

Relational Forests

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Abstract

We study second-order formalisations of graph properties expressed as first-order formulas in relation algebras extended with a Kleene star. The formulas quantify over relations while still avoiding quantification over elements of the base set. We formalise the property of undirected graphs being acyclic this way. This involves a study of various kinds of orientation of graphs. We also verify basic algorithms to constructively prove several second-order properties.

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1 Overview

The theories described in this document study second-order specifications of graph properties expressed as first-order formulas in Stone-Kleene relation algebras. Of particular interest are undirected forests and their orientations, developed in Section 2. We also verify the correctness of a number of basic graph algorithms, which we use in constructive proofs of graph properties in Section 3.

The theories formally verify results in [5]; results from this paper are annotated with the corresponding theorem numbers. See the paper for further details and related work.

2 Orientations and Undirected Forests

In this theory we study orientations and various second-order specifications of undirected forests. The results are structured by the classes in which they can be proved, which correspond to algebraic structures. Most classes are generalisations of Kleene relation algebras. None of the classes except *kleene-relation-algebra* assumes the double-complement law $--x = x$ available in Boolean algebras. The corresponding paper does not elaborate these fine distinctions, so some results take a different form in this theory. They usually specialise to Kleene relation algebras after simplification using $--x = x$.

theory *Forests*

imports *Stone-Kleene-Relation-Algebras.Kleene-Relation-Algebras*

begin

2.1 Orientability

context *bounded-distrib-allegory-signature*

begin

abbreviation *irreflexive-inf* :: 'a \Rightarrow bool **where** *irreflexive-inf* x \equiv x \sqcap 1 = bot

end

context *bounded-distrib-allegory*

begin

lemma *irreflexive-inf-arc-asymmetric*:

irreflexive-inf x \implies arc x \implies asymmetric x
 <proof>

lemma *asymmetric-inf*:

asymmetric x \longleftrightarrow *irreflexive-inf* (x * x)
 <proof>

lemma *asymmetric-irreflexive-inf*:

asymmetric x \implies *irreflexive-inf* x
 <proof>

lemma *transitive-asymmetric-irreflexive-inf*:

transitive $x \implies$ *asymmetric* $x \iff$ *irreflexive-inf* x
(proof)

abbreviation *orientation* $x y \equiv y \sqcup y^T = x \wedge$ *asymmetric* y

abbreviation *loop-orientation* $x y \equiv y \sqcup y^T = x \wedge$ *antisymmetric* y

abbreviation *super-orientation* $x y \equiv x \leq y \sqcup y^T \wedge$ *asymmetric* y

abbreviation *loop-super-orientation* $x y \equiv x \leq y \sqcup y^T \wedge$ *antisymmetric* y

lemma *orientation-symmetric*:

orientation $x y \implies$ *symmetric* x
(proof)

lemma *orientation-irreflexive-inf*:

orientation $x y \implies$ *irreflexive-inf* x
(proof)

lemma *loop-orientation-symmetric*:

loop-orientation $x y \implies$ *symmetric* x
(proof)

lemma *loop-orientation-diagonal*:

loop-orientation $x y \implies y \sqcap y^T = x \sqcap 1$
(proof)

lemma *super-orientation-irreflexive-inf*:

super-orientation $x y \implies$ *irreflexive-inf* x
(proof)

lemma *loop-super-orientation-diagonal*:

loop-super-orientation $x y \implies x \sqcap 1 \leq y \sqcap y^T$
(proof)

definition *orientable* $x \equiv \exists y .$ *orientation* $x y$

definition *loop-orientable* $x \equiv \exists y .$ *loop-orientation* $x y$

definition *super-orientable* $x \equiv \exists y .$ *super-orientation* $x y$

definition *loop-super-orientable* $x \equiv \exists y .$ *loop-super-orientation* $x y$

lemma *orientable-symmetric*:

orientable $x \implies$ *symmetric* x
(proof)

lemma *orientable-irreflexive-inf*:

orientable $x \implies$ *irreflexive-inf* x
(proof)

lemma *loop-orientable-symmetric*:

loop-orientable $x \implies$ *symmetric* x
(proof)

lemma *super-orientable-irreflexive-inf*:
super-orientable $x \implies$ *irreflexive-inf* x
 ⟨*proof*⟩

lemma *orientable-down-closed*:
 assumes *symmetric* x
 and $x \leq y$
 and *orientable* y
 shows *orientable* x
 ⟨*proof*⟩

lemma *loop-orientable-down-closed*:
 assumes *symmetric* x
 and $x \leq y$
 and *loop-orientable* y
 shows *loop-orientable* x
 ⟨*proof*⟩

lemma *super-orientable-down-closed*:
 assumes $x \leq y$
 and *super-orientable* y
 shows *super-orientable* x
 ⟨*proof*⟩

lemma *loop-super-orientable-down-closed*:
 assumes $x \leq y$
 and *loop-super-orientable* y
 shows *loop-super-orientable* x
 ⟨*proof*⟩

abbreviation *orientable-1* $x \equiv$ *loop-super-orientable* x

abbreviation *orientable-2* $x \equiv \exists y . x \leq y \sqcup y^T \wedge y \sqcap y^T \leq x \sqcap 1$

