

Basic Geometric Properties of Triangles

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Abstract

In this work, we define angles between vectors and between three points. Building on this, we prove basic geometric properties of triangles, such as the Isosceles Triangle Theorem, the Law of Sines and the Law of Cosines, that the sum of the angles of a triangle is π , and the congruence theorems for triangles.

The definitions and proofs were developed following those by John Harrison in HOL Light. However, due to Isabelle's type class system, all definitions and theorems in the Isabelle formalisation hold for all real inner product spaces.

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1 Definition of angles

theory *Angles*

imports

HOL-Analysis.Multivariate-Analysis

begin

lemma *collinear-translate-iff*: $collinear\ (((+)\ a)\ 'A) \longleftrightarrow collinear\ A$

by (*auto simp: collinear-def*)

definition *vangle* **where**

vangle $u\ v = (\text{if } u = 0 \vee v = 0 \text{ then } \pi / 2 \text{ else } \arccos (u \cdot v / (\text{norm } u * \text{norm } v)))$

definition *angle* **where**

angle $a\ b\ c = \text{vangle } (a - b)\ (c - b)$

lemma *angle-altdef*: $\text{angle } a\ b\ c = \arccos ((a - b) \cdot (c - b) / (\text{dist } a\ b * \text{dist } c\ b))$

by (*simp* *add*: *angle-def* *vangle-def* *dist-norm*)

lemma *vangle-0-left* [*simp*]: $\text{vangle } 0\ v = \pi / 2$

and *vangle-0-right* [*simp*]: $\text{vangle } u\ 0 = \pi / 2$

by (*simp*-*all* *add*: *vangle-def*)

lemma *vangle-refl* [*simp*]: $u \neq 0 \implies \text{vangle } u\ u = 0$

by (*simp* *add*: *vangle-def* *dot-square-norm* *power2-eq-square*)

lemma *angle-refl* [*simp*]: $\text{angle } a\ a\ b = \pi / 2$ $\text{angle } a\ b\ b = \pi / 2$

by (*simp*-*all* *add*: *angle-def*)

lemma *angle-refl-mid* [*simp*]: $a \neq b \implies \text{angle } a\ b\ a = 0$

by (*simp* *add*: *angle-def*)

lemma *cos-vangle*: $\cos (\text{vangle } u\ v) = u \cdot v / (\text{norm } u * \text{norm } v)$

unfolding *vangle-def* **using** *Cauchy-Schwarz-ineq2*[*of u v*] **by** (*auto* *simp*: *field-simps*)

lemma *cos-angle*: $\cos (\text{angle } a\ b\ c) = (a - b) \cdot (c - b) / (\text{dist } a\ b * \text{dist } c\ b)$

by (*simp* *add*: *angle-def* *cos-vangle* *dist-norm*)

lemma *inner-conv-angle*: $(a - b) \cdot (c - b) = \text{dist } a\ b * \text{dist } c\ b * \cos (\text{angle } a\ b\ c)$

by (*simp* *add*: *cos-angle*)

lemma *vangle-commute*: $\text{vangle } u\ v = \text{vangle } v\ u$

by (*simp* *add*: *vangle-def* *inner-commute* *mult.commute*)

lemma *angle-commute*: $\text{angle } a\ b\ c = \text{angle } c\ b\ a$

by (*simp* *add*: *angle-def* *vangle-commute*)

lemma *vangle-nonneg*: $\text{vangle } u\ v \geq 0$ **and** *vangle-le-pi*: $\text{vangle } u\ v \leq \pi$

using *Cauchy-Schwarz-ineq2*[*of u v*]

by (*auto* *simp*: *vangle-def* *field-simps* *intro!*: *arccos-lbound* *arccos-ubound*)

lemmas *vangle-bounds* = *vangle-nonneg* *vangle-le-pi*

lemma *angle-nonneg*: $\text{angle } a\ b\ c \geq 0$ **and** *angle-le-pi*: $\text{angle } a\ b\ c \leq \pi$

using *vangle-bounds* **unfolding** *angle-def* **by** *blast+*

lemmas *angle-bounds* = *angle-nonneg angle-le-pi*

lemma *sin-vangle-nonneg*: $\sin (\text{vangle } u \ v) \geq 0$
using *vangle-bounds* **by** (*rule sin-ge-zero*)

lemma *sin-angle-nonneg*: $\sin (\text{angle } a \ b \ c) \geq 0$
using *angle-bounds* **by** (*rule sin-ge-zero*)

