x \leq --y) \vee (\neg x \leq -y \wedge x \leq --y)$   
**by** (*simp add: non-bot-arc-in-partition-xor arc-not-bot*)

**end**

**class** *relation-algebra-tarski-consistent* = *relation-algebra* +  
*stone-relation-algebra-tarski-consistent*

**end**

## 5 Subalgebras of Relation Algebras

In this theory we consider the algebraic structure of regular elements, coreflexives, vectors and covectors in Stone relation algebras. These elements form important subalgebras and substructures of relation algebras.

**theory** *Relation-Subalgebras*

**imports** *Stone-Algebras.Stone-Construction Relation-Algebras*

**begin**

The regular elements of a Stone relation algebra form a relation subalgebra.

**instantiation** *regular* :: (*stone-relation-algebra*) *relation-algebra*  
**begin**

**lift-definition** *times-regular* :: '*a regular*  $\Rightarrow$  '*a regular*  $\Rightarrow$  '*a regular* **is** *times*  
**using** *regular-mult-closed regular-closed-p* **by** *blast*

**lift-definition** *conv-regular* :: '*a regular*  $\Rightarrow$  '*a regular* **is** *conv*  
**using** *conv-complement* **by** *blast*

**lift-definition** *one-regular* :: '*a regular* **is** *1*  
**using** *regular-one-closed* **by** *blast*

**instance**

**apply** *intro-classes*  
**apply** (*metis* (*mono-tags, lifting*) *times-regular.rep-eq Rep-regular-inject comp-associative*)  
**apply** (*metis* (*mono-tags, lifting*) *times-regular.rep-eq Rep-regular-inject mult-right-dist-sup sup-regular.rep-eq*)  
**apply** (*metis* (*mono-tags, lifting*) *times-regular.rep-eq Rep-regular-inject bot-regular.rep-eq semiring.mult-zero-left*)  
**apply** (*simp add: one-regular.rep-eq times-regular.rep-eq Rep-regular-inject[THEN sym]*)  
**using** *Rep-regular-inject conv-regular.rep-eq* **apply** *force*  
**apply** (*metis* (*mono-tags, lifting*) *Rep-regular-inject conv-dist-sup conv-regular.rep-eq sup-regular.rep-eq*)



```

apply (metis (mono-tags, lifting) conv-regular.rep-eq times-regular.rep-eq
Rep-regular-inject conv-dist-comp)
by (auto simp add: conv-regular.rep-eq dedekind-1 inf-regular.rep-eq
less-eq-regular.rep-eq times-regular.rep-eq)

```

**end**

The coreflexives (tests) in an idempotent semiring form a bounded idempotent subsemiring.

```

typedef (overloaded) 'a coreflexive =
coreflexives::'a::non-associative-left-semiring set
by auto

```

```

lemma simp-coreflexive [simp]:
   $\exists y . \text{Rep-coreflexive } x \leq 1$ 
using Rep-coreflexive by simp

```

```

setup-lifting type-definition-coreflexive

```

```

instantiation coreflexive :: (idempotent-semiring) bounded-idempotent-semiring
begin

```

```

lift-definition sup-coreflexive :: 'a coreflexive  $\Rightarrow$  'a coreflexive  $\Rightarrow$  'a coreflexive is
sup
by simp

```

```

lift-definition times-coreflexive :: 'a coreflexive  $\Rightarrow$  'a coreflexive  $\Rightarrow$  'a coreflexive
is times
by (simp add: coreflexive-mult-closed)

```

```

lift-definition bot-coreflexive :: 'a coreflexive is bot
by simp

```

```

lift-definition one-coreflexive :: 'a coreflexive is 1
by simp

```

```

lift-definition top-coreflexive :: 'a coreflexive is 1
by simp

```

```

lift-definition less-eq-coreflexive :: 'a coreflexive  $\Rightarrow$  'a coreflexive  $\Rightarrow$  bool is
less-eq .

```

```

lift-definition less-coreflexive :: 'a coreflexive  $\Rightarrow$  'a coreflexive  $\Rightarrow$  bool is less .

```

**instance**

```

apply intro-classes
apply (simp-all add: less-coreflexive.rep-eq less-eq-coreflexive.rep-eq
less-le-not-le)[2]
apply (meson less-eq-coreflexive.rep-eq order-trans)

```

```

apply (simp-all add: Rep-coreflexive-inject bot-coreflexive.rep-eq
less-eq-coreflexive.rep-eq sup-coreflexive.rep-eq)[5]
apply (simp add: semiring.distrib-left less-eq-coreflexive.rep-eq
sup-coreflexive.rep-eq times-coreflexive.rep-eq)
apply (metis (mono-tags, lifting) sup-coreflexive.rep-eq times-coreflexive.rep-eq
Rep-coreflexive-inject mult-right-dist-sup)
apply (simp add: times-coreflexive.rep-eq bot-coreflexive.rep-eq
Rep-coreflexive-inject[THEN sym])
apply (simp add: one-coreflexive.rep-eq times-coreflexive.rep-eq
Rep-coreflexive-inject[THEN sym])
apply (simp add: one-coreflexive.rep-eq less-eq-coreflexive.rep-eq
times-coreflexive.rep-eq)
apply (simp only: sup-coreflexive.rep-eq top-coreflexive.rep-eq
Rep-coreflexive-inject[THEN sym], metis Abs-coreflexive-cases
Abs-coreflexive-inverse mem-Collect-eq sup.absorb2)
apply (simp add: less-eq-coreflexive.rep-eq mult.assoc times-coreflexive.rep-eq)
apply (metis (mono-tags, lifting) times-coreflexive.rep-eq Rep-coreflexive-inject
mult.assoc)
using Rep-coreflexive-inject one-coreflexive.rep-eq times-coreflexive.rep-eq
apply fastforce
apply (metis (mono-tags, lifting) sup-coreflexive.rep-eq times-coreflexive.rep-eq
Rep-coreflexive-inject mult-left-dist-sup)
by (simp add: times-coreflexive.rep-eq bot-coreflexive.rep-eq
Rep-coreflexive-inject[THEN sym])

end

```

The coreflexives (tests) in a Stone relation algebra form a Stone relation algebra where the pseudocomplement is taken relative to the identity relation and converse is the identity function.

```

instantiation coreflexive :: (stone-relation-algebra) stone-relation-algebra
begin

```

```

lift-definition inf-coreflexive :: 'a coreflexive  $\Rightarrow$  'a coreflexive  $\Rightarrow$  'a coreflexive is
inf
by (simp add: le-infI1)

```

```

lift-definition minus-coreflexive :: 'a coreflexive  $\Rightarrow$  'a coreflexive  $\Rightarrow$  'a coreflexive
is  $\lambda x y . x \sqcap -y$ 
by (simp add: le-infI1)

```

```

lift-definition uminus-coreflexive :: 'a coreflexive  $\Rightarrow$  'a coreflexive is  $\lambda x . -x \sqcap 1$ 
by simp

```

```

lift-definition conv-coreflexive :: 'a coreflexive  $\Rightarrow$  'a coreflexive is id
by simp

```

```

instance
apply intro-classes

```

```

apply (auto simp: inf-coreflexive.rep-eq less-eq-coreflexive.rep-eq)[3]
apply simp
apply (metis (mono-tags, lifting) Rep-coreflexive-inject inf-coreflexive.rep-eq
sup-coreflexive.rep-eq sup-inf-distrib1)
apply (metis (mono-tags, lifting) Rep-coreflexive-inject bot-coreflexive.rep-eq
top-greatest coreflexive-pseudo-complement inf-coreflexive.rep-eq
less-eq-coreflexive.rep-eq one-coreflexive.rep-eq one-coreflexive-def
top-coreflexive-def uminus-coreflexive.rep-eq)
apply (metis (mono-tags, lifting) Rep-coreflexive-inject maddux-3-21-pp
one-coreflexive.rep-eq one-coreflexive-def pp-dist-inf pp-one regular-closed-p
sup-coreflexive.rep-eq sup-right-top top-coreflexive-def uminus-coreflexive.rep-eq)
apply (auto simp: mult.assoc mult-right-dist-sup)[4]
using Rep-coreflexive-inject conv-coreflexive.rep-eq apply fastforce
apply (metis (mono-tags) Rep-coreflexive-inject conv-coreflexive.rep-eq)
apply (metis (mono-tags, lifting) Rep-coreflexive-inject top-greatest
conv-coreflexive.rep-eq coreflexive-commutative less-eq-coreflexive.rep-eq
one-coreflexive.rep-eq one-coreflexive-def times-coreflexive.rep-eq
top-coreflexive-def)
apply (simp only: conv-coreflexive.rep-eq less-eq-coreflexive.rep-eq
one-coreflexive.rep-eq times-coreflexive.rep-eq inf-coreflexive.rep-eq
Rep-coreflexive-inject[THEN sym], metis coreflexive-dedekind Rep-coreflexive
mem-Collect-eq)
apply (metis (mono-tags, lifting) Rep-coreflexive Rep-coreflexive-inject
coreflexive-pp-dist-comp mem-Collect-eq times-coreflexive.rep-eq
uminus-coreflexive.rep-eq)
by (metis (mono-tags, opaque-lifting) Rep-coreflexive-inverse inf commute
inf.idem inf-import-p one-coreflexive.rep-eq pp-one uminus-coreflexive.rep-eq)

end

```

Vectors in a Stone relation algebra form a Stone subalgebra.

```

typedef (overloaded) 'a vector = vectors::'a::bounded-pre-left-semiring set
using surjective-top-closed by blast

```

```

lemma simp-vector [simp]:
   $\exists y . \text{Rep-vector } x * \text{top} = \text{Rep-vector } x$ 
using Rep-vector by simp

```

```

setup-lifting type-definition-vector

```

```

instantiation vector :: (stone-relation-algebra) stone-algebra
begin

```

```

lift-definition sup-vector :: 'a vector  $\Rightarrow$  'a vector  $\Rightarrow$  'a vector is sup
by (simp add: vector-sup-closed)

```

```

lift-definition inf-vector :: 'a vector  $\Rightarrow$  'a vector  $\Rightarrow$  'a vector is inf
by (simp add: vector-inf-closed)

```

```

lift-definition uminus-vector :: 'a vector  $\Rightarrow$  'a vector is uminus
  by (simp add: vector-complement-closed)

lift-definition bot-vector :: 'a vector is bot
  by simp

lift-definition top-vector :: 'a vector is top
  by simp

lift-definition less-eq-vector :: 'a vector  $\Rightarrow$  'a vector  $\Rightarrow$  bool is less-eq .

lift-definition less-vector :: 'a vector  $\Rightarrow$  'a vector  $\Rightarrow$  bool is less .

instance
  apply intro-classes
  apply (auto simp: Rep-vector-inject top-vector.rep-eq bot-vector.rep-eq
less-le-not-le inf-vector.rep-eq sup-vector.rep-eq less-eq-vector.rep-eq
less-vector.rep-eq)[12]
  apply (metis (mono-tags, lifting) Rep-vector-inject inf-vector.rep-eq
sup-inf-distrib1 sup-vector.rep-eq)
  apply (metis (mono-tags, lifting) Rep-vector-inject bot-vector-def
bot-vector.rep-eq pseudo-complement inf-vector.rep-eq less-eq-vector.rep-eq
uminus-vector.rep-eq)
  by (metis (mono-tags, lifting) sup-vector.rep-eq uminus-vector.rep-eq
Rep-vector-inverse stone top-vector.abs-eq)

end

```

Covectors in a Stone relation algebra form a Stone subalgebra.

```

typedef (overloaded) 'a covector = covectors::'a::bounded-pre-left-semiring set
  using surjective-top-closed by blast

lemma simp-covector [simp]:
   $\exists y . top * Rep-covector x = Rep-covector x$ 
  using Rep-covector by simp

setup-lifting type-definition-covector

instantiation covector :: (stone-relation-algebra) stone-algebra
begin

lift-definition sup-covector :: 'a covector  $\Rightarrow$  'a covector  $\Rightarrow$  'a covector is sup
  by (simp add: covector-sup-closed)

lift-definition inf-covector :: 'a covector  $\Rightarrow$  'a covector  $\Rightarrow$  'a covector is inf
  by (simp add: covector-inf-closed)

lift-definition uminus-covector :: 'a covector  $\Rightarrow$  'a covector is uminus
  by (simp add: covector-complement-closed)

```

```

lift-definition bot-covector :: 'a covector is bot
  by simp

lift-definition top-covector :: 'a covector is top
  by simp

lift-definition less-eq-covector :: 'a covector  $\Rightarrow$  'a covector  $\Rightarrow$  bool is less-eq .

lift-definition less-covector :: 'a covector  $\Rightarrow$  'a covector  $\Rightarrow$  bool is less .

instance
  apply intro-classes
  apply (auto simp: Rep-covector-inject less-eq-covector.rep-eq inf-covector.rep-eq
bot-covector.rep-eq top-covector.rep-eq sup-covector.rep-eq less-le-not-le
less-covector.rep-eq)[12]
  apply (metis (mono-tags, lifting) Rep-covector-inject inf-covector.rep-eq
sup-inf-distrib1 sup-covector.rep-eq)
  apply (metis (mono-tags, lifting) Rep-covector-inject bot-covector-def
bot-covector.rep-eq pseudo-complement inf-covector.rep-eq less-eq-covector.rep-eq
uminus-covector.rep-eq)
  by (metis (mono-tags, lifting) sup-covector.rep-eq uminus-covector.rep-eq
Rep-covector-inverse stone top-covector.abs-eq)

end

end

```

## 6 Matrix Relation Algebras

This theory gives matrix models of Stone relation algebras and more general structures. We consider only square matrices. The main result is that matrices over Stone relation algebras form a Stone relation algebra.