abbreviation *orientable-3* $x \equiv \exists y . x \leq y \sqcup y^T \wedge y \sqcap y^T = x \sqcap 1$

abbreviation *orientable-4* $x \equiv$ *irreflexive-inf* $x \longrightarrow$ *super-orientable* x

abbreviation *orientable-5* $x \equiv$ *symmetric* $x \longrightarrow$ *loop-orientable* x

abbreviation *orientable-6* $x \equiv$ *symmetric* $x \longrightarrow (\exists y . y \sqcup y^T = x \wedge y \sqcap y^T \leq x \sqcap 1)$

abbreviation *orientable-7* $x \equiv$ *symmetric* $x \longrightarrow (\exists y . y \sqcup y^T = x \wedge y \sqcap y^T = x \sqcap 1)$

abbreviation *orientable-8* $x \equiv$ *symmetric* $x \wedge$ *irreflexive-inf* $x \longrightarrow$ *orientable* x

lemma *super-orientation-diagonal*:

$x \leq y \sqcup y^T \implies y \sqcap y^T \leq x \sqcap 1 \implies y \sqcap y^T = x \sqcap 1$

⟨*proof*⟩

lemma *orientable-2-implies-1*:

orientable-2 $x \implies$ *orientable-1* x

⟨*proof*⟩

lemma orientable-2-3:
 $orientable-2\ x \longleftrightarrow orientable-3\ x$
(proof)

lemma orientable-5-6:
 $orientable-5\ x \longleftrightarrow orientable-6\ x$
(proof)

lemma orientable-6-7:
 $orientable-6\ x \longleftrightarrow orientable-7\ x$
(proof)

lemma orientable-7-implies-8:
 $orientable-7\ x \implies orientable-8\ x$
(proof)

lemma orientable-5-implies-1:
 $orientable-5\ (x \sqcup x^T) \implies orientable-1\ x$
(proof)

ternary predicate S called *split* here

abbreviation $split\ x\ y\ z \equiv y \sqcap y^T = x \wedge y \sqcup y^T = z$

Theorem 3.1

lemma orientation-split:
 $orientation\ x\ y \longleftrightarrow split\ bot\ y\ x$
(proof)

Theorem 3.2

lemma split-1-loop-orientation:
 $split\ 1\ y\ x \implies loop-orientation\ x\ y$
(proof)

Theorem 3.3

lemma loop-orientation-split:
 $loop-orientation\ x\ y \longleftrightarrow split\ (x \sqcap 1)\ y\ x$
(proof)

Theorem 3.4

lemma loop-orientation-split-inf-1:
 $loop-orientation\ x\ y \longleftrightarrow split\ (y \sqcap 1)\ y\ x$
(proof)

lemma loop-orientation-top-split:
 $loop-orientation\ top\ y \longleftrightarrow split\ 1\ y\ top$
(proof)

injective and transitive orientations

definition $injectively-orientable\ x \equiv \exists y . orientation\ x\ y \wedge injective\ y$

lemma *injectively-orientable-orientable:*
injectively-orientable $x \implies$ *orientable* x
<proof>

lemma *orientable-orientable-1:*
orientable $x \implies$ *orientable-1* x
<proof>

lemma *injectively-orientable-down-closed:*
assumes *symmetric* x
and $x \leq y$
and *injectively-orientable* y
shows *injectively-orientable* x
<proof>

definition *transitively-orientable* $x \equiv \exists y . \text{orientation } x y \wedge \text{transitive } y$

lemma *transitively-orientable-orientable:*
transitively-orientable $x \implies$ *orientable* x
<proof>

lemma *irreflexive-transitive-orientation-asymmetric:*
assumes *irreflexive-inf* x
and *transitive* y
and $y \sqcup y^T = x$
shows *asymmetric* y
<proof>

Theorem 12

lemma *transitively-orientable-2:*
transitively-orientable $x \longleftrightarrow$ *irreflexive-inf* $x \wedge (\exists y . y \sqcup y^T = x \wedge \text{transitive } y)$
<proof>

end

context *relation-algebra-signature*
begin

abbreviation *asymmetric-var* :: $'a \Rightarrow \text{bool}$ **where** *asymmetric-var* $x \equiv$
irreflexive $(x * x)$

end

context *pd-allegory*
begin

Theorem 1.4

lemma *asymmetric-var:*

asymmetric $x \longleftrightarrow$ *asymmetric-var* x
(proof)

Theorem 1.3

(Theorem 1.2 is *asymmetric-irreflexive* in *Relation-Algebras*)

lemma *transitive-asymmetric-irreflexive*:
transitive $x \implies$ *asymmetric* $x \longleftrightarrow$ *irreflexive* x
(proof)

lemma *orientable-irreflexive*:
orientable $x \implies$ *irreflexive* x
(proof)

lemma *super-orientable-irreflexive*:
super-orientable $x \implies$ *irreflexive* x
(proof)

lemma *orientation-diversity-split*:
orientation $(-1) y \longleftrightarrow$ *split bot* $y (-1)$
(proof)

abbreviation *linear-orderable-1* $x \equiv$ *linear-order* x

abbreviation *linear-orderable-2* $x \equiv$ *linear-strict-order* x

abbreviation *linear-orderable-3* $x \equiv$ *transitive* $x \wedge$ *asymmetric* $x \wedge$ *strict-linear* x

abbreviation *linear-orderable-3a* $x \equiv$ *transitive* $x \wedge$ *strict-linear* x

abbreviation *orientable-11* $x \equiv$ *split 1* x *top*

abbreviation *orientable-12* $x \equiv$ *split bot* $x (-1)$

lemma *linear-strict-order-split*:
linear-strict-order $x \longleftrightarrow$ *transitive* $x \wedge$ *split bot* $x (-1)$
(proof)