lemma *vangle-eq-0D*:

assumes *vangle* $u \ v = 0$

shows $\text{norm } u *_R v = \text{norm } v *_R u$

proof –

from *assms* **have** $u \cdot v = \text{norm } u * \text{norm } v$

using *arccos-eq-iff*[*of* $(u \cdot v) / (\text{norm } u * \text{norm } v) \ 1$] *Cauchy-Schwarz-ineq2*[*of* $u \ v$]

by (*fastforce simp: vangle-def split: if-split-asm*)

thus *?thesis* **by** (*subst (asm) norm-cauchy-schwarz-eq*) *simp-all*

qed

lemma *vangle-eq-piD*:

assumes *vangle* $u \ v = \pi$

shows $\text{norm } u *_R v + \text{norm } v *_R u = 0$

proof –

from *assms* **have** $(-u) \cdot v = \text{norm } (-u) * \text{norm } v$

using *arccos-eq-iff*[*of* $(u \cdot v) / (\text{norm } u * \text{norm } v) \ -1$] *Cauchy-Schwarz-ineq2*[*of* $u \ v$]

by (*simp add: field-simps vangle-def split: if-split-asm*)

thus *?thesis* **by** (*subst (asm) norm-cauchy-schwarz-eq*) *simp-all*

qed

lemma *dist-triangle-eq*:

fixes $a \ b \ c :: 'a :: \text{real-inner}$

shows $(\text{dist } a \ c = \text{dist } a \ b + \text{dist } b \ c) \longleftrightarrow \text{dist } a \ b *_R (c - b) + \text{dist } b \ c *_R (a - b) = 0$

using *norm-triangle-eq*[*of* $b - a \ c - b$]

by (*simp add: dist-norm norm-minus-commute algebra-simps*)

lemma *angle-eq-pi-imp-dist-additive*:

assumes *angle* $a \ b \ c = \pi$

shows $\text{dist } a \ c = \text{dist } a \ b + \text{dist } b \ c$

using *vangle-eq-piD*[*OF* *assms*[*unfolded angle-def*]]

by (*subst dist-triangle-eq*) (*simp add: dist-norm norm-minus-commute*)

lemma *orthogonal-iff-vangle*: $\text{orthogonal } u \ v \longleftrightarrow \text{vangle } u \ v = \pi / 2$

using *arccos-eq-iff*[*of* $u \cdot v / (\text{norm } u * \text{norm } v) \ 0$] *Cauchy-Schwarz-ineq2*[*of* $u \ v$]

by (auto simp: vangle-def orthogonal-def)

lemma *cos-minus1-imp-pi*:

assumes $\cos x = -1$ $x \geq 0$ $x < 3 * \pi$

shows $x = \pi$

proof –

have $\cos (x - \pi) = 1$ by (simp add: assms)

then obtain $n :: \text{int}$ where n : $\text{of-int } n = (x / \pi - 1) / 2$

by (subst (asm) cos-one-2pi-int) (auto simp: field-simps)

also from assms have $\dots \in \{-1 < .. < 1\}$ by (auto simp: field-simps)

finally have $n = 0$ by simp

with n show ?thesis by simp

qed

lemma *vangle-eqI*:

assumes $u \neq 0$ $v \neq 0$ $w \neq 0$ $x \neq 0$

assumes $(u \cdot v) * \text{norm } w * \text{norm } x = (w \cdot x) * \text{norm } u * \text{norm } v$

shows $\text{vangle } u \ v = \text{vangle } w \ x$

using assms Cauchy-Schwarz-ineq2[of $u \ v$] Cauchy-Schwarz-ineq2[of $w \ x$]

unfolding vangle-def by (auto simp: arccos-eq-iff field-simps)

lemma *angle-eqI*:

assumes $a \neq b$ $a \neq c$ $d \neq e$ $d \neq f$

assumes $((b-a) \cdot (c-a)) * \text{dist } d \ e * \text{dist } d \ f = ((e-d) \cdot (f-d)) * \text{dist } a \ b * \text{dist } a \ c$

shows $\text{angle } b \ a \ c = \text{angle } e \ d \ f$

using assms unfolding angle-def

by (intro vangle-eqI) (simp-all add: dist-norm norm-minus-commute)

lemma *cos-vangle-eqD*: $\cos (\text{vangle } u \ v) = \cos (\text{vangle } w \ x) \implies \text{vangle } u \ v = \text{vangle } w \ x$

by (rule cos-inj-pi) (simp-all add: vangle-bounds)