We use the monoid structure underlying semilattices to provide finite sums, which are necessary for defining the composition of two matrices. See [3, 4] for similar liftings to matrices for semirings and relation algebras. A technical difference is that those theories are mostly based on semirings whereas our hierarchy is mostly based on lattices (and our semirings directly inherit from semilattices).

Relation algebras have both a semiring and a lattice structure such that semiring addition and lattice join coincide. In particular, finite sums and finite suprema coincide. Isabelle/HOL has separate theories for semirings and lattices, based on separate addition and join operations and different operations for finite sums and finite suprema. Reusing results from both theories is beneficial for relation algebras, but not always easy to realise.

```

theory Matrix-Relation-Algebras

```

**imports** *Relation-Algebras*

**begin**

## 6.1 Finite Suprema

We consider finite suprema in idempotent semirings and Stone relation algebras. We mostly use the first of the following notations, which denotes the supremum of expressions  $t(x)$  over all  $x$  from the type of  $x$ . For finite types, this is implemented in Isabelle/HOL as the repeated application of binary suprema.

**syntax**

*-sum-sup-monoid* :: *idt*  $\Rightarrow$  *'a::bounded-semilattice-sup-bot*  $\Rightarrow$  *'a* ( $(\bigsqcup_{-} -)$   $[0,10]$   $10$ )

*-sum-sup-monoid-bounded* :: *idt*  $\Rightarrow$  *'b set*  $\Rightarrow$  *'a::bounded-semilattice-sup-bot*  $\Rightarrow$  *'a* ( $(\bigsqcup_{-\in} -)$   $[0,51,10]$   $10$ )

**translations**

$\bigsqcup_x t \Rightarrow XCONST\ sup-monoid.sum\ (\lambda x . t)\ \{x . CONST\ True\}$   
 $\bigsqcup_{x \in X} t \Rightarrow XCONST\ sup-monoid.sum\ (\lambda x . t)\ X$

**context** *idempotent-semiring*

**begin**

The following induction principles are useful for comparing two suprema. The first principle works because types are not empty.

**lemma** *one-sup-induct* [*case-names one sup*]:

**fixes** *f g* :: *'b::finite*  $\Rightarrow$  *'a*

**assumes** *one*:  $\bigwedge i . P\ (f\ i)\ (g\ i)$

**and** *sup*:  $\bigwedge j\ I . j \notin I \Longrightarrow P\ (\bigsqcup_{i \in I} f\ i)\ (\bigsqcup_{i \in I} g\ i) \Longrightarrow P\ (f\ j \sqcup (\bigsqcup_{i \in I} f\ i))\ (g\ j \sqcup (\bigsqcup_{i \in I} g\ i))$

**shows**  $P\ (\bigsqcup_k f\ k)\ (\bigsqcup_k g\ k)$

**proof** –

**let**  $?X = \{k :: 'b . True\}$

**have** *finite*  $?X$  **and**  $?X \neq \{\}$

**by** *auto*

**thus** *?thesis*

**proof** (*induct rule: finite-ne-induct*)

**case** (*singleton i*) **thus** *?case*

**using** *one* **by** *simp*

**next**

**case** (*insert j I*) **thus** *?case*

**using** *sup* **by** *simp*

**qed**

**qed**

**lemma** *bot-sup-induct* [*case-names bot sup*]:

**fixes** *f g* :: *'b::finite*  $\Rightarrow$  *'a*

```

assumes bot:  $P \text{ bot } \text{bot}$ 
and sup:  $\bigwedge j I . j \notin I \implies P (\bigsqcup_{i \in I} f i) (\bigsqcup_{i \in I} g i) \implies P (f j \sqcup (\bigsqcup_{i \in I} f i))$ 
 $(g j \sqcup (\bigsqcup_{i \in I} g i))$ 
shows  $P (\bigsqcup_k f k) (\bigsqcup_k g k)$ 
apply (induct rule: one-sup-induct)
using bot sup apply fastforce
using sup by blast

```

Now many properties of finite suprema follow by simple applications of the above induction rules. In particular, we show distributivity of composition, isotonicity and the upper-bound property.

```

lemma comp-right-dist-sum:
fixes  $f :: 'b::\text{finite} \Rightarrow 'a$ 
shows  $(\bigsqcup_k f k * x) = (\bigsqcup_k f k) * x$ 
proof (induct rule: one-sup-induct)
case one show ?case
by simp
next
case (sup j I) thus ?case
using mult-right-dist-sup by auto
qed

```

```

lemma comp-left-dist-sum:
fixes  $f :: 'b::\text{finite} \Rightarrow 'a$ 
shows  $(\bigsqcup_k x * f k) = x * (\bigsqcup_k f k)$ 
proof (induct rule: one-sup-induct)
case one show ?case
by simp
next
case (sup j I) thus ?case
by (simp add: mult-left-dist-sup)
qed

```

```

lemma leq-sum:
fixes  $f g :: 'b::\text{finite} \Rightarrow 'a$ 
shows  $(\forall k . f k \leq g k) \implies (\bigsqcup_k f k) \leq (\bigsqcup_k g k)$ 
proof (induct rule: one-sup-induct)
case one thus ?case
by simp
next
case (sup j I) thus ?case
using sup-mono by blast
qed

```

```

lemma ub-sum:
fixes  $f :: 'b::\text{finite} \Rightarrow 'a$ 
shows  $f i \leq (\bigsqcup_k f k)$ 
proof –
have  $i \in \{ k . \text{True} \}$ 

```

```

    by simp
  thus  $f i \leq (\bigsqcup_k f (k::'b))$ 
    by (metis finite-code sup-monoid.sum.insert sup-ge1 mk-disjoint-insert)
qed

```

```

lemma lub-sum:
  fixes  $f :: 'b::finite \Rightarrow 'a$ 
  assumes  $\forall k . f k \leq x$ 
  shows  $(\bigsqcup_k f k) \leq x$ 
proof (induct rule: one-sup-induct)
  case one show ?case
    by (simp add: assms)
next
  case (sup j I) thus ?case
    using assms le-supI by blast
qed

```

```

lemma lub-sum-iff:
  fixes  $f :: 'b::finite \Rightarrow 'a$ 
  shows  $(\forall k . f k \leq x) \longleftrightarrow (\bigsqcup_k f k) \leq x$ 
  using order.trans ub-sum lub-sum by blast

```

end

```

context stone-relation-algebra
begin

```

In Stone relation algebras, we can also show that converse, double complement and meet distribute over finite suprema.

```

lemma conv-dist-sum:
  fixes  $f :: 'b::finite \Rightarrow 'a$ 
  shows  $(\bigsqcup_k (f k)^T) = (\bigsqcup_k f k)^T$ 
proof (induct rule: one-sup-induct)
  case one show ?case
    by simp
next
  case (sup j I) thus ?case
    by (simp add: conv-dist-sup)
qed

```

```

lemma pp-dist-sum:
  fixes  $f :: 'b::finite \Rightarrow 'a$ 
  shows  $(\bigsqcup_k \text{--} f k) = \text{--}(\bigsqcup_k f k)$ 
proof (induct rule: one-sup-induct)
  case one show ?case
    by simp
next
  case (sup j I) thus ?case
    by simp

```



qed

**lemma** *inf-right-dist-sum*:

**fixes**  $f :: 'b::finite \Rightarrow 'a$

**shows**  $(\bigsqcup_k f k \sqcap x) = (\bigsqcup_k f k) \sqcap x$

**by** (*rule comp-inf.comp-right-dist-sum*)

end

## 6.2 Square Matrices

Because our semiring and relation algebra type classes only work for homogeneous relations, we only look at square matrices.

**type-synonym**  $('a,'b)$  *square* =  $'a \times 'a \Rightarrow 'b$

We use standard matrix operations. The Stone algebra structure is lifted componentwise. Composition is matrix multiplication using given composition and supremum operations. Its unit lifts given zero and one elements into an identity matrix. Converse is matrix transpose with an additional componentwise transpose.

**definition** *less-eq-matrix* ::  $('a,'b::ord)$  *square*  $\Rightarrow ('a,'b)$  *square*  $\Rightarrow bool$

(**infix**  $\preceq$  50) **where**  $f \preceq g = (\forall e . f e \leq g e)$

**definition** *less-matrix* ::  $('a,'b::ord)$  *square*  $\Rightarrow ('a,'b)$  *square*  $\Rightarrow bool$

(**infix**  $\prec$  50) **where**  $f \prec g = (f \preceq g \wedge \neg g \preceq f)$

**definition** *sup-matrix* ::  $('a,'b::sup)$  *square*  $\Rightarrow ('a,'b)$  *square*  $\Rightarrow ('a,'b)$  *square*

(**infixl**  $\oplus$  65) **where**  $f \oplus g = (\lambda e . f e \sqcup g e)$

**definition** *inf-matrix* ::  $('a,'b::inf)$  *square*  $\Rightarrow ('a,'b)$  *square*  $\Rightarrow ('a,'b)$  *square*

(**infixl**  $\otimes$  67) **where**  $f \otimes g = (\lambda e . f e \sqcap g e)$

**definition** *minus-matrix* ::  $('a,'b::\{uminus,inf\})$  *square*  $\Rightarrow ('a,'b)$  *square*  $\Rightarrow$

$('a,'b)$  *square* (**infixl**  $\ominus$  65) **where**  $f \ominus g = (\lambda e . f e \sqcap -g e)$

**definition** *implies-matrix* ::  $('a,'b::implies)$  *square*  $\Rightarrow ('a,'b)$  *square*  $\Rightarrow ('a,'b)$

*square* (**infixl**  $\otimes$  65) **where**  $f \otimes g = (\lambda e . f e \rightsquigarrow g e)$

**definition** *times-matrix* ::  $('a,'b::\{times,bounded-semilattice-sup-bot\})$  *square*  $\Rightarrow$

$('a,'b)$  *square*  $\Rightarrow ('a,'b)$  *square* (**infixl**  $\odot$  70) **where**  $f \odot g = (\lambda(i,j) . \bigsqcup_k f(i,k)$

$* g(k,j))$

**definition** *uminus-matrix* ::  $('a,'b::uminus)$  *square*  $\Rightarrow ('a,'b)$  *square*

( $\ominus$  - [80] 80) **where**  $\ominus f = (\lambda e . -f e)$

**definition** *conv-matrix* ::  $('a,'b::conv)$  *square*  $\Rightarrow ('a,'b)$  *square*

( $-^t$  [100] 100) **where**  $f^t = (\lambda(i,j) . (f(j,i))^T)$

**definition** *bot-matrix* ::  $('a,'b::bot)$  *square*

(*mbot*) **where** *mbot* =  $(\lambda e . bot)$

**definition** *top-matrix* ::  $('a,'b::top)$  *square*

(*mtop*) **where** *mtop* =  $(\lambda e . top)$

**definition** *one-matrix* ::  $('a,'b::\{one,bot\})$  *square*

(*mone*) **where** *mone* =  $(\lambda(i,j) . \text{if } i = j \text{ then } 1 \text{ else } bot)$

## 6.3 Stone Algebras

We first lift the Stone algebra structure. Because all operations are componentwise, this also works for infinite matrices.

**interpretation** *matrix-order*: *order* **where** *less-eq* = *less-eq-matrix* **and** *less* = *less-matrix* :: ('a,'b::order) square  $\Rightarrow$  ('a,'b) square  $\Rightarrow$  bool  
**apply** *unfold-locales*  
**apply** (*simp add: less-matrix-def*)  
**apply** (*simp add: less-eq-matrix-def*)  
**apply** (*meson less-eq-matrix-def order-trans*)  
**by** (*meson less-eq-matrix-def antisym ext*)

**interpretation** *matrix-semilattice-sup*: *semilattice-sup* **where** *sup* = *sup-matrix* **and** *less-eq* = *less-eq-matrix* **and** *less* = *less-matrix* :: ('a,'b::semilattice-sup) square  $\Rightarrow$  ('a,'b) square  $\Rightarrow$  bool  
**apply** *unfold-locales*  
**apply** (*simp add: sup-matrix-def less-eq-matrix-def*)  
**apply** (*simp add: sup-matrix-def less-eq-matrix-def*)  
**by** (*simp add: sup-matrix-def less-eq-matrix-def*)

**interpretation** *matrix-semilattice-inf*: *semilattice-inf* **where** *inf* = *inf-matrix* **and** *less-eq* = *less-eq-matrix* **and** *less* = *less-matrix* :: ('a,'b::semilattice-inf) square  $\Rightarrow$  ('a,'b) square  $\Rightarrow$  bool  
**apply** *unfold-locales*  
**apply** (*simp add: inf-matrix-def less-eq-matrix-def*)  
**apply** (*simp add: inf-matrix-def less-eq-matrix-def*)  
**by** (*simp add: inf-matrix-def less-eq-matrix-def*)

**interpretation** *matrix-bounded-semilattice-sup-bot*: *bounded-semilattice-sup-bot* **where** *sup* = *sup-matrix* **and** *less-eq* = *less-eq-matrix* **and** *less* = *less-matrix* **and** *bot* = *bot-matrix* :: ('a,'b::bounded-semilattice-sup-bot) square  
**apply** *unfold-locales*  
**by** (*simp add: bot-matrix-def less-eq-matrix-def*)

**interpretation** *matrix-bounded-semilattice-inf-top*: *bounded-semilattice-inf-top* **where** *inf* = *inf-matrix* **and** *less-eq* = *less-eq-matrix* **and** *less* = *less-matrix* **and** *top* = *top-matrix* :: ('a,'b::bounded-semilattice-inf-top) square  
**apply** *unfold-locales*  
**by** (*simp add: less-eq-matrix-def top-matrix-def*)

**interpretation** *matrix-lattice*: *lattice* **where** *sup* = *sup-matrix* **and** *inf* = *inf-matrix* **and** *less-eq* = *less-eq-matrix* **and** *less* = *less-matrix* :: ('a,'b::lattice) square  $\Rightarrow$  ('a,'b) square  $\Rightarrow$  bool ..

