

No Faster-Than-Light Observers (GenRel)

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Abstract

We have previously verified, in the first order theory `SpecRel` of Special Relativity, that inertial observers cannot travel faster than light [1, 2]. We now prove the corresponding result for `GenRel`, the first-order theory of General Relativity. Specifically, we prove that whenever an observer m encounters another observer k (so that m and k are both present at some spacetime location x), k will necessarily be observed by m to be traveling at less than light speed.

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1 Sorts

GenRel is a 2-sorted first-order logic. This theory introduces the two sorts and proves a number of basic arithmetical results. The two sorts are Bodies (things that can move) and Quantities (used to specify coordinates, masses, etc).

```
theory Sorts
  imports Main
begin
```

1.1 Bodies

There are two types of Body: photons and observers. We do not assume a priori that these sorts are disjoint.

```
record Body =
  Ph :: bool
  Ob :: bool
```

1.2 Quantities

The quantities are assumed to form a linearly ordered field. We may sometimes need to assume that the field is also Euclidean, i.e. that square roots exist, but this is not a general requirement so it will be added later using a separate axiom class, AxEField.

```
class Quantities = linordered-field
begin
```

```
abbreviation inRangeOO :: 'a ⇒ 'a ⇒ 'a ⇒ bool (↖ - < - < ↘)
  where (a < b < c) ≡ (a < b) ∧ (b < c)
```

```
abbreviation inRangeOC :: 'a ⇒ 'a ⇒ 'a ⇒ bool (↖ - < - ≤ ↘)
  where (a < b ≤ c) ≡ (a < b) ∧ (b ≤ c)
```

```
abbreviation inRangeCO :: 'a ⇒ 'a ⇒ 'a ⇒ bool (↖ ≤ - < ↘)
  where (a ≤ b < c) ≡ (a ≤ b) ∧ (b < c)
```

```
abbreviation inRangeCC :: 'a ⇒ 'a ⇒ 'a ⇒ bool (↖ ≤ - ≤ ↘)
```

where $(a \leq b \leq c) \equiv (a \leq b) \wedge (b \leq c)$

lemma *lemLEPlus*: $a \leq b + c \longrightarrow c \geq a - b$
by (*simp add: add-commute local.diff-le-eq*)

lemma *lemMultPosLT1*:
assumes $(a > 0) \wedge (b \geq 0) \wedge (b < 1)$
shows $(a * b) < a$
using *assms local.mult-less-cancel-left2 local.not-less* **by** *auto*

lemma *lemAbsRange*: $e > 0 \longrightarrow ((a-e) < b < (a+e)) \longleftrightarrow (abs$
 $(b-a) < e)$
by (*simp add: local.abs-diff-less-iff*)

lemma *lemAbsNeg*: $abs\ x = abs\ (-x)$
by *simp*

lemma *lemAbsNegNeg*: $abs\ (-a-b) = abs\ (a+b)$
using *add-commute local.abs-minus-commute* **by** *auto*

lemma *lemGENZGT*: $(x \geq 0) \wedge (x \neq 0) \longrightarrow x > 0$
by *auto*

lemma *lemLENZLT*: $(x \leq 0) \wedge (x \neq 0) \longrightarrow x < 0$
by *force*

lemma *lemSumOfNonNegAndPos*: $x \geq 0 \wedge y > 0 \longrightarrow x+y > 0$
by (*simp add: local.add-strict-increasing2*)

lemma *lemSumOfTwoHalves*: $x = x/2 + x/2$
using *mult-2[of x/2]* **by** *force*

lemma *lemDiffDiffAdd*: $(b-a)+(c-b) = (c-a)$
by (*auto simp add: field-simps*)

lemma *lemSumDiffCancelMiddle*: $(a - b) + (b - c) = (a - c)$
by (*auto simp add: field-simps*)

lemma *lemDiffSumCancelMiddle*: $(a - b) + (b + c) = (a + c)$
by (*auto simp add: field-simps*)

lemma *lemMultPosLT*: $((0 < a) \wedge (b < c)) \longrightarrow (a*b < a*c)$
using *mult-strict-left-mono* **by** *auto*

lemma *lemMultPosLE*: $((0 < a) \wedge (b \leq c)) \longrightarrow (a*b \leq a*c)$
using *mult-left-mono* **by** *auto*

lemma *lemNonNegLT*: $((0 \leq a) \wedge (b < c)) \longrightarrow (a*b \leq a*c)$
using *mult-left-mono* **by** *auto*

lemma *lemMultNonNegLE*: $((0 \leq a) \wedge (b \leq c)) \longrightarrow (a*b \leq a*c)$
using *mult-left-mono* **by** *auto*

abbreviation *sqr* :: 'a \Rightarrow 'a
where *sqr* *x* \equiv *x*x*

abbreviation *hasRoot* :: 'a \Rightarrow bool
where *hasRoot* *x* \equiv \exists *r* . *x* = *sqr* *r*

abbreviation *isNonNegRoot* :: 'a \Rightarrow 'a \Rightarrow bool
where *isNonNegRoot* *x* *r* \equiv $(r \geq 0) \wedge (x = \textit{sqr } r)$

abbreviation *hasUniqueRoot* :: 'a \Rightarrow bool
where *hasUniqueRoot* *x* \equiv $\exists!$ *r* . *isNonNegRoot* *x* *r*

abbreviation *sqr* :: 'a \Rightarrow 'a
where *sqr* *x* \equiv *THE* *r* . *isNonNegRoot* *x* *r*

lemma *lemAbsIsRootOfSquare*: *isNonNegRoot* (*sqr* *x*) (*abs* *x*)
by *simp*

lemma *lemSqrt*:
assumes *hasRoot* *x*
shows *hasUniqueRoot* *x*
proof –
obtain *r* **where** *x* = *sqr* *r* **using** *assms*(1) **by** *auto*
define *rt* **where** *rt* = (if (*r* \geq 0) then *r* else ($-r$))
hence *rt*: *rt* \geq 0 \wedge *sqr* *rt* = *x* **using** *rt-def* $\langle x = \textit{sqr } r \rangle$ **by** *auto*
hence *rtroot*: *isNonNegRoot* *x* *rt* **by** *auto*

{ **fix** *y*
assume *yprops*: *isNonNegRoot* *x* *y*
hence *y* = *rt*
using *local.square-eq-iff* *rt* **by** *auto*
hence $((y \geq 0) \wedge (x = \textit{sqr } y)) \longrightarrow (y = \textit{rt})$ **by** *auto*
}
hence *rtunique*: \forall *y* . *isNonNegRoot* *x* *y* \longrightarrow (*y* = *rt*) **by** *auto*
thus *?thesis* **using** *rtroot* **by** *auto*
qed

lemma *lemSqrMonoStrict*: **assumes** $(0 \leq u) \wedge (u < v)$

shows $(\text{sqr } u) < (\text{sqr } v)$

proof –

have $1: (u * u) \leq (u * v)$ **using** *assms comm-mult-left-mono* **by** *auto*

have $(u * v) < (v * v)$

using *assms mult-commute comm-mult-strict-left-mono* **by** *auto*

thus *?thesis* **using** *1 le-less-trans* **by** *auto*

qed

lemma *lemSqrMono*: $(0 \leq u) \wedge (u \leq v) \longrightarrow (\text{sqr } u) \leq (\text{sqr } v)$

by (*simp add: local.mult-mono*)

lemma *lemSqrOrderedStrict*: $(v > 0) \wedge (\text{sqr } u < \text{sqr } v) \longrightarrow (u < v)$

using *mult-mono[of v u v u]* **by** *force*

lemma *lemSqrOrdered*: $(v \geq 0) \wedge (\text{sqr } u \leq \text{sqr } v) \longrightarrow (u \leq v)$

using *mult-strict-mono[of v u v u]* **by** *force*

lemma *lemSquaredNegative*: $\text{sqr } x = \text{sqr } (-x)$

by *auto*

lemma *lemSqrDiffSymmetrical*: $\text{sqr } (x - y) = \text{sqr } (y - x)$

using *lemSquaredNegative[of y-x]* **by** *auto*

lemma *lemSquaresPositive*: $x \neq 0 \longrightarrow \text{sqr } x > 0$

by (*simp add: lemGENZGT*)

lemma *lemZeroRoot*: $(\text{sqr } x = 0) \longleftrightarrow (x = 0)$

by *simp*

lemma *lemSqrMult*: $\text{sqr } (a * b) = (\text{sqr } a) * (\text{sqr } b)$

using *mult-commute mult-assoc* **by** *simp*

lemma *lemEqualSquares*: $\text{sqr } u = \text{sqr } v \longrightarrow \text{abs } u = \text{abs } v$

by (*metis local.abs-mult-less local.abs-mult-self-eq local.not-less-iff-gr-or-eq*)

lemma *lemSqrtOfSquare*:

assumes $b = \text{sqr } a$

shows $\text{sqr } b = \text{abs } a$

proof –

have $b \geq 0$ **using** *assms* **by** *auto*

hence *conj1: hasUniqueRoot b* **using** *lemSqrt[of b] assms* **by** *auto*

moreover **have** *isNonNegRoot b (abs a)* **using** *lemAbsIsRootOf-Square assms* **by** *auto*

ultimately **have** $\text{sqr } b = \text{abs } a$

using *theI[of $\lambda r . 0 \leq r \wedge b = \text{sqr } r \text{ abs } a$]* **by** *blast*

thus *?thesis* **by** *auto*

qed

lemma *lemSquareOfSqrt*:

assumes *hasRoot* *b*

and $a = \text{sqr } b$

shows $\text{sqr } a = b$

proof –

obtain *r* **where** *r*: *isNonNegRoot* *b* *r* **using** *assms*(1) *lemSqrt*[of *b*]

by *auto*

hence $\forall x. 0 \leq x \wedge b = \text{sqr } x \longrightarrow x = r$ **using** *lemSqrt* **by** *blast*

hence $a = r$ **using** *r* *assms*(2) *the-equality*[of *isNonNegRoot* *b* *r*] **by**
blast

thus *?thesis* **using** *r* **by** *auto*

qed

lemma *lemSqrt1*: $\text{sqr } 1 = 1$

proof –

have *isNonNegRoot* 1 1 **by** *auto*

moreover **have** $\forall r. \text{isNonNegRoot } 1 r \longrightarrow r = 1$

proof –

{ **fix** *r* **assume** *isNonNegRoot* 1 *r*

hence $r: (r \geq 0) \wedge (1 = \text{sqr } r)$ **by** *simp*

hence $r = 1$ **using** *calculation* *lemSqrt* **by** *blast*

}

thus *?thesis* **by** *blast*

qed

ultimately **show** *?thesis* **using** *the-equality*[of *isNonNegRoot* 1 1]

by *blast*

qed

lemma *lemSqrt0*: $\text{sqr } 0 = 0$

using *lemZeroRoot* *local.mult-cancel-right1* **by** *blast*

lemma *lemSqrSum*: $\text{sqr } (x + y) = (x*x) + (2*x*y) + (y*y)$

proof –

have $x*y + y*x = x*y + x*y$ **using** *mult-commute* **by** *simp*

also **have** $\dots = (x+x)*y$ **using** *distrib-right* **by** *simp*

finally **have** $xy: x*y + y*x = 2*x*y$ **using** *mult-2* **by** *auto*

have $\text{sqr } (x+y) = x*(x+y) + y*(x+y)$ **using** *distrib-right* **by** *auto*

also **have** $\dots = x*x + x*y + y*x + y*y$ **using** *distrib-left* *add-assoc*

by *auto*

finally **have** $\text{sqr } (x+y) = (\text{sqr } x) + x*y + y*x + (\text{sqr } y)$

using *distrib-left* *add-assoc* **by** *auto*

thus *?thesis* using *xy add-assoc* by *auto*
qed

lemma *lemQuadraticGEZero*:

assumes $\forall x. a*(\text{sqr } x) + b*x + c \geq 0$
and $a > 0$
shows $(\text{sqr } b) \leq 4*a*c$
proof –
{ fix $x :: 'a$
have $a * \text{sqr } (x + (b/(2*a))) = a * ((\text{sqr } x) + 2*(b/(2*a))*x + (\text{sqr } (b/(2*a))))$
using *lemSqrSum*[of $x (b/(2*a))$] *mult-assoc*
mult-commute[of $x (b/(2*a))$]
by *auto*
hence 1: $a * \text{sqr } (x + (b/(2*a))) = (a * (\text{sqr } x)) + (a*(2*(b/(2*a))*x)) + (a * \text{sqr } (b/(2*a)))$
using *distrib-left* by *auto*
have $a*(2*(b/(2*a))*x) = b*x$ using *mult-assoc* *assms(2)* by *simp*

hence 2: $a * \text{sqr } (x + (b/(2*a))) = a*(\text{sqr } x) + (b*x) + (a * \text{sqr } (b/(2*a)))$
using 1 by *auto*

have $(a * \text{sqr } (b/(2*a))) = c + ((a * \text{sqr } (b/(2*a))) - c)$
using *add-commute* *diff-add-cancel* by *auto*
hence $(a * \text{sqr } (x + (b/(2*a)))) = (a*(\text{sqr } x) + (b*x) + c) + ((a * \text{sqr } (b/(2*a))) - c)$ using 2
add-assoc by *auto*
hence 3: $(a * \text{sqr } (x + (b/(2*a)))) \geq ((a * \text{sqr } (b/(2*a))) - c)$
using *assms(1)* by *auto*
}
hence $\forall x. (a * \text{sqr } (x + (b/(2*a)))) \geq ((a * \text{sqr } (b/(2*a))) - c)$
by *auto*

hence $(a * \text{sqr } ((-b/(2*a)) + (b/(2*a)))) \geq ((a * \text{sqr } (b/(2*a))) - c)$ by *fast*
hence $((a * \text{sqr } (b/(2*a))) - c) \leq 0$ by *simp*
hence $4*a*((a * \text{sqr } (b/(2*a))) - c) \leq 0$
using *local.mult-le-0-iff* *assms(2)* by *auto*
hence $4*a*((a * \text{sqr } (b/(2*a)))) - 4*a*c \leq 0$
using *right-diff-distrib* *mult-assoc* by *auto*
hence 4: $4*a*((a * \text{sqr } (b/(2*a)))) \leq 4*a*c$ by *simp*

have $\text{sqr } (b/(2*a)) = (\text{sqr } b)/(4*a*a)$
using *mult-assoc* *mult-commute* by *simp*
hence $4*a*((a * \text{sqr } (b/(2*a)))) = 4*a*((a * (\text{sqr } b)/(4*a*a)))$ by

auto
hence $4*a*((a * \text{sqr } (b/(2*a)))) = (4*a*a)*(\text{sqr } b)/(4*a*a)$
using *mult-commute* **by** *auto*
hence $4*a*((a * \text{sqr } (b/(2*a)))) = (\text{sqr } b)$
using *assms(2)* **by** *simp*

thus *?thesis* **using** *4* **by** *auto*
qed

lemma *lemSquareExistsAbove*:
shows $\exists x > 0 . (\text{sqr } x) > y$
proof –
have *cases*: $(y \leq 0) \vee (y > 0)$ **by** *auto*
have *one*: $1 \geq 0$ **by** *simp*
have *onestrict*: $0 < 1$ **by** *simp*

{ **assume** *yle0*: $y \leq 0$
hence $y < \text{sqr } 1$ **using** *yle0 le-less-trans* **by** *simp*
hence *?thesis* **using** *onestrict* **by** *fast*
}
hence *case1*: $(y \leq 0) \longrightarrow ?thesis$ **by** *auto*

{ **assume** *ygt0*: $y > 0$
{ **assume** *ytl1*: $y < 1$
hence $\text{sqr } y < y$ **using** *ygt0 mult-strict-left-mono[of y 1]* **by** *auto*
hence $\text{sqr } y < \text{sqr } 1$ **using** *ytl1* **by** *simp*
hence $y < 1$ **using** *ygt0 lemSqrOrderedStrict[of 1 y]* **by** *auto*
hence $y < \text{sqr } 1$ **by** *simp*
hence *?thesis* **using** *onestrict* **by** *best*
}
hence *a*: $(y < 1) \longrightarrow ?thesis$ **by** *auto*
{ **assume** $y = 1$
hence *b1*: $y < \text{sqr } 2$ **by** *simp*
have $2 > 0$ **by** *simp*
hence *?thesis* **using** *b1* **by** *fast*
}
hence *b*: $(y = 1) \longrightarrow ?thesis$ **by** *auto*
{ **assume** *ygt1*: $y > 1$
hence *yge1*: $y \geq 1$ **by** *simp*
have *yge0*: $y \geq 0$ **using** *ygt0* **by** *simp*
have $y \leq y$ **by** *simp*
hence $\text{sqr } y > y*1$ **using** *lemMultPosLT ygt0 ygt1* **by** *blast*
hence $\text{sqr } y > y$ **by** *simp*
hence *?thesis* **using** *ygt0* **by** *bestsimp*
}
hence $(y > 1) \longrightarrow ?thesis$ **by** *simp*

hence $((y < 1) \vee (y = 1) \vee (y > 1)) \longrightarrow ?thesis$ **using** *a b* **by** *auto*

```

    hence ?thesis by fastforce
  }
  hence ypos: (y > 0) → ?thesis by auto

  thus ?thesis using cases case1 by auto
qed

```

```

lemma lemSmallSquares:
  assumes x > 0
  shows ∃ y > 0. (sqr y < x)
proof -
  have invpos: 1/x > 0 using assms(1) by auto
  then obtain z where z: (z > 0) ∧ ((sqr z) > (1/x))
    using lemSquareExistsAbove by auto
  define y where y: y = 1/z
  hence ypos: y > 0 using z by auto
  have 1: 1/(sqr z) < 1/(1/x) using z invpos
    by (meson local.divide-strict-left-mono
      local.mult-pos-pos local.zero-less-one)
  hence (sqr y) < x using z y by simp
  thus ?thesis using ypos by auto
qed

```

```

lemma lemSqrLT1:
  assumes 0 < x < 1
  shows 0 < (sqr x) < x
using assms lemMultPosLT1[of x x] by auto

```

```

lemma lemReducedBound:
  assumes x > 0
  shows ∃ y > 0 . (y < x) ∧ (sqr y < y) ∧ (y < 1)
proof -
  have x2: x > x/2
    using assms lemSumOfTwoHalves[of x] add-strict-left-mono[of 0
x/2 x/2]
    by auto
  have x2pos: x/2 > 0 using assms by simp

  define y where y = min (x/2) (1/2)
  hence y: (y ≤ x/2) ∧ (y ≤ 1/2) ∧ (y > 0) using x2pos by auto

  have yltr: y < x using y x2 le-less-trans by auto
  have ylt1: y < 1 using y le-less-trans by auto

  hence sqr y < y using lemSqrLT1 y by simp

```

```

    thus ?thesis using yltx ylt1 y by auto
qed

end

```

```
end
```

2 Points

This theory defines (1+3)-dimensional spacetime points. The first coordinate is the time coordinate, and the remaining three coordinates give the spatial component.

```

theory Points
  imports Sorts
begin

```

```

record 'a Point =
  tval :: 'a
  xval :: 'a
  yval :: 'a
  zval :: 'a

```

```

record 'a Space =
  svalx :: 'a
  svaly :: 'a
  svalz :: 'a

```

```

abbreviation tComponent :: 'a Point  $\Rightarrow$  'a where
  tComponent p  $\equiv$  tval p

```

```

abbreviation sComponent :: 'a Point  $\Rightarrow$  'a Space where
  sComponent p  $\equiv$  (| svalx = xval p, svaly = yval p, svalz = zval p |)

```

```

abbreviation mkPoint :: 'a  $\Rightarrow$  'a  $\Rightarrow$  'a  $\Rightarrow$  'a  $\Rightarrow$  'a Point where
  mkPoint t x y z  $\equiv$  (| tval = t, xval = x, yval = y, zval = z |)

```

```

abbreviation stPoint :: 'a  $\Rightarrow$  'a Space  $\Rightarrow$  'a Point where
  stPoint t s  $\equiv$  mkPoint t (svalx s) (svaly s) (svalz s)

```

```

abbreviation mkSpace :: 'a  $\Rightarrow$  'a  $\Rightarrow$  'a  $\Rightarrow$  'a Space where
  mkSpace x y z  $\equiv$  (| svalx = x, svaly = y, svalz = z |)

```

Points have coordinates in the field of quantities, and can be

thought of as the end-points of vectors pinned to the origin. We can translate and scale them, define accumulation points, etc.

```
class Points = Quantities
begin
```

```
abbreviation moveBy :: 'a Point ⇒ 'a Point ⇒ 'a Point (⟨- ⊕ -⟩)
```

```
where
```

```
(p ⊕ q) ≡ (| tval = tval p + tval q,
             xval = xval p + xval q,
             yval = yval p + yval q,
             zval = zval p + zval q |)
```

```
abbreviation movebackBy :: 'a Point ⇒ 'a Point ⇒ 'a Point (⟨- ⊖
```

```
-⟩) where
```

```
(p ⊖ q) ≡ (| tval = tval p - tval q,
             xval = xval p - xval q,
             yval = yval p - yval q,
             zval = zval p - zval q |)
```

```
abbreviation sMoveBy :: 'a Space ⇒ 'a Space ⇒ 'a Space (⟨- ⊕s -⟩)
```

```
where
```

```
(p ⊕s q) ≡ (| svalx = svalx p + svalx q,
             svaly = svaly p + svaly q,
             svalz = svalz p + svalz q |)
```

```
abbreviation sMovebackBy :: 'a Space ⇒ 'a Space ⇒ 'a Space (⟨- ⊖s
```

```
-⟩) where
```

```
(p ⊖s q) ≡ (| svalx = svalx p - svalx q,
             svaly = svaly p - svaly q,
             svalz = svalz p - svalz q |)
```

```
abbreviation scaleBy :: 'a ⇒ 'a Point ⇒ 'a Point (⟨- ⊗ -⟩) where
```

```
scaleBy a p ≡ (| tval = a*tval p, xval = a*xval p,
                 yval = a*yval p, zval = a*zval p)
```

```
abbreviation sScaleBy :: 'a ⇒ 'a Space ⇒ 'a Space (⟨- ⊗s -⟩) where
```

```
sScaleBy a p ≡ (| svalx = a*svalx p,
                 svaly = a*svaly p,
                 svalz = a*svalz p)
```

```
abbreviation sOrigin :: 'a Space where
```

$sOrigin \equiv \langle \langle svalx = 0, svaly = 0, svalz = 0 \rangle \rangle$

abbreviation $origin :: 'a Point$ **where**
 $origin \equiv \langle \langle tval = 0, xval = 0, yval = 0, zval = 0 \rangle \rangle$

abbreviation $tUnit :: 'a Point$ **where**
 $tUnit \equiv \langle \langle tval = 1, xval = 0, yval = 0, zval = 0 \rangle \rangle$

abbreviation $xUnit :: 'a Point$ **where**
 $xUnit \equiv \langle \langle tval = 0, xval = 1, yval = 0, zval = 0 \rangle \rangle$

abbreviation $yUnit :: 'a Point$ **where**
 $yUnit \equiv \langle \langle tval = 0, xval = 0, yval = 1, zval = 0 \rangle \rangle$

abbreviation $zUnit :: 'a Point$ **where**
 $zUnit \equiv \langle \langle tval = 0, xval = 0, yval = 0, zval = 1 \rangle \rangle$

abbreviation $timeAxis :: 'a Point set$ **where**
 $timeAxis \equiv \{ p . xval p = 0 \wedge yval p = 0 \wedge zval p = 0 \}$

abbreviation $onTimeAxis :: 'a Point \Rightarrow bool$
where $onTimeAxis p \equiv (p \in timeAxis)$

2.1 Squared norms and separation functions

This theory defines squared norms and separations. We do not yet define unsquared norms because we are not assuming here that quantities necessarily have square roots.

abbreviation $norm2 :: 'a Point \Rightarrow 'a$ **where**
 $norm2 p \equiv sqr (tval p) + sqr (xval p) + sqr (yval p) + sqr (zval p)$

abbreviation $sep2 :: 'a Point \Rightarrow 'a Point \Rightarrow 'a$ **where**
 $sep2 p q \equiv norm2 (p \ominus q)$

abbreviation $sNorm2 :: 'a Space \Rightarrow 'a$ **where**
 $sNorm2 s \equiv sqr (svalx s)$
 $+ sqr (svaly s)$
 $+ sqr (svalz s)$

abbreviation $sSep2 :: 'a Point \Rightarrow 'a Point \Rightarrow 'a$ **where**
 $sSep2 p q \equiv sqr (xval p - xval q)$
 $+ sqr (yval p - yval q)$
 $+ sqr (zval p - zval q)$

abbreviation $mNorm2 :: 'a Point \Rightarrow 'a (\langle \! \! \langle - \! \! \rangle \! \rangle m)$
where $\| p \| m \equiv sqr (tval p) - sNorm2 (sComponent p)$

2.2 Topological concepts

We will need to define topological concepts like continuity and affine approximation later, so here we define open balls and accumulation points.

abbreviation $inBall :: 'a Point \Rightarrow 'a \Rightarrow 'a Point \Rightarrow bool$
 ($\langle \cdot \rangle$ - within - of \cdot)

where $inBall\ q\ \varepsilon\ p \equiv sep2\ q\ p < sqr\ \varepsilon$

abbreviation $ball :: 'a Point \Rightarrow 'a \Rightarrow 'a Point\ set$

where $ball\ q\ \varepsilon \equiv \{ p . inBall\ q\ \varepsilon\ p \}$

abbreviation $accPoint :: 'a Point \Rightarrow 'a Point\ set \Rightarrow bool$

where $accPoint\ p\ s \equiv \forall\ \varepsilon > 0. \exists\ q \in s. (p \neq q) \wedge (inBall\ q\ \varepsilon\ p)$

2.3 Lines

A line is specified by giving a point on the line, and a point (thought of as a vector) giving its direction. For these purposes it doesn't matter whether the direction is "positive" or "negative".

abbreviation $line :: 'a Point \Rightarrow 'a Point \Rightarrow 'a Point\ set$

where $line\ base\ drtn \equiv \{ p . \exists\ \alpha . p = (base \oplus (\alpha \otimes drtn)) \}$

abbreviation $lineJoining :: 'a Point \Rightarrow 'a Point \Rightarrow 'a Point\ set$

where $lineJoining\ p\ q \equiv line\ p\ (q \ominus p)$

abbreviation $isLine :: 'a Point\ set \Rightarrow bool$

where $isLine\ l \equiv \exists\ b\ d . (l = line\ b\ d)$

abbreviation $sameLine :: 'a Point\ set \Rightarrow 'a Point\ set \Rightarrow bool$

where $sameLine\ l1\ l2 \equiv ((isLine\ l1) \vee (isLine\ l2)) \wedge (l1 = l2)$

abbreviation $onLine :: 'a Point \Rightarrow 'a Point\ set \Rightarrow bool$

where $onLine\ p\ l \equiv (isLine\ l) \wedge (p \in l)$

2.4 Directions

Given any two distinct points on a line, the vector joining them can be used to specify the line's direction. The direction of a line is therefore a *set* of points/vectors. By `lemDrtn` these are all parallel

fun $drtn :: 'a Point\ set \Rightarrow 'a Point\ set$

where $drtn\ l = \{ d . \exists\ p\ q . (p \neq q) \wedge (onLine\ p\ l) \wedge (onLine\ q\ l) \wedge (d = (q \ominus p)) \}$

abbreviation $parallelLines :: 'a Point\ set \Rightarrow 'a Point\ set \Rightarrow bool$

where $parallelLines\ l1\ l2 \equiv (drtn\ l1) \cap (drtn\ l2) \neq \{\}$

abbreviation *parallel* :: 'a Point \Rightarrow 'a Point \Rightarrow bool ($\langle - \parallel - \rangle$)
where *parallel* p q \equiv ($\exists \alpha \neq 0 . p = (\alpha \otimes q)$)

The "slope" of a line can be either finite or infinite. We will often need to consider these two cases separately.

abbreviation *slopeFinite* :: 'a Point \Rightarrow 'a Point \Rightarrow bool
where *slopeFinite* p q \equiv (*tval* p \neq *tval* q)

abbreviation *slopeInfinite* :: 'a Point \Rightarrow 'a Point \Rightarrow bool
where *slopeInfinite* p q \equiv (*tval* p = *tval* q)

abbreviation *lineSlopeFinite* :: 'a Point set \Rightarrow bool
where *lineSlopeFinite* l \equiv ($\exists x y . (\text{onLine } x \ l) \wedge (\text{onLine } y \ l) \wedge (x \neq y) \wedge (\text{slopeFinite } x \ y)$)

2.5 Slopes and slopers

We specify the slope of a line by giving the spatial component ("sloper") of the point on the line at time 1. This is defined if and only if the slope is finite. If the slope is infinite (the line is "horizontal") we return the spatial origin. This avoids using "option" but means we need to consider carefully whether a sloper with value sOrigin indicates a truly zero slope or an infinite one.

fun *sloper* :: 'a Point \Rightarrow 'a Point \Rightarrow 'a Point
where *sloper* p q = (*if* (*slopeFinite* p q) *then* ((1 / (*tval* p - *tval* q)) \otimes (p \ominus q))
else *origin*)

fun *velocityJoining* :: 'a Point \Rightarrow 'a Point \Rightarrow 'a Space
where *velocityJoining* p q = *sComponent* (*sloper* p q)

fun *lineVelocity* :: 'a Point set \Rightarrow 'a Space set
where *lineVelocity* l = { v . $\exists d \in \text{drtn } l . v = \text{velocityJoining } \text{origin } d$ }

lemma *lemNorm2Decomposition*:
shows $\text{norm2 } u = \text{sqr } (\text{tval } u) + \text{sNorm2 } (\text{sComponent } u)$
by (*simp add: add-commute local.add.left-commute*)

lemma *lemPointDecomposition*:
shows $p = (((\text{tval } p) \otimes \text{tUnit}) \oplus (((\text{xval } p) \otimes \text{xUnit})$
 $\oplus (((\text{yval } p) \otimes \text{yUnit}) \oplus ((\text{zval } p) \otimes \text{zUnit}))))$
by *force*

lemma *lemScaleLeftSumDistrib*: $((a + b) \otimes p) = ((a \otimes p) \oplus (b \otimes p))$
using *distrib-right by auto*

lemma *lemScaleLeftDiffDistrib*: $((a - b) \otimes p) = ((a \otimes p) \ominus (b \otimes p))$
using *left-diff-distrib by auto*

lemma *lemScaleAssoc*: $(\alpha \otimes (\beta \otimes p)) = ((\alpha * \beta) \otimes p)$
using *semiring-normalization-rules(18) by auto*

lemma *lemScaleCommute*: $(\alpha \otimes (\beta \otimes p)) = (\beta \otimes (\alpha \otimes p))$
using *mult.left-commute by auto*

lemma *lemScaleDistribSum*: $(\alpha \otimes (p \oplus q)) = ((\alpha \otimes p) \oplus (\alpha \otimes q))$
using *distrib-left by auto*

lemma *lemScaleDistribDiff*: $(\alpha \otimes (p \ominus q)) = ((\alpha \otimes p) \ominus (\alpha \otimes q))$
using *right-diff-distrib by auto*

lemma *lemScaleOrigin*: $(\alpha \otimes \text{origin}) = \text{origin}$
by *auto*

lemma *lemMNorm2OfScaled*: $m\text{Norm2 } (\text{scaleBy } \alpha \ p) = (\text{sqr } \alpha) * m\text{Norm2 } p$
using *lemSqrMult distrib-left right-diff-distrib' by simp*

lemma *lemSNorm2OfScaled*: $s\text{Norm2 } (\text{sScaleBy } \alpha \ p) = (\text{sqr } \alpha) * s\text{Norm2 } p$
using *lemSqrMult distrib-left by auto*

lemma *lemNorm2OfScaled*: $\text{norm2 } (\alpha \otimes p) = (\text{sqr } \alpha) * \text{norm2 } p$
using *lemSqrMult distrib-left by auto*

lemma *lemScaleSep2*: $(\text{sqr } a) * (\text{sep2 } p \ q) = \text{sep2 } (a \otimes p) \ (a \otimes q)$
using *lemNorm2OfScaled*[of a $p \ominus q$] *lemScaleDistribDiff* **by** *auto*

lemma *lemSScaleAssoc*: $(\alpha \otimes s \ (\beta \otimes s \ p)) = ((\alpha * \beta) \otimes s \ p)$
using *semiring-normalization-rules(18)* **by** *auto*

lemma *lemScaleBall*:
assumes *x* *within e* *of y*
and $a \neq 0$
shows $(a \otimes x)$ *within* $(a * e)$ *of* $(a \otimes y)$
proof –
have *a2pos*: $\text{sqr } a > 0$ **using** *assms(2)* *lemSquaresPositive* **by** *auto*
have $\text{sep2 } (a \otimes x) \ (a \otimes y) = (\text{sqr } a) * (\text{sep2 } x \ y)$ **using** *lemScaleSep2*
by *auto*
hence $\text{sep2 } (a \otimes x) \ (a \otimes y) < (\text{sqr } a) * (\text{sqr } e)$
using *assms* *mult-strict-left-mono* *a2pos* **by** *auto*
thus *?thesis* **using** *mult-commute* *mult-assoc* **by** *auto*
qed

lemma *lemScaleBallAndBoundary*:
assumes $\text{sep2 } x \ y \leq \text{sqr } e$
and $a \neq 0$
shows $\text{sep2 } (a \otimes x) \ (a \otimes y) \leq \text{sqr } (a * e)$
proof –
have *a2pos*: $\text{sqr } a > 0$ **using** *assms(2)* *lemSquaresPositive* **by** *auto*
have $\text{sep2 } (a \otimes x) \ (a \otimes y) = (\text{sqr } a) * (\text{sep2 } x \ y)$ **using** *lemScaleSep2*
by *auto*
hence $\text{sep2 } (a \otimes x) \ (a \otimes y) \leq (\text{sqr } a) * (\text{sqr } e)$
using *assms* *mult-left-mono* *a2pos* **by** *auto*
thus *?thesis* **using** *mult-commute* *mult-assoc* **by** *auto*
qed

lemma *lemTimeAxisIsLine*: *isLine* *timeAxis*
proof –
{ **fix** *p*
{ **assume** *p*: $p \in \text{timeAxis}$
hence $p = (\text{origin} \oplus ((\text{tval } p) \otimes \text{tUnit}))$ **by** *auto*
}
hence *l2r*: $\text{onTimeAxis } p \longrightarrow (\exists v . (p = (\text{origin} \oplus (v \otimes \text{tUnit}))))$
by *blast*
{ **assume** *v*: $\exists v . p = (\text{origin} \oplus (v \otimes \text{tUnit}))$

```

    hence onTimeAxis p by auto
  }
  hence  $(\exists v . (p = (\text{origin} \oplus (v \otimes \text{tUnit})))) \longleftrightarrow \text{onTimeAxis } p$ 
    using l2r by blast
  }
  hence timeAxis = line origin tUnit by blast
  thus ?thesis by blast
qed

```

lemma *lemSameLine*:

```

  assumes  $p \in \text{line } b \ d$ 
  shows   sameLine (line b d) (line p d)
  proof -
    define l1 where  $l1 : l1 = \text{line } b \ d$ 
    define l2 where  $l2 : l2 = \text{line } p \ d$ 
    have lines:  $\text{isLine } l1 \wedge \text{isLine } l2$  using l1 l2 by blast

    obtain A where  $p : p = (b \oplus (A \otimes d))$  using assms by auto
    hence b:  $b = (p \ominus (A \otimes d))$  by auto

    { fix x
      { assume  $x : x \in l1$ 
        then obtain a where  $a : x = (b \oplus (a \otimes d))$  using l1 by auto
        hence  $x = ((p \ominus (A \otimes d)) \oplus (a \otimes d))$  using b by simp
        also have  $\dots = (p \oplus ((a \otimes d) \ominus (A \otimes d)))$ 
          using add-diff-eq diff-add-eq add-commute add-assoc by simp
        finally have  $x = (p \oplus ((a - A) \otimes d))$ 
          using lemScaleLeftDiffDistrib by presburger
        hence  $x \in l2$  using l2 by auto
      }
    }
    hence l2r:  $(x \in l1) \longrightarrow (x \in l2)$  using l2 by simp

    { assume  $x : x \in l2$ 
      then obtain a where  $a : x = (p \oplus (a \otimes d))$  using l2 by auto
      hence  $x = (b \oplus ((A + a) \otimes d))$ 
        using p add-assoc lemScaleAssoc distrib by auto
      hence  $x \in l1$  using l1 by auto
    }
    hence  $(x \in l1) \longleftrightarrow (x \in l2)$  using l2r by auto
  }
  thus ?thesis using lines l1 l2 by auto
qed

```

lemma *lemSSep2Symmetry*: $sSep2\ p\ q = sSep2\ q\ p$
using *lemSqrDiffSymmetrical* **by** *simp*

lemma *lemSep2Symmetry*: $sep2\ p\ q = sep2\ q\ p$
using *lemSqrDiffSymmetrical* **by** *simp*

lemma *lemSpatialNullImpliesSpatialOrigin*:
assumes $sNorm2\ s = 0$
shows $s = sOrigin$
using *assms local.add-nonneg-eq-0-iff* **by** *auto*

lemma *lemNorm2NonNeg*: $norm2\ p \geq 0$
by *simp*

lemma *lemNullImpliesOrigin*:
assumes $norm2\ p = 0$
shows $p = origin$
proof –
have $norm2\ p = sqr\ (tval\ p) + sNorm2\ (sComponent\ p)$ **using**
add-assoc **by** *simp*
hence a : $sqr\ (tval\ p) + sNorm2\ (sComponent\ p) = 0$ **using** *assms*
by *auto*
{ **assume** b : $sNorm2\ (sComponent\ p) > 0$
have $sqr\ (tval\ p) + sNorm2\ (sComponent\ p) > 0$
using b *lemSumOfNonNegAndPos* **by** *auto*
hence *False* **using** a **by** *auto*
}
hence c : $\neg(sNorm2\ (sComponent\ p) > 0)$ **by** *auto*
have d : $sNorm2\ (sComponent\ p) \geq 0$ **by** *auto*

have $\forall x. (\neg(x > 0)) \wedge (x \geq 0) \longrightarrow x = 0$ **by** *auto*
hence e : $sNorm2\ (sComponent\ p) = 0$ **using** $c\ d$ **by** *force*
hence f : $sComponent\ p = sOrigin$
using *lemSpatialNullImpliesSpatialOrigin* **by** *blast*

have $norm2\ p = sqr\ (tval\ p)$ **using** e *add-assoc* **by** *auto*
hence $sqr\ (tval\ p) = 0$ **using** *assms* **by** *simp*
hence $(tval\ p) = 0$ **using** *lemZeroRoot* **by** *simp*

thus *?thesis* **using** f **by** *auto*
qed

lemma *lemNotOriginImpliesPosNorm2*:
assumes $p \neq origin$

shows $\text{norm2 } p > 0$
proof –
have $1: \text{norm2 } p \geq 0$ **by** *simp*
have $2: \text{norm2 } p \neq 0$ **using** *assms(1) lemNullImpliesOrigin* **by** *force*
thus *?thesis* **using** $1\ 2$ *dual-order.not-eq-order-implies-strict* **by** *fast*
qed

lemma *lemNotEqualImpliesSep2Pos*:
assumes $y \neq x$
shows $\text{sep2 } y\ x > 0$
proof –
have $(y \ominus x) \neq \text{origin}$ **using** *assms* **by** *auto*
hence $1: \text{norm2 } (y \ominus x) > 0$ **using** *lemNotOriginImpliesPosNorm2*
by *fast*
have $\text{sep2 } y\ x = \text{norm2 } (y \ominus x)$ **by** *auto*
thus *?thesis* **using** 1 **by** *auto*
qed

lemma *lemBallContainsCentre*:
assumes $\varepsilon > 0$
shows x *within* ε *of* x
proof –
have $\text{sep2 } x\ x = 0$ **by** *auto*
thus *?thesis* **using** *assms* **by** *auto*
qed

lemma *lemPointLimit*:
assumes $\forall \varepsilon > 0 . (v \text{ within } \varepsilon \text{ of } u)$
shows $v = u$
proof –
define d **where** $d: d = \text{sep2 } v\ u$
{ **assume** $v \neq u$
hence $d > 0$ **using** *lemNotEqualImpliesSep2Pos* d **by** *auto*
then obtain s **where** $(0 < s) \wedge (\text{sqr } s < d)$ **using** *lemSmallSquares* **by** *auto*
hence v *within* s *of* u **using** d *assms(1)* **by** *auto*
hence $\text{sep2 } v\ u < \text{sep2 } v\ u$ **using** $s\ d$ **by** *auto*
hence *False* **by** *auto*
}
thus *?thesis* **by** *auto*
qed

lemma *lemBallPopulated*:
assumes $e > 0$
shows $\exists y . (y \text{ within } e \text{ of } x) \wedge (y \neq x)$

proof –
obtain $e1$ **where** $e1: (0 < e1) \wedge (e1 < e) \wedge (\text{sqr } e1 < e1)$
using *assms lemReducedBound* **by** *auto*
hence $e2: \text{sqr } e1 < \text{sqr } e$ **using** *lemSqrMonoStrict[of e1 e]* **by** *auto*

define y **where** $y: y = (x \oplus (\text{tval} = e1, \text{xval}=0, \text{yval}=0, \text{zval}=0))$
hence $(y \ominus x) = (\text{tval} = e1, \text{xval}=0, \text{yval}=0, \text{zval}=0)$ **by** *auto*
hence $\text{sep2 } y \ x = \text{sqr } e1$ **by** *auto*
hence $1: y$ *within* e **of** x **using** $e2$ **by** *auto*

have $\text{tval } y = \text{tval } x + e1$ **using** y **by** *simp*
hence $y \neq x$ **using** $e1$ **by** *auto*
thus *?thesis* **using** 1 **by** *auto*
qed

lemma *lemBallInBall*:
assumes p *within* x **of** q
and $0 < x \leq y$
shows p *within* y **of** q
proof –
have $\text{sqr } x \leq \text{sqr } y$ **using** *assms(2) lemSqrMono* **by** *auto*
thus *?thesis* **using** *le-less-trans* **using** *assms(1)* **by** *auto*
qed

lemma *lemSmallPoints*:
assumes $e > 0$
shows $\exists a > 0 . \text{norm2 } (a \otimes p) < \text{sqr } e$
proof –

{ **assume** $po: p = \text{origin}$
define a **where** $a: a = 1$
hence $apos: a > 0$ **by** *auto*
have $\text{norm2 } (a \otimes p) < \text{sqr } e$ **using** a po *assms* **by** *auto*
hence *?thesis* **using** $apos$ **by** *auto*
}

{ **assume** $pnoto: p \neq \text{origin}$

obtain $e1$ **where** $e1: (e1 > 0) \wedge (e1 < e) \wedge (\text{sqr } e1 < e1)$
using *lemReducedBound assms* **by** *auto*
hence $e1\text{sqr}: 0 < (\text{sqr } e1) < (\text{sqr } e)$ **using** *lemSqrMonoStrict* **by** *auto*

define $n2$ **where** $n2: n2 = \text{norm2 } p$
hence $n2\text{pos}: n2 > 0$ **using** $pnoto$ *lemNotOriginImpliesPosNorm2*

by *auto*
 then obtain s where $s: (s > 0) \wedge (\text{sqr } s > n^2)$
 using *lemSquareExistsAbove* by *auto*
 hence $0 < (n^2/(\text{sqr } s)) < 1$ using *n2pos* by *auto*
 hence $(\text{sqr } e1) * (n^2/(\text{sqr } s)) < \text{sqr } e1$
 using *lemMultPosLT1*[of *sqr e1 (n2/(sqr s))*] *e1sqr* by *auto*
 hence *ineq*: $(\text{sqr } e1) * (n^2/(\text{sqr } s)) < \text{sqr } e$ using *e1sqr* by *auto*

 define a where $a: a = e1/s$
 have $e1 > 0 \wedge s > 0$ using *e1 s* by *auto*
 hence *apos*: $a > 0$ using a by *auto*
 have $\text{norm2 } (a \otimes p) = (\text{sqr } e1) * (n^2/(\text{sqr } s))$
 using *lemNorm2OfScaled*[of a] a *n2* by *auto*
 hence $\text{norm2 } (a \otimes p) < \text{sqr } e$ using *ineq* by *auto*
 hence *?thesis* using *apos* by *auto*
 }
 hence $p \neq \text{origin} \rightarrow ?thesis$ by *auto*

 thus *?thesis* using *case1* by *auto*
 qed

lemma *lemLineJoiningContainsEndPoints*:
 assumes $l = \text{lineJoining } x \ p$
 shows $\text{onLine } x \ l \wedge \text{onLine } p \ l$
proof –
 have *line*: $\text{isLine } l$ using *assms(1)* by *blast*
 have $p: x = (x \oplus (0 \otimes (p \ominus x)))$ by *simp*
 have $x: p = (x \oplus (1 \otimes (p \ominus x)))$ using *add-commute diff-add-cancel*
 by *fastforce*
 thus *?thesis* using p *line* *assms(1)* by *blast*
 qed

lemma *lemLineAndPoints*:
 assumes $p \neq q$
 shows $(\text{onLine } p \ l \wedge \text{onLine } q \ l) \longleftrightarrow (l = \text{lineJoining } p \ q)$
proof –

 define lj where $lj: lj = \text{lineJoining } p \ q$
 define *lhs* where *lhs*: $\text{lhs} = (\text{onLine } p \ l \wedge \text{onLine } q \ l)$
 define *rhs* where *rhs*: $\text{rhs} = (l = lj)$

 { assume *hyp*: *lhs*
 then obtain $b \ d$ where $bd: l = \{ x. \exists a. x = (b \oplus (a \otimes d)) \}$
 using *lhs* by *auto*
 }

 obtain ap where $ap: p = (b \oplus (ap \otimes d))$ using *hyp lhs bd* by *auto*

obtain aq **where** $aq: q = (b \oplus (aq \otimes d))$ **using** *hyp lhs bd* **by**
auto
hence $(q \ominus p) = ((b \oplus (aq \otimes d)) \ominus (b \oplus (ap \otimes d)))$ **using** *ap* **by**
fast
also have $\dots = ((aq \otimes d) \ominus (ap \otimes d))$ **using** *add-diff-cancel* **by**
auto
finally have *qdiffp*: $(q \ominus p) = ((aq - ap) \otimes d)$
using *lemScaleLeftDiffDistrib*[of aq ap d] **by** *auto*

define R **where** $R: R = aq - ap$
hence *Rnz*: $R \neq 0$ **using** *assms(1)* *qdiffp* **by** *auto*
define r **where** $r: r = 1/R$
hence $(r \otimes (R \otimes d)) = (r \otimes (q \ominus p))$ **using** R *qdiffp* **by** *auto*
hence $d: d = (r \otimes (q \ominus p))$ **using** *lemScaleAssoc*[of r R d] r *Rnz*
by *force*

have $b = (p \ominus (ap \otimes d))$ **using** *ap* **by** *auto*
also have $\dots = (p \ominus (ap \otimes (r \otimes (q \ominus p))))$ **using** d **by** *auto*
finally have $b: b = (p \ominus ((ap * r) \otimes (q \ominus p)))$
using *lemScaleAssoc*[of ap r $q \ominus p$] **by** *auto*

{ **fix** x
assume $x \in l$
then obtain a **where** $x = (b \oplus (a \otimes d))$ **using** *bd* **by** *auto*
hence $x = ((p \ominus ((ap * r) \otimes (q \ominus p))) \oplus ((a * r) \otimes (q \ominus p)))$
using b d *lemScaleAssoc*[of a r $q \ominus p$] **by** *fastforce*
also have $\dots = (p \oplus (((a * r) \otimes (q \ominus p)) \ominus ((ap * r) \otimes (q \ominus p))))$
using *add-diff-eq* *diff-add-eq* **by** *force*
also have $\dots = (p \oplus (((a * r) - (ap * r)) \otimes (q \ominus p)))$
using *left-diff-distrib* **by** *force*
finally have $x \in lj$ **using** lj **by** *auto*
}
hence $l2r: l \subseteq lj$ **by** *auto*

{ **fix** x
assume $x \in lj$
then obtain a **where** $a: x = (p \oplus (a \otimes (q \ominus p)))$ **using** lj **by** *auto*
hence $x = ((b \oplus (ap \otimes d)) \oplus (a \otimes (R \otimes d)))$ **using** ap *qdiffp* R
by *auto*
also have $\dots = (b \oplus ((ap + a * R) \otimes d))$
using *add-assoc* *distrib-right* *lemScaleAssoc*
by *auto*
finally have *onLine* x l **using** *bd* **by** *auto*
}
hence $lj \subseteq l$ **by** *auto*
hence $l = lj$ **using** $l2r$ **by** *auto*
}
hence $L2R: lhs \longrightarrow rhs$ **using** rhs **by** *auto*

```

{ assume l: rhs
  hence line: isLine l using rhs lj by blast
  have p: p = (p ⊕ (0 ⊗ (q ⊖ p))) by simp
  have q: q = (p ⊕ (1 ⊗ (q ⊖ p))) using add-commute diff-add-cancel
by fastforce
  hence lhs using p line l lhs rhs lj by blast
}
hence rhs → lhs by auto

hence lhs ↔ rhs using L2R by auto

thus ?thesis using lhs rhs lj by auto
qed

```

```

lemma lemLineDefinedByPair:
  assumes x ≠ p
  and (onLine p l1) ∧ (onLine x l1)
  and (onLine p l2) ∧ (onLine x l2)
  shows l1 = l2
proof -
  have l1 = lineJoining x p
    using lemLineAndPoints[of x p l1] assms(1) assms(2) by auto
  also have ... = l2
    using lemLineAndPoints[of x p l2] assms(1) assms(3) by auto
  finally show l1 = l2 by auto
qed

```

```

lemma lemDrtn:
  assumes { d1, d2 } ⊆ drtn l
  shows ∃ α ≠ 0 . d2 = (α ⊗ d1)
proof -
  have d1d2: {d1, d2} ⊆ { d . ∃ p q . (p ≠ q) ∧ onLine p l ∧ onLine
q l ∧ (d = (q ⊖ p)) }
    using assms(1) by auto
  have d1: ∃ p1 q1 . (p1 ≠ q1) ∧ (onLine p1 l) ∧ (onLine q1 l) ∧
(d1 = (q1 ⊖ p1))
    using d1d2 by auto
  then obtain p1 q1
    where pq1: (p1 ≠ q1) ∧ (onLine p1 l) ∧ (onLine q1 l) ∧ (d1 =
(q1 ⊖ p1))
    by blast
  hence l1: l = lineJoining p1 q1 using lemLineAndPoints[of p1 q1
l] by auto

  have d2: ∃ p2 q2 . (p2 ≠ q2) ∧ (onLine p2 l) ∧ (onLine q2 l) ∧
(d2 = (q2 ⊖ p2))

```


using $d1d2$ **by** *auto*
then obtain $p2\ q2$
where $pq2: (p2 \neq q2) \wedge (\text{onLine } p2\ l) \wedge (\text{onLine } q2\ l) \wedge (d2 = (q2 \ominus p2))$
by *blast*

hence $(p2 \in \text{lineJoining } p1\ q1) \wedge (q2 \in \text{lineJoining } p1\ q1)$ **using** $l1$ **by** *blast*
then obtain $ap\ aq$
where $apaq: (p2 = (p1 \oplus (ap \otimes (q1 \ominus p1)))) \wedge ((q2 = (p1 \oplus (aq \otimes (q1 \ominus p1))))))$
by *blast*

define $diff$ **where** $diff: diff = aq - ap$
hence $diffnz: diff \neq 0$ **using** $apaq\ pq2$ **by** *auto*

have $d2 = (q2 \ominus p2)$ **using** $pq2$ **by** *simp*
also have $\dots = ((p1 \oplus (aq \otimes (q1 \ominus p1))) \ominus (p1 \oplus (ap \otimes (q1 \ominus p1))))$
using $apaq$ **by** *force*
also have $\dots = ((aq \otimes (q1 \ominus p1)) \ominus (ap \otimes (q1 \ominus p1)))$ **by** *auto*
also have $\dots = ((aq - ap) \otimes d1)$
using $pq1\ lemScaleLeftDiffDistrib$ [of $aq\ ap\ d1$] **by** *auto*
finally have $(d2 = (diff \otimes d1)) \wedge (diff \neq 0)$ **using** $diff\ diffnz$ **by** *auto*

thus *?thesis* **by** *auto*
qed

lemma *lemLineDeterminedByPointAndDrtn*:
assumes $(x \neq p) \wedge (p \in l1) \wedge (\text{onLine } x\ l1) \wedge (\text{onLine } x\ l2)$
and $drtn\ l1 = drtn\ l2$
shows $l1 = l2$
proof –

define $d1$ **where** $d1: d1 = drtn\ l1$
define $d2$ **where** $d2: d2 = drtn\ l2$
hence $dd: d1 = d2$ **using** $assms(2)$ $d1$ **by** *auto*

define px **where** $px: px = (p \ominus x)$

have $l1: (x \neq p) \wedge (\text{onLine } p\ l1) \wedge (\text{onLine } x\ l1)$ **using** $assms(1)$
by *auto*
hence $\exists p\ q. (p \neq q) \wedge \text{onLine } p\ l1 \wedge \text{onLine } q\ l1 \wedge (px = (q \ominus p))$ **using** px **by** *blast*
hence $px \in \{ d . \exists p\ q. (p \neq q) \wedge \text{onLine } p\ l1 \wedge \text{onLine } q\ l1 \wedge (d = (q \ominus p)) \}$
by *blast*
hence $px \in d1$ **using** $d1\ subst$ [of $d1\ drtn\ l1\ \lambda s. px \in s$] **by** *auto*
hence $px \in d2$ **using** dd **by** *simp*

hence $px \in drtn\ l2$ **using** $d2$ **by** *simp*
hence $\exists\ u\ v.\ (u \neq v) \wedge onLine\ u\ l2 \wedge onLine\ v\ l2 \wedge (px = (v \ominus u))$ **by** *auto*
then obtain $u\ v$ **where** $uv: (u \neq v) \wedge onLine\ u\ l2 \wedge onLine\ v\ l2 \wedge (px = (v \ominus u))$ **by** *blast*

hence $(x \neq u) \vee (x \neq v)$ **by** *blast*
then obtain w **where** $w: ((w = u) \vee (w = v)) \wedge (x \neq w)$ **by** *blast*
hence $xw: (x \neq w) \wedge (onLine\ x\ l2) \wedge (onLine\ w\ l2)$ **using** uv *assms(1)* **by** *blast*
hence $l2: l2 = lineJoining\ x\ w$ **using** $lemLineAndPoints[of\ x\ w\ l2]$ **by** *auto*
hence $(w \ominus x) \in drtn\ l2 \wedge px \in drtn\ l2$ **using** $xw\ px\ onl2$ **by** *auto*
then obtain a **where** $a: (a \neq 0) \wedge (p \ominus x) = (a \otimes (w \ominus x))$
using $lemDrtn[of\ w \ominus x\ p \ominus x\ l2]$ $px\ xw\ px\ onl2$ **by** *blast*
hence $p = (x \oplus (a \otimes (w \ominus x)))$ **by** (*auto simp add: field-simps*)
hence $onLine\ p$ (*lineJoining\ x\ w*) **by** *blast*

hence $l2lj: l2 = lineJoining\ x\ p$
using $lemLineAndPoints[of\ x\ p\ l2]$ $assms(1)\ l2\ xw$
by *auto*

have $l1lj: l1 = lineJoining\ x\ p$
using $lemLineAndPoints[of\ x\ p\ l1]$ $assms(1)$
by *auto*

thus *?thesis* **using** $l2lj$ **by** *blast*
qed

end

end

3 WorldView

This theory defines worldview transformations. These form the ultimate foundation for all of GenRel's axioms.

theory *WorldView*
imports *Points*
begin

class *WorldView* = *Points* +
fixes

$W :: Body \Rightarrow Body \Rightarrow 'a\ Point \Rightarrow bool$ (*<- sees - at ->*)

begin

abbreviation $ev :: Body \Rightarrow 'a Point \Rightarrow Body set$
where $ev\ h\ x \equiv \{ b . h\ sees\ b\ at\ x \}$

fun $wvt :: Body \Rightarrow Body \Rightarrow 'a Point \Rightarrow 'a Point set$
where $wvt\ m\ k\ p = \{ q . (\exists\ b . (m\ sees\ b\ at\ p)) \wedge (ev\ m\ p = ev\ k\ q) \}$

abbreviation $wvtFunc :: Body \Rightarrow Body \Rightarrow ('a Point \Rightarrow 'a Point \Rightarrow bool)$
where $wvtFunc\ m\ k \equiv (\lambda\ p\ q . q \in wvt\ m\ k\ p)$

abbreviation $wvtLine :: Body \Rightarrow Body \Rightarrow 'a Point set \Rightarrow 'a Point set \Rightarrow bool$
where $wvtLine\ m\ k\ l\ l' \equiv \exists\ p\ q\ p'\ q' . ($
 $(wvtFunc\ m\ k\ p\ p') \wedge (wvtFunc\ m\ k\ q\ q') \wedge$
 $(l = lineJoining\ p\ q) \wedge (l' = lineJoining$
 $p'\ q'))$

end

end

4 Functions

This theory characterises the various types of function (injective, bijective, etc).

theory *Functions*
imports *Points*
begin

We do not assume a priori that all of the functions we define are well-defined or total. We therefore need to allow for functions which are only partially defined, and also for "functions" which might be multi-valued. For example, we cannot say in advance whether one observer might see another's worldline as a bifurcating structure rather than a basic single-valued trajectory.