Theorem 1.6

lemma *linear-strict-order-without-irreflexive*:
linear-strict-order $x \longleftrightarrow$ *transitive* $x \wedge$ *strict-linear* x
(proof)

lemma *linear-order-without-reflexive*:
linear-order $x \longleftrightarrow$ *antisymmetric* $x \wedge$ *transitive* $x \wedge$ *linear* x
(proof)

lemma *linear-orderable-1-implies-2*:
linear-orderable-1 $x \implies$ *linear-orderable-2* $(x \sqcap -1)$
(proof)

lemma *linear-orderable-2-3*:
linear-orderable-2 $x \longleftrightarrow$ *linear-orderable-3* x
(proof)

lemma *linear-orderable-3-3a*:
linear-orderable-3 $x \longleftrightarrow$ *linear-orderable-3a* x
 ⟨*proof*⟩

lemma *linear-orderable-3-implies-orientable-12*:
linear-orderable-3 $x \implies$ *orientable-12* x
 ⟨*proof*⟩

lemma *orientable-11-implies-12*:
orientable-11 $x \implies$ *orientable-12* $(x \sqcap -1)$
 ⟨*proof*⟩

end

context *stone-relation-algebra*
begin

Theorem 3.5

lemma *split-symmetric-asymmetric*:
assumes *regular* x
shows *split* $x \ y \ z \longleftrightarrow y \sqcap y^T = x \wedge (y \sqcap -y^T) \sqcup (y \sqcap -y^T)^T = z \sqcap -x \wedge x$
 $\leq z$
 ⟨*proof*⟩

lemma *orientable-1-2*:
orientable-1 $x \longleftrightarrow$ *orientable-2* x
 ⟨*proof*⟩

lemma *orientable-8-implies-5*:
assumes *orientable-8* $(x \sqcap -1)$
shows *orientable-5* x
 ⟨*proof*⟩

lemma *orientable-4-implies-1*:
assumes *orientable-4* $(x \sqcap -1)$
shows *orientable-1* x
 ⟨*proof*⟩

lemma *orientable-1-implies-4*:
assumes *orientable-1* $(x \sqcup 1)$
shows *orientable-4* x
 ⟨*proof*⟩

lemma *orientable-1-implies-5*:
assumes *orientable-1* x
shows *orientable-5* x
 ⟨*proof*⟩

Theorem 2

lemma *all-orientable-characterisations:*

shows $(\forall x . \text{orientable-1 } x) \longleftrightarrow (\forall x . \text{orientable-2 } x)$
and $(\forall x . \text{orientable-1 } x) \longleftrightarrow (\forall x . \text{orientable-3 } x)$
and $(\forall x . \text{orientable-1 } x) \longleftrightarrow (\forall x . \text{orientable-4 } x)$
and $(\forall x . \text{orientable-1 } x) \longleftrightarrow (\forall x . \text{orientable-5 } x)$
and $(\forall x . \text{orientable-1 } x) \longleftrightarrow (\forall x . \text{orientable-6 } x)$
and $(\forall x . \text{orientable-1 } x) \longleftrightarrow (\forall x . \text{orientable-7 } x)$
and $(\forall x . \text{orientable-1 } x) \longleftrightarrow (\forall x . \text{orientable-8 } x)$
<proof>

lemma *orientable-12-implies-11:*

orientable-12 $x \implies \text{orientable-11 } (x \sqcup 1)$
<proof>

lemma *linear-strict-order-order:*

linear-strict-order $x \implies \text{linear-order } (x \sqcup 1)$
<proof>

lemma *linear-orderable-2-implies-1:*

linear-orderable-2 $x \implies \text{linear-orderable-1 } (x \sqcup 1)$
<proof>

[Theorem 4](#)

[Theorem 12](#)

[Theorem 13](#)

lemma *exists-split-characterisations:*

shows $(\exists x . \text{linear-orderable-1 } x) \longleftrightarrow (\exists x . \text{linear-orderable-2 } x)$
and $(\exists x . \text{linear-orderable-1 } x) \longleftrightarrow (\exists x . \text{linear-orderable-3 } x)$
and $(\exists x . \text{linear-orderable-1 } x) \longleftrightarrow (\exists x . \text{linear-orderable-3a } x)$
and $(\exists x . \text{linear-orderable-1 } x) \longleftrightarrow \text{transitively-orientable } (-1)$
and $(\exists x . \text{linear-orderable-1 } x) \implies (\exists x . \text{orientable-11 } x)$
and $(\exists x . \text{orientable-11 } x) \longleftrightarrow (\exists x . \text{orientable-12 } x)$
<proof>

[Theorem 4](#)