lemma *cos-angle-eqD*: $\cos (\text{angle } a \ b \ c) = \cos (\text{angle } d \ e \ f) \implies \text{angle } a \ b \ c = \text{angle } d \ e \ f$

unfolding angle-def by (rule cos-vangle-eqD)

lemma *sin-vangle-zero-iff*: $\sin (\text{vangle } u \ v) = 0 \iff \text{vangle } u \ v \in \{0, \pi\}$

proof

assume $\sin (\text{vangle } u \ v) = 0$

then obtain $n :: \text{int}$ where n : $\text{of-int } n = \text{vangle } u \ v / \pi$

by (subst (asm) sin-zero-iff-int2) auto

also have $\dots \in \{0..1\}$ using vangle-bounds by (auto simp: field-simps)

finally have $n \in \{0, 1\}$ by auto

thus $\text{vangle } u \ v \in \{0, \pi\}$ using n by (auto simp: field-simps)

qed auto

lemma *sin-angle-zero-iff*: $\sin (\text{angle } a \ b \ c) = 0 \iff \text{angle } a \ b \ c \in \{0, \pi\}$

unfolding *angle-def* **by** (*simp only: sin-vangle-zero-iff*)

lemma *vangle-collinear*: $vangle\ u\ v \in \{0, \pi\} \implies collinear\ \{0, u, v\}$
apply (*subst norm-cauchy-schwarz-equal [symmetric]*)
apply (*subst norm-cauchy-schwarz-abs-eq*)
apply (*auto dest!: vangle-eq-0D vangle-eq-piD simp: eq-neg-iff-add-eq-0*)
done

lemma *angle-collinear*: $angle\ a\ b\ c \in \{0, \pi\} \implies collinear\ \{a, b, c\}$
apply (*unfold angle-def, drule vangle-collinear*)
apply (*subst collinear-translate-iff [symmetric, of - -b]*)
apply (*auto simp: insert-commute*)
done

lemma *not-collinear-vangle*: $\neg collinear\ \{0, u, v\} \implies vangle\ u\ v \in \{0 < .. < \pi\}$
using *vangle-bounds [of u v] vangle-collinear [of u v]*
by (*cases vangle u v = 0 \vee vangle u v = pi*) *auto*

lemma *not-collinear-angle*: $\neg collinear\ \{a, b, c\} \implies angle\ a\ b\ c \in \{0 < .. < \pi\}$
using *angle-bounds [of a b c] angle-collinear [of a b c]*
by (*cases angle a b c = 0 \vee angle a b c = pi*) *auto*

1.1 Contributions from Lukas Bulwahn

lemma *vangle-scales*:
assumes $0 < c$
shows $vangle\ (c *_{\mathbb{R}} v_1)\ v_2 = vangle\ v_1\ v_2$
using *assms unfolding vangle-def* **by** *auto*

lemma *vangle-inverse*:
 $vangle\ (-v_1)\ v_2 = \pi - vangle\ v_1\ v_2$
proof –
have $|v_1 \cdot v_2 / (norm\ v_1 * norm\ v_2)| \leq 1$
proof *cases*
assume $v_1 \neq 0 \wedge v_2 \neq 0$
from this show *?thesis* **by** (*simp add: Cauchy-Schwarz-ineq2*)
next
assume $\neg (v_1 \neq 0 \wedge v_2 \neq 0)$
from this show *?thesis* **by** *auto*
qed
from this show *?thesis*
unfolding *vangle-def*
by (*simp add: arccos-minus-abs*)
qed

lemma *orthogonal-iff-angle*:
shows $orthogonal\ (A - B)\ (C - B) \longleftrightarrow angle\ A\ B\ C = \pi / 2$
unfolding *angle-def* **by** (*auto simp only: orthogonal-iff-vangle*)

lemma *angle-inverse*:

assumes *between* $(A, C) B$

assumes $A \neq B$ $B \neq C$

shows $\text{angle } A B D = \text{pi} - \text{angle } C B D$

proof –

from $\langle \text{between } (A, C) B \rangle$ **obtain** u **where** $u: u \geq 0 \ u \leq 1$

and $X: B = u *_R A + (1 - u) *_R C$

by (*metis add.commute betweenE between-commute*)

from $\langle A \neq B \rangle \langle B \neq C \rangle X$ **have** $u \neq 0 \ u \neq 1$ **by** *auto*