To achieve this we'll often think of functions as relations and write " $f\ x\ y = true$ " instead of " $f\ x = y$ ". Similarly, a spacetime set S will be sometimes be expressed as its characteristic function.

class *Functions = Points*
begin

abbreviation $bounded :: ('a Point \Rightarrow 'a Point) \Rightarrow bool$

where $\text{bounded } f \equiv \exists \text{ bnd} > 0 . (\forall p . (\text{norm2 } (f p) \leq \text{bnd} * (\text{norm2 } p)))$

abbreviation $\text{composeRel} :: ('a \text{ Point} \Rightarrow 'a \text{ Point} \Rightarrow \text{bool}) \Rightarrow ('a \text{ Point} \Rightarrow 'a \text{ Point} \Rightarrow \text{bool}) \Rightarrow ('a \text{ Point} \Rightarrow 'a \text{ Point} \Rightarrow \text{bool})$
where $(\text{composeRel } g f) p r \equiv (\exists q . ((f p q) \wedge (g q r)))$

abbreviation $\text{injective} :: ('a \text{ Point} \Rightarrow 'a \text{ Point} \Rightarrow \text{bool}) \Rightarrow \text{bool}$
where $\text{injective } f \equiv \forall x1 x2 y1 y2 . (f x1 y1 \wedge f x2 y2) \wedge (x1 \neq x2) \longrightarrow (y1 \neq y2)$

abbreviation $\text{definedAt} :: ('a \text{ Point} \Rightarrow 'a \text{ Point} \Rightarrow \text{bool}) \Rightarrow 'a \text{ Point} \Rightarrow \text{bool}$
where $\text{definedAt } f x \equiv \exists y . f x y$

abbreviation $\text{domain} :: ('a \text{ Point} \Rightarrow 'a \text{ Point} \Rightarrow \text{bool}) \Rightarrow 'a \text{ Point set}$
where $\text{domain } f \equiv \{ x . \text{definedAt } f x \}$

abbreviation $\text{total} :: ('a \text{ Point} \Rightarrow 'a \text{ Point} \Rightarrow \text{bool}) \Rightarrow \text{bool}$
where $\text{total } f \equiv \forall x . (\text{definedAt } f x)$

abbreviation $\text{surjective} :: ('a \text{ Point} \Rightarrow 'a \text{ Point} \Rightarrow \text{bool}) \Rightarrow \text{bool}$
where $\text{surjective } f \equiv \forall y . \exists x . f x y$

abbreviation $\text{bijective} :: ('a \text{ Point} \Rightarrow 'a \text{ Point} \Rightarrow \text{bool}) \Rightarrow \text{bool}$
where $\text{bijective } f \equiv (\text{injective } f) \wedge (\text{surjective } f)$

abbreviation $\text{invertible} :: ('a \text{ Point} \Rightarrow 'a \text{ Point}) \Rightarrow \text{bool}$
where $\text{invertible } f \equiv \forall q . (\exists p . (f p = q) \wedge (\forall x . f x = q \longrightarrow x = p))$

fun $\text{applyToSet} :: ('a \text{ Point} \Rightarrow 'a \text{ Point} \Rightarrow \text{bool}) \Rightarrow 'a \text{ Point set} \Rightarrow 'a \text{ Point set}$
where $\text{applyToSet } f s = \{ q . \exists p \in s . f p q \}$

abbreviation $\text{singleValued} :: ('a \text{ Point} \Rightarrow 'a \text{ Point} \Rightarrow \text{bool}) \Rightarrow 'a \text{ Point} \Rightarrow \text{bool}$
where $\text{singleValued } f x \equiv \forall y z . (((f x y) \wedge (f x z)) \longrightarrow (y = z))$

abbreviation $isFunction :: ('a Point \Rightarrow 'a Point \Rightarrow bool) \Rightarrow bool$
where $isFunction f \equiv \forall x . singleValued f x$

abbreviation $isTotalFunction :: ('a Point \Rightarrow 'a Point \Rightarrow bool) \Rightarrow bool$
where $isTotalFunction f \equiv (total f) \wedge (isFunction f)$

fun $toFunc :: ('a Point \Rightarrow 'a Point \Rightarrow bool) \Rightarrow 'a Point \Rightarrow 'a Point$
where $toFunc f x = (SOME y . f x y)$

fun $asFunc :: ('a Point \Rightarrow 'a Point) \Rightarrow ('a Point \Rightarrow 'a Point \Rightarrow bool)$
where $(asFunc f) x y = (y = f x)$

4.1 Differentiable approximation

Here we define differentiable approximation. This will be used later when we define what it means for a worldview transformation to be "approximated" by an affine transformation.

abbreviation $diffApprox :: ('a Point \Rightarrow 'a Point \Rightarrow bool) \Rightarrow ('a Point \Rightarrow 'a Point \Rightarrow bool) \Rightarrow 'a Point \Rightarrow bool$

where $diffApprox g f x \equiv (definedAt f x) \wedge$
 $(\forall \varepsilon > 0 . (\exists \delta > 0 . (\forall y .$
 $(y \text{ within } \delta \text{ of } x)$
 \longrightarrow
 $((definedAt f y) \wedge (\forall u v . (f y u \wedge g y v) \longrightarrow$
 $(sep2 v u) \leq (sqr \varepsilon) * sep2 y x))))$
 $))$

abbreviation $cts :: ('a Point \Rightarrow 'a Point \Rightarrow bool) \Rightarrow 'a Point \Rightarrow bool$
where $cts f x \equiv \forall y . (f x y) \longrightarrow (\forall \varepsilon > 0 . \exists \delta > 0 .$
 $(applyToSet f (ball x \delta)) \subseteq ball y \varepsilon)$

fun $invFunc :: ('a Point \Rightarrow 'a Point \Rightarrow bool) \Rightarrow ('a Point \Rightarrow 'a Point \Rightarrow bool)$
where $(invFunc f) p q = f q p$

lemma $lemBijInv: bijective (asFunc f) \longleftrightarrow invertible f$
by $(metis asFunc.elims(1))$

4.2 lemApproxEqualAtBase

The following lemma shows (as one would expect) that when one function differentiably approximates another at a point, they take equal values at that point.

lemma *lemApproxEqualAtBase*:

assumes *diffApprox g f x*

shows $(f\ x\ y \wedge g\ x\ z) \longrightarrow (y = z)$

proof –

{ **fix** *y z*

assume *hyp: f x y \wedge g x z*

have *lt01: 0 < 1* **by** *auto*

then obtain *d* **where** *dprops: (d > 0) \wedge (\forall y .*

(y within d of x)

\longrightarrow

(\forall u v . (f y u \wedge g y v) \longrightarrow

*(sep2 v u) \leq (sqr 1) * sep2 y x)*)

using *assms(1)* **by** *best*

hence *x within d of x* **by** *auto*

hence \forall u v . (f x u \wedge g x v) \longrightarrow (sep2 v u) \leq (sqr 1) * sep2 x x

using *dprops* **by** *blast*

hence *sep0: (sep2 z y) \leq 0* **using** *hyp* **by** *auto*

 { **assume** *z \neq y*

hence *sep2 z y > 0* **using** *lemNotEqualImpliesSep2Pos[of z y]*

by *auto*

hence *False* **using** *sep0* **by** *auto*

 }

hence *z = y* **by** *auto*

}

thus *?thesis* **by** *auto*

qed

lemma *lemCtsOfCtsIsCts*:

assumes *cts f x*

and \forall y . (f x y) \longrightarrow (cts g y)

shows *cts (composeRel g f) x*

proof –

{ **fix** *z*

assume *z: (composeRel g f) x z*

then obtain *y* **where** *y: f x y \wedge g y z* **by** *auto*

{ **fix** *e*

assume *epos: e > 0*

have $(\forall \varepsilon > 0. \exists \delta > 0. (\text{applyToSet } g \text{ (ball y } \delta)) \subseteq \text{ball } z \ \varepsilon)$

using *assms(2)* *y* **by** *auto*

then obtain dy
where $dy: (dy > 0) \wedge ((\text{applyToSet } g \text{ (ball } y \text{ } dy)) \subseteq \text{ball } z \text{ } e)$
using $\text{epos } y$ **by** auto

have $(\forall \varepsilon > 0. \exists \delta > 0. (\text{applyToSet } f \text{ (ball } x \text{ } \delta)) \subseteq \text{ball } y \text{ } \varepsilon)$
using $y \text{ assms}(1)$ **by** auto

then obtain d
where $d: (d > 0) \wedge ((\text{applyToSet } f \text{ (ball } x \text{ } d)) \subseteq \text{ball } y \text{ } dy)$
using dy **by** auto

{ fix w
assume $w: w \in \text{applyToSet } (\text{composeRel } g \text{ } f) \text{ (ball } x \text{ } d)$
then obtain $u \text{ } v$
where $v: (u \in \text{ball } x \text{ } d) \wedge (f \text{ } u \text{ } v) \wedge (g \text{ } v \text{ } w)$ **by** auto
hence $v \in \text{ball } y \text{ } dy$ **using** d **by** auto
hence $w \in \text{ball } z \text{ } e$ **using** $v \text{ } dy$ **by** auto

}
hence $\text{applyToSet } (\text{composeRel } g \text{ } f) \text{ (ball } x \text{ } d) \subseteq \text{ball } z \text{ } e$ **by** auto
hence $\exists d > 0. (\text{applyToSet } (\text{composeRel } g \text{ } f) \text{ (ball } x \text{ } d) \subseteq \text{ball } z \text{ } e)$

$e)$
using d **by** auto

}
hence $\forall e > 0. \exists d > 0. \text{applyToSet } (\text{composeRel } g \text{ } f) \text{ (ball } x \text{ } d) \subseteq \text{ball } z \text{ } e$ **by** auto

}
thus $?thesis$ **by** auto

qed

lemma lemInjOfInjIsInj :
assumes $\text{injective } f$
and $\text{injective } g$
shows $\text{injective } (\text{composeRel } g \text{ } f)$
proof –

{ fix $x1 \text{ } z1 \text{ } x2 \text{ } z2$
assume $\text{hyp}: (\text{composeRel } g \text{ } f) \text{ } x1 \text{ } z1 \wedge (\text{composeRel } g \text{ } f) \text{ } x2 \text{ } z2 \wedge (x1 \neq x2)$
then obtain $y1 \text{ } y2$
where $ys: (f \text{ } x1 \text{ } y1) \wedge (g \text{ } y1 \text{ } z1) \wedge (f \text{ } x2 \text{ } y2) \wedge (g \text{ } y2 \text{ } z2)$ **by** auto
hence $y1 \neq y2$ **using** $\text{hyp assms}(1)$ **by** auto
hence $z1 \neq z2$ **using** $\text{assms}(2) \text{ } ys$ **by** auto

}
thus $?thesis$ **by** auto

qed

lemma $\text{lemInverseComposition}$:
assumes $h = \text{composeRel } g \text{ } f$
shows $(\text{invFunc } h) = \text{composeRel } (\text{invFunc } f) \text{ (invFunc } g)$

proof –
 { **fix** $p r$
 { **assume** $hyp: h p r$
 then obtain q **where** $f p q \wedge g q r$ **using** $assms$ **by** $auto$
 hence $(invFunc\ g)\ r\ q \wedge (invFunc\ f)\ q\ p$ **by** $force$
 hence $(composeRel\ (invFunc\ f)\ (invFunc\ g))\ r\ p$ **by** $blast$
 }
hence $l2r: (invFunc\ h)\ r\ p \longrightarrow (composeRel\ (invFunc\ f)\ (invFunc\ g))\ r\ p$ **by** $auto$

 { **assume** $(composeRel\ (invFunc\ f)\ (invFunc\ g))\ r\ p$
 then obtain q **where** $(invFunc\ g)\ r\ q \wedge (invFunc\ f)\ q\ p$ **by**
 $auto$
 hence $(invFunc\ h)\ r\ p$ **using** $assms$ **by** $auto$
 }
hence $(composeRel\ (invFunc\ f)\ (invFunc\ g))\ r\ p \longleftrightarrow (invFunc\ h)\ r\ p$
 using $l2r$ **by** $auto$
 }
thus $?thesis$ **by** $fastforce$
qed

lemma $lemToFuncAsFunc$:
assumes $isFunction\ f$
and $total\ f$
shows $asFunc\ (toFunc\ f) = f$
proof –
 { **fix** $p r$
 { **assume** $(asFunc\ (toFunc\ f))\ p\ r$
 hence $f\ p\ r$ **using** $someI[of\ f\ p]$ $assms(2)$ **by** $auto$
 }
hence $l2r: (asFunc\ (toFunc\ f))\ p\ r \longrightarrow f\ p\ r$ **by** $auto$
 { **assume** $fpr: f\ p\ r$
 hence $(asFunc\ (toFunc\ f))\ p\ r$ **using** $someI[of\ f\ p]$ $assms(1)$ **by**
 $auto$
 }
 }
hence $f\ p\ r \longleftrightarrow (asFunc\ (toFunc\ f))\ p\ r$ **using** $l2r$ **by** $auto$
 }
thus $?thesis$ **by** $blast$
qed

lemma $lemAsFuncToFunc$: $toFunc\ (asFunc\ f) = f$
by $fastforce$

end

end

5 WorldLine

This theory defines worldlines.

theory *WorldLine*

imports *WorldView Functions*

begin

class *WorldLine* = *WorldView* + *Functions*

begin

abbreviation *wline* :: *Body* \Rightarrow *Body* \Rightarrow 'a *Point set*

where *wline* *m* *k* \equiv { *p* . *m* sees *k* at *p* }

lemma *lemWorldLineUnderWVT*:

shows *applyToSet* (*wvtFunc* *m* *k*) (*wline* *m* *b*) \subseteq *wline* *k* *b*

by *auto*

lemma *lemFiniteLineVelocityUnique*:

assumes (*u* \in *lineVelocity* *l*) \wedge (*v* \in *lineVelocity* *l*)

and *lineSlopeFinite* *l*

shows *u* = *v*

proof –

have \exists *d1* \in *drtn* *l* . *u* = *velocityJoining* *origin* *d1* **using** *assms* **by**
simp

then obtain *d1*

where *d1*: *d1* \in *drtn* *l* \wedge *u* = *velocityJoining* *origin* *d1* **by** *blast*

have \exists *d2* \in *drtn* *l* . *v* = *velocityJoining* *origin* *d2* **using** *assms* **by**
simp

then obtain *d2*

where *d2*: *d2* \in *drtn* *l* \wedge *v* = *velocityJoining* *origin* *d2* **by** *blast*

hence (*d1* \in *drtn* *l*) \wedge (*d2* \in *drtn* *l*) **using** *d1* *d2* **by** *auto*

then obtain *a* **where** *a*: (*a* \neq 0) \wedge (*d2* = (*a* \otimes *d1*))

using *lemDrtn*[of *d1* *d2* *l*] **by** *blast*

have *slopes*: (*tval* *d1* \neq 0) \wedge (*tval* *d2* \neq 0)

\wedge (*slopeFinite* *origin* *d1*) \wedge (*slopeFinite* *origin* *d2*)

```

proof –
  obtain  $x\ y$  where  $xy: (x \neq y) \wedge (\text{onLine } x\ l) \wedge (\text{onLine } y\ l) \wedge$ 
   $(\text{slopeFinite } x\ y)$ 
    using  $\text{assms}(2)$  by  $\text{blast}$ 
    hence  $\text{slopeFinite } x\ y$  by  $\text{blast}$ 
    hence  $\text{tvalnz}: \text{tval } y - \text{tval } x \neq 0$  by  $\text{simp}$ 

  define  $yx$  where  $yx = (y \ominus x)$ 
    hence  $(x \neq y) \wedge (\text{onLine } x\ l) \wedge (\text{onLine } y\ l) \wedge (yx = (y \ominus x))$ 
using  $xy$  by  $\text{simp}$ 
    hence  $\exists x\ y. (x \neq y) \wedge (\text{onLine } x\ l) \wedge (\text{onLine } y\ l) \wedge (yx = (y$ 
 $\ominus x))$  by  $\text{blast}$ 
    hence  $(y \ominus x) \in \text{drtn } l$  using  $yx\text{-def}$  by  $\text{auto}$ 
    then obtain  $b$  where  $b: (b \neq 0) \wedge (d2 = (b \otimes (y \ominus x)))$ 
    using  $d2\ \text{lemDrtn}[of\ y \ominus x\ d2\ l]$  by  $\text{blast}$ 

  hence  $\text{tval2}: \text{tval } d2 \neq \text{tval } \text{origin}$  using  $\text{tvalnz } b$  by  $\text{simp}$ 
  hence  $\text{tval1}: \text{tval } d1 \neq \text{tval } \text{origin}$  using  $a$  by  $\text{auto}$ 
  hence  $\text{finite}: (\text{slopeFinite } \text{origin } d1) \wedge (\text{slopeFinite } \text{origin } d2)$ 
  using  $\text{tval2}$  by  $\text{auto}$ 
  have  $\text{tval } \text{origin} = 0$  by  $\text{simp}$ 
  thus ?thesis using  $\text{tval1 } \text{tval2 } \text{finite}$  by  $\text{blast}$ 
qed

  have  $\text{t1nz}: \text{tval } d1 \neq 0$  using  $\text{slopes}$  by  $\text{auto}$ 
  have  $\text{anz}: a \neq 0$  using  $a$  by  $\text{blast}$ 
  hence  $\text{equ}: 1/(\text{tval } d1) = (1/(a*\text{tval } d1))*a$  by  $\text{simp}$ 

  hence  $\text{sloper } \text{origin } d1 = (((1/(a*\text{tval } d1))*a) \otimes d1)$  using  $\text{slopes}$ 
by  $\text{auto}$ 
  also have  $\dots = ((1/(\text{tval } d2)) \otimes d2)$ 
  using  $\text{lemScaleAssoc}[of\ 1/(a*\text{tval } d1)\ a\ d1]\ a$  by  $\text{auto}$ 
  finally have  $\text{equalslopes}: \text{sloper } \text{origin } d1 = \text{sloper } \text{origin } d2$  using
 $\text{slopes}$  by  $\text{auto}$ 

  thus ?thesis using  $d1\ d2$  by  $\text{auto}$ 
qed

```

end

end

6 Translations

This theory describes translation maps.

```

theory Translations
  imports Functions
begin

```

class *Translations* = *Functions*
begin

abbreviation *mkTranslation* :: 'a *Point* \Rightarrow ('a *Point* \Rightarrow 'a *Point*)
where (*mkTranslation* *t*) \equiv ($\lambda p . (p \oplus t)$)

abbreviation *translation* :: ('a *Point* \Rightarrow 'a *Point*) \Rightarrow *bool*
where *translation* *T* \equiv $\exists q . \forall p . ((T p) = (p \oplus q))$

lemma *lemMkTrans*: $\forall t . \text{translation } (\text{mkTranslation } t)$
by *auto*

lemma *lemInverseTranslation*:
assumes ($T = \text{mkTranslation } t$) \wedge ($T' = \text{mkTranslation } (\text{origin} \ominus t)$)
shows $(T' \circ T = \text{id}) \wedge (T \circ T' = \text{id})$
using *assms* **by** *auto*

lemma *lemTranslationSum*:
assumes *translation* *T*
shows $T (u \oplus v) = ((T u) \oplus v)$
proof –
obtain *t* **where** $t: \forall x . T x = (x \oplus t)$ **using** *assms(1)* **by** *auto*
thus *?thesis* **using** *add-commute add-assoc t* **by** *auto*
qed

lemma *lemIdIsTranslation*: *translation id*
proof –
have $\forall p . (\text{id } p) = (p \oplus \text{origin})$ **by** *simp*
thus *?thesis* **by** *blast*
qed

lemma *lemTranslationCancel*:
assumes *translation* *T*
shows $((T p) \ominus (T q)) = (p \ominus q)$

proof –
obtain t **where** $t: \forall x. T x = (x \oplus t)$ **using** $assms(1)$ **by** $auto$
hence $((p \oplus t) \ominus (q \oplus t)) = (p \ominus q)$ **by** $simp$
thus $?thesis$ **using** t **by** $auto$
qed

lemma $lemTranslationSwap$:
assumes $translation\ T$
shows $(p \oplus (T\ q)) = ((T\ p) \oplus q)$
proof –
obtain t **where** $t: \forall x. T x = (x \oplus t)$ **using** $assms(1)$ **by** $auto$
thus $?thesis$ **using** $add-commute\ add-assoc$ **by** $simp$
qed

lemma $lemTranslationPreservesSep2$:
assumes $translation\ T$
shows $sep2\ p\ q = sep2\ (T\ p)\ (T\ q)$
proof –
obtain t **where** $\forall x. T x = (x \oplus t)$ **using** $assms(1)$ **by** $auto$
thus $?thesis$ **by** $force$
qed

lemma $lemTranslationInjective$:
assumes $translation\ T$
shows $injective\ (asFunc\ T)$
proof –
obtain t **where** $t: \forall x. T x = (x \oplus t)$ **using** $assms(1)$ **by** $auto$
define $Tinv$ **where** $Tinv: Tinv = mkTranslation\ (origin\ \ominus\ t)$
{ **fix** $x\ y$
assume $T\ x = T\ y$
hence $(Tinv\ \circ\ T)\ x = (Tinv\ \circ\ T)\ y$ **by** $auto$
hence $x = y$ **using** $Tinv\ t$ **by** $auto$
}
thus $?thesis$ **by** $auto$
qed

lemma $lemTranslationSurjective$:
assumes $translation\ T$
shows $surjective\ (asFunc\ T)$
proof –
obtain t **where** $t: \forall x. T x = (x \oplus t)$ **using** $assms(1)$ **by** $auto$
hence $mkT: T = mkTranslation\ t$ **by** $auto$

define T_{inv} **where** $T_{inv}: T_{inv} = mkTranslation (origin \ominus t)$
hence $\forall y . y = T (T_{inv} y)$ **using** mkT $lemInverseTranslation$ **by**
auto
thus *?thesis* **by** *auto*
qed

lemma $lemTranslationTotalFunction$:
assumes $translation\ T$
shows $isTotalFunction (asFunc\ T)$
by *simp*

lemma $lemTranslationOfLine$:
assumes $translation\ T$
shows $(applyToSet (asFunc\ T) (line\ B\ D)) = line (T\ B)\ D$
proof –
define l **where** $l = line\ B\ D$
{ **fix** q'
{ **assume** $q' \in (applyToSet (asFunc\ T)\ l)$
then obtain q **where** $q: q \in l \wedge (asFunc\ T)\ q\ q'$ **by** *auto*
then obtain α **where** $\alpha: q = (B \oplus (\alpha \otimes D))$ **using** l **by** *auto*
have $q' = T\ q$ **using** q **by** *auto*
also have $\dots = ((T\ B) \oplus (\alpha \otimes D))$ **using** α *assms* $lemTranslationSum$ **by** *blast*
finally have $q' \in line (T\ B)\ D$ **by** *auto*
}
hence $l2r: q' \in (applyToSet (asFunc\ T)\ l) \longrightarrow q' \in line (T\ B)\ D$
by *auto*
{ **assume** $q' \in line (T\ B)\ D$
then obtain α **where** $\alpha: q' = ((T\ B) \oplus (\alpha \otimes D))$ **by** *auto*
hence $q' = T (B \oplus (\alpha \otimes D))$ **using** *assms* $lemTranslationSum$ **[of**
 $T\ B\ (\alpha \otimes D)]$ **by** *auto*
moreover have $(B \oplus (\alpha \otimes D)) \in l$ **using** l **by** *auto*
ultimately have $q' \in (applyToSet (asFunc\ T)\ l)$ **by** *auto*
}
hence $q' \in line (T\ B)\ D \longleftrightarrow q' \in (applyToSet (asFunc\ T)\ l)$
using $l2r$ **by** *auto*
}
thus *?thesis* **using** l **by** *auto*
qed

lemma $lemOnLineTranslation$:
assumes $(translation\ T) \wedge (onLine\ p\ l)$
shows $onLine (T\ p) (applyToSet (asFunc\ T)\ l)$
proof –
obtain $B\ D$ **where** $BD: l = line\ B\ D$ **using** *assms* **by** *auto*
hence $(applyToSet (asFunc\ T)\ l) = line (T\ B)\ D$ **using** *assms*

lemTranslationOfLine **by** *auto*
moreover **have** $T p \in (\text{applyToSet } (\text{asFunc } T) l)$ **using** *assms* **by**
auto
ultimately **show** *?thesis* **by** *blast*
qed

lemma *lemLineJoiningTranslation*:
assumes *translation* T
shows $\text{applyToSet } (\text{asFunc } T) (\text{lineJoining } p q) = \text{lineJoining } (T p)$
 $(T q)$
proof $-$
define D **where** $D: D = (q \ominus p)$
hence $\text{lineJoining } p q = \text{line } p D$ **by** *auto*
hence $\text{applyToSet } (\text{asFunc } T) (\text{lineJoining } p q) = \text{line } (T p) D$
using *assms* *lemTranslationOfLine* **by** *auto*
moreover **have** $((T q) \ominus (T p)) = (q \ominus p)$ **using** *assms* *lemTranslationCancel* **by** *auto*
ultimately **show** *?thesis* **using** D **by** *auto*
qed

lemma *lemBallTranslation*:
assumes *translation* T
and x *within* e *of* y
shows $(T x)$ *within* e *of* $(T y)$
proof $-$
have $\text{sep2 } (T x) (T y) = \text{sep2 } x y$
using *assms*(1) *lemTranslationPreservesSep2*[*of* T] **by** *auto*
thus *?thesis* **using** *assms*(2) **by** *auto*
qed

lemma *lemBallTranslationWithBoundary*:
assumes *translation* T
and $\text{sep2 } x y \leq \text{sqr } e$
shows $\text{sep2 } (T x) (T y) \leq \text{sqr } e$
proof $-$
have $\text{sep2 } (T x) (T y) = \text{sep2 } x y$
using *assms*(1) *lemTranslationPreservesSep2*[*of* $T x y$] **by** *simp*
thus *?thesis* **using** *assms*(2) **by** *auto*
qed

lemma *lemTranslationIsCts*:

```

assumes translation T
shows cts (asFunc T) x
proof –
  { fix x'
    assume x': x' = T x

    { fix e
      assume epos: e > 0
      { fix p'
        assume p': p' ∈ applyToSet (asFunc T) (ball x e)
        then obtain p where p: (p ∈ ball x e) ∧ p' = T p by auto
        hence sep2 p x < sqr e using lemSep2Symmetry by force
        hence sep2 p' x' < sqr e using assms(1) p x' lemBallTranslation
      }
    }
  }
  hence applyToSet (asFunc T) (ball x e) ⊆ ball x' e
  using lemSep2Symmetry by force
  hence ∃ d>0. applyToSet (asFunc T) (ball x d) ⊆ ball x' e
  using epos lemSep2Symmetry by auto
  }
  hence ∀ e>0. ∃ d>0. applyToSet (asFunc T) (ball x d) ⊆ ball x' e
  by auto
}
thus ?thesis by auto
qed

```

```

lemma lemAccPointTranslation:
  assumes translation T
  and accPoint x s
  shows accPoint (T x) (applyToSet (asFunc T) s)
  proof –
    { fix e
      assume e > 0
      then obtain q where q: q ∈ s ∧ (x ≠ q) ∧ (inBall q e x)
      using assms(2) by auto

      have acc1: q ∈ s using q by auto
      have acc2: x ≠ q using q by auto
      have acc3: inBall q e x using q by auto

      define q' where q': q' = T q

      have rtp1: q' ∈ applyToSet (asFunc T) s using q' acc1 by auto
      have rtp2: T x ≠ q' using assms(1) acc2 lemTranslationInjective[of
T] q' by force
      have rtp3: inBall q' e (T x)
      using assms(1) acc3 q' lemBallTranslation[of T q x e] by auto
    }

```

hence $\exists q' . (q' \in \text{applyToSet } (\text{asFunc } T) s) \wedge (T x \neq q')$
 $\wedge (\text{inBall } q' e (T x))$
 using *rtp1 rtp2* by *auto*
 }
 thus *?thesis* by *auto*
 qed

lemma *lemInverseOfTransIsTrans*:

assumes *translation T*
 and $T' = \text{invFunc } (\text{asFunc } T)$
 shows *translation (toFunc T')*
 proof –
 obtain *t* where $t: \forall p . T p = (p \oplus t)$ using *assms(1)* by *auto*
 hence *mkT*: $T = \text{mkTranslation } t$ by *auto*
 define *T1* where $T1: T1 = \text{mkTranslation } (\text{origin } \ominus t)$
 hence *transT1*: *translation T1* using *lemMkTrans* by *blast*

 have *TT1*: $(T \circ T1 = \text{id}) \wedge (T1 \circ T = \text{id})$ using *t T1 lemInverseTranslation* by *auto*

{ fix *p r*
 { assume *invFunc (asFunc T) p r*
 hence $T r = p$ by *simp*
 hence $T1 p = (T1 \circ T) r$ by *auto*
 hence $T1 p = r$ using *TT1* by *simp*
 }
 hence *l2r*: $\text{invFunc } (\text{asFunc } T) p r \longrightarrow (\text{asFunc } T1) p r$ by *auto*
 { assume *(asFunc T1) p r*
 hence $T'p: T1 p = r$ by *simp*
 have $(T \circ T1) p = T r$ using *T'p* by *auto*
 hence $p = T r$ using *TT1* by *auto*
 }
 hence $(\text{asFunc } T1) p r \longleftarrow \text{invFunc } (\text{asFunc } T) p r$ using *l2r*
 by *force*
 }
 hence $(\text{asFunc } T1) = T'$ using *assms(2)* by *fastforce*

hence $\text{toFunc } T' = \text{toFunc } (\text{asFunc } T1)$ using *assms(2)* by *fastforce*
 hence $\text{toFunc } T' = T1$ by *fastforce*
 thus *?thesis* using *transT1* by *auto*
 qed

lemma *lemInverseTrans*:

assumes *translation T*
 shows $\exists T' . (\text{translation } T') \wedge (\forall p q . T p = q \longleftrightarrow T' q = p)$


```

proof –
  obtain  $t$  where  $t: \forall p . T p = (p \oplus t)$  using assms by auto
  hence  $mkT: T = mkTranslation\ t$  by auto
  define  $T'$  where  $T': T' = mkTranslation\ (origin \ominus t)$ 
  hence  $trans'$ : translation  $T'$  using lemMkTrans by blast

  have  $TT'$ :  $(T' \circ T = id) \wedge (T \circ T' = id)$  using  $mkT\ T'$  lemInverse-Translation by auto

  { fix  $p\ q$ 
    { assume  $T\ p = q$ 
      hence  $T'\ q = (T' \circ T)\ p$  by auto
      hence  $T'\ q = p$  using  $TT'$  by auto
    }
    hence  $l2r: T\ p = q \longrightarrow T'\ q = p$  by auto
    { assume  $T'\ q = p$ 
      hence  $T\ p = (T \circ T')\ q$  by auto
      hence  $T\ p = q$  using  $TT'$  by auto
    }
    hence  $T'\ q = p \longleftrightarrow T\ p = q$  using  $l2r$  by blast
  }
  thus ?thesis using  $trans'$  by blast
qed

```

end

end

7 AXIOM: AxSelfMinus

This theory declares the axiom AxSelfMinus.

```

theory AxSelfMinus
  imports WorldView
begin

```

AxSelfMinus: The worldline of an observer is a subset of the time axis in their own worldview.

```

class axSelfMinus = WorldView
begin
  abbreviation  $axSelfMinus :: Body \Rightarrow 'a\ Point \Rightarrow bool$ 
    where  $axSelfMinus\ m\ p \equiv (m\ sees\ m\ at\ p) \longrightarrow onTimeAxis\ p$ 
end

```

```

class AxSelfMinus = axSelfMinus +
  assumes AxSelfMinus :  $\forall m p . axSelfMinus m p$ 
begin
end

end

```

8 TangentLines

This theory defines tangent lines and establishes their key properties.

```

theory TangentLines
  imports Translations AxSelfMinus
begin

```

At each point along the worldline of a body, we can ask what its instantaneous direction of motion is. Unfortunately we do not know a priori that the "worldline" actually has tangents. Dealing with tangent lines is one of the more complicated aspects of the main proof.

```

class TangentLines = Translations + AxSelfMinus
begin

```

```

abbreviation tangentLine :: 'a Point set  $\Rightarrow$  'a Point set  $\Rightarrow$  'a Point
 $\Rightarrow$  bool

```

```

  where tangentLine l s x  $\equiv$ 
    (x  $\in$  s)  $\wedge$  (onLine x l)  $\wedge$  (accPoint x s)
   $\wedge$ 
    ( $\exists p . ((onLine p l) \wedge (p \neq x) \wedge$ 
      ( $\forall \varepsilon > 0 . \exists \delta > 0 . \forall y \in s . ($ 
        (y within  $\delta$  of x)  $\wedge$  (y  $\neq$  x) )
       $\longrightarrow$ 
      ( $\exists r . ((onLine r (lineJoining x y)) \wedge (r$  within  $\varepsilon$  of p))))
    )
  ))

```

```

abbreviation tangentLineA :: 'a Point set  $\Rightarrow$  'a Point set  $\Rightarrow$  'a Point
 $\Rightarrow$  bool

```

```

  where tangentLineA l s x  $\equiv$ 
    (x  $\in$  s)  $\wedge$  (onLine x l)  $\wedge$  (accPoint x s)
   $\wedge$ 
    ( $\forall p . (((onLine p l) \wedge (p \neq x)) \longrightarrow$ 
      ( $\forall \varepsilon > 0 . \exists \delta > 0 . \forall y \in s . ($ 
        (y within  $\delta$  of x)  $\wedge$  (y  $\neq$  x) )
       $\longrightarrow$ 
      ( $\exists r . ((onLine r (lineJoining x y)) \wedge (r$  within  $\varepsilon$  of p))))
    )

```

)
))

abbreviation $hasTangent :: 'a Point set \Rightarrow 'a Point \Rightarrow bool$
where $hasTangent\ s\ p \equiv \exists\ l.\ tangentLine\ l\ s\ p$

The instantaneous velocity of a body is defined to be the velocity of a co-moving body moving along the tangent line (assuming a tangent line exists).

fun $vel :: 'a Point set \Rightarrow 'a Point \Rightarrow 'a Space \Rightarrow bool$
where $vel\ wl\ p\ v = (\exists\ l.\ ((tangentLine\ l\ wl\ p) \wedge (v \in lineVelocity\ l)))$

lemma $lemTangentLineTranslation:$

assumes $translation\ T$

and $tangentLine\ l\ s\ x$

shows $tangentLine\ (applyToSet\ (asFunc\ T)\ l)$
 $(applyToSet\ (asFunc\ T)\ s)\ (T\ x)$

proof –

define x' **where** $x' = T\ x$

define l' **where** $l' = applyToSet\ (asFunc\ T)\ l$

define s' **where** $s' = applyToSet\ (asFunc\ T)\ s$

have $tgt1: x \in s$ **using** $assms(2)$ **by** $simp$

have $tgt2: onLine\ x\ l$ **using** $assms(2)$ **by** $simp$

hence $linel: isLine\ l$ **by** $auto$

have $tgt3: accPoint\ x\ s$ **using** $assms(2)$ **by** $simp$

have $tgt4: \exists\ p.\ ((onLine\ p\ l) \wedge (p \neq x)) \wedge$
 $(\forall\ \varepsilon > 0.\ \exists\ \delta > 0.\ \forall\ y \in s.\$
 $(y\ within\ \delta\ of\ x) \wedge (y \neq x))$
 \longrightarrow
 $(\exists\ r.\ ((onLine\ r\ (lineJoining\ x\ y)) \wedge (r\ within\ \varepsilon\ of\ p))))$
 $)$

) using $assms(2)$ **by** $simp$

have $rtp1: x' \in s'$ **using** $x'\ s'\ tgt1$ **by** $auto$

have $rtp2: onLine\ x'\ l'$

using $lemOnLineTranslation[of\ T\ l\ x]\ x'\ l'\ assms(1)\ linel\ tgt2$

by $auto$

have $rtp3: accPoint\ x'\ s'$

using $assms(1)\ tgt3\ lemAccPointTranslation\ x'\ s'$

by $simp$

obtain p **where** p : $((\text{onLine } p \ l) \wedge (p \neq x)) \wedge$
 $(\forall \varepsilon > 0 . \exists \delta > 0 . \forall y \in s . ($
 $(y \text{ within } \delta \text{ of } x) \wedge (y \neq x))$
 \longrightarrow
 $(\exists r . ((\text{onLine } r \ (\text{lineJoining } x \ y)) \wedge (r \text{ within } \varepsilon \text{ of } p))))$
) using tgt4 **by** auto

define p' **where** p' : $p' = (T \ p)$
hence p' - $\text{on-}l'$: $\text{onLine } p' \ l'$ **using** $l' \ \text{rtp2 } p$ **by** auto
have p' - $\text{not-}x'$: $p' \neq x'$
using $p' \ p \ \text{assms}(1) \ x' \ \text{lemTranslationInjective}[\text{of } T]$ **by** force

{ fix e
assume epos : $e > 0$
then obtain d **where** d : $(d > 0) \wedge (\forall y \in s . ($
 $(y \text{ within } d \text{ of } x) \wedge (y \neq x))$
 \longrightarrow
 $(\exists r . ((\text{onLine } r \ (\text{lineJoining } x \ y)) \wedge (r \text{ within } e \text{ of } p))))$
) using p **by** blast

{ fix y'
assume y' : $(y' \in s') \wedge (y' \text{ within } d \text{ of } x') \wedge (y' \neq x')$
then obtain y **where** y : $y \in s \wedge y' = T \ y$ **using** s' **by** force

hence $y1$: $y \in s$ **using** y **by** auto
have $y2$: $y \text{ within } d \text{ of } x$
using $\text{assms}(1) \ x' \ y \ y' \ \text{lemBallTranslation}$ **by** fastforce
have $y3$: $y \neq x$ **using** $y' \ y \ x' \ \text{assms}(1)$ **by** fastforce

then obtain r
where r : $(\text{onLine } r \ (\text{lineJoining } x \ y)) \wedge (r \text{ within } e \text{ of } p)$
using $y1 \ y2 \ d$ **by** force

define r' **where** r' : $r' = T \ r$
hence $r' \in \text{applyToSet} \ (\text{asFunc } T) \ (\text{lineJoining } x \ y)$ **using** r **by**
 auto

hence $r1$: $\text{onLine } r' \ (\text{lineJoining } x' \ y')$
using $\text{assms}(1) \ \text{lemLineJoiningTranslation}[\text{of } T \ x \ y] \ x' \ y$
by blast
have $r2$: $r' \text{ within } e \text{ of } p'$
using $\text{assms}(1) \ r \ r' \ p' \ \text{lemBallTranslation}$ **by** auto

hence $\exists r' . (\text{onLine } r' \ (\text{lineJoining } x' \ y')) \wedge (r' \text{ within } e \text{ of } p')$
using $r1$ **by** auto
hence $(y' \text{ within } d \text{ of } x') \wedge (y' \neq x')$
 $\longrightarrow (\exists r' . (\text{onLine } r' \ (\text{lineJoining } x' \ y')) \wedge (r' \text{ within } e \text{ of } p'))$
using y' **by** blast

}

hence $\forall y' \in s'. (y' \text{ within } d \text{ of } x') \wedge (y' \neq x')$
 $\rightarrow (\exists r'. (\text{onLine } r' (\text{lineJoining } x' y')) \wedge (r' \text{ within } e \text{ of } p'))$
by auto

hence $\exists d > 0. \forall y' \in s'. (y' \text{ within } d \text{ of } x') \wedge (y' \neq x')$
 $\rightarrow (\exists r'. (\text{onLine } r' (\text{lineJoining } x' y')) \wedge (r' \text{ within } e \text{ of } p'))$
using d by auto

hence $\forall e > 0. \exists d > 0. \forall y' \in s'. (y' \text{ within } d \text{ of } x') \wedge (y' \neq x')$
 $\rightarrow (\exists r'. (\text{onLine } r' (\text{lineJoining } x' y')) \wedge (r' \text{ within } e \text{ of } p'))$
by force

hence $(\text{onLine } p' l') \wedge (p' \neq x')$
 $\wedge (\forall e > 0. \exists d > 0. \forall y' \in s'. (y' \text{ within } d \text{ of } x') \wedge (y' \neq x'))$
 $\rightarrow (\exists r'. (\text{onLine } r' (\text{lineJoining } x' y')) \wedge (r' \text{ within } e \text{ of } p'))$
using p'-not-x' p'-on-l' by auto

hence $\text{rtp4}: \exists p'. ((\text{onLine } p' l') \wedge (p' \neq x'))$
 $\wedge (\forall e > 0. \exists d > 0. \forall y' \in s'. (y' \text{ within } d \text{ of } x') \wedge (y' \neq x'))$
 $\rightarrow (\exists r'. (\text{onLine } r' (\text{lineJoining } x' y')) \wedge (r' \text{ within } e \text{ of } p'))$
by auto

hence $?thesis \longleftrightarrow (x' \in s') \wedge (\text{onLine } x' l') \wedge (\text{accPoint } x' s')$
using x' s' l' by simp

thus $?thesis$ **using rtp1 rtp2 rtp3 by blast**

qed

lemma *lemTangentLineA:*

assumes *tangentLine l s x*

shows *tangentLineA l s x*

proof –

have 1: $(x \in s) \wedge (\text{onLine } x l) \wedge (\text{accPoint } x s)$ **using** *assms* **by auto**

have $\exists P. (\text{onLine } P l) \wedge (P \neq x) \wedge$
 $(\forall \varepsilon > 0. \exists \delta > 0. \forall y \in s. ($
 $(y \text{ within } \delta \text{ of } x) \wedge (y \neq x))$
 \rightarrow
 $(\exists r. ((\text{onLine } r (\text{lineJoining } x y)) \wedge (r \text{ within } \varepsilon \text{ of } P))))$
 $)$

using *assms* **by simp**

then obtain *P* **where** $P: (\text{onLine } P l) \wedge (P \neq x) \wedge$

$(\forall \varepsilon > 0. \exists \delta > 0. \forall y \in s. ($
 $(y \text{ within } \delta \text{ of } x) \wedge (y \neq x))$
 \rightarrow
 $(\exists r. ((\text{onLine } r (\text{lineJoining } x y)) \wedge (r \text{ within } \varepsilon \text{ of } P))))$

)
by *blast*

{ **fix** p
assume $p: \text{onLine } p \ l \wedge p \neq x$

hence $\text{onLine } x \ l \wedge \text{onLine } p \ l \wedge x \neq p$ **using** 1 **by** *auto*
hence $lxp: l = \text{lineJoining } x \ p$
using 1 *lemLineAndPoints*[of $x \ p \ l$] **by** *auto*

then obtain a **where** $a: P = (x \oplus (a \otimes (p \ominus x)))$ **using** P **by** *auto*
hence $anz: a \neq 0$ **using** P **by** *auto*

{ **fix** e
assume $epos: e > 0$
hence $aenz: a * e \neq 0$ **using** anz **by** *auto*
define $e1$ **where** $e1: e1 = \text{abs } (a * e)$
hence $e1pos: e1 > 0$ **using** $aenz$ **by** *auto*

then obtain d **where** $d: (d > 0) \wedge (\forall y \in s. ($
 $(y \text{ within } d \text{ of } x) \wedge (y \neq x))$
 \rightarrow
 $(\exists r . ((\text{onLine } r \ (\text{lineJoining } x \ y)) \wedge (r \text{ within } e1 \text{ of } P))))$
 $)$
using P **by** *auto*

{ **fix** y
assume $y: (y \in s) \wedge (y \text{ within } d \text{ of } x) \wedge (y \neq x)$
then obtain R
where $R: (\text{onLine } R \ (\text{lineJoining } x \ y)) \wedge (R \text{ within } e1 \text{ of } P)$
using d **by** *blast*

define r **where** $r: r = (x \oplus ((1/a) \otimes (R \ominus x)))$
hence $(r \ominus x) = ((x \oplus ((1/a) \otimes (R \ominus x))) \ominus x)$ **using** r **by** *auto*
also have $\dots = ((1/a) \otimes (R \ominus x))$
using *add-commute add-assoc diff-add-cancel* **by** *auto*
finally have $nrx: (r \ominus x) = ((1/a) \otimes (R \ominus x))$ **by** *metis*

define T **where** $T: T = \text{mkTranslation } (\text{origin } \ominus x)$
hence $transT: \text{translation } T$ **using** *lemMkTrans* **by** *blast*
have $R \text{ within } e1 \text{ of } P$ **using** R **by** *simp*
hence $(T \ R) \text{ within } e1 \text{ of } (T \ P)$
using $transT$ *lemBallTranslation*[of $T \ R \ P \ e1$]
by *fastforce*
hence $near1: ((1/a) \otimes (R \ominus x)) \text{ within } (e1/a) \text{ of } ((1/a) \otimes (P \ominus x))$
using *lemScaleBall*[of $R \ominus x \ P \ominus x \ e1 \ 1/a$] $anz \ T$
by *auto*

```

define  $T'$  where  $T'$ :  $T' = mkTranslation\ x$ 
hence  $transT'$ : translation  $T'$  using  $lemMkTrans$  by blast
  hence  $near2$ : ( $T' ((1/a)\otimes(R\ominus x))$ ) within  $(e1/a)$  of  $(T'$ 
 $((1/a)\otimes(P\ominus x))$ )
  using  $near1\ transT'$ 
     $lemBallTranslation[of\ T'\ (1/a)\otimes(R\ominus x)\ (1/a)\otimes(P\ominus x)$ 
 $e1/a]$ 
  by blast

have  $term1$ : ( $T' ((1/a)\otimes(R\ominus x)) = r$ ) using  $T'$  add-commute
 $r$  by auto

have ( $P \ominus x = (a \otimes (p\ominus x))$ ) using  $a$  by auto
hence ( $T' ((1/a)\otimes(P\ominus x)) = (x \oplus ((1/a)\otimes(a \otimes (p\ominus x))))$ )
  using  $T'$  add-commute by auto
hence ( $T' ((1/a)\otimes(P\ominus x)) = (x \oplus (p\ominus x))$ )
  using  $lemScaleAssoc[of\ 1/a\ a\ P\ominus x]$  anz by auto
hence  $term2$ : ( $T' ((1/a)\otimes(P\ominus x)) = p$ )
  using diff-add-cancel add-commute by auto

have  $e1/a = abs\ (a*e)/a$  using  $e1$  by auto
hence  $sqr\ (e1/a) = (sqr\ (abs\ (a*e)))/(sqr\ a)$  by auto
hence  $sqr\ (e1/a) = (sqr\ (a*e))/(sqr\ a)$  by auto
hence  $sqr\ (e1/a) = (sqr\ a)*(sqr\ e)/(sqr\ a)$  using  $lemSqrMult$ 
by auto
hence  $term3$ :  $sqr\ (e1/a) = (sqr\ e)$  using anz by simp

hence  $r$ -near- $p$ :  $r$  within  $e$  of  $p$  using  $near2\ term1\ term2\ term3$ 
by auto

have  $cases$ : ( $R = x$ )  $\vee$  ( $R \neq x$ ) by auto
have  $x$ -on- $xy$ :  $onLine\ x\ (lineJoining\ x\ y)$ 
  using  $y\ lemLineAndPoints[of\ x\ y\ lineJoining\ x\ y]$  by auto
{ assume  $R = x$ 
  hence  $r = x$  using  $nrx\ anz$  by auto
  hence  $onLine\ r\ (lineJoining\ x\ y)$  using  $x$ -on- $xy$  by blast
}
hence  $case1$ : ( $R = x$ )  $\longrightarrow$  ( $onLine\ r\ (lineJoining\ x\ y)$ ) by auto
{ assume  $R \neq x$ 
  hence  $lineJoining\ x\ R = lineJoining\ x\ y$ 
  using  $R\ x$ -on- $xy\ lemLineAndPoints[of\ x\ R\ lineJoining\ x\ y]$ 
  by auto
  hence  $onLine\ r\ (lineJoining\ x\ y)$  using  $r$  by blast
}
hence ( $R \neq x$ )  $\longrightarrow$  ( $onLine\ r\ (lineJoining\ x\ y)$ ) by auto
hence  $onLine\ r\ (lineJoining\ x\ y)$  using  $cases\ case1$  by auto

hence  $\exists r$ . ( $onLine\ r\ (lineJoining\ x\ y)$ )  $\wedge$  ( $r$  within  $e$  of  $p$ )

```

using *r-near-p* **by** *auto*
}
hence $\forall y \in s . (y \text{ within } d \text{ of } x) \wedge (y \neq x)$
 $\longrightarrow (\exists r . (\text{onLine } r (\text{lineJoining } x \ y)) \wedge (r \text{ within } e \text{ of } p))$
by *auto*
hence $\exists d > 0 . \forall y \in s . (y \text{ within } d \text{ of } x) \wedge (y \neq x)$
 $\longrightarrow (\exists r . (\text{onLine } r (\text{lineJoining } x \ y)) \wedge (r \text{ within } e \text{ of } p))$
using *d* **by** *auto*
}
hence $\forall e > 0 . \exists d > 0 . \forall y \in s . (y \text{ within } d \text{ of } x) \wedge (y \neq x)$
 $\longrightarrow (\exists r . (\text{onLine } r (\text{lineJoining } x \ y)) \wedge (r \text{ within } e \text{ of } p))$
by *blast*
}
hence 2: $\forall p . (\text{onLine } p \ l \wedge p \neq x) \longrightarrow$
 $(\forall e > 0 . \exists d > 0 . \forall y \in s . (y \text{ within } d \text{ of } x) \wedge (y \neq x)$
 $\longrightarrow (\exists r . (\text{onLine } r (\text{lineJoining } x \ y)) \wedge (r \text{ within } e \text{ of } p)))$
by *blast*
thus *?thesis* **using** 1 **by** *auto*
qed

lemma *lemTangentLineE*:

assumes *tangentLineA* *l s x*
and $\exists p \neq x . \text{onLine } p \ l$
shows *tangentLine* *l s x*

proof –

have 1: $(x \in s) \wedge (\text{onLine } x \ l) \wedge (\text{accPoint } x \ s)$ **using** *assms(1)* **by** *auto*

obtain *p* **where** $p: (p \neq x) \wedge (\text{onLine } p \ l)$ **using** *assms(2)* **by** *auto*

hence $\forall \varepsilon > 0 . \exists \delta > 0 . \forall y \in s . ($
 $(y \text{ within } \delta \text{ of } x) \wedge (y \neq x))$

\longrightarrow

$(\exists r . ((\text{onLine } r (\text{lineJoining } x \ y)) \wedge (r \text{ within } \varepsilon \text{ of } p)))$

using *assms(1)* **by** *blast*

thus *?thesis* **using** 1 *p* **by** *auto*

qed

end

end

9 Cones

This theory defines (light)cones, regular cones, and their properties.

```
theory Cones
imports WorldLine TangentLines
begin

class Cones = WorldLine + TangentLines
begin

abbreviation tl :: 'a Point set  $\Rightarrow$  Body  $\Rightarrow$  Body  $\Rightarrow$  'a Point  $\Rightarrow$  bool
where tl l m b x  $\equiv$  tangentLine l (wline m b) x

The cone of a body at a point comprises the set of points that lie
on tangent lines of photons emitted by the body at that point.

abbreviation cone :: Body  $\Rightarrow$  'a Point  $\Rightarrow$  'a Point  $\Rightarrow$  bool
where cone m x p
 $\equiv \exists l . (onLine p l) \wedge (onLine x l) \wedge (\exists ph . Ph\ ph \wedge tl\ l$ 
m ph x)

abbreviation regularCone :: 'a Point  $\Rightarrow$  'a Point  $\Rightarrow$  bool
where regularCone x p  $\equiv \exists l . (onLine p l) \wedge (onLine x l)$ 
 $\wedge (\exists v \in lineVelocity\ l . sNorm2\ v = 1)$ 

abbreviation coneSet :: Body  $\Rightarrow$  'a Point  $\Rightarrow$  'a Point set
where coneSet m x  $\equiv \{ p . cone\ m\ x\ p \}$ 

abbreviation regularConeSet :: 'a Point  $\Rightarrow$  'a Point set
where regularConeSet x  $\equiv \{ p . regularCone\ x\ p \}$ 

end
end
```

10 AXIOM: AxLightMinus

This theory declares the axiom AxLightMinus.

```
theory AxLightMinus
imports WorldLine TangentLines
```

begin

AxLightMinus: If an observer sends out a light signal, then the speed of the light signal is 1 according to the observer. Moreover it is possible to send out a light signal in any direction.

class *axLightMinus* = *WorldLine* + *TangentLines*
begin

The definition of AxLightMinus used in this Isabelle proof is slightly different to the one used in the paper-based proof on which it is based. We have established elsewhere, however, that each entails the other in all relevant contexts.

abbreviation *axLightMinusOLD* :: *Body* \Rightarrow '*a Point* \Rightarrow '*a Space* \Rightarrow *bool*
where *axLightMinusOLD* *m p v* \equiv (*m sees m at p*) \longrightarrow (
 $(\exists$ *ph* . (*Ph ph* \wedge (*vel (wline m ph) p v*))) \longleftrightarrow (*sNorm2 v = 1*)
)

abbreviation *axLightMinus* :: *Body* \Rightarrow '*a Point* \Rightarrow '*a Space* \Rightarrow *bool*
where *axLightMinus* *m p v* \equiv (*m sees m at p*)
 \longrightarrow (\forall *l* . \forall *v* \in *lineVelocity l* .
 $(\exists$ *ph* . (*Ph ph* \wedge (*tangentLine l (wline m ph) p*))) \longleftrightarrow
 (*sNorm2 v = 1*))

end

class *AxLightMinus* = *axLightMinus* +
 assumes *AxLightMinus*: \forall *m p v* . *axLightMinus* *m p v*
begin
end

end

11 Proposition1

This theory shows that observers consider their own lightcones to be upright.

theory *Proposition1*
 imports *Cones AxLightMinus*
begin

class *Proposition1* = *Cones* + *AxLightMinus*
begin

lemma *lemProposition1*:

assumes $x \in wline\ m\ m$
shows $cone\ m\ x\ p = regularCone\ x\ p$
proof –
have mmx : $m\ sees\ m\ at\ x$ **using** $assms$ **by** $simp$

have $axlight$: $\forall\ l.\ \forall\ v \in lineVelocity\ l.$
 $(\exists\ ph.\ (Ph\ ph \wedge (tangentLine\ l\ (wline\ m\ ph)\ x))) \iff$
 $(sNorm2\ v = 1)$
using $AxLightMinus\ mmx$ **by** $auto$

define $axph$ **where** $axph$: $axph = (\lambda\ l.\ \lambda\ ph.\ (Ph\ ph \wedge (tangentLine\ l\ (wline\ m\ ph)\ x)))$

define lhs **where** lhs : $lhs = cone\ m\ x\ p$
define rhs **where** rhs : $rhs = regularCone\ x\ p$

{ assume lhs
hence $\exists\ l.\ onLine\ p\ l \wedge onLine\ x\ l \wedge (\exists\ ph.\ axph\ l\ ph)$
using $lhs\ axph$ **by** $auto$
then obtain l
where l : $onLine\ p\ l \wedge onLine\ x\ l \wedge (\exists\ ph.\ axph\ l\ ph)$ **by** $auto$

have $xonl$: $onLine\ x\ l$ **using** l **by** $auto$
have $ponl$: $onLine\ p\ l$ **using** l **by** $auto$

have $exph$: $\exists\ ph.\ axph\ l\ ph$ **using** l **by** $auto$
then obtain ph **where** ph : $axph\ l\ ph$ **by** $auto$

have $axlight'$: $\forall\ v \in lineVelocity\ l.\ (\exists\ ph.\ axph\ l\ ph) \iff$
 $(sNorm2\ v = 1)$
using $axph\ axlight$ **by** $force$

hence $lw1$: $\forall\ v \in lineVelocity\ l.\ (sNorm2\ v = 1)$ **using** $exph$ **by** $blast$

have $tterm1$: $tl\ l\ m\ ph\ x$ **using** $ph\ axph$ **by** $force$

hence $\exists\ p.\ ((onLine\ p\ l) \wedge (p \neq x) \wedge (\forall\ \varepsilon > 0.\ \exists\ \delta > 0.\ \forall$
 $y \in (wline\ m\ ph). ($
 $(y\ within\ \delta\ of\ x) \wedge (y \neq x)) \implies$
 $(\exists\ r.\ ((onLine\ r\ (lineJoining\ x\ y)) \wedge (r\ within\ \varepsilon\ of\ p))))))$
by $auto$
then obtain q **where** q : $onLine\ q\ l \wedge q \neq x$ **by** $auto$
define qx **where** qx : $qx = (q \ominus x)$

hence $(x \neq q) \wedge \text{onLine } x \ l \wedge \text{onLine } q \ l \wedge (qx = (q \ominus x))$ **using**
 $q \ \text{xonl}$ **by** *auto*
hence $\exists p \ q . (p \neq q) \wedge \text{onLine } p \ l \wedge \text{onLine } q \ l \wedge (qx = (q \ominus p))$ **by** *blast*
hence $qxl: qx \in \text{drtn } l$ **by** *auto*

define v **where** $v: v = \text{velocityJoining origin } qx$
hence $\exists d \in \text{drtn } l . v = \text{velocityJoining origin } d$ **using** qxl **by**
blast
hence $\text{existsv}: v \in \text{lineVelocity } l$ **by** *auto*
hence $\text{norm2v}: s\text{Norm2 } v = 1$ **using** $lv1$ **by** *auto*
hence $\exists v \in \text{lineVelocity } l . s\text{Norm2 } v = 1$ **using** existsv **by** *force*

hence $\text{onLine } p \ l \wedge \text{onLine } x \ l \wedge (\exists v \in \text{lineVelocity } l . s\text{Norm2 } v = 1)$
using $\text{ponl } \text{xonl}$ **by** *auto*
hence $\exists l . \text{onLine } p \ l \wedge \text{onLine } x \ l \wedge (\exists v \in \text{lineVelocity } l . s\text{Norm2 } v = 1)$
by *blast*
hence $\text{regularCone } x \ p$ **by** *auto*
}
hence $l2r: lhs \longrightarrow rhs$ **using** rhs **by** *blast*

{ **assume** rhs
hence $\exists l . \text{onLine } p \ l \wedge \text{onLine } x \ l \wedge (\exists v \in \text{lineVelocity } l . s\text{Norm2 } v = 1)$
using rhs **by** *auto*
then obtain l
where $l: (\text{onLine } p \ l) \wedge (\text{onLine } x \ l) \wedge (\exists v \in \text{lineVelocity } l . s\text{Norm2 } v = 1)$
by *blast*

have $\text{xonl}: \text{onLine } x \ l$ **using** l **by** *auto*
have $\text{ponl}: \text{onLine } p \ l$ **using** l **by** *auto*

have $\exists v \in \text{lineVelocity } l . s\text{Norm2 } v = 1$ **using** l **by** *blast*
then obtain v **where** $v: (v \in \text{lineVelocity } l) \wedge (s\text{Norm2 } v = 1)$
by *blast*

define final
where $\text{final}: \text{final} = (\lambda l . \text{onLine } p \ l \wedge \text{onLine } x \ l \wedge (\exists ph . \text{axph } l \ ph))$

have $\exists ph . \text{axph } l \ ph$ **using** $v \ \text{axlight } \text{axph}$ **by** *blast*
hence $\text{final } l$ **using** $\text{ponl } \text{xonl } \text{final}$ **by** *auto*
hence $\exists l . \text{final } l$ **by** *auto*
hence $\text{cone } m \ x \ p$ **using** $\text{final } \text{axph}$ **by** *auto*
hence lhs **using** lhs **by** *auto*

```

}
hence r2l: rhs  $\longrightarrow$  lhs using lhs by blast

hence lhs  $\longleftrightarrow$  rhs using l2r by auto
thus ?thesis using lhs rhs by auto
qed

```

end

end

12 AXIOM: AxEField

This theory defines the axiom AxEField, which states that the linearly ordered field of quantities is Euclidean, i.e. that all non-negative values have square roots in the field.

```

theory AxEField
  imports Sorts
begin

```

```

class axEField = Quantities
begin
  abbreviation axEField :: 'a  $\Rightarrow$  bool
    where axEField x  $\equiv$  (x  $\geq$  0)  $\longrightarrow$  hasRoot x
end

```

```

class AxEField = axEField +
  assumes AxEField:  $\forall$  x . axEField x
begin
end

```

end

13 Norms

This theory defines norms, assuming that roots exist.

```

theory Norms
  imports Points AxEField
begin

```

```

class Norms = Points + AxEField

```

begin

abbreviation $norm :: 'a \text{ Point} \Rightarrow 'a \langle \| - \| \rangle$
where $norm\ p \equiv sqrt\ (norm2\ p)$

abbreviation $sNorm :: 'a \text{ Space} \Rightarrow 'a$
where $sNorm\ p \equiv sqrt\ (sNorm2\ p)$

13.1 axTriangleInequality

Given that norms exist, we can define the triangle inequality for specific cases. This will be asserted more generally as an axiom later.

abbreviation $axTriangleInequality :: 'a \text{ Point} \Rightarrow 'a \text{ Point} \Rightarrow bool$
where $axTriangleInequality\ p\ q \equiv (norm\ (p \oplus q) \leq norm\ p + norm\ q)$

lemma $lemNormSqrIsNorm2: norm2\ p = sqr\ (norm\ p)$

proof –

have $norm2\ p \geq 0$ **by** *simp*
moreover **have** $axEField\ (norm2\ p)$ **using** $AxEField$ **by** *simp*
ultimately **show** $?thesis$ **using** $lemSquareOfSqrt[of\ norm2\ p\ norm\ p]$ **by** *force*
qed

lemma $lemZeroNorm:$

shows $(p = origin) \longleftrightarrow (norm\ p = 0)$

proof –

{ **assume** $p = origin$
hence $norm2\ p = 0$ **by** *auto*
hence $norm\ p = 0$ **using** $lemSquareOfSqrt\ lemZeroRoot\ AxEField$
by *force*
}
hence $l2r: (p = origin) \longrightarrow (norm\ p = 0)$ **by** *auto*

{ **assume** $norm\ p = 0$
hence $norm2\ p = 0$ **using** $lemNormSqrIsNorm2[of\ p]$ **by** *auto*
hence $p = origin$ **using** $lemNullImpliesOrigin$ **by** *auto*
}
hence $(norm\ p = 0) \longrightarrow (p = origin)$ **by** *auto*

thus *?thesis* **using** *l2r* **by** *blast*
qed

lemma *lemNormNonNegative*: $\text{norm } p \geq 0$
proof –
have $\text{norm2 } p \geq 0$ **by** *auto*
hence *unique*: $\exists! r. 0 \leq r \wedge \text{norm2 } p = \text{sqr } r$ **using** *AxEField*
lemSqrt[of $\text{norm2 } p$] **by** *auto*
then obtain r **where** $r: 0 \leq r \wedge \text{norm2 } p = \text{sqr } r \wedge (\forall x .$
isNonNegRoot ($\text{norm2 } p$) $x \longrightarrow x = r$)
by *auto*
hence $r = \text{norm } p$ **using** *the-equality*[of *isNonNegRoot* ($\text{norm2 } p$)
 r] **by** *blast*
moreover have $r \geq 0$ **using** r **by** *blast*
ultimately show *?thesis* **by** *auto*
qed

lemma *lemNotOriginImpliesPositiveNorm*:
assumes $p \neq \text{origin}$
shows ($\text{norm } p > 0$)
proof –
have $1: \text{norm } p \neq 0$ **using** *lemZeroNorm* *assms(1)* **by** *auto*
have $\text{norm } p \geq 0$ **using** *lemNormNonNegative* *assms(1)* **by** *auto*
hence $2: \text{norm } p > 0$ **using** 1 **by** *auto*
thus *?thesis* **by** *auto*
qed

lemma *lemNormSymmetry*: $\text{norm } (p \ominus q) = \text{norm } (q \ominus p)$
proof –
have $\text{norm2 } (p \ominus q) = \text{norm2 } (q \ominus p)$ **using** *lemSep2Symmetry* **by**
simp
thus *?thesis* **by** *presburger*
qed

lemma *lemNormOfScaled*: $\text{norm } (\alpha \otimes p) = (\text{abs } \alpha) * (\text{norm } p)$
proof –
have $\text{sqr } (\text{norm } (\alpha \otimes p)) = \text{norm2 } (\alpha \otimes p)$ **using** *lemNormSqrIsNorm2*
by *presburger*
also have $\dots = (\text{sqr } \alpha) * (\text{norm2 } p)$ **using** *lemNorm2OfScaled* **by**
auto
also have $\dots = (\text{sqr } \alpha) * (\text{sqr } (\text{norm } p))$ **using** *lemNormSqrIsNorm2*
by *force*

also have $\dots = \text{sqr} (\alpha * (\text{norm } p))$ **using** *lemSqrMult* **by** *auto*
finally have $\text{abs} (\text{norm} (\alpha \otimes p)) = \text{abs} (\alpha * (\text{norm } p))$ **using** *lemEqualSquares* **by** *blast*
moreover have $\text{abs} (\text{norm} (\alpha \otimes p)) = \text{norm} (\alpha \otimes p)$
using *lemNormNonNegative*[of $(\alpha \otimes p)$] *abs-of-nonneg* **by** *auto*
moreover have $\text{abs} (\alpha * (\text{norm } p)) = (\text{abs } \alpha) * (\text{abs} (\text{norm } p))$
using *abs-mult* **by** *auto*
ultimately show *?thesis* **using** *lemNormNonNegative*[of p] *abs-of-nonneg*
by *auto*
qed

lemma *lemDistancesAdd*:

assumes *triangle*: $\text{axTriangleInequality} (q \ominus p) (r \ominus q)$
and *distances*: $(x > 0) \wedge (y > 0) \wedge (\text{sep2 } p \ q < \text{sqr } x) \wedge (\text{sep2 } r \ q < \text{sqr } y)$
shows r *within* $(x+y)$ *of* p
proof –
define npq **where** $npq: npq = \text{norm} (q \ominus p)$
hence $\text{sqr } npq < \text{sqr } x$
using *lemNormSqrIsNorm2* *distances* *lemSep2Symmetry* **by** *presburger*
hence $npq < x$ **using** *lemSqrOrderedStrict* *distances* **by** *blast*

define nqr **where** $nqr: nqr = \text{norm} (r \ominus q)$
hence $\text{sqr } nqr < \text{sqr } y$ **using** *lemNormSqrIsNorm2* *distances* **by** *presburger*
hence $nqr < y$ **using** *lemSqrOrderedStrict* *distances* **by** *blast*

have $r \text{minus } p: (r \ominus p) = ((q \ominus p) \oplus (r \ominus q))$ **using** *lemDiffDiffAdd* **by** *fastforce*
define npr **where** $npr: npr = \text{norm} (r \ominus p)$

have $nx: \text{norm} (q \ominus p) = npq$ **using** npq *lemSqr* **by** *fast*
have $ny: \text{norm} (r \ominus q) = nqr$ **using** nqr *lemSqr* **by** *fast*
have $nz: \text{norm} (r \ominus p) = npr$ **using** npr *lemSqr* **by** *fast*

have $\text{norm} (r \ominus p) \leq (\text{norm} (q \ominus p) + \text{norm} (r \ominus q))$ **using** *triangle* *rminus* **by** *fastforce*
hence $npr \leq (npq + nqr)$ **using** $nx \ ny \ nz$ *lemSqr* $npq \ nqr \ npr$ **by** *simp*
hence $npr < x + y$ **using** $npq \ nqr$ *add-strict-mono*[of $npq \ x \ nqr \ y$]
by *simp*

hence $\text{sqr } npr < \text{sqr} (x+y)$ **using** npr *lemNormNonNegative*[of $(r \ominus p)$] *lemSqrMonoStrict* **by** *auto*
hence $\text{sep2 } r \ p < \text{sqr} (x+y)$ **using** npr *lemSquareOfSqr* *axE-Field* **by** *auto*

thus ?thesis using npr lemSep2Symmetry by auto
qed

lemma lemDistancesAddStrictR:

assumes *triangle: axTriangleInequality* $(q \ominus p) (r \ominus q)$
and *distances: $(x > 0) \wedge (y > 0) \wedge (sep2\ p\ q \leq sqr\ x) \wedge (sep2\ r\ q < sqr\ y)$*

shows *r within $(x+y)$ of p*

proof –

define *npq where npq: $npq = norm\ (q \ominus p)$*

hence *$sqr\ npq \leq sqr\ x$ using lemNormSqrIsNorm2 distances lemSep2Symmetry by presburger*

hence *$npq \leq x$ using lemSqrOrdered[*of x npq*] distances npq by auto*

define *nqr where nqr: $nqr = norm\ (r \ominus q)$*

hence *$sqr\ nqr < sqr\ y$ using lemNormSqrIsNorm2 distances by presburger*

hence *$nqr < y$ using lemSqrOrderedStrict distances by blast*

define *npr where npr: $npr = norm\ (r \ominus p)$*

have *$nx: norm\ (q \ominus p) = npq$ using npq lemSqr by blast*

have *$ny: norm\ (r \ominus q) = nqr$ using nqr lemSqr by blast*

have *$nz: norm\ (r \ominus p) = npr$ using npr lemSqr by blast*

have *$norm\ (r \ominus p) \leq (norm\ (q \ominus p) + norm\ (r \ominus q))$ using triangle lemDiffDiffAdd by fastforce*

hence *$npr \leq (npq + nqr)$ using nx ny nz by simp*

hence *$npr < x + y$ using npqx nqry add-le-less-mono[*of npq x nqr y*]*

by auto

hence *$sqr\ npr < sqr\ (x+y)$ using npr lemNormNonNegative[*of $(r \ominus p)$*] lemSqrMonoStrict by auto*

hence *$sep2\ r\ p < sqr\ (x+y)$ using npr lemSquareOfSqr AxE-Field by auto*

thus ?thesis using npr lemSep2Symmetry[*of r p*] by auto
qed

end

end

14 AxTriangleInequality

This theory declares the Triangle Inequality as an axiom.

```
theory AxTriangleInequality
  imports Norms
begin
```

Although AxTriangleInequality can be proven rather than asserted we have left it as an axiom to illustrate the flexibility of using Isabelle for mathematical physics: well-known mathematical results can be asserted, leaving the researcher free to concentrate on the physics. We can return later to prove the mathematical results when time permits.

```
class AxTriangleInequality = Norms +
  assumes AxTriangleInequality:  $\forall p q . axTriangleInequality p q$ 
begin
end
```

```
end
```