[Theorem 12](#)

lemma *exists-all-orientable:*

shows $(\exists x . \text{orientable-11 } x) \longleftrightarrow (\forall x . \text{orientable-1 } x)$
and $\text{transitively-orientable } (-1) \implies (\forall x . \text{orientable-8 } x)$
<proof>

end

2.2 Undirected forests

We start with a few general results in Kleene algebras and a few basic properties of directed acyclic graphs.

context *kleene-algebra*
begin

[Theorem 1.9](#)

lemma *plus-separate-comp-bot*:
 assumes $x * y = \text{bot}$
 shows $(x \sqcup y)^+ = x^+ \sqcup y^+ \sqcup y^+ * x^+$
 $\langle \text{proof} \rangle$
end

context *bounded-distrib-kleene-allegory*
begin

lemma *reflexive-inf-plus-star*:
 assumes *reflexive* x
 shows $x \sqcap y^+ \leq 1 \longleftrightarrow x \sqcap y^* = 1$
 $\langle \text{proof} \rangle$

end

context *pd-kleene-allegory*
begin

lemma *acyclic-star-inf-conv-iff*:
 assumes *irreflexive* w
 shows *acyclic* $w \longleftrightarrow w^* \sqcap w^{T^*} = 1$
 $\langle \text{proof} \rangle$

[Theorem 1.7](#)

lemma *acyclic-irreflexive-star-antisymmetric*:
 acyclic $x \longleftrightarrow \text{irreflexive } x \wedge \text{antisymmetric } (x^*)$
 $\langle \text{proof} \rangle$

[Theorem 1.8](#)

lemma *acyclic-plus-asymmetric*:
 acyclic $x \longleftrightarrow \text{asymmetric } (x^+)$
 $\langle \text{proof} \rangle$

[Theorem 1.3](#)

([Theorem 1.1](#) is *acyclic-asymmetric* in *Kleene-Relation-Algebras*)

lemma *transitive-acyclic-irreflexive*:
 transitive $x \implies \text{acyclic } x \longleftrightarrow \text{irreflexive } x$
 $\langle \text{proof} \rangle$

lemma *transitive-acyclic-asymmetric*:
 transitive $x \implies \text{acyclic } x \longleftrightarrow \text{asymmetric } x$

<proof>

Theorem 1.5

lemma *strict-order-transitive-acyclic:*

strict-order $x \longleftrightarrow$ *transitive* $x \wedge$ *acyclic* x

<proof>

lemma *linear-strict-order-transitive-acyclic:*

linear-strict-order $x \longleftrightarrow$ *transitive* $x \wedge$ *acyclic* $x \wedge$ *strict-linear* x

<proof>

The following are various specifications of an undirected graph being acyclic.

definition *acyclic-1* $x \equiv \forall y . \text{orientation } x y \longrightarrow \text{acyclic } y$

definition *acyclic-1b* $x \equiv \forall y . \text{orientation } x y \longrightarrow y^* \sqcap y^{T*} = 1$

definition *acyclic-2* $x \equiv \forall y . y \leq x \wedge \text{asymmetric } y \longrightarrow \text{acyclic } y$

definition *acyclic-2a* $x \equiv \forall y . y \sqcup y^T \leq x \wedge \text{asymmetric } y \longrightarrow \text{acyclic } y$

definition *acyclic-2b* $x \equiv \forall y . y \sqcup y^T \leq x \wedge \text{asymmetric } y \longrightarrow y^* \sqcap y^{T*} = 1$

definition *acyclic-3a* $x \equiv \forall y . y \leq x \wedge x \leq y^* \longrightarrow y = x$

definition *acyclic-3b* $x \equiv \forall y . y \leq x \wedge y^* = x^* \longrightarrow y = x$

definition *acyclic-3c* $x \equiv \forall y . y \leq x \wedge x \leq y^+ \longrightarrow y = x$

definition *acyclic-3d* $x \equiv \forall y . y \leq x \wedge y^+ = x^+ \longrightarrow y = x$

definition *acyclic-4* $x \equiv \forall y . y \leq x \longrightarrow x \sqcap y^* \leq \neg\neg y$

definition *acyclic-4a* $x \equiv \forall y . y \leq x \longrightarrow x \sqcap y^* \leq y$

definition *acyclic-4b* $x \equiv \forall y . y \leq x \longrightarrow x \sqcap y^* = y$

definition *acyclic-4c* $x \equiv \forall y . y \leq x \longrightarrow y \sqcap (x \sqcap \neg y)^* = \text{bot}$

definition *acyclic-5a* $x \equiv \forall y . y \leq x \longrightarrow y^* \sqcap (x \sqcap \neg y)^* = 1$

definition *acyclic-5b* $x \equiv \forall y . y \leq x \longrightarrow y^* \sqcap (x \sqcap \neg y)^+ \leq 1$

definition *acyclic-5c* $x \equiv \forall y . y \leq x \longrightarrow y^+ \sqcap (x \sqcap \neg y)^* \leq 1$

definition *acyclic-5d* $x \equiv \forall y . y \leq x \longrightarrow y^+ \sqcap (x \sqcap \neg y)^+ \leq 1$

definition *acyclic-5e* $x \equiv \forall y z . y \leq x \wedge z \leq x \wedge y \sqcap z = \text{bot} \longrightarrow y^* \sqcap z^* = 1$

definition *acyclic-5f* $x \equiv \forall y z . y \sqcup z \leq x \wedge y \sqcap z = \text{bot} \longrightarrow y^* \sqcap z^* = 1$

definition *acyclic-5g* $x \equiv \forall y z . y \sqcup z = x \wedge y \sqcap z = \text{bot} \longrightarrow y^* \sqcap z^* = 1$

definition *acyclic-6* $x \equiv \exists y . y \sqcup y^T = x \wedge \text{acyclic } y \wedge \text{injective } y$