**interpretation** *matrix-distrib-lattice*: *distrib-lattice* **where** *sup* = *sup-matrix* **and** *inf* = *inf-matrix* **and** *less-eq* = *less-eq-matrix* **and** *less* = *less-matrix* :: ('a,'b::distrib-lattice) square  $\Rightarrow$  ('a,'b) square  $\Rightarrow$  bool  
**apply** *unfold-locales*  
**by** (*simp add: sup-inf-distrib1 sup-matrix-def inf-matrix-def*)

**interpretation** *matrix-bounded-lattice*: *bounded-lattice* **where** *sup* = *sup-matrix*

**and**  $inf = inf\text{-matrix}$  **and**  $less\text{-eq} = less\text{-eq-matrix}$  **and**  $less = less\text{-matrix}$  **and**  
 $bot = bot\text{-matrix} :: ('a, 'b :: bounded\text{-lattice})\ square$  **and**  $top = top\text{-matrix} ..$

**interpretation**  $matrix\text{-bounded-distrib-lattice}$ :  $bounded\text{-distrib-lattice}$  **where**  $sup = sup\text{-matrix}$  **and**  $inf = inf\text{-matrix}$  **and**  $less\text{-eq} = less\text{-eq-matrix}$  **and**  $less = less\text{-matrix}$  **and**  
 $bot = bot\text{-matrix} :: ('a, 'b :: bounded\text{-distrib-lattice})\ square$  **and**  $top = top\text{-matrix} ..$

**interpretation**  $matrix\text{-p-algebra}$ :  $p\text{-algebra}$  **where**  $sup = sup\text{-matrix}$  **and**  $inf = inf\text{-matrix}$  **and**  $less\text{-eq} = less\text{-eq-matrix}$  **and**  $less = less\text{-matrix}$  **and**  $bot = bot\text{-matrix} :: ('a, 'b :: p\text{-algebra})\ square$  **and**  $top = top\text{-matrix}$  **and**  $uminus = uminus\text{-matrix}$

**apply**  $unfold\text{-locales}$

**apply** ( $unfold\ inf\text{-matrix-def}\ bot\text{-matrix-def}\ less\text{-eq-matrix-def}\ uminus\text{-matrix-def}$ )

**by** ( $meson\ pseudo\text{-complement}$ )

**interpretation**  $matrix\text{-pd-algebra}$ :  $pd\text{-algebra}$  **where**  $sup = sup\text{-matrix}$  **and**  $inf = inf\text{-matrix}$  **and**  $less\text{-eq} = less\text{-eq-matrix}$  **and**  $less = less\text{-matrix}$  **and**  $bot = bot\text{-matrix} :: ('a, 'b :: pd\text{-algebra})\ square$  **and**  $top = top\text{-matrix}$  **and**  $uminus = uminus\text{-matrix} ..$

In particular, matrices over Stone algebras form a Stone algebra.

**interpretation**  $matrix\text{-stone-algebra}$ :  $stone\text{-algebra}$  **where**  $sup = sup\text{-matrix}$  **and**  $inf = inf\text{-matrix}$  **and**  $less\text{-eq} = less\text{-eq-matrix}$  **and**  $less = less\text{-matrix}$  **and**  
 $bot = bot\text{-matrix} :: ('a, 'b :: stone\text{-algebra})\ square$  **and**  $top = top\text{-matrix}$  **and**  $uminus = uminus\text{-matrix}$

**by**  $unfold\text{-locales}\ (simp\ add:\ sup\text{-matrix-def}\ uminus\text{-matrix-def}\ top\text{-matrix-def})$

**interpretation**  $matrix\text{-heyting-stone-algebra}$ :  $heyting\text{-stone-algebra}$  **where**  $sup = sup\text{-matrix}$  **and**  $inf = inf\text{-matrix}$  **and**  $less\text{-eq} = less\text{-eq-matrix}$  **and**  $less = less\text{-matrix}$  **and**  
 $bot = bot\text{-matrix} :: ('a, 'b :: heyting\text{-stone-algebra})\ square$  **and**  $top = top\text{-matrix}$  **and**  $uminus = uminus\text{-matrix}$  **and**  $implies = implies\text{-matrix}$

**apply**  $unfold\text{-locales}$

**apply** ( $unfold\ inf\text{-matrix-def}\ sup\text{-matrix-def}\ bot\text{-matrix-def}\ top\text{-matrix-def}\ less\text{-eq-matrix-def}\ uminus\text{-matrix-def}\ implies\text{-matrix-def}$ )

**apply** ( $simp\ add:\ implies\text{-galois}$ )

**apply** ( $simp\ add:\ uminus\text{-eq}$ )

**by**  $simp$

**interpretation**  $matrix\text{-boolean-algebra}$ :  $boolean\text{-algebra}$  **where**  $sup = sup\text{-matrix}$  **and**  $inf = inf\text{-matrix}$  **and**  $less\text{-eq} = less\text{-eq-matrix}$  **and**  $less = less\text{-matrix}$  **and**  
 $bot = bot\text{-matrix} :: ('a, 'b :: boolean\text{-algebra})\ square$  **and**  $top = top\text{-matrix}$  **and**  $uminus = uminus\text{-matrix}$  **and**  $minus = minus\text{-matrix}$

**apply**  $unfold\text{-locales}$

**apply**  $simp$

**apply** ( $simp\ add:\ sup\text{-matrix-def}\ uminus\text{-matrix-def}\ top\text{-matrix-def}$ )

**by** ( $simp\ add:\ inf\text{-matrix-def}\ uminus\text{-matrix-def}\ minus\text{-matrix-def}$ )

## 6.4 Semirings

Next, we lift the semiring structure. Because of composition, this requires a restriction to finite matrices.

**interpretation** *matrix-monoid*: *monoid-mult* **where** *times = times-matrix* **and** *one = one-matrix* :: (*a*::*finite*, *b*::*idempotent-semiring*) *square*

**proof**

```

fix f g h :: ('a,'b) square
show (f ∘ g) ∘ h = f ∘ (g ∘ h)
proof (rule ext, rule prod-cases)
  fix i j
  have ((f ∘ g) ∘ h) (i,j) = (⊔l (f ∘ g) (i,l) * h (l,j))
    by (simp add: times-matrix-def)
  also have ... = (⊔l (⊔k f (i,k) * g (k,l)) * h (l,j))
    by (simp add: times-matrix-def)
  also have ... = (⊔l ⊔k (f (i,k) * g (k,l)) * h (l,j))
    by (metis (no-types) comp-right-dist-sum)
  also have ... = (⊔l ⊔k f (i,k) * (g (k,l) * h (l,j)))
    by (simp add: mult.assoc)
  also have ... = (⊔k ⊔l f (i,k) * (g (k,l) * h (l,j)))
    using sup-monoid.sum.swap by auto
  also have ... = (⊔k f (i,k) * (⊔l g (k,l) * h (l,j)))
    by (metis (no-types) comp-left-dist-sum)
  also have ... = (⊔k f (i,k) * (g ∘ h) (k,j))
    by (simp add: times-matrix-def)
  also have ... = (f ∘ (g ∘ h)) (i,j)
    by (simp add: times-matrix-def)
  finally show ((f ∘ g) ∘ h) (i,j) = (f ∘ (g ∘ h)) (i,j)
    .
  qed
next
fix f :: ('a,'b) square
show mone ∘ f = f
proof (rule ext, rule prod-cases)
  fix i j
  have (mone ∘ f) (i,j) = (⊔k mone (i,k) * f (k,j))
    by (simp add: times-matrix-def)
  also have ... = (⊔k (if i = k then 1 else bot) * f (k,j))
    by (simp add: one-matrix-def)
  also have ... = (⊔k if i = k then 1 * f (k,j) else bot * f (k,j))
    by (metis (full-types, opaque-lifting))
  also have ... = (⊔k if i = k then f (k,j) else bot)
    by (meson mult-left-one mult-left-zero)
  also have ... = f (i,j)
    by simp
  finally show (mone ∘ f) (i,j) = f (i,j)
    .
  qed
next

```

```

fix f :: ('a,'b) square
show f  $\odot$  mone = f
proof (rule ext, rule prod-cases)
  fix i j
  have (f  $\odot$  mone) (i,j) = ( $\bigsqcup_k$  f (i,k) * mone (k,j))
    by (simp add: times-matrix-def)
  also have ... = ( $\bigsqcup_k$  f (i,k) * (if k = j then 1 else bot))
    by (simp add: one-matrix-def)
  also have ... = ( $\bigsqcup_k$  if k = j then f (i,k) * 1 else f (i,k) * bot)
    by (metis (full-types, opaque-lifting))
  also have ... = ( $\bigsqcup_k$  if k = j then f (i,k) else bot)
    by (meson mult.right-neutral semiring.mult-zero-right)
  also have ... = f (i,j)
    by simp
  finally show (f  $\odot$  mone) (i,j) = f (i,j)
  .
qed
qed

```

**interpretation** matrix-idempotent-semiring: idempotent-semiring **where** sup = sup-matrix **and** less-eq = less-eq-matrix **and** less = less-matrix **and** bot = bot-matrix :: ('a::finite,'b::idempotent-semiring) square **and** one = one-matrix **and** times = times-matrix

```

proof
  fix f g h :: ('a,'b) square
  show f  $\odot$  g  $\oplus$  f  $\odot$  h  $\leq$  f  $\odot$  (g  $\oplus$  h)
  proof (unfold less-eq-matrix-def, rule allI, rule prod-cases)
    fix i j
    have (f  $\odot$  g  $\oplus$  f  $\odot$  h) (i,j) = (f  $\odot$  g) (i,j)  $\sqcup$  (f  $\odot$  h) (i,j)
      by (simp add: sup-matrix-def)
    also have ... = ( $\bigsqcup_k$  f (i,k) * g (k,j))  $\sqcup$  ( $\bigsqcup_k$  f (i,k) * h (k,j))
      by (simp add: times-matrix-def)
    also have ... = ( $\bigsqcup_k$  f (i,k) * g (k,j)  $\sqcup$  f (i,k) * h (k,j))
      by (simp add: sup-monoid.sum.distrib)
    also have ... = ( $\bigsqcup_k$  f (i,k) * (g (k,j)  $\sqcup$  h (k,j)))
      by (simp add: mult-left-dist-sup)
    also have ... = ( $\bigsqcup_k$  f (i,k) * (g  $\oplus$  h) (k,j))
      by (simp add: sup-matrix-def)
    also have ... = (f  $\odot$  (g  $\oplus$  h)) (i,j)
      by (simp add: times-matrix-def)
    finally show (f  $\odot$  g  $\oplus$  f  $\odot$  h) (i,j)  $\leq$  (f  $\odot$  (g  $\oplus$  h)) (i,j)
      by simp
  qed

```

```

next
  fix f g h :: ('a,'b) square
  show (f  $\oplus$  g)  $\odot$  h = f  $\odot$  h  $\oplus$  g  $\odot$  h
  proof (rule ext, rule prod-cases)
    fix i j
    have ((f  $\oplus$  g)  $\odot$  h) (i,j) = ( $\bigsqcup_k$  (f  $\oplus$  g) (i,k) * h (k,j))