15 Sublemma3

This theory establishes how closely tangent lines approximate world lines.

```
theory Sublemma3
  imports WorldLine AxTriangleInequality TangentLines
begin
```

```
class Sublemma3 = WorldLine + AxTriangleInequality + TangentLines
begin
```

```
lemma sublemma3:
assumes onLine p l
and norm2 p = 1
and tangentLine l wl origin
shows
 $\forall \varepsilon > 0 . \exists \delta > 0 . \forall y ny . ($ 
   $((y \text{ within } \delta \text{ of origin}) \wedge (y \neq origin) \wedge (y \in wl) \wedge (norm y =$ 
   $ny))$ 
   $\longrightarrow$ 
   $((((1/ny) \otimes y) \text{ within } \varepsilon \text{ of } p) \vee (((-1/ny) \otimes y) \text{ within } \varepsilon \text{ of } p))$ 
 $)$ 
```

```

proof –
  { fix  $e :: 'a$ 
    { assume  $epos: e > 0$ 

      hence  $e2pos: e/2 > 0$  by simp

      have  $prop1: origin \in wl$  using  $assms(3)$  by auto
      have  $prop2: onLine\ origin\ l$  using  $assms(3)$  by auto
      hence  $prop3: \forall \varepsilon > 0. \exists q \in wl. (origin \neq q) \wedge (inBall\ q\ \varepsilon$ 
origin)
        using  $assms(3)$  by auto

      have  $prop4: \forall p. ((onLine\ p\ l) \wedge (p \neq origin)) \longrightarrow$ 
        ( $\forall \varepsilon > 0. \exists \delta > 0. \forall y \in wl. ($ 
          ( $y\ within\ \delta\ of\ origin) \wedge (y \neq origin) )$ 
           $\longrightarrow$ 
          ( $\exists r. ((onLine\ r\ (lineJoining\ origin\ y)) \wedge (r\ within\ \varepsilon\ of$ 
p))))
        )
        using  $assms(3)$  lemTangentLineA[of origin]
        by auto

      have  $p \neq origin$  using  $assms(2)$  lemNullImpliesOrigin by auto

      hence  $ballprops: \forall \varepsilon > 0. \exists \delta > 0. \forall y \in wl. ($ 
        ( $y\ within\ \delta\ of\ origin) \wedge (y \neq origin) )$ 
         $\longrightarrow$ 
        ( $\exists r. ((onLine\ r\ (lineJoining\ origin\ y)) \wedge (r\ within\ \varepsilon\ of$ 
p))))
        )
        using  $assms(1)$   $prop4$  by auto

      define  $eps$  where  $eps = (if\ (e/2 < 1/2)\ then\ (e/2)\ else\ (1/2))$ 

      hence  $eps-le-e2: eps \leq e/2$  by auto

      have  $epspos: eps > 0$  using  $e2pos\ eps-def$  by simp

      { assume  $ass1: e/2 < 1/2$ 
        hence  $eps = e/2$  using  $eps-def$  by auto
        hence  $eps < 1/2$  using  $ass1$  by simp
        hence  $eps \leq 1/2$  by simp
      }
      hence  $case1: (e/2 < 1/2) \longrightarrow eps \leq 1/2$  by auto
      have  $\neg(e/2 < 1/2) \longrightarrow eps = 1/2$  using  $eps-def$  by simp

```

hence case2: $\neg(e/2 < 1/2) \longrightarrow eps \leq 1/2$ **by auto**
hence $(eps \leq (1/2))$ **using case1 case2 by auto**
hence eps-lt-1: $eps < 1$ **using le-less-trans by auto**
hence sqr eps < eps using epspos lemMultPosLT1 by auto
hence epssqu: $sqr\ eps < 1$ **using eps-lt-1 le-less-trans by auto**

then obtain d where dprops: $(d > 0) \wedge (\forall y \in wl. ($
 $(y\ within\ d\ of\ origin) \wedge (y \neq origin))$
 \longrightarrow
 $(\exists r . ((onLine\ r\ (lineJoining\ origin\ y)) \wedge (r\ within\ eps\ of$
 $p))))$
) using epspos ballprops by auto

{ fix y ny assume ny: ny = norm y
{ assume y: (y within d of origin) \wedge (y \neq origin) \wedge (y \in wl)

**hence $\exists r . ((onLine\ r\ (lineJoining\ origin\ y)) \wedge (r\ within\ eps$
of p))**

using dprops by blast
then obtain r
where r: (onLine r (lineJoining origin y)) \wedge (r within eps
of p)

by auto

hence $\exists \alpha . r = (\alpha \otimes y)$ by simp
then obtain α where alpha: $r = (\alpha \otimes y)$ by auto

{ assume $\alpha = 0$
hence rnull: $r = origin$ using alpha by simp
hence one: $sep2\ r\ p = 1$ using assms(2) by auto
have $sep2\ r\ p < sqr\ eps$ using r by auto
hence not-one: $sep2\ r\ p < 1$ using epssqu by auto
hence False using one not-one by auto
}
hence anz: $\alpha \neq 0$ by auto

define np where np = norm p
hence np: np = 1 using assms(2) lemSqrt1 by auto

define npr where npr = norm (p \ominus r)
hence sqr npr = sep2 p r using local.lemNormSqrIsNorm2
by presburger

hence sqr npr < sqr eps using r lemSep2Symmetry by auto
hence sqr npr < sqr eps \wedge eps > 0 using epspos by auto
hence npr: npr < eps
using lemSqrOrderedStrict[of eps npr] by auto
hence npr1: $1 - npr > 1 - eps$

using *diff-strict-left-mono* **by** *simp*

have *npr-lt-e2*: $npr < e/2$ **using** *npr eps-le-e2 le-less-trans*
by *auto*

define *nr* **where** $nr = norm\ r$
hence *sqr nr* $= norm2\ (\alpha \otimes y)$ **using** *alpha lemNormSqrIsNorm2* **by** *presburger*
hence *nr*: $sqr\ nr = (sqr\ \alpha) * norm2\ y$ **using** *lemNorm2OfScaled*
by *auto*

have *axTriangleInequality* $(p \oplus r)$ **using** *AxTriangleInequality*
by *blast*
hence $(np \leq npr + nr)$ **using** *np-def npr-def nr-def* **by** *simp*
hence $nr \geq 1 - npr$ **using** *np lemLEPlus* **by** *auto*
hence *triangle1*: $nr > 1 - eps$ **using** *npr1 le-less-trans* **by**
simp

define *nrp* **where** $nrp = norm\ (r \oplus p)$
hence *nrppr*: $nrp = npr$ **using** *npr-def nrp-def lemSep2Symmetry[of p r]* **by** *auto*

have *axTriangleInequality* $(r \oplus p)$ **using** *AxTriangleInequality*
by *blast*
hence $(nr \leq npr + 1)$
using *np-def npr-def nr-def np nrp-def nrppr* **by** *auto*
hence *triangle2*: $nr < 1 + eps$
using *npr add-strict-right-mono le-less-trans add-commute*
by *simp*

have *range*: $(1 - eps) < nr < (1 + eps)$
using *triangle1 triangle2* **by** *simp*

have $(ny = 0) \longrightarrow (y = origin)$
using *ny lemNormSqrIsNorm2[of y] lemNullImpliesOrigin*
by *auto*
hence *nynz*: $ny \neq 0$ **using** *y* **by** *auto*

have $norm\ ((1/ny) \otimes y) = ((abs\ (1/ny)) * ny)$ **using** *ny lemNormOfScaled[of 1/ny y]* **by** *auto*
hence *nyunit*: $norm\ ((1/ny) \otimes y) = 1$ **using** *y nynz ny lemNormNonNegative* **by** *auto*

have $norm\ r = ((abs\ \alpha) * ny)$ **using** *ny alpha lemNormOfScaled[of \alpha y]* **by** *auto*
hence *nr-is-any*: $nr = ((abs\ \alpha) * ny)$ **using** *nr-def lemSqrt*
by *auto*

```

    hence  $(1 - \text{eps}) < ((\text{abs } \alpha) * \text{ny}) < (1 + \text{eps})$  using range
  by auto
  hence star:  $\text{abs } (((\text{abs } \alpha) * \text{ny}) - 1) < \text{eps}$ 
    using epspos lemAbsRange[of eps 1 ((abs alpha) * ny)] by auto

  have cases:  $(\alpha > 0) \vee (\alpha < 0)$  using anz by auto

  { assume apos:  $\alpha > 0$ 
    hence  $\text{abs } \alpha = \alpha$  by auto
    hence case1range:  $\text{abs } ((\alpha * \text{ny}) - 1) < \text{eps}$  using star by
auto

    define w1 where  $w1 = ((\alpha \otimes y) \ominus ((1/\text{ny}) \otimes y))$ 
    define nw1 where  $nw1 = \text{norm } w1$ 

    have  $(\alpha \otimes y) = ((1/\text{ny}) \otimes ((\alpha * \text{ny}) \otimes y))$ 
      using nynz lemScaleAssoc by auto
    hence  $w1 = (((1/\text{ny}) \otimes ((\alpha * \text{ny}) \otimes y)) \ominus ((1/\text{ny}) \otimes y))$ 
      using w1-def by simp
    hence  $w1 = ((1/\text{ny}) \otimes (((\alpha * \text{ny}) \otimes y) \ominus y))$ 
      using lemScaleDistribDiff[of 1/ny (alpha * ny) \otimes y y] by force
    hence  $w1 = (((\alpha * \text{ny}) - 1) \otimes ((1/\text{ny}) \otimes y))$ 
      using lemScaleLeftDiffDistrib lemScaleCommute by auto
    hence 2:  $\text{norm } w1 = (\text{abs } ((\alpha * \text{ny}) - 1))$ 
      using lemNormOfScaled[of  $((\alpha * \text{ny}) - 1) (1/\text{ny}) \otimes y$ ]
nyunit by auto

    {
      define pp where  $pp = (p \ominus (\alpha \otimes y))$ 
      define qq where  $qq = ((\alpha \otimes y) \ominus ((1/\text{ny}) \otimes y))$ 
      have axTriangleInequality pp qq using AxTriangleInequality
    by simp
      hence  $\text{norm } (pp \oplus qq) \leq \text{norm } pp + \text{norm } qq$  by auto
      hence  $\text{norm } ((p \ominus ((1/\text{ny}) \otimes y))) \leq \text{norm } pp + \text{norm } qq$ 
        using lemSumDiffCancelMiddle pp qq by simp
      hence  $\text{norm } ((p \ominus ((1/\text{ny}) \otimes y))) \leq \text{norm } (p \ominus r) + \text{norm } w1$ 

        using alpha w1-def pp qq by auto
      }
    hence 3:  $\text{norm } ((p \ominus ((1/\text{ny}) \otimes y))) \leq \text{npr} + \text{nw1}$ 
      using nw1-def npr-def by force

    define nminus where  $nminus = \text{norm } ((p \ominus ((1/\text{ny}) \otimes y)))$ 

    hence almost1:  $nminus \leq \text{npr} + \text{nw1}$  using 3 nminus-def
  by auto

```

```

      have abs ((ny * α) - 1) ≥ 0 by auto
      hence nw1 = abs ((α * ny) - 1) using nw1-def 2 lem.Sqrt
by blast
      hence nw1 < eps using case1range le-less-trans by auto
      hence nw1 < e/2 using eps-le-e2 le-less-trans by auto

      hence nminus < (e/2 + e/2)
      using almost1 npr-lt-e2 add-strict-mono le-less-trans by
simp
      hence nminus < e using lem.SumOfTwoHalves by simp

      hence sqr nminus < sqr e
      using lem.SqrMonoStrict[of nminus e] nminus-def
      lem.NormNonNegative[of ((p ⊖ ((1/ny)⊗y)))]
      by auto

      hence norm2 ((p ⊖ ((1/ny)⊗y))) < sqr e
      using lem.NormSqrIsNorm2[of ((p ⊖ ((1/ny)⊗y)))]
nminus-def by auto
      hence p within e of ((1/ny)⊗y) by auto
      hence ((1/ny)⊗y) within e of p
      using lem.Sep2Symmetry[of ((1/ny)⊗y)] by auto
    }
  hence case1: (α > 0) → (((1/ny)⊗y) within e of p) by blast

  { assume aneg: α < 0
    hence abs α = -α by auto
    hence abs -(α * ny) - 1 < eps using star by auto
    hence case2range: abs (α*ny + 1) < eps
      using lem.AbsNegNeg[of α*ny 1] by auto

    define w2 where w2 = ((α⊗y) ⊕ ((1/ny)⊗y))
    define nw2 where nw2 = norm w2

    have (α ⊗ y) = ((1/ny) ⊗ ((α * ny) ⊗ y))
      using nynz lem.ScaleAssoc by auto
    hence w2 = (((1/ny) ⊗ ((α * ny) ⊗ y)) ⊕ ((1/ny)⊗y))
      using w2-def by simp
    also have ... = ((1/ny) ⊗ (((α * ny) ⊗ y) ⊕ y))
      using lem.ScaleDistribSum[of 1/ny (α * ny) ⊗ y y] by
simp
    also have ... = (((α * ny) + 1) ⊗ ((1/ny) ⊗ y))
      using lem.ScaleLeftDiffDistrib[where b=-1] lem.ScaleCom-
mute by auto
    finally have 4: norm w2 = (abs ((α * ny) + 1))
      using lem.NormOfScaled[of ((α * ny) + 1) (1/ny) ⊗ y]
nyunit by auto
  }

```

```

{
  define pp where pp: pp = (p⊖(α⊗y))
  define qq where qq: qq = ((α⊗y) ⊕ ((1/ny)⊗y))
  have axTriangleInequality pp qq using AxTriangleInequality
by simp
  hence norm (pp ⊕ qq) ≤ norm pp + norm qq by auto
  hence norm ((p ⊕ ((1/ny)⊗y))) ≤ norm pp + norm qq
    using lemDiffSumCancelMiddle pp qq by force
  hence norm ((p ⊕ ((1/ny)⊗y))) ≤ norm (p⊖r) + norm
w2
    using alpha w2-def pp qq by auto
}
  hence 5: norm ((p ⊕ ((1/ny)⊗y))) ≤ npr + nw2 using
nw2-def npr-def by auto

  define nplus where nplus = norm ((p ⊕ ((1/ny)⊗y)))

  hence almost2: nplus ≤ npr + nw2 using 5 nplus-def by
auto

  have abs ((ny * α) - 1) ≥ 0 by auto
  hence nw2 = abs ((α * ny) + 1) using nw2-def 4 lemSqrt[of
norm2 w2] by auto
  hence nw2 < eps using case2range le-less-trans by auto
  hence nw2 < e/2 using eps-le-e2 le-less-trans by auto

  hence nplus < (e/2 + e/2)
    using almost2 npr-lt-e2 add-strict-mono le-less-trans by
simp

  hence nplus < e using lemSumOfTwoHalves by simp
  hence sqr nplus < sqr e using
    lemSqrMonoStrict[of nplus e] nplus-def
    lemNormNonNegative[of ((p ⊕ ((1/ny)⊗y)))]
  by auto

  hence norm2 ((p ⊕ ((1/ny)⊗y))) < sqr e
  using lemNormSqrIsNorm2[of ((p ⊕ ((1/ny)⊗y)))] nplus-def
by auto

  hence sep2 p ((-1/ny)⊗y) < sqr e by simp
  hence (((-1/ny)⊗y) within e of p)
    using lemSep2Symmetry[of ((-1/ny)⊗y)] by auto
}
  hence case2: (α < 0) → (((-1/ny)⊗y) within e of p) by
blast

```


hence $((1/ny) \otimes y)$ within e of p \vee $((-1/ny) \otimes y)$ within e
of p)
using cases case1 by auto
}
hence $((y$ within d of origin) \wedge $(y \neq$ origin) \wedge $(y \in$ $wl) \wedge$
(norm $y = ny)$)
 \rightarrow $((1/ny) \otimes y)$ within e of p \vee $((-1/ny) \otimes y)$ within e
of p)
by blast
}
hence $\exists \delta > 0 . \forall y ny . ((y$ within δ of origin)
 \wedge $(y \neq$ origin) \wedge $(y \in$ $wl) \wedge$ (norm $y = ny)$)
 \rightarrow $((1/ny) \otimes y)$ within e of p \vee $((-1/ny) \otimes y)$ within e
of p)
using dprops by blast
}
hence $e > 0 \rightarrow$
 $(\exists \delta > 0 . \forall y ny . ((y$ within δ of origin) \wedge $(y \neq$ origin) \wedge $(y \in$
 $wl) \wedge$ (norm $y = ny)$)
 \rightarrow $((1/ny) \otimes y)$ within e of p \vee $((-1/ny) \otimes y)$ within e
of p))
by blast
}
thus ?thesis by blast
qed

lemma *sublemma3Translation:*

assumes *onLine* p l

and $norm2$ $(p \ominus x) = 1$

and *tangentLine* l wl x

shows $\forall \varepsilon > 0 . \exists \delta > 0 . \forall y nyx .$

$((y$ within δ of $x) \wedge (y \neq x) \wedge (y \in wl) \wedge (norm (y \ominus x)$
 $= nyx))$

\rightarrow

$((1/nyx) \otimes (y \ominus x))$ within ε of $(p \ominus x)$
 \vee $((-1/nyx) \otimes (y \ominus x))$ within ε of $(p \ominus x)$)

proof –

define pre

where $pre: pre = (\lambda d y nyx . (y$ within d of $x) \wedge (y \neq x) \wedge (y \in$
 $wl) \wedge (norm (y \ominus x) = nyx))$

define $post$

where $post: post = (\lambda e y nyx . (((1/nyx) \otimes (y \ominus x))$ within e of
 $(p \ominus x))$

\vee $((-1/nyx) \otimes (y \ominus x))$ within e of $(p \ominus x))$)

define T where $T = mkTranslation$ (origin $\ominus x$)

hence *transT*: translation T **using** *lemMkTrans* **by** *blast*
have $T: \forall p. T p = (p \oplus (\text{origin} \ominus x))$ **using** *T-def* **by** *simp*

define p' **where** $p': p' = T p$
define l' **where** $l': l' = (\text{applyToSet } (\text{asFunc } T) l)$
define x' **where** $x': x' = T x$
define wl' **where** $wl': wl' = (\text{applyToSet } (\text{asFunc } T) wl)$

have 1 : *onLine* $p' l'$
using *assms(1)* $T p' l'$ *lemOnLineTranslation*[of $T l p$]
by *blast*

have $x'0$: $x' = \text{origin}$ **using** $T x'$ *add-diff-eq* **by** *auto*
hence $sep2 p' \text{origin} = 1$
using $T \text{assms}(2)$ p' *lemTranslationPreservesSep2* **by** *simp*
hence 2 : *norm2* $p' = 1$ **by** *auto*

have *tangentLine* ($\text{applyToSet } (\text{asFunc } T) l$)
 $(\text{applyToSet } (\text{asFunc } T) wl) (T x)$
using *transT* *assms(3)* *lemTangentLineTranslation*[of $T x wl l$]
by *auto*
hence 3 : *tangentLine* $l' wl' \text{origin}$ **using** $l' wl' x' x'0$ **by** *auto*

hence *conc*: $\forall \varepsilon > 0 . \exists \delta > 0 . \forall y' ny' . ($
 $((y' \text{ within } \delta \text{ of origin}) \wedge (y' \neq \text{origin}) \wedge (y' \in wl') \wedge (\text{norm } y'$
 $= ny'))$
 \longrightarrow
 $((((1/ny') \otimes y') \text{ within } \varepsilon \text{ of } p') \vee (((-1/ny') \otimes y') \text{ within } \varepsilon \text{ of}$
 $p')))$
using $1 2 3$ *sublemma3*[of $l' p'$]
by *auto*

{ fix e
assume *epos*: $e > 0$
then obtain d **where** $d: (d > 0) \wedge (\forall y' ny' . ($
 $((y' \text{ within } d \text{ of origin}) \wedge (y' \neq \text{origin}) \wedge (y' \in wl') \wedge (\text{norm } y'$
 $= ny'))$
 \longrightarrow
 $((((1/ny') \otimes y') \text{ within } e \text{ of } p') \vee (((-1/ny') \otimes y') \text{ within } e \text{ of}$
 $p'))))$
using *conc* **by** *blast*

{ fix $y nyx$
assume *hyp*: $pre d y nyx$

define y' **where** $y': y' = T y$
hence *rtp1*: $y' \text{ within } d \text{ of origin}$
using *transT* *hyp* $x' x'0$ *lemBallTranslation* *pre* **by** *auto*

```

have p'px: p' = (p ⊖ x) using p' T by simp
have y'yx: y' = (y ⊖ x) using y' T by simp
hence nyx: norm y' = nyx using hyp pre by force

{ have (T x = x') ∧ (T y = y') ∧ (injective (asFunc T))
  using x' y' lemTranslationInjective[of T] transT by blast
  moreover have x ≠ y using hyp pre by auto
  ultimately have y' ≠ x' by auto
}
hence rtp2: y' ≠ origin using x'0 by simp

have rtp3: y' ∈ wl' using hyp pre y' wl' by force

  hence (y' within d of origin) ∧ (y' ≠ origin) ∧ (y' ∈ wl') ∧
(norm y' = nyx)
  using rtp1 rtp2 rtp3 nyx by blast

  hence (((1/nyx)⊗y') within e of p') ∨ (((-1/nyx)⊗y') within e
of p')
  using d by auto
  hence post e y nyx using post y'yx p'px by auto
}
hence ∀ y nyx . pre d y nyx → post e y nyx by auto
hence ∃ δ>0. ∀ y nyx . pre δ y nyx → post e y nyx using d by
auto
}
hence ∀ ε>0 . ∃ δ>0. ∀ y nyx . pre δ y nyx → post ε y nyx by
auto
thus ?thesis using post pre by blast
qed

```

end

end

16 Vectors

In this theory we define dot-products, and explain what we mean by timelike, lightlike (null), causal and spacelike vectors.

```

theory Vectors
  imports Norms
begin

class Vectors = Norms
begin

```

```

fun dot :: 'a Point ⇒ 'a Point ⇒ 'a (⟨- ∘ -⟩)
  where dot u v = (tval u)*(tval v) + (xval u)*(xval v) +
    (yval u)*(yval v) + (zval u)*(zval v)

fun sdot :: 'a Space ⇒ 'a Space ⇒ 'a (⟨- ∘s -⟩)
  where sdot u v = (svalx u)*(svalx v) + (svaly u)*(svaly v) + (svalz
u)*(svalz v)

fun mdot :: 'a Point ⇒ 'a Point ⇒ 'a (⟨- ∘m -⟩)
  where mdot u v = (tval u)*(tval v) - ((sComponent u) ∘s (sComponent
v))

abbreviation timelike :: 'a Point ⇒ bool
  where timelike p ≡ mNorm2 p > 0

abbreviation lightlike :: 'a Point ⇒ bool
  where lightlike p ≡ (p ≠ origin ∧ mNorm2 p = 0)

abbreviation spacelike :: 'a Point ⇒ bool
  where spacelike p ≡ mNorm2 p < 0

abbreviation causal :: 'a Point ⇒ bool
  where causal p ≡ timelike p ∨ lightlike p

abbreviation orthog :: 'a Point ⇒ 'a Point ⇒ bool
  where orthog p q ≡ (p ∘ q) = 0

abbreviation orthogs :: 'a Space ⇒ 'a Space ⇒ bool
  where orthogs p q ≡ (p ∘s q) = 0

abbreviation orthogm :: 'a Point ⇒ 'a Point ⇒ bool
  where orthogm p q ≡ (p ∘m q) = 0

```

```

lemma lemDotDecomposition:
  shows (u ∘ v) = (tval u * tval v) + ((sComponent u) ∘s (sComponent
v))
  by (simp add: add-commute local.add.left-commute)

```

```

lemma lemDotCommute: dot u v = dot v u
  by (simp add: mult-commute)

```

```

lemma lemDotScaleLeft: dot (a⊗u) v = a * (dot u v)

```

using *mult-assoc distrib-left* **by** *force*

lemma *lemDotScaleRight*: $\text{dot } u (a \otimes v) = a * (\text{dot } u v)$
using *mult-assoc mult-commute distrib-left* **by** *auto*

lemma *lemDotSumLeft*: $\text{dot } (u \oplus v) w = (\text{dot } u w) + (\text{dot } v w)$
using *distrib-right add-assoc add-commute* **by** *force*

lemma *lemDotSumRight*: $\text{dot } u (v \oplus w) = (\text{dot } u v) + (\text{dot } u w)$
using *distrib-left add-assoc add-commute* **by** *auto*

lemma *lemDotDiffLeft*: $\text{dot } (u \ominus v) w = (\text{dot } u w) - (\text{dot } v w)$
by (*simp add: field-simps*)

lemma *lemDotDiffRight*: $\text{dot } u (v \ominus w) = (\text{dot } u v) - (\text{dot } u w)$
by (*simp add: field-simps*)

lemma *lemNorm2OfSum*: $\text{norm2 } (u \oplus v) = \text{norm2 } u + 2*(u \odot v) + \text{norm2 } v$

proof –

have $\text{norm2 } (u \oplus v) = ((u \oplus v) \odot (u \oplus v))$ **by** *auto*

also have $\dots = (u \odot (u \oplus v)) + (v \odot (u \oplus v))$

using *lemDotSumLeft*[*of u v (u \oplus v)*] **by** *auto*

also have $\dots = (u \odot u) + ((u \odot v) + (v \odot u)) + (v \odot v)$

using *lemDotSumRight*[*of u u v*] *lemDotSumRight*[*of v u v*]
add-assoc **by** *auto*

finally show *?thesis* **using** *mult-2 lemDotCommute*[*of u v*]
by *auto*

qed

lemma *lemSDotCommute*: $\text{sdot } u v = \text{sdot } v u$
by (*simp add: mult-commute*)

lemma *lemSDotScaleLeft*: $\text{sdot } (a \otimes s u) v = a * (\text{sdot } u v)$
using *mult-assoc distrib-left* **by** *force*

lemma *lemSDotScaleRight*: $\text{sdot } u (a \otimes s v) = a * (\text{sdot } u v)$
using *mult-assoc mult-commute distrib-left* **by** *auto*

lemma *lemSDotSumLeft*: $\text{sdot } (u \oplus s v) w = (\text{sdot } u w) + (\text{sdot } v w)$
using *distrib-right add-assoc add-commute* **by** *force*

lemma *lemSDotSumRight*: $\text{sdot } u (v \oplus s w) = (\text{sdot } u v) + (\text{sdot } u w)$
using *distrib-left add-assoc add-commute* **by** *auto*

lemma *lemSDotDiffLeft*: $\text{sdot } (u \ominus s v) w = (\text{sdot } u w) - (\text{sdot } v w)$
by (*simp add: field-simps*)

lemma *lemSDotDiffRight*: $s\dot{d}ot\ u\ (v \ominus s\ w) = (s\dot{d}ot\ u\ v) - (s\dot{d}ot\ u\ w)$
by (*simp add: field-simps*)

lemma *lemMDotDiffLeft*: $m\dot{d}ot\ (u \ominus v)\ w = (m\dot{d}ot\ u\ w) - (m\dot{d}ot\ v\ w)$
by (*simp add: field-simps*)

lemma *lemMDotSumLeft*: $m\dot{d}ot\ (u \oplus v)\ w = (m\dot{d}ot\ u\ w) + (m\dot{d}ot\ v\ w)$

proof –

have $m\dot{d}ot\ (u \oplus v)\ w = (tval\ (u \oplus v)) * (tval\ w) - ((sComponent\ (u \oplus v)) \odot s(sComponent\ w))$

by *auto*

also have $\dots = (tval\ u * tval\ w) + (tval\ v * tval\ w) - ((sComponent\ u) \odot s(sComponent\ w)) + ((sComponent\ v) \odot s(sComponent\ w))$

using *distrib lemSDotSumLeft* [of (*sComponent u*) (*sComponent v*) (*sComponent w*)]

by *auto*

also have $\dots = ((tval\ u * tval\ w) - ((sComponent\ u) \odot s(sComponent\ w))) + ((tval\ v * tval\ w) - ((sComponent\ v) \odot s(sComponent\ w)))$

using *add-diff-eq add-commute diff-diff-add* **by** *auto*

finally show *?thesis* **by** *simp*

qed

lemma *lemMDotScaleLeft*: $m\dot{d}ot\ (a \otimes u)\ v = a * (m\dot{d}ot\ u\ v)$

proof –

have $m\dot{d}ot\ (a \otimes u)\ v = a * (tval\ u * tval\ v) - a * ((sComponent\ u) \odot s(sComponent\ v))$

using *lemSDotScaleLeft* [of *a sComponent u sComponent v*]

by (*simp add: mult-assoc*)

thus *?thesis* **by** (*simp add: local.right-diff-distrib'*)

qed

lemma *lemMDotScaleRight*: $m\dot{d}ot\ u\ (a \otimes v) = a * (m\dot{d}ot\ u\ v)$

proof –

have $m\dot{d}ot\ u\ (a \otimes v) = a * (tval\ u * tval\ v) - a * ((sComponent\ u) \odot s(sComponent\ v))$

using *lemSDotScaleRight* [of *sComponent u a sComponent v*]

by (*simp add: local.mult.left-commute*)

thus *?thesis* **by** (*simp add: local.right-diff-distrib'*)

qed

lemma *lemSNorm2OfSum*: $sNorm2 (u \oplus s v) = sNorm2 u + 2*(u \odot s v) + sNorm2 v$

proof –

have $sNorm2 (u \oplus s v) = ((u \oplus s v) \odot s (u \oplus s v))$ **by** *auto*

also have $\dots = (u \odot s (u \oplus s v)) + (v \odot s (u \oplus s v))$

using *lemSDotSumLeft*[of $u v (u \oplus s v)$] **by** *auto*

also have $\dots = (u \odot s u) + ((u \odot s v) + (v \odot s u)) + (v \odot s v)$

using *lemSDotSumRight*[of $u u v$] *lemSDotSumRight*[of $v u v$]
add-assoc **by** *auto*

finally show *?thesis* **using** *mult-2 lemSDotCommute*[of $u v$]
by *auto*

qed

lemma *lemSNormNonNeg*:

shows $sNorm v \geq 0$

proof –

have *hasUniqueRoot* ($sNorm2 v$) **using** *AxEField lemSqrt* **by** *auto*

thus *?thesis* **using** *the1-equality*[of *isNonNegRoot* ($sNorm2 v$)] **by**

blast

qed

lemma *lemMNorm2OfSum*: $mNorm2 (u \oplus v) = mNorm2 u + 2*(u \odot m v) + mNorm2 v$

proof –

define su **where** $su: su = sComponent u$

define sv **where** $sv: sv = sComponent v$

have $mNorm2 (u \oplus v) = ((u \oplus v) \odot m (u \oplus v))$ **by** *auto*

also have $\dots = (sqr (tval u) + 2*(tval u)*(tval v) + sqr (tval v))$
 $- sNorm2 (su \oplus s sv)$

using *lemSqrSum* $su sv$ **by** *auto*

also have $\dots = (sqr (tval u) + 2*(tval u)*(tval v) + sqr (tval v))$
 $- (sNorm2 su + 2*(su \odot s sv) + sNorm2 sv)$

using *lemSNorm2OfSum* **by** *auto*

also have $\dots = (sqr (tval u) - sNorm2 su)$
 $+ (2*(tval u)*(tval v) - 2*(su \odot s sv))$
 $+ (sqr (tval v) - sNorm2 sv)$

using *add-commute add-assoc add-diff-eq diff-add-eq diff-diff-add*
by *simp*

finally show *?thesis* **using** $su sv$ *right-diff-distrib'* *mult-assoc* **by**
auto

qed

lemma *lemMNorm2OfDiff*: $mNorm2 (u \ominus v) = mNorm2 u - 2*(u \odot m v) + mNorm2 v$

proof –

define *vm* **where** $vm: vm = ((-1) \otimes v)$

hence $mNorm2 (u \ominus v) = mNorm2 (u \oplus vm)$ **by** *auto*

hence $mNorm2 (u \ominus v) = mNorm2 u + 2*(u \odot m vm) + mNorm2 vm$

using *lemMNorm2OfSum* **by** *auto*

moreover $have (u \odot m vm) = -(u \odot m v)$

using *lemMDotScaleRight*[of $u (-1) v$] *vm* **by** *auto*

moreover $have mNorm2 vm = mNorm2 v$ **using** *vm lemMNorm2OfScaled* **by** *auto*

ultimately **show** *?thesis*

by (*metis local.diff-conv-add-uminus local.mult-minus-right*)

qed

lemma *lemMNorm2Decomposition*: $mNorm2 p = (p \odot m p)$

by *auto*

lemma *lemMDecomposition*:

assumes $(u \odot m v) \neq 0$

and $mNorm2 v \neq 0$

and $a = (u \odot m v) / (mNorm2 v)$

and $up = (a \otimes v)$

and $uo = (u \ominus up)$

shows $u = (up \oplus uo) \wedge \text{parallel } up \ v \wedge \text{orthogm } uo \ v \wedge (up \odot m v) = (u \odot m v)$

proof –

have *anz*: $a \neq 0$ **using** *assms* **by** *auto*

have *psum*: $u = (up \oplus uo)$ **using** *assms add-diff-eq* **by** *auto*

moreover $have \text{parallel } up \ v$ **using** *assms(4) anz* **by** *auto*

moreover $have \text{ppdot}: (up \odot m v) = (u \odot m v)$

proof –

have $(up \odot m v) = a*(v \odot m v)$ **using** *assms lemMDotScaleLeft*[of $a \ v \ v$] **by** *auto*

thus *?thesis* **using** *assms* **by** *auto*

qed

moreover $have \text{orthogm } uo \ v$

proof –

have $(uo \odot m v) = (u \odot m v) - (up \odot m v)$ **using** *lemMDotSumLeft* *psum* **by** *force*

thus *?thesis* **using** *ppdot* **by** *auto*

qed

ultimately **show** *?thesis* **by** *blast*

qed

end

end

17 CauchySchwarz

This theory defines and proves the Cauchy-Schwarz inequality for both spatial and spacetime vectors.

```
theory CauchySchwarz  
  imports Vectors  
begin
```

We essentially prove the same result twice, once for 3-dimensional spatial points, and once for 4-dimensional spacetime points. While this is clearly inefficient, it keeps things straightforward for non-Isabelle experts.

```
class CauchySchwarz = Vectors  
begin
```

```
lemma lemCauchySchwarz4:  
  shows  $abs (dot\ u\ v) \leq (norm\ u)*(norm\ v)$   
proof -  
  have vorigin:  $v = origin \longrightarrow abs (dot\ u\ v) \leq (norm\ u)*(norm\ v)$   
  proof -  
    { assume  $v = origin$   
      hence  $abs (dot\ u\ v) = 0$  by simp  
      also have  $\dots \leq (norm\ u)*(norm\ v)$  using lemNormNonNegative  
by simp  
      finally have  $abs (dot\ u\ v) \leq (norm\ u)*(norm\ v)$  by auto  
    }  
  thus ?thesis by blast  
qed
```

```
define a where  $a = dot\ v\ v$   
define b where  $b = 2 * dot\ u\ v$   
define c where  $c = dot\ u\ u$ 
```

```
{ fix  $x :: 'a$   
  define w where  $w = (u \oplus (x \otimes v))$   
  have ww:  $(dot\ w\ w) \geq 0$  by simp
```

```
define xv where  $xv = (x \otimes v)$   
define middle2 where  $middle2 = dot\ u\ xv + dot\ xv\ u$ 
```

have $\text{dot } xv \ u = \text{dot } u \ xv$ **using** *lemDotCommute* **by** *blast*
hence $\text{middle2} = \text{dot } u \ xv + \text{dot } u \ xv$ **using** *middle2-def* **by** *simp*
also have $\dots = 2 * \text{dot } u \ xv$ **using** *mult-2* **by** *simp*
finally have *bterm*: $\text{middle2} = b * x$
using *lemDotScaleRight* *mult-assoc* *mult-commute* *b-def* *xv* **by**
auto

have *vxv*: $(\text{dot } v \ xv) = (x * \text{dot } v \ v)$ **using** *xv* *lemDotScaleRight* **by**
blast
have $\text{dot } xv \ xv = x * (\text{dot } v \ xv)$ **using** *lemDotScaleLeft* *xv* **by** *blast*
also have $\dots = (\text{sqr } x) * (\text{dot } v \ v)$ **using** *vxv* *mult-assoc* **by** *simp*
finally have *aterm*: $\text{dot } xv \ xv = a * (\text{sqr } x)$ **using** *mult-commute*
a-def **by** *simp*

have *uw*: $\text{dot } u \ w = \text{dot } u \ u + \text{dot } u \ xv$ **using** *lemDotSumRight*
w-def *xv* **by** *blast*
have *vw*: $\text{dot } xv \ w = \text{dot } xv \ u + \text{dot } xv \ xv$ **using** *lemDotSumRight*
w-def *xv* **by** *blast*
have $\text{dot } w \ w = \text{dot } u \ w + \text{dot } xv \ w$ **using** *lemDotSumLeft* *w-def*
xv **by** *blast*
also have $\dots = (\text{dot } u \ u + \text{dot } u \ xv) + (\text{dot } xv \ u + \text{dot } xv \ xv)$
using *uw* *vw* **by** *simp*
also have $\dots = (\text{dot } u \ u) + (\text{dot } u \ xv + \text{dot } xv \ u) + \text{dot } xv \ xv$
using *add-assoc* **by** *force*
also have $\dots = (\text{dot } u \ u) + \text{middle2} + \text{dot } xv \ xv$
using *middle2-def* **by** *simp*
also have $\dots = c + b * x + a * (\text{sqr } x)$ **using** *c-def* *bterm* *aterm* **by**
force
finally have $\text{dot } w \ w = a * (\text{sqr } x) + b * x + c$ **using** *add-commute*
add-assoc **by** *auto*

hence $a * \text{sqr}(x) + b * x + c \geq 0$ **using** *uw* **by** *simp*
}
hence *quadratic*: $\forall x. a * \text{sqr}(x) + b * x + c \geq 0$ **by** *auto*

{ assume *vnot0*: $v \neq \text{origin}$
hence $a > 0$ **using** *a-def* *lemNullImpliesOrigin*[*of* *v*]
by (*metis* *local.AxEField* *local.not-less* *local.not-less-iff-gr-or-eq*
local.not-sum-squares-lt-zero *dot.simps*)
hence $(\text{sqr } b) \leq 4 * a * c$ **using** *lemQuadraticGEZero* *quadratic* **by**
auto
hence $(\text{sqr } b) \leq 4 * (\text{dot } v \ v) * (\text{dot } u \ u)$ **using** *a-def* *c-def* **by** *auto*
hence *sqrle*: $(\text{sqr } (\text{abs } b)) \leq 4 * (\text{dot } v \ v) * (\text{dot } u \ u)$ **by** *auto*

define *nv* **where** *nv*: $nv = \text{norm } v$
define *nu* **where** *nu*: $nu = \text{norm } u$

have $nvpos: nv \geq 0$ **using** nv *lemNormNonNegative* **by** *auto*
have $nupos: nu \geq 0$ **using** nu *lemNormNonNegative* **by** *auto*
hence $nvnu: 2*nv*nu \geq 0$ **using** $nvpos$ **by** *auto*

have $n2v: norm2\ v = \text{sqr}\ nv$ **using** *AxEField* nv $nvpos$ *lemNormSqrIsNorm2* **by** *presburger*

have $n2u: norm2\ u = \text{sqr}\ nu$ **using** *AxEField* nu $nupos$ *lemNormSqrIsNorm2* **by** *presburger*

have $4*(\text{dot}\ v\ v)*(\text{dot}\ u\ u) = 4*(norm2\ v)*(norm2\ u)$ **by** *auto*
also have $\dots = (\text{sqr}\ 2)*(\text{sqr}\ nv)*(\text{sqr}\ nu)$ **using** $n2u$ $n2v$ **by** *auto*
also have $\dots = (\text{sqr}\ (2* nv))*(\text{sqr}\ nu)$ **using** *lemSqrMult*[of 2 nv]
by *auto*
also have $\dots = \text{sqr}\ (2*nv*nu)$ **using** *lemSqrMult*[of 2* nv nu] **by** *auto*

finally have $(\text{sqr}\ (\text{abs}\ b)) \leq \text{sqr}\ (2*nv*nu)$ **using** *sqrle* **by** *auto*
hence $bvnu: \text{abs}\ b \leq 2*nv*nu$
using nu nv $nvnu$ *lemSqrOrdered*[of 2* $nv*nu$]
by *auto*

have $pos2: 0 < 2$ **by** *simp*
have $b = 2*\text{dot}\ u\ v$ **using** *b-def* **by** *auto*
hence $\text{abs}\ b = 2*\text{abs}(\text{dot}\ u\ v)$ **using** *abs-mult* **by** *auto*
hence $2*\text{abs}(\text{dot}\ u\ v) \leq 2*(nv*nu)$ **using** $bvnu$ *mult-assoc* **by** *auto*
hence $2*\text{abs}(\text{dot}\ u\ v) \leq 2*(nu*nv)$ **using** *mult-commute* **by** *simp*
hence $\text{abs}(\text{dot}\ u\ v) \leq (nu*nv)$ **using** *mult-le-cancel-left*[of 2] $pos2$
by *blast*
hence *?thesis* **using** nu nv **by** *auto*
}
hence $(v \neq \text{origin}) \longrightarrow ?thesis$ **by** *auto*

thus *?thesis* **using** *vorigin* **by** *auto*
qed

lemma *lemCauchySchwarzSqr4*:

shows $\text{sqr}(\text{dot}\ u\ v) \leq (norm2\ u)*(norm2\ v)$

proof –

have $1: \text{abs}(\text{dot}\ u\ v) \geq 0$ **by** *simp*

have $\text{sqr}(\text{dot}\ u\ v) = \text{sqr}(\text{abs}(\text{dot}\ u\ v))$ **by** *simp*

also have $\dots \leq \text{sqr}((norm\ u)*(norm\ v))$ **using** 1 *lemCauchySchwarz4*
lemSqrMono **by** *blast*

also have $\dots = \text{sqr}(norm\ u) * \text{sqr}(norm\ v)$ **using** *lemSqrMult* **by** *auto*

also have $\dots = norm2\ u * norm2\ v$

using *lemSquareOfSqrt* *lem.Sqrt* *AxEField* *lemNormSqrIsNorm2*
by *force*

finally show *?thesis* **by** *simp*
qed

lemma *lemCauchySchwarz*:
shows $\text{abs } (\text{sdot } u \ v) \leq (\text{sNorm } u) * (\text{sNorm } v)$
proof –
have *vorigin*: $v = \text{sOrigin} \longrightarrow \text{abs } (\text{sdot } u \ v) \leq (\text{sNorm } u) * (\text{sNorm } v)$
proof –
{ **assume** $v = \text{sOrigin}$
hence $\text{abs } (\text{sdot } u \ v) = 0$ **by** *simp*
also have $\dots \leq (\text{sNorm } u) * (\text{sNorm } v)$ **using** *lemSNormNonNeg*
by *simp*
finally have $\text{abs } (\text{sdot } u \ v) \leq (\text{sNorm } u) * (\text{sNorm } v)$ **by** *auto*
}
thus *?thesis* **by** *blast*
qed

define *a* **where** $a = \text{sdot } v \ v$
define *b* **where** $b = 2 * \text{sdot } u \ v$
define *c* **where** $c = \text{sdot } u \ u$

{ **fix** $x :: 'a$
define *w* **where** $w = (u \oplus s \ (x \otimes s \ v))$
have *ww*: $(\text{sdot } w \ w) \geq 0$ **by** *simp*

define *xv* **where** $xv = (x \otimes s \ v)$
define *middle2* **where** $\text{middle2} = \text{sdot } u \ xv + \text{sdot } xv \ u$

have $\text{sdot } xv \ u = \text{sdot } u \ xv$ **using** *lemSDotCommute* **by** *blast*
hence $\text{middle2} = \text{sdot } u \ xv + \text{sdot } u \ xv$ **using** *middle2-def* **by**
simp
also have $\dots = 2 * \text{sdot } u \ xv$ **using** *mult-2* **by** *simp*
finally have *bterm*: $\text{middle2} = b * x$
using *lemSDotScaleRight* *mult-assoc* *mult-commute* *b-def* *xv* **by**
auto

have *v xv*: $(\text{sdot } v \ xv) = (x * \text{sdot } v \ v)$ **using** *xv* *lemSDotScaleRight*
by *blast*
have $\text{sdot } xv \ xv = x * (\text{sdot } v \ xv)$ **using** *lemSDotScaleLeft* *xv* **by**
blast
also have $\dots = (\text{sqr } x) * (\text{sdot } v \ v)$ **using** *v xv* *mult-assoc* **by** *simp*
finally have *aterm*: $\text{sdot } xv \ xv = a * (\text{sqr } x)$ **using** *mult-commute*
a-def **by** *simp*

have uw : $\text{sdot } u w = \text{sdot } u u + \text{sdot } u xv$ **using** *lemSDotSumRight*
w-def xv **by** *blast*
have vw : $\text{sdot } xv w = \text{sdot } xv u + \text{sdot } xv xv$ **using** *lemSDotSumRight*
w-def xv **by** *blast*
have $\text{sdot } w w = \text{sdot } u w + \text{sdot } xv w$ **using** *lemSDotSumLeft*
w-def xv **by** *blast*
also have $\dots = (\text{sdot } u u + \text{sdot } u xv) + (\text{sdot } xv u + \text{sdot } xv xv)$
using $uw\ vw$ **by** *simp*
also have $\dots = (\text{sdot } u u) + (\text{sdot } u xv + \text{sdot } xv u) + \text{sdot } xv xv$
using *add-assoc* **by** *force*
also have $\dots = (\text{sdot } u u) + \text{middle2} + \text{sdot } xv xv$
using *middle2-def* **by** *simp*
also have $\dots = c + b*x + a*(\text{sqr } x)$ **using** *c-def bterm aterm* **by**
force
finally have $\text{sdot } w w = a*(\text{sqr } x) + b*x + c$ **using** *add-commute*
add-assoc **by** *auto*

hence $a*\text{sqr}(x) + b*x + c \geq 0$ **using** uw **by** *simp*
}
hence quadratic: $\forall x. a*\text{sqr}(x) + b*x + c \geq 0$ **by** *auto*

{ assume $v\text{not}0$: $v \neq sOrigin$
hence $a > 0$ **using** *a-def lemSpatialNullImpliesSpatialOrigin* [of v]
by (*metis local.AxEField local.not-less local.not-less-iff-gr-or-eq*
local.not-sum-squares-lt-zero sdot.simps)
hence $(\text{sqr } b) \leq 4*a*c$ **using** *lemQuadraticGEZero quadratic* **by**
auto
hence $(\text{sqr } b) \leq 4*(\text{sdot } v v)*(\text{sdot } u u)$ **using** *a-def c-def* **by** *auto*
hence $\text{sqr}le$: $(\text{sqr } (abs\ b)) \leq 4*(\text{sdot } v v)*(\text{sdot } u u)$ **by** *auto*

define nv **where** nv : $nv = sNorm\ v$
define nu **where** nu : $nu = sNorm\ u$

have $nvpos$: $nv \geq 0$ **using** nv *lemSNormNonNeg* **by** *auto*
have $nu\text{pos}$: $nu \geq 0$ **using** nu *lemSNormNonNeg* **by** *auto*
hence $nvnu$: $2*nv*nu \geq 0$ **using** $nvpos$ **by** *auto*

have $n2v$: $sNorm2\ v = \text{sqr } nv$ **using** *AxEField lemSquareOfSqrt*
 $nv\ nvpos$ **by** *auto*
have $n2u$: $sNorm2\ u = \text{sqr } nu$ **using** *AxEField lemSquareOfSqrt*
 $nu\ nvpos$ **by** *auto*

have $4*(\text{sdot } v v)*(\text{sdot } u u) = 4*(sNorm2\ v)*(sNorm2\ u)$ **by**
auto
also have $\dots = (\text{sqr } 2)*(\text{sqr } nv)*(\text{sqr } nu)$ **using** $n2u\ n2v$ **by** *auto*
also have $\dots = (\text{sqr } (2* nv))*(\text{sqr } nu)$ **using** *lemSqrMult* [of $2\ nv$]
by *auto*
also have $\dots = \text{sqr } (2*nv*nu)$ **using** *lemSqrMult* [of $2*nv\ nu$] **by**
auto

finally have $(\text{sqr } (\text{abs } b)) \leq \text{sqr } (2 * \text{nv} * \text{nu})$ **using** *sqrle* **by** *auto*
hence *bnvnu*: $\text{abs } b \leq 2 * \text{nv} * \text{nu}$
using *nu nv nvn* *lemSqrOrdered*[of $2 * \text{nv} * \text{nu}$]
by *auto*

have *pos2*: $0 < 2$ **by** *simp*
have $b = 2 * \text{sdot } u \ v$ **using** *b-def* **by** *auto*
hence $\text{abs } b = 2 * \text{abs}(\text{sdot } u \ v)$ **using** *abs-mult* **by** *auto*
hence $2 * \text{abs}(\text{sdot } u \ v) \leq 2 * (\text{nv} * \text{nu})$ **using** *bnvnu mult-assoc* **by**
auto
hence $2 * \text{abs}(\text{sdot } u \ v) \leq 2 * (\text{nu} * \text{nv})$ **using** *mult-commute* **by** *simp*
hence $\text{abs}(\text{sdot } u \ v) \leq (\text{nu} * \text{nv})$ **using** *mult-le-cancel-left*[of 2] *pos2*
by *blast*
hence *?thesis* **using** *nu nv* **by** *auto*
}
hence $(v \neq \text{sOrigin}) \longrightarrow ?thesis$ **by** *auto*

thus *?thesis* **using** *vorigin* **by** *auto*
qed

lemma *lemCauchySchwarzSqr*:
shows $\text{sqr}(\text{sdot } u \ v) \leq (\text{sNorm2 } u) * (\text{sNorm2 } v)$
proof –
have *1*: $\text{abs}(\text{sdot } u \ v) \geq 0$ **by** *simp*
have $\text{sqr}(\text{sdot } u \ v) = \text{sqr}(\text{abs}(\text{sdot } u \ v))$ **by** *simp*
also have $\dots \leq \text{sqr}((\text{sNorm } u) * (\text{sNorm } v))$ **using** *1 lemCauchySchwarz*
lemSqrMono **by** *blast*
also have $\dots = \text{sqr}(\text{sNorm } u) * \text{sqr}(\text{sNorm } v)$ **using** *lemSqrMult*
by *auto*
also have $\dots = \text{sNorm2 } u * \text{sNorm2 } v$ **using** *lemSquareOfSqrt*
lemSqrt AxEField **by** *auto*
finally show *?thesis* **by** *simp*
qed

lemma *lemCauchySchwarzEquality*:
assumes $\text{sqr } (\text{sdot } u \ v) = (\text{sNorm2 } u) * (\text{sNorm2 } v)$
and $u \neq \text{sOrigin} \wedge v \neq \text{sOrigin}$
shows $\exists a \neq 0 . u = (a \otimes v)$
proof –
define *a* **where** $a = (\text{sdot } u \ v) / (\text{sNorm2 } v)$
have *wnz*: $\text{sNorm2 } u \neq 0 \wedge \text{sNorm2 } v \neq 0$ **using** *assms lemSpatialNullImpliesSpatialOrigin* **by** *blast*
hence $\text{sqr } (\text{sdot } u \ v) \neq 0$ **using** *assms* **by** *auto*

hence $anz: a \neq 0$ **using** $assms\ uwnz\ a$ **by** $auto$

define upv **where** $upv: upv = (a \otimes s\ v)$
hence $sdotupv: sdot\ upv\ v = sdot\ u\ v$
proof –
have $sdot\ upv\ v = a * sNorm2\ v$ **using** $upv\ lemSDotScaleLeft$ **by** $auto$
thus $?thesis$ **using** $a\ uwnz$ **by** $auto$
qed
have $sn2upv: sNorm2\ upv = (sqr\ a)*sNorm2\ v$ **using** $upv\ lemSNorm2OfScaled$ **by** $auto$

define uov **where** $uov: uov = (u \oplus s\ upv)$
have $usum: u = (upv \oplus s\ uov)$ **using** $uov\ add-diff-eq$ **by** $auto$
hence $sdotuov: sdot\ uov\ v = 0$ **using** $lemSDotSumLeft\ sdotupv$ **by** $force$
hence $pdoto: sdot\ uov\ upv = 0$ **using** $upv\ lemSDotScaleRight\ local.mult-not-zero$ **by** $metis$

have $sqr\ (sdot\ u\ v) = sqr\ (sdot\ (a \otimes s\ v)\ v)$ **using** $sdotupv\ upv$ **by** $auto$
also **have** $\dots = (sqr\ a) * sqr\ (sNorm2\ v)$
using $lemSDotScaleLeft[of\ a\ v\ v]\ lemSqrMult[of\ a]$ **by** $auto$
finally **have** $lhs: sqr\ (sdot\ u\ v) = (sqr\ a) * sqr\ (sNorm2\ v)$ **by** $auto$

have $sNorm2\ u = sNorm2\ upv + 2*(upv \odot s\ uov) + sNorm2\ uov$
using $lemSNorm2OfSum\ usum$ **by** $auto$
also **have** $\dots = (sqr\ a)*sNorm2\ v + sNorm2\ uov$ **using** $sn2upv\ pdoto\ lemSDotCommute$ **by** $auto$
finally **have** $rhs: (sNorm2\ u)*(sNorm2\ v) = (sqr\ a)*sqr(sNorm2\ v) + (sNorm2\ uov)*(sNorm2\ v)$
using $distrib-right[of\ (sqr\ a)*sNorm2\ v\ sNorm2\ uov\ sNorm2\ v]$
 $mult-assoc$ **by** $auto$

hence $(sqr\ a) * sqr\ (sNorm2\ v) = (sqr\ a)*sqr(sNorm2\ v) + (sNorm2\ uov)*(sNorm2\ v)$
using $lhs\ assms(1)$ **by** $auto$
hence $(sNorm2\ uov)*(sNorm2\ v) = 0$ **using** $add-diff-eq$ **by** $auto$
hence $uov = sOrigin$ **using** $uwnz\ lemSpatialNullImpliesSpatialOrigin$ **by** $auto$

hence $a \neq 0 \wedge u = (a \otimes s\ v)$ **using** $anz\ usum\ upv$ **by** $auto$
thus $?thesis$ **by** $auto$
qed

lemma *lemCauchySchwarzEqualityInUnitSphere:*
assumes $(sNorm2\ u \leq 1) \wedge (sNorm2\ v \leq 1)$
and $sdot\ u\ v = 1$
shows $u = v$
proof –
have *wnz*: $u \neq sOrigin \wedge v \neq sOrigin$ **using** *assms(2)* **by** *auto*
{ **assume** *ass*: $(sNorm2\ u < 1) \vee (sNorm2\ v < 1)$
have $(sNorm2\ u > 0) \wedge (sNorm2\ v > 0)$
using *wnz lemSpatialNullImpliesSpatialOrigin add-less-zeroD*
less-linear not-square-less-zero
by *blast*
hence $(sNorm2\ u) * (sNorm2\ v) < 1$
by (*metis ass assms(1) local.dual-order.not-eq-order-implies-strict*
local.leD
local.less-imp-le local.mult-le-one local.mult-less-cancel-left1
local.mult-less-cancel-right1)
hence *False* **using** *lemCauchySchwarzSqr assms(2)*
by (*metis local.dual-order.strict-iff-not local.mult-cancel-right1*)
}
hence *norms1*: $sNorm2\ u = 1 \wedge sNorm2\ v = 1$ **using** *assms(1)* **by**
force
hence *sqr* $(sdot\ u\ v) = (sNorm2\ u) * (sNorm2\ v)$ **using** *assms(2)* **by**
auto
hence $\exists a \neq 0 . u = (a \otimes s v)$ **using** *lemCauchySchwarzEquality*
wnz **by** *blast*
then obtain *a* **where** $a \neq 0 \wedge u = (a \otimes s v)$ **by** *auto*
hence $sdot\ u\ v = a * sNorm2\ v$ **using** *lemSDotScaleLeft* **by** *auto*
hence $a = 1$ **using** *assms(2) norms1* **by** *auto*
thus *?thesis* **using** *a* **by** *auto*
qed

lemma *lemCausalOrthogmToLightlikeImpliesParallel:*
assumes *causal p*
and *lightlike q*
and *orthogm p q*
shows *parallel p q*
proof –
have *tpnz*: $tval\ p \neq 0$
proof –
have $p \neq origin$ **using** *assms(1)* **by** *auto*
have *case1*: *lightlike p* \longrightarrow *?thesis*
by (*metis local.diff-add-cancel local.lemNorm2Decomposition*
local.lemNullImpliesOrigin local.lemZeroRoot)
have *case2*: *timelike p* \longrightarrow *?thesis*
by (*metis local.add-less-zeroD local.diff-gt-0-iff-gt*
local.lemZeroRoot local.not-square-less-zero)
thus *?thesis* **using** *assms(1) case1* **by** *blast*
qed

have $tqnz$: $tval\ q \neq 0$ **using** $assms(2)$
by ($metis\ local.diff-add-cancel\ local.lemNorm2Decomposition$
 $local.lemNullImpliesOrigin\ local.lemZeroRoot$)

define $phat$ **where** $phat$: $phat = ((1/tval\ p) \otimes p)$
define $qhat$ **where** $qhat$: $qhat = ((1/tval\ q) \otimes q)$

have $phatcausal$: $causal\ phat$
proof –
have $n2$: $mNorm2\ phat = (sqr\ (1/tval\ p)) * mNorm2\ p$ **using** $phat$
 $lemMNorm2OfScaled$ **by** $blast$
have $lightlike\ p \rightarrow lightlike\ phat$ **using** $phat\ n2\ tpnz$ **by** $auto$
moreover **have** $timelike\ p \rightarrow timelike\ phat$ **using** $phat\ n2\ tpnz$
by ($simp\ add$: $local.lemSquaresPositive$)
ultimately **show** $?thesis$ **using** $assms(1)$ **by** $blast$
qed

have $qhatlightlike$: $lightlike\ qhat$
proof –
have $mNorm2\ qhat = (sqr\ (1/tval\ q)) * mNorm2\ q$ **using** $qhat$
 $lemMNorm2OfScaled$ **by** $blast$
thus $?thesis$ **using** $assms(2)\ tqnz\ qhat\ local.divide-eq-0-iff$ **by** $force$

qed

have $hatsorthog$: $orthogm\ phat\ qhat$
proof –
have ($phat \odot m\ qhat$) = $(1/tval\ p) * (p \odot m\ qhat)$
using $phat\ lemMDotScaleLeft[of\ 1/tval\ p\ p\ qhat]$ **by** $auto$
thus $?thesis$
using $qhat\ lemMDotScaleRight[of\ p\ 1/tval\ q\ q]\ tpnz\ tqnz\ assms(3)$
by $auto$
qed

define ps **where** ps : $ps = sComponent\ phat$
define qs **where** qs : $qs = sComponent\ qhat$

have p : $phat = stPoint\ 1\ ps$ **using** $phat\ ps\ tpnz$ **by** $auto$
have q : $qhat = stPoint\ 1\ qs$ **using** $qhat\ qs\ tqnz$ **by** $auto$

have $sNorm2\ ps \leq 1$ **using** $p\ phatcausal$ **by** $auto$
moreover **have** $sNorm2\ qs = 1$ **using** $q\ qhatlightlike$ **by** $auto$
moreover **have** $sdot\ ps\ qs = 1$ **using** $hatsorthog\ p\ q$ **by** $auto$
ultimately **have** $ps = qs$
using $lemCauchySchwarzEqualityInUnitSphere$ **by** $auto$

hence $phat = qhat$ **using** $p\ q$ **by** $auto$
hence $((1/tval\ p) \otimes p) = ((1/tval\ q) \otimes q)$ **using** $phat\ qhat$ **by** $auto$

```

hence p = (((tval p)/(tval q)) ⊗ q)
  using tpnz tqnz
        lemScaleAssoc[of tval p 1/tval p p]
        lemScaleAssoc[of tval p 1/tval q q]
  by auto
thus ?thesis using tpnz tqnz using local.divide-eq-0-iff
  by blast
qed

```

end

end

18 Matrices

This theory defines 4×4 matrices.

```

theory Matrices
  imports Vectors
begin

```

```

record 'a Matrix =
  trow :: 'a Point
  xrow :: 'a Point
  yrow :: 'a Point
  zrow :: 'a Point

```

```

class Matrices = Vectors
begin

```

```

fun applyMatrix :: 'a Matrix ⇒ 'a Point ⇒ 'a Point
  where applyMatrix m p = (| tval = dot (trow m) p, xval = dot (xrow
m) p,
                          yval = dot (yrow m) p, zval = dot (zrow m) p |)

```

```

fun tcol :: 'a Matrix ⇒ 'a Point
  where tcol m = (| tval = tval (trow m), xval = tval (xrow m),
                  yval = tval (yrow m), zval = tval (zrow m) |)

```

```

fun xcol :: 'a Matrix ⇒ 'a Point
  where xcol m = (| tval = xval (trow m), xval = xval (xrow m),
                  yval = xval (yrow m), zval = xval (zrow m) |)

```

```

fun ycol :: 'a Matrix ⇒ 'a Point
  where ycol m = (| tval = yval (trow m), xval = yval (xrow m),
                  yval = yval (yrow m), zval = yval (zrow m) |)

```

```

fun zcol :: 'a Matrix  $\Rightarrow$  'a Point
  where zcol m = ( $\lambda$  tval = zval (trow m), xval = zval (xrow m),
    yval = zval (yrow m), zval = zval (zrow m)  $\lambda$ )

fun transpose :: 'a Matrix  $\Rightarrow$  'a Matrix
  where transpose m = ( $\lambda$  trow = (tcol m), xrow = (xcol m),
    yrow = (ycol m), zrow = (zcol m)  $\lambda$ )

fun mprod :: 'a Matrix  $\Rightarrow$  'a Matrix  $\Rightarrow$  'a Matrix
  where mprod m1 m2 =
    transpose ( $\lambda$  trow = applyMatrix m1 (tcol m2), xrow =
    applyMatrix m1 (xcol m2),
    yrow = applyMatrix m1 (ycol m2), zrow =
    applyMatrix m1 (zcol m2)  $\lambda$ )

end

end

```

19 LinearMaps

This theory defines linear maps and establishes their main properties.