Theorem 6

lemma *acyclic-2-2a:*

assumes *symmetric* x

shows *acyclic-2* $x \longleftrightarrow$ *acyclic-2a* x

<proof>

Theorem 6

lemma *acyclic-2a-2b:*

shows *acyclic-2a* $x \longleftrightarrow$ *acyclic-2b* x

<proof>

Theorem 5

lemma *acyclic-1-1b:*

shows *acyclic-1* $x \longleftrightarrow$ *acyclic-1b* x

<proof>

Theorem 10

lemma *acyclic-6-1-injectively-orientable:*

acyclic-6 $x \iff \text{acyclic-1 } x \wedge \text{injectively-orientable } x$
<proof>

lemma *acyclic-6-symmetric:*

acyclic-6 $x \implies \text{symmetric } x$
<proof>

lemma *acyclic-6-irreflexive:*

acyclic-6 $x \implies \text{irreflexive } x$
<proof>

lemma *acyclic-4-irreflexive:*

acyclic-4 $x \implies \text{irreflexive } x$
<proof>

Theorem 6.4

lemma *acyclic-2-implies-1:*

acyclic-2 $x \implies \text{acyclic-1 } x$
<proof>

Theorem 8

lemma *acyclic-4a-4b:*

acyclic-4a $x \iff \text{acyclic-4b } x$
<proof>

Theorem 7

lemma *acyclic-3a-3b:*

acyclic-3a $x \iff \text{acyclic-3b } x$
<proof>

Theorem 7

lemma *acyclic-3a-3c:*

assumes *irreflexive* x
shows *acyclic-3a* $x \iff \text{acyclic-3c } x$
<proof>

Theorem 7

lemma *acyclic-3c-3d:*

shows *acyclic-3c* $x \iff \text{acyclic-3d } x$
<proof>

Theorem 8

lemma *acyclic-4a-implies-3a:*

acyclic-4a $x \implies \text{acyclic-3a } x$
<proof>

lemma *acyclic-4a-implies-4*:
acyclic-4a $x \implies$ *acyclic-4* x
(*proof*)

lemma *acyclic-4b-implies-4c*:
acyclic-4b $x \implies$ *acyclic-4c* x
(*proof*)

[Theorem 8.5](#)

lemma *acyclic-4-implies-2*:
assumes *symmetric* x
shows *acyclic-4* $x \implies$ *acyclic-2* x
(*proof*)

[Theorem 10.3](#)

lemma *acyclic-6-implies-4a*:
acyclic-6 $x \implies$ *acyclic-4a* x
(*proof*)

[Theorem 1.10](#)

lemma *top-injective-inf-complement*:
assumes *injective* x
shows $top * (x \sqcap y) \sqcap top * (x \sqcap -y) = bot$
(*proof*)

lemma *top-injective-inf-complement-2*:
assumes *injective* x
shows $(x^T \sqcap y) * top \sqcap (x^T \sqcap -y) * top = bot$
(*proof*)

[Theorem 10.3](#)

lemma *acyclic-6-implies-5a*:
acyclic-6 $x \implies$ *acyclic-5a* x
(*proof*)

[Theorem 9.7](#)

lemma *acyclic-5b-implies-4*:
assumes *irreflexive* x
and *acyclic-5b* x
shows *acyclic-4* x
(*proof*)

[Theorem 9](#)

lemma *acyclic-5a-5b*:
acyclic-5a $x \iff$ *acyclic-5b* x
(*proof*)

[Theorem 9](#)

lemma *acyclic-5a-5c*:
acyclic-5a $x \longleftrightarrow$ *acyclic-5c* x
 ⟨*proof*⟩

Theorem 9

lemma *acyclic-5b-5d*:
acyclic-5b $x \longleftrightarrow$ *acyclic-5d* x
 ⟨*proof*⟩

lemma *acyclic-5a-5e*:
acyclic-5a $x \longleftrightarrow$ *acyclic-5e* x
 ⟨*proof*⟩