have $0 < ((1 - u) / u)$

using $\langle u \neq 0 \rangle \langle u \neq 1 \rangle \langle u \geq 0 \rangle \langle u \leq 1 \rangle$ **by** *simp*

from X **have** $A - B = - (1 - u) *_R (C - A)$

by (*simp add: real-vector.scale-right-diff-distrib real-vector.scale-left-diff-distrib*)

moreover from X **have** $C - B = u *_R (C - A)$

by (*simp add: scaleR-diff-left real-vector.scale-right-diff-distrib*)

ultimately have $A - B = - (((1 - u) / u) *_R (C - B))$

using $\langle u \neq 0 \rangle$ **by** *simp* (*metis minus-diff-eq real-vector.scale-minus-left*)

from *this* **have** $\text{vangle } (A - B) (D - B) = \text{pi} - \text{vangle } (C - B) (D - B)$

using $\langle 0 < (1 - u) / u \rangle$ **by** (*simp add: vangle-inverse vangle-scales*)

from *this* **show** *?thesis*

unfolding *angle-def* **by** *simp*

qed

lemma *strictly-between-implies-angle-eq-pi*:

assumes *between* $(A, C) B$

assumes $A \neq B$ $B \neq C$

shows $\text{angle } A B C = \text{pi}$

proof –

from $\langle \text{between } (A, C) B \rangle$ **obtain** u **where** $u: u \geq 0 \ u \leq 1$

and $X: B = u *_R A + (1 - u) *_R C$

by (*metis add.commute betweenE between-commute*)

from $\langle A \neq B \rangle \langle B \neq C \rangle X$ **have** $u \neq 0 \ u \neq 1$ **by** *auto*

from $\langle A \neq B \rangle \langle B \neq C \rangle \langle \text{between } (A, C) B \rangle$ **have** $A \neq C$ **by** *auto*

from X **have** $A - B = - (1 - u) *_R (C - A)$

by (*simp add: real-vector.scale-right-diff-distrib real-vector.scale-left-diff-distrib*)

moreover from *this* **have** $\text{dist } A B = \text{norm } ((1 - u) *_R (C - A))$

using $\langle u \geq 0 \rangle \langle u \leq 1 \rangle$ **by** (*simp add: dist-norm*)

moreover from X **have** $C - B = u *_R (C - A)$

by (*simp add: scaleR-diff-left real-vector.scale-right-diff-distrib*)

moreover from *this* **have** $\text{dist } C B = \text{norm } (u *_R (C - A))$

by (*simp add: dist-norm*)

ultimately have $(A - B) \cdot (C - B) / (\text{dist } A B * \text{dist } C B) = u * (u - 1) / (|1 - u| * |u|)$

using $\langle A \neq C \rangle$ **by** (*simp add: dot-square-norm power2-eq-square*)

also have $\dots = -1$

using $\langle u \neq 0 \rangle \langle u \neq 1 \rangle \langle u \geq 0 \rangle \langle u \leq 1 \rangle$ **by** (*simp add: divide-eq-minus-1-iff*)

finally show *?thesis*

unfolding *angle-altdef* **by** *simp*

qed

end

2 Basic Properties of Triangles

```
theory Triangle
imports
  Angles
begin
```

We prove a number of basic geometric properties of triangles. All theorems hold in any real inner product space.

2.1 Thales' theorem

```
theorem thales:
  fixes A B C :: 'a :: real-inner
  assumes dist B (midpoint A C) = dist A C / 2
  shows orthogonal (A - B) (C - B)
proof -
  have dist A C ^ 2 = dist B (midpoint A C) ^ 2 * 4
  by (subst assms) (simp add: field-simps power2-eq-square)
  thus ?thesis
  by (auto simp: orthogonal-def dist-norm power2-norm-eq-inner midpoint-def
    algebra-simps inner-commute)
qed
```

2.2 Sine and cosine laws

The proof of the Law of Cosines follows trivially from the definition of the angle, the definition of the norm in vector spaces with an inner product and the bilinearity of the inner product.

```
lemma cosine-law-vector:
  norm (u - v) ^ 2 = norm u ^ 2 + norm v ^ 2 - 2 * norm u * norm v * cos
  (vangle u v)
  by (simp add: power2-norm-eq-inner cos-vangle algebra-simps inner-commute)
```

```
lemma cosine-law-triangle:
  dist b c ^ 2 = dist a b ^ 2 + dist a c ^ 2 - 2 * dist a b * dist a c * cos (angle
  b a c)
  using cosine-law-vector[of b - a c - a]
  by (simp add: dist-norm angle-def vangle-commute norm-minus-commute)
```