theory *LinearMaps*

imports *Functions CauchySchwarz Matrices*
begin

class *LinearMaps* = *Functions* + *CauchySchwarz* + *Matrices*
begin

abbreviation *linear* :: ('a Point \Rightarrow 'a Point) \Rightarrow bool **where**
linear L \equiv (L *origin* = *origin*)
 \wedge (\forall a p . L (a \otimes p) = (a \otimes (L p)))
 \wedge (\forall p q . L (p \oplus q) = ((L p) \oplus (L q)))
 \wedge (\forall p q . L (p \ominus q) = ((L p) \ominus (L q)))

```

lemma lemLinearProps:
  assumes linear L
  shows ( $L \text{ origin} = \text{origin}$ )  $\wedge$  ( $L (a \otimes p) = (a \otimes (L p))$ )
           $\wedge$  ( $L (p \oplus q) = ((L p) \oplus (L q))$ )
           $\wedge$  ( $L (p \ominus q) = ((L p) \ominus (L q))$ )
using assms by simp

lemma lemMatrixApplicationIsLinear: linear (applyMatrix m)
  using lemDotScaleRight lemDotSumRight lemDotDiffRight
  by fastforce

lemma lemLinearIsMatrixApplication:
  assumes linear L
  shows  $\exists m . L = (\text{applyMatrix } m)$ 
proof –
  define Lt where  $Lt = L \text{ tUnit}$ 
  define Lx where  $Lx = L \text{ xUnit}$ 
  define Ly where  $Ly = L \text{ yUnit}$ 
  define Lz where  $Lz = L \text{ zUnit}$ 
  define M where  $M = \text{transpose } (\text{trow} = Lt, \text{xrow} = Lx, \text{yrow} =$ 
 $Ly, \text{zrow} = Lz \text{ })$ 

  have trowM:  $\text{trow } M = (\text{tval} = (\text{tval } Lt), \text{xval} = (\text{tval } Lx),$ 
 $\text{yval} = (\text{tval } Ly), \text{zval} = (\text{tval } Lz) \text{ })$ 
    using M-def by auto
  have xrowM:  $\text{xrow } M = (\text{tval} = (\text{xval } Lt), \text{xval} = (\text{xval } Lx),$ 
 $\text{yval} = (\text{xval } Ly), \text{zval} = (\text{xval } Lz) \text{ })$ 
    using M-def by auto
  have yrowM:  $\text{yrow } M = (\text{tval} = (\text{yval } Lt), \text{xval} = (\text{yval } Lx),$ 
 $\text{yval} = (\text{yval } Ly), \text{zval} = (\text{yval } Lz) \text{ })$ 
    using M-def by auto
  have zrowM:  $\text{zrow } M = (\text{tval} = (\text{zval } Lt), \text{xval} = (\text{zval } Lx),$ 
 $\text{yval} = (\text{zval } Ly), \text{zval} = (\text{zval } Lz) \text{ })$ 
    using M-def by auto

  { fix u :: 'a Point
    define tvu where  $tvu = ((\text{tval } u) \otimes \text{tUnit})$ 
    define xvu where  $xvu = ((\text{xval } u) \otimes \text{xUnit})$ 
    define yvu where  $yvu = ((\text{yval } u) \otimes \text{yUnit})$ 
    define zvu where  $zvu = ((\text{zval } u) \otimes \text{zUnit})$ 

    have u:  $u = (tvu \oplus (xvu \oplus (yvu \oplus zvu)))$ 
      using tvu xvu yvu zvu lemPointDecomposition[of u] by simp

```

```

have Mu: applyMatrix M u = (| tval = dot (trow M) u,
                             xval = dot (xrow M) u,
                             yval = dot (yrow M) u,
                             zval = dot (zrow M) u |) by simp

have tvalMu: tval (applyMatrix M u) =
  (tval Lt)*(tval u) + (tval Lx)*(xval u) + (tval Ly)*(yval u) +
  (tval Lz)*(zval u)
using Mu trowM by force
have xvalMu: xval (applyMatrix M u) =
  (xval Lt)*(tval u) + (xval Lx)*(xval u) + (xval Ly)*(yval u) +
  (xval Lz)*(zval u)
using Mu xrowM by force
have yvalMu: yval (applyMatrix M u) =
  (yval Lt)*(tval u) + (yval Lx)*(xval u) + (yval Ly)*(yval u) +
  (yval Lz)*(zval u)
using Mu yrowM by force
have zvalMu: zval (applyMatrix M u) =
  (zval Lt)*(tval u) + (zval Lx)*(xval u) + (zval Ly)*(yval u) +
  (zval Lz)*(zval u)
using Mu zrowM by force

hence Lu: L u = ((L tvu) ⊕ ((L xv u) ⊕ ((L yv u) ⊕ (L zv u))))
using assms u
  lemLinearProps[of L 0 tvu xv u ⊕ (yv u ⊕ zv u)]
  lemLinearProps[of L 0 xv u yv u ⊕ zv u]
by auto
have Ltvu: L tvu = ((tval u) ⊗ Lt)
using tvu Lt-def assms lemLinearProps[of L tval u tUnit] by auto
have Lxvu: L xv u = ((xval u) ⊗ Lx)
using xv u Lx-def assms lemLinearProps[of L xval u xUnit] by
auto
have Lyvu: L yv u = ((yval u) ⊗ Ly)
using yv u Ly-def assms lemLinearProps[of L yval u yUnit] by
auto
have Lzvu: L zv u = ((zval u) ⊗ Lz)
using zv u Lz-def assms lemLinearProps[of L zval u zUnit] by
auto

hence Lu': L u = (((tval u) ⊗ Lt) ⊕ (((xval u) ⊗ Lx)
  ⊕ (((yval u) ⊗ Ly) ⊕ ((zval u) ⊗ Lz))))
using Lu Ltvu Lxvu Lyvu Lzvu by force

hence L u = applyMatrix M u
using Lu' add-assoc tvalMu xvalMu yvalMu zvalMu mult-commute
by simp
}

```

hence $\forall u. L u = \text{applyMatrix } M u$ **by** *auto*
thus *?thesis* **by** *force*
qed

lemma *lemLinearIffMatrix*: *linear* $L \longleftrightarrow (\exists M. L = \text{applyMatrix } M)$
using *lemMatrixApplicationIsLinear* *lemLinearIsMatrixApplication*
by *auto*

lemma *lemIdIsLinear*: *linear* *id*
by *simp*

lemma *lemLinearIsBounded*:

assumes *linear* L
shows *bounded* L

proof –

obtain M **where** $M: L = \text{applyMatrix } M$ **using** *assms* *lemLinearIffMatrix* **by** *auto*

define tr **where** $tr = \text{trow } M$

define xr **where** $xr = \text{xrow } M$

define yr **where** $yr = \text{yrow } M$

define zr **where** $zr = \text{zrow } M$

define bnd **where** $bnd = (\text{sqr}(\text{norm } tr) + \text{sqr}(\text{norm } xr) + \text{sqr}(\text{norm } yr) + \text{sqr}(\text{norm } zr))$

define n

where $n: n = (\lambda tval=\text{norm } tr, xval=\text{norm } xr, yval=\text{norm } yr, zval=\text{norm } zr)$

hence $bnd = \text{dot } n n$ **using** *bnd-def* **by** *auto*

hence *norm2n*: $bnd = \text{norm2 } n$ **by** *simp*

hence *bndnonneg*: $bnd \geq 0$ **by** *simp*

{ assume *bndpos*: $bnd > 0$

{ fix $p :: 'a \text{ Point}$

define q **where** $q = \text{applyMatrix } M p$

hence $q = (\lambda tval=\text{dot } tr p, xval=\text{dot } xr p, yval=\text{dot } yr p, zval=\text{dot } zr p)$

using *tr-def* *xr-def* *yr-def* *zr-def* **by** *auto*

hence *1*: $\text{dot } q q = \text{sqr}(\text{dot } tr p) + \text{sqr}(\text{dot } xr p) + \text{sqr}(\text{dot } yr p) + \text{sqr}(\text{dot } zr p)$

by *auto*

also have $\dots \leq \text{sqr}(\text{dot } tr p) + \text{sqr}(\text{dot } xr p) + \text{sqr}(\text{dot } yr p) + (\text{sqr}(\text{norm } zr) * \text{sqr}(\text{norm } p))$

```

    using lemCauchySchwarzSqr4 [of zr p] lemNormSqrIsNorm2
  by auto
    also have ... ≤ sqr (dot tr p) + sqr (dot xr p) + (sqr(norm
  yr)*sqr(norm p))
      + (sqr(norm zr)*sqr(norm p))
    using lemCauchySchwarzSqr4 [of yr p] lemNormSqrIsNorm2
  by auto
    also have ... ≤ sqr (dot tr p) + (sqr(norm xr)*sqr(norm p)) +
  (sqr(norm yr)*sqr(norm p))
      + (sqr(norm zr)*sqr(norm p))
    using lemCauchySchwarzSqr4 [of xr p] lemNormSqrIsNorm2
  by auto
    also have ... ≤ (sqr(norm tr)*sqr(norm p)) + (sqr(norm
  xr)*sqr(norm p)) + (sqr(norm yr)*sqr(norm p))
      + (sqr(norm zr)*sqr(norm p))
    using lemCauchySchwarzSqr4 [of tr p] lemNormSqrIsNorm2
  by auto
    finally have dot q q ≤ (sqr(norm tr)*sqr(norm p)) + (sqr(norm
  xr)*sqr(norm p)) + (sqr(norm yr)*sqr(norm p))
      + (sqr(norm zr)*sqr(norm p)) by auto
    hence dot q q ≤ (sqr(norm tr)+sqr(norm xr)+sqr(norm yr)+sqr(norm
  zr))*sqr(norm p)
      using distrib-right by auto
    hence norm2 q ≤ bnd * sqr(norm p) using bnd-def by simp
    hence norm2 (applyMatrix M p) ≤ bnd * norm2 p
      using q-def lemNormSqrIsNorm2 by simp
  }
  hence ∀ p. norm2 (applyMatrix M p) ≤ bnd * norm2 p by auto
  hence ∃ bnd > 0 . ∀ p. norm2 (applyMatrix M p) ≤ bnd * norm2
p
    using bndpos by auto
  }
  hence case1: (bnd > 0) → (bounded (applyMatrix M)) by simp

{ assume bnd0: bnd = 0
  hence n = origin using lemNullImpliesOrigin norm2n by auto
  hence (norm tr = 0) ∧ (norm xr = 0) ∧ (norm yr = 0) ∧ (norm
  zr = 0)
    using n by simp
  hence allzero: (tr = origin) ∧ (xr = origin) ∧ (yr = origin) ∧ (zr = origin)
    using lemZeroNorm by auto

  define one where one = (1::'a)
  hence onepos: one > 0 by simp
  { fix p :: 'a Point
    have applyMatrix M p = origin
      using allzero tr-def xr-def yr-def zr-def by auto
    hence norm2(applyMatrix M p) = 0 by auto
    hence norm2(applyMatrix M p) ≤ one * (norm2 p) using onepos
  }
}

```

```

by auto
}
hence  $\forall p . \text{norm2}(\text{applyMatrix } M p) \leq \text{one} * (\text{norm2 } p)$  by auto
hence  $\exists \text{one} > 0 . \forall p . \text{norm2}(\text{applyMatrix } M p) \leq \text{one} * (\text{norm2 } p)$ 
}
using onepos by auto
hence bounded (applyMatrix M) by simp
}
hence case2: (bnd = 0)  $\longrightarrow$  (bounded (applyMatrix M)) by simp

thus ?thesis using case1 case2 bndnonneg M by auto
qed

```

```

lemma lemLinearIsCts:
  assumes linear L
  shows cts (asFunc L) x
proof -
  { fix x'
    assume x': x' = L x

    have bounded L using assms(1) lemLinearIsBounded[of L] by auto
    then obtain bnd where bnd: (bnd > 0)  $\wedge$  ( $\forall p . \text{norm2}(L p) \leq \text{bnd} * (\text{norm2 } p)$ )
    by auto
    then obtain bb where bb: (bb > 0)  $\wedge$  (sqr bb) > bnd
    using bnd lemSquareExistsAbove[of bnd] by auto

    { fix p
      have p1:  $\text{norm2}(L p) \leq \text{bnd} * (\text{norm2 } p)$  using bnd by simp
      have  $\text{bnd} * (\text{norm2 } p) \leq (\text{sqr } bb) * (\text{norm2 } p)$  using bb mult-mono
    }
    by auto
    hence  $\text{norm2}(L p) \leq (\text{sqr } bb) * (\text{norm2 } p)$  using p1 by simp
  }
  hence bbbnd:  $\forall p . \text{norm2}(L p) \leq (\text{sqr } bb) * (\text{norm2 } p)$  by auto

  { fix e
    assume epos: e > 0
    define d where d: d = e/bb
    hence dpos: d > 0 using epos bb by simp
    have (d = e/bb)  $\wedge$  (bb  $\neq$  0) using d bb by auto
    hence esqr: (sqr d) * (sqr bb) = sqr e by simp

    { fix p'
      assume p': p'  $\in$  applyToSet (asFunc L) (ball x d)
      then obtain p where p: (p  $\in$  ball x d)  $\wedge$  (p' = L p) by auto
      hence p-near-x: p within d of x using lemSep2Symmetry[of p

```


$x]$ **by force**
have $\text{norm2 } (L (p \ominus x)) \leq (\text{sqr } bb) * \text{norm2 } (p \ominus x)$ **using** *bbnd*
by *blast*
hence $1: \text{norm2 } (L (p \ominus x)) \leq (\text{sqr } bb) * (\text{sep2 } p \ x)$ **by** *auto*
have $(\text{sqr } bb) * (\text{sep2 } p \ x) < (\text{sqr } bb) * (\text{sqr } d)$
using *lemMultPosLT bb p-near-x* **by** *auto*
hence $2: \text{norm2 } (L (p \ominus x)) < (\text{sqr } bb) * (\text{sqr } d)$ **using** 1 **by**
simp

have $(L (p \ominus x)) = ((L \ p) \ominus (L \ x))$ **using** *assms(1)* **by** *auto*
hence $\text{norm2 } (L (p \ominus x)) = \text{sep2 } p' \ x'$ **using** $p \ x'$ **by** *force*
hence $\text{sep2 } p' \ x' < (\text{sqr } bb) * (\text{sqr } d)$ **using** 2 **by** *simp*
hence $\text{sep2 } p' \ x' < \text{sqr } e$ **using** $d \ bb$ **by** *auto*
hence $p' \in \text{ball } x' \ e$ **using** *lemSep2Symmetry* **by** *auto*
}
hence $\text{applyToSet } (\text{asFunc } L) (\text{ball } x \ d) \subseteq \text{ball } x' \ e$ **by** *auto*
hence $\exists d > 0. \text{applyToSet } (\text{asFunc } L) (\text{ball } x \ d) \subseteq \text{ball } x' \ e$
using *dpos* **by** *auto*
}
hence $\forall e > 0. \exists d > 0. \text{applyToSet } (\text{asFunc } L) (\text{ball } x \ d) \subseteq \text{ball } x' \ e$
by *auto*
}
thus *?thesis* **by** *auto*
qed

lemma *lemLinOfLinIsLin:*
assumes $(\text{linear } A) \wedge (\text{linear } B)$
shows $\text{linear } (B \circ A)$
proof –
have $1: (B \circ A) \text{ origin} = \text{origin}$ **using** *assms* **by** *auto*
have $2: \forall a \ p. (B \circ A)(a \otimes p) = (a \otimes ((B \circ A) \ p))$ **using** *assms*
by *auto*
have $3: \forall p \ q. (B \circ A) (p \oplus q) = (((B \circ A) \ p) \oplus ((B \circ A) \ q))$
using *assms* **by** *auto*
have $4: \forall p \ q. (B \circ A) (p \ominus q) = (((B \circ A) \ p) \ominus ((B \circ A) \ q))$
using *assms* **by** *auto*
thus *?thesis* **using** $1 \ 2 \ 3$ **by** *force*
qed

lemma *lemInverseLinear:*
assumes $\text{linear } A$
and $\text{invertible } A$
shows $\exists A'. (\text{linear } A') \wedge (\forall p \ q. A \ p = q \longleftrightarrow A' \ q = p)$
proof –
obtain L **where** $L: (\forall p \ q. A \ p = q \longleftrightarrow L \ q = p)$

using *assms(2)* **by** *metis*

have 1: $L \text{ origin} = \text{origin}$ **using** *assms L* **by** *auto*

{ **fix** $p' q' a$

obtain p **where** $p: (A p = p') \wedge (\forall z. A z = p' \longrightarrow z = p)$ **using** *assms(2)* **by** *blast*

obtain q **where** $q: (A q = q') \wedge (\forall z. A z = q' \longrightarrow z = q)$ **using** *assms(2)* **by** *blast*

have $L (a \otimes p') = L (a \otimes (A p))$ **using** p **by** *auto*

also have $\dots = L (A (a \otimes p))$ **using** *assms(1)* **by** *auto*

also have $\dots = (a \otimes p)$ **using** L **by** *blast*

finally have 2: $L (a \otimes p') = (a \otimes (L p'))$ **using** $p L$ **by** *auto*

have $L (p' \oplus q') = L ((A p) \oplus (A q))$ **using** $p q$ **by** *auto*

also have $\dots = L (A (p \oplus q))$ **using** *assms(1)* **by** *auto*

also have $\dots = (p \oplus q)$ **using** $p q L$ **by** *auto*

finally have 3: $L (p' \oplus q') = ((L p') \oplus (L q'))$ **using** $p q L$ **by** *auto*

have $L (p' \ominus q') = L ((A p) \ominus (A q))$ **using** $p q$ **by** *auto*

also have $\dots = L (A (p \ominus q))$ **using** *assms(1)* **by** *auto*

also have $\dots = (p \ominus q)$ **using** $p q L$ **by** *auto*

finally have 4: $L (p' \ominus q') = ((L p') \ominus (L q'))$ **using** $p q L$ **by** *auto*

hence $(L \text{ origin} = \text{origin}) \wedge$

$(L (a \otimes p') = (a \otimes (L p')))$ \wedge

$(L (p' \oplus q') = ((L p') \oplus (L q')))$ \wedge

$(L (p' \ominus q') = ((L p') \ominus (L q')))$

using 1 2 3 **by** *auto*

}

hence *linear L* **by** *auto*

thus *?thesis* **using** L **by** *auto*

qed

end

end

20 Affine

This theory defines affine transformations and established their key properties.

```
theory Affine
imports Translations LinearMaps
begin
```

```
class Affine = Translations + LinearMaps
begin
```

```
abbreviation affine :: ('a Point  $\Rightarrow$  'a Point)  $\Rightarrow$  bool
where affine A  $\equiv$   $\exists$  L T . (linear L)  $\wedge$  (translation T)  $\wedge$  (A = T  $\circ$  L)
```

```
abbreviation affInvertible :: ('a Point  $\Rightarrow$  'a Point)  $\Rightarrow$  bool
where affInvertible A  $\equiv$  affine A  $\wedge$  invertible A
```

```
abbreviation isLinearPart :: ('a Point  $\Rightarrow$  'a Point)  $\Rightarrow$  ('a Point  $\Rightarrow$ 
'a Point)  $\Rightarrow$  bool
where isLinearPart A L  $\equiv$  (affine A)  $\wedge$  (linear L)  $\wedge$ 
( $\exists$  T. (translation T)  $\wedge$  A = T  $\circ$  L)
```

```
abbreviation isTranslationPart :: ('a Point  $\Rightarrow$  'a Point)  $\Rightarrow$  ('a Point
 $\Rightarrow$  'a Point)  $\Rightarrow$  bool
where isTranslationPart A T  $\equiv$  (affine A)  $\wedge$  (translation T)  $\wedge$ 
( $\exists$  L. (linear L)  $\wedge$  A = T  $\circ$  L)
```

20.1 Affine approximation

A key concept in the proof is affine approximation. We will eventually assert that worldview transformation can be approximated by invertible affine transformations.

```
abbreviation affineApprox :: ('a Point  $\Rightarrow$  'a Point)  $\Rightarrow$ 
('a Point  $\Rightarrow$  'a Point  $\Rightarrow$  bool)  $\Rightarrow$ 
'a Point  $\Rightarrow$  bool
where affineApprox A f x  $\equiv$  (isFunction f)  $\wedge$ 
(affInvertible A)  $\wedge$  (diffApprox (asFunc A) f x)
```

```
fun applyAffineToLine :: ('a Point  $\Rightarrow$  'a Point)
 $\Rightarrow$  'a Point set  $\Rightarrow$  'a Point set  $\Rightarrow$  bool
where applyAffineToLine A l l'  $\longleftrightarrow$  (affine A)  $\wedge$ 
```

$$(\exists T L b d . ((\text{linear } L) \wedge (\text{translation } T) \wedge (A = T \circ L) \wedge (l = \text{line } b d) \wedge (l' = (\text{line } (A b) (L d))))))$$

abbreviation *affConstantOn* :: ('a Point \Rightarrow 'Point) \Rightarrow 'a Point \Rightarrow 'a Point set \Rightarrow bool
where *affConstantOn* A x s \equiv ($\exists \varepsilon > 0. \forall y \in s. (y \text{ within } \varepsilon \text{ of } x) \longrightarrow ((A y) = (A x))$)

lemma *lemTranslationPartIsUnique*:
assumes *isTranslationPart* A T1
and *isTranslationPart* A T2
shows T1 = T2
proof –
obtain L1 **where** T1: *linear* L1 \wedge A = T1 \circ L1 **using** *assms*(1)
by *auto*
obtain L2 **where** T2: *linear* L2 \wedge A = T2 \circ L2 **using** *assms*(2)
by *auto*
obtain t1 **where** t1: $\forall x. T1 x = (x \oplus t1)$ **using** *assms*(1) **by** *auto*
obtain t2 **where** t2: $\forall x. T2 x = (x \oplus t2)$ **using** *assms*(2) **by** *auto*

have T1 *origin* = A *origin* **using** T1 *assms*(1) **by** *auto*
also have ... = T2 *origin* **using** T2 *assms*(2) **by** *auto*
finally have T1 *origin* = T2 *origin* **by** *auto*
hence t1 = t2 **using** t1 t2 **by** *auto*
hence $\forall x. (T1 x = T2 x)$ **using** t1 t2 **by** *auto*
thus *?thesis* **by** *auto*
qed

lemma *lemLinearPartIsUnique*:
assumes *isLinearPart* A L1
and *isLinearPart* A L2
shows L1 = L2
proof –
obtain T1 **where** T1: *translation* T1 \wedge A = T1 \circ L1 **using** *assms*(1) **by** *auto*
obtain T2 **where** T2: *translation* T2 \wedge A = T2 \circ L2 **using** *assms*(2) **by** *auto*

have 1: *isTranslationPart* A T1 **using** *assms*(1) T1 **by** *auto*
have 2: *isTranslationPart* A T2 **using** *assms*(2) T2 **by** *auto*

hence $T1T2: T1 = T2$ using 1 2 *lemTranslationPartIsUnique*[of A
 $T1 T2$] by *auto*

obtain t where $t: \forall x. T1 x = (x \oplus t)$ using $T1$ by *auto*
define T where $T = mkTranslation (origin \ominus t)$
hence $\exists: T \circ A = L1$ using $T1 t$ *lemInverseTranslation* by *auto*
have $T \circ A = L2$ using $T-def T2 t T1T2$ *lemInverseTranslation*
by *auto*

thus *?thesis* using \exists by *auto*
qed

lemma *lemLinearImpliesAffine*:
assumes *linear* L
shows *affine* L
proof –
have 1: $L = id \circ L$ by *fastforce*
thus *?thesis* using *assms lemIdIsTranslation* by *blast*
qed

lemma *lemTranslationImpliesAffine*:
assumes *translation* T
shows *affine* T
proof –
have $T = T \circ id$ by *force*
thus *?thesis* using *assms lemIdIsLinear* by *blast*
qed

lemma *lemAffineDiff*:
assumes *linear* L
and $\exists T. ((translation T) \wedge (A = T \circ L))$
shows $((A p) \ominus (A q)) = L (p \ominus q)$
proof –
obtain T where $T: (translation T) \wedge (A = T \circ L)$ using *assms(2)*
by *auto*
thus *?thesis* using *assms(1)* by *auto*
qed

lemma *lemAffineImpliesTotalFunction*:
assumes *affine* A
shows *isTotalFunction* (*asFunc* A)
by *simp*

lemma *lemAffineEqualAtBase*:

```

assumes affineApprox A f x
shows  $\forall y. (f\ x\ y) \longleftrightarrow (y = A\ x)$ 
proof -
  have diff: diffApprox (asFunc A) f x using assms(1) by simp
  { fix y
    assume y: f x y
    hence f x y  $\wedge$  (asFunc A) x (A x) by auto
    hence A x = y using diff lemApproxEqualAtBase[of f x asFunc A
y]
    by auto
  }
  hence l2r:  $\forall y. f\ x\ y \longrightarrow y = A\ x$  by auto

  { obtain y where y: f x y using diff by auto
    hence y = A x using l2r by auto
    hence f x (A x) using y by auto
  }
  thus ?thesis using l2r by blast
qed

```

```

lemma lemAffineOfPointOnLine:
  assumes (linear L)  $\wedge$  (translation T)  $\wedge$  (A = T  $\circ$  L)
  and x = (b  $\oplus$  (a  $\otimes$  d))
  shows A x = ((A b)  $\oplus$  (a  $\otimes$  (L d)))
proof -
  have (L x = ((L b)  $\oplus$  (L (a  $\otimes$  d))))  $\wedge$  (L (a  $\otimes$  d) = (a  $\otimes$  (L d)))
  using assms by blast
  hence A x = T ((L b)  $\oplus$  (a  $\otimes$  (L d))) using assms(1) by auto
  also have ... = ((T (L b))  $\oplus$  (a  $\otimes$  (L d)))
  using assms(1) lemTranslationSum[of T L b a  $\otimes$  (L d)] by auto
  finally show ?thesis using assms(1) by auto
qed

```

```

lemma lemAffineOfLineIsLine:
  assumes isLine l
  shows (applyAffineToLine A l l')  $\longleftrightarrow$  (affine A  $\wedge$  l' = applyToSet
(asFunc A) l)
proof -
  { assume lhs: applyAffineToLine A l l'
    hence affA: affine A by fastforce
    have  $\exists T\ L\ b\ d. (linear\ L) \wedge (translation\ T) \wedge (A = T \circ L) \wedge$ 
      (l = line b d)  $\wedge$  (l' = (line (A b) (L d))) using lhs by auto
    then obtain T L b d where TL: (linear L)  $\wedge$  (translation T)  $\wedge$ 
      (A = T  $\circ$  L)  $\wedge$ 
      (l = line b d)  $\wedge$  (l' = (line (A b) (L d)))
  }

```

```

    using lhs by blast
  { fix p'
    { assume p' ∈ l'
      then obtain a where a: p' = ( (A b) ⊕ (a ⊗ (L d)) ) using
TL by auto
      define p where p: p = (b ⊕ (a ⊗ d))
      hence p' ∈ applyToSet (asFunc A) l using a TL lemAffineOf-
PointOnLine by auto
    }
    hence (p' ∈ l') → (p' ∈ applyToSet (asFunc A) l) by auto
  }
  hence l2r: l' ⊆ (applyToSet (asFunc A) l) by auto

  { fix p'
    { assume p' ∈ applyToSet (asFunc A) l
      then obtain p where p: p ∈ l ∧ p' = A p by auto
      then obtain a where a: p = (b ⊕ (a ⊗ d)) using TL by auto
      hence A p = ((A b) ⊕ (a ⊗ (L d))) using TL lemAffineOf-
PointOnLine by auto
      hence p' ∈ l' using TL p by auto
    }
    hence (p' ∈ applyToSet (asFunc A) l) → (p' ∈ l') using l2r
by auto
  }
  hence (applyToSet (asFunc A) l) ⊆ l' by auto
  hence affine A ∧ l' = applyToSet (asFunc A) l using affA l2r by
auto
  }
  hence rtp1: (applyAffineToLine A l l') → (affine A ∧ l' = apply-
ToSet (asFunc A) l)
  by blast

  { assume rhs: (affine A) ∧ (l' = applyToSet (asFunc A) l)

  obtain b d where bd: l = line b d using assms(1) by auto
  obtain T L where TL: (linear L) ∧ (translation T) ∧ (A = T ∘
L)
  using rhs by auto

  { fix p'
    assume p' ∈ l'
    then obtain p where p: (p ∈ l) ∧ (A p = p') using rhs by auto
    then obtain a where a: p = (b ⊕ (a ⊗ d)) using bd by auto
    hence A p = ((A b) ⊕ (a ⊗ (L d)))
      using TL lemAffineOfPointOnLine by auto
    hence p' ∈ line (A b) (L d) using p by auto
  }
  hence l2r: l' ⊆ line (A b) (L d) by force

```

```

    { fix p'
      assume p' ∈ line (A b) (L d)
      then obtain a where a: p' = ( (A b) ⊕ (a ⊗ (L d)) ) using
TL by auto
      define p where p: p = (b ⊕ (a ⊗ d))
      hence A p = ((A b) ⊕ (a ⊗ (L d)))
      using TL lemAffineOfPointOnLine by auto
      hence A p = p' using a by simp
      hence p' ∈ applyToSet (asFunc A) l using p bd by auto
    }
  hence line (A b) (L d) = l' using rhs l2r by blast

  hence applyAffineToLine A l l' using TL bd by auto
}
hence (affine A) ∧ (l' = applyToSet (asFunc A) l)
      → (applyAffineToLine A l l')
  by blast

thus ?thesis using rtp1 by blast
qed

```

lemma *lemOnLineUnderAffine*:

```

  assumes (affine A) ∧ (onLine p l)
  shows onLine (A p) (applyToSet (asFunc A) l)
  proof –

```

```

  define l' where l': l' = applyToSet (asFunc A) l
  have lineL: isLine l using assms by auto

```

```

  hence TLl': applyAffineToLine A l l'
    using lemAffineOfLineIsLine[of l A l'] assms l'
    by blast

```

```

  hence ∃ T' L b d . (linear L) ∧ (translation T') ∧ (A = T' ∘ L) ∧
    (l = line b d) ∧ (l' = (line (A b) (L d))) by force

```

```

  then obtain T' L b d

```

```

    where TLbd: (linear L) ∧ (translation T') ∧ (A = T' ∘ L) ∧
      (l = line b d) ∧ (l' = (line (A b) (L d))) by blast

```

```

  then obtain a where a: p = (b ⊕ (a ⊗ d)) using assms by auto

```

```

  hence A p = ((A b) ⊕ (a ⊗ (L d))) using lemAffineOfPointOnLine
  TLbd by auto

```

```

  thus ?thesis using l' TLbd by blast

```

qed

lemma *lemLineJoiningUnderAffine*:

assumes *affine A*
shows $\text{applyToSet } (\text{asFunc } A) (\text{lineJoining } p \ q) = \text{lineJoining } (A \ p) \ (A \ q)$
proof –
obtain $T \ L$ **where** $TL: \text{translation } T \wedge \text{linear } L \wedge A = T \circ L$ **using** $\text{assms}(1)$ **by** *auto*
hence $((A \ q) \ominus (A \ p)) = L \ (q \ominus p)$ **by** *auto*

{ **fix** a
have $(a \otimes ((A \ q) \ominus (A \ p))) = L \ (a \otimes (q \ominus p))$
using $TL \ \text{lemLinearProps}[of \ L \ a \ q \ominus p]$ **by** *force*
}
hence $as: \forall a. (a \otimes ((A \ q) \ominus (A \ p))) = L \ (a \otimes (q \ominus p))$ **by** *auto*

{ **fix** x'
assume $x' \in \text{applyToSet } (\text{asFunc } A) (\text{lineJoining } p \ q)$
then obtain x **where** $x: x \in (\text{lineJoining } p \ q) \wedge x' = A \ x$ **by** *force*
then obtain a **where** $a: x = (p \oplus (a \otimes (q \ominus p)))$ **by** *force*

have $\text{expandL}: L \ (p \oplus (a \otimes (q \ominus p))) = ((L \ p) \oplus (L \ (a \otimes (q \ominus p))))$
using $TL \ \text{lemLinearProps}[of \ L \ 0 \ p \ (a \otimes (q \ominus p))]$
by *fast*

have $x' = A \ (p \oplus (a \otimes (q \ominus p)))$ **using** $x \ a$ **by** *fast*
also have $\dots = (T \ (L \ (p \oplus (a \otimes (q \ominus p))))$ **using** TL **by** *force*
also have $\dots = T \ ((L \ p) \oplus (L \ (a \otimes (q \ominus p))))$ **using** expandL **by** *force*

finally have $x' = ((T \ (L \ p)) \oplus (L \ (a \otimes (q \ominus p))))$
using $TL \ \text{lemTranslationSum}[of \ T \ L \ p \ L \ (a \otimes (q \ominus p))]$
by *auto*
hence $x' \in \text{lineJoining } (A \ p) \ (A \ q)$ **using** $TL \ as$ **by** *auto*

}
hence $l2r: \text{applyToSet } (\text{asFunc } A) (\text{lineJoining } p \ q) \subseteq \text{lineJoining } (A \ p) \ (A \ q)$
by *force*

{ **fix** x'
assume $x' \in \text{lineJoining } (A \ p) \ (A \ q)$
hence $\exists a. x' = ((T \ (L \ p)) \oplus (a \otimes ((A \ q) \ominus (A \ p))))$
using TL **by** *auto*
then obtain a **where** $a: x' = ((T \ (L \ p)) \oplus (a \otimes ((A \ q) \ominus (A \ p))))$
using TL **by** *fast*
hence $x' = ((T \ (L \ p)) \oplus (L \ (a \otimes (q \ominus p))))$ **using** as **by** *force*
also have $\dots = T \ ((L \ p) \oplus (L \ (a \otimes (q \ominus p))))$
using $TL \ \text{lemTranslationSum}[of \ T \ L \ p \ L \ (a \otimes (q \ominus p))]$ **by** *simp*
also have $\dots = T \ (L \ (p \oplus (a \otimes (q \ominus p))))$
using $TL \ \text{lemLinearProps}[of \ L \ 0 \ p \ a \otimes (q \ominus p)]$ **by** *auto*
finally have $x' = A \ (p \oplus (a \otimes (q \ominus p)))$ **using** TL **by** *auto*

hence $x' \in \text{applyToSet } (\text{asFunc } A) (\text{lineJoining } p \ q)$ **by** *auto*
}
thus *?thesis* **using** *l2r* **by** *auto*
qed

lemma *lemAffineIsCts*:
assumes *affine* A
shows $\text{cts } (\text{asFunc } A) \ x$
proof –

have $\exists \ T \ L . (\text{translation } T) \wedge (\text{linear } L) \wedge (A = T \circ L)$ **using** *assms*
by *auto*
then obtain $T \ L$ **where** $TL: (\text{translation } T) \wedge (\text{linear } L) \wedge (A = T \circ L)$ **by** *auto*

define f **where** $f: f = \text{asFunc } L$
define g **where** $g: g = \text{asFunc } T$
have $1: \text{cts } f \ x$ **using** $f \ TL \ \text{lemLinearIsCts[of } L \ x]$ **by** *auto*
have $2: \forall y. (f \ x \ y) \longrightarrow (\text{cts } g \ y)$
using $f \ g \ TL \ \text{lemTranslationIsCts[of } T \ x]$ **by** *auto*
have $\text{cts } (\text{composeRel } g \ f) \ x$ **using** $1 \ 2 \ \text{lemCtsOfCtsIsCts[of } f \ x \ g]$
by *simp*
thus *?thesis* **using** $f \ g \ TL$ **by** *auto*
qed

lemma *lemAffineContinuity*:

assumes *affine* A
shows $\forall x. \forall \varepsilon > 0. \exists \delta > 0 . \forall p. (p \ \text{within } \delta \ \text{of } x) \longrightarrow ((A \ p) \ \text{within } \varepsilon \ \text{of } (A \ x))$

proof –

{ fix x
{ fix e
assume $\text{epos}: e > 0$

have $(\text{asFunc } A) \ x \ (A \ x) \wedge (\text{cts } (\text{asFunc } A) \ x)$
using *assms* $\text{lemAffineIsCts[of } A \ x]$ **by** *auto*
hence $u: (\forall \varepsilon > 0. \exists \delta > 0. (\text{applyToSet } (\text{asFunc } A) (\text{ball } x \ \delta)) \subseteq \text{ball } (A \ x) \ \varepsilon)$
by *force*

then obtain d **where** $d: (d > 0) \wedge (\text{applyToSet } (\text{asFunc } A) (\text{ball } x \ d)) \subseteq \text{ball } (A \ x) \ e$
using epos **by** *force*

{ fix p

assume p within d of x
hence $(A p)$ within e of $(A x)$ **using** d *lemSep2Symmetry* **by**
force
}
hence $\exists d > 0 . \forall p . (p \text{ within } d \text{ of } x) \longrightarrow ((A p) \text{ within } e \text{ of } (A x))$
using d **by** *auto*
}
hence $\forall e > 0 . \exists d > 0 . \forall p . (p \text{ within } d \text{ of } x) \longrightarrow ((A p) \text{ within } e \text{ of } (A x))$
by *auto*
}
thus *?thesis* **by** *auto*
qed

lemma *lemAffOfAffIsAff*:

assumes $(\text{affine } A) \wedge (\text{affine } B)$
shows $\text{affine } (B \circ A)$
proof –
obtain $TA \ LA \ TB \ LB$ **where** *props*:
 $\text{translation } TA \wedge \text{linear } LA \wedge \text{translation } TB \wedge \text{linear } LB \wedge$
 $A = TA \circ LA \wedge B = TB \circ LB$ **using** *assms* **by** *blast*
then obtain $ta \ tb$ **where** $ts: (\forall p . TA \ p = (p \oplus ta)) \wedge (\forall p . TB \ p = (p \oplus tb))$ **by** *auto*

{ **fix** p
have $(B \circ A) \ p = ((LB \ (LA \ p) \oplus ta) \oplus tb)$ **using** *props* **ts** **by**
force
also have $\dots = (((LB \ (LA \ p)) \oplus (LB \ ta)) \oplus tb)$ **using** *props* **by**
force
also have $\dots = (((LB \circ LA) \ p) \oplus ((LB \ ta) \oplus tb))$ **using** *add-assoc*
by *force*
finally have $(B \circ A) \ p = ((mkTranslation \ ((LB \ ta) \oplus tb)) \circ (LB \circ LA))$
 p **by** *force*
}
hence $BA: (B \circ A) = (mkTranslation \ ((LB \ ta) \oplus tb)) \circ (LB \circ LA)$ **by**
auto

define T **where** $T: T = mkTranslation \ ((LB \ ta) \oplus tb)$
hence *trans*: *translation* T **using** *lemMkTrans* **by** *blast*
define L **where** $L: L = (LB \circ LA)$
hence *lin*: *linear* L **using** *lemLinOfLinIsLin*[of $LA \ LB$] *props* **by**
auto

hence $(\text{translation } T) \wedge (\text{linear } L) \wedge ((B \circ A) = (T \circ L))$ **using** $T \ L$
trans lin BA **by** *auto*
thus *?thesis* **by** *auto*
qed

```

lemma lemInverseAffine:
  assumes affInvertible A
  shows  $\exists A' . (\text{affine } A') \wedge (\forall p q . A p = q \longleftrightarrow A' q = p)$ 
  proof -
    obtain A' where A':  $(\forall p q . A p = q \longleftrightarrow A' q = p)$ 
      using assms by metis

    obtain T L where TL: translation T  $\wedge$  linear L  $\wedge$  (A = T  $\circ$  L)
      using assms(1) by auto

    obtain T' where T': (translation T')  $\wedge$   $(\forall p q . T p = q \longleftrightarrow T' q = p)$ 
      using TL lemInverseTrans[of T] by auto

    {
      fix p
      {
        fix q
        assume Ap: A p = q
        hence T (L p) = q using TL by auto
        hence L p = T' q using T' by auto
        hence L p = (T'  $\circ$  A) p using Ap by auto
      }
    }
    hence L: L = (T'  $\circ$  A) by auto

    {
      fix q
      obtain r where r: (T' r = q) using T' by auto
      then obtain p where p: (A p = r)  $\wedge$   $(\forall x . A x = r \longrightarrow x = p)$ 
      using A' by auto
      hence 1: L p = q using L r by auto
      {
        fix x
        assume Lx: L x = q
        hence T' (A x) = q using L by auto
        hence A x = r using r T' lemTranslationInjective[of T'] by
        force
        hence x = p using p A' by blast
      }
      hence  $\exists p . (L p = q) \wedge (\forall x . L x = q \longrightarrow x = p)$  using 1 by
      auto
    }
    hence invL: invertible L by blast

    then obtain L' where L': (linear L')  $\wedge$   $(\forall p q . L p = q \longleftrightarrow L' q = p)$ 
      using TL lemInverseLinear[of L] by blast

```

```

{ fix p q
  have A' q = p  $\longleftrightarrow$  T (L p) = q using A' TL by auto
  also have ...  $\longleftrightarrow$  T' q = L p using T' by auto
  also have ...  $\longleftrightarrow$  L p = T' q by auto
  also have ...  $\longleftrightarrow$  L' (T' q) = p using L' by auto
  finally have A' q = p  $\longleftrightarrow$  (L' o T') q = p by auto
}
hence A' = L' o T' by auto
hence affine A' using lemAffOfAffIsAff[of T' L']
                           lemTranslationImpliesAffine[of T'] T'
                           lemLinearImpliesAffine[of L'] L'

  by auto

thus ?thesis using A' by auto
qed

```

lemma *lemAffineApproxDomainTranslation*:

```

  assumes translation T
  and     affineApprox A f x
  and      $\forall p q . T p = q \longleftrightarrow T' q = p$ 
  shows   affineApprox (A o T) (composeRel f (asFunc T)) (T' x)
  proof -

```

```

  define A0 where A0: A0 = A o T
  define g where g: g = composeRel f (asFunc T)

```

```

  have ToT':  $\forall p . T (T' p) = p$  using assms(3) by force
  have T'oT:  $\forall p . T' (T p) = p$  using assms(3) by force
  obtain t where t:  $\forall p . T p = (p \oplus t)$  using assms(1) by force
  hence mkT: T = mkTranslation t by force

```

```

{ fix p q
  have T' p = q  $\longleftrightarrow$  T q = p using assms(3) by auto
  also have ...  $\longleftrightarrow$  (q  $\oplus$  t) = p using t by auto
  also have ...  $\longleftrightarrow$  q = (p  $\oplus$  (origin  $\ominus$  t)) by force
  finally have T' p = q  $\longleftrightarrow$  q = (p  $\oplus$  (origin  $\ominus$  t)) by force
  hence T' p = q  $\longleftrightarrow$  q = mkTranslation (origin  $\ominus$  t) p by force
}
hence mkT': T' = mkTranslation (origin  $\ominus$  t) by force
hence transT': translation T' using lemMkTrans by blast

```

```

  have funcF: isFunction f using assms(2) by auto
  hence rtp3a: isFunction g using g by auto

```

```

  have affA: affine A using assms(2) by auto

```

```

hence rtp3b: affine A0
  using lemAffOfAffIsAff[of T A] lemTranslationImpliesAffine[of T]
    A0 affA assms(1)
  by blast

{ fix q
  obtain p where p: (A p = q) ∧ (∀ x. A x = q → x = p) using
  assms(2) by blast
  define p0 where p0: p0 = T' p
  hence Tp0: T p0 = p using assms(3) by blast
  hence 1: A0 p0 = q using A0 p by auto
  { fix x
    assume A0 x = q
    hence T x = p using A0 p by fastforce
    hence x = p0 using Tp0 assms(1) lemTranslationInjective[of
  T] by force
  }
  hence ∀ x. A0 x = q → x = p0 by auto

  hence ∃ p0. (A0 p0 = q) ∧ (∀ x. A0 x = q → x = p0) using 1
by auto
}
hence rtp3c: invertible A0 by auto

have diffApprox (asFunc A) f x using assms(2) by auto
hence dAx: (definedAt f x) ∧
  (∀ ε > 0 . (∃ δ > 0 . (∀ y .
    ( y within δ of x
      →
        ( (definedAt f y) ∧ (∀ u v . (f y u ∧ (asFunc A) y v) →
          ( sep2 v u ) ≤ (sqr ε) * sep2 y x ))) )
  )) by blast
hence (definedAt f x) ∧ (x = T (T' x)) using assms(1) ToT' by
  auto
hence rtp3d1: (definedAt g (T' x)) using g by auto

{ fix e
  assume epos: e > 0
  then obtain d where d: (d > 0) ∧ (∀ y .
    ( y within d of x
      →
        ( (definedAt f y) ∧ (∀ u v . (f y u ∧ (asFunc A) y v) →
          ( sep2 v u ) ≤ (sqr e) * sep2 y x ))) )
  using dAx by force
  { fix y
    assume y within d of (T' x)
    hence (T y) within d of (T (T' x)) using assms(1) lemBall-

```

Translation by auto
hence $(T\ y)$ *within* d *of* x **using** ToT' **by** *auto*
hence $(\text{definedAt } f\ (T\ y)) \wedge (\forall\ u\ v.\ (f\ (T\ y)\ u \wedge (\text{asFunc } A)\ (T\ y)\ v) \longrightarrow$
 $(\text{sep2 } v\ u) \leq (\text{sqr } e) * \text{sep2 } (T\ y)\ x)$
using d **by** *blast*
hence $(\text{definedAt } g\ y) \wedge (\forall\ u\ v.\ (g\ y\ u \wedge (\text{asFunc } A0)\ y\ v) \longrightarrow$
 $(\text{sep2 } v\ u) \leq (\text{sqr } e) * \text{sep2 } (T\ y)\ x)$ **using** $g\ A0$ **by** *auto*
hence $(\text{definedAt } g\ y) \wedge (\forall\ u\ v.\ (g\ y\ u \wedge (\text{asFunc } A0)\ y\ v) \longrightarrow$
 $(\text{sep2 } v\ u) \leq (\text{sqr } e) * \text{sep2 } y\ (T'\ x))$
using $\text{trans } T'\ \text{lemTranslationPreservesSep2}[of\ T'\ T\ y\ x]$ $T' \circ T$
by *auto*
}
hence $\exists d > 0.\ \forall y.\ (y\ \text{within } d\ \text{of } (T'\ x)) \longrightarrow$
 $(\text{definedAt } g\ y) \wedge (\forall\ u\ v.\ (g\ y\ u \wedge (\text{asFunc } A0)\ y\ v) \longrightarrow$
 $(\text{sep2 } v\ u) \leq (\text{sqr } e) * \text{sep2 } y\ (T'\ x))$
using d **by** *fast*
}
hence $\text{rtp3d2}:\ \forall e > 0.\ \exists d > 0.\ \forall y.\ (y\ \text{within } d\ \text{of } (T'\ x)) \longrightarrow$
 $(\text{definedAt } g\ y) \wedge (\forall\ u\ v.\ (g\ y\ u \wedge (\text{asFunc } A0)\ y\ v) \longrightarrow$
 $(\text{sep2 } v\ u) \leq (\text{sqr } e) * \text{sep2 } y\ (T'\ x))$
by *auto*
hence $\text{rtp3d}:\ \text{diffApprox } (\text{asFunc } A0)\ g\ (T'\ x)$ **using** rtp3d1 **by** *fast*

have $\text{rtp3}:\ \text{affineApprox } A0\ g\ (T'\ x)$ **using** $\text{rtp3a}\ \text{rtp3b}\ \text{rtp3c}\ \text{rtp3d}$
by *blast*

thus *?thesis* **using** $A0\ g$ **by** *fast*
qed

lemma *lemAffineApproxRangeTranslation:*

assumes *translation* T
and $\text{affineApprox } A\ f\ x$
shows $\text{affineApprox } (T \circ A)\ (\text{composeRel } (\text{asFunc } T)\ f)\ x$
proof –

define $A0$ **where** $A0:\ A0 = T \circ A$
define g **where** $g:\ g = \text{composeRel } (\text{asFunc } T)\ f$

obtain T' **where** $T':\ (\text{translation } T') \wedge (\forall\ p\ q.\ T\ p = q \iff T'\ p = q)$
using $\text{assms}(1)$ $\text{lemInverseTrans}[of\ T]$ **by** *auto*

have $ToT':\ \forall p.\ T\ (T'\ p) = p$ **using** T' **by** *force*
have $T' \circ T:\ \forall p.\ T'\ (T\ p) = p$ **using** T' **by** *force*
obtain t **where** $t:\ \forall p.\ T\ p = (p \oplus t)$ **using** $\text{assms}(1)$ **by** *auto*

hence $mkT: T = mkTranslation\ t$ **by** *auto*
{ **fix** $p\ q$
 have $T' p = q \longleftrightarrow T\ q = p$ **using** T' **by** *auto*
 also have $\dots \longleftrightarrow (q \oplus t) = p$ **using** t **by** *auto*
 also have $\dots \longleftrightarrow q = (p \oplus (origin \ominus t))$ **by** *force*
 finally have $T' p = q \longleftrightarrow q = (p \oplus (origin \ominus t))$ **by** *force*
 hence $T' p = q \longleftrightarrow q = mkTranslation\ (origin \ominus t)\ p$ **by** *force*
}
hence $mkT': T' = mkTranslation\ (origin \ominus t)$ **by** *auto*
hence $transT': translation\ T'$ **using** $lemMkTrans$ **by** *blast*

have $funcF: isFunction\ f$ **using** $assms(2)$ **by** *auto*
hence $rtp3a: isFunction\ g$ **using** g **by** *auto*

have $affA: affine\ A$ **using** $assms(2)$ **by** *auto*
hence $rtp3b: affine\ A0$
 using $lemAffOfAffIsAff[of\ A\ T]$ $lemTranslationImpliesAffine[of\ T]$
 $A0\ affA\ assms(1)$
 by *blast*

{ **fix** q
 obtain p **where** $p: (A\ p = T' q) \wedge (\forall x. A\ x = T' q \longrightarrow x = p)$
using $assms(2)$ **by** *blast*
 hence $T' q = A\ p$ **by** *auto*
 hence $T\ (A\ p) = q$ **using** $T'\ ToT'$ **by** *auto*
 hence $1: A0\ p = q$ **using** $A0$ **by** *auto*

{ **fix** x
 assume $A0\ x = q$
 hence $T\ (A\ x) = q$ **using** $A0$ **by** *auto*
 hence $T'\ (T\ (A\ x)) = T' q$ **by** *auto*
 hence $A\ x = T' q$ **using** $T'oT$ **by** *auto*
 hence $x = p$ **using** p **by** *auto*
}

hence $\exists p0. (A0\ p0 = q) \wedge (\forall x. A0\ x = q \longrightarrow x = p0)$ **using** 1
by *auto*
}
hence $rtp3c: invertible\ A0$ **by** *auto*

have $diffApprox\ (asFunc\ A)\ f\ x$ **using** $assms(2)$ **by** *auto*
hence $dAx: (definedAt\ f\ x) \wedge$
 $(\forall \varepsilon > 0 . (\exists \delta > 0 . (\forall y .$


```

    ( (y within δ of x)
      →
      ( (definedAt f y) ∧ (∀ u v . (f y u ∧ (asFunc A) y v) →
        ( sep2 v u ) ≤ (sqr ε) * sep2 y x ))) )
  )) by blast
hence rtp3d1: definedAt g x using g by auto

{ fix e
  assume epos: e > 0
  then obtain d where d: (d > 0) ∧ (∀ y .
    (y within d of x)
      →
      ( (definedAt f y) ∧ (∀ u v . (f y u ∧ (asFunc A) y v) →
        ( sep2 v u ) ≤ (sqr e) * sep2 y x ))) )
    using dAx by auto
  { fix y
    assume y within d of x
    hence (definedAt f y) ∧ (∀ u v . (f y u ∧ (asFunc A) y v) →
      ( sep2 v u ) ≤ (sqr e) * sep2 y x ) using d by force
    hence (definedAt g y) ∧ (∀ u v . (f y u ∧ (asFunc A) y v) →
      ( sep2 v u ) ≤ (sqr e) * sep2 y x ) using g by force
    hence (definedAt g y) ∧ (∀ u v . (g y u ∧ (asFunc A0) y v) →
      ( sep2 v u ) ≤ (sqr e) * sep2 y x )
      using g A0 assms(1) lemBallTranslation by force
    }
  hence ∃ d>0. ∀ y . (y within d of x) →
    (definedAt g y) ∧ (∀ u v . (g y u ∧ (asFunc A0) y v) →
      ( sep2 v u ) ≤ (sqr e) * sep2 y x )
    using d by force
  }
hence rtp3d2: ∀ e>0. ∃ d > 0. ∀ y . (y within d of x) →
  (definedAt g y) ∧ (∀ u v . (g y u ∧ (asFunc A0) y v) →
    ( sep2 v u ) ≤ (sqr e) * sep2 y x )
  by auto
hence rtp3d: diffApprox (asFunc A0) g x using rtp3d1 by auto

hence rtp3: affineApprox A0 g x using rtp3a rtp3b rtp3c rtp3d by
auto

```

thus ?thesis using g A0 mkT by best

qed

lemma lemAffineIdentity:
 assumes affine A
 and e > 0

and $\forall y . (y \text{ within } e \text{ of } x) \longrightarrow (A y = y)$
shows $A = id$
proof –

obtain $T L$ **where** TL : translation $T \wedge$ linear $L \wedge A = T \circ L$ **using**
assms(1) **by** *auto*

have x *within* e **of** x **using** *assms(2)* **by** *auto*
hence x *fixed*: $A x = x$ **using** *assms(3)* **by** *auto*

{ **fix** p
define d **where** d : $d = (p \ominus x)$
then obtain a **where** a : $(a > 0) \wedge (\text{norm2 } (a \otimes d) < \text{sqr } e)$
using *assms(2)* *lemSmallPoints[of e d]* **by** *auto*

define p' **where** p' : $p' = ((a \otimes d) \oplus x)$
hence p' *fixed*: $A p' = p'$ **using** a *assms(3)* *lemSep2Symmetry* **by**
auto

have $p'x$: $(p' \ominus x) = (a \otimes (p \ominus x))$ **using** p' d **by** *auto*
hence $((1/a) \otimes (p' \ominus x)) = (p \ominus x)$ **using** a *lemScaleAssoc[of 1/a a*
 $p \ominus x]$ **by** *auto*
hence p : $p = (((1/a) \otimes (p' \ominus x)) \oplus x)$ **by** *auto*

hence $L p = L (((1/a) \otimes (p' \ominus x)) \oplus x)$ **by** *auto*
also have $\dots = (L ((1/a) \otimes (p' \ominus x))) \oplus (L x)$ **using** TL **by** *blast*
also have $\dots = (L x) \oplus (L ((1/a) \otimes (p' \ominus x)))$ **using** *add-commute*
by *simp*

finally have $A p = (A x) \oplus (L ((1/a) \otimes (p' \ominus x)))$
using TL *lemTranslationSum* **by** *auto*

hence 1 : $A p = (x \oplus (L ((1/a) \otimes (p' \ominus x))))$ **using** x *fixed* **by** *auto*

have $(L ((1/a) \otimes (p' \ominus x))) = ((1/a) \otimes (L (p' \ominus x)))$ **using** TL **by**
blast

also have $\dots = ((1/a) \otimes ((L p') \ominus (L x)))$ **using** TL **by** *auto*
also have $\dots = ((1/a) \otimes ((A p') \ominus (A x)))$ **using** TL **by** *auto*
also have $\dots = ((1/a) \otimes (p' \ominus x))$ **using** p' *fixed* x *fixed* **by** *auto*
finally have $(L ((1/a) \otimes (p' \ominus x))) = (p \ominus x)$ **using** p **by** *auto*

hence $A p = (x \oplus (p \ominus x))$ **using** 1 **by** *auto*

hence $A p = p$ **using** *add-diff-eq* **by** *auto*

}
thus *thesis* **by** *auto*

qed

end

end

21 Sublemma4

This theory shows that functions with affine approximations are continuous where approximated.

```
theory Sublemma4
imports Affine AxTriangleInequality
begin
```

Our naming of lemmas, propositions, etc., is sometimes counterintuitive. This is because the proof follows a hand-written proof, and we need to maintain the link between the paper-based and Isabelle versions. We will specifically be discussing how we translated from one to the other in a forthcoming paper (under construction). In fact, sublemmas 1 and 2 were eventually found to be unnecessary during construction of the Isabelle proof, and so do not appear in this documentation.

```
class Sublemma4 = Affine + AxTriangleInequality
begin
```

```
lemma sublemma4:
assumes affineApprox A f x
shows  $(\exists \delta > 0. \forall p. (p \text{ within } \delta \text{ of } x) \longrightarrow (\text{definedAt } f p)) \wedge (\text{cts } f x)$ 
proof -
```

```
have diff:  $(\text{definedAt } f x) \wedge$ 
 $(\forall \varepsilon > 0. (\exists \delta > 0. (\forall y. (y \text{ within } \delta \text{ of } x)$ 
 $\longrightarrow$ 
 $(\text{definedAt } f y) \wedge (\forall u v. (f y u \wedge (\text{asFunc } A) y v) \longrightarrow$ 
 $(\text{sep2 } v u) \leq (\text{sqr } \varepsilon) * \text{sep2 } y x)))$ 
)) using assms by simp
```

```
have  $0 < 1$  by simp
then obtain d where  $d: (d > 0) \wedge (\forall y. (y \text{ within } d \text{ of } x)$ 
 $\longrightarrow$ 
 $((\text{definedAt } f y) \wedge (\forall u v. (f y u \wedge (\text{asFunc } A) y v) \longrightarrow$ 
 $(\text{sep2 } v u \leq (\text{sqr } 1) * \text{sep2 } y x))))$  using diff by blast
hence  $\forall p. (p \text{ within } d \text{ of } x) \longrightarrow (\text{definedAt } f p)$  by blast
hence rtp1:  $\exists \delta > 0. \forall p. (p \text{ within } \delta \text{ of } x) \longrightarrow (\text{definedAt } f p)$ 
using d by auto
```

```

have funcF: isFunction f using assms by simp
have affA: affine A using assms by simp
have funcA: isFunction (asFunc A) using assms by simp

{ fix x'
  assume x': f x x'
  hence ax: x' = A x
    using assms lemAffineEqualAtBase[of f A x] by blast

  { fix e
    assume epos: e > 0
    hence e2pos: e/2 > 0 by simp

    obtain d1 where d1: (d1 > 0) ∧ (∀ y .
      ((y within d1 of x) → ((A y) within (e/2) of (A x))))
      using e2pos affA lemAffineContinuity by blast

    obtain d2' where d2': (d2' > 0) ∧ (∀ y .
      ( (y within d2' of x) → ((definedAt f y) ∧
        (∀ fy Ay . (f y fy ∧ (asFunc A) y Ay) →
          ( sep2 Ay fy ) ≤ (sqr (e/2)) * sep2 y x ))))
      using e2pos assms by auto
    then obtain d2
      where d2: (d2 > 0) ∧ (d2 < d2') ∧ (sqr d2 < d2) ∧ (d2 < 1)
      using lemReducedBound[of d2'] by auto

    define d where d: d = min d1 d2
    have dd1: d ≤ d1 using d by auto
    have dd2: d ≤ d2 using d by auto
    have dpos: d > 0 using d1 d2 d by auto

    { fix y'
      assume y': y' ∈ applyToSet f (ball x d)
      then obtain y where y: (y ∈ ball x d) ∧ (f y y') by auto
      hence y-near-x: y within d of x using lemSep2Symmetry by
      auto

      have y within d1 of x using lemBallInBall y-near-x dpos dd1
      by auto
      hence dist1: (A y) within (e/2) of (A x) using d1 by auto

      have yd2'x: y within d2' of x using lemBallInBall y-near-x
      dpos d2 dd2 by auto
      hence ∀ fy Ay . (f y fy ∧ (asFunc A) y Ay) →

```

```

      ( sep2 Ay fy ≤ (sqr (e/2)) * sep2 y x )
      using d2' by auto
      hence conc2: sep2 (A y) y' ≤ (sqr (e/2)) * sep2 y x using y
by auto

      have y within d2 of x using lemBallInBall y-near-x dpos d2
dd2 by auto
      hence yx1: y within 1 of x using lemBallInBall d2 by auto

      have sqr (e/2) > 0 using e2pos lemSqrMonoStrict[of 0 e/2]
by auto
      hence (sqr (e/2)) * sep2 y x < sqr (e/2)
      using mult-strict-left-mono[of sep2 y x 1 sqr (e/2)]
      lemNorm2NonNeg[of y⊖x] yx1
      by auto
      hence dist2: sep2 (A y) y' < sqr (e/2) using conc2 by auto

define p where p: p = (A x)
define q where q: q = (A y)
define r where r: r = y'

      have tri: axTriangleInequality (q⊖p) (r⊖q)
      using AxTriangleInequality by blast
      have Dist1: p within (e/2) of q
      using dist1 p q lemSep2Symmetry by auto
      have Dist2: r within (e/2) of q
      using dist2 q r lemSep2Symmetry by auto

      have r within ((e/2)+(e/2)) of p
      using e2pos Dist1 Dist2 tri
      lemDistancesAdd[of q p r e/2 e/2]
      by blast
      hence r within e of p using lemSumOfTwoHalves by auto
      hence y' ∈ ball x' e using p r ax lemSep2Symmetry by auto
    }
      hence ∃ d>0. applyToSet f (ball x d) ⊆ (ball x' e) using dpos
by auto
    }
      hence (∀ e>0. ∃ d>0. applyToSet f (ball x d) ⊆ (ball x' e))
      by auto
    }
      hence ∀ x'. (f x x') → (∀ e>0. ∃ d>0. applyToSet f (ball x d) ⊆
(ball x' e))
      by auto
      hence rtp2: cts f x by simp

      thus ?thesis using rtp1 by auto
qed

```

end

end

22 MainLemma

This theory establishes conditions under which a function maps tangent lines to tangent lines.

theory *MainLemma*

imports *Sublemma3 Sublemma4*

begin

class *MainLemma* = *Sublemma3* + *Sublemma4*

begin

lemma *lemMainLemmaBasic*:

assumes *tgt*: *tangentLine l wl origin*

and *injf*: *injective f*

and *affapp*: *affineApprox A f origin*

and *f00*: *f origin origin*

and *ctsf'0*: *cts (invFunc f) origin*

and *affline*: *applyAffineToLine A l l'*

shows *tangentLine l' (applyToSet f wl) origin*

proof –

define *goal1* **where**

goal1: *goal1* \equiv *origin* \in (*applyToSet f wl*)

define *goal2* **where**

goal2: *goal2* \equiv *onLine origin l'*

define *goal3* **where**

goal3: *goal3* \equiv *accPoint origin (applyToSet f wl)*

define *subgoal4a* **where**

subgoal4a: *subgoal4a* \equiv ($\lambda p' .$ *onLine p' l'*)

define *subgoal4b* **where**

subgoal4b: *subgoal4b* \equiv ($\lambda p' . p' \neq$ *origin*)

define *subgoal4c1* **where**

subgoal4c1: *subgoal4c1* \equiv ($\lambda p' d e .$

$(\forall y' \in$ (*applyToSet f wl*) . (*y'* *within d of origin*) \wedge (*y'* \neq *origin*))

\longrightarrow ($\exists r .$ (*onLine r (lineJoining origin y')*) \wedge (*r within e of p'*))))

define *subgoal4c* **where**

subgoal4c: *subgoal4c* \equiv ($\lambda p' . \forall e > 0 . \exists d > 0 .$ *subgoal4c1 p' d e*)

define *goal4* **where**

goal4: $goal4 \equiv (\exists p'. (subgoal4a\ p') \wedge (subgoal4b\ p') \wedge (subgoal4c\ p'))$

have *GOAL*: $goal1 \wedge goal2 \wedge goal3 \wedge goal4$
 $\longrightarrow tangentLine\ l'\ (applyToSet\ f\ wl)\ origin$
using *goal1 goal2 goal3 goal4 subgoal4a subgoal4b subgoal4c1 subgoal4c*
by *force*

have *affA*: *affine A* **using** *affapp* **by** *auto*
then obtain *T L* **where** *TL*: *translation T* \wedge *linear L* \wedge $A = T \circ L$
by *auto*
then obtain *t* **where** $t: \forall u. T\ u = (u \oplus t)$ **by** *auto*
define *Tinv* **where** *Tinv*: $Tinv = mkTranslation\ (origin \ominus t)$
hence *transTinv*: *translation Tinv* **using** *lemMkTrans* **by** *blast*

have *linel*: *isLine l* **using** *tgt* **by** *auto*

hence *linel'*: *isLine l'*
using *affA affine lemAffineOfLineIsLine*
by *auto*

have *funcF*: *isFunction f* **using** *affapp* **by** *auto*

have *A00*: $A\ origin = origin$
using *lemAffineEqualAtBase[of f A origin] affapp f00*
by *auto*

have $A\ origin = ((L\ origin) \oplus t)$ **using** *TL t* **by** *auto*
also have $\dots = (origin \oplus t)$ **using** *TL* **by** *auto*
finally have $origin = t$ **using** *A00* **by** *auto*
hence $\forall p. T\ p = p$ **using** *t* **by** *auto*
hence $T = id$ **by** *auto*
hence $A = L$ **using** *TL* **by** *auto*

hence *linA*: *linear A* **using** *TL* **by** *auto*

have $((invFunc\ f)\ origin\ origin)$
 $\wedge (\forall x. ((invFunc\ f)\ origin\ x) \longrightarrow (\forall \varepsilon > 0. \exists \delta > 0.$
 $(applyToSet\ (invFunc\ f)\ (ball\ origin\ \delta)) \subseteq ball\ x\ \varepsilon))$
using *f00 ctsf'0* **by** *auto*

hence $ctsfinv$: $(\forall \varepsilon > 0. \exists \delta > 0. (applyToSet (invFunc f) (ball\ origin\ \delta)) \subseteq ball\ origin\ \varepsilon)$
by *blast*

have $ctsA$: $\forall x. \forall \varepsilon > 0. \exists \delta > 0. \forall p. (p\ within\ \delta\ of\ x) \longrightarrow ((A\ p)\ within\ \varepsilon\ of\ (A\ x))$
using *affA lemAffineContinuity* **by** *auto*

have $tgt1$: $origin \in wl$ **using** tgt **by** *auto*
have $tgt2$: $onLine\ origin\ l$ **using** tgt **by** *auto*
have $tgt3$: $\forall \varepsilon > 0. \exists q \in wl. (origin \neq q) \wedge (inBall\ q\ \varepsilon\ origin)$
using tgt **by** *auto*

have $sub4$: $(\exists \delta > 0. \forall p. (p\ within\ \delta\ of\ origin) \longrightarrow (definedAt\ f\ p)) \wedge (cts\ f\ origin)$
using *affapp sublemma4 [of f A origin]* **by** *auto*

hence $ctsfx$: $(\forall \varepsilon > 0. \exists \delta > 0. (applyToSet\ f\ (ball\ origin\ \delta)) \subseteq ball\ origin\ \varepsilon)$
using $f00$ **by** *auto*

obtain $ddef$ **where** $ddef$: $(ddef > 0) \wedge (\forall p. (p\ within\ ddef\ of\ origin) \longrightarrow (definedAt\ f\ p))$
using $sub4$ **by** *auto*

have $rtp1$: $goal1$ **using** $tgt1\ f00\ goal1$ **by** *auto*

have l' -*from-l*: $l' = applyToSet (asFunc\ A)\ l$
using $tgt\ affine\ lemAffineOfLineIsLine$ **by** *auto*
have $(asFunc\ A)\ origin\ origin$ **using** $linA$ **by** *auto*
hence $rtp2$: $goal2$ **using** l' -*from-l* $tgt2\ affine\ goal2$ **by** *auto*