```

```

    by (simp add: times-matrix-def)
  also have ... = ( $\bigsqcup_k (f (i,k) \sqcup g (i,k)) * h (k,j)$ )
    by (simp add: sup-matrix-def)
  also have ... = ( $\bigsqcup_k f (i,k) * h (k,j) \sqcup g (i,k) * h (k,j)$ )
    by (meson mult-right-dist-sup)
  also have ... = ( $\bigsqcup_k f (i,k) * h (k,j) \sqcup \bigsqcup_k g (i,k) * h (k,j)$ )
    by (simp add: sup-monoid.sum.distrib)
  also have ... = ( $f \odot h$ ) (i,j)  $\sqcup$  ( $g \odot h$ ) (i,j)
    by (simp add: times-matrix-def)
  also have ... = ( $f \odot h \oplus g \odot h$ ) (i,j)
    by (simp add: sup-matrix-def)
  finally show (( $f \oplus g$ )  $\odot$   $h$ ) (i,j) = ( $f \odot h \oplus g \odot h$ ) (i,j)
    .
qed
next
fix f :: ('a,'b) square
show mbot  $\odot$  f = mbot
proof (rule ext, rule prod-cases)
  fix i j
  have (mbot  $\odot$  f) (i,j) = ( $\bigsqcup_k$  mbot (i,k) * f (k,j))
    by (simp add: times-matrix-def)
  also have ... = ( $\bigsqcup_k$  bot * f (k,j))
    by (simp add: bot-matrix-def)
  also have ... = bot
    by simp
  also have ... = mbot (i,j)
    by (simp add: bot-matrix-def)
  finally show (mbot  $\odot$  f) (i,j) = mbot (i,j)
    .
qed
next
fix f :: ('a,'b) square
show mone  $\odot$  f = f
  by simp
next
fix f :: ('a,'b) square
show f  $\preceq$  f  $\odot$  mone
  by simp
next
fix f g h :: ('a,'b) square
show f  $\odot$  (g  $\oplus$  h) = f  $\odot$  g  $\oplus$  f  $\odot$  h
proof (rule ext, rule prod-cases)
  fix i j
  have (f  $\odot$  (g  $\oplus$  h)) (i,j) = ( $\bigsqcup_k$  f (i,k) * (g  $\oplus$  h) (k,j))
    by (simp add: times-matrix-def)
  also have ... = ( $\bigsqcup_k$  f (i,k) * (g (k,j)  $\sqcup$  h (k,j)))
    by (simp add: sup-matrix-def)
  also have ... = ( $\bigsqcup_k$  f (i,k) * g (k,j)  $\sqcup$  f (i,k) * h (k,j))
    by (meson mult-left-dist-sup)

```

```

    also have ... = ( $\bigsqcup_k f (i,k) * g (k,j)$ )  $\sqcup$  ( $\bigsqcup_k f (i,k) * h (k,j)$ )
      by (simp add: sup-monoid.sum.distrib)
    also have ... = ( $f \odot g$ ) ( $i,j$ )  $\sqcup$  ( $f \odot h$ ) ( $i,j$ )
      by (simp add: times-matrix-def)
    also have ... = ( $f \odot g \oplus f \odot h$ ) ( $i,j$ )
      by (simp add: sup-matrix-def)
    finally show ( $f \odot (g \oplus h)$ ) ( $i,j$ ) = ( $f \odot g \oplus f \odot h$ ) ( $i,j$ )
      .
  qed
next
fix f :: ('a,'b) square
show  $f \odot mbot = mbot$ 
proof (rule ext, rule prod-cases)
  fix i j
  have ( $f \odot mbot$ ) ( $i,j$ ) = ( $\bigsqcup_k f (i,k) * mbot (k,j)$ )
    by (simp add: times-matrix-def)
  also have ... = ( $\bigsqcup_k f (i,k) * bot$ )
    by (simp add: bot-matrix-def)
  also have ... = bot
    by simp
  also have ... = mbot ( $i,j$ )
    by (simp add: bot-matrix-def)
  finally show ( $f \odot mbot$ ) ( $i,j$ ) = mbot ( $i,j$ )
    .
  qed
qed

interpretation matrix-bounded-idempotent-semiring:
bounded-idempotent-semiring where sup = sup-matrix and less-eq =
less-eq-matrix and less = less-matrix and bot = bot-matrix ::
('a::finite,'b::bounded-idempotent-semiring) square and top = top-matrix and one
= one-matrix and times = times-matrix
proof
  fix f :: ('a,'b) square
  show  $f \oplus mtop = mtop$ 
  proof
    fix e
    have ( $f \oplus mtop$ ) e =  $f e \sqcup mtop e$ 
      by (simp add: sup-matrix-def)
    also have ... =  $f e \sqcup top$ 
      by (simp add: top-matrix-def)
    also have ... = top
      by simp
    also have ... = mtop e
      by (simp add: top-matrix-def)
    finally show ( $f \oplus mtop$ ) e = mtop e
      .
  qed
qed

```

## 6.5 Stone Relation Algebras

Finally, we show that matrices over Stone relation algebras form a Stone relation algebra.

**interpretation** *matrix-stone-relation-algebra*: *stone-relation-algebra* **where**  $sup = sup\text{-matrix}$  **and**  $inf = inf\text{-matrix}$  **and**  $less\text{-eq} = less\text{-eq-matrix}$  **and**  $less = less\text{-matrix}$  **and**  $bot = bot\text{-matrix}$  **::**  $( 'a::finite, 'b::stone\text{-relation-algebra} )$  *square* **and**  $top = top\text{-matrix}$  **and**  $uminus = uminus\text{-matrix}$  **and**  $one = one\text{-matrix}$  **and**  $times = times\text{-matrix}$  **and**  $conv = conv\text{-matrix}$

**proof**

```

fix f g h :: ('a,'b) square
show (f  $\odot$  g)  $\odot$  h = f  $\odot$  (g  $\odot$  h)
  by (simp add: matrix-monoid.mult-assoc)
next
fix f g h :: ('a,'b) square
show (f  $\oplus$  g)  $\odot$  h = f  $\odot$  h  $\oplus$  g  $\odot$  h
  by (simp add: matrix-idempotent-semiring.mult-right-dist-sup)
next
fix f :: ('a,'b) square
show mbot  $\odot$  f = mbot
  by simp
next
fix f :: ('a,'b) square
show mone  $\odot$  f = f
  by simp
next
fix f :: ('a,'b) square
show ftt = f
proof (rule ext, rule prod-cases)
  fix i j
  have (ftt) (i,j) = ((ft) (j,i))T
    by (simp add: conv-matrix-def)
  also have ... = f (i,j)
    by (simp add: conv-matrix-def)
  finally show (ftt) (i,j) = f (i,j)
  ·
qed
next
fix f g :: ('a,'b) square
show (f  $\oplus$  g)t = ft  $\oplus$  gt
proof (rule ext, rule prod-cases)
  fix i j
  have ((f  $\oplus$  g)t) (i,j) = ((f  $\oplus$  g) (j,i))T
    by (simp add: conv-matrix-def)
  also have ... = (f (j,i)  $\sqcup$  g (j,i))T
    by (simp add: sup-matrix-def)
  also have ... = (ft) (i,j)  $\sqcup$  (gt) (i,j)
    by (simp add: conv-matrix-def conv-dist-sup)
  also have ... = (ft  $\oplus$  gt) (i,j)

```



by (*simp add: sup-matrix-def*)  
 finally show  $((f \oplus g)^t) (i,j) = (f^t \oplus g^t) (i,j)$   
 .  
 qed  
 next  
 fix  $f g :: ('a, 'b)$  square  
 show  $(f \odot g)^t = g^t \odot f^t$   
 proof (*rule ext, rule prod-cases*)  
 fix  $i j$   
 have  $((f \odot g)^t) (i,j) = ((f \odot g) (j,i))^T$   
 by (*simp add: conv-matrix-def*)  
 also have  $\dots = (\bigsqcup_k f (j,k) * g (k,i))^T$   
 by (*simp add: times-matrix-def*)  
 also have  $\dots = (\bigsqcup_k (f (j,k) * g (k,i))^T)$   
 by (*metis (no-types) conv-dist-sum*)  
 also have  $\dots = (\bigsqcup_k (g (k,i))^T * (f (j,k))^T)$   
 by (*simp add: conv-dist-comp*)  
 also have  $\dots = (\bigsqcup_k (g^t) (i,k) * (f^t) (k,j))$   
 by (*simp add: conv-matrix-def*)  
 also have  $\dots = (g^t \odot f^t) (i,j)$   
 by (*simp add: times-matrix-def*)  
 finally show  $((f \odot g)^t) (i,j) = (g^t \odot f^t) (i,j)$   
 .  
 qed  
 next  
 fix  $f g h :: ('a, 'b)$  square  
 show  $(f \odot g) \otimes h \leq f \odot (g \otimes (f^t \odot h))$   
 proof (*unfold less-eq-matrix-def, rule allI, rule prod-cases*)  
 fix  $i j$   
 have  $((f \odot g) \otimes h) (i,j) = (f \odot g) (i,j) \sqcap h (i,j)$   
 by (*simp add: inf-matrix-def*)  
 also have  $\dots = (\bigsqcup_k f (i,k) * g (k,j)) \sqcap h (i,j)$   
 by (*simp add: times-matrix-def*)  
 also have  $\dots = (\bigsqcup_k f (i,k) * g (k,j) \sqcap h (i,j))$   
 by (*metis (no-types) inf-right-dist-sum*)  
 also have  $\dots \leq (\bigsqcup_k f (i,k) * (g (k,j) \sqcap (f^t (i,k))^T * h (i,j)))$   
 by (*rule leq-sum, meson dedekind-1*)  
 also have  $\dots = (\bigsqcup_k f (i,k) * (g (k,j) \sqcap (f^t) (k,i) * h (i,j)))$   
 by (*simp add: conv-matrix-def*)  
 also have  $\dots \leq (\bigsqcup_k f (i,k) * (g (k,j) \sqcap (\bigsqcup_l (f^t) (k,l) * h (l,j))))$   
 by (*rule leq-sum, rule allI, rule comp-right-isotone, rule inf.sup-right-isotone, rule ub-sum*)  
 also have  $\dots = (\bigsqcup_k f (i,k) * (g (k,j) \sqcap (f^t \odot h) (k,j)))$   
 by (*simp add: times-matrix-def*)  
 also have  $\dots = (\bigsqcup_k f (i,k) * (g \otimes (f^t \odot h)) (k,j))$   
 by (*simp add: inf-matrix-def*)  
 also have  $\dots = (f \odot (g \otimes (f^t \odot h))) (i,j)$   
 by (*simp add: times-matrix-def*)  
 finally show  $((f \odot g) \otimes h) (i,j) \leq (f \odot (g \otimes (f^t \odot h))) (i,j)$

```

      .
    qed
  next
  fix f g :: ('a,'b) square
  show  $\ominus\ominus(f \odot g) = \ominus\ominus f \odot \ominus\ominus g$ 
  proof (rule ext, rule prod-cases)
    fix i j
    have  $(\ominus\ominus(f \odot g)) (i,j) = --((f \odot g) (i,j))$ 
      by (simp add: uminus-matrix-def)
    also have  $\dots = --(\bigsqcup_k f (i,k) * g (k,j))$ 
      by (simp add: times-matrix-def)
    also have  $\dots = (\bigsqcup_k --(f (i,k) * g (k,j)))$ 
      by (metis (no-types) pp-dist-sum)
    also have  $\dots = (\bigsqcup_k --(f (i,k)) * --(g (k,j)))$ 
      by (meson pp-dist-comp)
    also have  $\dots = (\bigsqcup_k (\ominus\ominus f) (i,k) * (\ominus\ominus g) (k,j))$ 
      by (simp add: uminus-matrix-def)
    also have  $\dots = (\ominus\ominus f \odot \ominus\ominus g) (i,j)$ 
      by (simp add: times-matrix-def)
    finally show  $(\ominus\ominus(f \odot g)) (i,j) = (\ominus\ominus f \odot \ominus\ominus g) (i,j)$ 
  .
  qed
  next
  let ?o = mone :: ('a,'b) square
  show  $\ominus\ominus ?o = ?o$ 
  proof (rule ext, rule prod-cases)
    fix i j
    have  $(\ominus\ominus ?o) (i,j) = --(?o (i,j))$ 
      by (simp add: uminus-matrix-def)
    also have  $\dots = --(\text{if } i = j \text{ then } 1 \text{ else bot})$ 
      by (simp add: one-matrix-def)
    also have  $\dots = (\text{if } i = j \text{ then } --1 \text{ else } --\text{bot})$ 
      by simp
    also have  $\dots = (\text{if } i = j \text{ then } 1 \text{ else bot})$ 
      by auto
    also have  $\dots = ?o (i,j)$ 
      by (simp add: one-matrix-def)
    finally show  $(\ominus\ominus ?o) (i,j) = ?o (i,j)$ 
  .
  qed
  qed
end

```

## 7 Matrices over Bounded Linear Orders

In this theory we characterise relation-algebraic properties of matrices over bounded linear orders (for example, extended real numbers) in terms of the

entries in the matrices. We consider, in particular, the following properties: univalent, injective, total, surjective, mapping, bijective, vector, covector, point, arc, reflexive, coreflexive, irreflexive, symmetric, antisymmetric, asymmetric. We also consider the effect of composition with the matrix of greatest elements and with coreflexives (tests).

**theory** *Linear-Order-Matrices*

**imports** *Matrix-Relation-Algebras*

**begin**

**class** *non-trivial-linorder-stone-relation-algebra-expansion* =  
*linorder-stone-relation-algebra-expansion* + *non-trivial*

**begin**

**subclass** *non-trivial-bounded-order* ..

**end**

Before we look at matrices, we generalise selectivity to finite suprema.