According to our definition, angles are always between 0 and π and therefore, the sign of an angle is always non-negative. We can therefore look at $\sin(\alpha)^2$, which we can express in terms of $\cos(\alpha)$ using the identity $\sin(\alpha)^2 + \cos(\alpha)^2 = 1$. The remaining proof is then a trivial consequence of the definitions.

lemma *sine-law-triangle*:
 $\sin (\text{angle } a \ b \ c) * \text{dist } b \ c = \sin (\text{angle } b \ a \ c) * \text{dist } a \ c$ (**is** $?A = ?B$)
proof (*cases* $a = b$)
assume *neq*: $a \neq b$
show *?thesis*
proof (*rule power2-eq-imp-eq*)
from *neq* **have** $(\sin (\text{angle } a \ b \ c) * \text{dist } b \ c) ^ 2 * \text{dist } a \ b ^ 2 =$
 $\text{dist } a \ b ^ 2 * \text{dist } b \ c ^ 2 - ((a - b) \cdot (c - b)) ^ 2$
by (*simp add: sin-squared-eq cos-angle dist-commute field-simps*)
also **have** $\dots = \text{dist } a \ b ^ 2 * \text{dist } a \ c ^ 2 - ((b - a) \cdot (c - a)) ^ 2$
by (*simp only: dist-norm power2-norm-eq-inner*)
(simp add: power2-eq-square algebra-simps inner-commute)
also from *neq* **have** $\dots = (\sin (\text{angle } b \ a \ c) * \text{dist } a \ c) ^ 2 * \text{dist } a \ b ^ 2$
by (*simp add: sin-squared-eq cos-angle dist-commute field-simps*)
finally show $?A ^ 2 = ?B ^ 2$ **using** *neq* **by** (*subst (asm) mult-cancel-right*)
simp-all
qed (*auto intro!: mult-nonneg-nonneg sin-angle-nonneg*)
qed *simp-all*

The following forms of the Law of Sines/Cosines are more convenient for eliminating sines/cosines from a goal completely.

lemma *cosine-law-triangle'*:
 $2 * \text{dist } a \ b * \text{dist } a \ c * \cos (\text{angle } b \ a \ c) = (\text{dist } a \ b ^ 2 + \text{dist } a \ c ^ 2 - \text{dist } b \ c ^ 2)$
using *cosine-law-triangle[of b c a]* **by** *simp*

lemma *cosine-law-triangle''*:
 $\cos (\text{angle } b \ a \ c) = (\text{dist } a \ b ^ 2 + \text{dist } a \ c ^ 2 - \text{dist } b \ c ^ 2) / (2 * \text{dist } a \ b * \text{dist } a \ c)$
using *cosine-law-triangle[of b c a]* **by** *simp*

lemma *sine-law-triangle'*:
 $b \neq c \implies \sin (\text{angle } a \ b \ c) = \sin (\text{angle } b \ a \ c) * \text{dist } a \ c / \text{dist } b \ c$
using *sine-law-triangle[of a b c]* **by** (*simp add: divide-simps*)

lemma *sine-law-triangle''*:
 $b \neq c \implies \sin (\text{angle } c \ b \ a) = \sin (\text{angle } b \ a \ c) * \text{dist } a \ c / \text{dist } b \ c$
using *sine-law-triangle[of a b c]* **by** (*simp add: divide-simps angle-commute*)

2.3 Sum of angles

context
begin

private lemma *gather-squares*: $a * (a * b) = a ^ 2 * (b :: \text{real})$
by (*simp-all add: power2-eq-square*)

private lemma *eval-power*: $x \wedge \text{numeral } n = x * x \wedge \text{pred-numeral } n$
by (*subst numeral-eq-Suc, subst power-Suc*) *simp*

The proof that the sum of the angles in a triangle is π is somewhat more involved. Following the HOL Light proof by John Harrison, we first prove that $\cos(\alpha + \beta + \gamma) = -1$ and $\alpha + \beta + \gamma \in [0; 3\pi)$, which then implies the theorem.

The main work is proving $\cos(\alpha + \beta + \gamma)$. This is done using the addition theorems for the sine and cosine, then using the Laws of Sines to eliminate all sin terms save $\sin(\gamma)^2$, which only appears squared in the remaining goal. We then use $\sin(\gamma)^2 = 1 - \cos(\gamma)^2$ to eliminate this term and apply the law of cosines to eliminate this term as well.