{ **fix** e
assume $epos$: $e > 0$
then **obtain** dd'
where dd' : $(dd' > 0) \wedge ((applyToSet\ f\ (ball\ origin\ dd')) \subseteq ball$

origin e
using *ctsfx* **by** *auto*

define *dd* **where** *dd*: $dd = \min dd' ddef$
hence *ddpos*: $dd > 0$ **using** *dd' ddef* **by** *simp*
then obtain *q* **where** $q: (q \in wl) \wedge (origin \neq q) \wedge (q \text{ within } dd \text{ of } origin)$
using *tgt3* **by** *auto*

have $dd \leq ddef$ **using** *dd* **by** *auto*
hence *q* **within** *ddef* **of** *origin*
using *ddpos q lemBallInBall[of q origin dd ddef]* **by** *auto*
then obtain *q'* **where** $q': (f q q')$ **using** *ddef* **by** *auto*

hence *fact3a*: $q' \in (applyToSet f) wl$ **using** *q* **by** *auto*

have $q \neq origin$ **using** *q* **by** *auto*
hence *fact3b*: $q' \neq origin$ **using** *injf q' f00* **by** *auto*

have $dd \leq dd'$ **using** *dd* **by** *auto*
hence $q \in ball\ origin\ dd'$
using *q lemBallInBall[of q origin dd dd'] ddpos* **by** *auto*
hence $q' \in ball\ origin\ e$ **using** *dd' q'* **by** *auto*
hence *fact3c*: $q' \text{ within } e \text{ of } origin$ **using** *lemSep2Symmetry* **by** *auto*

hence $\exists y' \in ((applyToSet f) wl) . (origin \neq y') \wedge (y' \text{ within } e \text{ of } origin)$
using *fact3a fact3b q'* **by** *auto*

hence *rtp3*: *goal3* **using** *goal3* **by** *auto*

obtain *P* **where** $P: (onLine P l) \wedge (P \neq origin) \wedge$
 $(\forall \varepsilon > 0 . \exists \delta > 0 . \forall y \in wl. ($
 $(y \text{ within } \delta \text{ of } origin) \wedge (y \neq origin))$
 \rightarrow
 $(\exists r . ((onLine r (lineJoining origin y)) \wedge (r \text{ within } \varepsilon \text{ of } P))))$
using *tgt* **by** *auto*

define *nP* **where** *nP*: $nP = norm P$
have $P \neq origin$ **using** *P* **by** *auto*
hence *nPpos*: $nP > 0$ **using** *P nP lemNotOriginImpliesPositiveNorm[of P]*
by *auto*
define *a* **where** $a: a = 1/nP$
hence *apos*: $a > 0$ **using** *nPpos* **by** *auto*

define p **where** $p: p = (a \otimes P)$
{ **assume** $p = origin$
hence $(a \otimes P) = origin$ **using** p **by** *auto*
hence $(nP \otimes (a \otimes P)) = (nP \otimes origin)$ **by** *simp*
hence $P = origin$ **using** a *apos* $lemScaleAssoc$ **by** *auto*
}
hence $p\text{-not-0}: p \neq origin$ **using** P **by** *auto*

define p' **where** $p': p' = A p$
obtain A' **where** $A': (affine A') \wedge ((affine A') \wedge (\forall p q . A p = q \longleftrightarrow A' q = p))$
using *affapp lemInverseAffine[of A]* **by** *auto*
hence $A' origin = origin \wedge A' p' = p$ **using** $A00 p'$ **by** *blast*
hence $p'\text{-not-0}: p' \neq origin$ **using** $p\text{-not-0}$ **by** *auto*

have $(onLine origin l) \wedge (onLine P l) \wedge (origin \neq P)$ **using** P $tgt2$
by *auto*
hence $l\text{-is-0P}: l = lineJoining origin P$
using *lemLineAndPoints[of origin P l]* **by** *auto*

have $p = (origin \oplus (a \otimes (P \ominus origin)))$ **using** p **by** *auto*
hence $onLine p (lineJoining origin P)$ **by** *blast*

hence $p\text{-on-l}: onLine p l$ **using** $l\text{-is-0P}$ **by** *auto*
moreover **have** $l' = applyToSet (asFunc A) l \wedge isLine l'$
using *lemAffineOfLineIsLine [of l A l']*
affline
by *auto*
ultimately **have** $p'\text{-on-l'}: onLine p' l'$ **using** $p\text{-on-l } p'$ **by** *auto*

have $p = (a \otimes P)$ **using** p **by** *auto*
hence $norm2 p = (sqr a) * (norm2 P)$
using *lemNorm2OfScaled[of a P]* **by** *auto*
hence $norm2 p = (sqr a) * (sqr nP)$
using nP *lemNormSqrIsNorm2[of P]* **by** *auto*
hence $np1: norm2 p = 1$ **using** a nP *pos apos mult-assoc mult-commute*
by *auto*

have $(onLine p l) \wedge (norm2 p = 1) \wedge (tangentLine l wl origin)$
using $p\text{-on-l } np1$ tgt **by** *auto*
hence $sub3: \forall \varepsilon > 0 . \exists \delta > 0 . \forall y ny . ($
 $((y \text{ within } \delta \text{ of } origin) \wedge (y \neq origin) \wedge (y \in wl) \wedge (norm y =$
 $ny))$
 \longrightarrow
 $(((1/ny) \otimes y) \text{ within } \varepsilon \text{ of } p) \vee (((-1/ny) \otimes y) \text{ within } \varepsilon \text{ of } p))$

using *sublemma3*[*of l p wl*]
by *auto*

```

{ fix e
  assume epos:  $e > 0$ 
  define e1 where e1:  $e1 = nP * e$ 
  hence e1pos:  $e1 > 0$  using nPpos epos by auto
  define e2 where e2:  $e2 = e/2$ 
  hence e2pos:  $e2 > 0$  using epos by auto

  obtain dctsA0 where  $(dctsA0 > 0) \wedge (\forall q.$ 
     $(q \text{ within } dctsA0 \text{ of origin}) \longrightarrow ((A \ q) \text{ within } e2 \text{ of } (A \ origin)))$ 
    using ctsA e2pos A00 by blast
  hence dctsA0:  $(dctsA0 > 0) \wedge (\forall q.$ 
     $(q \text{ within } dctsA0 \text{ of origin}) \longrightarrow ((A \ q) \text{ within } e2 \text{ of origin}))$ 
    using A00 by auto

  obtain dctsAp where  $dctsAp$ :  $(dctsAp > 0) \wedge (\forall q.$ 
     $(q \text{ within } dctsAp \text{ of } p) \longrightarrow ((A \ q) \text{ within } e2 \text{ of } (A \ p)))$ 
    using ctsA e2pos by blast

  obtain dsub where dsub:  $(dsub > 0) \wedge (\forall y \ ny .$ 
     $((y \text{ within } dsub \text{ of origin}) \wedge (y \neq origin) \wedge (y \in wl) \wedge (norm \ y$ 
     $= ny)))$ 
     $\longrightarrow$ 
     $((((1/ny) \otimes y) \text{ within } (dctsAp) \text{ of } p)$ 
     $\vee (((-1/ny) \otimes y) \text{ within } (dctsAp) \text{ of } p))$ 
    using apos dctsAp sub3 by blast

  obtain daff where daff:  $(daff > 0) \wedge (\forall y .$ 
     $(y \text{ within } daff \text{ of origin})$ 
     $\longrightarrow$ 
     $((\text{definedAt } f \ y) \wedge (\forall fy \ Ay . (f \ y \ fy \wedge (\text{asFunc } A) \ y \ Ay) \longrightarrow$ 
     $(\text{sep2 } Ay \ fy) \leq (\text{sqr } e2) * \text{sep2 } y \ origin)))$ 
    using e2pos affapp by auto

  define dmin where dmin:  $dmin = \min \ dsub \ daff$ 
  hence dminsub:  $dmin \leq dsub$  by auto
  have dminaff:  $dmin \leq daff$  using dmin by auto
  have dminpos:  $dmin > 0$  using dmin dsub daff by auto

  obtain dfinv
    where dfinv:  $(dfinv > 0)$ 
     $\wedge ((\text{applyToSet } (\text{invFunc } f) (\text{ball } origin \ dfinv))$ 

```

\subseteq ball origin dmin)
using ctsfinv dminpos **by** auto

{ fix y'
assume y' : $(y' \in (\text{applyToSet } f \text{ } wl)) \wedge (y' \neq \text{origin})$
then obtain y **where** y : $(f \ y \ y') \wedge (y \in wl)$ **by** auto

have $y\text{-not-0}$: $y \neq \text{origin}$ **using** $y \ y' \ f00 \ \text{funcF}$ **by** auto
obtain ny **where** ny : $\text{norm } y = ny$ **by** auto

hence $nypos$: $ny > 0$
using $y\text{-not-0} \ \text{lemNotOriginImpliesPositiveNorm}[of \ y] \ ny$ **by**

auto

define $p1$ **where** $p1$: $p1 = ((1/ny) \otimes y')$
define $q1$ **where** $q1$: $q1 = (A \ ((1/ny) \otimes y))$
define $p2$ **where** $p2$: $p2 = ((-1/ny) \otimes y')$
define $q2$ **where** $q2$: $q2 = (A \ ((-1/ny) \otimes y))$
define r **where** r : $r = (A \ p)$

assume $y'2$: $(y' \text{ within } d\text{finv} \ \text{of } \text{origin})$
hence $y' \in$ ball origin $d\text{finv}$ **using** lemSep2Symmetry **by** auto
hence $y \in$ applyToSet $(\text{invFunc } f) \ (\text{ball } \text{origin } d\text{finv})$ **using** y **by**

auto

hence $y\text{dmin}$: $y \in$ ball origin dmin **using** $d\text{finv}$ **by** auto

have $d\text{min} \leq d\text{sub}$ **using** $d\text{min}$ **by** auto
hence $y\text{dsub}$: y within $d\text{sub}$ of origin
using $\text{lemBallInBall}[of \ y \ \text{origin} \ d\text{min} \ d\text{sub}] \ d\text{minpos} \ y\text{dmin}$
by auto

hence $(y \text{ within } d\text{sub} \ \text{of } \text{origin}) \wedge (y \neq \text{origin})$
 $\wedge (y \in wl) \wedge (\text{norm } y = ny)$
using $y\text{dsub} \ y\text{-not-0} \ y \ ny$ **by** force
hence cases: $((1/ny) \otimes y)$ within $d\text{ctsAp}$ of p
 $\vee ((-1/ny) \otimes y)$ within $d\text{ctsAp}$ of p
using $d\text{sub}$ **by** blast

hence casesA: $(q1 \text{ within } e2 \ \text{of } r) \vee (q2 \text{ within } e2 \ \text{of } r)$
using $d\text{ctsAp} \ q1 \ q2 \ r$ **by** auto

have $d\text{min} \leq d\text{aff}$ **using** $d\text{min}$ **by** auto
hence y within $d\text{aff}$ of origin
using $\text{lemBallInBall}[of \ y \ \text{origin} \ d\text{min} \ d\text{aff}] \ d\text{minpos} \ y\text{dmin}$
by auto

```

hence (definedAt f y) ∧ (∀ fy Ay . (f y fy ∧ (asFunc A) y Ay)
→
  ( sep2 Ay fy ) ≤ (sqr e2) * sep2 y origin)
using daff by auto
hence sep2 (A y) y' ≤ (sqr ny) * (sqr e2)
using y ny lemNormSqrIsNorm2 mult-commute by auto
hence sep2 (A y) y' ≤ sqr (ny*e2)
using lemSqrMult[of ny e2] by auto
hence sep2 ((1/ny)⊗(A y)) ((1/ny)⊗y') ≤ sqr e2
using nypos
      lemScaleBallAndBoundary[of A y y' ny*e2 1/ny]
by auto
hence part1: sep2 (A ((1/ny)⊗y)) ((1/ny)⊗y') ≤ sqr e2
using linA lemLinearProps[of A 1/ny y] by auto

{
  assume case1: q1 within e2 of r

  have pq: sep2 p1 q1 ≤ sqr e2
    using part1 lemSep2Symmetry[of p1 q1] p1 q1 by auto
  hence rq: sep2 r q1 < sqr e2 using case1 lemSep2Symmetry
r q1 by auto

  { define pp where pp: pp = (q1⊖p1)
    define qq where qq: qq = (r⊖q1)
    have tri1: axTriangleInequality pp qq using AxTriangleInequality by simp
    hence r within (e2 + e2) of p1
      using pp qq pq rq e2pos lemDistancesAddStrictR[of q1 p1 r]
      by blast
    }
  hence done1: p1 within e of r using lemSep2Symmetry lem-
SumOfTwoHalves e2 by auto

  have p1 = (origin ⊕ ((1/ny)⊗(y'⊖origin))) using p1 by auto
  hence onLine p1 (lineJoining origin y') by fastforce
  hence onLine p1 (lineJoining origin y') ∧ (p1 within e of p')
    using p' r done1 by blast
  }
hence case1: (q1 within e2 of r)
  → (onLine p1 (lineJoining origin y') ∧ (p1 within
e of p'))
  by blast

{
  assume case2: q2 within e2 of r

  have p2 = (((-1)*(1/ny))⊗y') using p2 by auto

```

hence $p2'$: $p2 = ((-1) \otimes p1)$ **using** *lemScaleAssoc*[of -1 $1/ny$
 y'] $p1$ **by** *auto*
have $q2 = (A (((-1) * (1/ny)) \otimes y))$ **using** $q2$ **by** *auto*
hence $q2q1$: $q2 = ((-1) \otimes q1)$
using *linA lemLinearProps*[of A -1 $((1/ny) \otimes y)$] $q1$
by *auto*
hence $sep2$ $p2$ $q2 = sep2$ $p1$ $q1$ **using** *lemScaleSep2*[of -1]
 $p2'$ **by** *auto*
hence pq : $sep2$ $p2$ $q2 \leq sqr$ $e2$
using *part1 lemSep2Symmetry*[of $p1$ $q1$] $p1$ $q1$ **by** *auto*

hence rq : $sep2$ r $q2 < sqr$ $e2$ **using** *case2 lemSep2Symmetry*
 r $q2$ **by** *auto*

{ define pp **where** pp : $pp = (q2 \ominus p2)$
define qq **where** qq : $qq = (r \ominus q2)$
have $tri2$: *axTriangleInequality* pp qq **using** *AxTriangleInequality*
 by *simp*
hence r *within* $(e2 + e2)$ *of* $p2$
using pp qq pq rq $e2pos$ *lemDistancesAddStrictR*[of $q2$ $p2$ r]
by *blast*
}
hence $p2$ *within* e *of* r **using** *lemSep2Symmetry lemSumOfTwoHalves* $e2$ **by** *auto*
hence $done2$: $p2$ *within* e *of* p' **using** r p' **by** *simp*

have $p2 = (origin \oplus ((-1/ny) \otimes (y' \ominus origin)))$ **using** $p2$ **by**
auto
hence *onLine* $p2$ (*lineJoining* $origin$ y') **by** *blast*
hence *onLine* $p2$ (*lineJoining* $origin$ y') \wedge ($p2$ *within* e *of* p')
using p' $done2$ **by** *blast*
}
hence *case2*: ($q2$ *within* $e2$ *of* r)
 \rightarrow (*onLine* $p2$ (*lineJoining* $origin$ y') \wedge ($p2$ *within* e *of* p'))
by *blast*

hence $\exists r$. (*onLine* r (*lineJoining* $origin$ y')) \wedge (r *within* e *of* p')
using *casesA case1 case2* **by** *blast*

hence ($(y' \in applyToSet f wl) \wedge (y' \text{ within } dfinv \text{ of } origin) \wedge (y' \neq origin)$)
 \rightarrow ($\exists r$. (*onLine* r (*lineJoining* $origin$ y')) \wedge (r *within* e *of* p'))
using *dfinv* **by** *blast*

}
hence *subgoal4c1* p' *dfinv* e **using** *dfinv subgoal4c1* **by** *blast*
hence $\exists d > 0$. *subgoal4c1* p' d e **using** *dfinv* **by** *auto*
}
hence $\forall e > 0$. $\exists d > 0$. *subgoal4c1* p' d e **by** *auto*

hence $subgoal4c\ p'$ **using** $subgoal4c\ subgoal4c1$ **by** *force*
hence $(subgoal4a\ p') \wedge (subgoal4b\ p') \wedge (subgoal4c\ p')$
using $p'-not-0\ p'-on-l'\ subgoal4a\ subgoal4b$ **by** *auto*
hence $rtp4: goal4$ **using** $goal4\ subgoal4a\ subgoal4b\ subgoal4c$ **by** *blast*

thus *?thesis* **using** $rtp1\ rtp2\ rtp3\ GOAL$ **by** *fastforce*
qed

lemma *lemMainLemmaOrigin*:
assumes $tgtx: tangentLine\ l\ wl\ x$
and $injf: injective\ f$
and $affappx: affineApprox\ A\ f\ x$
and $fx0: f\ x\ origin$
and $ctsf'0: cts\ (invFunc\ f)\ origin$
and $affline: applyAffineToLine\ A\ l\ l'$
shows $tangentLine\ l'\ (applyToSet\ f\ wl)\ origin$
proof –

define T **where** $T: T = mkTranslation\ x$
hence $transT: translation\ T$ **using** $lemMkTrans$ **by** *blast*
define T' **where** $T': T' = mkTranslation\ (origin \ominus x)$
hence $transT': translation\ T'$ **using** $lemMkTrans$ **by** *blast*

have $TT': \forall\ p\ q . T\ p = q \longleftrightarrow T'\ q = p$ **using** $T\ T'$ **by** *auto*

define g **where** $g: g = composeRel\ f\ (asFunc\ T)$

define $l0$ **where** $l0: l0 = applyToSet\ (asFunc\ T')\ l$
define $wl0$ **where** $wl0: wl0 = applyToSet\ (asFunc\ T')\ wl$
define $A0$ **where** $A0: A0 = A \circ T$

have $T'\ x = origin$ **using** T' **by** *auto*
hence $rtp1: tangentLine\ l0\ wl0\ origin$
using $l0\ wl0\ transT'\ tgtx\ lemTangentLineTranslation[of\ T'\ x\ wl\ l]$
by *auto*

have $rtp2: injective\ g$
using $transT\ lemTranslationInjective[of\ T]\ lemInjOfInjIsInj[of\ asFunc\ T\ f]$

inj g
by *blast*

have $T' x = origin$ **using** T' **by** *auto*
hence $rtp3$: *affineApprox* $A0$ g *origin*
using *transT* TT'
lemAffineApproxDomainTranslation[*of* T f A x T']
affappx g $A0$
by *auto*

have $(T origin = x) \wedge (f x origin)$ **using** $T fx0$ **by** *auto*
hence $\exists x . ((asFunc T) origin x) \wedge (f x origin)$ **by** *auto*
hence $rtp4$: $g origin origin$ **using** $g T fx0$ **by** *auto*

define h **where** h : $h = (invFunc (asFunc T))$
hence *invcomp*: *composeRel* h $(invFunc f) = invFunc g$
using *lemInverseComposition*[*of* g $asFunc T$ f] g **by** *auto*

{ **fix** p r
have $inv1$: $invFunc (asFunc T) p r \longleftrightarrow (T' \circ T) r = T' p$
using *transT'* *lemTranslationInjective* **by** *auto*
hence $invFunc (asFunc T) p r \longleftrightarrow r = T' p$
using $T T'$ *lemInverseTranslation*[*of* T x T'] **by** *auto*
}
hence hT : $h = asFunc T'$ **using** h **by** *force*
hence $\forall y. cts h y$
using *transT'* *lemTranslationImpliesAffine*[*of* T']
lemAffineIsCts[*of* T']
by *blast*
hence $ctsh$: $\forall y. (invFunc f) origin y \longrightarrow cts h y$ **by** *auto*

define g' **where** g' : $g' = composeRel h (invFunc f)$
hence $invg$: $g' = invFunc g$ **using** hT *invcomp* **by** *simp*
have $cts g' origin$
using $ctsf'0$ $ctsh$ *lemCtsOfCtsIsCts*[*of* $invFunc f$ $origin$ h] g'
by *auto*
hence $rtp5$: $cts (invFunc g) origin$ **using** $invg$ **by** *auto*

have $affA$: *affine* A **using** $assms(3)$ **by** *auto*
hence $rtp3b$: *affine* $A0$
using *lemAffOfAffIsAff*[*of* T A] *lemTranslationImpliesAffine*[*of* T]
 $A0$ $affA$ *transT*

by *auto*
define $l0'$ **where** $l0'$: $l0' = \text{applyToSet } (asFunc\ A0)\ l0$
hence $rtp6$: $\text{applyAffineToLine } A0\ l0\ l0'$
 using $rtp1\ rtp3b\ lemAffineOfLineIsLine$ [of $l0\ A0\ l0'$]
 by *auto*

have $(\text{tangentLine } l0\ wl0\ origin) \longrightarrow$ (
 $(\text{injective } g) \longrightarrow$
 $(\text{affineApprox } A0\ g\ origin) \longrightarrow$
 $(g\ origin\ origin) \longrightarrow$
 $((cts\ (invFunc\ g)\ origin) \longrightarrow$
 $((\text{applyAffineToLine } A0\ l0\ l0') \longrightarrow$
 $(\text{tangentLine } l0'\ (applyToSet\ g\ wl0)\ origin))))$
using $lemMainLemmaBasic$ [of $wl0\ l0\ g\ A0\ l0'$]
by *blast*

hence $basic$: $(\text{tangentLine } l0'\ (applyToSet\ g\ wl0)\ origin)$
using $rtp1\ rtp2\ rtp3\ rtp4\ rtp5\ rtp6$ **by** *meson*

obtain A' **where** A' : $\forall\ p\ q . A\ p = q \longleftrightarrow A'\ q = p$
using $affappx$ **by** *metis*

have ToT' : $T \circ T' = id$ **using** TT' **by** *auto*
have $A0 \circ T' = (A \circ T) \circ T'$ **using** $A0$ **by** *auto*
also have $\dots = A \circ (T \circ T')$ **by** *auto*
finally have $A0T'$: $A0 \circ T' = A$ **using** ToT' **by** *auto*

have $l0' = \text{applyToSet } (asFunc\ (A0 \circ T'))\ l$ **using** $l0\ l0'$ **by** *auto*
hence $l0' = \text{applyToSet } (asFunc\ A)\ l$ **using** $A0T'$ **by** *auto*
hence $l0'l$: $l0' = l'$ **using** $tgtx\ affine\ lemAffineOfLineIsLine$ [of $l\ A\ l'$] **by** *auto*

have $\text{applyToSet } g\ wl0 = \text{applyToSet } (composeRel\ f\ (asFunc\ (T \circ T')))$
 wl **using** $wl0\ g$ **by** *auto*
also have $\dots = \text{applyToSet } (composeRel\ f\ (asFunc\ id))\ wl$ **using**
 ToT' **by** *auto*
also have $\dots = \text{applyToSet } f\ wl$ **by** *auto*
finally have $\text{applyToSet } g\ wl0 = \text{applyToSet } f\ wl$ **by** *auto*

hence $\text{tangentLine } l'\ (applyToSet\ f\ wl)\ origin$ **using** $basic\ l0'l$ **by**
auto
thus $?thesis$ **by** *auto*

qed

lemma *lemMainLemma*:

```
  assumes tgtx: tangentLine l wl x
  and     injf: injective f
  and     affappx: affineApprox A f x
  and     fx: f x y
  and     ctsf'y: cts (invFunc f) y
  and     affline: applyAffineToLine A l l'
  shows   tangentLine l' (applyToSet f wl) y
  proof -
    define Ty where Ty: Ty = mkTranslation y
    hence transTy: translation Ty using lemMkTrans by auto
    define Ty' where Ty': Ty' = mkTranslation (origin  $\ominus$  y)
    hence transTy': translation Ty' using lemMkTrans by blast
    define g where g: g = composeRel (asFunc Ty') f
    define Ay where Ay: Ay = Ty'  $\circ$  A

    define ly' where ly': ly' = applyToSet (asFunc Ty') l'

    have lineL: isLine l using tgtx by auto
    have affA: affine A using affappx by auto

    have TT':  $\forall p q . Ty\ p = q \longleftrightarrow Ty'\ q = p$  using Ty Ty' by auto

    have rtp1: tangentLine l wl x by (rule tgtx)

    have rtp2: injective g
      using transTy' lemTranslationInjective[of Ty'] lemInjOfInjIsInj[of
f asFunc Ty']
      injf g
      by blast

    have (translation Ty')  $\longrightarrow$  (affineApprox A f x)
       $\longrightarrow$  (affineApprox (Ty'  $\circ$  A) (composeRel (asFunc Ty') f) x)
      using lemAffineApproxRangeTranslation[of Ty' f A x]
      by blast
    hence rtp3: affineApprox Ay g x using Ay g transTy' affappx by
meson

    have rtp4: g x origin using g Ty' fxy by auto
```

```

define f' where f': f' = invFunc f
define h where h: h = (invFunc (asFunc Ty'))
define g' where g': g' = invFunc g

hence invcomp: g' = composeRel f' h
  using lemInverseComposition g f' h by auto

{ fix p r
  have inv1: invFunc (asFunc Ty') p r  $\longleftrightarrow$  (Ty $\circ$ Ty') r = Ty p
    using transTy lemTranslationInjective by auto
  hence invFunc (asFunc Ty') p r  $\longleftrightarrow$  r = Ty p using Ty Ty' by
auto
}
hence hT: h = asFunc Ty using h by force

hence ctsh0: cts h origin
  using transTy lemTranslationImpliesAffine[of Ty]
    lemAffineIsCts[of Ty]
  by blast

{ fix p
  assume h origin p
  hence (asFunc Ty) origin p using hT by auto
  hence p = y using Ty by auto
  hence cts (invFunc f) p using ctsf'y by auto
}
hence ctsf:  $\forall p. h \text{ origin } p \longrightarrow cts \ f' \ p$  using f' by auto

have cts g' origin
  using invcomp ctsh0 ctsf lemCtsOfCtsIsCts[of h origin f']
  by blast

hence rtp5: cts (invFunc g) origin using g' by auto

have affAy: affine Ay
  using affA lemTranslationImpliesAffine[of Ty'] transTy'
    lemAffOfAffIsAff[of A Ty'] Ay
  by auto
have l' = applyToSet (asFunc A) l
  using affline lineL affA lemAffineOfLineIsLine[of l A l'] by auto
hence ly' = applyToSet (asFunc Ay) l using ly' Ay by auto
hence rtp6: applyAffineToLine Ay l ly'
  using lineL affAy lemAffineOfLineIsLine[of l Ay ly']
  by auto

```

```

have (tangentLine l wl x) →
  (injective g) →
  (affineApprox Ay g x) →
  (g x origin) →
  (cts (invFunc g) origin) →
  (applyAffineToLine Ay l ly') →
  (tangentLine ly' (applyToSet g wl) origin)
using lemMainLemmaOrigin[of x wl l g Ay ly']
by fastforce

hence tgt': tangentLine ly' (applyToSet g wl) origin
using rtp1 rtp2 rtp3 rtp4 rtp5 rtp6 by meson

define wl' where wl': wl' = (applyToSet g wl)
define Term1 where Term1: Term1 = applyToSet (asFunc Ty) ly'
define Term2 where Term2: Term2 = applyToSet (asFunc Ty) wl'
define Term3 where Term3: Term3 = Ty origin

have tangentLine ly' wl' origin using tgt' wl' by auto

hence goal: tangentLine (applyToSet (asFunc Ty) ly')
  (applyToSet (asFunc Ty) wl')
  (Ty origin)
using transTy lemTangentLineTranslation[of Ty origin wl' ly']
by fastforce
hence goal: tangentLine Term1 Term2 Term3
using Term1 Term2 Term3 by auto

have ToT': Ty ∘ Ty' = id using TT' by auto
have Term1 = applyToSet (asFunc Ty) (applyToSet (asFunc Ty')
l')
using ly' Term1 by auto
also have ... = applyToSet (asFunc (Ty ∘ Ty')) l' by auto
also have ... = applyToSet (asFunc id) l' using ToT' by auto
finally have term1: Term1 = l' by auto

have composeRel (asFunc Ty) g = composeRel (asFunc Ty) (composeRel
(asFunc Ty') f)
using g by auto
also have ... = composeRel (asFunc (Ty ∘ Ty')) f by auto
also have ... = composeRel (asFunc id) f using ToT' by auto
finally have Tog: composeRel (asFunc Ty) g = f by auto

have Term2 = applyToSet (asFunc Ty) (applyToSet g wl)
using wl' Term2 by auto
also have ... = applyToSet (composeRel (asFunc Ty) g) wl by auto
finally have term2: Term2 = applyToSet f wl using Tog by auto

have term3: Term3 = y using Ty Term3 by auto

```

```
thus ?thesis using goal term1 term2 term3
by fastforce
```

```
qed
```

```
end
```

```
end
```

23 AXIOM: AxDiff

This theory declares the axiom AxDiff.

```
theory AxDiff
imports Affine WorldView
begin
```

AxDiff: Worldview transformations are differentiable wherever they are defined - they can be approximated locally by affine transformations.

```
class axDiff = Affine + WorldView
begin
  abbreviation axDiff :: Body  $\Rightarrow$  Body  $\Rightarrow$  'a Point  $\Rightarrow$  bool
  where axDiff m k p  $\equiv$  (definedAt (wvtFunc m k) p)
     $\longrightarrow$  ( $\exists$  A . (affineApprox A (wvtFunc m k) p))
end
```

```
class AxDiff = axDiff +
  assumes AxDiff:  $\forall$  m k p . axDiff m k p
begin
end
```

```
end
```

24 TangentLineLemma

This theory shows that affine approximations map tangent lines to tangent lines.

```
theory TangentLineLemma
imports MainLemma AxDiff Cones
begin
```

```
class TangentLineLemma = MainLemma + AxDiff + Cones
```

begin

```
lemma lemWVTImpliesFunction: isFunction (wvtFunc k h)
proof -
  { fix x p q
    assume hyp: wvtFunc k h x p  $\wedge$  wvtFunc k h x q

    have axDiff k h x using AxDiff by blast
    hence axdiff: ( $\exists$  r . wvtFunc k h x r)
       $\longrightarrow$  ( $\exists$  A . (affineApprox A (wvtFunc k h) x ))
      by auto

    then obtain A where A: affineApprox A (wvtFunc k h) x using
    hyp by auto
    hence  $\forall z$ . (wvtFunc k h x z)  $\longleftrightarrow$  (z = A x)
      using lemAffineEqualAtBase[of wvtFunc k h A x]
      by auto
    hence p = A x  $\wedge$  q = A x using hyp by blast
    moreover have affine A using A by auto
    ultimately have p = q by auto
  }
  thus ?thesis by force
qed
```

```
lemma lemWVTcts:
  assumes definedAt (wvtFunc h k) p
  shows cts (wvtFunc h k) p
proof -
  have axDiff h k p using AxDiff by blast
  hence axdiff: ( $\exists$  r . wvtFunc h k p r)  $\longrightarrow$  ( $\exists$  A . (affineApprox A
(wvtFunc h k) p ))
  by auto
  then obtain A where A: affineApprox A (wvtFunc h k) p using
assms by auto
  thus ?thesis using sublemma4[of wvtFunc h k A p] by auto
qed
```

```
lemma lemWVTInverse: invFunc (wvtFunc k h) = wvtFunc h k
  by force
```

```
lemma lemWVTInverseCts:
  assumes wvtFunc k h p q
  shows cts (wvtFunc h k) q
proof -
```

```

define whk where whk: whk = wvtFunc h k
have definedAt whk q  $\longrightarrow$  cts whk q
  using lemWVTCTs[of h k q] whk by fast
moreover have definedAt whk q using whk assms by auto
ultimately have cts whk q by auto
thus ?thesis using whk by auto
qed

```

```

lemma lemWVTInjective: injective (wvtFunc k h)
proof –

```

```

  define wkh where wkh: wkh = wvtFunc k h
  define inv where inv: inv = invFunc wkh
  define inv2 where inv2: inv2 = invFunc inv
  define whk where whk: whk = wvtFunc h k

```

```

  have 1: inv = whk using inv whk wkh by force
  have 2: inv2 = wkh using inv2 inv wkh by force

```

```

  have isFunction whk using lemWVTImpliesFunction whk by auto
  hence isFunction inv using 1 by auto
  hence injective inv2 using inv2 by auto
  hence injective wkh using 2 by auto
  thus ?thesis using wkh by auto

```

qed

```

lemma lemPresentation:

```

```

  assumes x  $\in$  wline m b
  and tangentLine l (wline m b) x
  and affineApprox A (wvtFunc m k) x
  and wvtFunc m k x y
  and applyAffineToLine A l l'
  shows tangentLine l' (wline k b) y
proof –

```

```

  have main: (tangentLine l (wline m b) x)  $\longrightarrow$ 
    (injective (wvtFunc m k))  $\longrightarrow$ 
    (affineApprox A (wvtFunc m k) x)  $\longrightarrow$ 
    ((wvtFunc m k) x y)  $\longrightarrow$ 
    (cts (invFunc (wvtFunc m k)) y)  $\longrightarrow$ 
    (applyAffineToLine A l l')  $\longrightarrow$ 
    (tangentLine l' (applyToSet (wvtFunc m k) (wline m b)) y)
  using lemMainLemma[of x wline m b l wvtFunc m k A y l']
  by blast

```

```

  have 1: (tangentLine l (wline m b) x) using assms(2) by auto
  have 2: injective (wvtFunc m k) using lemWVTInjective by auto

```

have 3: *affineApprox* A (wvtFunc m k) x **using** *assms*(3) **by** *auto*
have 4: (wvtFunc m k) x y **using** *assms*(4) **by** *auto*

have *invFunc* (wvtFunc m k) = wvtFunc k m **using** *lemWVTInverse*
by *auto*
moreover **have** *cts* (wvtFunc k m) y
using *assms*(4) *lemWVTInverseCts*[of y m k x] **by** *auto*
ultimately **have** 5: *cts* (*invFunc* (wvtFunc m k)) y **by** *force*

have 6: *applyAffineToLine* A l l' **using** *assms*(5) **by** *auto*

hence *tgt*: *tangentLine* l' (*applyToSet* (wvtFunc m k) (*wline* m b)) y
using *main* 1 2 3 4 5 **by** *meson*

have *axdiff*: *axDiff* k m y **using** *AxDiff* **by** *blast*
hence ($\exists r . \text{wvtFunc } k \ m \ y \ r$)
 $\longrightarrow (\exists A' . (\text{affineApprox } A' \ (\text{wvtFunc } k \ m) \ y))$ **by** *blast*
then obtain A' **where** A': *affineApprox* A' (wvtFunc k m) y **using**
assms(4) **by** *auto*
hence ($\exists \delta > 0 . \forall p . (p \text{ within } \delta \text{ of } y) \longrightarrow (\text{definedAt } (\text{wvtFunc } k \ m) \ p)$)
using *sublemma4*[of wvtFunc k m A' y] **by** *auto*
then obtain d **where** d: ($d > 0$) \wedge ($\forall p .$
 $(p \text{ within } d \text{ of } y) \longrightarrow (\text{definedAt } (\text{wvtFunc } k$
m) p))
by *auto*
hence *dpos*: $d > 0$ **by** *auto*

define *Ball* **where** *Ball*: *Ball* = *ball* y d

have *l2r*: (*applyToSet* (wvtFunc m k) (*wline* m b)) \cap *Ball* \subseteq (*wline*
k b) \cap *Ball*
using *Ball* **by** *auto*

{ **fix** q
assume q: q \in (*wline* k b) \cap *Ball*
hence q *within* d of y **using** *Ball* *lemSep2Symmetry* **by** *auto*
hence *definedAt* (wvtFunc k m) q **using** d **by** *auto*
hence *qset*: q \in *applyToSet* (wvtFunc m k) (wvt k m q) **by** *auto*

have wvt k m q \subseteq *applyToSet* (wvtFunc k m) (*wline* k b) **using** q
by *auto*
hence wvt k m q \subseteq *wline* m b **by** *auto*
hence *applyToSet* (wvtFunc m k) (wvt k m q)


```

      ⊆ applyToSet (wvtFunc m k) (wline m b) by auto
hence q ∈ applyToSet (wvtFunc m k) (wline m b) using qset by
auto
hence q ∈ (applyToSet (wvtFunc m k) (wline m b)) ∩ Ball using
qset q by auto
}
hence r2l: (wline k b) ∩ Ball ⊆ (applyToSet (wvtFunc m k) (wline
m b)) ∩ Ball
by auto

define lBall where lBall: lBall = (applyToSet (wvtFunc m k) (wline
m b)) ∩ Ball
define rBall where rBall: rBall = (wline k b) ∩ Ball

hence equ: lBall = rBall using l2r r2l lBall rBall by auto

have yinBall: y ∈ Ball using Ball d by auto

have tgt1: y ∈ (applyToSet (wvtFunc m k) (wline m b)) using tgt
by auto
hence y ∈ lBall using yinBall lBall by auto
hence rtp1: y ∈ wline k b using equ rBall by auto

have rtp2: onLine y l' using tgt by auto

have tgt3: accPoint y (applyToSet (wvtFunc m k) (wline m b)) using
tgt by auto
hence tgt3': ∀ ε > 0. ∃ q ∈ (applyToSet (wvtFunc m k) (wline m
b)) . (y ≠ q) ∧ (inBall q ε y)
by auto
{ fix e
assume epos: e > 0
define d1 where d': d1 = min d e
have dd: d1 ≤ d using d' by auto
have de: d1 ≤ e using d' by auto
have d'pos: d1 > 0 using dpos epos d' by auto

then obtain q
where q: q ∈ (applyToSet (wvtFunc m k) (wline m b)) ∧ (y ≠
q) ∧ (inBall q d1 y)
using tgt3' by blast
hence q ∈ (applyToSet (wvtFunc m k) (wline m b)) ∧ (inBall q d
y) ∧ (y ≠ q)
using lemBallInBall[of q y d1 d] d'pos dd by auto
hence q ∈ lBall ∧ (y ≠ q) ∧ (inBall q d1 y)

```

```

    using q Ball lemSep2Symmetry lBall by auto
  hence q ∈ rBall ∧ (y ≠ q) ∧ (inBall q e y)
    using lemBallInBall[of q y d1 e] d'pos de equ by auto

  hence ∃ q ∈ rBall . (y ≠ q) ∧ (inBall q e y) by auto
}
hence rtp3: ∀ e > 0. ∃ q ∈ wline k b . (y ≠ q) ∧ (inBall q e y)
using rBall by auto

have tgt4: (∃ p . ((onLine p l') ∧ (p ≠ y) ∧
  (∀ ε > 0 . ∃ δ > 0 . ∀ y' ∈ (applyToSet (wvtFunc m k) (wline
m b)). (
    (y' within δ of y) ∧ (y' ≠ y) )
    →
    (∃ r . ((onLine r (lineJoining y y')) ∧ (r within ε of p))))
  )) using tgt by auto
then obtain p where p: ((onLine p l') ∧ (p ≠ y) ∧
  (∀ ε > 0 . ∃ δ > 0 . ∀ y' ∈ (applyToSet (wvtFunc m k) (wline
m b)). (
    (y' within δ of y) ∧ (y' ≠ y) )
    →
    (∃ r . ((onLine r (lineJoining y y')) ∧ (r within ε of p))))
  )) by auto
have p1: onLine p l' using p by auto
have p2: p ≠ y using p by auto
{ fix e
  assume epos: e > 0
  then obtain d2 where d2: (d2 > 0) ∧
  (∀ y' ∈ (applyToSet (wvtFunc m k) (wline m b)). (
    (y' within d2 of y) ∧ (y' ≠ y) )
    →
    (∃ r . ((onLine r (lineJoining y y')) ∧ (r within e of p))))
  ) using p by auto
  hence d2pos: d2 > 0 by auto

  define dm where dm: dm = min d2 d
  have dmd2: dm ≤ d2 using dm by auto
  have dmd: dm ≤ d using dm by auto
  have dmpos: dm > 0 using dpos d2pos dm by auto

  { fix y'
    assume y': (y' ∈ wline k b) ∧ (y' within dm of y) ∧ (y' ≠ y)
    hence ydm: y' within dm of y by auto
    hence y' within d of y using dmpos dmd lemBallInBall[of y' y
dm d] by auto
    hence y' ∈ Ball using Ball lemSep2Symmetry by auto
    hence y' ∈ rBall using y' rBall by auto

```

hence $yL: y' \in lBall$ **using** *equ* **by** *auto*
have y' *within* $d2$ *of* y
using *ydm dmpos dmd2 lemBallInBall*[*of* $y' y dm d2$] **by** *auto*
hence $y' \in (applyToSet (wvtFunc m k) (wline m b)) \wedge (y' \text{ within } d2 \text{ of } y) \wedge (y' \neq y)$
using $y' yL lBall$ **by** *auto*
hence $\exists r . ((onLine r (lineJoining y y')) \wedge (r \text{ within } e \text{ of } p))$
using $d2$ **by** *auto*
}
hence $\exists dm > 0 . \forall y' \in (wline k b) .$
 $(y' \text{ within } dm \text{ of } y) \wedge (y' \neq y)$
 $\rightarrow (\exists r . ((onLine r (lineJoining y y')) \wedge (r \text{ within } e$
of $p)))$
using *dmpos* **by** *blast*
}
hence $\forall e > 0 . \exists dm > 0 . \forall y' \in (wline k b) .$
 $(y' \text{ within } dm \text{ of } y) \wedge (y' \neq y)$
 $\rightarrow (\exists r . ((onLine r (lineJoining y y')) \wedge (r \text{ within } e$
of $p)))$
by *auto*
hence *rtp4*: $\exists p . ((onLine p l') \wedge (p \neq y) \wedge (\forall e > 0 . \exists dm > 0 . \forall y' \in (wline k b) .$
 $(y' \text{ within } dm \text{ of } y) \wedge (y' \neq y)$
 $\rightarrow (\exists r . ((onLine r (lineJoining y y')) \wedge (r \text{ within } e$
of $p))))))$
using $p1 p2$ **by** *auto*
hence *tangentLine* $l' (wline k b) y$ **using** *rtp1 rtp2 rtp3 rtp4* **by**
blast
thus *?thesis* **by** *auto*
qed

lemma *lemTangentLines*:

assumes *affineApprox* $A (wvtFunc m k) x$
and $tl l m b x$
and *applyAffineToLine* $A l l'$
and $wvtFunc m k x y$
shows $tl l' k b y$
proof –
have *pres*: $x \in wline m b$
 $\rightarrow tangentLine l (wline m b) x$
 $\rightarrow affineApprox A (wvtFunc m k) x$
 $\rightarrow wvtFunc m k x y$
 $\rightarrow applyAffineToLine A l l'$
 $\rightarrow tangentLine l' (wline k b) y$

using *lemPresentation*[*of x m b l k A y l'*]
by *blast*

have 1: $x \in \text{wline } m \ b$ **using** *assms(2)* **by** *auto*
have 2: *tangentLine* l (*wline* $m \ b$) x **using** *assms(2)* **by** *auto*
have 3: *affineApprox* A (*wvtFunc* $m \ k$) x **using** *assms(1)* **by** *simp*
have 4: *wvtFunc* $m \ k \ x \ y$ **using** *assms(4)* **by** *simp*
have 5: *applyAffineToLine* $A \ l \ l'$ **using** *assms(3)* **by** *simp*

have *tangentLine* l' (*wline* $k \ b$) y **using** *pres 1 2 3 4 5* **by** *meson*
thus *?thesis* **by** *auto*
qed

lemma *lemSelfTangentIsTimeAxis*:

assumes *tangentLine* l (*wline* $k \ k$) x

shows $l = \text{timeAxis}$

proof –

define s **where** $s = \text{wline } k \ k$

hence $s \subseteq \text{timeAxis}$ **using** $s \text{ AxSelfMinus}$ **by** *blast*

hence $x \text{ OnAxis}$: *onTimeAxis* x **using** *assms(1)* s **by** *auto*

have x : $(x \in s) \wedge (\text{onLine } x \ l) \wedge (\text{accPoint } x \ s)$
 $\wedge (\exists p . ((\text{onLine } p \ l) \wedge (p \neq x) \wedge$
 $(\forall \varepsilon > 0 . \exists \delta > 0 . \forall z \in s . ($
 $(z \text{ within } \delta \text{ of } x) \wedge (z \neq x))$
 \longrightarrow
 $(\exists r . ((\text{onLine } r \ (\text{lineJoining } x \ z)) \wedge (r \text{ within } \varepsilon \text{ of } p))))$

))) **using** $s \text{ assms(1)}$ **by** *auto*

then obtain p **where**

p : $(\text{onLine } p \ l) \wedge (p \neq x) \wedge$
 $(\forall \varepsilon > 0 . \exists \delta > 0 . \forall z \in s . ($
 $(z \text{ within } \delta \text{ of } x) \wedge (z \neq x))$
 \longrightarrow
 $(\exists r . ((\text{onLine } r \ (\text{lineJoining } x \ z)) \wedge (r \text{ within } \varepsilon \text{ of } p))))$
)) **by** *auto*

have accxs : *accPoint* $x \ s$ **using** x **by** *auto*

define $p0$ **where**

$p0$: $p0 = (\text{ tval} = \text{tval } p, \text{ xval} = 0, \text{ yval} = 0, \text{ zval} = 0 \text{ })$

hence $p0 \text{ OnAxis}$: *onTimeAxis* $p0$ **by** *auto*

define dp **where** $dp = \text{sep2 } p \ p0$

have $pp0$: $dp = \text{sqr } (tval\ p0 - tval\ p) + \text{sqr } (xval\ p0 - xval\ p) +$
 $\text{sqr } (yval\ p0 - yval\ p) + \text{sqr } (zval\ p0 - zval\ p)$
using $dp\ p0$ **by** *simp*
moreover **have** $\dots = \text{sqr } (xval\ p) + \text{sqr } (yval\ p) + \text{sqr } (zval\ p)$
using $p0$ **by** *auto*
ultimately **have** $dpval$: $dp = \text{sqr } (xval\ p) + \text{sqr } (yval\ p) + \text{sqr } (zval$
 $p)$
using dp **by** *simp*

define e **where** e : $e = (\text{min } dp\ 1) / 2$
define $e2$ **where** $e2$: $e2 = \text{sqr } e$
have $e2le dp$: $e2 \leq dp$
proof –
have $m\text{small}$: $0 \leq (\text{min } dp\ 1) \leq 1$ **using** *lemNorm2NonNeg* dp
by *auto*
hence $e\text{small}$: $0 \leq e < 1$ **using** $e\ leI$ **by** *force*
hence $e2lte$: $e2 \leq e$ **using** $e2\ \text{mult-left-le}$ **by** *force*

have $m\text{range}$: $0 \leq (\text{min } dp\ 1) \leq dp$ **using** *lemNorm2NonNeg* dp
by *auto*
hence $e \leq dp/2$ **using** $e\ \text{divide-right-mono}\ \text{zero-le-numeral}$ **by**
blast
hence $e \leq dp$ **using** $m\text{small}\ e\ \text{add-increasing2}\ \text{divide-nonneg-nonneg}$

 $\text{le-cases}\ \text{lemSumOfTwoHalves}\ \text{min-def}\ \text{zero-le-numeral}$
by *metis*

thus $?thesis$ **using** $e2lte$ **by** *auto*
qed

have $offaxis$: $\forall z . (dp > 0) \wedge \text{onTimeAxis } z \longrightarrow \neg (z\ \text{within } e\ \text{of}$
 $p)$
proof –
{ **fix** z
{ **assume** z : $(dp > 0) \wedge \text{onTimeAxis } z$

have $sep2\ z\ p = \text{sqr } (tval\ z - tval\ p)$
 $+ \text{sqr } (xval\ z - xval\ p)$
 $+ \text{sqr } (yval\ z - yval\ p)$
 $+ \text{sqr } (zval\ z - zval\ p)$ **using** $p0$ **by** *simp*
moreover **have** $\dots = sep2\ z\ p0$
 $+ \text{sqr } (xval\ p) + \text{sqr } (yval\ p) + \text{sqr } (zval\ p)$
using $p0\ z$ **by** *auto*
moreover **have** $\dots = sep2\ z\ p0 + dp$
using $dpval\ \text{add-assoc}$
by *presburger*
moreover **have** $\dots \geq dp$ **using** *lemNorm2NonNeg* **by** *simp*
ultimately **have** $sep2\ z\ p \geq e2$

```

    using e2ledp dual-order.trans by presburger
  }
  hence (0 < dp) ∧ onTimeAxis z → ¬ (z within e of p)
    using e2 by auto
  }
  thus ?thesis by auto
qed

{ assume dpnz: dp > 0

  hence enz: e > 0 using e by auto
  then obtain d where d: (d > 0) ∧ (∀ z ∈ s. (
    (z within d of x) ∧ (z ≠ x) )
    →
    (∃ r . ((onLine r (lineJoining x z)) ∧ (r within e of p))))
    using p by blast

  obtain q where q: (q ∈ s) ∧ (x ≠ q) ∧ (inBall q d x)
    using accxs dpnz enz d by blast

  hence qOnAxis: q ∈ timeAxis using s AxSelfMinus by blast

  have qprops: (q within d of x) ∧ (q ≠ x) using q by auto
  then obtain r where r: (onLine r (lineJoining x q)) ∧ (r within
e of p)
    using d q by blast

  have x ≠ q using q by auto
  moreover have onLine x timeAxis using xOnAxis lemTimeAxisIsLine by auto
  moreover have onLine q timeAxis using qOnAxis lemTimeAxisIsLine by auto
  ultimately have timeAxis = lineJoining x q
    using lemLineAndPoints[of x q timeAxis]
    by auto
  hence rOnAxis: (onTimeAxis r) using r by auto

  hence ¬ (r within e of p) using offaxis dpnz by blast

  hence False using r by blast
}
hence ¬ (dp > 0) ∧ (dp ≥ 0) using lemNorm2NonNeg dp by auto
hence dp = 0 by auto
hence p = p0 using dp lemNullImpliesOrigin[of p ⊖ p0] by auto

hence onLine p timeAxis using p0OnAxis lemTimeAxisIsLine by
auto

```

moreover have *onLine x timeAxis* **using** *xOnAxis lemTimeAxisIsLine* **by** *auto*
moreover have *pnotx: p ≠ x* **using** *p* **by** *blast*
ultimately have *xp: timeAxis = lineJoining x p*
using *lemLineAndPoints[of x p timeAxis]*
by *auto*

have *onLine p l* **using** *p* **by** *auto*
moreover have *onLine x l* **using** *x* **by** *auto*
ultimately have *l = lineJoining x p*
using *lemLineAndPoints[of x p l] pnotx*
by *auto*

hence *timeAxis = l* **using** *xp* **by** *auto*
thus *?thesis* **using** *s* **by** *blast*
qed

lemma *lemTangentLineUnique:*

assumes *tl l1 m k x*
and *tl l2 m k x*
and *affineApprox A (wvtFunc m k) x*
and *wvtFunc m k x y*
and *x ∈ wline m k*
shows *l1 = l2*
proof –

define *L1* **where** *L1: L1 = applyToSet (asFunc A) l1*
define *L2* **where** *L2: L2 = applyToSet (asFunc A) l2*

define *p1* **where** *p1: p1 = (x ∈ wline m k)*
define *p2a* **where** *p2a: p2a = tangentLine l1 (wline m k) x*
define *p2b* **where** *p2b: p2b = tangentLine l2 (wline m k) x*
define *p3* **where** *p3: p3 = affineApprox A (wvtFunc m k) x*
define *p4* **where** *p4: p4 = wvtFunc m k x y*
define *p5a* **where** *p5a: p5a = applyAffineToLine A l1 L1*
define *p5b* **where** *p5b: p5b = applyAffineToLine A l2 L2*

define *tgt1* **where** *tgt1: tgt1 = tangentLine L1 (wline k k) y*
define *tgt2* **where** *tgt2: tgt2 = tangentLine L2 (wline k k) y*

have *pre1: p1* **using** *p1* *assms(5)* **by** *auto*
have *pre2a: p2a* **using** *p2a* *assms(1)* **by** *auto*
have *pre2b: p2b* **using** *p2b* *assms(2)* **by** *auto*
have *pre3: p3* **using** *p3* *assms(4)* **using** *assms(3)* **by** *auto*
have *pre4: p4* **using** *p4* *assms(4)* **by** *auto*

have *isLine l1* **using** *assms(1)* **by** *auto*
hence *pre5a: p5a* **using** *p5a* *L1* *assms(3)* *lemAffineOfLineIsLine[of*

```

l1 A L1] by auto

have isLine l2 using assms(2) by auto
hence pre5b: p5b using p5b L2 assms(3) lemAffineOfLineIsLine[of
l2 A L2] by auto

have [[ p1; p2a; p3; p4; p5a ]] ==> tgt1
  using p1 p2a p3 p4 p5a tgt1 lemPresentation[of x m k l1 k A y L1]
  by fast
hence tgt1 using pre1 pre2a pre3 pre4 pre5a by auto
hence L1axis: L1 = timeAxis using tgt1 lemSelfTangentIsTimeAxis
by auto

have [[ p1; p2b; p3; p4; p5b ]] ==> tgt2
  using p1 p2b p3 p4 p5b tgt2 lemPresentation[of x m k l2 k A y L2]
  by fast
hence tgt2 using pre1 pre2b pre3 pre4 pre5b by auto
hence L2 = timeAxis using tgt2 lemSelfTangentIsTimeAxis by auto

hence L1L2: L1 = L2 using L1axis by auto

obtain A' where A': (affine A') ∧ (∀ p q . A p = q ↔ A' q = p)
  using assms(3) lemInverseAffine[of A] by auto
{ fix p
  define q where q: q = A p
  hence A'q: A' q = p using A' by auto

  { assume p ∈ l1
    hence q ∈ L2 using q L1 L1L2 by auto
    then obtain p2 where p2: q = A p2 ∧ p2 ∈ l2 using L2 by
auto
    hence A' q = p2 using A' by auto
    hence p = p2 using A'q by auto
    hence p ∈ l2 using p2 by auto
  }
  hence l2r: p ∈ l1 → p ∈ l2 by blast

  { assume p ∈ l2
    hence q ∈ L1 using q L2 L1L2 by auto
    then obtain p1 where p1: q = A p1 ∧ p1 ∈ l1 using L1 by
auto
    hence A' q = p1 using A' by auto
    hence p = p1 using A'q by auto
    hence p ∈ l1 using p1 by auto
  }
  hence p ∈ l2 → p ∈ l1 by blast

```



```

    hence  $p \in l1 \iff p \in l2$  using l2r by auto
  }

  thus ?thesis by blast
qed

```

```
end
```

```
end
```

25 Proposition2

This theory shows that affine approximations map surfaces of cones to (subsets of) surfaces of cones.

```

theory Proposition2
  imports TangentLineLemma
begin

```

```

class Proposition2 = TangentLineLemma
begin

```

```

lemma lemProposition2:
  assumes affineApprox  $A$  (wvtFunc  $m$   $k$ )  $x$ 
  shows applyToSet (asFunc  $A$ ) (coneSet  $m$   $x$ )  $\subseteq$  coneSet  $k$  ( $A$   $x$ )
proof -

```

```

  define y where  $y = A$   $x$ 
  define lhs where lhs: lhs = applyToSet (asFunc  $A$ ) (coneSet  $m$   $x$ )
  define rhs where rhs: rhs = coneSet  $k$   $y$ 

```

```

  have mkxy: wvtFunc  $m$   $k$   $x$   $y$ 
    using assms lemAffineEqualAtBase[of wvtFunc  $m$   $k$   $A$   $x$ ]  $y$ 
    by auto
  have affA: affine  $A$  using assms by auto

```

```

  { fix  $q$ 
    { assume  $q \in$  lhs
      hence  $\exists p . (p \in$  coneSet  $m$   $x$ )  $\wedge$  (asFunc  $A$ )  $p$   $q$  using lhs by
auto
      then obtain  $p$  where
         $p \in$  coneSet  $m$   $x$   $\wedge$  (asFunc  $A$ )  $p$   $q$ 
        by presburger
    }
  }

```

hence $qAp: q = A p$ **using** $affA$ **by** $auto$
have $cone\ m\ x\ p$ **using** p **by** $auto$
then obtain l **where**
 $l: (onLine\ p\ l) \wedge (onLine\ x\ l) \wedge (\exists\ ph.\ Ph\ ph \wedge tl\ l\ m\ ph\ x)$
by $auto$
then obtain ph **where** $ph: Ph\ ph \wedge tl\ l\ m\ ph\ x$ **by** $auto$
have $lineL: isLine\ l$ **using** l **by** $auto$
have $tll: tl\ l\ m\ ph\ x$ **using** ph **by** $auto$

define l' **where** $l': l' = applyToSet\ (asFunc\ A)\ l$
hence $aatl: applyAffineToLine\ A\ l\ l'$
using $lineL\ affA\ lemAffineOfLineIsLine[of\ l\ A\ l']$
by $simp$

hence $tll': tl\ l'\ k\ ph\ y$
using $assms(1)\ tll\ mkxy$
 $lemTangentLines[of\ m\ k\ A\ x\ ph\ l\ l'\ y]$
by $simp$

hence $(Ph\ ph \wedge tl\ l'\ k\ ph\ y)$
using ph **by** $auto$
hence $exPh: \exists\ ph.\ (Ph\ ph \wedge tl\ l'\ k\ ph\ y)$
using $exI[of\ \lambda\ b.\ (Ph\ b \wedge tl\ l'\ k\ b\ y)\ ph]$
by $auto$

have $p \in l$ **using** l **by** $auto$
hence $q \in l'$ **using** $qAp\ q\ l'$ **by** $auto$
moreover have $lineL': isLine\ l'$ **using** tll' **by** $auto$
ultimately have $qonl': onLine\ q\ l'$ **by** $auto$

hence $(onLine\ q\ l') \wedge (onLine\ y\ l') \wedge (\exists\ ph.\ Ph\ ph \wedge tl\ l'\ k\ ph$
 $y)$
using $exPh\ tll'$ **by** $blast$

hence $q \in rhs$ **using** $y\ tll'\ rhs$ **by** $auto$
 $\}$
hence $q \in lhs \longrightarrow q \in rhs$ **by** $auto$
 $\}$
hence $l2r: lhs \subseteq rhs$ **by** $auto$
thus $?thesis$ **using** $lhs\ rhs\ y$ **by** $auto$
qed

end

end

26 AXIOM: AxEventMinus

This theory declares the axiom AxEventMinus

```
theory AxEventMinus
  imports WorldView
begin
```

AxEventMinus: An observer encounters the events in which they are observed.

```
class axEventMinus = WorldView
begin
```

```
  abbreviation axEventMinus :: Body  $\Rightarrow$  Body  $\Rightarrow$  'a Point  $\Rightarrow$  bool
    where axEventMinus m k p  $\equiv$  (m sees k at p)
       $\longrightarrow$  ( $\exists$  q .  $\forall$  b . (m sees b at p)  $\longleftrightarrow$  (k sees b at q))
```

end

```
class AxEventMinus = axEventMinus +
  assumes AxEventMinus:  $\forall$  m k p . axEventMinus m k p
begin
end
```

end

27 Proposition3

This theory collects together earlier results to show that world-view transformations can be approximated by affine transformations that have various useful properties.

```
theory Proposition3
  imports Proposition1 Proposition2 AxEventMinus
begin
```

```
class Proposition3 = Proposition1 + Proposition2 + AxEventMinus
begin
```

lemma *lemProposition3*:

assumes *m sees k at x*

shows $\exists A y . (wvtFunc\ m\ k\ x\ y)$
 \wedge $(affineApprox\ A\ (wvtFunc\ m\ k)\ x)$
 \wedge $(applyToSet\ (asFunc\ A)\ (coneSet\ m\ x) \subseteq coneSet\ k\ y)$
 \wedge $(coneSet\ k\ y = regularConeSet\ y)$

proof –

define *g1* **where** *g1*: *g1* = $(\lambda y . wvtFunc\ m\ k\ x\ y)$

define *g2* **where** *g2*: *g2* = $(\lambda A . affineApprox\ A\ (wvtFunc\ m\ k)\ x)$

define *g3* **where** *g3*: *g3* = $(\lambda A y . applyToSet\ (asFunc\ A)\ (coneSet\ m\ x) \subseteq coneSet\ k\ y)$

define *g4* **where** *g4*: *g4* = $(\lambda y . coneSet\ k\ y = regularConeSet\ y)$

have *axEventMinus m k x* **using** *AxEventMinus* **by** *simp*

hence $(\exists q . \forall b . (m\ sees\ b\ at\ x) \longleftrightarrow (k\ sees\ b\ at\ q))$
using *assms* **by** *simp*

then obtain *y* **where** *y*: $\forall b . (m\ sees\ b\ at\ x) \longleftrightarrow (k\ sees\ b\ at\ y)$ **by** *auto*

hence *ev m x = ev k y* **by** *blast*

hence *goal1*: *g1 y* **using** *assms g1* **by** *auto*

have *axDiff m k x* **using** *AxDiff* **by** *simp*

hence $\exists A . affineApprox\ A\ (wvtFunc\ m\ k)\ x$ **using** *g1 goal1* **by** *blast*

then obtain *A* **where** *goal2*: *g2 A* **using** *g2* **by** *auto*

have $applyToSet\ (asFunc\ A)\ (coneSet\ m\ x) \subseteq coneSet\ k\ (A\ x)$
using *g2 goal2 lemProposition2*[*of m k A x*]
by *auto*

moreover **have** *A x = y*
using *goal1 goal2 g1 g2 lemAffineEqualAtBase*[*of wvtFunc m k A x*]
by *blast*

ultimately **have** *goal3*: *g3 A y* **using** *g3* **by** *auto*

have *k sees k at y* **using** *assms(1) g1 goal1* **by** *fastforce*

hence $\forall p . cone\ k\ y\ p = regularCone\ y\ p$
using *lemProposition1*[*of y k*] **by** *auto*

hence *goal4*: *g4 y* **using** *g4* **by** *force*

hence $\exists A y . (g1\ y) \wedge (g2\ A) \wedge (g3\ A\ y) \wedge (g4\ y)$
using *goal1 goal2 goal3 goal4* **by** *blast*

thus *?thesis* **using** *g1 g2 g3 g4* **by** *fastforce*
qed

end

end

28 ObserverConeLemma

This theory gives sufficient conditions for an observed observer's cone to appear upright to that observer.