Theorem 9

lemma *acyclic-5e-5f*:
acyclic-5e $x \longleftrightarrow$ *acyclic-5f* x
 ⟨*proof*⟩

lemma *acyclic-5e-down-closed*:
assumes $x \leq y$
and *acyclic-5e* y
shows *acyclic-5e* x
 ⟨*proof*⟩

lemma *acyclic-5a-down-closed*:
assumes $x \leq y$
and *acyclic-5a* y
shows *acyclic-5a* x
 ⟨*proof*⟩

further variants of the existence of a linear order

abbreviation *linear-orderable-4* $x \equiv$ *transitive* $x \wedge$ *acyclic* $x \wedge$ *strict-linear* x

abbreviation *linear-orderable-5* $x \equiv$ *transitive* $x \wedge$ *acyclic* $x \wedge$ *linear* (x^*)

abbreviation *linear-orderable-6* $x \equiv$ *acyclic* $x \wedge$ *linear* (x^*)

abbreviation *linear-orderable-7* $x \equiv$ *split 1* (x^*) *top*

abbreviation *linear-orderable-8* $x \equiv$ *split bot* (x^+) (-1)

lemma *linear-orderable-3-4*:
linear-orderable-3 $x \longleftrightarrow$ *linear-orderable-4* x
 ⟨*proof*⟩

lemma *linear-orderable-5-implies-6*:
linear-orderable-5 $x \implies$ *linear-orderable-6* x
 ⟨*proof*⟩

lemma *linear-orderable-6-implies-3*:
assumes *linear-orderable-6* x
shows *linear-orderable-3* (x^+)
 ⟨*proof*⟩

lemma *linear-orderable-7-implies-1:*
linear-orderable-7 $x \implies$ *linear-orderable-1* (x^*)
\langle proof \rangle

lemma *linear-orderable-6-implies-8:*
linear-orderable-6 $x \implies$ *linear-orderable-8* x
\langle proof \rangle

abbreviation *path-orderable* $x \equiv$ *univalent* $x \wedge$ *injective* $x \wedge$ *acyclic* $x \wedge$ *linear* (x^*)

lemma *path-orderable-implies-linear-orderable-6:*
path-orderable $x \implies$ *linear-orderable-6* x
\langle proof \rangle

definition *simple-paths* $x \equiv \exists y . y \sqcup y^T = x \wedge$ *acyclic* $y \wedge$ *injective* $y \wedge$ *univalent* y

Theorem 14.1

lemma *simple-paths-acyclic-6:*
simple-paths $x \implies$ *acyclic-6* x
\langle proof \rangle

Theorem 14.2

lemma *simple-paths-transitively-orientable:*
assumes *simple-paths* x
shows *transitively-orientable* $(x^+ \sqcap -1)$
\langle proof \rangle

abbreviation *spanning* $x y \equiv y \leq x \wedge x \leq (y \sqcup y^T)^* \wedge$ *acyclic* $y \wedge$ *injective* y
definition *spannable* $x \equiv \exists y .$ *spanning* $x y$

lemma *acyclic-6-implies-spannable:*
acyclic-6 $x \implies$ *spannable* x
\langle proof \rangle

lemma *acyclic-3a-spannable-implies-6:*
assumes *acyclic-3a* x
and *spannable* x
and *symmetric* x
shows *acyclic-6* x
\langle proof \rangle

Theorem 10.3

lemma *acyclic-6-implies-3a:*
acyclic-6 $x \implies$ *acyclic-3a* x
\langle proof \rangle

Theorem 10.3

lemma *acyclic-6-implies-2*:
 $acyclic-6\ x \implies acyclic-2\ x$
(proof)

Theorem 11

lemma *acyclic-6-3a-spannable*:
 $acyclic-6\ x \iff symmetric\ x \wedge spannable\ x \wedge acyclic-3a\ x$
(proof)

end

context *stone-kleene-relation-algebra*
begin

Theorem 11.3

lemma *point-spanning*:
assumes *point* p
shows *spanning* (-1) $(p \sqcap -1)$
spannable (-1)
(proof)

lemma *irreflexive-star*:
 $(x \sqcap -1)^* = x^*$
(proof)

Theorem 6.5

lemma *acyclic-2-1*:
assumes *orientable* x
shows $acyclic-2\ x \iff acyclic-1\ x$
(proof)

Theorem 8

lemma *acyclic-4-4c*:
 $acyclic-4\ x \iff acyclic-4c\ x$
(proof)

Theorem 9

lemma *acyclic-5f-5g*:
 $acyclic-5f\ x \iff acyclic-5g\ x$
(proof)

lemma *linear-orderable-3-implies-5*:
assumes *linear-orderable-3* x
shows *linear-orderable-5* x
(proof)

lemma *linear-orderable-8-implies-7*:
 $linear-orderable-8\ x \implies linear-orderable-7\ x$

<proof>

Theorem 13

lemma *exists-split-characterisations-2:*

shows $(\exists x . \text{linear-orderable-1 } x) \longleftrightarrow (\exists x . \text{linear-orderable-4 } x)$

and $(\exists x . \text{linear-orderable-1 } x) \longleftrightarrow (\exists x . \text{linear-orderable-5 } x)$

and $(\exists x . \text{linear-orderable-1 } x) \longleftrightarrow (\exists x . \text{linear-orderable-6 } x)$

and $(\exists x . \text{linear-orderable-1 } x) \longleftrightarrow (\exists x . \text{linear-orderable-7 } x)$

and $(\exists x . \text{linear-orderable-1 } x) \longleftrightarrow (\exists x . \text{linear-orderable-8 } x)$