The remaining goal is a non-linear equation containing only the length of the sides of the triangle. It can be shown by simple algebraic rewriting.

```

lemma angle-sum-triangle:
  assumes  $a \neq b \vee b \neq c \vee a \neq c$ 
  shows  $\text{angle } c \ a \ b + \text{angle } a \ b \ c + \text{angle } b \ c \ a = \text{pi}$ 
proof (rule cos-minus1-imp-pi)
  show  $\cos(\text{angle } c \ a \ b + \text{angle } a \ b \ c + \text{angle } b \ c \ a) = -1$ 
  proof (cases a ≠ b)
    case True
      thus  $\cos(\text{angle } c \ a \ b + \text{angle } a \ b \ c + \text{angle } b \ c \ a) = -1$ 
      apply (simp add: cos-add sin-add cosine-law-triangle'' field-simps
        sine-law-triangle''[of a b c] sine-law-triangle''[of b a c]
        angle-commute dist-commute gather-squares sin-squared-eq)
      apply (simp add: eval-power algebra-simps dist-commute)
      done
    qed (insert assms, auto)

  show  $\text{angle } c \ a \ b + \text{angle } a \ b \ c + \text{angle } b \ c \ a < 3 * \text{pi}$ 
  proof (rule ccontr)
    assume  $\neg(\text{angle } c \ a \ b + \text{angle } a \ b \ c + \text{angle } b \ c \ a < 3 * \text{pi})$ 
    with angle-le-pi[of c a b] angle-le-pi[of a b c] angle-le-pi[of b c a]
    have A:  $\text{angle } c \ a \ b = \text{pi} \ \text{angle } a \ b \ c = \text{pi}$  by simp-all
    thus False using angle-eq-pi-imp-dist-additive[of c a b]
      angle-eq-pi-imp-dist-additive[of a b c] by (simp add: dist-commute)
  qed
qed (auto intro!: add-nonneg-nonneg angle-nonneg)

end

```

2.4 Congruence Theorems

If two triangles agree on two angles at a non-degenerate side, the third angle must also be equal.

```

lemma similar-triangle-aa:
  assumes  $b1 \neq c1 \ b2 \neq c2$ 
  assumes  $\text{angle } a1 \ b1 \ c1 = \text{angle } a2 \ b2 \ c2$ 
  assumes  $\text{angle } b1 \ c1 \ a1 = \text{angle } b2 \ c2 \ a2$ 
  shows  $\text{angle } b1 \ a1 \ c1 = \text{angle } b2 \ a2 \ c2$ 

```

proof –

from *assms angle-sum-triangle[of a1 b1 c1] angle-sum-triangle[of a2 b2 c2, symmetric]*

show *?thesis* **by** (*auto simp: algebra-simps angle-commute*)

qed

A triangle is defined by its three angles and the lengths of three sides up to congruence. Two triangles are congruent if they have their angles are the same and their sides have the same length.

locale *congruent-triangle* =

fixes *a1 b1 c1* :: '*a*' :: *real-inner* **and** *a2 b2 c2* :: '*b*' :: *real-inner*

assumes *sides'*: *dist a1 b1 = dist a2 b2 dist a1 c1 = dist a2 c2 dist b1 c1 = dist b2 c2*

and *angles'*: *angle b1 a1 c1 = angle b2 a2 c2 angle a1 b1 c1 = angle a2 b2 c2 angle a1 c1 b1 = angle a2 c2 b2*

begin

lemma *sides*:

dist a1 b1 = dist a2 b2 dist a1 c1 = dist a2 c2 dist b1 c1 = dist b2 c2

dist b1 a1 = dist a2 b2 dist c1 a1 = dist a2 c2 dist c1 b1 = dist b2 c2

dist a1 b1 = dist b2 a2 dist a1 c1 = dist c2 a2 dist b1 c1 = dist c2 b2

dist b1 a1 = dist b2 a2 dist c1 a1 = dist c2 a2 dist c1 b1 = dist c2 b2

using *sides'* **by** (*simp-all add: dist-commute*)

lemma *angles*:

angle b1 a1 c1 = angle b2 a2 c2 angle a1 b1 c1 = angle a2 b2 c2 angle a1 c1 b1 = angle a2 c2 b2

angle c1 a1 b1 = angle b2 a2 c2 angle c1 b1 a1 = angle a2 b2 c2 angle b1 c1 a1 = angle a2 c2 b2

angle b1 a1 c1 = angle c2 a2 b2 angle a1 b1 c1 = angle c2 b2 a2 angle a1 c1 b1 = angle b2 c2 a2

angle c1 a1 b1 = angle c2 a2 b2 angle c1 b1 a1 = angle c2 b2 a2 angle b1 c1 a1 = angle b2 c2 a2

using *angles'* **by** (*simp-all add: angle-commute*)

end

lemmas *congruent-triangleD = congruent-triangle.sides congruent-triangle.angles*

Given two triangles that agree on a subset of its side lengths and angles that are sufficient to define a triangle uniquely up to congruence, one can conclude that they must also agree on all remaining quantities, i.e. that they are congruent.