**lemma** *linorder-finite-sup-selective*:

**fixes**  $f :: 'a::\text{finite} \Rightarrow 'b::\text{linorder-stone-algebra-expansion}$

**shows**  $\exists i . (\bigsqcup_k f k) = f i$

**apply** (*induct rule: comp-inf.one-sup-induct*)

**apply** *blast*

**using** *sup-selective* **by** *fastforce*

**lemma** *linorder-top-finite-sup*:

**fixes**  $f :: 'a::\text{finite} \Rightarrow 'b::\text{linorder-stone-algebra-expansion}$

**assumes**  $\forall k . f k \neq \text{top}$

**shows**  $(\bigsqcup_k f k) \neq \text{top}$

**by** (*metis assms linorder-finite-sup-selective*)

The following results show the effect of composition with the *top* matrix from the left and from the right.

**lemma** *comp-top-linorder-matrix*:

**fixes**  $f :: ('a::\text{finite}, 'b::\text{linorder-stone-relation-algebra-expansion}) \text{ square}$

**shows**  $(f \odot \text{mtop}) (i, j) = (\bigsqcup_k f (i, k))$

**apply** (*unfold times-matrix-def top-matrix-def*)

**by** (*metis (no-types, lifting) case-prod-conv comp-right-one one-def sup-monoid.sum.cong*)

**lemma** *top-comp-linorder-matrix*:

**fixes**  $f :: ('a::\text{finite}, 'b::\text{linorder-stone-relation-algebra-expansion}) \text{ square}$

**shows**  $(\text{mtop} \odot f) (i, j) = (\bigsqcup_k f (k, j))$

**apply** (*unfold times-matrix-def top-matrix-def*)

**by** (*metis (no-types, lifting) case-prod-conv comp-left-one one-def sup-monoid.sum.cong*)

We characterise univalent matrices: in each row, at most one entry may be different from *bot*.

**lemma** *univalent-linorder-matrix-1*:

**fixes**  $f :: ('a::\text{finite}, 'b::\text{linorder-stone-relation-algebra-expansion}) \text{ square}$   
**assumes** *matrix-stone-relation-algebra.univalent*  $f$

**and**  $f (i,j) \neq \text{bot}$

**and**  $f (i,k) \neq \text{bot}$

**shows**  $j = k$

**proof** –

**have**  $(f^t \odot f) (j,k) = (\bigsqcup_l (f^t) (j,l) * f (l,k))$

**by** (*simp add: times-matrix-def*)

**also have**  $\dots = (\bigsqcup_l (f (l,j))^T * f (l,k))$

**by** (*simp add: conv-matrix-def*)

**also have**  $\dots = (\bigsqcup_l f (l,j) * f (l,k))$

**by** *simp*

**also have**  $\dots \geq f (i,j) * f (i,k)$

**using** *comp-inf.ub-sum* **by** *fastforce*

**finally have**  $(f^t \odot f) (j,k) \neq \text{bot}$

**using** *assms(2,3) bot.extremum-uniqueI times-dense* **by** *fastforce*

**hence**  $\text{mone} (j,k) \neq (\text{bot}::'b)$

**by** (*metis assms(1) bot.extremum-uniqueI less-eq-matrix-def*)

**thus** *?thesis*

**by** (*metis (mono-tags, lifting) case-prod-conv one-matrix-def*)

**qed**

**lemma** *univalent-linorder-matrix-2*:

**fixes**  $f :: ('a::\text{finite}, 'b::\text{linorder-stone-relation-algebra-expansion}) \text{ square}$

**assumes**  $\forall i j k . f (i,j) \neq \text{bot} \wedge f (i,k) \neq \text{bot} \longrightarrow j = k$

**shows** *matrix-stone-relation-algebra.univalent*  $f$

**proof** –

**show**  $f^t \odot f \preceq \text{mone}$

**proof** (*unfold less-eq-matrix-def, rule allI, rule prod-cases*)

**fix**  $j k$

**show**  $(f^t \odot f) (j,k) \leq \text{mone} (j,k)$

**proof** (*cases j = k*)

**assume**  $j = k$

**thus** *?thesis*

**by** (*simp add: one-matrix-def*)

**next**

**assume**  $j \neq k$

**hence**  $(\bigsqcup_l f (i,j) * f (i,k)) = \text{bot}$

**by** (*metis (no-types, lifting) assms semiring.mult-not-zero*

*sup-monoid.sum.neutral*)

**thus** *?thesis*

**by** (*simp add: times-matrix-def conv-matrix-def*)

**qed**

**qed**

**qed**

**lemma** *univalent-linorder-matrix*:  
**fixes**  $f :: ('a::\text{finite}, 'b::\text{linorder-stone-relation-algebra-expansion}) \text{square}$   
**shows**  $\text{matrix-stone-relation-algebra.univalent } f \longleftrightarrow (\forall i j k . f (i,j) \neq \text{bot} \wedge f (i,k) \neq \text{bot} \longrightarrow j = k)$   
**using** *univalent-linorder-matrix-1 univalent-linorder-matrix-2 by auto*

Injective matrices can then be characterised by applying *converse*: in each column, at most one entry may be different from *bot*.

**lemma** *injective-linorder-matrix*:  
**fixes**  $f :: ('a::\text{finite}, 'b::\text{linorder-stone-relation-algebra-expansion}) \text{square}$   
**shows**  $\text{matrix-stone-relation-algebra.injective } f \longleftrightarrow (\forall i j k . f (j,i) \neq \text{bot} \wedge f (k,i) \neq \text{bot} \longrightarrow j = k)$   
**by** (*unfold matrix-stone-relation-algebra.injective-conv-univalent univalent-linorder-matrix*) (*simp add: conv-matrix-def*)

Next come total matrices: each row has a *top* entry.

**lemma** *total-linorder-matrix-1*:  
**fixes**  $f :: ('a::\text{finite}, 'b::\text{linorder-stone-relation-algebra-expansion}) \text{square}$   
**assumes**  $\text{matrix-stone-relation-algebra.total-var } f$   
**shows**  $\exists j . f (i,j) = \text{top}$   
**proof** –  
**have**  $\text{mone } (i,i) \leq (f \odot f^t) (i,i)$   
**using** *assms less-eq-matrix-def by blast*  
**hence**  $\text{top} = (f \odot f^t) (i,i)$   
**by** (*simp add: one-matrix-def top.extremum-unique*)  
**also have**  $\dots = (\bigsqcup_j f (i,j) * (f^t) (j,i))$   
**by** (*simp add: times-matrix-def*)  
**also have**  $\dots = (\bigsqcup_j f (i,j) * f (i,j))$   
**by** (*simp add: conv-matrix-def*)  
**also have**  $\dots = (\bigsqcup_j f (i,j))$   
**by** *simp*  
**finally show** *?thesis*  
**by** (*metis linorder-top-finite-sup*)  
**qed**

**lemma** *total-linorder-matrix-2*:  
**fixes**  $f :: ('a::\text{finite}, 'b::\text{linorder-stone-relation-algebra-expansion}) \text{square}$   
**assumes**  $\forall i . \exists j . f (i,j) = \text{top}$   
**shows**  $\text{matrix-stone-relation-algebra.total-var } f$   
**proof** (*unfold less-eq-matrix-def, rule allI, rule prod-cases*)  
**fix**  $j k$   
**show**  $\text{mone } (j,k) \leq (f \odot f^t) (j,k)$   
**proof** (*cases j = k*)  
**assume**  $j = k$   
**hence**  $(\bigsqcup_i f (j,i) * (f^t) (i,k)) = (\bigsqcup_i f (j,i))$   
**by** (*simp add: conv-matrix-def*)  
**also have**  $\dots = \text{top}$   
**by** (*metis (no-types) assms comp-inf.ub-sum sup.absorb2 sup-top-left*)  
**finally show** *?thesis*

```

    by (simp add: times-matrix-def)
  next
    assume  $j \neq k$ 
    thus ?thesis
      by (simp add: one-matrix-def)
  qed
qed

```

**lemma** *total-linorder-matrix*:

```

fixes  $f :: ('a::finite, 'b::linorder-stone-relation-algebra-expansion) \text{square}$ 
shows matrix-bounded-idempotent-semiring.total  $f \longleftrightarrow (\forall i . \exists j . f (i,j) = \text{top})$ 
using total-linorder-matrix-1 total-linorder-matrix-2
matrix-stone-relation-algebra.total-var by auto

```

Surjective matrices are again characterised by applying *converse*: each column has a *top* entry.

**lemma** *surjective-linorder-matrix*:

```

fixes  $f :: ('a::finite, 'b::linorder-stone-relation-algebra-expansion) \text{square}$ 
shows matrix-bounded-idempotent-semiring.surjective  $f \longleftrightarrow (\forall j . \exists i . f (i,j) = \text{top})$ 
by (unfold matrix-stone-relation-algebra.surjective-conv-total total-linorder-matrix) (simp add: conv-matrix-def)

```

A mapping therefore means that each row has exactly one *top* entry and all others are *bot*.

**lemma** *mapping-linorder-matrix*:

```

fixes  $f :: ('a::finite, 'b::linorder-stone-relation-algebra-expansion) \text{square}$ 
shows matrix-stone-relation-algebra.mapping  $f \longleftrightarrow (\forall i . \exists j . f (i,j) = \text{top} \wedge (\forall k . j \neq k \longrightarrow f (i,k) = \text{bot}))$ 
by (unfold total-linorder-matrix univalent-linorder-matrix) (metis (mono-tags, opaque-lifting) comp-inf.mult-1-right comp-inf.mult-right-zero)

```

**lemma** *mapping-linorder-matrix-unique*:

```

fixes  $f :: ('a::finite, 'b::non-trivial-linorder-stone-relation-algebra-expansion) \text{square}$ 
shows matrix-stone-relation-algebra.mapping  $f \longleftrightarrow (\forall i . \exists! j . f (i,j) = \text{top} \wedge (\forall k . j \neq k \longrightarrow f (i,k) = \text{bot}))$ 
apply (unfold mapping-linorder-matrix)
using bot-not-top by auto

```

Conversely, *bijjective* means that each column has exactly one *top* entry and all others are *bot*.

**lemma** *bijjective-linorder-matrix*:

```

fixes  $f :: ('a::finite, 'b::linorder-stone-relation-algebra-expansion) \text{square}$ 
shows matrix-stone-relation-algebra.bijjective  $f \longleftrightarrow (\forall j . \exists i . f (i,j) = \text{top} \wedge (\forall k . i \neq k \longrightarrow f (k,j) = \text{bot}))$ 
by (unfold matrix-stone-relation-algebra.bijjective-conv-mapping mapping-linorder-matrix) (simp add: conv-matrix-def)

```

**lemma** *bijjective-linorder-matrix-unique*:  
**fixes**  $f :: ('a::finite, 'b::non-trivial-linorder-stone-relation-algebra-expansion)$   
*square*  
**shows**  $matrix-stone-relation-algebra.bijjective\ f \longleftrightarrow (\forall j . \exists ! i . f\ (i,j) = top \wedge (\forall k . i \neq k \longrightarrow f\ (k,j) = bot))$   
**by** (*unfold matrix-stone-relation-algebra.bijjective-conv-mapping mapping-linorder-matrix-unique*) (*simp add: conv-matrix-def*)

We derive algebraic characterisations of matrices in which each row has an entry that is different from *bot*.

**lemma** *pp-total-linorder-matrix-1*:  
**fixes**  $f :: ('a::finite, 'b::non-trivial-linorder-stone-relation-algebra-expansion)$   
*square*  
**assumes**  $\ominus(f \odot mtop) = mbot$   
**shows**  $\exists j . f\ (i,j) \neq bot$   
**proof** –  
**have**  $\neg(\exists j . f\ (i,j) \neq bot) \implies \ominus(f \odot mtop) \neq mbot$   
**proof** –  
**assume**  $\neg(\exists j . f\ (i,j) \neq bot)$   
**hence**  $top = -(f \odot mtop)\ (i,i)$   
**by** (*simp add: comp-top-linorder-matrix linorder-finite-sup-selective*)  
**also have**  $\dots = (\ominus(f \odot mtop))\ (i,i)$   
**by** (*simp add: uminus-matrix-def*)  
**finally show**  $\ominus(f \odot mtop) \neq mbot$   
**by** (*metis bot-matrix-def bot-not-top*)  
**qed**  
**thus** *?thesis*  
**using** *assms* **by** *blast*  
**qed**

**lemma** *pp-total-linorder-matrix-2*:  
**fixes**  $f :: ('a::finite, 'b::linorder-stone-relation-algebra-expansion)$  *square*  
**assumes**  $\forall i . \exists j . f\ (i,j) \neq bot$   
**shows**  $\ominus(f \odot mtop) = mbot$   
**proof** (*rule ext, rule prod-cases*)  
**fix**  $i\ j$   
**have**  $(\ominus(f \odot mtop))\ (i,j) = -(\bigsqcup_k f\ (i,k))$   
**by** (*simp add: comp-top-linorder-matrix uminus-matrix-def*)  
**also have**  $\dots = bot$   
**by** (*metis antisym assms bot.extremum comp-inf.ub-sum uminus-def*)  
**finally show**  $(\ominus(f \odot mtop))\ (i,j) = mbot\ (i,j)$   
**by** (*simp add: bot-matrix-def*)  
**qed**

**lemma** *pp-total-linorder-matrix-3*:  
**fixes**  $f :: ('a::finite, 'b::non-trivial-linorder-stone-relation-algebra-expansion)$   
*square*  
**shows**  $\ominus(f \odot mtop) = mbot \longleftrightarrow (\forall i . \exists j . f\ (i,j) \neq bot)$   
**using** *pp-total-linorder-matrix-1 pp-total-linorder-matrix-2* **by** *auto*

**lemma** *pp-total-linorder-matrix*:  
**fixes**  $f :: ('a::\text{finite}, 'b::\text{non-trivial-linorder-stone-relation-algebra-expansion})$   
*square*  
**shows**  $\text{matrix-bounded-idempotent-semiring.total } (\ominus \ominus f) \longleftrightarrow (\forall i . \exists j . f (i,j) \neq \text{bot})$   
**using** *matrix-stone-relation-algebra.pp-total pp-total-linorder-matrix-1 pp-total-linorder-matrix-2* **by** *auto*

**lemma** *pp-mapping-linorder-matrix*:  
**fixes**  $f :: ('a::\text{finite}, 'b::\text{non-trivial-linorder-stone-relation-algebra-expansion})$   
*square*  
**shows**  $\text{matrix-stone-relation-algebra.pp-mapping } f \longleftrightarrow (\forall i . \exists j . f (i,j) \neq \text{bot} \wedge (\forall k . j \neq k \longrightarrow f (i,k) = \text{bot}))$   
**by** (*metis (mono-tags, opaque-lifting) pp-total-linorder-matrix univalent-linorder-matrix-1 univalent-linorder-matrix-2*)

**lemma** *pp-mapping-linorder-matrix-unique*:  
**fixes**  $f :: ('a::\text{finite}, 'b::\text{non-trivial-linorder-stone-relation-algebra-expansion})$   
*square*  
**shows**  $\text{matrix-stone-relation-algebra.pp-mapping } f \longleftrightarrow (\forall i . \exists !j . f (i,j) \neq \text{bot} \wedge (\forall k . j \neq k \longrightarrow f (i,k) = \text{bot}))$   
**apply** (*rule iffI*)  
**using** *pp-mapping-linorder-matrix apply blast*  
**by** (*metis pp-total-linorder-matrix univalent-linorder-matrix*)

Next follow matrices in which each column has an entry that is different from *bot*.