theory *ObserverConeLemma*

imports *Proposition3*

begin

class *ObserverConeLemma* = *Proposition3*

begin

lemma *lemConeOfObserved*:

assumes *affineApprox A (wvtFunc m k) x*

and *m sees k at x*

shows *coneSet k (A x) = regularConeSet (A x)*

proof –

have *Ax: $\forall y. (wvtFunc m k x y) \longleftrightarrow (y = A x)$*

using *assms(1) lemAffineEqualAtBase[of (wvtFunc m k) A x]*

by *auto*

define *set1* **where** *set1: set1 = coneSet k (A x)*

define *set2* **where** *set2: set2 = regularConeSet (A x)*

define *P* **where** *P: P = ($\lambda A' y. (wvtFunc m k x y)$*

\wedge *(affineApprox A' (wvtFunc m k) x)*

\wedge *(applyToSet (asFunc A') (coneSet m x) \subseteq coneSet k*

y)

\wedge *(coneSet k y = regularConeSet y))*

have *m sees k at x* **using** *assms(2)* **by** *auto*

hence $\exists A' y. P A' y$ **using** *P lemProposition3[of m k x]* **by** *fast*

then obtain *A' y* **where** *A'y: P A' y* **by** *auto*

have *wvtFunc m k x y* **using** *P A'y* **by** *auto*

hence *y = A x* **using** *Ax* **by** *auto*

moreover have *coneSet k y = regularConeSet y* **using** *A'y P* **by** *auto*

ultimately show *?thesis* **using** *set1 set2* **by** *auto*

qed

end

end

29 Quadratics

This theory shows how to find the roots of a quadratic, assuming that roots exist (AxEField).

theory *Quadratics*

imports *Functions AxEField*

begin

class *Quadratics* = *Functions* + *AxEField*

begin

abbreviation *quadratic* :: 'a \Rightarrow 'a \Rightarrow 'a \Rightarrow ('a \Rightarrow 'a)

where *quadratic* a b c \equiv λ x . a*(sqr x) + b*x + c

abbreviation *root* :: 'a \Rightarrow 'a \Rightarrow 'a \Rightarrow 'a \Rightarrow bool

where *root* a b c r \equiv (*quadratic* a b c) r = 0

abbreviation *roots* :: 'a \Rightarrow 'a \Rightarrow 'a \Rightarrow 'a set

where *roots* a b c \equiv { r . *root* a b c r }

abbreviation *discriminant* :: 'a \Rightarrow 'a \Rightarrow 'a \Rightarrow 'a

where *discriminant* a b c \equiv (sqr b) - 4*a*c

abbreviation *qcase1* :: 'a \Rightarrow 'a \Rightarrow 'a \Rightarrow bool

where *qcase1* a b c \equiv (a = 0 \wedge b = 0 \wedge c = 0)

abbreviation *qcase2* :: 'a \Rightarrow 'a \Rightarrow 'a \Rightarrow bool

where *qcase2* a b c \equiv (a = 0 \wedge b = 0 \wedge c \neq 0)

abbreviation *qcase3* :: 'a \Rightarrow 'a \Rightarrow 'a \Rightarrow bool

where *qcase3* a b c \equiv (a = 0 \wedge b \neq 0 \wedge (c = 0 \vee c \neq 0))

abbreviation *qcase4* :: 'a \Rightarrow 'a \Rightarrow 'a \Rightarrow bool

where *qcase4* a b c \equiv (a \neq 0 \wedge *discriminant* a b c < 0)

abbreviation *qcase5* :: 'a \Rightarrow 'a \Rightarrow 'a \Rightarrow bool

where *qcase5* a b c \equiv (a \neq 0 \wedge *discriminant* a b c = 0)

abbreviation *qcase6* :: 'a \Rightarrow 'a \Rightarrow 'a \Rightarrow bool

where *qcase6* a b c \equiv (a \neq 0 \wedge *discriminant* a b c > 0)

lemma *lemQuadRootCondition*:

assumes a \neq 0

shows (sqr (2*a*r + b) = *discriminant* a b c) \longleftrightarrow *root* a b c r

proof –

have $\text{sqr } (2*a*r) = (4*a) * (a * \text{sqr } r)$
using *lemSqrMult local.numeral-sqr mult-assoc sqr.simps(1) sqr.simps(2)*
by *metis*
moreover have $2*(2*a*r)*b = (4*a) * (b*r)$
by (*metis dbl-def dbl-simps(5) mult.left-commute mult-2 mult-2-right mult-assoc*)
ultimately have $s: \text{sqr } (2*a*r) + 2*(2*a*r)*b = (4*a) * ((a * \text{sqr } r) + b * r)$
by (*simp add: local.distrib-left*)

have $\text{sqr}(2*a*r + b) = \text{sqr } (2*a*r) + 2*(2*a*r)*b + \text{sqr } b$
using *lemSqrSum* **by** *auto*
moreover have $\dots = (4*a) * ((a * \text{sqr } r) + b * r) + \text{sqr } b$ **using**
s **by** *auto*
moreover have $\dots = (4*a) * ((a * \text{sqr } r) + b * r + c) - (4*a)*c$
 $+ \text{sqr } b$
by (*simp add: distrib-left*)
ultimately have $\text{eqn1}: \text{sqr}(2*a*r + b) = (4*a)*(quadratic a b c r)$
 $+ (discriminant a b c)$
by (*simp add: add-diff-eq diff-add-eq*)

{ **assume** $\text{groot } a b c r$
hence $\text{sqr } (2*a*r + b) = \text{discriminant } a b c$ **using** *eqn1* **by** *simp*
}
hence $\text{l2r}: \text{groot } a b c r \longrightarrow \text{sqr } (2*a*r + b) = \text{discriminant } a b c$
by *auto*

{ **assume** $\text{sqr } (2*a*r + b) = \text{discriminant } a b c$
hence $0 = (4*a)*(quadratic a b c r)$ **using** *eqn1* **by** *auto*
hence $\text{groot } a b c r$ **by** (*metis assms divisors-zero zero-neq-numeral*)
}
hence $(\text{sqr } (2*a*r + b) = \text{discriminant } a b c) \longrightarrow \text{groot } a b c r$ **by**
blast

thus *?thesis* **using** *l2r* **by** *blast*

qed

lemma *lemQuadraticCasesComplete*:

shows $\text{qcase1 } a b c \vee \text{qcase2 } a b c \vee \text{qcase3 } a b c \vee \text{qcase4 } a b c \vee$
 $\text{qcase5 } a b c \vee \text{qcase6 } a b c$
using *not-less-iff-gr-or-eq* **by** *blast*

lemma *lemQCase1*:

assumes $\text{qcase1 } a b c$
shows $\forall r . \text{groot } a b c r$
using *assms* **by** *simp*

```

lemma lemQCase2:
  assumes qcase2 a b c
  shows  $\neg (\exists r . \text{groot } a \ b \ c \ r)$ 
  by (simp add: assms)

```

```

lemma lemQCase3:
  assumes qcase3 a b c
  shows  $\text{groot } a \ b \ c \ r \longleftrightarrow r = -c/b$ 
proof -
  have  $\text{groot } a \ b \ c \ r \longrightarrow r = -c/b$ 
  proof -
    { assume hyp:  $\text{groot } a \ b \ c \ r$ 
      hence  $b*r + c = 0$  using assms by auto
      hence  $b*r = -c$  by (simp add: local.eq-neg-iff-add-eq-0)
      hence  $r = -c/b$  by (metis assms local.nonzero-mult-div-cancel-left)
    }
    thus ?thesis by auto
  qed
  moreover have  $r = -c/b \longrightarrow \text{groot } a \ b \ c \ r$  by (simp add: assms)
  ultimately show ?thesis by blast
qed

```

```

lemma lemQCase4:
  assumes qcase4 a b c
  shows  $\neg (\exists r . \text{groot } a \ b \ c \ r)$ 
proof -
  have props:  $(a \neq 0 \wedge \text{discriminant } a \ b \ c < 0)$  using assms by auto
  { assume hyp:  $\exists r . \text{groot } a \ b \ c \ r$ 
    then obtain r where  $r: \text{groot } a \ b \ c \ r$  by auto
    hence  $\text{sqr } (2 * a * r + b) = \text{discriminant } a \ b \ c$ 
      using props lemQuadRootCondition[of a r b c] by auto
    hence  $\text{sqr } (2*a*r + b) < 0$  using props by auto
    hence False using lemSquaresPositive by auto
  }
  thus ?thesis by auto
qed

```

```

lemma lemQCase5:
  assumes qcase5 a b c
  shows  $\text{groot } a \ b \ c \ r \longleftrightarrow r = -b/(2*a)$ 
proof -

```



```

have qroot a b c r  $\longrightarrow r = -b/(2*a)$ 
proof -
  { assume hyp: qroot a b c r
    hence sqr (2 * a * r + b) = 0
      using assms lemQuadRootCondition[of a r b c] by auto
    hence  $2*a*r + b = 0$  by simp
    hence  $2*a*r = -b$  using local.eq-neg-iff-add-eq-0 by auto
    moreover have  $2*a \neq 0$  using assms by auto
    ultimately have  $r = ((-b)/(2*a))$  by (metis local.nonzero-mult-div-cancel-left)
  }
  thus ?thesis by auto
qed
moreover have  $r = -b/(2*a) \longrightarrow$  qroot a b c r
proof -
  { assume hyp: r = -b/(2*a)
    hence  $(2*a)*r + b = \text{discriminant } a \ b \ c$  by (simp add: assms)
    hence qroot a b c r using lemQuadRootCondition[of a r b c]
assms by auto
  }
  thus ?thesis by auto
qed
ultimately show ?thesis by blast
qed

```

```

lemma lemQCase6:
  assumes qcase6 a b c
  and rd = sqrt (discriminant a b c)
  and rp = ((-b) + rd) / (2*a)
  and rm = ((-b) - rd) / (2*a)
  shows  $(rp \neq rm) \wedge \text{roots } a \ b \ c = \{ rp, rm \}$ 
proof -
  define d where d: d = discriminant a b c

```

```

  have dpos: d > 0 using assms d by auto
  hence rootd: hasUniqueRoot d using AxEField lemSqrt[of d] by
auto
  hence rdprops: 0 ≤ rd ∧ d = sqr rd
    using assms(2) d theI'[of isNonNegRoot d] by auto
  hence rdnot0: rd ≠ 0 using assms dpos mult-nonneg-nonpos by
auto
  hence rdpos: rd > 0 using rdprops by auto

```

```

  define pp where pp: pp = (-b) + rd
  define mm where mm: mm = (-b) - rd
  have  $rd \neq -rd$  using rdnot0 by simp
  hence  $pp \neq mm$  using pp mm add-left-imp-eq[of -b rd -rd] by

```

auto
moreover have $aa: 2*a \neq 0$ **using** *assms* **by** *auto*
ultimately have $pp/(2*a) \neq mm/(2*a)$ **by** *auto*
hence *conj1*: $rp \neq rm$ **using** *assms pp mm* **by** *simp*

have *conj2*: $roots\ a\ b\ c = \{rp, rm\}$
proof –
{ **fix** *r* **assume** $r \in roots\ a\ b\ c$
hence $sqr\ (2*a*r + b) = d$
using *assms lemQuadRootCondition d* **by** *auto*
hence $sqr\ d = abs\ (2*a*r + b)$ **using** *lemSqrOfSquare* **by** *blast*
moreover have $sqr\ d = rd$ **using** *d assms* **by** *auto*
ultimately have *rdprops*: $rd = abs\ (2*a*r + b)$ **by** *auto*

define $v :: 'a$ **where** $v: v = 2*a*r + b$
hence *vnot0*: $v \neq 0$ **using** *rdprops rdnnot0* **by** *simp*
hence *cases*: $(v < 0) \vee (v > 0)$ **by** *auto*

{ **assume** $v < 0$
hence $2*a*r + b = -rd$ **using** *v rdprops*
by (*metis local.abs-if local.minus-minus*)
hence $2*a*r = (-b) - rd$
by (*metis local.add-diff-cancel-right' local.minus-diff-commute*)
hence $r = rm$ **using** *aa assms(4)*
by (*metis local.nonzero-mult-div-cancel-left*)
}

hence *case1*: $v < 0 \longrightarrow r = rm$ **by** *auto*

{ **assume** $v > 0$
hence $2*a*r + b = rd$ **using** *v rdprops* **by** *simp*
hence $2*a*r = (-b) + rd$ **by** *auto*
hence $r = rp$ **using** *aa assms(3)*
by (*metis local.nonzero-mult-div-cancel-left*)
}

hence $v > 0 \longrightarrow r = rp$ **by** *auto*

hence $r = rm \vee r = rp$ **using** *case1 cases* **by** *blast*
hence $r \in \{rm, rp\}$ **by** *blast*

}

hence $\forall r. r \in roots\ a\ b\ c \longrightarrow r \in \{rm, rp\}$ **by** *blast*
hence *l2r*: $roots\ a\ b\ c \subseteq \{rm, rp\}$ **by** *auto*

have *rootm*: $root\ a\ b\ c\ rm$
proof –
have $rm = ((-b) - rd) / (2*a)$ **using** *assms* **by** *auto*
hence $(2*a)*rm = (-b) - rd$ **using** *aa* **by** *simp*
hence $(2*a)*rm + b = -rd$ **by** (*simp add: local.diff-add-eq*)
hence $sqr\ ((2*a)*rm + b) = sqr\ rd$ **by** *simp*
moreover have $\dots = discriminant\ a\ b\ c$

```

    using assms(2) rootd d lemSquareOfSqrt[of discriminant a b c
rd] by auto
    ultimately show ?thesis
    using assms lemQuadRootCondition[of a rm b c] by auto
qed

have rootp: qroot a b c rp
proof -
  have rp = ((-b) + rd) / (2*a) using assms by auto
  hence (2*a)*rp = (-b) + rd using aa by simp
  hence (2*a)*rp + b = rd by (simp add: local.diff-add-eq)
  hence sqr( (2*a)*rp + b ) = sqr rd by simp
  moreover have ... = discriminant a b c
    using assms(2) rootd d lemSquareOfSqrt[of discriminant a b c
rd] by auto
  ultimately show ?thesis
    using assms lemQuadRootCondition[of a rp b c] by auto
qed

hence {rm, rp} ⊆ qroots a b c using rootm rootp by auto
thus ?thesis using l2r by blast
qed

thus ?thesis using conj1 by blast
qed

```

```

lemma lemQuadraticRootCount:
  assumes ¬(qcase1 a b c)
  shows finite (qroots a b c) ∧ card (qroots a b c) ≤ 2
proof -
  define d where d: d = discriminant a b c

  have case1: qcase1 a b c → ?thesis using assms by auto
  moreover have case2: qcase2 a b c → ?thesis using lemQCase2
by auto
  moreover have case3: qcase3 a b c → ?thesis using lemQCase3
by auto
  moreover have case4: qcase4 a b c → ?thesis using lemQCase4
by auto
  moreover have case5: qcase5 a b c → ?thesis using lemQCase5
by auto
  moreover have case6: qcase6 a b c → ?thesis using lemQCase6
card-2-iff by auto
  ultimately show ?thesis using lemQuadraticCasesComplete by
blast
qed

```

end

end

30 Classification

This theory explains how to establish whether a point lies inside, on or outside a cone.

```
theory Classification  
  imports Cones Quadratics CauchySchwarz  
begin
```

We want to establish where a point lies in relation to a cone, and will later show that this relationship is preserved under relevant affine transformations. We therefore need a classification scheme that relies on purely affine concepts. To do this we consider lines that can be drawn through the point, and ask how many points lie in the intersection of such a line and the cone.

```
class Classification = Cones + Quadratics + CauchySchwarz  
begin
```

```
abbreviation vertex :: 'a Point  $\Rightarrow$  'a Point  $\Rightarrow$  bool  
  where vertex x p  $\equiv$  (x = p)
```

```
abbreviation insideRegularCone :: 'a Point  $\Rightarrow$  'a Point  $\Rightarrow$  bool  
  where insideRegularCone x p  $\equiv$   
    (slopeFinite x p)  $\wedge$  ( $\exists$  v  $\in$  lineVelocity (lineJoining x p) . sNorm2  
    v < 1)
```

```
abbreviation outsideRegularCone :: 'a Point  $\Rightarrow$  'a Point  $\Rightarrow$  bool  
  where outsideRegularCone x p  $\equiv$   
    (x  $\neq$  p)  $\wedge$   
    ((slopeInfinite x p)  $\vee$  ( $\exists$  v  $\in$  lineVelocity (lineJoining x p) .  
    sNorm2 v > 1))
```

```
abbreviation onRegularCone :: 'a Point  $\Rightarrow$  'a Point  $\Rightarrow$  bool  
  where onRegularCone x p  $\equiv$  (x = p)  $\vee$  ( $\exists$  v  $\in$  lineVelocity (lineJoining  
  x p) . sNorm2 v = 1)
```

lemma *lemDrtnLineJoining*:
assumes $l = \text{lineJoining } x \ p$
and $x \neq p$
shows $(p \ominus x) \in \text{drtn } l$
proof –
define d **where** $d: d = (p \ominus x)$
have $l\text{props}: \text{onLine } x \ l \wedge \text{onLine } p \ l$
using *assms(1)* *lemLineJoiningContainsEndPoints* **by** *blast*
hence $\exists x \ p . (x \neq p) \wedge (\text{onLine } x \ l) \wedge (\text{onLine } p \ l) \wedge (d = (p \ominus x))$
using *assms(2)* d **by** *blast*
thus *?thesis* **using** d **by** *auto*
qed

lemma *lemVelocityLineJoining*:
assumes $l = \text{lineJoining } x \ p$
and $v = \text{velocityJoining origin } (p \ominus x)$
and $x \neq p$
shows $v \in \text{lineVelocity } l$
proof –
define d **where** $d: d = (p \ominus x)$
hence $d \in \text{drtn } l$ **using** *assms* *lemDrtnLineJoining* **by** *auto*
hence $\exists d \in \text{drtn } l . v = \text{velocityJoining origin } d$ **using** *assms* d
by *blast*
thus *?thesis* **by** *auto*
qed

lemma *lemSlopeLineJoining*:
assumes $l = \text{lineJoining } p \ q$
and $p \neq q$
shows $\text{lineSlopeFinite } l \longleftrightarrow \text{slopeFinite } p \ q$
proof –
have $pq: \text{onLine } p \ l \wedge \text{onLine } q \ l$
using *assms(1)* *lemLineJoiningContainsEndPoints* **by** *auto*

have $l2r: \text{lineSlopeFinite } l \longrightarrow \text{slopeFinite } p \ q$
proof –
{ **assume** $\text{lineSlopeFinite } l$
then obtain $x \ y$
where $xy: (\text{onLine } x \ l) \wedge (\text{onLine } y \ l) \wedge (x \neq y) \wedge (\text{slopeFinite } x \ y)$ **by** *blast*
hence $lxy: l = \text{lineJoining } x \ y$ **using** *lemLineAndPoints*[*of* $x \ y \ l$]
}

by *auto*

define *tdiff* **where** *tdiff*: $tdiff = tval\ y - tval\ x$
hence *tdnot0*: $tdiff \neq 0$ **using** *xy* **by** *auto*

obtain *a* **where** $a: p = (x \oplus (a \otimes (y \ominus x)))$ **using** *pql lxy* **by** *auto*
hence *tvalp*: $tval\ p = tval\ x + a * (tval\ y - tval\ x)$ **by** *simp*

obtain *b* **where** $b: q = (x \oplus (b \otimes (y \ominus x)))$ **using** *pql lxy* **by** *auto*
hence *tvalq*: $tval\ q = tval\ x + b * (tval\ y - tval\ x)$ **by** *simp*

have *anotb*: $b - a \neq 0$ **using** *a b assms(2)* **by** *auto*

have $tval\ q - tval\ p = (b - a) * tdiff$
using *tdiff tvalp tvalq*
by (*simp add: local.left-diff-distrib*)
hence *slopeFinite p q* **using** *anotb tdnot0*
by (*metis local.diff-self local.divisors-zero*)

}

thus *?thesis* **by** *auto*

qed

have *r2l*: $slopeFinite\ p\ q \longrightarrow lineSlopeFinite\ l$ **using** *pql assms(2)*
by *blast*

thus *?thesis* **using** *l2r* **by** *blast*

qed

lemma *lemVelocityJoiningUsingPoints*:

assumes $p \neq q$

shows $velocityJoining\ p\ q = velocityJoining\ origin\ (q \ominus p)$

proof –

define *t1* **where** $t1: t1 = tval\ p - tval\ q$

define *t2* **where** $t2: t2 = tval\ origin - tval\ (q \ominus p)$

define *v1* **where** $v1: v1 = (p \ominus q)$

define *v2* **where** $v2: v2 = (origin \ominus (q \ominus p))$

have *ts*: $t1 = t2$ **using** *t1 t2* **by** *simp*

{ **assume** *slopeFinite p q*

hence $(tval\ origin) - (tval\ (q \ominus p)) \neq 0$ **by** *simp*

hence *sf2*: $slopeFinite\ origin\ (q \ominus p)$ **using** *diff-self* **by** *metis*

hence $sloper\ p\ q = sloper\ origin\ (q \ominus p)$ **using** *t2 v2 sloper.simps*

by *auto*

hence *?thesis* **by** *auto*

}

hence *sf*: $slopeFinite\ p\ q \longrightarrow ?thesis$ **by** *auto*

{ **assume** *hyp*: $\neg (slopeFinite\ p\ q)$

hence \neg (*slopeFinite origin (q \ominus p)*) **using** *t1 t2 ts* **by** *simp*
 hence *sloper p q = sloper origin (q \ominus p)* **using** *hyp* **by** *simp*
 hence *?thesis* **by** *auto*
 }
 thus *?thesis* **using** *sf* **by** *blast*
qed

lemma *lemLineVelocityNonZeroImpliesFinite:*

assumes $u \in \text{lineVelocity } l$
and $s\text{Norm2 } u \neq 0$
shows *lineSlopeFinite l*
proof –
have $u \in \{ u . \exists d \in \text{drtn } l . u = \text{velocityJoining origin } d \}$ **using**
assms(1) **by** *auto*
then obtain d **where** $d \in \text{drtn } l \wedge u = \text{velocityJoining origin } d$
by *blast*
hence $d \in \{ d . \exists p q . (p \neq q) \wedge (\text{onLine } p l) \wedge (\text{onLine } q l) \wedge (d = (q \ominus p)) \}$
by *auto*
then obtain $p q$ **where** $pq: (p \neq q) \wedge (\text{onLine } p l) \wedge (\text{onLine } q l)$
 $\wedge (d = (q \ominus p))$
by *blast*

hence $upq: u = \text{velocityJoining } p q$ **using** *lemVelocityJoiningUsingPoints d* **by** *auto*

{ **assume** *slopeInfinite p q*
 hence *sloper p q = origin* **by** *simp*
 hence $u = s\text{Origin}$ **using** upq **by** *simp*
 hence *False* **using** *assms(2)* **by** *auto*
 }
hence *slopeFinite p q* **by** *auto*
thus *?thesis* **using** pq **by** *blast*
qed

lemma *lemLineVelocityUsingPoints:*

assumes *slopeFinite p q*
and $\text{onLine } p l \wedge \text{onLine } q l$
shows $\text{lineVelocity } l = \{ \text{velocityJoining } p q \}$
proof –
define v **where** $v: v = \text{velocityJoining } p q$
hence $v': v = \text{velocityJoining origin } (q \ominus p)$
using *lemVelocityJoiningUsingPoints[of p q]* *assms(1)* **by** *blast*

have $p \neq q$ **using** *assms(1)* **by** *auto*
hence $l = \text{lineJoining } p q$ **using** *lemLineAndPoints[of p q l]* *assms*
by *auto*

hence $vinlv: v \in lineVelocity\ l$
using $lemVelocityLineJoining[of\ l\ p\ q\ v]\ v'\ assms$ **by** $blast$
hence $r2l: \{v\} \subseteq lineVelocity\ l$ **by** $blast$

{ **fix** u **assume** $u: u \in lineVelocity\ l$
hence $u = v$
using $vinlv\ pnotq\ assms\ lemFiniteLineVelocityUnique[of\ u\ l\ v]$ **by**
 $blast$
}
hence $lineVelocity\ l \subseteq \{v\}$ **by** $blast$

thus $?thesis$ **using** $r2l\ v$ **by** $blast$
qed

lemma $lemSNorm2VelocityJoining:$
assumes $slopeFinite\ x\ p$
and $v = velocityJoining\ x\ p$
shows $sqr\ (tval\ p - tval\ x) * sNorm2\ v = sNorm2\ (sComponent\ (p \ominus x))$
proof $-$
have $sloper\ x\ p = ((1 / (tval\ x - tval\ p)) \otimes (x \ominus p))$ **using** $assms(1)$
by $auto$
hence $v = ((1 / (tval\ x - tval\ p)) \otimes s\ (sComponent(x \ominus p)))$ **using**
 $assms(2)$ **by** $simp$
hence $sNorm2\ v = sqr\ (1 / (tval\ x - tval\ p)) * sNorm2\ (sComponent\ (x \ominus p))$
using $lemSNorm2OfScaled\ assms(1)$ **by** $blast$
also **have** $\dots = sqr\ (1 / (tval\ p - tval\ x)) * sNorm2\ (sComponent\ (p \ominus x))$
using $lemSSep2Symmetry\ assms(1)\ lemSqrDiffSymmetrical$ **by**
 $simp$
finally **show** $?thesis$ **using** $assms(1)$ **by** $simp$
qed

lemma $lemOrthogonalSpaceVectorExists:$
shows $\exists w. (w \neq sOrigin) \wedge (w \odot s\ v) = 0$
proof $-$
obtain $x\ y\ z$ **where** $xyz: v = mkSpace\ x\ y\ z$ **using** $Space.cases$ **by**
 $blast$
define w **where** $w: w = (if\ x = 0\ then\ (mkSpace\ 1\ 0\ 0)\ else\ (mkSpace\ (y/x)\ (-1)\ 0))$

have $wnot0: (w \neq sOrigin)$ **using** w **by** $simp$

moreover **have** $orth: (w \odot s\ v) = 0$
proof $-$


```

{ assume x0: x = 0
  hence w = mkSpace 1 0 0 using w by simp
  hence (w ⊙ s v) = 0 using x0 xyz by simp
}
hence case0: x = 0 → ?thesis by blast
{ assume xnot0: x ≠ 0
  hence w = mkSpace (y/x) (-1) 0 using w by simp
  hence (w ⊙ s v) = 0 using xnot0 xyz by simp
}
hence x ≠ 0 → ?thesis by blast
thus ?thesis using case0 by blast
qed
ultimately show ?thesis by force
qed

```

lemma *lemNonParallelVectorsExist*:

```

shows ∃ w . ((w ≠ origin) ∧ (tval v = tval w)) ∧ (¬ (∃ α . (α ≠ 0) ∧ v = (α ⊗ w)))

```

proof –

```

have cases: xval v = 0 ∨ xval v ≠ 0 by auto

```

```

{ assume case1: xval v = 0

```

```

  define diff where diff: diff = (if ((v ⊕ xUnit) = origin) then
(2⊗xUnit) else xUnit)

```

```

  define w where w: w = (v ⊕ diff)

```

```

  hence w1: (xval w) = 1 using case1 diff by auto

```

```

{ assume ∃ α . (α ≠ 0) ∧ v = (α ⊗ w)

```

```

  then obtain a where a: (a ≠ 0) ∧ v = (a ⊗ w) by auto

```

```

  hence xval v = a * xval w by simp

```

```

  hence 0 = a * 1 using case1 w1 by auto

```

```

  hence a = 0 by auto

```

```

  hence False using a by blast

```

```

}

```

```

hence (¬ (∃ α . (α ≠ 0) ∧ v = (α ⊗ w))) by auto

```

```

moreover have tval v = tval w using w diff by auto

```

```

ultimately have (w ≠ origin) ∧ (tval v = tval w) ∧ (¬ (∃ α . (α
≠ 0) ∧ v = (α ⊗ w)))

```

```

  using w1 by auto

```

```

}

```

```

hence lhs: xval v = 0 → ?thesis by blast

```

```

{ assume case2: xval v ≠ 0

```

```

  define w where w: w = (v ⊕ yUnit)

```

```

  hence wx: xval w = xval v using case2 by auto

```

```

  have wy: yval w = yval v + 1 using w by auto

```

```

{ assume ∃ α . (α ≠ 0) ∧ v = (α ⊗ w)

```

then obtain a **where** $a: (a \neq 0) \wedge v = (a \otimes w)$ **by** *auto*
hence $xv: xval\ v = a * xval\ w$ **by** *simp*
hence $a1: xval\ v = a * xval\ v$ **using** wx **by** *simp*
hence $a = 1$ **using** *case2* **by** *simp*
hence $yval\ v = yval\ w$ **using** a **by** *auto*
hence *False* **using** wy **by** *auto*
}
hence $(\neg (\exists \alpha . (\alpha \neq 0) \wedge v = (\alpha \otimes w)))$ **by** *auto*
moreover have $tval\ v = tval\ w$ **using** w **by** *auto*
moreover have $xval\ w \neq 0$ **using** w *case2* **by** *auto*
ultimately have $(w \neq origin) \wedge (tval\ v = tval\ w) \wedge (\neg (\exists \alpha . (\alpha \neq 0) \wedge v = (\alpha \otimes w)))$
by *auto*
}
hence $rhs: xval\ v \neq 0 \longrightarrow ?thesis$ **by** *blast*

thus $?thesis$ **using** *cases lhs* **by** *auto*
qed

lemma *lemConeContainsVertex:*

shows *regularCone* $x\ x$

proof –

define d **where** $d: d = (tUnit \oplus xUnit)$

define p **where** $p: p = (d \oplus x)$

define l **where** $l: l = lineJoining\ x\ p$

define v **where** $v: v = velocityJoining\ origin\ d$

have $xnotp: x \neq p$

proof –

{ **assume** $x = p$

hence $(d \oplus x) = x$ **using** p **by** *auto*

hence $d = origin$ **using** *add-cancel-left-left*

by *(metis dot.simps lemDotSumRight lemNullImpliesOrigin)*

hence *False* **using** d **by** *auto*

}

thus $?thesis$ **by** *auto*

qed

moreover have $d = (p \ominus x)$ **using** p **by** *auto*

ultimately have $vel: v \in lineVelocity\ l$

using $l\ v\ d$ *lemVelocityLineJoining*[of $l\ x\ p\ v$] **by** *blast*

have $lprops: onLine\ x\ l \wedge onLine\ p\ l$

using $xnotp\ l$ *lemLineAndPoints*[of $x\ p\ l$] **by** *auto*

have $slope: sNorm2\ v = 1$

proof –

define sx **where** $sx: sx = (\mid svalx = 1, svaly = 0, svalz = 0 \mid)$

have *slopeFinite* $origin\ d$ **using** d **by** *auto*

hence *sloper origin* $d = ((1 / ((tval\ origin) - (tval\ d))) \otimes (origin \ominus d))$ **by** *simp*
moreover have $\dots = ((-1) \otimes (origin \ominus d))$ **using** *d* **by** *auto*
moreover have $\dots = d$ **by** *auto*
ultimately have *sloper origin* $d = d$ **by** *simp*
hence *velocityJoining origin* $d = sComponent\ d$ **by** *simp*
hence $v = sx$ **using** *v d sx* **by** *auto*
thus *?thesis* **using** *sx* **by** *auto*
qed

hence $v \in lineVelocity\ l \wedge sNorm2\ v = 1$ **using** *vel* **by** *auto*
hence $\exists l . (onLine\ x\ l) \wedge (\exists v \in lineVelocity\ l . sNorm2\ v = 1)$
using *lprops* **by** *blast*
thus *?thesis* **by** *blast*
qed

lemma *lemConesExist*:
shows *regularConeSet* $x \neq \{\}$
proof –
have $x \in regularConeSet\ x$ **using** *lemConeContainsVertex* **by** *auto*
thus *?thesis* **by** *blast*
qed

lemma *lemRegularCone*:
shows $((x = p) \vee onRegularCone\ x\ p) \longleftrightarrow regularCone\ x\ p$
proof –
define *l* **where** $l = lineJoining\ x\ p$
hence *lprops*: $onLine\ p\ l \wedge onLine\ x\ l$
using *lemLineJoiningContainsEndPoints* **by** *auto*

define *LHS* **where** *LHS*: $LHS = ((x = p) \vee (onRegularCone\ x\ p))$
define *RHS* **where** *RHS*: $RHS = (regularCone\ x\ p)$

have *LHS* \longrightarrow *RHS*
proof –
{ **assume** $x = p$
hence *?thesis* **using** *RHS lemConeContainsVertex* **by** *auto*
}
hence *case1*: $x = p \longrightarrow regularCone\ x\ p$ **using** *LHS RHS* **by** *auto*
{ **assume** $x \neq p \wedge onRegularCone\ x\ p$
then **obtain** *v* **where** $v: v \in lineVelocity\ l \wedge sNorm2\ v = 1$
using *l* **by** *blast*
hence $\exists l . (onLine\ p\ l) \wedge (onLine\ x\ l) \wedge (\exists v \in lineVelocity\ l . sNorm2\ v = 1)$
using *lprops* **by** *blast*
}
thus *?thesis* **using** *case1 LHS RHS* **by** *blast*

qed

moreover have $RHS \longrightarrow LHS$

proof –

{ assume $rhs: RHS$

have cases: $x = p \vee x \neq p$ by auto

have case1: $x = p \longrightarrow (x = p \vee onRegularCone\ x\ p)$ by auto

{ assume $xnotp: x \neq p$

then obtain $l1$ where

$l1: (onLine\ x\ l1) \wedge (onLine\ p\ l1)$

$\wedge (\exists v \in lineVelocity\ l1 . sNorm2\ v = 1)$

using $rhs\ RHS$ by blast

hence $l1 = l$ using $xnotp\ l1\ lemLineAndPoints[of\ x\ p\ l1]$ by

auto

hence $\exists v \in lineVelocity\ l . sNorm2\ v = 1$ using $l1$ by blast

hence $onRegularCone\ x\ p$ using l by blast

hence $(x = p \vee onRegularCone\ x\ p)$ by blast

}

hence case2: $x \neq p \longrightarrow LHS$

using $l\ lprops\ LHS$ by blast

hence $(x = p \vee onRegularCone\ x\ p)$ using cases case1 LHS by

blast

}

thus ?thesis using $LHS\ RHS$ by auto

qed

ultimately have $LHS \longleftrightarrow RHS$ by blast

thus ?thesis using $LHS\ RHS$ by fastforce

qed

lemma *lemSlopeInfiniteImpliesOutside*:

assumes $x \neq p$

and $slopeInfinite\ x\ p$

shows $\exists l\ p' . (p' \neq p) \wedge onLine\ p'\ l \wedge onLine\ p\ l$

$\wedge (l \cap regularConeSet\ x = \{\})$

proof –

define dxp where $dxp = (x \ominus p)$

hence $x = (d xp \oplus p)$ by simp

hence $x d xp: x = (p \oplus dxp)$ using *add-commute* by blast

have $xp: tval\ x = tval\ p$ using *assms(2)* by blast

hence $tval d xp: tval\ dxp = 0$ using $d xp$ by simp

obtain $dnew$ where

$dnew: (dnew \neq origin) \wedge (tval\ dnew = tval\ dxp) \wedge \neg(\exists \alpha . \alpha \neq 0$
 $\wedge dxp = (\alpha \otimes dnew))$

```

    using lemNonParallelVectorsExist[of dxp]
    by auto
  hence tvaldnew: tval dnew = 0 using tvaldxp by simp

  define w where w: w = (p ⊕ dnew)
  hence wmp: (w ⊖ p) = dnew by simp

  have wx: tval w = tval x
  proof -
    have tval dnew = tval x - tval p using dnew dxp by auto
    hence tval w = tval p + (tval x - tval p) using w by auto
    thus ?thesis using add-commute diff-add-cancel by auto
  qed

  define lw where lw: lw = lineJoining w p

  have xNotOnLw: ¬ (x ∈ lw)
  proof -
    { assume x ∈ lw
      then obtain a where a: x = (w ⊕ (a ⊗ (p ⊖ w))) using lw by
    auto
      hence (p ⊕ dxp) = ((p ⊕ dnew) ⊕ (a ⊗ (p ⊖ w))) using xdxp w
    by auto
      hence dxp = (dnew ⊕ (a ⊗ (p ⊖ w))) using add-assoc by auto
      moreover have (p ⊖ w) = ((-1) ⊗ (w ⊖ p)) by simp
      hence (a ⊗ (p ⊖ w)) = ((-a) ⊗ (w ⊖ p)) using lemScaleAssoc[of
    a -1 w ⊖ p] by simp
      ultimately have dxp = (dnew ⊕ ((-a) ⊗ (w ⊖ p))) by auto
      hence dxp = ((1 ⊗ dnew) ⊕ ((-a) ⊗ dnew)) using wmp by
    auto
      hence dxp = ((1 - a) ⊗ dnew) using left-diff-distrib' by fastforce
      hence (1 - a) = 0 using dnew by blast
      hence a = 1 by simp
      hence x = (w ⊕ (p ⊖ w)) using a by auto
      hence x = p by (simp add: local.add-diff-eq)
    }
    thus ?thesis using assms(1) by auto
  qed

  have dnew ≠ origin using dnew by auto
  hence wNotp: w ≠ p using w diff-self wmp by blast
  hence pwOnLw: onLine p lw ∧ onLine w lw
    using lw lemLineAndPoints[of w p lw] by auto

  hence target1: w ≠ p ∧ onLine w lw ∧ onLine p lw using wNotp
  by auto

  define MeetW where MeetW: MeetW = lw ∩ regularConeSet x
  { assume nonempty: ¬ (MeetW = {})

```

then obtain z where $z: z \in MeetW$ by *blast*

have $zx: tval\ z = tval\ x$

proof –

have $z \in lineJoining\ w\ p$ using $z\ MeetW\ lw$ by *auto*

then obtain a where $a: z = (w \oplus (a \otimes (p \ominus w)))$ by *blast*

have $tval\ (p \ominus w) = 0$ using $w\ tvaldnew$ by *auto*

hence $tval\ z = tval\ w$ using a by *auto*

thus *?thesis* using wx by *auto*

qed

have *regularCone* $x\ z$ using $z\ MeetW$ by *auto*

then obtain $l1$ where $l1: (onLine\ z\ l1) \wedge (onLine\ x\ l1)$

$\wedge (\exists\ v \in lineVelocity\ l1 . sNorm2\ v =$

$1)$ by *blast*

then obtain v where $v: v \in lineVelocity\ l1 \wedge sNorm2\ v = 1$ by *blast*

hence $\exists\ d \in drtn\ l1 . v = velocityJoining\ origin\ d \wedge sNorm2\ v = 1$ by *auto*

then obtain $d1$ where $d1: d1 \in drtn\ l1 \wedge v = velocityJoining\ origin\ d1 \wedge sNorm2\ v = 1$

by *blast*

hence $v \neq sOrigin$ by *fastforce*

hence $velocityJoining\ origin\ d1 \neq sOrigin$ using $d1$ by *auto*

hence $drtnNotZero: tval\ d1 \neq 0$ by *auto*

define $d2$ where $d2: d2 = (z \ominus x)$

hence $tvald2: tval\ d2 = 0$ using zx by *simp*

have $zNotz: x \neq z$ using $xNotOnLw\ z\ MeetW$ by *blast*

hence $(x \neq z) \wedge (onLine\ z\ l1) \wedge (onLine\ x\ l1) \wedge (d2 = (z \ominus x))$

using $l1\ d2$ by *auto*

hence $\exists\ x\ z . (x \neq z) \wedge (onLine\ x\ l1) \wedge (onLine\ z\ l1) \wedge (d2 = (z \ominus x))$ by *blast*

hence $d2 \in drtn\ l1$ by *auto*

then obtain b where $b: b \neq 0 \wedge d1 = (b \otimes d2)$

using *lemDrtn*[of $d2\ d1\ l1$] $d1$ by *blast*

hence $tval\ d1 = b * tval\ d2$ by *simp*

hence $tval\ d1 = 0$ using $tvald2$ by *simp*

hence *False* using $drtnNotZero$ by *auto*

}

hence $MeetW = \{\}$ by *auto*

hence $(w \neq p) \wedge onLine\ w\ lw \wedge onLine\ p\ lw \wedge (lw \cap regularConeSet\ x = \{\})$

using *target1* $MeetW$ by *auto*

thus *?thesis* **by** *blast*
qed

lemma *lemClassification:*

shows $(\text{insideRegularCone } x \ p) \vee (\text{vertex } x \ p \vee \text{outsideRegularCone } x \ p \vee \text{onRegularCone } x \ p)$

proof –

define *l* **where** *l*: *l* = *lineJoining* *x p*

define *v* **where** *v*: *v* = *velocityJoining origin* (*p*⊖*x*)

{ **assume** *xnotp*: *x* ≠ *p*

hence *vel*: *v* ∈ *lineVelocity* *l*

using *l v lemVelocityLineJoining*[of *l x p v*] **by** *auto*

have $(\text{sNorm2 } v < 1) \vee (\text{sNorm2 } v > 1) \vee (\text{sNorm2 } v = 1)$ **by**

auto

hence *?thesis* **using** *xnotp l v vel* **by** *blast*

}

hence *x* ≠ *p* → *?thesis* **by** *auto*

moreover **have** *x* = *p* → *?thesis* **by** *auto*

ultimately show *?thesis* **by** *blast*

qed

lemma *lemQuadCoordinates:*

assumes *p* = (*B* ⊕ (*α* ⊗ *D*))

and *a* = *mNorm2* *D*

and *b* = $2 * (\text{tval } (B \ominus x)) * (\text{tval } D) - 2 * ((\text{sComponent } D) \odot s (\text{sComponent } (B \ominus x)))$

and *c* = *mNorm2* (*B*⊖*x*)

shows $\text{sqr } (\text{tval } (p \ominus x)) - \text{sNorm2 } (\text{sComponent } (p \ominus x)) = a * (\text{sqr } \alpha) + b * \alpha + c$

proof –

define *X* **where** *X*: *X* = (*B*⊖*x*)

have *pmx*: $(p \ominus x) = (X \oplus (\alpha \otimes D))$ **using** *diff-add-eq assms X* **by** *simp*

have *pmxt*: $\text{tval } p - \text{tval } x = \text{tval } X + \alpha * \text{tval } D$ **using** *pmx* **by** *simp*

have *pmxs*: $\text{sComponent } (p \ominus x) = ((\text{sComponent } X) \oplus s (\alpha \otimes s (\text{sComponent } D)))$

using *pmx* **by** *simp*

have *tsqr*: $\text{sqr } (\text{tval } (p \ominus x))$

$= \text{sqr } (\text{tval } X) + \alpha * (2 * (\text{tval } X) * (\text{tval } D)) + (\text{sqr } \alpha) * (\text{sqr } (\text{tval } D))$

using *pmxt lemSqrSum*[of *tval X α*(tval D)*] *mult-assoc mult-commute* **by** *auto*

have $ssqr: sNorm2 (sComponent (p\ominus x))$
 $= (sNorm2 (sComponent X))$
 $+ \alpha*(2*((sComponent X) \odot s (sComponent D)))$
 $+ (sqr \alpha)*(sNorm2 (sComponent D))$
using *lemSDotScaleRight lemSNorm2OfScaled lemSNorm2OfSum*
mult.left-commute pmxs
by *presburger*

hence $sqr (tval (p\ominus x)) - sNorm2 (sComponent (p\ominus x))$
 $= (sqr (tval X) + \alpha*(2*(tval X)*(tval D)) + (sqr \alpha)*(sqr (tval D)))$
 $- ((sNorm2 (sComponent X))$
 $+ \alpha*(2*((sComponent X) \odot s (sComponent D)))$
 $+ (sqr \alpha)*(sNorm2 (sComponent D)))$
using *tsqr by auto*
also have ...
 $= (sqr (tval X) + \alpha*(2*(tval X)*(tval D)))$
 $+ ((sqr \alpha)*(sqr (tval D)) - (sqr \alpha)*(sNorm2 (sComponent D)))$
 $- ((sNorm2 (sComponent X))$
 $+ \alpha*(2*((sComponent X) \odot s (sComponent D))))$
using *diff-add-eq add-diff-eq diff-add-eq-diff-diff-swap* **by** *fastforce*
also have ...
 $= sqr (tval X) +$
 $(\alpha*(2*(tval X)*(tval D)) - \alpha*(2*((sComponent X) \odot s$
 $(sComponent D))))$
 $+ ((sqr \alpha)*(sqr (tval D)) - (sqr \alpha)*(sNorm2 (sComponent D)))$
 $- (sNorm2 (sComponent X))$
using *diff-add-eq add-diff-eq diff-add-eq-diff-diff-swap add-commute*
by *simp*
also have ...
 $= sqr (tval X) + \alpha*b + (sqr \alpha)* a - (sNorm2 (sComponent X))$
using *right-diff-distrib' assms(2) assms(3) X lemSDotCommute*
by *presburger*
also have ... $= c + \alpha*b + (sqr \alpha)*a$
using *right-diff-distrib' assms(4) X add-commute add-diff-eq* **by**
simp

finally show *?thesis* **using** *add-commute mult-commute add-assoc*
by *auto*
qed

lemma *lemConeCoordinates:*

shows *(onRegularCone x p \longleftrightarrow $sqr (tval p - tval x) = sNorm2 (sComponent (p\ominus x))$)*

\wedge (*insideRegularCone* $x p \longleftrightarrow \text{sqr } (tval p - tval x) > sNorm2$
(sComponent (p⊖x)))
 \wedge (*outsideRegularCone* $x p \longleftrightarrow \text{sqr } (tval p - tval x) < sNorm2$
(sComponent (p⊖x)))

proof –

define *tdiff* **where** *tdiff*: *tdiff* = *tval p* – *tval x*

define *sdiff* **where** *sdiff*: *sdiff* = *sComponent (p⊖x)*

have *cases*: $x = p \vee x \neq p$ **by** *simp*

have *case1*: $x = p \longrightarrow ?thesis$

proof –

{ **assume** *xisp*: $x = p$

hence *on*: *onRegularCone* $x p$ **by** *auto*

moreover **have** *both0*: $\text{sqr } tdiff = 0 \wedge sNorm2 \text{ } sdiff = 0$

using *xisp* *tdiff* *sdiff* **by** *simp*

ultimately **have** *onRegularCone* $x p \longleftrightarrow \text{sqr } tdiff = sNorm2$

sdiff **by** *simp*

moreover **have** *outsideRegularCone* $x p \longleftrightarrow \text{sqr } tdiff > sNorm2$
sdiff

proof –

have \neg *outsideRegularCone* $x p$ **using** *xisp* **by** *simp*

moreover **have** $\neg (\text{sqr } tdiff > sNorm2 \text{ } sdiff)$ **using** *both0* **by**

simp

ultimately **show** *?thesis* **by** *blast*

qed

moreover **have** *insideRegularCone* $x p \longleftrightarrow \text{sqr } tdiff < sNorm2$
sdiff

proof –

have \neg *insideRegularCone* $x p$ **using** *xisp* **by** *simp*

moreover **have** $\neg (\text{sqr } tdiff < sNorm2 \text{ } sdiff)$ **using** *both0* **by**

simp

ultimately **show** *?thesis* **by** *blast*

qed

ultimately **have** *?thesis* **using** *tdiff* *sdiff* **by** *blast*

}

thus *?thesis* **by** *blast*

qed

have *case2*: $x \neq p \longrightarrow ?thesis$

proof –

define *l* **where** *l*: *l* = *lineJoining* $x p$

hence *onl*: *onLine* $x l \wedge \text{onLine } p l$ **using** *lemLineJoiningContainsEndPoints* **by** *blast*

define *v* **where** *v*: *v* = *velocityJoining* $x p$

```

{ assume xnotp:  $x \neq p$ 

  { assume sinf: slopeInfinite  $x p$ 

    hence t0:  $\text{sqr } tdiff = 0$  using tdiff by simp
    hence sdiff  $\neq$  sOrigin using xnotp sdiff tdiff by auto
    hence sNorm2 sdiff  $\neq$  0 using lemSpatialNullImpliesSpatialO-
origin by blast
    moreover have sNorm2 sdiff  $\geq$  0 by simp
    ultimately have sNorm2 sdiff  $>$  0 using lemGENZGT by
auto

    hence eqn:  $\text{sqr } tdiff < \text{sNorm2 } sdiff$  using t0 by auto
    have out: outsideRegularCone  $x p$  using sinf xnotp by blast

    have notin:  $\neg$  insideRegularCone  $x p$  using sinf by blast
    have notgt:  $\neg$  ( $\text{sqr } tdiff > \text{sNorm2 } sdiff$ ) using eqn by auto

    have noton:  $\neg$  onRegularCone  $x p$ 
    proof -
      { assume onRegularCone  $x p$ 
        then obtain u where  $u \in \text{lineVelocity } l \wedge \text{sNorm2 } u =$ 
1
          using l xnotp by blast
        hence slopeFinite  $x p$ 
        using xnotp lemLineVelocityNonZeroImpliesFinite[of u l]
          zero-neq-one l
        by fastforce
        hence False using sinf by auto
      }
      thus ?thesis by blast
    qed
    have noteq:  $\neg$  ( $\text{sqr } tdiff = \text{sNorm2 } sdiff$ ) using eqn by auto

    have outs: ( $\text{outsideRegularCone } x p$ )  $\longleftrightarrow$  ( $\text{sqr } tdiff < \text{sNorm2}$ 
sdiff)
      using out eqn by blast
    have ins: ( $\text{insideRegularCone } x p$ )  $\longleftrightarrow$  ( $\text{sqr } tdiff > \text{sNorm2}$ 
sdiff)
      using notin notgt by blast
    have ons: ( $\text{onRegularCone } x p$ )  $\longleftrightarrow$  ( $\text{sqr } tdiff = \text{sNorm2 } sdiff$ )

      using noton noteq by blast

    hence ?thesis using ins outs ons tdiff sdiff by blast
  }
  hence ifsinf: slopeInfinite  $x p \longrightarrow$  ?thesis by blast

```

```

    { assume sf: slopeFinite x p
      hence lv: lineVelocity l = {v}
        using lemLineVelocityUsingPoints[of x p l] v onl xnotp by
auto
      have formula: sqr tdiff *(sNorm2 v) = sNorm2 sdiff
        using lemSNorm2VelocityJoining[of x p v] sf v tdiff sdiff by
auto

    { assume onRegularCone x p
      hence ( $\exists v \in \text{lineVelocity } l . \text{sNorm2 } v = 1$ ) using xnotp l
by auto
      then obtain u where u:  $u \in \text{lineVelocity } l \wedge \text{sNorm2 } u = 1$ 
by blast
        hence  $u = v$  using lv by blast
        hence  $\text{sNorm2 } v = 1$  using u by auto
        hence  $\text{sqr } tdiff = \text{sNorm2 } sdiff$  using formula by auto
      }
      hence on1: (onRegularCone x p)  $\longrightarrow$  ( $\text{sqr } tdiff = \text{sNorm2 } sdiff$ )
by auto

    { assume insideRegularCone x p
      hence ( $\exists v \in \text{lineVelocity } l . \text{sNorm2 } v < 1$ ) using xnotp l
by auto
      then obtain u where u:  $u \in \text{lineVelocity } l \wedge \text{sNorm2 } u < 1$ 
by blast
        hence  $u = v$  using lv by blast
        hence  $\text{sNorm2 } v < 1$  using u by auto

    { assume  $\text{sNorm2 } v = 0$ 
      hence v0:  $v = \text{sOrigin}$  using lemSpatialNullImpliesSpatialOrigin by auto
      have sloper x p =  $((1/(\text{tval } x - \text{tval } p)) \otimes (x \ominus p))$  using sf
by auto
      hence  $v = ((1/(\text{tval } x - \text{tval } p)) \otimes \text{sComponent } (x \ominus p))$ 
using v by simp
      hence  $\text{sOrigin} = ((1/(\text{tval } x - \text{tval } p)) \otimes \text{sComponent } (x \ominus p))$ 
using v0 by force
      hence  $((\text{tval } x - \text{tval } p) \otimes \text{sOrigin}) = \text{sComponent } (x \ominus p)$ 
using lemSScaleAssoc[of  $(\text{tval } x - \text{tval } p) 1/(\text{tval } x - \text{tval } p)$ 
p)
         $(\text{sComponent } (x \ominus p))]$  sf
        mult-eq-0-iff right-minus-eq by auto
      hence s0:  $\text{sComponent } (x \ominus p) = \text{sOrigin}$  by auto
      hence pmxs:  $\text{sNorm2 } sdiff = 0$  using sdiff lemSSep2Symmetry
by auto

      have  $tdiff \neq 0$  using tdiff xnotp s0 by auto

```

```

    hence  $\text{sqr } tdiff > sNorm2 \text{ sdiff}$  using pmxs lemSquaresPositive
  by auto
}
hence ifv0:  $sNorm2 v = 0 \longrightarrow \text{sqr } tdiff > sNorm2 \text{ sdiff}$  by
blast

{ assume vne0:  $sNorm2 v \neq 0$ 
  hence  $sNorm2 v > 0$  using lemGENZGT by auto
  moreover have tpos:  $\text{sqr } tdiff > 0$ 
    using sf lemSquaresPositive tdiff by auto
  ultimately have lpos:  $(\text{sqr } tdiff) * (sNorm2 v) > 0$  by auto
  hence rpos:  $sNorm2 \text{ sdiff} > 0$  using formula by auto

  hence  $(\text{sqr } tdiff) * (sNorm2 v) < (\text{sqr } tdiff)$  using tpos lpos
  vlt1
    using lemMultPosLT1 [of sqr tdiff sNorm2 v] tpos by auto
  hence  $\text{sqr } tdiff > sNorm2 \text{ sdiff}$  using formula by auto
}
hence  $sNorm2 v \neq 0 \longrightarrow \text{sqr } tdiff > sNorm2 \text{ sdiff}$  by auto

  hence  $\text{sqr } tdiff > sNorm2 \text{ sdiff}$  using ifv0 by blast
}
hence in1:  $\text{insideRegularCone } x p \longrightarrow \text{sqr } tdiff > sNorm2 \text{ sdiff}$ 
by auto

{ assume out:  $\text{outsideRegularCone } x p$ 
  have xnotp:  $(x \neq p)$  using out by simp
  have  $(\exists v \in \text{lineVelocity } (\text{lineJoining } x p) . sNorm2 v > 1)$ 
    using sf out by blast
  then obtain u where u:  $u \in \text{lineVelocity } (\text{lineJoining } x p) \wedge$ 
    ( $sNorm2 u > 1$ )
    by blast
  hence  $u = v$  using lv l by blast
  hence  $sNorm2 v > 1$  using u by auto
  moreover have  $\text{sqr } tdiff > 0$  using sf tdiff lemSquaresPositive
  by auto
  ultimately have  $(\text{sqr } tdiff) * (sNorm2 v) > (\text{sqr } tdiff)$ 
    using local.mult-strict-left-mono by fastforce
  hence  $\text{sqr } tdiff < sNorm2 \text{ sdiff}$  using formula by auto
}
hence out1:  $(\text{outsideRegularCone } x p) \longrightarrow (\text{sqr } tdiff < sNorm2$ 
 $\text{ sdiff})$  by auto

  have in2:  $(\text{sqr } tdiff > sNorm2 \text{ sdiff}) \longrightarrow (\text{insideRegularCone } x$ 
   $p)$ 
  proof -
    { assume lhs:  $\text{sqr } tdiff > sNorm2 \text{ sdiff}$ 
      { assume  $\neg \text{insideRegularCone } x p$ 

```

```

      hence options: onRegularCone x p  $\vee$  outsideRegularCone
x p      using lemClassification xnotp by blast

      { assume onRegularCone x p
        hence sqr tdiff = sNorm2 sdiff using xnotp on1 by blast
          hence False using lhs by auto
        }
      hence notOn:  $\neg$ onRegularCone x p by blast

      { assume outsideRegularCone x p
        hence sqr tdiff < sNorm2 sdiff using xnotp out1 by
blast
          hence False using lhs by auto
        }
      hence notIn:  $\neg$ outsideRegularCone x p by blast

      hence False using notOn options by blast
    }
  }
  hence insideRegularCone x p by blast
}
}
thus ?thesis by blast
qed

have out2: (sqr tdiff < sNorm2 sdiff)  $\longrightarrow$  (outsideRegularCone
x p)
proof -
  { assume lhs: sqr tdiff < sNorm2 sdiff
    { assume  $\neg$  outsideRegularCone x p
      hence options: onRegularCone x p  $\vee$  insideRegularCone x
p
        using lemClassification xnotp by blast

        { assume onRegularCone x p
          hence sqr tdiff = sNorm2 sdiff using xnotp on1 by blast
            hence False using lhs by auto
          }
        hence notOn:  $\neg$ onRegularCone x p by blast

        { assume insideRegularCone x p
          hence sqr tdiff > sNorm2 sdiff using xnotp in1 by blast
            hence False using lhs by auto
          }
        hence notIn:  $\neg$ insideRegularCone x p by blast

        hence False using notOn options by blast
      }
    }
  }
  hence outsideRegularCone x p by blast
}
}

```

thus ?thesis **by** blast
qed

have on2: (sqr tdiff = sNorm2 sdiff) \longrightarrow (onRegularCone x p)

proof –

{ **assume** lhs: sqr tdiff = sNorm2 sdiff
 { **assume** \neg onRegularCone x p
hence options: outsideRegularCone x p \vee insideRegularCone

x p

using lemClassification xnotp **by** blast

{ **assume** outsideRegularCone x p
hence sqr tdiff < sNorm2 sdiff **using** xnotp out1 **by**

blast

hence False **using** lhs **by** auto

}

hence notOut: \neg outsideRegularCone x p **by** blast

{ **assume** insideRegularCone x p
hence sqr tdiff > sNorm2 sdiff **using** xnotp in1 **by** blast
hence False **using** lhs **by** auto

}

hence notIn: \neg insideRegularCone x p **by** blast

hence False **using** notOut options **by** blast

}

hence onRegularCone x p **by** blast

}

thus ?thesis **by** blast

qed

hence ?thesis **using** in1 in2 out1 out2 on1 on2 tdiff sdiff **by**

blast

}

hence slopeFinite x p \longrightarrow ?thesis **by** blast

hence ?thesis **using** ifsinf **by** blast

}

thus ?thesis **by** blast

qed

thus ?thesis **using** cases case1 **by** blast

qed

lemma lemConeCoordinates1:

shows $p \in \text{regularConeSet } x \iff \text{norm2 } (p \ominus x) = 2 * \text{sqr } (\text{tval } p - \text{tval } x)$

proof –

define $tdiff$ **where** $tdiff: tdiff = tval\ p - tval\ x$
hence $tdiff'$: $tdiff = tval\ (p \ominus x)$ **by** *simp*
define $sdiff$ **where** $sdiff: sdiff = (sComponent\ (p \ominus x))$

have n : $norm2\ (p \ominus x) = sqr\ tdiff + sNorm2\ sdiff$
using *lemNorm2Decomposition* $sdiff\ tdiff'$ **by** *blast*

have reg : $onRegularCone\ x\ p \longleftrightarrow sqr\ tdiff = sNorm2\ sdiff$
using *lemConeCoordinates* $tdiff\ sdiff$ **by** *blast*

{ **assume** $p \in regularConeSet\ x$
hence $onRegularCone\ x\ p$ **using** *lemRegularCone*[*of* $x\ p$] **by** *auto*
hence $sqr\ tdiff = sNorm2\ sdiff$ **using** reg **by** *blast*
hence $norm2\ (p \ominus x) = 2*sqr\ tdiff$ **using** $n\ mult-2$ **by** *force*
}

hence $l2r$: $p \in regularConeSet\ x \longrightarrow norm2\ (p \ominus x) = 2*sqr\ tdiff$
by *auto*

{ **assume** $norm2\ (p \ominus x) = 2*sqr\ tdiff$
hence $sqr\ tdiff + sNorm2\ sdiff = 2*sqr\ tdiff$ **using** n **by** *auto*
hence $sNorm2\ sdiff = sqr\ tdiff$ **using** $mult-2\ add-diff-eq$ **by** *auto*
hence $onRegularCone\ x\ p$ **using** reg **by** *auto*
hence $p \in regularConeSet\ x$
using *lemConeContainsVertex* *lemRegularCone*[*of* $x\ p$] **by** *blast*
}

hence $norm2\ (p \ominus x) = 2*sqr\ tdiff \longrightarrow p \in regularConeSet\ x$ **by**
blast

thus *?thesis* **using** $l2r\ tdiff$ **by** *blast*

qed

lemma *lemWhereLineMeetsCone*:

assumes $a = mNorm2\ D$
and $b = 2*(tval\ (B \ominus x))*(tval\ D) - 2*((sComponent\ D) \odot s(sComponent\ (B \ominus x)))$
and $c = mNorm2\ (B \ominus x)$
shows $groot\ a\ b\ c\ \alpha \longleftrightarrow regularCone\ x\ (B \oplus (\alpha \otimes D))$

proof –

{ **fix** α **assume** $\alpha: groot\ a\ b\ c\ \alpha$
define p **where** $p: p = (B \oplus (\alpha \otimes D))$
hence $mNorm2\ (p \ominus x) = a*(sqr\ \alpha) + b*\alpha + c$
using *lemQuadCoordinates*[*of* $p\ B\ \alpha\ D\ a\ b\ x\ c$] *assms* **by** *auto*
hence $sqr\ (tval\ (p \ominus x)) - sNorm2\ (sComponent\ (p \ominus x)) = 0$ **using**
 α **by** *auto*
hence $onRegularCone\ x\ p$ **using** *lemConeCoordinates*[*of* $x\ p$] **by**
auto
hence $regularCone\ x\ (B \oplus (\alpha \otimes D))$ **using** *lemRegularCone* p **by**

```

blast
}
hence l2r:  $\text{root } a \ b \ c \ \alpha \longrightarrow \text{regularCone } x \ (B \oplus (\alpha \otimes D))$  by blast

{ assume reg:  $\text{regularCone } x \ (B \oplus (\alpha \otimes D))$ 
  define p where p:  $p = (B \oplus (\alpha \otimes D))$ 
  hence onRegularCone x p using lemRegularCone reg by blast
  hence  $\text{sqr } (\text{tval } (p \ominus x)) - \text{sNorm2 } (\text{sComponent } (p \ominus x)) = 0$ 
    using lemConeCoordinates[of x p] by auto
  hence  $a * (\text{sqr } \alpha) + b * \alpha + c = 0$ 
    using lemQuadCoordinates[of p B \alpha D a b x c] p assms
    by auto
  hence  $\text{groot } a \ b \ c \ \alpha$  by auto
}
hence  $\text{regularCone } x \ (B \oplus (\alpha \otimes D)) \longrightarrow \text{root } a \ b \ c \ \alpha$  by auto

thus ?thesis using l2r by blast
qed

```

```

lemma lemLineMeetsCone1:
  assumes  $\neg (x \in l)$ 
  and isLine l
  and  $S = l \cap \text{regularConeSet } x$ 
  and l:  $l = \text{line } B \ D$ 
  and X:  $X = (B \ominus x)$ 
  and a:  $a = \text{mNorm2 } D$ 
  and b:  $b = 2 * (\text{tval } X) * (\text{tval } D) - 2 * ((\text{sComponent } D) \odot_s (\text{sComponent } X))$ 
  and c:  $c = \text{mNorm2 } X$ 
  shows (qcase1 a b c  $\longrightarrow S = \{B\}$ )
  proof -
    { assume hyp1: qcase1 a b c

      have impa:  $\text{norm2 } D = 2 * \text{sqr } (\text{tval } D)$ 
      proof -
        have  $a = 0$  using hyp1 by simp
        hence  $\text{sqr } (\text{tval } D) = \text{sNorm2 } (\text{sComponent } D)$  using a by auto
        hence onRegularCone origin D
          using lemConeCoordinates[of origin D] by auto
        hence regularCone origin D using lemRegularCone by blast
        thus ?thesis using lemConeCoordinates1 by auto
      }
    qed

    have impb:  $(D \odot X) = 2 * \text{tval } X * \text{tval } D$ 
    proof -
      have  $2 * (\text{tval } X) * (\text{tval } D) = 2 * ((\text{sComponent } D) \odot_s (\text{sComponent } X))$ 
      using hyp1 b by auto
    }