The following four congruence theorems state what constitutes such a uniquely-defining subset of quantities. Each theorem states in its name which quantities are required and in which order (clockwise or counter-clockwise): an “s” stands for a side, an “a” stands for an angle.

The lemma “congruent-triangleI-sas, for example, requires that two adjacent

sides and the angle inbetween are the same in both triangles.

lemma *congruent-triangleI-sss*:

fixes $a1\ b1\ c1 :: 'a :: \text{real-inner}$ **and** $a2\ b2\ c2 :: 'b :: \text{real-inner}$

assumes $\text{dist } a1\ b1 = \text{dist } a2\ b2$

assumes $\text{dist } b1\ c1 = \text{dist } b2\ c2$

assumes $\text{dist } a1\ c1 = \text{dist } a2\ c2$

shows $\text{congruent-triangle } a1\ b1\ c1\ a2\ b2\ c2$

proof –

have $A: \text{angle } a1\ b1\ c1 = \text{angle } a2\ b2\ c2$

if $\text{dist } a1\ b1 = \text{dist } a2\ b2\ \text{dist } b1\ c1 = \text{dist } b2\ c2\ \text{dist } a1\ c1 = \text{dist } a2\ c2$

for $a1\ b1\ c1 :: 'a$ **and** $a2\ b2\ c2 :: 'b$

proof –

from $\text{that cosine-law-triangle''[of } a1\ b1\ c1] \text{ cosine-law-triangle''[of } a2\ b2\ c2]$

show $?thesis$ **by** $(\text{intro cos-angle-eqD}) (\text{simp add: dist-commute})$

qed

from $\text{assms show } ?thesis$ **by** $\text{unfold-locales (auto intro!: A simp: dist-commute)}$

qed

lemmas $\text{congruent-triangle-sss} = \text{congruent-triangleD}[OF \text{congruent-triangleI-sss}]$

lemma *congruent-triangleI-sas*:

assumes $\text{dist } a1\ b1 = \text{dist } a2\ b2$

assumes $\text{dist } b1\ c1 = \text{dist } b2\ c2$

assumes $\text{angle } a1\ b1\ c1 = \text{angle } a2\ b2\ c2$

shows $\text{congruent-triangle } a1\ b1\ c1\ a2\ b2\ c2$

proof $(\text{rule congruent-triangleI-sss})$

show $\text{dist } a1\ c1 = \text{dist } a2\ c2$

proof $(\text{rule power2-eq-imp-eq})$

from $\text{cosine-law-triangle[of } a1\ c1\ b1] \text{ cosine-law-triangle[of } a2\ c2\ b2] \text{ assms}$

show $(\text{dist } a1\ c1)^2 = (\text{dist } a2\ c2)^2$ **by** $(\text{simp add: dist-commute})$

qed simp-all

qed fact+

lemmas $\text{congruent-triangle-sas} = \text{congruent-triangleD}[OF \text{congruent-triangleI-sas}]$

lemma *congruent-triangleI-aas*:

assumes $\text{angle } a1\ b1\ c1 = \text{angle } a2\ b2\ c2$

assumes $\text{angle } b1\ c1\ a1 = \text{angle } b2\ c2\ a2$

assumes $\text{dist } a1\ b1 = \text{dist } a2\ b2$

assumes $\neg \text{collinear } \{a1, b1, c1\}$

shows $\text{congruent-triangle } a1\ b1\ c1\ a2\ b2\ c2$

proof $(\text{rule congruent-triangleI-sas})$

from $\langle \neg \text{collinear } \{a1, b1, c1\} \rangle$ **have** $\text{neq: } a1 \neq b1$ **by** auto

with $\text{assms}(3)$ **have** $\text{neq': } a2 \neq b2$ **by** auto

have $A: \text{angle } c1\ a1\ b1 = \text{angle } c2\ a2\ b2$ **using** neq neq' assms