**lemma** *pp-surjective-linorder-matrix-1*:  
**fixes**  $f :: ('a::\text{finite}, 'b::\text{non-trivial-linorder-stone-relation-algebra-expansion})$   
*square*  
**shows**  $\ominus(\text{mtop} \odot f) = \text{mbot} \longleftrightarrow (\forall j . \exists i . f (i,j) \neq \text{bot})$   
**proof** –  
**have**  $\ominus(\text{mtop} \odot f) = \text{mbot} \longleftrightarrow (\ominus(\text{mtop} \odot f))^t = \text{mbot}^t$   
**by** (*metis matrix-stone-relation-algebra.conv-involutive*)  
**also have**  $\dots \longleftrightarrow \ominus(f^t \odot \text{mtop}) = \text{mbot}$   
**by** (*simp add: matrix-stone-relation-algebra.conv-complement matrix-stone-relation-algebra.conv-dist-comp*)  
**also have**  $\dots \longleftrightarrow (\forall i . \exists j . (f^t) (i,j) \neq \text{bot})$   
**using** *pp-total-linorder-matrix-3* **by** *auto*  
**also have**  $\dots \longleftrightarrow (\forall j . \exists i . f (i,j) \neq \text{bot})$   
**by** (*simp add: conv-matrix-def*)  
**finally show** *?thesis*

•  
**qed**

**lemma** *pp-surjective-linorder-matrix*:  
**fixes**  $f :: ('a::\text{finite}, 'b::\text{non-trivial-linorder-stone-relation-algebra-expansion})$   
*square*



**shows** *matrix-bounded-idempotent-semiring.surjective*  $(\ominus \ominus f) \longleftrightarrow (\forall j . \exists i . f (i,j) \neq \text{bot})$   
**using** *matrix-stone-relation-algebra.pp-surjective pp-surjective-linorder-matrix-1*  
**by** *auto*

**lemma** *pp-bijective-linorder-matrix*:

**fixes**  $f :: ('a::\text{finite}, 'b::\text{non-trivial-linorder-stone-relation-algebra-expansion})$   
*square*  
**shows** *matrix-stone-relation-algebra.pp-bijective*  $f \longleftrightarrow (\forall j . \exists i . f (i,j) \neq \text{bot} \wedge (\forall k . i \neq k \longrightarrow f (k,j) = \text{bot}))$   
**by** (*unfold matrix-stone-relation-algebra.pp-bijective-conv-mapping pp-mapping-linorder-matrix*) (*simp add: conv-matrix-def*)

**lemma** *pp-bijective-linorder-matrix-unique*:

**fixes**  $f :: ('a::\text{finite}, 'b::\text{non-trivial-linorder-stone-relation-algebra-expansion})$   
*square*  
**shows** *matrix-stone-relation-algebra.pp-bijective*  $f \longleftrightarrow (\forall j . \exists ! i . f (i,j) \neq \text{bot} \wedge (\forall k . i \neq k \longrightarrow f (k,j) = \text{bot}))$   
**by** (*unfold matrix-stone-relation-algebra.pp-bijective-conv-mapping pp-mapping-linorder-matrix-unique*) (*simp add: conv-matrix-def*)

The regular matrices are those which contain only *bot* or *top* entries.

**lemma** *regular-linorder-matrix*:

**fixes**  $f :: ('a::\text{finite}, 'b::\text{linorder-stone-relation-algebra-expansion})$  *square*  
**shows** *matrix-p-algebra.regular*  $f \longleftrightarrow (\forall e . f e = \text{bot} \vee f e = \text{top})$

**proof** –

**have** *matrix-p-algebra.regular*  $f \longleftrightarrow (\ominus \ominus f = f)$   
**by** *auto*  
**also have**  $\dots \longleftrightarrow (\forall e . \text{--} f e = f e)$   
**by** (*metis uminus-matrix-def ext*)  
**also have**  $\dots \longleftrightarrow (\forall e . f e = \text{bot} \vee f e = \text{top})$   
**by** *force*  
**finally show** *?thesis*

**qed**

Vectors are precisely the row-constant matrices.

**lemma** *vector-linorder-matrix-0*:

**fixes**  $f :: ('a::\text{finite}, 'b::\text{linorder-stone-relation-algebra-expansion})$  *square*  
**assumes** *matrix-bounded-idempotent-semiring.vector*  $f$   
**shows**  $f (i,j) = (\bigsqcup_k f (i,k))$   
**by** (*metis assms comp-top-linorder-matrix*)

**lemma** *vector-linorder-matrix-1*:

**fixes**  $f :: ('a::\text{finite}, 'b::\text{linorder-stone-relation-algebra-expansion})$  *square*  
**assumes** *matrix-bounded-idempotent-semiring.vector*  $f$   
**shows**  $f (i,j) = f (i,k)$   
**by** (*metis assms vector-linorder-matrix-0*)

**lemma** *vector-linorder-matrix-2*:  
**fixes**  $f :: ('a::finite, 'b::linorder-stone-relation-algebra-expansion)$  *square*  
**assumes**  $\forall i j k . f (i,j) = f (i,k)$   
**shows** *matrix-bounded-idempotent-semiring.vector*  $f$   
**proof** (*rule ext, rule prod-cases*)  
**fix**  $i j$   
**have**  $(f \odot mtop) (i,j) = (\bigsqcup_k f (i,k))$   
**by** (*simp add: comp-top-linorder-matrix*)  
**also have**  $\dots = f (i,j)$   
**by** (*metis assms linorder-finite-sup-selective*)  
**finally show**  $(f \odot mtop) (i,j) = f (i,j)$   
**qed**

**lemma** *vector-linorder-matrix*:  
**fixes**  $f :: ('a::finite, 'b::linorder-stone-relation-algebra-expansion)$  *square*  
**shows** *matrix-bounded-idempotent-semiring.vector*  $f \longleftrightarrow (\forall i j k . f (i,j) = f (i,k))$   
**using** *vector-linorder-matrix-1 vector-linorder-matrix-2* **by** *auto*

Hence covectors are precisely the column-constant matrices.

**lemma** *covector-linorder-matrix-0*:  
**fixes**  $f :: ('a::finite, 'b::linorder-stone-relation-algebra-expansion)$  *square*  
**assumes** *matrix-bounded-idempotent-semiring.covector*  $f$   
**shows**  $f (i,j) = (\bigsqcup_k f (k,j))$   
**by** (*metis assms top-comp-linorder-matrix*)

**lemma** *covector-linorder-matrix*:  
**fixes**  $f :: ('a::finite, 'b::linorder-stone-relation-algebra-expansion)$  *square*  
**shows** *matrix-bounded-idempotent-semiring.covector*  $f \longleftrightarrow (\forall i j k . f (i,j) = f (k,j))$   
**by** (*unfold matrix-stone-relation-algebra.covector-conv-vector vector-linorder-matrix*) (*metis (no-types, lifting) case-prod-conv conv-matrix-def conv-def*)

A point is a matrix that has exactly one row, which is constant *top*, and all other rows are constant *bot*.

**lemma** *point-linorder-matrix*:  
**fixes**  $f :: ('a::finite, 'b::linorder-stone-relation-algebra-expansion)$  *square*  
**shows** *matrix-stone-relation-algebra.point*  $f \longleftrightarrow (\exists i . \forall j . f (i,j) = top \wedge (\forall k . i \neq k \longrightarrow f (k,j) = bot))$   
**apply** (*unfold vector-linorder-matrix bijective-linorder-matrix*)  
**apply** (*rule iffI*)  
**apply** *metis*  
**by** *metis*

**lemma** *point-linorder-matrix-unique*:  
**fixes**  $f :: ('a::finite, 'b::non-trivial-linorder-stone-relation-algebra-expansion)$  *square*

**shows** *matrix-stone-relation-algebra.point*  $f \longleftrightarrow (\exists ! i . \forall j . f (i, j) = \text{top} \wedge (\forall k . i \neq k \longrightarrow f (k, j) = \text{bot}))$   
**apply** (*unfold vector-linorder-matrix bijective-linorder-matrix*)  
**apply** (*rule iffI*)  
**apply** (*metis bot-not-top*)  
**by** *metis*

**lemma** *pp-point-linorder-matrix*:

**fixes**  $f :: ('a::\text{finite}, 'b::\text{non-trivial-linorder-stone-relation-algebra-expansion})$   
*square*  
**shows** *matrix-stone-relation-algebra.pp-point*  $f \longleftrightarrow (\exists i . \forall j . f (i, j) \neq \text{bot} \wedge (\forall k . f (i, j) = f (i, k)) \wedge (\forall k . i \neq k \longrightarrow f (k, j) = \text{bot}))$   
**apply** (*unfold vector-linorder-matrix pp-bijective-linorder-matrix*)  
**apply** (*rule iffI*)  
**apply** *metis*  
**by** *metis*

**lemma** *pp-point-linorder-matrix-unique*:

**fixes**  $f :: ('a::\text{finite}, 'b::\text{non-trivial-linorder-stone-relation-algebra-expansion})$   
*square*  
**shows** *matrix-stone-relation-algebra.pp-point*  $f \longleftrightarrow (\exists ! i . \forall j . f (i, j) \neq \text{bot} \wedge (\forall k . f (i, j) = f (i, k)) \wedge (\forall k . i \neq k \longrightarrow f (k, j) = \text{bot}))$   
**apply** (*unfold vector-linorder-matrix pp-bijective-linorder-matrix*)  
**apply** (*rule iffI*)  
**apply** *metis*  
**by** *metis*

An arc is a matrix that has exactly one *top* entry and all other entries are *bot*.