<proof>

end

2.3 Arc axiom

class *stone-kleene-relation-algebra-arc* = *stone-kleene-relation-algebra* +

assumes *arc-axiom*: $x \neq \text{bot} \implies \exists y . \text{arc } y \wedge y \leq \text{--}x$

begin

subclass *stone-relation-algebra-tarski*

<proof>

context

assumes *orientable-path*: $\text{arc } x \implies x \leq \text{--}y^* \implies \exists z . z \leq y \wedge \text{asymmetric } z \wedge x \leq \text{--}z^*$

begin

Theorem 8.6

lemma *acyclic-2-4:*

assumes *irreflexive* x

and *symmetric* x

shows $\text{acyclic-2 } x \longleftrightarrow \text{acyclic-4 } x$

<proof>

end

end

context *kleene-relation-algebra*

begin

Theorem 8

lemma *acyclic-3a-implies-4b:*

assumes *acyclic-3a* x

shows *acyclic-4b* x

<proof>

lemma *acyclic-3a-4b:*

$\text{acyclic-3a } x \longleftrightarrow \text{acyclic-4b } x$

<proof>

lemma *acyclic-4-4a:*

acyclic-4 x \longleftrightarrow acyclic-4a x

<proof>

2.4 Counterexamples

Calls to nitpick have been put into comments to save processing time.

independence of (0)

lemma *symmetric x \implies irreflexive-inf x \implies orientable x*

nitpick[expect=genuine,card=4,timeout=600]

<proof>

lemma *linear-orderable-6 x \implies path-orderable x*

nitpick[expect=genuine,card=8,timeout=600]

<proof>

(5) does not imply (6)

lemma *symmetric x \implies irreflexive x \implies acyclic-5a x \implies acyclic-6 x*

nitpick[expect=genuine,card=4,timeout=600]

<proof>

(2) does not imply (4)

lemma *symmetric x \implies irreflexive x \implies acyclic-2 x \implies acyclic-4 x*

nitpick[expect=genuine,card=8,timeout=600]

<proof>

end

end

3 Axioms and Algorithmic Proofs

In this theory we verify the correctness of three basic graph algorithms. We use them to constructively prove a number of graph properties.

theory *Algorithms*

imports *HOL-Hoare.Hoare-Logic Forests*

begin

context *stone-kleene-relation-algebra-arc*

begin

Assuming the arc axiom we can define the function *choose-arc* that selects an arc in a non-empty graph.

definition *choose-arc* $x \equiv$ if $x = \text{bot}$ then bot else $\text{SOME } y . \text{arc } y \wedge y \leq --x$

lemma *choose-arc-below*:

choose-arc $x \leq --x$
(*proof*)

lemma *choose-arc-arc*:

assumes $x \neq \text{bot}$
shows *arc* (*choose-arc* x)
(*proof*)

lemma *choose-arc-bot*:

choose-arc $\text{bot} = \text{bot}$
(*proof*)

lemma *choose-arc-bot-iff*:

choose-arc $x = \text{bot} \longleftrightarrow x = \text{bot}$
(*proof*)

lemma *choose-arc-regular*:

regular (*choose-arc* x)
(*proof*)

3.1 Constructing a spanning tree

definition *spanning-forest* $f g \equiv$ *forest* $f \wedge f \leq --g \wedge$ *components* $g \leq$
forest-components $f \wedge$ *regular* f

definition *kruskal-spanning-invariant* $f g h \equiv$ *symmetric* $g \wedge h = h^T \wedge g \sqcap --h$
 $= h \wedge$ *spanning-forest* $f (-h \sqcap g)$

lemma *spanning-forest-spanning*:

spanning-forest $f g \implies$ *spanning* ($--g$) f
(*proof*)

lemma *spanning-forest-spanning-regular*:

assumes *regular* f
and *regular* g
shows *spanning-forest* $f g \longleftrightarrow$ *spanning* $g f$
(*proof*)

We prove total correctness of Kruskal's spanning tree algorithm (ignoring edge weights) [6]. The algorithm and proof are adapted from the AFP theory *Relational-Minimum-Spanning-Trees.Kruskal* to work in Stone-Kleene relation algebras [3, 4].

lemma *kruskal-vc-1*:

assumes *symmetric g*
shows *kruskal-spanning-invariant bot g g*
 ⟨*proof*⟩

For the remainder of this theory we assume there are finitely many regular elements. This means that the graphs are finite and is needed for proving termination of the algorithms.

context
assumes *finite-regular: finite { x . regular x }*
begin

lemma *kruskal-vc-2:*

assumes *kruskal-spanning-invariant f g h*
and *h ≠ bot*
shows $(\text{choose-arc } h \leq \text{-forest-components } f \longrightarrow \text{kruskal-spanning-invariant } ((f \sqcap \text{-}(top * \text{choose-arc } h * f^{T*})) \sqcup (f \sqcap top * \text{choose-arc } h * f^{T*})^T \sqcup \text{choose-arc } h) g (h \sqcap \text{-choose-arc } h \sqcap \text{-choose-arc } h^T) \wedge \text{card } \{ x . \text{regular } x \wedge x \leq \text{-}h \wedge x \leq \text{-choose-arc } h \wedge x \leq \text{-choose-arc } h^T \} < \text{card } \{ x . \text{regular } x \wedge x \leq \text{-}h \}) \wedge (\neg \text{choose-arc } h \leq \text{-forest-components } f \longrightarrow \text{kruskal-spanning-invariant } f g (h \sqcap \text{-choose-arc } h \sqcap \text{-choose-arc } h^T) \wedge \text{card } \{ x . \text{regular } x \wedge x \leq \text{-}h \wedge x \leq \text{-choose-arc } h \wedge x \leq \text{-choose-arc } h^T \} < \text{card } \{ x . \text{regular } x \wedge x \leq \text{-}h \})$
 ⟨*proof*⟩