```



```

    hence (tval X)*(tval D) = ((sComponent D) ⊙s (sComponent
X))
    by (simp add: mult-assoc)
    thus ?thesis using mult-2 lemDotDecomposition[of X D]
        lemSDotCommute mult-assoc lemDotCommute by metis
qed

have impc: norm2 X = 2*sqr (tval X)
proof -
    have sqr (tval X) = sNorm2 (sComponent X) using hyp1 c by
auto
    hence onRegularCone x B using X lemConeCoordinates by auto
    hence regularCone x B using lemRegularCone by blast
    thus ?thesis using X lemConeCoordinates1 by auto
qed

have allOnCone: ∀ α . regularCone x (B ⊕ (α ⊗ D))
proof -
    { fix α
      define y where y: y = (B ⊕ (α ⊗ D))
      have qroot a b c α using hyp1 by simp
      hence regularCone x y
        using lemWhereLineMeetsCone[of a D b B x c α] using y
assms by auto
    }
    thus ?thesis by auto
qed

have tval D = 0
proof -
    { assume Dnot0: tval D ≠ 0
      define α where α: α = (tval x - tval B)/(tval D)
      define y where y: y = (B ⊕ (α⊗D))
      hence yOnl: y ∈ l using l by blast

      hence ty0: tval y = tval x
      proof -
        have tval y = tval ((B ⊕ (α⊗D))) using y by auto
        also have ... = tval B + α*(tval D) by simp
        also have ... = tval B + (tval x - tval B)/(tval D)*(tval D)
using α by simp
        also have ... = tval B + (tval x - tval B) using Dnot0 by
simp
        finally show ?thesis using add-commute local.diff-add-cancel
by auto
      qed

      have regularCone x y using y allOnCone by blast
      hence norm2 (y⊖x) = 2*sqr (tval y - tval x)

```

```

    using lemConeCoordinates1 by auto
    hence norm2 (y⊖x) = 0 using ty0 by auto
    hence (y⊖x) = origin using lemNullImpliesOrigin by blast
    hence y = x by simp

    hence False using yOnl assms by blast
  }
  thus ?thesis by blast
qed

hence norm2 D = 0 using impa by auto
hence D0: D = origin using lemNullImpliesOrigin by auto

have B0: B = (B ⊕ (0⊗D)) by simp

have regularCone x (B ⊕ (0⊗D)) using allOnCone by blast
hence BonCone: regularCone x B
  using B0 by (metis (mono-tags, lifting))
hence BinS: B ∈ S using assms BonCone B0 l by blast

hence SisB: S = {B}
proof -
  { fix y assume y: y ∈ S
    then obtain α where y = (B ⊕ (α⊗D)) using assms l by
blast
    hence y = B using D0 by simp
    hence y ∈ {B} by blast
  }
  hence S ⊆ {B} by blast
  thus ?thesis using BinS by blast
qed

}
thus ?thesis by auto
qed

```

```

lemma lemLineMeetsCone2:
  assumes ¬ (x ∈ l)
  and isLine l
  and S = l ∩ regularConeSet x
  and l: l = line B D
  and X: X = (B ⊖ x)
  and a = mNorm2 D
  and b = 2*(tval (B⊖x))*(tval D) - 2*((sComponent D) ⊙s (sComponent
(B⊖x)))
  and c = mNorm2 (B⊖x)
  shows qcase2 a b c → S = {}

```

```

proof –
  { assume hyp2: qcase2 a b c
    { assume  $S \neq \{\}$ 
      then obtain y where  $y: y \in S$  by auto
      then obtain  $\alpha$  where  $\alpha: y = (B \oplus (\alpha \otimes D))$  using assms by
    }
  }
  blast
  hence regularCone x  $(B \oplus (\alpha \otimes D))$  using y assms by blast
  hence groot a b c  $\alpha$ 
  using lemWhereLineMeetsCone[of a D b B x c  $\alpha$ ] assms
  by auto
  hence False using lemQCase2[of a b c] hyp2 by auto
  }
  hence  $S = \{\}$  by auto
  }
  thus ?thesis by auto
qed

```

lemma *lemLineMeetsCone3*:

```

  assumes  $\neg (x \in l)$ 
  and isLine l
  and  $S = l \cap \text{regularConeSet } x$ 
  and  $l: l = \text{line } B D$ 
  and  $X: X = (B \ominus x)$ 
  and  $a: a = mNorm2 D$ 
  and  $b: b = 2*(tval X)*(tval D) - 2*((sComponent D) \odot s (sComponent X))$ 
  and  $c: c = \text{sqr } (tval X) - sNorm2 (sComponent X)$ 
  and  $y3: y3 = (B \oplus ((-c/b) \otimes D))$ 
  shows qcase3 a b c  $\longrightarrow S = \{y3\}$ 
  proof –
    { assume hyp3: qcase3 a b c
      define T where  $T: T = \{y3\}$ 

```

have $S \subseteq T$

proof –

```

  { fix y assume  $y: y \in S$ 

```

```

    then obtain  $r$  where  $r: y = (B \oplus (r \otimes D))$  using l assms by

```

blast

```

    hence regularCone x y using y assms by auto

```

```

    hence abcr: groot a b c r

```

```

    using a b c r X

```

```

      lemWhereLineMeetsCone[of a D b B x c r]

```

```

    by auto

```

```

    hence  $r = -c/b$  using lemQCase3[of a b c r] abcr hyp3 by

```

blast

```

    hence  $y = y3$  using  $y3 r$  by auto

```

hence $y \in T$ using T by *blast*
 }
 thus ?thesis by *auto*
 qed

moreover have $T \subseteq S$
 proof -

{ fix y assume $y \in T$
 hence $y: y = (B \oplus ((-c/b) \otimes D))$ using T *assms* by *blast*
 have *groot* $a\ b\ c\ (-c/b)$ using *lemQCase3* *hyp3* by *auto*

hence *rc*: *regularCone* $x\ y$
 using *hyp3* *assms* y *lemWhereLineMeetsCone*[*of* $a\ D\ b\ B\ x\ c$
 $(-c/b)$]
 by *auto*
 have $y \in l$ using *assms* y by *blast*
 hence $y \in S$ using *rc* *assms* by *auto*
 }
 thus ?thesis by *blast*
 qed

ultimately have $S = \{y\}$ using T by *auto*
 }
 thus ?thesis by *blast*
 qed

lemma *lemLineMeetsCone4*:

assumes $\neg (x \in l)$
 and *isLine* l
 and $S = l \cap \text{regularConeSet } x$
 and $l: l = \text{line } B\ D$
 and $X: X = (B \ominus x)$
 and $a: a = \text{mNorm2 } D$
 and $b: b = 2*(\text{tval } X)*(\text{tval } D) - 2*((\text{sComponent } D) \odot_s (\text{sComponent } X))$
 and $c: c = \text{sqr } (\text{tval } X) - \text{sNorm2 } (\text{sComponent } X)$
 shows (*qcase4* $a\ b\ c \longrightarrow S = \{\}$)
 proof -
 { assume *hyp4*: *qcase4* $a\ b\ c$
 { assume $S \neq \{\}$
 then obtain y where $y: y \in S$ by *blast*
 then obtain r where $r: y = (B \oplus (r \otimes D))$ using l *assms* by
blast
 hence *regularCone* $x\ y$ using y *assms* by *auto*
 hence *abcr*: *groot* $a\ b\ c\ r$
 using $a\ b\ c\ r\ X$
lemWhereLineMeetsCone[*of* $a\ D\ b\ B\ x\ c\ r$]

```

    by auto
    hence False using lemQCase4 hyp4 by auto
  }
  hence S = {} by auto
}
thus ?thesis by blast
qed

```

lemma *lemLineMeetsCone5*:

```

  assumes  $\neg (x \in l)$ 
  and      isLine l
  and      S = l  $\cap$  regularConeSet x
  and      l: l = line B D
  and      X: X = (B  $\ominus$  x)
  and      a: a = mNorm2 D
  and      b: b = 2*(tval X)*(tval D) - 2*((sComponent D)  $\odot$ s (sComponent X))
  and      c: c = sqr (tval X) - sNorm2 (sComponent X)
  and      y5: y5 = (B  $\oplus$  ((-b/(2*a)) $\otimes$ D))
  shows (qcase5 a b c  $\longrightarrow$  S = {y5})
  proof -
    { assume hyp5: qcase5 a b c
      define T where T: T = {y5}

      have S  $\subseteq$  T
      proof -
        { fix y assume y: y  $\in$  S
          then obtain r where r: y = (B  $\oplus$  (r $\otimes$ D)) using l assms by
blast
          hence regularCone x y using y assms by auto
          hence abcr: qroot a b c r
            using a b c r X
              lemWhereLineMeetsCone[of a D b B x c r]
            by auto
          hence r = -b/(2*a) using lemQCase5 abcr hyp5 by blast
          hence y = y5 using r y5 by auto
          hence y  $\in$  T using T by blast
        }
      }
    thus ?thesis by blast
  qed

```

moreover have $T \subseteq S$

```

  proof -
    { fix y assume y  $\in$  T
      hence y: y = (B  $\oplus$  ((-b/(2*a)) $\otimes$ D)) using T assms by blast
      have qroot a b c (-b/(2*a)) using lemQCase5 hyp5 by blast
      hence rc: regularCone x y

```

```

      using hyp5 assms y lemWhereLineMeetsCone[of a D b B x c
(-b/(2*a))]
      by auto
      have y ∈ l using assms y by blast
      hence y ∈ S using rc assms by auto
    }
    thus ?thesis by blast
  qed

  ultimately have S = {y5} using T by auto
}
thus ?thesis by blast
qed

```

lemma *lemLineMeetsCone6*:

```

  assumes ¬ (x ∈ l)
  and isLine l
  and S = l ∩ regularConeSet x
  and l: l = line B D
  and X: X = (B ⊖ x)
  and a: a = mNorm2 D
  and b: b = 2*(tval X)*(tval D) - 2*((sComponent D) ⊙s (sComponent
X))
  and c: c = sqr (tval X) - sNorm2 (sComponent X)
  and ym: ym = (B ⊕ (((-b - (sqrt (discriminant a b c))) / (2*a)) ⊗
D))
  and yp: yp = (B ⊕ (((-b + (sqrt (discriminant a b c))) / (2*a)) ⊗
D))
  shows (qcase6 a b c → (ym ≠ yp) ∧ S = {ym, yp})
  proof -
    { assume hyp6: qcase6 a b c

      define T where T: T = {ym, yp}
      define rm where rm: rm = (-b - (sqrt (discriminant a b c))) /
(2*a)
      define rp where rp: rp = (-b + (sqrt (discriminant a b c))) /
(2*a)

      have ymnotyp: ym ≠ yp
      proof -
        define d where d: d = discriminant a b c
        define sd where sd: sd = sqrt d

        have sdn0: sqrt d ≠ 0
        proof -
          have dpos: d > 0 using d hyp6 by simp

```

hence *hasRoot d* **using** *AxEField* **by** *auto*
thus *?thesis* **using** *lemSquareOfSqrt[of d] dpos* **by** *auto*
qed

have *Dnot0: D ≠ origin*
proof –
{ **assume** *D = origin*
hence *a = 0* **using** *a* **by** *simp*
hence *False* **using** *hyp6* **by** *simp*
}
thus *?thesis* **by** *auto*
qed

have *rmnotrp: rm ≠ rp*
proof –
{ **assume** *rm = rp*
hence $(-b - sd) / (2*a) = (-b + sd)/(2*a)$ **using** *sd d rm*
rp **by** *simp*
hence $-b - sd = -b + sd$ **using** *hyp6* **by** *simp*
hence $-sd = sd$ **using** *add-left-imp-eq diff-conv-add-uminus*
by *metis*
hence *False* **using** *snot0 sd* **by** *simp*
}
thus *?thesis* **by** *auto*
qed

{ **assume** *ym = yp*
hence $(B \oplus (rm \otimes D)) = (B \oplus (rp \otimes D))$ **using** *ym yp rm rp*
by *auto*
hence $(rm \otimes D) = (rp \otimes D)$ **by** *simp*
hence $((rm - rp) \otimes D) = origin$ **by** *auto*
hence $rm - rp = 0$ **using** *Dnot0* **by** *auto*
hence *False* **using** *rmnotrp* **by** *auto*
}
thus *?thesis* **by** *auto*
qed

have $S \subseteq T$
proof –
{ **fix** *y* **assume** *y: y ∈ S*
then obtain *r* **where** $r: y = (B \oplus (r \otimes D))$ **using** *l assms* **by**
blast
hence *regularCone x y* **using** *y assms* **by** *auto*
hence *abcr: qroot a b c r*
using *a b c r X*
lemWhereLineMeetsCone[of a D b B x c r]
by *auto*
hence $qroots a b c = \{rp, rm\}$

```

    using lemQCase6[of a b c sqrt (discriminant a b c) rp rm]
      rp rm hyp6 by auto
  hence rchoice: (r = rm  $\vee$  r = rp) using abcr by blast
  hence ychoice: (y = ym  $\vee$  y = yp) using r ym yp rm rp by
blast
  hence yinT: y  $\in$  T using T by blast
}
thus ?thesis by auto
qed

moreover have T  $\subseteq$  S
proof -
  { fix y assume y  $\in$  T
    hence y: y = ym  $\vee$  y = yp using T assms by blast

    have qroot a b c rm using rm lemQCase6 hyp6 by blast
    hence rcm: regularCone x ym
      using hyp6 assms ym rm lemWhereLineMeetsCone[of a D b
B x c rm]
      by auto
    have qroot a b c rp using rp lemQCase6 hyp6 by blast
    hence rcp: regularCone x yp
      using hyp6 assms yp rp lemWhereLineMeetsCone[of a D b B
x c rp]
      by auto
    hence regularCone x y using rcm y by blast
    moreover have y  $\in$  l using assms y by blast
    ultimately have y  $\in$  S using assms by blast
  }
  thus ?thesis by blast
qed

ultimately have (ym  $\neq$  yp)  $\wedge$  S = {ym, yp} using T ymnotyp
by auto
}
thus ?thesis by blast
qed

```

lemma lemConeLemma1:

```

  assumes  $\neg$  (x  $\in$  l)
  and isLine l
  and S = l  $\cap$  regularConeSet x
  shows finite S  $\wedge$  card S  $\leq$  2
proof -
  obtain B D where BD: l = line B D using assms(2) by auto

```

```

define X where X: X = (B  $\ominus$  x)
define a where a: a = mNorm2 D

```



```

define b where b:  $b = 2*(\text{tval } X)*(\text{tval } D) - 2*(\text{sComponent } D)$ 
 $\odot s (\text{sComponent } X)$ 
define c where c:  $c = \text{sqr } (\text{tval } X) - \text{sNorm2 } (\text{sComponent } X)$ 

have qcase1 a b c  $\longrightarrow ?thesis$ 
  using assms X a b c lemLineMeetsCone1[of x l S B D X a b c] BD
  by auto
moreover have qcase2 a b c  $\longrightarrow ?thesis$ 
  using assms X a b c lemLineMeetsCone2[of x l S B D X a b c] BD
  by auto
moreover have qcase3 a b c  $\longrightarrow ?thesis$ 
  using assms X a b c lemLineMeetsCone3[of x l S B D X a b c] BD
  by auto
moreover have qcase4 a b c  $\longrightarrow ?thesis$ 
  using assms X a b c lemLineMeetsCone4[of x l S B D X a b c] BD
  by auto
moreover have qcase5 a b c  $\longrightarrow ?thesis$ 
  using assms X a b c lemLineMeetsCone5[of x l S B D X a b c] BD
  by auto
moreover have qcase6 a b c  $\longrightarrow ?thesis$ 
proof –
  { assume hyp6: qcase6 a b c
    define ym where ym:  $ym = (B \oplus (((-b - (\text{sqr } (\text{discriminant } a b c))) / (2*a)) \otimes D))$ 
    define yp where yp:  $yp = (B \oplus (((-b + (\text{sqr } (\text{discriminant } a b c))) / (2*a)) \otimes D))$ 

    have  $(ym \neq yp) \wedge S = \{ ym, yp \}$ 
    using assms X a b c ym yp hyp6
    lemLineMeetsCone6[of x l S B D X a b c ym yp] BD
    by auto
    hence  $\text{card } S = 2$  using card-2-iff by blast
    hence  $\text{finite } S \wedge \text{card } S \leq 2$  using card.infinite by fastforce
  }
  thus ?thesis by auto
qed

  ultimately show ?thesis using lemQuadraticCasesComplete by
blast
qed

```

```

lemma lemConeLemma2:
  assumes  $\neg (\text{regularCone } x w)$ 
  shows  $\exists l . (\text{onLine } w l) \wedge (\neg (x \in l)) \wedge (\text{card } (l \cap (\text{regularConeSet } x))) = 2)$ 
proof –
  have xnotw:  $x \neq w$  using assms lemConeContainsVertex by blast

```

```

have iftalsequal:  $tval\ x = tval\ w \longrightarrow ?thesis$ 
proof -
  { assume ts:  $tval\ x = tval\ w$ 
    define l where l:  $l = line\ w\ tUnit$ 

    hence wonl:  $onLine\ w\ l$ 
    proof -
      have  $w = (w \oplus (0 \otimes tUnit))$  by simp
      thus ?thesis using l by blast
    qed

    have xnotinl:  $\neg(x \in l)$ 
    proof -
      { assume  $x \in l$ 
        then obtain a where  $a: x = (w \oplus (a \otimes tUnit))$  using l by
blast

        hence  $tval\ x = tval\ w + a$  by simp
        hence  $a = 0$  using ts by simp
        hence  $x = w$  using a by simp
        hence False using xnotw by simp
      }
      thus ?thesis by blast
    qed

    have  $card\ (l \cap (regularConeSet\ x)) = 2$ 
    proof -
      define S where S:  $S = l \cap regularConeSet\ x$ 
      hence  $cardS$ :  $finite\ S \wedge card\ S \leq 2$ 
      using xnotinl l lemConeLemma1[of x l S] by blast

      have  $(sNorm2\ (sComponent\ (w \ominus x))) \geq 0$  by simp
      hence sExists:  $hasRoot\ (sNorm2\ (sComponent\ (w \ominus x)))$  using
AxEField by auto

      define s where s:  $s = sqrt\ (sNorm2\ (sComponent\ (w \ominus x)))$ 
      define yp where yp:  $yp = (w \oplus (s \otimes tUnit))$ 
      define ym where ym:  $ym = (w \ominus (s \otimes tUnit))$ 

      have ypnotym:  $yp \neq ym$ 
      proof -
        { assume  $yp = ym$ 
          hence  $(w \oplus (s \otimes tUnit)) = (w \ominus (s \otimes tUnit))$  using yp ym
        }
        by auto

        hence  $tval\ w + s = tval\ w - s$  by simp
        hence  $s = 0$ 
        by (metis local.add-cancel-right-right
          local.double-zero-sym local.lemDiffSumCancelMiddle)
        hence  $sNorm2\ (sComponent\ (w \ominus x)) = sqr\ 0$ 
        using s lemSquareOfSqrt[of sNorm2 (sComponent (w  $\ominus$  x))]

```

```

s] sExists
  by auto
  hence norm2 (w⊖x) = 0 using lemNorm2Decomposition
ts by auto
  hence (w⊖x) = origin using lemNullImpliesOrigin by blast
  hence w = x by simp
  hence False using xnotw by simp
}
thus ?thesis by auto
qed

have ypinl: yp ∈ l using yp l by blast
have yminl: ym ∈ l
proof -
  have ym = (w ⊕ ((-s)⊗tUnit)) using ym by simp
  thus ?thesis using l by blast
qed

have ypcone: yp ∈ regularConeSet x
proof -
  have (yp ⊖ x) = ((w ⊕ (s⊗tUnit)) ⊖ x) using yp by auto
  hence tval (yp ⊖ x) = s using ts by simp
  hence tsqr: sqr (tval (yp⊖x)) = (sNorm2 (sComponent
(w⊖x)))
    using s sExists lemSquareOfSqrt AxEField by blast
  hence sComponent (yp⊖x) = sComponent ((w ⊕ (s⊗tUnit))
⊖ x) using yp by auto
  also have ... = ((sComponent (w ⊕ (s⊗tUnit))) ⊖ s (sComponent
x)) by simp
  also have ... = (((sComponent w) ⊕ s (sComponent (s⊗tUnit)))
⊖ s (sComponent x)) by simp
  also have ... = ((sComponent w) ⊖ s (sComponent x)) by
simp
  finally have sComponent (yp⊖x) = sComponent (w⊖x) by
simp
  hence ssqr: sNorm2 (sComponent (yp⊖x)) = (sNorm2
(sComponent (w⊖x)))
    by auto
  hence sqr (tval (yp⊖x)) = (sNorm2 (sComponent (yp⊖x)))
using tsqr by auto
  hence onRegularCone x yp using lemConeCoordinates[of x
yp] by auto
  thus ?thesis using lemRegularCone by blast
qed

have ymcone: ym ∈ regularConeSet x
proof -
  have (ym ⊖ x) = ((w ⊖ (s⊗tUnit)) ⊖ x) using ym by auto

```

hence $tval (ym \ominus x) = tval (w \ominus (s \otimes tUnit)) - tval x$ **by**
simp
also have $\dots = (tval w - tval(s \otimes tUnit)) - tval x$ **by** *simp*
also have $\dots = (tval w - s) - tval w$ **using** *ts* **by** *simp*
finally have $tval (ym \ominus x) = -s$ **using** *diff-right-commute*
by (*metis local.add-implies-diff local.uminus-add-conv-diff*)
hence $sqr (tval (ym \ominus x)) = sqr s$ **by** *simp*
hence $tsqr: sqr (tval (ym \ominus x)) = (sNorm2 (sComponent$
 $(w \ominus x)))$
using *s sExists lemSquareOfSqrt AxEField* **by** *force*

hence $sComponent (ym \ominus x) = sComponent ((w \ominus (s \otimes tUnit))$
 $\ominus x)$ **using** *ym* **by** *auto*
also have $\dots = ((sComponent (w \ominus (s \otimes tUnit))) \ominus s (sComponent$
 $x))$ **by** *simp*
also have $\dots = (((sComponent w) \ominus s (sComponent (s \otimes tUnit)))$
 $\ominus s (sComponent x))$ **by** *simp*
also have $\dots = ((sComponent w) \ominus s (sComponent x))$ **by**
simp
finally have $sComponent (ym \ominus x) = sComponent (w \ominus x)$ **by**
simp
hence $ssqr: sNorm2 (sComponent (ym \ominus x)) = (sNorm2$
 $(sComponent (w \ominus x)))$
by *auto*
hence $sqr (tval (ym \ominus x)) = (sNorm2 (sComponent (ym \ominus x)))$
using *tsqr* **by** *auto*
hence *onRegularCone x ym* **using** *lemConeCoordinates[of x*
 $ym]$ **by** *auto*
thus *?thesis* **using** *lemRegularCone* **by** *blast*
qed

define T **where** $T: T = \{yp, ym\}$

hence $T \subseteq S$ **using** *ypinl ypcone yminl ymcone S* **by** *auto*
hence $TleS: card T \leq card S$ **using** *cardS card-mono* **by** *blast*
have $cardT: card T = 2$ **using** T *yynotym card-2-iff* **by** *blast*

hence $(2 \leq card S) \wedge finite S \wedge card S \leq 2$ **using** $TleS$ *cardS*
by *auto*
thus *?thesis* **using** S **by** *simp*
qed

hence *?thesis* **using** *xnotinl wonl* **by** *blast*
}
thus *?thesis* **by** *auto*

qed

have *iftvalsne: tval x \neq tval w \longrightarrow ?thesis*

```

proof –
  { assume ts:  $tval\ x \neq tval\ w$ 

    define x0 where x0:  $x0 = mkPoint\ (tval\ w)\ (xval\ x)\ (yval\ x)$ 
    (zval x)
    have xnotx0:  $x \neq x0$  using x0 ts by (metis Point.select-convs(1))
    have tdiff0:  $tval\ w = tval\ x0$  using x0 by simp

    define dir where dir:  $dir = (if\ (w \neq x0)\ then\ (w \ominus x0)\ else\ xUnit)$ 

    hence tdir0:  $tval\ dir = 0$ 
    proof –
      { assume  $w \neq x0$ 
        hence dir =  $(w \ominus x0)$  using dir by simp
      }
      hence wnotx0:  $(w \neq x0) \longrightarrow ?thesis$  using tdiff0 by auto
      { assume  $w = x0$ 
        hence dir =  $xUnit$  using dir by simp
      }
      hence  $(w = x0) \longrightarrow ?thesis$  by simp
      thus  $?thesis$  using wnotx0 by auto
    }
    qed

    define l where l:  $l = lineJoining\ x0\ (dir \oplus x0)$ 
    hence lprops:  $l = line\ x0\ dir$  using dir by auto

    hence wonl:  $onLine\ w\ l$ 
    proof –
      { assume wnotx0:  $w \neq x0$ 
        hence dir =  $(w \ominus x0)$  using dir by simp
        hence  $(dir \oplus x0) = ((w \ominus x0) \oplus x0)$  by simp
        hence  $w = (dir \oplus x0)$  using diff-add-eq by auto
        hence  $?thesis$  using dir lemLineJoiningContainsEndPoints l
      }
      by blast
    }
    moreover have  $(w = x0) \longrightarrow ?thesis$  using lemLineJoining-
ContainsEndPoints l by blast
    ultimately show  $?thesis$  by auto
    qed

    then obtain A where A:  $w = (x0 \oplus (A \otimes dir))$  using l by
auto

    have xnotinl:  $\neg(x \in l)$ 
    proof –
      { assume  $x \in l$ 
        then obtain a where a:  $x = (x0 \oplus (a \otimes dir))$  using l by auto
        hence  $tval\ x = tval\ x0$  using tdir0 by simp
        hence False using ts tdiff0 by auto
      }
    }
  }

```

```

}
thus ?thesis by blast
qed

have card (l ∩ (regularConeSet x)) = 2
proof -
  define S where S: S = l ∩ regularConeSet x
  hence cardS: finite S ∧ card S ≤ 2
  using xnotinl l lemConeLemma1[of x l S] by blast

  have (sNorm2 (sComponent (w⊖x0))) ≥ 0 by simp
  hence sExists: hasRoot (sNorm2 (sComponent (w⊖x0))) using
  AxEField by auto
  define s where s: s = sqrt (sNorm2 (sComponent (w⊖x0)))

  define unit where unit: unit = (if (w = x0) then xUnit else
  ((1/s)⊗(w⊖x0)))

  have tunit0: tval unit = 0
  proof -
    { assume w = x0
      hence unit = xUnit using unit by simp
    }
    hence w=x0 → ?thesis by auto
    moreover have w≠x0 → ?thesis
    proof -
      { assume wnotx0: w ≠ x0
        hence unit = ((1/s)⊗dir) using unit dir by simp
      }
      thus ?thesis using tdir0 by auto
    qed
    ultimately show ?thesis by auto
  qed

  have snot0: w ≠ x0 → s ≠ 0
  proof -
    { assume wnotx0: w ≠ x0
      hence norm2 (w⊖x0) > 0
      using local.lemNotEqualImpliesSep2Pos by presburger
      also have norm2 (w⊖x0) = sNorm2 (sComponent (w⊖x0))
      using tdiff0 lemNorm2Decomposition[of w⊖x0] by auto
      finally have s2pos: sNorm2 (sComponent (w⊖x0)) > 0 by
  auto
      { assume s = 0
        hence False using lemSquareOfSqrt[of sNorm2 (sComponent
  (w⊖x0)) s]
          s2pos s sExists by auto
      }
      hence s ≠ 0 by auto
    }
  qed

```

```

    }
    thus ?thesis by auto
qed

hence unit1: sNorm2 (sComponent unit) = 1
proof -
  have case0: w=x0 → ?thesis using unit by auto
  have case1: w≠x0 → ?thesis
  proof -
    { assume case1: w ≠ x0
      have unit = ((1/s)⊗(w⊖x0)) using unit case1 by simp
      hence sComponent unit = ((1/s) ⊗ s (sComponent (w⊖x0)))
    }
  by simp
  hence sNorm2 (sComponent unit) = sqr (1/s) * sNorm2
(sComponent (w⊖x0))
  using lemSNorm2OfScaled[of (1/s) sComponent (w⊖x0)]
  by auto
  also have ... = sqr (1/s) * sqr s
  using lemSquareOfSqrt[of sNorm2 (sComponent (w⊖x0))]
s] sExists s
  by auto
  finally have sNorm2 (sComponent unit) = 1 using snot0
case1 by simp
}
thus ?thesis by auto
qed
thus ?thesis using case0 by blast
qed

define dt where dt: dt = tval w - tval x
define mdt where mdt: mdt = -dt
define yp where yp: yp = (x0 ⊕ (dt ⊗ unit))
define ym where ym: ym = (x0 ⊖ (dt ⊗ unit))
hence ymalt: ym = (x0 ⊕ (mdt ⊗ unit)) using mdt by simp

have ypnoty: yp ≠ ym
proof -
  { assume yp = ym
    hence (x0 ⊕ (dt⊗unit)) = (x0 ⊖ (dt⊗unit)) using yp ym by
auto
  }
  hence ((x0 ⊕ (dt⊗unit)) ⊕ (dt⊗unit)) = x0 by auto
  hence (x0 ⊕ (2⊗(dt⊗unit))) = x0 using add-assoc mult-2
by auto
  hence ((x0 ⊕ (2⊗(dt⊗unit))) ⊖ x0) = origin by simp
  hence (2⊗(dt⊗unit)) = origin using add-diff-eq by auto
  hence False using unit1 ts dt by simp
}
thus ?thesis by auto
qed

```

```

have ypinl: yp ∈ l
proof -
  { assume w = x0
    hence yp = (w ⊕ (dt ⊗ dir)) using dir unit yp by simp
    hence ∃ a . yp = (w ⊕ (a ⊗ dir)) using yp by auto
  }
  hence wx0: w=x0 → ?thesis using l by auto

  { assume wnotx0: w ≠ x0
    hence u: unit = ((1/s) ⊗ dir) using unit dir by auto
    hence yp = (x0 ⊕ ((dt/s) ⊗ dir)) using lemScaleAssoc yp by
auto
    hence ∃ a . yp = (x0 ⊕ (a ⊗ dir)) using snot0 by blast
  }
  hence w≠x0 → ?thesis using l by auto
  thus ?thesis using wx0 by blast
qed

have yminl: ym ∈ l
proof -
  { assume w = x0
    hence ym = (x0 ⊕ (mdt ⊗ dir)) using dir unit ymalt by simp
    hence ∃ a . ym = (x0 ⊕ (a ⊗ dir)) using ym by auto
  }
  hence wx0: w=x0 → ?thesis using l by auto

  { assume wnotx0: w ≠ x0
    hence u: unit = ((1/s) ⊗ dir) using unit dir by auto
    hence ym = (x0 ⊕ ((mdt/s) ⊗ dir)) using lemScaleAssoc ymalt
by auto
    hence ∃ a . ym = (x0 ⊕ (a ⊗ dir)) using snot0 by blast
  }
  hence w≠x0 → ?thesis using l by auto
  thus ?thesis using wx0 by blast
qed

have ypcone: yp ∈ regularConeSet x
proof -
  have sNorm2 (sComponent (yp ⊖ x0)) = sqr dt
  proof -
    have yp = (x0 ⊕ (dt ⊗ unit)) using yp by simp
    hence (yp ⊖ x0) = (dt ⊗ unit) using add-diff-eq diff-add-eq
by auto
    hence sComponent (yp ⊖ x0) = (dt ⊗ s (sComponent unit))
by auto
    thus ?thesis
using lemSNorm2OfScaled[of dt sComponent unit] unit1 by
auto

```


qed
hence $sNorm2 (sComponent (yp \ominus x)) = sqr dt$ **using** $x0$ **by**
simp
also have $\dots = sqr (tval (yp \ominus x))$ **using** $dt tunit0 yp tdiff0$ **by**
simp
finally have $sNorm2 (sComponent (yp \ominus x)) = sqr (tval (yp \ominus x))$
by *blast*
hence *onRegularCone* $x yp$ **using** *lemConeCoordinates*[*of x yp*]
by *auto*
thus *?thesis* **using** *lemRegularCone* **by** *blast*
qed

have $ymcone: ym \in regularConeSet x$
proof –
have $sNorm2 (sComponent (ym \ominus x0)) = sqr dt$
proof –
have $ym = (x0 \oplus (mdt \otimes unit))$ **using** *ymalt* **by** *simp*
hence $(ym \ominus x0) = (mdt \otimes unit)$ **using** *add-diff-eq* *diff-add-eq*
by *auto*
hence $sComponent (ym \ominus x0) = (mdt \otimes sComponent unit)$
by *auto*
thus *?thesis*
using *lemSNorm2OfScaled*[*of mdt sComponent unit*] *unit1*
 mdt **by** *auto*
qed
hence $sNorm2 (sComponent (ym \ominus x)) = sqr dt$ **using** $x0$ **by**
simp
also have $\dots = sqr (tval (ym \ominus x))$ **using** $ym mdt dt tunit0$
 $tdiff0$ **by** *auto*
finally have $sNorm2 (sComponent (ym \ominus x)) = sqr (tval$
 $(ym \ominus x))$ **by** *blast*
hence *onRegularCone* $x ym$ **using** *lemConeCoordinates*[*of x*
 ym] **by** *auto*
thus *?thesis* **using** *lemRegularCone* **by** *blast*
qed

define T **where** $T: T = \{yp, ym\}$

hence $T \subseteq S$ **using** *ypinl* *ypcone* *yminl* *ymcone* S **by** *auto*
hence $TleS: card T \leq card S$ **using** *cardS* *card-mono* **by** *blast*
have $cardT: card T = 2$ **using** T *ypnotym* *card-2-iff* **by** *blast*

hence $(2 \leq card S) \wedge finite S \wedge card S \leq 2$ **using** $TleS$ $cardS$
by *auto*
thus *?thesis* **using** S **by** *simp*
qed

hence *?thesis* **using** *xnotinl* *wonl* **by** *blast*
}

```

thus ?thesis by auto

qed
thus ?thesis using iftvalsequal by blast
qed

lemma lemLineInsideRegularConeHasFiniteSlope:
  assumes insideRegularCone  $x\ p$ 
and  $l = \text{lineJoining } x\ p$ 
shows lineSlopeFinite  $l$ 
proof -
  { assume converse:  $\neg (\text{lineSlopeFinite } l)$ 
    hence slope: slopeInfinite  $x\ p$ 
    using assms lemSlopeLineJoining[of  $l$ ] by blast
    hence False using assms(1) assms(2) slope by simp
  }
thus ?thesis by auto
qed

```

```

lemma lemInvertibleOnMeet:
  assumes invertible  $f$ 
and  $S = A \cap B$ 
shows applyToSet (asFunc  $f$ )  $S = (\text{applyToSet } (\text{asFunc } f) A) \cap$ 
  ( $\text{applyToSet } (\text{asFunc } f) B$ )
proof -
  define  $S'$  where  $S': S' = \text{applyToSet } (\text{asFunc } f) S$ 
  define  $A'$  where  $A': A' = \text{applyToSet } (\text{asFunc } f) A$ 
  define  $B'$  where  $B': B' = \text{applyToSet } (\text{asFunc } f) B$ 

  have  $S' \subseteq A' \cap B'$ 
  proof -
    { fix  $s'$  assume  $s' \in S'$ 
      then obtain  $s$  where  $s: s \in S \wedge f\ s = s'$  using  $S'$  by auto
      have inA:  $s' \in A'$ 
      proof -
        have  $s \in A$  using assms  $s$  by auto
        thus ?thesis using  $s\ A'$  by auto
      qed
      have inB:  $s' \in B'$ 
      proof -
        have  $s \in B$  using assms  $s$  by auto
        thus ?thesis using  $s\ B'$  by auto
      qed
      hence  $s' \in A' \cap B'$  using inA by auto
    }
  }

```

thus *?thesis* **by** *auto*
qed

moreover have $A' \cap B' \subseteq S'$
proof –
{ **fix** s' **assume** $s': s' \in A' \cap B'$
then obtain a **where** $a: a \in A \wedge f a = s'$ **using** A' **by** *auto*
obtain b **where** $b: b \in B \wedge f b = s'$ **using** $s' B'$ **by** *auto*

have $(\exists p . (f p = s') \wedge (\forall x . f x = s' \longrightarrow x = p))$ **using** *assms(1)*
by *auto*
then obtain p **where** $p: (f p = s') \wedge (\forall x . f x = s' \longrightarrow x = p)$
by *auto*
hence $a = b$ **using** $a b$ **by** *blast*
hence $a \in S \wedge f a = s'$ **using** $a b$ *assms(2)* **by** *auto*
hence $s' \in S'$ **using** S' **by** *auto*

}
thus *?thesis* **by** *auto*
qed

ultimately show *?thesis* **using** $S' A' B'$ **by** *auto*
qed

lemma *lemInsideCone*:
shows *insideRegularCone* $x p \longleftrightarrow$
 $\neg(\text{vertex } x p \vee \text{outsideRegularCone } x p \vee \text{onRegularCone } x$
 $p)$

proof –
{ **assume** *lhs*: *insideRegularCone* $x p$
hence $(\text{slopeFinite } x p) \wedge (\exists v \in \text{lineVelocity } (\text{lineJoining } x p) .$
 $s\text{Norm2 } v < 1)$
by *auto*
hence *rtp1*: $\neg(\text{vertex } x p)$ **by** *blast*

define l **where** $l: l = \text{lineJoining } x p$

obtain vin **where** $vin: vin \in \text{lineVelocity } l \wedge s\text{Norm2 } vin < 1$
using l *lhs* **by** *blast*
hence *vs*: $\forall v . v \in \text{lineVelocity } l \longrightarrow s\text{Norm2 } v < 1$
proof –
{ **fix** v **assume** $v: v \in \text{lineVelocity } l$
have *slopeFinite* $x p$ **using** *lhs* **by** *blast*
moreover have $\text{onLine } x l \wedge \text{onLine } p l$ **using** l *lemLineJoiningContainsEndpoints*
by *auto*
ultimately have $v = vin$
using *rtp1* $v vin$ *lemFiniteLineVelocityUnique[of v l vin]* **by**
blast

```

    }
    thus ?thesis using vin by blast
qed

{ assume outsideRegularCone x p
  then obtain v where v: v ∈ lineVelocity l ∧ sNorm2 v > 1
using l lhs by blast
  hence sNorm2 v < 1 using vs by blast
  hence False using v by force
}
hence rtp2: ¬ outsideRegularCone x p by blast
{ assume onRegularCone x p
  then obtain v where v: v ∈ lineVelocity l ∧ sNorm2 v = 1
using l lhs by blast
  hence sNorm2 v < 1 using vs by blast
  hence False using v by force
}
hence rtp3: ¬ onRegularCone x p by blast
hence ¬(vertex x p ∨ outsideRegularCone x p ∨ onRegularCone x
p)
  using rtp1 rtp2 by blast
}
hence l2r: insideRegularCone x p →
  ¬(vertex x p ∨ outsideRegularCone x p ∨ onRegularCone x
p)
  by blast

{ assume rhs: ¬(vertex x p ∨ outsideRegularCone x p ∨ onRegular-
Cone x p)
  define v where v: v = (insideRegularCone x p)
  define z where z: z = (vertex x p ∨ outsideRegularCone x p ∨
onRegularCone x p)
  hence v ∨ z using v z lemClassification[of x p] by auto
  hence insideRegularCone x p using rhs v z by blast
}
thus ?thesis using l2r by blast
qed

```

lemma *lemOnRegularConeIff*:

assumes $l = \text{lineJoining } x \ p$

shows $\text{onRegularCone } x \ p \iff (l \cap \text{regularConeSet } x = l)$

proof –

{ **assume** $rc: \text{onRegularCone } x \ p$

hence $reg: \text{regularCone } x \ p$ using *lemRegularCone* by blast

define S where $S: S = l \cap \text{regularConeSet } x$

have $\text{SinL}: S \subseteq l$ using S by blast

```

have  $l \subseteq S$ 
proof -
  { fix  $q$  assume  $q: q \in l$ 
    then obtain  $a$  where  $a: q = (x \oplus (a \otimes (p \ominus x)))$  using assms
  by blast
    hence  $qmx: (q \ominus x) = (a \otimes (p \ominus x))$  by simp

    hence  $sqr (tval (q \ominus x)) = sqr (tval (a \otimes (p \ominus x)))$  by auto
    also have  $\dots = (sqr a) * (sqr (tval p - tval x))$  using lemSqrMult
  by auto
    also have  $\dots = (sqr a) * (sNorm2 (sComponent (p \ominus x)))$ 
      using rc lemConeCoordinates[of x p] by auto
    also have  $\dots = sNorm2 (a \otimes s (sComponent (p \ominus x)))$ 
      using lemSNorm2OfScaled[of a (sComponent (p \ominus x))] by auto
    also have  $\dots = sNorm2 (sComponent (a \otimes (p \ominus x)))$  by simp
    finally have  $sqr (tval (q \ominus x)) = sNorm2 (sComponent (q \ominus x))$ 
  ) using qmx by simp
    hence onRegularCone  $x q$  using lemConeCoordinates[of x q]
  by auto
    hence regularCone  $x q$  using lemRegularCone by blast
    hence  $q \in S$  using S q by auto
  }
  hence  $\forall q . q \in l \longrightarrow q \in S$  by blast
  thus ?thesis by blast
qed

  hence  $(l \cap \text{regularConeSet } x = l)$  using S SinL by blast
}
hence l2r: onRegularCone  $x p \longrightarrow (l \cap \text{regularConeSet } x = l)$  by
blast

{ assume rhs:  $(l \cap \text{regularConeSet } x = l)$ 
  have  $p \in l$ 
    using lemLineJoiningContainsEndPoints[of l x p] assms(1) by
auto
  hence regularCone  $x p$  using rhs by blast
  hence onRegularCone  $x p$  using lemRegularCone by blast
}
thus ?thesis using l2r by blast
qed

```

lemma *lemOutsideRegularConeImplies*:

```

shows outsideRegularCone  $x p$ 
   $\longrightarrow (\exists l p' . (p' \neq p) \wedge \text{onLine } p' l \wedge \text{onLine } p l$ 
     $\wedge (l \cap \text{regularConeSet } x = \{\}))$ 

```

proof -

```

{ assume lhs: outsideRegularCone  $x p$ 

```

hence $xnotp$: $(x \neq p)$ **by** *auto*
hence *formula*: $sqr (tval\ p - tval\ x) < sNorm2 (sComponent\ (p \ominus x))$
using *lemConeCoordinates*[*of x p*] **using** *lhs* **by** *auto*

have *cases*: $(slopeInfinite\ x\ p) \vee ((slopeFinite\ x\ p) \wedge (\exists\ v \in lineVelocity\ (lineJoining\ x\ p) . sNorm2\ v > 1))$
using *lhs* **by** *blast*

have *case1*: $slopeInfinite\ x\ p \longrightarrow (\exists\ l\ p' . (p' \neq p) \wedge onLine\ p'\ l \wedge onLine\ p\ l \wedge (l \cap regularConeSet\ x = \{\}))$
using *xnotp lemSlopeInfiniteImpliesOutside*
by *blast*

have *case2*: $((slopeFinite\ x\ p) \wedge (\exists\ v \in lineVelocity\ (lineJoining\ x\ p) . sNorm2\ v > 1)) \longrightarrow (\exists\ l\ p' . (p' \neq p) \wedge onLine\ p'\ l \wedge onLine\ p\ l \wedge (l \cap regularConeSet\ x = \{\}))$

proof –
define *l* **where** $l = lineJoining\ x\ p$
hence *onl*: $onLine\ x\ l \wedge onLine\ p\ l$ **using** *lemLineJoiningContainsEndpoints* **by** *blast*

{ assume *hyp*: $(slopeFinite\ x\ p) \wedge (\exists\ v \in lineVelocity\ (lineJoining\ x\ p) . sNorm2\ v > 1)$
then obtain *v* **where** $v: v \in lineVelocity\ l \wedge sNorm2\ v > 1$
using *l* **by** *blast*

define *x0* **where** $x0: x0 = mkPoint\ (tval\ p)\ (xval\ x)\ (yval\ x)\ (zval\ x)$
define *dsqr* **where** $dsqr: dsqr = norm2\ (p \ominus x0)$
define *d* **where** $d: d = sqrt\ dsqr$

have *dExists*: $hasRoot\ dsqr$ **using** *dsqr lemNorm2NonNeg AxEField* **by** *auto*

have *xnotp*: $x \neq p$ **using** *hyp* **by** *auto*

have *dnot0*: $d \neq 0$
proof –
{ assume *d0*: $d = 0$

hence $dsqr = 0$ **using** $lemSquareOfSqrt[of\ dsqr\ d]$ $dExists$
d **by** *auto*
hence $(p \ominus x0) = origin$ **using** $dsqr\ lemNullImpliesOrigin[of$
 $(p \ominus x0)]$ **by** *auto*
hence $p = x0$ **by** *simp*
hence $sloper\ x\ p = ((1/(tval\ x - tval\ p)) \otimes (x \ominus x0))$ **using**
x0 **by** *auto*
moreover **have** $sComponent\ (x \ominus x0) = sOrigin$ **using** *x0*
by *simp*
ultimately **have** $velocityJoining\ x\ p = sOrigin$ **using** *hyp*
by *auto*
hence $sOrigin \in lineVelocity\ l$
using $lemLineVelocityUsingPoints[of\ x\ p\ l]$ *l* *hyp* *xnotp* *onl*
by *auto*
hence $sOrigin = v$
using $lemFiniteLineVelocityUnique[of\ sOrigin\ l\ v]$
hyp *v* *onl* *xnotp* **by** *blast*
hence $sNorm2\ v = 0$ **by** *auto*
hence *False* **using** *v* **by** *auto*
}
thus *?thesis* **by** *auto*
qed

hence $dsqrnot0: dsqr \neq 0$
using $d\ dExists\ lemSquareOfSqrt[of\ dsqr\ d]$ $lemZeroRoot$ **by**
blast

have $dpos: d > 0$
using $d\ theI'[of\ isNonNegRoot\ dsqr]$ $lemSqrt\ dExists\ dnot0$
by *auto*

define *T* **where** $T: T = tval\ p$
define *radius* **where** $radius: radius = tval\ p - tval\ x$
define *R0* **where** $R0: R0 = sComponent\ (p \ominus x)$

have $R0gtRadius: sqr\ radius < sNorm2\ R0$ **using** *formula*
radius *R0* **by** *auto*

have $dsqr': dsqr = sNorm2\ R0$
proof –
have $sComponent\ x = sComponent\ x0$ **using** *x0* **by** *simp*
hence $R0 = sComponent\ (p \ominus x0)$ **using** *R0* **by** *auto*
moreover **have** $tval\ (p \ominus x0) = 0$ **using** *x0* **by** *simp*
ultimately **show** *?thesis* **using** $lemNorm2Decomposition\ dsqr$
by *auto*
qed

hence $radialnot0: R0 \neq sOrigin$ **using** $dsqrnot0$ **by** *auto*

```

obtain  $D0$  where  $D0: D0 \neq sOrigin \wedge ((D0 \odot s R0) = 0)$ 
using lemOrthogonalSpaceVectorExists[of R0] by auto

define  $D$  where  $D: D = stPoint\ 0\ D0$ 
define  $L$  where  $L: L = line\ p\ D$ 

hence  $pOnLine: onLine\ p\ L$ 
using lemLineJoiningContainsEndPoints[of L p (p⊕D)] by
auto

have  $meetEmpty: L \cap regularConeSet\ x = \{\}$ 
proof -
  { assume  $L \cap regularConeSet\ x \neq \{\}$ 
    then obtain  $Q$  where  $Q: Q \in L \cap regularConeSet\ x$  by
blast
    then obtain  $\alpha$  where  $\alpha: Q = (p \oplus (\alpha \otimes D))$  using  $L$  by
blast

    have  $((p \oplus (\alpha \otimes D)) \ominus x) = ((p \ominus x) \oplus (\alpha \otimes D))$ 
using add-diff-eq diff-add-eq by auto
hence  $Qmx: (Q \ominus x) = ((p \ominus x) \oplus (\alpha \otimes D))$  using  $\alpha$  by
simp

    hence  $Qmxt: tval\ Q - tval\ x = tval\ (p \ominus x)$  using  $D$  by simp

    have  $sComponent\ (Q \ominus x) = sComponent\ ((p \ominus x) \oplus (\alpha \otimes D))$ 
using  $Qmx$  by simp
also have  $\dots = ((sComponent\ (p \ominus x)) \oplus s\ (sComponent\ (\alpha \otimes D)))$ 
by simp
finally have  $sNorm2\ (sComponent\ (Q \ominus x))$ 
 $= sNorm2\ ((sComponent\ (p \ominus x)) \oplus s\ (sComponent\ (\alpha \otimes D)))$ 
by simp
also have  $\dots = sNorm2\ (R0 \oplus s\ (\alpha \otimes s\ D0))$  using  $R0\ D$ 
by auto
also have  $\dots = sNorm2\ R0 + 2*(R0 \odot s\ (\alpha \otimes s\ D0)) +$ 
 $sNorm2\ (\alpha \otimes s\ D0)$ 
using lemSNorm2OfSum[of R0 (α ⊗ s D0)] by auto
finally have
 $sNorm2\ (sComponent\ (Q \ominus x)) = sNorm2\ R0 + 2*(R0 \odot s$ 
 $(\alpha \otimes s\ D0)) + sNorm2\ (\alpha \otimes s\ D0)$ 
by auto

moreover have  $(R0 \odot s\ (\alpha \otimes s\ D0)) = 0$ 
using  $D0$  lemSDotCommute lemSDotScaleRight by simp

```


moreover have $sNorm2 (\alpha \otimes s D0) \geq 0$ **by simp**
ultimately have $sNorm2 (sComponent (Q \ominus x)) \geq sNorm2$
 $R0$ **by simp**

hence $Qmax: sNorm2 (sComponent (Q \ominus x)) > sqr radius$
using $R0gtRadius$ **by simp**

hence $sqr (tval Q - tval x) < sNorm2 (sComponent (Q \ominus x))$
using $radius Qmax$ **by simp**
hence $\neg (onRegularCone x Q)$
using $lemConeCoordinates[of x Q]$ **by force**
hence $\neg (regularCone x Q)$ **using** $lemRegularCone$ **by blast**
hence $False$ **using** Q **by blast**
}
thus $?thesis$ **by blast**
qed

define p' **where** $p' = (p \oplus D)$
have $Dnot0: D \neq origin$ **using** $D D0$ **by auto**

hence $p' \neq p$
proof $-$
{ **assume** $p' = p$
hence $(p \oplus D) = p$ **using** p' **by auto**
hence $((p \oplus D) \ominus p) = origin$ **by simp**
hence $D = origin$ **using** $add-diff-cancel$ **by auto**
hence $False$ **using** $Dnot0$ **by auto**
}
thus $?thesis$ **by blast**

qed
moreover have $onLine p' L$ **using** $L p'$ **by auto**
ultimately have $target1: p' \neq p \wedge onLine p' L$ **by blast**

hence $(\exists l p' . (p' \neq p) \wedge onLine p' l \wedge onLine p l$
 $\wedge (l \cap regularConeSet x = \{\}))$ **using** $meetEmpty$
 $pOnLine$ **by blast**
}
thus $?thesis$ **by blast**
qed

hence $(\exists l p' . (p' \neq p) \wedge onLine p' l \wedge onLine p l$
 $\wedge (l \cap regularConeSet x = \{\}))$
using $cases case1$ **by blast**
}
hence $l2r: outsideRegularCone x p \longrightarrow$
 $(\exists l p' . (p' \neq p) \wedge onLine p' l \wedge onLine p l$
 $\wedge (l \cap regularConeSet x = \{\}))$

by *blast*

thus *?thesis* by *blast*

qed

lemma *lemTimelikeInsideCone*:

assumes *insideRegularCone* $x\ p$

shows *timelike* $(p \ominus x)$

proof –

have $tval\ p - tval\ x \neq 0$ using *assms* by *auto*

hence *tdiffpos*: $sqr\ (tval\ p - tval\ x) > 0$ using *lemSquaresPositive*

by *auto*

define l where $l = lineJoining\ x\ p$

hence *slopeFinite* $x\ p \wedge (\exists\ v . v \in lineVelocity\ l \wedge sNorm2\ v < 1)$

using *assms* by *auto*

then obtain v where $v : v \in lineVelocity\ l \wedge sNorm2\ v < 1$

using *assms* by *blast*

have $lineVelocity\ l = \{ velocityJoining\ x\ p \}$

using *lemLineVelocityUsingPoints*[of $x\ p\ l$] *assms*

lemLineJoiningContainsEndPoints l

by *blast*

hence $vv : v = velocityJoining\ x\ p \wedge sNorm2\ v < 1$ using v by *auto*

hence formula: $sqr\ (tval\ p - tval\ x) * (sNorm2\ v) = sNorm2\ (sComponent\ (p \ominus x))$

using *lemSNorm2VelocityJoining*[of $x\ p\ v$] *assms* by *blast*

have cases: $sNorm2\ v = 0 \vee sNorm2\ v > 0$

using *local.add-less-zeroD* *local.not-less-iff-gr-or-eq*

local.not-square-less-zero

by *blast*

have case1: $sNorm2\ v > 0 \longrightarrow timelike\ (p \ominus x)$

proof –

define snv where $snv : snv = sNorm2\ v$

{ **assume** $sNorm2\ v > 0$

hence $0 < snv < 1$ using $vv\ snv$ by *auto*

moreover have $sqr\ (tval\ p - tval\ x) * snv = sNorm2\ (sComponent\ (p \ominus x))$

using *formula* snv by *simp*

ultimately have $sqr\ (tval\ p - tval\ x) > sNorm2\ (sComponent\ (p \ominus x))$

using *lemMultPosLT*[of $sqr\ (tval\ p - tval\ x)\ snv$]

tdiffpos by *force*

hence *timelike* $(p \ominus x)$ by *auto*

}

thus *?thesis* using snv by *auto*

qed

```

{ assume sNorm2 v = 0
  hence sNorm2 (sComponent (p ⊖ x)) = 0 using formula by auto
  hence timelike (p⊖x) using tdiffpos by auto
}
hence case2: sNorm2 v = 0 → timelike (p⊖x) by auto

thus ?thesis using case1 cases by auto
qed

end
end

```

31 ReverseCauchySchwarz

This theory defines and proves the "reverse" Cauchy-Schwarz inequality for timelike vectors in the Minkowski metric.

```

theory ReverseCauchySchwarz
  imports CauchySchwarz
begin

```

Rather than construct the proof, one could simply have asserted the claim as an axiom. We did this during development of the main proof, and then returned to this section later. In practice the axiom we chose to assert contained far more information than required, because we eventually found a proof that only required consideration of timelike vectors (our axiom considered lightlike vectors as well).

```

class ReverseCauchySchwarz = CauchySchwarz

begin

```

```

lemma lemTimelikeNotZeroTime:
  assumes timelike v
  shows tval v ≠ 0
proof -
  { assume converse: tval v = 0
    have sNorm2 (sComponent v) < sqr (tval v) using assms by auto
    hence sNorm2 (sComponent v) < 0 using converse by auto
    hence False using local.add-less-zeroD local.not-square-less-zero
  }
  by blast
}
thus ?thesis by auto
qed

```

```

lemma lemOrthogmToTimelike:
  assumes timelike u
  and orthogm u v
  and  $v \neq \text{origin}$ 
  shows spacelike v
  proof -
    have tvalu:  $\text{tval } u \neq 0$  using assms(1) lemTimelikeNotZeroTime
  by auto

    define us where us:  $us = sComponent\ u$ 
    define vs where vs:  $vs = sComponent\ v$ 
    have sqr  $((\text{tval } u) * (\text{tval } v)) = \text{sqr } (us \odot_s vs)$  using assms(2) us
  vs by auto
    also have  $\dots \leq sNorm2\ us * sNorm2\ vs$  using lemCauchySchwarzSqr
  by auto
    finally have inequ:  $\text{sqr } (\text{tval } u) * \text{sqr } (\text{tval } v) \leq sNorm2\ us * sNorm2\ vs$ 
  vs
    using mult-assoc mult-commute by auto

  have ifvsnz:  $vs \neq sOrigin \longrightarrow sNorm2\ vs > 0$ 
    by (meson local.add-less-zeroD local.antisym-conv3
      local.lemSpatialNullImpliesSpatialOrigin local.not-square-less-zero)

  have iftv0:  $\text{tval } v = 0 \longrightarrow \text{spacelike } v$ 
  proof -
    { assume v0:  $\text{tval } v = 0$ 
      hence  $vs \neq sOrigin$  using assms vs by auto
      hence  $sNorm2\ vs > 0$  using ifvsnz by auto
      hence spacelike v using v0 vs
        by (metis local.less-iff-diff-less-0 local.mult-not-zero)
    }
    thus ?thesis by auto
  qed

  moreover have  $(\text{tval } v \neq 0 \wedge vs \neq sOrigin) \longrightarrow \text{spacelike } v$ 
  proof -
    { assume vnz:  $(\text{tval } v \neq 0 \wedge vs \neq sOrigin)$ 

      have utpos:  $\text{sqr } (\text{tval } u) > 0$  using tvalu lemSquaresPositive by
    simp
      have vspos:  $sNorm2\ vs > 0$  using vnz ifvsnz by auto

      have  $\text{sqr } (\text{tval } u) * \text{sqr } (\text{tval } v) \leq sNorm2\ us * sNorm2\ vs$  using
    inequ by simp
      hence  $\text{sqr } (\text{tval } v) \leq sNorm2\ us * sNorm2\ vs / \text{sqr } (\text{tval } u)$ 
        using utpos
      by (metis local.divide-right-mono local.divisors-zero local.dual-order.strict-implies-order)
    }
  qed

```

$local.nonzero-mult-div-cancel-left\ tval u)$
hence $sqr\ (tval\ v) / sNorm2\ vs \leq sNorm2\ us / sqr\ (tval\ u)$
using $vspos\ mult-commute$ **by** $(simp\ add:\ local.mult-imp-div-pos-le)$

moreover **have** $sNorm2\ us / sqr\ (tval\ u) < 1$ **using** $assms(1)$
 $us\ utpos$ **by** $auto$
ultimately **have** $sqr\ (tval\ v) / sNorm2\ vs < 1$ **by** $simp$
hence $spacelike\ v$ **using** $vs\ vspos$ **by** $auto$
}
thus $?thesis$ **by** $auto$
qed

moreover **have** $\neg\ (tval\ v \neq 0 \wedge vs = sOrigin)$
proof $-$
{ **assume** $(tval\ v \neq 0 \wedge vs = sOrigin)$
hence $(u \odot m\ v) \neq 0$ **using** $tvalu\ vs$ **by** $auto$
hence $False$ **using** $assms$ **by** $auto$
}
thus $?thesis$ **by** $auto$
qed

ultimately **show** $?thesis$ **by** $blast$
qed

lemma $lemNormaliseTimelike$:
assumes $timelike\ v$
and $s = sComponent\ ((1/tval\ v) \otimes v)$
shows $(0 \leq sNorm2\ s < 1) \wedge (tval\ ((1/tval\ v) \otimes v) = 1)$
proof $-$
have $sqr\ (tval\ v) > sNorm2\ (sComponent\ v)$ **using** $assms$ **by** $auto$
hence $1 > sqr\ (1/tval\ v) * sNorm2\ (sComponent\ v)$
using $local.divide-less-eq$ **by** $force$
hence $sNorm2\ s < 1$ **using** $lemSNorm2OfScaled[of\ 1/tval\ v\ sComponent\ v]$ $assms$
by $auto$
hence $(0 \leq sNorm2\ s < 1)$ **by** $simp$
moreover **have** $(tval\ ((1/tval\ v) \otimes v) = 1)$
proof $-$
have $sqr\ (tval\ v) > sNorm2\ (sComponent\ v)$ **using** $assms$ **by** $auto$
hence $sqr\ (tval\ v) \neq 0$
by $(metis\ local.add-less-zeroD\ local.not-square-less-zero)$
hence $tval\ v \neq 0$ **by** $auto$
thus $?thesis$ **by** $auto$
qed
ultimately **show** $?thesis$ **by** $blast$
qed

```

lemma lemReverseCauchySchwarz:
  assumes timelike X  $\wedge$  timelike D
  shows  $\text{sqr } (X \odot m D) \geq (m\text{Norm2 } X) * (m\text{Norm2 } D)$ 
  proof -
    have case1: parallel X D  $\longrightarrow$  ?thesis
    proof -
      { assume parallel X D
        then obtain a where  $a: X = (a \otimes D)$  by auto
        hence  $(X \odot m D) = a * m\text{Norm2 } D$  using lemMDotScaleLeft by
        auto
        moreover have  $m\text{Norm2 } X = (\text{sqr } a) * m\text{Norm2 } D$  using
        lemMNorm2OfScaled a by auto
        ultimately have  $\text{sqr } (X \odot m D) = (m\text{Norm2 } X) * (m\text{Norm2 } D)$ 
        using local.lemSqrMult mult-assoc by auto
      }
      thus ?thesis by simp
    qed

  have  $(\neg \text{parallel } X D) \longrightarrow \textit{?thesis}$ 
  proof -
    { assume case2:  $\neg (\text{parallel } X D)$ 
      define u where  $u: u = ((1/\text{tval } X) \otimes X)$ 
      define v where  $v: v = ((1/\text{tval } D) \otimes D)$ 
      define su where  $su: su = (s\text{Component } u)$ 
      define sv where  $sv: sv = (s\text{Component } v)$ 

      have sphere:  $(0 \leq s\text{Norm2 } su < 1) \wedge (0 \leq s\text{Norm2 } sv < 1)$ 
      using lemNormaliseTimelike u su v sv assms by blast
      have tvals1:  $\text{tval } u = 1 \wedge \text{tval } v = 1$ 
      using lemNormaliseTimelike u su v sv assms by blast

      have worksuv:  $\text{sqr } (u \odot m v) > (m\text{Norm2 } u) * (m\text{Norm2 } v)$ 
      proof -

        have uupos:  $m\text{Norm2 } u > 0$  using assms u lemNormaliseTime-
        like by auto
        have vupos:  $m\text{Norm2 } v > 0$  using assms v lemNormaliseTimelike
        by auto
        have uvpos:  $(u \odot m v) > 0$ 
        proof -
          have  $\text{sqr } (s\text{dot } su sv) \leq (s\text{Norm2 } su) * (s\text{Norm2 } sv)$ 
          using lemCauchySchwarzSqr by auto
          also have  $\dots < 1$ 
          using mult-le-one sphere local.mult-strict-mono by fastforce
          finally have  $\text{sqr } (s\text{dot } su sv) < 1$  by auto
          hence  $(s\text{dot } su sv) < 1$ 
          using local.less-1-mult local.not-less-iff-gr-or-eq by fastforce
          thus ?thesis using u v su sv tvals1 by auto
        qed
      qed
    }
  qed