**lemma** *arc-linorder-matrix-1*:

**fixes**  $f :: ('a::\text{finite}, 'b::\text{non-trivial-linorder-stone-relation-algebra-expansion})$   
*square*  
**assumes** *matrix-stone-relation-algebra.arc*  $f$   
**shows**  $\exists e . f e = \text{top} \wedge (\forall d . e \neq d \longrightarrow f d = \text{bot})$   
**proof** –  
**have** *matrix-stone-relation-algebra.point*  $(f \odot \text{mtop})$   
**by** (*simp add: assms matrix-bounded-idempotent-semiring.vector-mult-closed*)  
**from this obtain**  $i$  **where**  $1: \forall j . (f \odot \text{mtop}) (i, j) = \text{top} \wedge (\forall k . i \neq k \longrightarrow (f \odot \text{mtop}) (k, j) = \text{bot})$   
**using** *point-linorder-matrix* **by** *blast*  
**have** *matrix-stone-relation-algebra.point*  $(f^t \odot \text{mtop})$   
**by** (*simp add: assms matrix-bounded-idempotent-semiring.vector-mult-closed*)  
**from this obtain**  $j$  **where**  $\forall i . (f^t \odot \text{mtop}) (j, i) = \text{top} \wedge (\forall k . j \neq k \longrightarrow (f^t \odot \text{mtop}) (k, i) = \text{bot})$   
**using** *point-linorder-matrix* **by** *blast*  
**hence**  $2: \forall i . (\text{mtop} \odot f) (i, j) = \text{top} \wedge (\forall k . j \neq k \longrightarrow (\text{mtop} \odot f) (i, k) = \text{bot})$   
**by** (*metis (no-types) old.prod.case conv-matrix-def conv-def*)  
*matrix-stone-relation-algebra.conv-dist-comp*  
*matrix-stone-relation-algebra.conv-top*

```

have 3:  $\forall i k . j \neq k \longrightarrow f (i,k) = bot$ 
proof (intro allI, rule impI)
  fix i k
  assume j  $\neq$  k
  hence  $(\bigsqcup_l f (l,k)) = bot$ 
    using 2 by (simp add: top-comp-linorder-matrix)
  thus  $f (i,k) = bot$ 
    by (metis bot.extremum-uniqueI comp-inf.ub-sum)
qed
have  $(\bigsqcup_k f (i,k)) = top$ 
  using 1 by (simp add: comp-top-linorder-matrix)
hence 4:  $f (i,j) = top$ 
  using 3 by (metis bot-not-top linorder-finite-sup-selective)
have  $\forall k l . k \neq i \vee l \neq j \longrightarrow f (k,l) = bot$ 
proof (intro allI, unfold imp-disjL, rule conjI)
  fix k l
  show  $k \neq i \longrightarrow f (k,l) = bot$ 
  proof
    assume  $k \neq i$ 
    hence  $(\bigsqcup_m f (k,m)) = bot$ 
      using 1 by (simp add: comp-top-linorder-matrix)
    thus  $f (k,l) = bot$ 
      by (metis bot.extremum-uniqueI comp-inf.ub-sum)
  qed
  show  $l \neq j \longrightarrow f (k,l) = bot$ 
    using 3 by simp
qed
thus ?thesis using 4
  by (metis old.prod.exhaust)
qed

lemma pp-arc-linorder-matrix-2:
  fixes f :: ('a::finite, 'b::linorder-stone-relation-algebra-expansion) square
  assumes  $\exists e . f e \neq bot \wedge (\forall d . e \neq d \longrightarrow f d = bot)$ 
  shows matrix-stone-relation-algebra.pp-arc f
proof (unfold matrix-stone-relation-algebra.pp-arc-expanded, intro conjI)
  show  $f \odot mtop \odot f^t \preceq mone$ 
  proof (unfold less-eq-matrix-def, rule allI, rule prod-cases)
    fix i j
    show  $(f \odot mtop \odot f^t) (i,j) \leq mone (i,j)$ 
    proof (cases i = j)
      assume i = j
      thus ?thesis
        by (simp add: one-matrix-def)
    next
      assume i  $\neq$  j
      hence 1:  $\forall k l . f (i,k) * f (j,l) = bot$ 
        by (metis assms Pair-inject semiring.mult-not-zero)
      have  $(f \odot mtop \odot f^t) (i,j) = (\bigsqcup_l (f \odot mtop) (i,l) * (f^t) (l,j))$ 

```

```

    by (simp add: times-matrix-def)
  also have ... = ( $\bigsqcup_l (f \odot mtop) (i,l) * f (j,l)$ )
    by (simp add: conv-matrix-def)
  also have ... = ( $\bigsqcup_l (\bigsqcup_k f (i,k)) * f (j,l)$ )
    by (simp add: comp-top-linorder-matrix)
  also have ... = ( $\bigsqcup_l \bigsqcup_k f (i,k) * f (j,l)$ )
    by (metis comp-right-dist-sum)
  also have ... = bot
    using 1 linorder-finite-sup-selective by simp
  finally show ?thesis
    by simp
qed
qed
next
show  $f^t \odot mtop \odot f \leq mone$ 
proof (unfold less-eq-matrix-def, rule allI, rule prod-cases)
  fix i j
  show  $(f^t \odot mtop \odot f) (i,j) \leq mone (i,j)$ 
  proof (cases i = j)
    assume i = j
    thus ?thesis
      by (simp add: one-matrix-def)
  next
    assume i  $\neq$  j
    hence 2:  $\forall k l . f (k,i) * f (l,j) = bot$ 
      by (metis assms Pair-inject semiring.mult-not-zero)
    have  $(f^t \odot mtop \odot f) (i,j) = (\bigsqcup_l (f^t \odot mtop) (i,l) * f (l,j))$ 
      by (simp add: times-matrix-def)
    also have ... = ( $\bigsqcup_l (\bigsqcup_k (f^t) (i,k)) * f (l,j)$ )
      by (simp add: comp-top-linorder-matrix)
    also have ... = ( $\bigsqcup_l (\bigsqcup_k f (k,i)) * f (l,j)$ )
      by (simp add: conv-matrix-def)
    also have ... = ( $\bigsqcup_l \bigsqcup_k f (k,i) * f (l,j)$ )
      by (metis comp-right-dist-sum)
    also have ... = bot
      using 2 linorder-finite-sup-selective by simp
    finally show ?thesis
      by simp
  qed
qed
next
show  $mtop \odot \ominus \ominus f \odot mtop = mtop$ 
proof (rule ext, rule prod-cases)
  fix i j
  from assms obtain k l where  $f (k,l) \neq bot$ 
    using prod.collapse by auto
  hence  $top = --f (k,l)$ 
    by simp
  also have ...  $\leq (\bigsqcup_k --f (k,l))$ 

```

```

    using comp-inf.ub-sum by metis
  also have ... ≤ (⊔l ⊔k --f (k,l))
    using comp-inf.ub-sum by simp
  finally have 3: top ≤ (⊔l ⊔k --f (k,l))
    by simp
  have (mtop ⊙ ⊖⊖f ⊙ mtop) (i,j) = (⊔l (⊔k top * --f (k,l)) * top)
    by (simp add: times-matrix-def top-matrix-def uminus-matrix-def)
  also have ... = (⊔l ⊔k --f (k,l))
    by (metis (no-types, lifting) sup-monoid.sum.cong comp-inf.mult-1-left
times-inf comp-inf.mult-1-right)
  also have ... = top
    using 3 top.extremum-unique by blast
  finally show (mtop ⊙ ⊖⊖f ⊙ mtop) (i,j) = mtop (i,j)
    by (simp add: top-matrix-def)
qed
qed

```

**lemma** *arc-linorder-matrix-2*:

**fixes**  $f :: ('a::finite, 'b::non-trivial-linorder-stone-relation-algebra-expansion)$   
*square*

**assumes**  $\exists e . f e = top \wedge (\forall d . e \neq d \longrightarrow f d = bot)$

**shows** *matrix-stone-relation-algebra.arc f*

**proof** (*unfold matrix-stone-relation-algebra.arc-expanded, intro conjI*)

**show**  $f \odot mtop \odot f^t \preceq mone$

**by** (*metis (no-types, lifting) assms bot-not-top*

*matrix-stone-relation-algebra.pp-arc-expanded pp-arc-linorder-matrix-2*)

**next**

**show**  $f^t \odot mtop \odot f \preceq mone$

**by** (*metis (no-types, lifting) assms bot-not-top*

*matrix-stone-relation-algebra.pp-arc-expanded pp-arc-linorder-matrix-2*)

**next**

**show**  $mtop \odot f \odot mtop = mtop$

**proof** (*rule ext, rule prod-cases*)

**fix**  $i j$

**from** *assms* **obtain**  $k l$  **where**  $f (k,l) = top$

**using** *prod.collapse* **by** *auto*

**hence**  $(\bigcup_k f (k,l)) = top$

**by** (*metis (mono-tags) comp-inf.ub-sum top-unique*)

**hence** 3:  $top \leq (\bigcup_l \bigcup_k f (k,l))$

**by** (*metis (no-types) comp-inf.ub-sum*)

**have**  $(mtop \odot f \odot mtop) (i,j) = (\bigcup_l (\bigcup_k top * f (k,l)) * top)$

**by** (*simp add: times-matrix-def top-matrix-def*)

**also have**  $... = (\bigcup_l \bigcup_k f (k,l))$

**by** (*metis (no-types, lifting) sup-monoid.sum.cong comp-inf.mult-1-left*  
*times-inf comp-inf.mult-1-right*)

**also have**  $... = top$

**using** 3 *top.extremum-unique* **by** *blast*

**finally show**  $(mtop \odot f \odot mtop) (i,j) = mtop (i,j)$

**by** (*simp add: top-matrix-def*)

qed  
qed

**lemma** *arc-linorder-matrix*:

**fixes**  $f :: ('a::finite, 'b::non-trivial-linorder-stone-relation-algebra-expansion)$   
*square*  
**shows**  $matrix-stone-relation-algebra.arc\ f \longleftrightarrow (\exists e . f\ e = top \wedge (\forall d . e \neq d \longrightarrow f\ d = bot))$   
**using** *arc-linorder-matrix-1 arc-linorder-matrix-2 by blast*

**lemma** *arc-linorder-matrix-unique*:

**fixes**  $f :: ('a::finite, 'b::non-trivial-linorder-stone-relation-algebra-expansion)$   
*square*  
**shows**  $matrix-stone-relation-algebra.arc\ f \longleftrightarrow (\exists !e . f\ e = top \wedge (\forall d . e \neq d \longrightarrow f\ d = bot))$   
**apply** (*rule iffI*)  
**apply** (*metis (no-types, opaque-lifting) arc-linorder-matrix bot-not-top*)  
**using** *arc-linorder-matrix by blast*

**lemma** *pp-arc-linorder-matrix-1*:

**fixes**  $f :: ('a::finite, 'b::non-trivial-linorder-stone-relation-algebra-expansion)$   
*square*

**assumes**  $matrix-stone-relation-algebra.pp-arc\ f$   
**shows**  $\exists e . f\ e \neq bot \wedge (\forall d . e \neq d \longrightarrow f\ d = bot)$

**proof** –

**have**  $matrix-stone-relation-algebra.pp-point\ (f \odot mtop)$   
**by** (*simp add: assms matrix-bounded-idempotent-semiring.vector-mult-closed*)  
**from this obtain**  $i$  **where**  $1: \forall j . (f \odot mtop)\ (i, j) \neq bot \wedge (\forall k . (f \odot mtop)\ (i, j) = (f \odot mtop)\ (i, k)) \wedge (\forall k . i \neq k \longrightarrow (f \odot mtop)\ (k, j) = bot)$   
**by** (*metis pp-point-linorder-matrix*)  
**have**  $matrix-stone-relation-algebra.pp-point\ (f^t \odot mtop)$   
**by** (*simp add: assms matrix-bounded-idempotent-semiring.vector-mult-closed*)  
**from this obtain**  $j$  **where**  $\forall i . (f^t \odot mtop)\ (j, i) \neq bot \wedge (\forall k . (f^t \odot mtop)\ (j, i) = (f^t \odot mtop)\ (j, k)) \wedge (\forall k . j \neq k \longrightarrow (f^t \odot mtop)\ (k, i) = bot)$   
**by** (*metis pp-point-linorder-matrix*)  
**hence**  $2: \forall i . (mtop \odot f)\ (i, j) \neq bot \wedge (\forall k . (mtop \odot f)\ (i, j) = (mtop \odot f)\ (k, j)) \wedge (\forall k . j \neq k \longrightarrow (mtop \odot f)\ (i, k) = bot)$   
**by** (*metis (no-types) old.prod.case conv-matrix-def conv-def matrix-stone-relation-algebra.conv-dist-comp matrix-stone-relation-algebra.conv-top*)  
**have**  $3: \forall i\ k . j \neq k \longrightarrow f\ (i, k) = bot$   
**proof** (*intro allI, rule impI*)  
**fix**  $i\ k$   
**assume**  $j \neq k$   
**hence**  $(\bigsqcup_l f\ (l, k)) = bot$   
**using**  $2$  **by** (*simp add: top-comp-linorder-matrix*)  
**thus**  $f\ (i, k) = bot$   
**by** (*metis bot.extremum-uniqueI comp-inf.ub-sum*)  
qed

```

have ( $\bigsqcup_k f (i,k) \neq \text{bot}$ )
  using 1 by (simp add: comp-top-linorder-matrix)
hence 4:  $f (i,j) \neq \text{bot}$ 
  using 3 by (metis linorder-finite-sup-selective)
have  $\forall k l . k \neq i \vee l \neq j \longrightarrow f (k,l) = \text{bot}$ 
proof (intro allI, unfold imp-disjL, rule conjI)
  fix k l
  show  $k \neq i \longrightarrow f (k,l) = \text{bot}$ 
  proof
    assume  $k \neq i$ 
    hence ( $\bigsqcup_m f (k,m) = \text{bot}$ )
      using 1 by (simp add: comp-top-linorder-matrix)
    thus  $f (k,l) = \text{bot}$ 
      by (metis bot.extremum-uniqueI comp-inf.ub-sum)
  qed
  show  $l \neq j \longrightarrow f (k,l) = \text{bot}$ 
    using 3 by simp
  qed
thus ?thesis using 4
  by (metis old.prod.exhaust)
qed

lemma pp-arc-linorder-matrix:
  fixes f :: ('a::finite,'b::non-trivial-linorder-stone-relation-algebra-expansion)
  square
  shows matrix-stone-relation-algebra.pp-arc f  $\longleftrightarrow$  ( $\exists e . f e \neq \text{bot} \wedge (\forall d . e \neq d \longrightarrow f d = \text{bot})$ )
  using pp-arc-linorder-matrix-1 pp-arc-linorder-matrix-2 by blast

lemma pp-arc-linorder-matrix-unique:
  fixes f :: ('a::finite,'b::non-trivial-linorder-stone-relation-algebra-expansion)
  square
  shows matrix-stone-relation-algebra.pp-arc f  $\longleftrightarrow$  ( $\exists ! e . f e \neq \text{bot} \wedge (\forall d . e \neq d \longrightarrow f d = \text{bot})$ )
  apply (rule iffI)
  apply (metis (no-types, opaque-lifting) pp-arc-linorder-matrix)
  using pp-arc-linorder-matrix by blast