theorem *kruskal-spanning:*

VARs e f h
 [*symmetric g*]
f := bot;
h := g;
WHILE *h ≠ bot*
INV { kruskal-spanning-invariant f g h }
VAR { card { x . regular x ∧ x ≤ --h } }
DO e := choose-arc h;
IF e ≤ -forest-components f THEN
*f := (f ⊓ -(top * e * f^{T*})) ⊔ (f ⊓ top * e * f^{T*})^T ⊔ e*
ELSE
SKIP
FI;
h := h ⊓ -e ⊓ -e^T
OD
 [*spanning-forest f g*]
 ⟨*proof*⟩

lemma *kruskal-exists-spanning:*

symmetric g ⇒ ∃ f . spanning-forest f g
 ⟨*proof*⟩

Theorem 16

lemma *symmetric-spannable*:
 $\text{symmetric } g \implies \text{spannable } (---g)$
 ⟨proof⟩

3.2 Breadth-first search

We prove total correctness of a simple breadth-first search algorithm. It is a variant of an algorithm discussed in [1].

theorem *bfs-reachability*:

VARs $p \ q \ t$
 [*regular* $r \wedge \text{regular } s \wedge \text{vector } s$]
 $t := \text{bot};$
 $q := s;$
 $p := -s \sqcap r^T * s;$
 WHILE $p \neq \text{bot}$
 INV { *regular* $r \wedge \text{regular } q \wedge \text{vector } q \wedge \text{asymmetric } t \wedge t \leq r \wedge t \leq q \wedge q = t^{T*} * s \wedge p = -q \sqcap r^T * q$ }
 VAR { *card* { $x . \text{regular } x \wedge x \leq ---(-q \sqcap r^{T*} * s)$ } }
 DO $t := t \sqcup (r \sqcap q * p^T);$
 $q := q \sqcup p;$
 $p := -q \sqcap r^T * p$
 OD
 [*asymmetric* $t \wedge t \leq r \wedge q = t^{T*} * s \wedge q = r^{T*} * s$]
 ⟨proof⟩

Theorem 18

lemma *bfs-reachability-exists*:

regular $r \wedge \text{regular } s \wedge \text{vector } s \implies \exists t . \text{asymmetric } t \wedge t \leq r \wedge t^{T*} * s = r^{T*} * s$
 ⟨proof⟩

Theorem 17

lemma *orientable-path*:

arc $x \implies x \leq ---y^* \implies \exists z . z \leq y \wedge \text{asymmetric } z \wedge x \leq ---z^*$
 ⟨proof⟩

3.3 Extending partial orders to linear orders

We prove total correctness of Szpilrajn's algorithm [7]. A partial-correctness proof using Prover9 is given in [2].

theorem *szpilrajn*:

VARs $e \ t$
 [*order* $p \wedge \text{regular } p$]
 $t := p;$
 WHILE $t \sqcup t^T \neq \text{top}$
 INV { *order* $t \wedge \text{regular } t \wedge p \leq t$ }
 VAR { *card* { $x . \text{regular } x \wedge x \leq -(t \sqcup t^T)$ } }
 DO $e := \text{choose-arc } (-(t \sqcup t^T));$

$$t := t \sqcup t * e * t$$

OD
 [linear-order $t \wedge p \leq t$]
 ⟨proof⟩

Theorem 15

lemma *szpilrajn-exists*:
 order $p \wedge$ regular $p \implies \exists t .$ linear-order $t \wedge p \leq t$
 ⟨proof⟩

lemma *complement-one-transitively-orientable*:
 transitively-orientable (-1)
 ⟨proof⟩

end

end

end

References

- [1] R. Berghammer. Combining relational calculus and the Dijkstra–Gries method for deriving relational programs. *Information Sciences*, 119(3–4):155–171, 1999.
- [2] R. Berghammer and G. Struth. On automated program construction and verification. In C. Bolduc, J. Desharnais, and B. Ktari, editors, *Mathematics of Program Construction*, volume 6120 of *Lecture Notes in Computer Science*, pages 22–41. Springer, 2010.
- [3] W. Guttmann. Stone-Kleene relation algebras. *Archive of Formal Proofs*, 2017.
- [4] W. Guttmann. Verifying minimum spanning tree algorithms with Stone relation algebras. *Journal of Logical and Algebraic Methods in Programming*, 101:132–150, 2018.
- [5] W. Guttmann. Second-order properties of undirected graphs. In U. Fahrenberg, M. Gehrke, L. Santocanale, and M. Winter, editors, *Relational and Algebraic Methods in Computer Science (RAMiCS 2021)*, Lecture Notes in Computer Science. Springer, 2021. To appear.
- [6] J. B. Kruskal, Jr. On the shortest spanning subtree of a graph and the traveling salesman problem. *Proceedings of the American Mathematical Society*, 7(1):48–50, 1956.

- [7] E. Szpilrajn. Sur l'extension de l'ordre partiel. *Fundamenta Mathematicae*, 16:386–389, 1930.