```

qed

define a where $a: a = (u \odot m v) / (mNorm2 v)$
define up where $up: up = (a \otimes v)$
define uo where $uo: uo = (u \ominus up)$

have $apos: a > 0$ using a $wvpos$ $vvpos$ by *auto*

have $updotup: mNorm2 up > 0$
proof –
have $mNorm2 up = (sqr a) * mNorm2 v$ using up *lemMNorm2OfScaled* by *auto*
thus *?thesis* using $apos$ *lemSquaresPositive* $vvpos$ by *auto*
qed

have $uparts: u = (up \oplus uo) \wedge parallel\ up\ v \wedge orthogm\ uo\ v \wedge (up \odot m v) = (u \odot m v)$
using *lemMDdecomposition* a up uo $vvpos$ $wvpos$ by *auto*

have $updotuo: (up \odot m uo) = 0$
proof –
have $(up \odot m uo) = a * (v \odot m uo)$ using up *lemMDotScaleLeft*
by *auto*
moreover have $(v \odot m uo) = (uo \odot m v)$ using *mult-commute*
by *auto*
ultimately have $(up \odot m uo) = 0$ using $uparts$ by *force*
thus *?thesis* by *auto*
qed

have $udotu: mNorm2 u = mNorm2 up + mNorm2 uo$
proof –
have $mNorm2 u = mNorm2 (up \oplus uo)$ using $uparts$ by *auto*
also have $\dots = mNorm2 up + 2 * (up \odot m uo) + mNorm2 uo$
using *lemMNorm2OfSum* by *auto*
finally show *?thesis* using $updotuo$ by *auto*
qed

moreover have $uodotu: mNorm2 uo < 0$
proof –
have *timelike up* using $updotup$ by *auto*
moreover have *orthogm up uo* using $updotuo$ by *auto*
moreover have $uo \neq origin$
proof –
define α where $\alpha: \alpha = (tval X) * a * (1 / tval D)$
have $\alpha pos: \alpha \neq 0$ using $apos$ *lemTimelikeNotZeroTime*
assms α by *simp*

{ **assume** $uo = origin$
hence $u = (a \otimes v)$ using uo up by *auto*

moreover have $X = ((tval\ X) \otimes u)$
using u *lemScaleAssoc* *assms* *lemTimelikeNotZeroTime*
by auto
ultimately have $X = ((tval\ X) \otimes (a \otimes v))$ **by auto**
hence $X = ((tval\ X) \otimes (a \otimes ((1/tval\ D) \otimes D)))$ **using** v **by**
auto
hence $X = (\alpha \otimes D)$ **using** α *lemScaleAssoc* *mult-assoc*
by (*metis* *Point.select-convs(3-4)*)
hence *False* **using** *case2* *apos* **by** *blast*
}
thus *?thesis* **by auto**
qed
ultimately show *?thesis* **using** *lemOrthogmToTimelike* **by**
auto
qed

ultimately have *upgeu: mNorm2 up > mNorm2 u* **by auto**

have $(u \odot m\ v) = (up \odot m\ v)$ **using** *uparts* **by auto**
also have $\dots = a * mNorm2\ v$ **using** up *lemMDotScaleLeft* **by**
auto
finally have *final: sqr (u \odot m v) = ((sqr a)*mNorm2 v) * (mNorm2 v)*
using *lemSqrMult[of a mNorm2 v]* *mult-assoc* **by auto**

hence $sqr (u \odot m\ v) = (mNorm2\ up) * (mNorm2\ v)$ **using**
lemMNorm2OfScaled up **by auto**
thus *?thesis*
using *upgeu* *vvpos* *local.mult-strict-right-mono* **by** *simp*
qed

have $(u \odot m\ v) = (((1/tval\ X) \otimes X) \odot m\ ((1/tval\ D) \otimes D))$ **using**
 $u\ v$ **by auto**
hence *udotv: (u \odot m v) = (1/tval X)*(1/tval D) * (X \odot m D)*
using *lemMDotScaleRight* *lemMDotScaleLeft* *mult-assoc* *mult-commute*
by *metis*

have *udotu: mNorm2 u = sqr (1/tval X) * mNorm2 X* **using** u
lemMNorm2OfScaled **by** *blast*
moreover have *vdotv: mNorm2 v = sqr (1/tval D) * mNorm2 D*
using v *lemMNorm2OfScaled* **by** *blast*
ultimately have $(mNorm2\ u) * (mNorm2\ v) = sqr ((1/tval\ X) * (1/tval\ D)) * mNorm2\ X * mNorm2\ D$
using *mult-commute* *mult-assoc* **by auto**

hence
 $sqr ((1/tval\ X) * (1/tval\ D) * (X \odot m\ D)) >$
 $sqr ((1/tval\ X) * (1/tval\ D)) * mNorm2\ X *$


```

mNorm2 D
  using worksuv udotv by auto
  moreover have sqr ((1/tval X)*(1/tval D)) > 0
  using lemTimelikeNotZeroTime
  by (metis calculation local.lemSquaresPositive local.mult-cancel-left1)
  ultimately have ?thesis
  using mult-less-cancel-left-pos[of sqr ((1/tval X)*(1/tval D))]
  by auto
}

  thus ?thesis by auto
qed

  thus ?thesis using case1 by auto
qed

end

end

```

32 KeyLemma

This theory establishes a "key lemma": if you draw a line through a point inside a cone, that line will intersect the cone in no fewer than 1 and no more than 2 points.

```

theory KeyLemma
  imports Classification ReverseCauchySchwarz
begin

class KeyLemma = Classification + ReverseCauchySchwarz
begin

```

```

lemma lemInsideRegularConeImplies:
  assumes insideRegularCone x p
  and     D ≠ origin
  and     l = line p D
  shows   0 < card (l ∩ regularConeSet x) ≤ 2
proof -
  define S where S: S = (l ∩ regularConeSet x)
  define X where X: X = (p ⊖ x)
  define a where a: a = mNorm2 D
  define b where b: b = 2*(tval X)*(tval D) - 2*((sComponent D)
⊙s (sComponent X))

```

```

define c where c:  $c = mNorm2\ X$ 
define d where d:  $d = (sqr\ b) - (4*a*c)$ 

have tlX: timelike X using lemTimelikeInsideCone assms(1) X by
auto
hence cpos:  $c > 0$  using c by auto

have xnotp:  $x \neq p$  using assms(1) by auto

have aval:  $a = mNorm2\ D$  using a by auto
have bval:  $b = 2*(X \odot m\ D)$ 
  using b local.lemSDotCommute local.right-diff-distrib' mult-assoc
  using local.mdotsimps by presburger
have cval:  $c = mNorm2\ X$  using c by auto
have dval:  $d = 4 * ( (sqr\ (X \odot m\ D)) - (mNorm2\ X)*(mNorm2\ D) )$ 
proof -
  have  $d = (sqr\ b) - (4*a*c)$  using d by simp
  moreover have  $(sqr\ b) = 4*(sqr\ (X \odot m\ D))$ 
    using lemSqrMult[of 2 (X \odot m\ D)] bval by auto
  moreover have  $4*a*c = 4*(mNorm2\ X)*(mNorm2\ D)$ 
    using aval cval mult-commute mult-assoc by auto
  ultimately show ?thesis using right-diff-distrib' mult-assoc by
metis
qed

define r2p where r2p:  $r2p = (\lambda\ r . (p \oplus (r \otimes D)))$ 
define p2r where p2r:  $p2r = (\lambda\ q . (THE\ a . q = (p \oplus (a \otimes D))))$ 

have bij:  $\forall\ r\ q . r2p\ r = q \iff (\exists\ w . (r2p\ w = q)) \wedge (p2r\ q = r)$ 
proof -
  have uniqueroots:  $\forall\ a\ r . r2p\ a = r2p\ r \implies a = r$ 
  proof -
    { fix a r assume  $r2p\ a = r2p\ r$ 
      hence  $(a \otimes D) = (r \otimes D)$  using r2p add-diff-eq by auto
      hence  $((a-r) \otimes D) = origin$  using lemScaleDistribDiff by auto
      hence  $(a-r) = 0$  using assms(2) by auto
      hence  $a = r$  by simp
    }
  thus ?thesis by blast
qed
  { fix q r assume lhs:  $r2p\ r = q$ 
    have  $(THE\ a . q = r2p\ a) = r$ 
    proof -
      { fix a assume  $q = r2p\ a$ 
        hence  $a = r$  using uniqueroots lhs r2p by blast
      }
    }
  hence  $\forall\ a . q = r2p\ a \implies a = r$  by auto

```

```

      thus ?thesis using lhs the-equality[of  $\lambda a . q = r2p a r$ ]
        by force
    qed
  }
  hence l2r:  $\forall q r . r2p r = q \longrightarrow (\exists w . (r2p w = q)) \wedge (p2r q =$ 
r)
    using p2r r2p by blast

  { fix r q assume ass:  $(\exists w . (r2p w = q)) \wedge (p2r q = r)$ 
    then obtain w where w:  $r2p w = q$  by blast
    hence unique:  $\forall a . q = r2p a \longrightarrow a = w$  using uniqueroots by
auto
    have rdef:  $r = (THE a . q = r2p a)$  using ass r2p p2r by simp

    have q = r2p w using w by simp
    hence q = r2p r using theI[of  $\lambda a . q = r2p a$ ] rdef unique
      by blast
  }
  hence  $\forall q r . (\exists w . (r2p w = q)) \wedge (p2r q = r) \longrightarrow q = r2p r$ 
    by blast

  thus ?thesis using l2r by blast
qed

have equalr2p:  $\forall x y . r2p x = r2p y \longrightarrow x = y$  using bij by metis

have SbijRoots:  $S = \{ y . \exists x \in \text{roots } a b c . y = r2p x \}$ 
proof -
  { fix y assume y:  $y \in S$ 
    then obtain r where r:  $y = r2p r$  using r2p S assms by blast
    hence regularCone x  $(p \oplus (r \otimes D))$  using r2p y S by auto
    hence  $r \in \text{roots } a b c$ 
      using lemWhereLineMeetsCone[of a D b p x c r]
      a b c X by auto
    hence  $\exists r \in \text{roots } a b c . y = r2p r$  using r by blast
  }
  hence l2r:  $S \subseteq \{ y . \exists x \in \text{roots } a b c . y = r2p x \}$  by blast
  { fix y assume y:  $y \in \{ y . \exists x \in \text{roots } a b c . y = r2p x \}$ 
    then obtain r where r:  $r \in \text{roots } a b c \wedge y = r2p r$  by blast
    hence regularCone x  $(r2p r)$ 
      using lemWhereLineMeetsCone[of a D b p x c r]
      a b c X r2p by auto
    moreover have  $r2p r \in l$  using assms(3) r2p by auto
    ultimately have  $y \in S$  using S r by auto
  }
  thus ?thesis using l2r by blast
qed

```

have *equalcard*: $((\text{card } (\text{roots } a \ b \ c) = 1) \vee (\text{card } (\text{roots } a \ b \ c) = 2))$
 $\longrightarrow (\text{card } S = \text{card } (\text{roots } a \ b \ c))$

proof –

{ **assume** *cases*: $\text{card } (\text{roots } a \ b \ c) = 1 \vee \text{card } (\text{roots } a \ b \ c) = 2$

have *case1*: $\text{card } (\text{roots } a \ b \ c) = 1 \longrightarrow (\text{card } S = \text{card } (\text{roots } a \ b \ c))$

proof –

{ **assume** *card1*: $\text{card } (\text{roots } a \ b \ c) = 1$

hence $\exists r . (\text{roots } a \ b \ c) = \{r\}$ **by** (*meson card-1-singletonE*)

then obtain *r* **where** $r: (\text{roots } a \ b \ c) = \{r\}$ **by** *blast*

hence *l2r*: $\{ r2p \ r \} \subseteq S$ **using** *SbijRoots* **by** *auto*

{ **fix** *y* **assume** $y: y \in S$

then obtain *x* **where** $x: x \in \text{roots } a \ b \ c \wedge y = r2p \ x$

using *SbijRoots* **by** *blast*

hence $r2p \ r = y$ **using** *bij* **using** *r* **by** *auto*

}

hence $\forall y . y \in S \longrightarrow y \in \{ r2p \ r \}$ **by** *auto*

hence $S = \{ r2p \ r \}$ **using** *l2r* **by** *blast*

hence $\exists r . S = \{r\}$ **by** *blast*

hence $\text{card } S = 1$

using *card-1-singleton-iff*[*of S*] **by** *auto*

}

thus *?thesis* **by** *auto*

qed

have *case2*: $\text{card } (\text{roots } a \ b \ c) = 2 \longrightarrow (\text{card } S = \text{card } (\text{roots } a \ b \ c))$

proof –

{ **assume** *card2*: $\text{card } (\text{roots } a \ b \ c) = 2$

hence $\exists r1 \ r2 . (\text{roots } a \ b \ c) = \{r1, r2\} \wedge r1 \neq r2$

using *card-2-iff* **by** *blast*

then obtain *r1 r2* **where** $rs: (\text{roots } a \ b \ c) = \{r1, r2\} \wedge r1 \neq r2$ **by** *blast*

hence *l2r*: $\{ r2p \ r1, r2p \ r2 \} \subseteq S$ **using** *SbijRoots* **by** *auto*

{ **fix** *y* **assume** $y: y \in S$

then obtain *x* **where** $x: x \in \text{roots } a \ b \ c \wedge y = r2p \ x$

using *SbijRoots* **by** *blast*

hence $x = r1 \vee x = r2$ **using** *rs* **by** *auto*

hence $r2p \ r1 = y \vee r2p \ r2 = y$ **using** *x* **by** *blast*

}

hence $\forall y . y \in S \longrightarrow y \in \{ r2p \ r1, r2p \ r2 \}$ **by** *auto*

hence $S2: S = \{ r2p \ r1, r2p \ r2 \}$ **using** *l2r* **by** *blast*

moreover **have** $r2p \ r1 \neq r2p \ r2$ **using** *rs* *bij* **by** *metis*

ultimately **have** $\exists y1 \ y2 . S = \{y1, y2\} \wedge y1 \neq y2$ **by** *blast*

hence $\text{card } S = 2$ **using** *card-2-iff* **by** *blast*

}

thus *?thesis* **by** *auto*

```

qed

  hence (card S = card (roots a b c)) using case1 cases by auto
}
thus ?thesis by auto
qed

have qc1: ¬ qcase1 a b c using cpos by auto

have qc2: ¬ qcase2 a b c
proof -
  { assume qcase2 a b c
    hence qc2: a = 0 ∧ b = 0 ∧ c > 0 using d cpos by auto

    have llD: lightlike D using qc2 aval assms(2) by simp

    have sqr (X ⊙m D) = (mNorm2 X)*(mNorm2 D)
      using qc2 bval aval by simp
    hence orthogm X D using llD lemSqrt0 by auto
    hence parXD: parallel X D
      using lemCausalOrthogmToLightlikeImpliesParallel tlX llD by
auto

    then obtain α where α: α ≠ 0 ∧ X = (α ⊗ D) by blast

    have Dnot0: origin ≠ D using assms(2) by simp
    hence lightlike X
    proof -
      have tsqr: sqr (tval X) = (sqr α)* sqr (tval D)
        using lemSqrMult α by simp
      have sComponent X = (α ⊗s (sComponent D)) using α by
simp
      hence sNorm2 (sComponent X) = (sqr α) * sNorm2 (sComponent
D)
        using lemSNorm2OfScaled[of α sComponent D] by auto
      hence mNorm2 X = (sqr α) * mNorm2 D
        using lemMNorm2Decomposition[of X] tsqr
        by (simp add: local.right-diff-distrib')
      thus ?thesis using llD qc2 xnotp X by auto
    qed

    hence False using tlX by auto
  }
thus ?thesis by auto
qed

```

```

have qc3: qcase3 a b c  $\longrightarrow$  card S = 1
proof -
  { assume qcase3 a b c
    hence qc3: qroots a b c =  $\{-c/b\}$  using lemQCase3 by auto
    hence  $\exists$  val . (qroots a b c =  $\{val\}$ ) by simp
    hence card (qroots a b c) = 1 using card-1-singleton-iff by auto
    hence card S = 1 using equalcard by auto
  }
  thus ?thesis by auto
qed

have qc4:  $\neg$  qcase4 a b c
proof -
  { assume qcase4 a b c
    hence qc4:  $a \neq 0 \wedge d < 0$  using d by auto
    { assume a > 0
      hence t1D: timelike D using aval by auto

      hence  $\text{sqr } (X \odot_m D) \geq (mNorm2 X) * (mNorm2 D)$ 
        using lemReverseCauchySchwarz[of X D] t1X
        using local.dual-order.order-iff-strict by blast
      hence EQN:  $4 * \text{sqr } (X \odot_m D) \geq 4 * (mNorm2 X) * (mNorm2$ 
D)
        using qc4 d dval local.leD by fastforce

      have  $(\text{sqr } b) < 4 * a * c$  using d qc4 by simp
      hence  $4 * \text{sqr } (X \odot_m D) < 4 * (mNorm2 X) * (mNorm2 D)$ 
        using aval bval cval mult-assoc mult-commute
          lemSqrMult[of 2 (X  $\odot_m$  D)] by auto

      hence False using EQN by force
    }
    hence aneg:  $a < 0$  using qc4 by force
    hence  $4 * a * c < 0$  using cpos
      by (simp add: local.mult-pos-neg local.mult-pos-neg2)
    hence  $d > \text{sqr } b$  using d
    by (metis add-commute local.add-less-same-cancel2 local.diff-add-cancel)
    hence  $d > 0$ 
      using local.less-trans local.not-square-less-zero qc4 by blast
    hence False using qc4 by auto
  }
  thus ?thesis by auto
qed

have qc5: qcase5 a b c  $\longrightarrow$  card S = 1
proof -
  {

```

```

    assume qc5: qcase5 a b c
    hence roots a b c =  $\{-b/(2*a)\}$  using lemQCase5 by auto
    hence  $\exists$  val . roots a b c = {val} by simp
    hence card (roots a b c) = 1 using card-1-singleton-iff by auto
    hence card S = 1 using equalcard by simp
  }
  thus ?thesis by simp
qed

have qc6: qcase6 a b c  $\longrightarrow$  card S = 2
proof -
  { define rd where rd: rd = sqrt (discriminant a b c)
    define rp where rp: rp = (-b + rd) / (2 * a)
    define rm where rm: rm = (-b - rd) / (2 * a)

    assume qc6: qcase6 a b c
    hence rp  $\neq$  rm  $\wedge$  roots a b c = {rp, rm}
      using lemQCase6[of a b c rd rp rm] a b c rd rm rp
      by auto

    hence  $\exists$  v1 v2 . roots a b c = { v1, v2 }  $\wedge$  (v1  $\neq$  v2) by blast
    hence card (roots a b c) = 2 using card-2-iff[of roots a b c]
  }
  by blast
  hence card S = 2 using equalcard by simp
}
thus ?thesis by simp
qed

define n where n: n = card S
hence (n = 1  $\vee$  n = 2)
  using qc1 qc2 qc3 qc4 qc5 qc6 lemQuadraticCasesComplete
  by blast
hence 0 < n  $\leq$  2 by auto
thus ?thesis using n S by auto
qed

end
end

```

33 Cardinalities

For our purposes the only relevant cardinalities are 0, 1, 2 and more-than-2 (a proxy for "infinite"). We will use these cardinalities when looking at how lines intersect cones, using the size of the intersection set to characterise whether points are inside, on or outside of lightcones.

```

theory Cardinalities
  imports Functions

```

begin

class *Cardinalities = Functions*
begin

lemma *lemInjectiveValueUnique*:
 assumes *injective f*
 and *isFunction f*
 and *f x y*
shows $\{ q. f x q \} = \{ y \}$
 using *assms(2) assms(3) by force*

lemma *lemBijectionOnTwo*:
 assumes *bijection f*
 and *isFunction f*
 and *s ⊆ domain f*
 and *card s = 2*
shows $\text{card } (\text{applyToSet } f s) = 2$
proof –
 obtain *x y* **where** *xy: s = {x,y} ∧ x ≠ y* **using** *assms(4)*
 by (*meson card-2-iff*)
 obtain *fx* **where** *fx: f x fx* **using** *xy assms(1) assms(3) by blast*
 obtain *fy* **where** *fy: f y fy* **using** *xy assms(1) assms(3) by blast*
 have *applyToSet f s = { q . ∃ p ∈ s . f p q }* **by** *simp*
 moreover **have** $\dots = \{ q. f x q \vee f y q \}$ **using** *xy by auto*
 moreover **have** $\dots = \{ q. f x q \} \cup \{ q. f y q \}$ **by** *auto*
 ultimately **have** *applyToSet f s = { fx } ∪ { fy }*
 using *fx fy assms(1) assms(2) lemInjectiveValueUnique by force*
 moreover **have** *fx ≠ fy* **using** *fx fy assms(1) xy by blast*
 thus *?thesis* **using** *calculation by force*
qed

lemma *lemElementsOfSet2*:
 assumes *card S = 2*
shows $\exists p q . (p \neq q) \wedge p \in S \wedge q \in S$
 by (*meson assms card-2-iff'*)

lemma *lemThirdElementOfSet2*:
 assumes $(p \neq q) \wedge p \in S \wedge q \in S \wedge (\text{card } S = 2)$
 and *r ∈ S*
shows $p = r \vee q = r$
proof –
 have *card S = 2* **using** *assms(1) by auto*

then obtain $x y$ **where** $xy: (x \in S) \wedge (y \in S) \wedge (x \neq y) \wedge (\forall z \in S. z = x \vee z = y)$
using *card-2-iff'[of S]* **by** *auto*
have $p: p = x \vee p = y$ **using** *xy assms(1)* **by** *auto*
have $q: q = x \vee q = y$ **using** *xy assms(1)* **by** *auto*
hence $pq: (p = x \wedge q = y) \vee (p = y \wedge q = x)$ **using** *assms(1)* p
by *blast*
moreover have $r = x \vee r = y$ **using** *xy assms(2)* **by** *auto*
ultimately show *?thesis* **by** *auto*
qed

lemma *lemSmallCardUnderInvertible:*

assumes *invertible f*
and $0 < \text{card } S \leq 2$
shows $\text{card } S = \text{card } (\text{applyToSet } (\text{asFunc } f) S)$
proof –
have cases: $\text{card } S = 1 \vee \text{card } S = 2$ **using** *assms(2)* **by** *auto*

have case1: $\text{card } S = 1 \longrightarrow ?thesis$
proof –
{ **assume** *card1: card S = 1*
hence $\exists a. S = \{a\}$ **by** (*meson card-1-singletonE*)
then obtain a **where** $a: S = \{a\}$ **by** *blast*
define b **where** $b: b = f a$
hence $\text{applyToSet } (\text{asFunc } f) S = \{b\}$
proof –
have $\{b\} \subseteq \text{applyToSet } (\text{asFunc } f) S$ **using** $a b$ **by** *auto*
moreover have $\text{applyToSet } (\text{asFunc } f) S \subseteq \{b\}$
proof –
{ **fix** c **assume** $c: c \in \text{applyToSet } (\text{asFunc } f) S$
hence $c \in \{c. \exists a' \in S. (\text{asFunc } f) a' c\}$ **by** *auto*
then obtain a' **where** $a': a' \in S \wedge (\text{asFunc } f) a' c$ **by** *blast*
hence $a' = a \wedge f a = c$ **using** a **by** *auto*
hence $c \in \{b\}$ **using** b **by** *auto*
}

thus *?thesis* **by** *blast*
qed
ultimately show *?thesis* **by** *blast*
qed
hence $\exists b. \text{applyToSet } (\text{asFunc } f) S = \{b\}$ **by** *blast*
hence $\text{card } (\text{applyToSet } (\text{asFunc } f) S) = 1$ **by** *auto*
}

thus *?thesis* **by** *auto*
qed

have case2: $\text{card } S = 2 \longrightarrow ?thesis$

proof –

```

{ assume card2: card S = 2
  hence  $\exists a u . a \neq u \wedge S = \{a, u\}$  by (meson card-2-iff)
  then obtain a u where au:  $a \neq u \wedge S = \{a, u\}$  by blast
  define b where b:  $b = f a$ 
  define v where v:  $v = f u$ 
  hence applyToSet (asFunc f) S = { b, v }
  proof -
    have  $\{b, v\} \subseteq \text{applyToSet } (asFunc f) S$  using au b v by auto
    moreover have  $\text{applyToSet } (asFunc f) S \subseteq \{b, v\}$ 
    proof -
      { fix c assume c:  $c \in \text{applyToSet } (asFunc f) S$ 
        hence  $c \in \{c . \exists a' \in S . (asFunc f) a' c\}$  by auto
        then obtain a' where a':  $a' \in S \wedge (asFunc f) a' c$  by blast
        hence  $(a' = a \wedge f a = c) \vee (a' = u \wedge f u = c)$  using au
      }
    by auto
    hence  $c \in \{b, v\}$  using b v by auto
  }
  thus ?thesis by blast
qed
ultimately show ?thesis by blast
qed
moreover have  $b \neq v$ 
proof -
  { assume b = v
    hence  $f a = f u$  using b v by simp
    hence  $a = u$  using assms(1) by blast
    hence False using au by auto
  }
  thus ?thesis by auto
qed
ultimately have  $\exists b v . b \neq v \wedge \text{applyToSet } (asFunc f) S = \{b, v\}$  by blast

  hence  $\text{card } (\text{applyToSet } (asFunc f) S) = 2$  using card-2-iff by
auto
}
thus ?thesis by auto
qed

thus ?thesis using cases case1 by blast
qed

```

lemma lemCardOfLineIsBig:

```

  assumes  $x \neq p$ 
  and     onLine x l  $\wedge$  onLine p l
  shows    $\exists p1 p2 p3 . (\text{onLine } p1 l \wedge \text{onLine } p2 l \wedge \text{onLine } p3 l)$ 
           $\wedge (p1 \neq p2 \wedge p2 \neq p3 \wedge p3 \neq p1)$ 
  proof -

```

obtain $b\ d$ **where** $bd: l = \text{line } b\ d$ **using** $\text{assms}(2)$ **by** blast
hence $d \neq \text{origin}$ **using** assms **by** auto
have $lpd: l = \text{line } p\ d$ **using** $\text{lemSameLine}[of\ p\ b\ d]$ $bd\ \text{assms}(2)$ **by**
 auto

define $p1$ **where** $p1: p1 = (p \oplus (1 \otimes d))$
define $p2$ **where** $p2: p2 = (p \oplus (2 \otimes d))$
define $p3$ **where** $p3: p3 = (p \oplus (3 \otimes d))$

have $onl: \text{onLine } p1\ l \wedge \text{onLine } p2\ l \wedge \text{onLine } p3\ l$ **using** $lpd\ p1\ p2$
 $p3$ **by** auto

have $psdiff: p1 \neq p2 \wedge p2 \neq p3 \wedge p3 \neq p1$
proof –

have $p1 \neq p2$ **using** $p1\ p2\ dnot0$ **by** auto
moreover **have** $p2 \neq p3$ **using** $p2\ p3\ dnot0$ **by** auto
moreover **have** $p3 \neq p1$ **using** $p3\ p1\ dnot0$ **by** auto
ultimately show $?thesis$ **by** blast

qed

hence $(\text{onLine } p1\ l \wedge \text{onLine } p2\ l \wedge \text{onLine } p3\ l) \wedge (p1 \neq p2 \wedge p2 \neq p3$
 $\wedge p3 \neq p1)$

using onl **by** blast

thus $?thesis$ **using** $p1\ p2\ p3$ **by** meson
qed

end
end

34 AffineConeLemma

This theory shows that affine approximations preserve "inside-ness" of points relative to cones.

theory AffineConeLemma
imports $\text{KeyLemma}\ \text{TangentLineLemma}\ \text{Cardinalities}$
begin

class $\text{AffineConeLemma} = \text{KeyLemma} + \text{TangentLineLemma} + \text{Cardinalities}$
begin

lemma $\text{lemInverseOfAffInvertibleIsAffInvertible}$:
assumes $\text{affInvertible } A$
and $\forall x\ y. A\ x = y \iff A'\ y = x$
shows $\text{affInvertible } A'$
proof –

```

have invA': invertible A' using assms(2) by force
moreover have affine A'
proof –
  obtain L T where LT: (linear L)  $\wedge$  (translation T)  $\wedge$  (A = T  $\circ$ 
L)
    using assms(1) by blast
    then obtain t where t:  $\forall x . T x = (x \oplus t)$  using LT by auto

have invertible L
proof –
  { fix q
    define p where p: p = A' (T q)
    hence Lpq: (L p = q)
    proof –
      have A p = T q using p assms(2) by simp
      thus ?thesis using LT by auto
    qed
    moreover have ( $\forall x . L x = q \longrightarrow x = p$ )
    proof –
      { fix x assume L x = q
        hence L x = L p using Lpq by simp
        hence A x = A p using LT by auto
        hence x = p using assms(2) by force
      }
    thus ?thesis by auto
    qed
    ultimately have  $\exists p . (L p = q) \wedge (\forall x . L x = q \longrightarrow x = p)$ 
by blast
  }
  thus ?thesis by blast
qed
then obtain L' where L':  $\forall x y . L x = y \longleftrightarrow L' y = x$  by metis

have linL: linear L using LT by auto
have linL': linear L'
proof –
  have part1: L' origin = origin using linL L' by auto
  have part2:  $\forall a p . L' (a \otimes p) = (a \otimes (L' p))$ 
  proof –
    { fix a p
      have L (L' p) = p using L' by auto
      hence L (a  $\otimes$  (L' p)) = (a  $\otimes$  p)
      using linL lemLinearProps[of L a (L' p)] by auto
      hence (a  $\otimes$  (L' p)) = (L' (a  $\otimes$  p)) using L' by auto
    }
    thus ?thesis by auto
  qed
  have  $\forall p q . (L' (p \oplus q) = ((L' p) \oplus (L' q))) \wedge (L' (p \ominus q) =$ 
 $((L' p) \ominus (L' q)))$ 

```

```

proof -
  { fix  $p\ q$ 
    have  $(L ((L' p) \oplus (L' q)) = ((L (L' p)) \oplus (L (L' q))))$ 
       $\wedge (L ((L' p) \ominus (L' q)) = ((L (L' p)) \ominus (L (L' q))))$ 
    using  $\text{linL lemLinearProps[of L 0 (L' p) (L' q)]}$  by auto
    moreover have  $L (L' p) = p \wedge L (L' q) = q$  using  $L'$  by
auto
    ultimately have  $(L ((L' p) \oplus (L' q)) = (p \oplus q)) \wedge (L ((L'
p) \ominus (L' q)) = (p \ominus q))$ 
      using  $L'$  by auto
      hence  $((L' p) \oplus (L' q)) = L' (p \oplus q) \wedge ((L' p) \ominus (L' q)) =
L' (p \ominus q)$ 
        using  $L'$  by force
      }
    thus ?thesis by force
  } qed

thus ?thesis using part1 part2 by blast
qed

define  $t'$  where  $t': t' = (\text{origin} \ominus (L' t))$ 
define  $T'$  where  $T': T' = \text{mkTranslation } t'$ 

have  $\text{trans}T'$ : translation  $T'$  using  $T' t'$  by fastforce

have  $A' = T' \circ L'$ 
proof -
  { fix  $q$  define  $p$  where  $p: p = A' q$ 
    hence  $A p = q$  using assms(2) by force
    hence  $((L p) \oplus t) = q$  using  $LT\ t$  by auto
    hence  $L p = (q \ominus t)$  using add-diff-eq by auto
    hence  $p = L' (q \ominus t)$  using  $L'$  by auto
    hence  $p = ((L' q) \ominus (L' t))$  using  $\text{lemLinearProps[of L'] linL'}$ 
  } by auto
  hence  $p = T' (L' q)$  using  $T' t'$  by auto
  hence  $A' q = (T' \circ L') q$  using  $p$  by auto
  }
  thus ?thesis by blast
qed

thus ?thesis using  $\text{linL' trans}T'$  by blast
qed

ultimately show ?thesis by blast
qed

```

```

lemma lemInsideRegularConeUnderAffInvertible:
  assumes affInvertible A
  and     insideRegularCone x p
  and     regularConeSet (A x) = applyToSet (asFunc A) (regularConeSet x)
  shows   insideRegularCone (A x) (A p)
  proof -
    define y where y: y = A x
    define q where q: q = A p
    define cx where cx: cx = regularConeSet x
    define cy where cy: cy = regularConeSet y

    obtain A' where A':  $\forall x y . A x = y \longleftrightarrow A' y = x$  using assms(1)
  by metis
    hence invA': invertible A' by force
    have affA': affine A'
      using A' assms(1) lemInverseOfAffInvertibleIsAffInvertible
      by auto

    have p': A' q = p using A' q by auto
    have x': A' y = x using A' y by auto

    have xnotp: x  $\neq$  p using assms(2) by auto
    have ynotq: y  $\neq$  q using p' x' xnotp by auto

    have cy': cy = applyToSet (asFunc A) cx using y cx cy assms(3)
  by auto
    have cx': cx = applyToSet (asFunc A') cy
  proof -
    { fix z assume z  $\in$  cx
      hence (A z)  $\in$  cy using cy' by auto
      hence A' (A z)  $\in$  applyToSet (asFunc A') cy by auto
      hence z  $\in$  applyToSet (asFunc A') cy using A' by metis
    }
    hence l2r: cx  $\subseteq$  applyToSet (asFunc A') cy by blast
    { fix z assume rhs: z  $\in$  applyToSet (asFunc A') cy
      hence z  $\in$  { z .  $\exists z' . z'  $\in$  cy  $\wedge$  (asFunc A') z' z }$  by auto
      then obtain z1 where z1: z1  $\in$  cy  $\wedge$  (asFunc A') z1 z by blast
      hence z1  $\in$  { z1 .  $\exists z2 . z2  $\in$  cx  $\wedge$  (asFunc A) z2 z1 }$  using
    cy' by auto
      then obtain z2 where z2: z2  $\in$  cx  $\wedge$  (asFunc A) z2 z1 by blast
      hence z = z2 using z1 A' by auto
      hence z  $\in$  cx using z2 by auto
    }
    thus ?thesis using l2r by blast
  qed

```

```

have noton:  $\neg$  onRegularCone y q
proof -
  { assume on: onRegularCone y q

    define lx where lx: lx = lineJoining x p
    define ly where ly': ly = applyToSet (asFunc A) lx
    have onlx: onLine x lx  $\wedge$  onLine p lx
      using lemLineJoiningContainsEndPoints[of lx x p] lx by auto

    have linelx: isLine lx using lx by blast
    have linely: applyAffineToLine A lx ly
      using lemAffineOfLineIsLine[of lx A ly] assms(1) ly' linelx by
auto

    have  $\exists$  D . lx = line p D
    proof -
      obtain b d where lx = line b d using linelx by blast
      hence lx = line p d using lemSameLine[of p b d] onlx by auto
      thus ?thesis by auto
    qed
    then obtain D where D: lx = line p D by auto

    have Dnot0: D  $\neq$  origin
    proof -
      { assume D = origin
        hence False using D onlx xnotp by auto
      }
      thus ?thesis by auto
    qed

    have ly: ly = lineJoining y q
    proof -
      have applyToSet (asFunc A) {x,p}  $\subseteq$  applyToSet (asFunc A)
lx using onlx by auto
      hence {y,q}  $\subseteq$  ly using y q ly' by auto
      moreover have isLine ly using linely by auto
      ultimately show ?thesis using lemLineAndPoints[of y q ly]
      by (simp add: ynotq)
    qed

    hence only: { y, q }  $\subseteq$  ly
      using lemLineJoiningContainsEndPoints[of ly y q] ly' by auto

    have SxSy: applyToSet (asFunc A) (lx  $\cap$  cx) = (ly  $\cap$  cy)
      using lemInvertibleOnMeet[of A lx  $\cap$  cx lx cx] assms(1) ly' cy'
      by auto

    have cardx: 0 < card (lx  $\cap$  cx)  $\leq$  2

```

```

using lemInsideRegularConeImplies[of  $x$   $p$   $D$   $lx$ ]
      assms(2) Dnot0  $lx$   $D$   $cx$ 
by fastforce

hence cardy:  $\text{card } (ly \cap cy) = \text{card } (lx \cap cx)$ 
      using lemSmallCardUnderInvertible[of  $A$   $lx \cap cx$ ] assms(1)
SxSy by auto

hence lycy:  $ly \cap cy = ly$ 
      using lemOnRegularConeIff[of  $ly$   $y$   $q$ ] ly ynotq cy on
      by blast
hence  $\exists p1\ p2\ p3 . (p1 \in ly \wedge p2 \in ly \wedge p3 \in ly)$ 
       $\wedge (p1 \neq p2 \wedge p2 \neq p3 \wedge p3 \neq p1)$ 
      using lemCardOfLineIsBig[of  $y$   $q$   $ly$ ] ynotq only linely by auto
then obtain  $p1\ p2\ p3$ 
      where  $ps$ :  $(p1 \in ly \wedge p2 \in ly \wedge p3 \in ly) \wedge (p1 \neq p2 \wedge p2 \neq p3$ 
 $\wedge p3 \neq p1)$ 
      by auto

      have not1:  $\text{card } ly \neq 1$  using  $ps$  card-1-singleton-iff[of  $ly$ ] by
auto
      have not2:  $\text{card } ly \neq 2$  using  $ps$  card-2-iff[of  $ly$ ] by auto
      hence  $\neg (0 < \text{card } (ly \cap cy) \leq 2)$  using lycy not1 by auto
      hence False using cardy cardx by auto
    }
thus ?thesis by blast
qed

have notout:  $\neg \text{outsideRegularCone } y\ q$ 
proof –
  { assume out: outsideRegularCone  $y\ q$ 
    hence  $(\exists l\ q' . (q' \neq q) \wedge \text{onLine } q'\ l \wedge \text{onLine } q\ l$ 
       $\wedge (l \cap cy = \{\}))$ 
    using lemOutsideRegularConeImplies[of  $y$   $q$ ] cy
    by auto
    then obtain  $l\ q'$ 
    where  $l$ :  $(q' \neq q) \wedge \text{onLine } q'\ l \wedge \text{onLine } q\ l \wedge (l \cap cy = \{\})$ 
  }
by blast

define  $lx$  where  $lx$ :  $lx = \text{applyToSet } (asFunc\ A')\ l$ 
have  $(lx \cap cx) = \text{applyToSet } (asFunc\ A')\ (l \cap cy)$ 
using lemInvertibleOnMeet[of  $A'$   $l \cap cy$   $l\ cy$ ]
      invA'  $lx$   $cx'$  by auto
hence  $(lx \cap cx) = \text{applyToSet } (asFunc\ A')\ \{\}$  using  $l$  by auto
hence int0:  $(lx \cap cx) = \{\}$  by simp

hence card0:  $\text{card } (lx \cap cx) = 0$  by simp

```



```

have linelx: isLine lx
proof -
  have isLine l using l by blast
  thus ?thesis using lemAffineOfLineIsLine[of l A' lx] lx affA'
  by auto
qed

have ponlx: onLine p lx
proof -
  have  $q \in l$  using l by simp
  thus ?thesis using lx p' linelx by auto
qed

have  $\exists D . lx = line\ p\ D$ 
proof -
  obtain b d where lx = line b d using linelx by blast
  hence lx = line p d using lemSameLine[of p b d] ponlx by auto
  thus ?thesis by auto
qed
then obtain D where D: lx = line p D by auto

have Dnot0: D  $\neq$  origin
proof -
  { assume D0: D = origin
    have allp:  $\forall pt. onLine\ pt\ lx \longrightarrow pt = p$ 
    proof -
      { fix pt assume onLine pt lx
        then obtain a where  $pt = (p \oplus (a \otimes D))$  using D by
          auto
          hence  $pt = p$  using D0 by simp
        }
      thus ?thesis by blast
    }
  qed

define p1 where p1:  $p1 = A' q'$ 
have AA':  $\forall pt . A (A' pt) = pt$  by (simp add: A')

hence  $p1 \neq p$ 
proof -
  { assume pp:  $p1 = p$ 
    hence  $A (A' q') = A (A' q)$  using p' p1 by auto
    hence  $q' = q$  using AA' by simp
    hence False using l by auto
  }
  thus ?thesis by auto
qed

```

```

moreover have onLine p1 lx
proof –
  have  $p1 = A' q'$  using l p1 by blast
  hence  $p1 \in \text{applyToSet } (asFunc A') l$  using l by auto
  hence  $p1 \in lx$  by (simp add: lx)
  thus ?thesis using linelx by auto
qed

  ultimately have False using l allp by blast
}
thus ?thesis by auto
qed

have  $0 < \text{card } (lx \cap cx) \leq 2$ 
using lemInsideRegularConeImplies[of x p D lx]
  assms(2) Dnot0 D cx
by blast

  hence False using card0 by simp
}
thus ?thesis by blast
qed

hence  $\neg (\text{vertex } y q) \wedge \neg (\text{onRegularCone } y q) \wedge \neg (\text{outsideRegularCone } y q)$ 
using ynotq noton notout by blast
hence insideRegularCone y q using lemInsideCone[of y q]
by fastforce

thus ?thesis using y q by blast
qed

end
end

```

35 NoFTLGR

This theory completes the proof of NoFTLGR.

```

theory NoFTLGR
  imports ObserverConeLemma AffineConeLemma
begin

  class NoFTLGR = ObserverConeLemma + AffineConeLemma
begin

```

The theorem says: if observer m encounters observer k (so that

they are both present at the same spacetime point x), then k is moving at sub-light speed relative to m . In other words, no observer ever encounters another observer who appears to be moving at or above lightspeed.

theorem *lemNoFTLGR*:

assumes $ass1: x \in wline\ m\ m \cap wline\ m\ k$
and $ass2: tl\ l\ m\ k\ x$
and $ass3: v \in lineVelocity\ l$
and $ass4: \exists\ p . (p \neq x) \wedge (p \in l)$
shows $(lineSlopeFinite\ l) \wedge (sNorm2\ v < 1)$
proof –

define s **where** $s: s = (wline\ k\ k)$

have $axEventMinus\ m\ k\ x$ **using** $AxEventMinus$ **by** *force*
hence $(\exists\ q . \forall\ b . (m\ sees\ b\ at\ x) \longleftrightarrow (k\ sees\ b\ at\ q))$
using $ass1$ **by** *blast*
then obtain y **where** $y: \forall\ b . (m\ sees\ b\ at\ x) \longleftrightarrow (k\ sees\ b\ at\ y)$ **by** *auto*
hence $mkxy: wvtFunc\ m\ k\ x\ y$ **using** $ass1$ **by** *auto*

have $axDiff\ m\ k\ x$ **using** $AxDiff$ **by** *simp*
hence $\exists\ A . (affineApprox\ A\ (wvtFunc\ m\ k)\ x)$ **using** $mkxy$ **by** *fast*
then obtain A **where** $A: affineApprox\ A\ (wvtFunc\ m\ k)\ x$ **by** *auto*

hence $affA: affine\ A$ **by** *auto*
have $lineL: isLine\ l$ **using** $ass2$ **by** *auto*

define l' **where** $l': l' = applyToSet\ (asFunc\ A)\ l$

hence $lineL': isLine\ l'$
using $lineL\ affA\ lemAffineOfLineIsLine[of\ l\ A\ l']$
by *auto*

have $tglt': tangentLine\ l'\ s\ y$

proof –

define $g1$ **where** $g1: g1 \equiv x \in wline\ m\ k$
define $g2$ **where** $g2: g2 \equiv tangentLine\ l\ (wline\ m\ k)\ x$
define $g3$ **where** $g3: g3 \equiv affineApprox\ A\ (wvtFunc\ m\ k)\ x$
define $g4$ **where** $g4: g4 \equiv wvtFunc\ m\ k\ x\ y$
define $g5$ **where** $g5: g5 \equiv applyAffineToLine\ A\ l\ l'$
define $g6$ **where** $g6: g6 \equiv tangentLine\ l'\ (wline\ k\ k)\ y$

have $x \in wline\ m\ k$
 $\longrightarrow tangentLine\ l\ (wline\ m\ k)\ x$
 $\longrightarrow affineApprox\ A\ (wvtFunc\ m\ k)\ x$
 $\longrightarrow wvtFunc\ m\ k\ x\ y$
 $\longrightarrow applyAffineToLine\ A\ l\ l'$

$\longrightarrow \text{tangentLine } l' \text{ (wline } k \text{ } k) \text{ } y$
using *lemPresentation*[of $x \ m \ k \ l \ k \ A \ y \ l'$]
by *blast*

hence *pres*: $g1 \longrightarrow g2 \longrightarrow g3 \longrightarrow g4 \longrightarrow g5 \longrightarrow g6$
using $g1 \ g2 \ g3 \ g4 \ g5 \ g6$ **by** *fastforce*

have 1 : $g1$ **using** *ass1* $g1$ **by** *auto*
have 2 : $g2$ **using** *ass2* $g2$ **by** *fast*
have 3 : $g3$ **using** $A \ g3$ **by** *fast*
have 4 : $g4$ **using** *mkxy* $g4$ **by** *fast*
have 5 : $g5$ **using** $1 \ \text{lineL } l' \ \text{affA } \text{lemAffineOfLineIsLine}$ [of $l \ A \ l'$]
 $g5$
by *auto*

hence $g6$ **using** $1 \ 2 \ 3 \ 4 \ 5 \ \text{pres}$ **by** *meson*
thus *?thesis* **using** $s \ g6$ **by** *auto*
qed

have *ykk*: $y \in \text{wline } k \ k$ **using** *ass1* y **by** *auto*

have $c2$: $l' = \text{timeAxis}$
proof –
have $tl \ l' \ k \ k \ y$ **using** *tgll'* $l' \ s$ **by** *auto*
thus *?thesis*
using *lemSelfTangentIsTimeAxis*[of $y \ k \ l'$] **by** *auto*
qed

have *yOnAxis*: $\text{onLine } y \ \text{timeAxis}$
using *lemTimeAxisIsLine* *ykk* $AxSelfMinus$ **by** *blast*

hence *yOnl'*: $\text{onLine } y \ l'$ **using** $c2$ **by** *auto*

have $\forall p . \text{cone } k \ y \ p \longleftrightarrow \text{regularCone } y \ p$
using *ykk* *lemProposition1*[of $y \ k$] **by** *auto*
hence *ycone*: $\text{coneSet } k \ y = \text{regularConeSet } y$ **by** *auto*

have *xcone*: $\text{coneSet } m \ x = \text{regularConeSet } x$
proof –
have $x \in \text{wline } m \ m$ **using** *ass1* **by** *auto*
hence $\forall p . \text{cone } m \ x \ p \longleftrightarrow \text{regularCone } x \ p$
using *lemProposition1*[of $x \ m$] **by** *auto*
thus *?thesis* **by** *auto*
qed

have $assm1'$: $y \in wline\ k\ k \cap wline\ k\ m$
using $ass1\ y$ **by** $auto$
have $axEventMinus\ k\ m\ y$ **using** $AxEventMinus$ **by** $force$
hence $(\exists\ q . \forall\ b . (k\ sees\ b\ at\ y) \longleftrightarrow (m\ sees\ b\ at\ q))$
using $assm1'$ **by** $blast$
then obtain z **where** z : $\forall\ b . (k\ sees\ b\ at\ y) \longleftrightarrow (m\ sees\ b\ at\ z)$
by $auto$
hence $kmyz$: $wtFunc\ k\ m\ y\ z$ **using** $assm1'$ **by** $auto$

have $axDiff\ k\ m\ y$ **using** $AxDiff$ **by** $simp$
hence $\exists\ A . (affineApprox\ A\ (wtFunc\ k\ m)\ y)$ **using** $kmyz$ **by** $fast$
then obtain $Akmy$ **where** $Akmy$: $affineApprox\ Akmy\ (wtFunc\ k\ m)\ y$ **by** $auto$

hence $affA'$: $affine\ Akmy$ **by** $auto$
have $invA'$: $invertible\ Akmy$ **using** $Akmy$ **by** $auto$

then obtain $Amkx$ **where**
 $Amkx$: $(affine\ Amkx) \wedge (\forall\ p\ q . Akmy\ p = q \longleftrightarrow Amkx\ q = p)$
using $lemInverseAffine[of\ Akmy]$ $affA'$ **by** $blast$

have $wtFunc\ m\ k\ x\ y$ **using** $mkxy$ **by** $auto$
hence $kmyx$: $wtFunc\ k\ m\ y\ x$ **by** $auto$
hence $xisz$: $x = z$ **using** $kmyz$ $lemWVTImpliesFunction$ **by** $blast$

moreover have $z = Akmy\ y$
using $lemAffineEqualAtBase[of\ wtFunc\ k\ m\ Akmy\ y]$ $Akmy\ kmyz$
by $blast$
ultimately have $xA'y$: $x = Akmy\ y$ **by** $auto$

hence $p35a$: $applyToSet\ (asFunc\ Akmy)\ (coneSet\ k\ y) \subseteq coneSet\ m$
 x
using $Akmy\ lemProposition2[of\ k\ m\ Akmy\ y]$
by $simp$

have $p35aRegular$: $applyToSet\ (asFunc\ Akmy)\ (regularConeSet\ y)$
 $=\ regularConeSet\ x$
proof –
have $applyToSet\ (asFunc\ Akmy)\ (regularConeSet\ y) \subseteq coneSet\ m$
 x
using $ycone\ p35a$ **by** $auto$
hence $l2r$: $applyToSet\ (asFunc\ Akmy)\ (regularConeSet\ y) \subseteq regularConeSet\ x$

```

using xcone by auto

have r2l: regularConeSet x  $\subseteq$  applyToSet (asFunc Akmy) (regularConeSet
y)
  proof -
    { assume converse:  $\neg$ (regularConeSet x  $\subseteq$  applyToSet (asFunc
Akmy) (regularConeSet y))
      then obtain z where
        z: z  $\in$  regularConeSet x  $\wedge$   $\neg$ (z  $\in$  applyToSet (asFunc Akmy)
(regularConeSet y))
          by blast
        define z' where z': z' = Amkx z

        have z'NotOnCone:  $\neg$ (z'  $\in$  regularConeSet y)
          proof -
            { assume conv: z'  $\in$  regularConeSet y
              have Akmy z' = z using Amkx z' by auto
              hence (asFunc Akmy) z' z by auto
              hence  $\exists$  z'  $\in$  regularConeSet y . (asFunc Akmy) z' z using
conv by blast
            }
            hence z  $\in$  applyToSet (asFunc Akmy) (regularConeSet y)
          by auto
            hence False using z by blast
          }
          thus ?thesis by blast
        qed

        hence  $\neg$  (regularCone y z') by auto
        then obtain l where
          l: (onLine z' l)  $\wedge$  ( $\neg$  (y  $\in$  l))  $\wedge$  (card (l  $\cap$  (regularConeSet y))
= 2)
            using lemConeLemma2[of z' y] by blast
            then obtain p q where
              pq: (p  $\neq$  q)  $\wedge$  p  $\in$  (l  $\cap$  (regularConeSet y))  $\wedge$  q  $\in$  (l  $\cap$ 
(regularConeSet y))
                using lemElementsOfSet2[of l  $\cap$  (regularConeSet y)] by blast

            have lineL: isLine l using l by auto

            define p' where p': p' = Akmy p
            define q' where q': q' = Akmy q
            have p'inv: Amkx p' = p using Amkx p' by auto
            have q'inv: Amkx q' = q using Amkx q' by auto

            have pOnCone: p  $\in$  regularConeSet y using pq by blast
            moreover have (asFunc Akmy) p p' using p' by auto
            ultimately have  $\exists$  p  $\in$  regularConeSet y . (asFunc Akmy) p
p' by blast
            hence p  $\in$  applyToSet (asFunc Akmy) (regularConeSet y) by

```

```

auto
  hence  $A_p: p' \in \text{regularConeSet } x$  using  $l2r$  by blast

  have  $q_{\text{OnCone}}: q \in \text{regularConeSet } y$  using  $pq$  by blast
  moreover have  $(\text{asFunc } Akmy) q q'$  using  $q'$  by auto
  ultimately have  $\exists q \in \text{regularConeSet } y . (\text{asFunc } Akmy) q$ 
q' by blast
  hence  $q' \in \text{applyToSet } (\text{asFunc } Akmy) (\text{regularConeSet } y)$  by
auto
  hence  $A_q: q' \in \text{regularConeSet } x$  using  $l2r$  by blast

  have  $p'q': p' \neq q'$ 
  proof -
    { assume  $p' = q'$ 
      hence  $Akmy p' = Akmy q'$  by auto
      hence  $p = q$  by  $(metis p' q' Amkx)$ 
      hence False using  $pq$  by simp
    }
    thus ?thesis by auto
  qed

  have  $p'z: p' \neq z$ 
  proof -
    { assume  $p' = z$ 
      hence  $p = z'$  using  $p'inv z'$  by auto
      hence False using  $p_{\text{OnCone}} z'_{\text{NotOnCone}}$  by auto
    }
    thus ?thesis by auto
  qed

  have  $q'z: q' \neq z$ 
  proof -
    { assume  $q' = z$ 
      hence  $q = z'$  using  $q'inv z'$  by auto
      hence False using  $q_{\text{OnCone}} z'_{\text{NotOnCone}}$  by auto
    }
    thus ?thesis by auto
  qed

  define  $l'$  where  $l': l' = \text{applyToSet } (\text{asFunc } Akmy) l$ 
  have affine  $Akmy$  using  $Akmy$  by auto
  hence  $All': \text{applyAffineToLine } Akmy l l'$ 
    using  $l' \text{ lineL } lemAffineOfLineIsLine[\text{of } l Akmy l']$ 
    by blast

  have  $lineL': isLine l'$  using  $All'$  by auto

  define  $S$  where  $S: S = l' \cap \text{regularConeSet } x$ 

```

```

have  $xNotInL'$ :  $\neg (x \in l')$ 
proof -
  { assume  $x \in l'$ 
    hence  $\exists y1 \in l . (asFunc Akmy) y1 x$  using  $l'$  by auto
    then obtain  $y1$  where  $y1: (y1 \in l) \wedge (Akmy y1 = x)$  by
auto
    hence  $Akmy y1 = Akmy y$  using  $xA'y$  by auto
    hence  $y1 = y$  using  $invA'$  by auto
    hence  $y \in l$  using  $y1$  by auto
    hence  $False$  using  $l$  by auto
  }
  thus ?thesis by auto
qed

have  $p'InMeet$ :  $p' \in S$ 
proof -
  have  $p \in l \wedge (asFunc Akmy) p p'$  using  $p' pq$  by auto
  hence  $\exists p \in l . (asFunc Akmy) p p'$  by auto
  hence  $p' \in l'$  using  $l'$  by auto
  thus ?thesis using  $Ap S$  by blast
qed

have  $q'InMeet$ :  $q' \in S$ 
proof -
  have  $q \in l \wedge (asFunc Akmy) q q'$  using  $q' pq$  by auto
  hence  $\exists q \in l . (asFunc Akmy) q q'$  by auto
  hence  $q' \in l'$  using  $l'$  by auto
  thus ?thesis using  $Aq S$  by blast
qed

have  $zInMeet$ :  $z \in S$ 
proof -
  have  $Akmy z' = z$  using  $z' Amkx$  by blast
  moreover have  $z' \in l$  using  $l$  by auto
  ultimately have  $z' \in l \wedge (asFunc Akmy) z' z$  by auto
  hence  $\exists z' \in l . (asFunc Akmy) z' z$  by auto
  hence  $z \in l'$  using  $l'$  by auto
  thus ?thesis using  $z S$  by blast
qed

have  $finite S \wedge card S \leq 2$ 
  using  $xNotInL' lineL' S lemConeLemma1[of x l' S]$ 
  by auto

moreover have  $S \neq \{\}$  using  $zInMeet$  by auto

ultimately have  $card S = 1 \vee card S = 2$ 
  using  $card-0-eq$  by fastforce

```



```

moreover have card S ≠ 2
proof –
  { assume card S = 2
    hence  $p' = z \vee q' = z$ 
      using p'q' p'InMeet q'InMeet zInMeet
            lemThirdElementOfSet2[of p' q' S z]
      by auto
    hence False using  $p'z$   $q'z$  by auto
  }
thus ?thesis by auto
qed

```

```

moreover have card S ≠ 1
using p'InMeet q'InMeet p'q' card-1-singletonE by force

```

```

  ultimately have False by blast
}
thus ?thesis by blast
qed
thus ?thesis using l2r by blast
qed

```

```

have lprops:  $l = \text{applyToSet } (\text{asFunc } Akmy) \text{ timeAxis}$ 
proof –
  define t' where  $t' = \text{applyToSet } (\text{asFunc } Akmy) \text{ timeAxis}$ 

  define p1 where  $p1: p1 = (y \in \text{wline } k \ k)$ 
  define p2 where  $p2: p2 = \text{tangentLine } \text{timeAxis } (\text{wline } k \ k) \ y$ 
  define p3 where  $p3: p3 = \text{affineApprox } Akmy \ (\text{wvtFunc } k \ m) \ y$ 
  define p4 where  $p4: p4 = \text{wvtFunc } k \ m \ y \ x$ 
  define p5 where  $p5: p5 = \text{applyAffineToLine } Akmy \ \text{timeAxis } t'$ 

  define tgt where  $tgt: tgt = \text{tangentLine } t' \ (\text{wline } m \ k) \ x$ 

  have pre1: p1 using p1 ykk by auto
  have pre2: p2
  proof –
    have  $\text{tangentLine } l' \ (\text{wline } k \ k) \ y$  using tgtl' s by auto
    hence  $\text{tangentLine } \text{timeAxis } (\text{wline } k \ k) \ y$  using c2 by meson
    thus ?thesis using p2 by blast
  qed
  have pre3: p3 using p3 Akmy by auto
  have pre4: p4 using p4 kmyx by auto
  have pre5: p5

```

using $p5$ $affA'$ $lemTimeAxisIsLine$ t' $Akmy$
 $lemAffineOfLineIsLine$ [of $timeAxis$ $Akmy$ t']
by $blast$

have $p1 \rightarrow p2 \rightarrow p3 \rightarrow p4 \rightarrow p5 \rightarrow tgt$
using $p1$ $p2$ $p3$ $p4$ $p5$ tgt
 $lemPresentation$ [of y k k $timeAxis$ m $Akmy$ x t']
by $fast$
hence tl t' m k x **using** tgt $pre1$ $pre2$ $pre3$ $pre4$ $pre5$ **by** $auto$
moreover **have** tl l m k x **using** $ass2$ **by** $auto$
moreover **have** $affineApprox$ A ($wotFunc$ m k) x **using** A **by** $auto$
moreover **have** $wotFunc$ m k x y **using** $mkxy$ **by** $auto$
moreover **have** $x \in wline$ m k **using** $ass1$ **by** $auto$
ultimately **have** $t' = l$
using $lemTangentLineUnique$ [of x m k t' l A y]
by $fast$
thus $?thesis$ **using** t' **by** $blast$
qed

{ **fix** py **assume** $py: onTimeAxis$ $py \wedge py \neq y$

have $pyInsideCone: insideRegularCone$ y py
proof –
have $pyOnAxis: onLine$ py $timeAxis$ **using** py $lemTimeAxisIsLine$
by $blast$

hence $pyprops: timeAxis = lineJoining$ y py
using py $yOnAxis$ $lemLineAndPoints$ [of y py $timeAxis$] **by** $auto$

define d **where** $d: d = (y \ominus py)$
hence \exists py $y . (py \neq y) \wedge (onLine$ py $timeAxis)$
 $\wedge (onLine$ y $timeAxis) \wedge (d = (y \ominus py))$
using py $pyOnAxis$ $yOnAxis$ **by** $blast$
hence $ddrtn: d \in drtn$ $timeAxis$ **by** $simp$

have $scomp0: sComponent$ $d = sOrigin$ **using** d py $yOnAxis$ **by**
 $auto$

have $sf: slopeFinite$ py y **using** py $yOnAxis$ **by** $force$
hence $sloper$ py $y = ((-1) \otimes ((1 / (tval$ $py - tval$ $y)) \otimes d))$
using d **by** $auto$
hence $velocityJoining$ py $y = sOrigin$ **using** $scomp0$ **by** $simp$
hence $velocityJoining$ $origin$ $d = sOrigin$ **using** d **by** $auto$

hence $(d \in drtn$ $timeAxis) \wedge (sOrigin = velocityJoining$ $origin$
 $d)$
using $ddrtn$ **by** $auto$

hence $\exists d . (d \in \text{drtn } \text{timeAxis}) \wedge (sOrigin = \text{velocityJoining } \text{origin } d)$
by *blast*
hence $(sOrigin \in \text{lineVelocity } \text{timeAxis})$ **by** *auto*

hence $(sOrigin \in \text{lineVelocity } \text{timeAxis}) \wedge (sNorm2 \text{ } sOrigin < 1)$
by *auto*
hence $\exists v . (v \in \text{lineVelocity } \text{timeAxis}) \wedge (sNorm2 \text{ } v < 1)$
by *blast*
thus *?thesis using pyprops sf* **by** *auto*
qed

define *px* **where** *px*: *px* = *Akmy py*

have *insideRegularCone x px*

proof –

have *insideRegularCone y py* **using** *pyInsideCone* **by** *blast*

moreover **have** *affInvertible Akmy* **using** *affA' invA'* **by** *blast*

moreover **have** $x = \text{Akmy } y$ **by** (*simp add: xA'y*)

moreover **have** $px = \text{Akmy } py$ **by** (*simp add: px*)

moreover **have** *regularConeSet x = applyToSet (asFunc Akmy)*

(*regularConeSet y*)

using *p35aRegular* **by** *simp*

ultimately **show** *?thesis*

using *lemInsideRegularConeUnderAffInvertible[of Akmy y py]*

by *auto*

qed

moreover **have** $x \neq px$

proof –

{ **assume** *xispx:x = px*

hence *False* **using** *xispx invA' px xA'y py* **by** *auto*

}

thus *?thesis* **by** *auto*

qed

ultimately **have** *insideRegularCone x (Akmy py) \wedge x \neq (Akmy py)*

using *px* **by** *blast*

}

hence *result: $\forall py . (\text{onTimeAxis } py \wedge py \neq y)$*

\longrightarrow *insideRegularCone x (Akmy py) \wedge x \neq (Akmy*

py)

by *blast*

{

obtain p **where** $p: (p \neq x) \wedge (p \in l)$ **using** $assms(4)$ **by** *blast*

have $l = applyToSet (asFunc Akmy) timeAxis$ **using** $lprops$ **by** *simp*

hence $p \in \{ p . \exists py \in timeAxis . (asFunc Akmy) py p \}$ **using** p **by** *auto*

then obtain py **where** $py: py \in timeAxis \wedge (asFunc Akmy) py p$ **by** *blast*

hence $onTimeAxis py$ **by** *blast*

moreover have $py \neq y$

proof –

- { **assume** $py = y$
- hence** $False$ **using** $py p$ **by** (*simp add: xA'y*)
- }

thus *?thesis* **by** *auto*

qed

ultimately have $onTimeAxis py \wedge py \neq y$ **by** *blast*

hence $inside: insideRegularCone x p \wedge x \neq p$ **using** $result py$ **by** *auto*

have $onl: onLine x l \wedge onLine p l$ **using** $ass2$ **using** p **by** *blast*

have $pnotx: p \neq x$ **using** $inside$ **by** *auto*

hence $xnotp: x \neq p$ **by** *simp*

hence $lj: l = lineJoining x p$

using $lemLineAndPoints[of x p l]$ $xnotp onl$ **by** *auto*

hence $lineSlopeFinite l$ **using** $onl inside$ **by** *blast*

moreover have $(sNorm2 v < 1)$

proof –

- have** $(\exists v \in lineVelocity l . sNorm2 v < 1)$ **using** $lj inside$ **by** *auto*

then obtain u **where** $u: u \in lineVelocity l \wedge sNorm2 u < 1$ **by** *blast*

hence $u = v$

using $lemFiniteLineVelocityUnique[of u l v]$ $ass3$ *calculation* **by** *presburger*

thus *?thesis* **using** u **by** *auto*

qed

ultimately have $(lineSlopeFinite l) \wedge (sNorm2 v < 1)$ **by** *auto*

thus *?thesis* **by** *auto*

qed

end

end

References

- [1] M. Stannett and I. Németi. Using Isabelle/HOL to verify first-order relativity theory. *Journal of Automated Reasoning*, 52(4):361–378, 2014.
- [2] M. Stannett and I. Németi. No faster-than-light observers. *Archive of Formal Proofs*, April 2016. https://isa-afp.org/entries/No_FTL_observers.html, Formal proof development.