```

Reflexive matrices are those with a constant *top* diagonal.

```

lemma reflexive-linorder-matrix-1:
  fixes f :: ('a::finite,'b::linorder-stone-relation-algebra-expansion) square
  assumes matrix-idempotent-semiring.reflexive f
  shows  $f (i,i) = \text{top}$ 
proof -
  have ( $\text{top}::'b) = \text{mone} (i,i)$ 
    by (simp add: one-matrix-def)
  also have  $\dots \leq f (i,i)$ 
    using assms less-eq-matrix-def by blast
  finally show ?thesis

```



by (*simp add: top.extremum-unique*)  
 qed

**lemma** *reflexive-linorder-matrix-2*:

fixes  $f :: ('a::finite, 'b::linorder-stone-relation-algebra-expansion) \text{ square}$   
 assumes  $\forall i . f (i,i) = \text{top}$   
 shows *matrix-idempotent-semiring.reflexive*  $f$   
**proof** (*unfold less-eq-matrix-def, rule allI, rule prod-cases*)  
 fix  $i j$   
 show  $\text{mone } (i,j) \leq f (i,j)$   
**proof** (*cases i = j*)  
 assume  $i = j$   
 thus ?thesis  
 by (*simp add: assms*)  
 next  
 assume  $i \neq j$   
 hence  $(\text{bot}::'b) = \text{mone } (i,j)$   
 by (*simp add: one-matrix-def*)  
 thus ?thesis  
 by *simp*  
 qed  
 qed

**lemma** *reflexive-linorder-matrix*:

fixes  $f :: ('a::finite, 'b::linorder-stone-relation-algebra-expansion) \text{ square}$   
 shows *matrix-idempotent-semiring.reflexive*  $f \longleftrightarrow (\forall i . f (i,i) = \text{top})$   
 using *reflexive-linorder-matrix-1 reflexive-linorder-matrix-2* **by** *auto*

Coreflexive matrices are those in which all non-diagonal entries are *bot*.

**lemma** *coreflexive-linorder-matrix-1*:

fixes  $f :: ('a::finite, 'b::linorder-stone-relation-algebra-expansion) \text{ square}$   
 assumes *matrix-idempotent-semiring.coreflexive*  $f$   
 and  $i \neq j$   
 shows  $f (i,j) = \text{bot}$   
**proof** –  
 have  $f (i,j) \leq \text{mone } (i,j)$   
 using *assms less-eq-matrix-def* **by** *blast*  
 also have  $\dots = \text{bot}$   
 by (*simp add: assms one-matrix-def*)  
 finally **show** ?thesis  
 by (*simp add: bot.extremum-unique*)  
 qed

**lemma** *coreflexive-linorder-matrix-2*:

fixes  $f :: ('a::finite, 'b::linorder-stone-relation-algebra-expansion) \text{ square}$   
 assumes  $\forall i j . i \neq j \longrightarrow f (i,j) = \text{bot}$   
 shows *matrix-idempotent-semiring.coreflexive*  $f$   
**proof** (*unfold less-eq-matrix-def, rule allI, rule prod-cases*)  
 fix  $i j$

```

show  $f (i,j) \leq mone (i,j)$ 
proof (cases  $i = j$ )
  assume  $i = j$ 
  hence  $(top::'b) = mone (i,j)$ 
  by (simp add: one-matrix-def)
  thus ?thesis
  by simp
next
  assume  $i \neq j$ 
  thus ?thesis
  by (simp add: assms)
qed

```

**lemma** *coreflexive-linorder-matrix:*

```

fixes  $f :: ('a::finite, 'b::linorder-stone-relation-algebra-expansion) \text{ square}$ 
shows matrix-idempotent-semiring.coreflexive  $f \longleftrightarrow (\forall i j . i \neq j \longrightarrow f (i,j) = bot)$ 
using coreflexive-linorder-matrix-1 coreflexive-linorder-matrix-2 by auto

```

Irreflexive matrices are those with a constant *bot* diagonal.

**lemma** *irreflexive-linorder-matrix-1:*

```

fixes  $f :: ('a::finite, 'b::linorder-stone-relation-algebra-expansion) \text{ square}$ 
assumes matrix-stone-relation-algebra.irreflexive  $f$ 
shows  $f (i,i) = bot$ 
proof -
  have  $(top::'b) = mone (i,i)$ 
  by (simp add: one-matrix-def)
  hence  $(bot::'b) = (\ominus mone) (i,i)$ 
  by (simp add: uminus-matrix-def)
  hence  $f (i,i) \leq bot$ 
  by (metis assms less-eq-matrix-def)
  thus ?thesis
  by (simp add: bot.extremum-unique)
qed

```

**lemma** *irreflexive-linorder-matrix-2:*

```

fixes  $f :: ('a::finite, 'b::linorder-stone-relation-algebra-expansion) \text{ square}$ 
assumes  $\forall i . f (i,i) = bot$ 
shows matrix-stone-relation-algebra.irreflexive  $f$ 
proof (unfold less-eq-matrix-def, rule allI, rule prod-cases)
  fix  $i j$ 
  show  $f (i,j) \leq (\ominus mone) (i,j)$ 
  proof (cases  $i = j$ )
    assume  $i = j$ 
    thus ?thesis
    by (simp add: assms)
  next
    assume  $i \neq j$ 

```

**hence**  $(bot::'b) = mone (i,j)$   
**by**  $(simp\ add:\ one\ matrix\ def)$   
**hence**  $(top::'b) = (\ominus mone) (i,j)$   
**by**  $(simp\ add:\ uminus\ matrix\ def)$   
**thus**  $?thesis$   
**by**  $simp$   
**qed**  
**qed**

**lemma** *irreflexive-linorder-matrix*:  
**fixes**  $f :: ('a::finite, 'b::linorder\ stone\ relation\ algebra\ expansion)\ square$   
**shows**  $matrix\ stone\ relation\ algebra.\ irreflexive\ f \longleftrightarrow (\forall i . f (i,i) = bot)$   
**using** *irreflexive-linorder-matrix-1 irreflexive-linorder-matrix-2* **by** *auto*

As usual, symmetric matrices are those which do not change under transposition.

**lemma** *symmetric-linorder-matrix*:  
**fixes**  $f :: ('a::finite, 'b::linorder\ stone\ relation\ algebra\ expansion)\ square$   
**shows**  $matrix\ stone\ relation\ algebra.\ symmetric\ f \longleftrightarrow (\forall i\ j . f (i,j) = f (j,i))$   
**by**  $(metis\ (mono\ tags,\ lifting)\ case\ prod\ conv\ cond\ case\ prod\ eta\ conv\ matrix\ def\ conv\ def)$

Antisymmetric matrices are characterised as follows: each entry not on the diagonal or its mirror entry across the diagonal must be *bot*.

**lemma** *antisymmetric-linorder-matrix*:  
**fixes**  $f :: ('a::finite, 'b::linorder\ stone\ relation\ algebra\ expansion)\ square$   
**shows**  $matrix\ stone\ relation\ algebra.\ antisymmetric\ f \longleftrightarrow (\forall i\ j . i \neq j \longrightarrow f (i,j) = bot \vee f (j,i) = bot)$   
**proof** –  
**have**  $matrix\ stone\ relation\ algebra.\ antisymmetric\ f \longleftrightarrow (\forall i\ j . i \neq j \longrightarrow f (i,j) \sqcap f (j,i) \leq bot)$   
**by**  $(simp\ add:\ conv\ matrix\ def\ inf\ matrix\ def\ less\ eq\ matrix\ def\ one\ matrix\ def)$   
**thus**  $?thesis$   
**by**  $(metis\ (no\ types,\ opaque\ lifting)\ inf.\ absorb\ iff1\ inf.\ cobounded1\ inf.\ bot\ right\ inf.\ dense)$   
**qed**

For asymmetric matrices the diagonal is included: each entry or its mirror entry across the diagonal must be *bot*.

**lemma** *asymmetric-linorder-matrix*:  
**fixes**  $f :: ('a::finite, 'b::linorder\ stone\ relation\ algebra\ expansion)\ square$   
**shows**  $matrix\ stone\ relation\ algebra.\ asymmetric\ f \longleftrightarrow (\forall i\ j . f (i,j) = bot \vee f (j,i) = bot)$   
**proof** –  
**have**  $matrix\ stone\ relation\ algebra.\ asymmetric\ f \longleftrightarrow (\forall i\ j . f (i,j) \sqcap f (j,i) \leq bot)$   
**apply**  $(unfold\ conv\ matrix\ def\ inf\ matrix\ def\ conv\ def\ id\ def\ bot\ matrix\ def)$

**by** (*metis* (*mono-tags*, *lifting*) *bot.extremum* *bot.extremum-unique1*  
*case-prod-conv* *old.prod.exhaust*)  
**thus** *?thesis*  
**by** (*metis* (*no-types*, *opaque-lifting*) *inf.absorb-iff1* *inf.cobounded1* *inf-bot-right*  
*inf-dense*)  
**qed**

In a transitive matrix, the weight of one of the edges on an indirect route must be below the weight of the direct edge.

**lemma** *transitive-linorder-matrix*:

**fixes**  $f :: ('a::\text{finite}, 'b::\text{linorder-stone-relation-algebra-expansion}) \text{square}$   
**shows** *matrix-idempotent-semiring.transitive*  $f \longleftrightarrow (\forall i j k . f(i,k) \leq f(i,j) \vee f(k,j) \leq f(i,j))$

**proof** –

**have** *matrix-idempotent-semiring.transitive*  $f \longleftrightarrow (\forall i j . (\bigsqcup_k f(i,k) * f(k,j)) \leq f(i,j))$

**by** (*simp add: times-matrix-def less-eq-matrix-def*)

**also have**  $\dots \longleftrightarrow (\forall i j k . f(i,k) * f(k,j) \leq f(i,j))$

**by** (*simp add: lub-sum-iff*)

**also have**  $\dots \longleftrightarrow (\forall i j k . f(i,k) \leq f(i,j) \vee f(k,j) \leq f(i,j))$

**using** *inf-less-eq* **by** *fastforce*

**finally show** *?thesis*

**qed**

We finally show the effect of composing with a coreflexive (test) from the left and from the right. This amounts to a restriction of each row or column to the entry on the diagonal of the coreflexive. In this case, restrictions are formed by meets.

**lemma** *coreflexive-comp-linorder-matrix*:

**fixes**  $f g :: ('a::\text{finite}, 'b::\text{linorder-stone-relation-algebra-expansion}) \text{square}$

**assumes** *matrix-idempotent-semiring.coreflexive*  $f$

**shows**  $(f \odot g)(i,j) = f(i,i) \sqcap g(i,j)$

**proof** –

**have**  $1: \forall k . i \neq k \longrightarrow f(i,k) = \text{bot}$

**using** *assms coreflexive-linorder-matrix* **by** *auto*

**have**  $(\bigsqcup_k f(i,k)) = f(i,i) \sqcup (\bigsqcup_{k \in \text{UNIV} - \{i\}} f(i,k))$

**by** (*metis* (*no-types*) *UNIV-def* *brouwer.inf-bot-right* *finite-UNIV* *insert-def* *sup-monoid.sum.insert-remove*)

**hence**  $2: (\bigsqcup_k f(i,k)) = f(i,i)$

**using**  $1$  **by** (*metis* (*no-types*) *linorder-finite-sup-selective* *sup-not-bot*)

**have**  $(f \odot g)(i,j) = (f \odot \text{mtop} \otimes g)(i,j)$

**by** (*metis* *assms matrix-stone-relation-algebra.coreflexive-comp-top-inf*)

**also have**  $\dots = (\bigsqcup_k f(i,k)) \sqcap g(i,j)$

**by** (*metis* *inf-matrix-def* *comp-top-linorder-matrix*)

**finally show** *?thesis*

**using**  $2$  **by** *simp*

**qed**

```

lemma comp-coreflexive-linorder-matrix:
  fixes  $f\ g :: ('a::finite, 'b::linorder-stone-relation-algebra-expansion)$  square
  assumes matrix-idempotent-semiring.coreflexive g
  shows  $(f \odot g)\ (i,j) = f\ (i,j) \sqcap g\ (j,j)$ 
proof –
  have  $(f \odot g)\ (i,j) = ((f \odot g)^t)\ (j,i)$ 
  by (simp add: conv-matrix-def)
  also have  $\dots = (g \odot f^t)\ (j,i)$ 
  by (simp add: assms matrix-stone-relation-algebra.conv-dist-comp
matrix-stone-relation-algebra.coreflexive-symmetric)
  also have  $\dots = g\ (j,j) \sqcap (f^t)\ (j,i)$ 
  by (simp add: assms coreflexive-comp-linorder-matrix)
  also have  $\dots = f\ (i,j) \sqcap g\ (j,j)$ 
  by (metis (no-types, lifting) conv-def old.prod.case conv-matrix-def
inf-commute)
  finally show ?thesis
  .
qed
end

```

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