using $\text{angle-sum-triangle[of } a1\ b1\ c1] \text{ angle-sum-triangle[of } a2\ b2\ c2]$

by simp

from $\text{assms have } B: \text{angle } b1\ a1\ c1 \in \{0 <.. < \pi\}$

by $(\text{intro not-collinear-angle}) (\text{simp-all add: insert-commute})$

from *sine-law-triangle*[of $c1\ a1\ b1$] *sine-law-triangle*[of $c2\ a2\ b2$] *assms* $A\ B$
show $dist\ b1\ c1 = dist\ b2\ c2$
by (*auto simp: angle-commute dist-commute sin-angle-zero-iff*)
qed fact+

lemmas *congruent-triangle-aas* = *congruent-triangleD*[*OF congruent-triangleI-aas*]

lemma *congruent-triangleI-asa*:

assumes $angle\ a1\ b1\ c1 = angle\ a2\ b2\ c2$
assumes $dist\ a1\ b1 = dist\ a2\ b2$
assumes $angle\ b1\ a1\ c1 = angle\ b2\ a2\ c2$
assumes $\neg collinear\ \{a1,\ b1,\ c1\}$
shows *congruent-triangle* $a1\ b1\ c1\ a2\ b2\ c2$
proof (*rule congruent-triangleI-aas*)
from *assms* **have** $neg: a1 \neq b1\ a2 \neq b2$ **by** *auto*
show $angle\ b1\ c1\ a1 = angle\ b2\ c2\ a2$
by (*rule similar-triangle-aa*) (*insert assms neg, simp-all add: angle-commute*)
qed fact+

lemmas *congruent-triangle-asa* = *congruent-triangleD*[*OF congruent-triangleI-asa*]

2.5 Isosceles Triangle Theorem

We now prove the Isosceles Triangle Theorem: in a triangle where two sides have the same length, the two angles that are adjacent to only one of the two sides must be equal.

lemma *isosceles-triangle*:

assumes $dist\ a\ c = dist\ b\ c$
shows $angle\ b\ a\ c = angle\ a\ b\ c$
by (*rule congruent-triangle-sss*) (*insert assms, simp-all add: dist-commute*)

For the non-degenerate case (i.e. the three points are not collinear), We also prove the converse.

lemma *isosceles-triangle-converse*:

assumes $angle\ a\ b\ c = angle\ b\ a\ c\ \neg collinear\ \{a,b,c\}$
shows $dist\ a\ c = dist\ b\ c$
by (*rule congruent-triangle-asa*[*OF assms(1) - - assms(2)*])
(simp-all add: dist-commute angle-commute assms)

2.6 Contributions by Lukas Bulwahn

lemma *Pythagoras*:

fixes $A\ B\ C :: 'a :: real-inner$
assumes *orthogonal* $(A - C)\ (B - C)$
shows $(dist\ B\ C) \wedge^2 + (dist\ C\ A) \wedge^2 = (dist\ A\ B) \wedge^2$
proof -
from *assms* **have** $cos\ (angle\ A\ C\ B) = 0$
by (*metis orthogonal-iff-angle cos-pi-half*)

```

from this show ?thesis
  by (simp add: cosine-law-triangle[of A B C] dist-commute)
qed

lemma isosceles-triangle-orthogonal-on-midpoint:
  fixes A B C :: 'a :: euclidean-space
  assumes dist C A = dist C B
  shows orthogonal (C - midpoint A B) (A - midpoint A B)
proof (cases A = B)
  assume A ≠ B
  let ?M = midpoint A B
  from ⟨A ≠ B⟩ have angle A ?M C = pi - angle B ?M C
    by (intro angle-inverse between-midpoint)
    (auto simp: between-midpoint eq-commute[of - midpoint A B for A B])
  moreover have angle A ?M C = angle C ?M B
  proof -
    have congruence: congruent-triangle C A ?M C B ?M
    proof (rule congruent-triangleI-sss)
      show dist C A = dist C B using assms .
      show dist A ?M = dist B ?M by (simp add: dist-midpoint)
      show dist C (midpoint A B) = dist C (midpoint A B) ..
    qed
  from this show ?thesis by (simp add: congruent-triangle.angles(6))
qed
  ultimately have angle A ?M C = pi / 2 by (simp add: angle-commute)
from this show ?thesis
  by (simp add: orthogonal-iff-angle orthogonal-commute)
next
  assume A = B
  from this show ?thesis
  by (simp add: orthogonal-clauses(1))
qed

end

```