Geometric Axioms for Minkowski Spacetime

Richard Schmoetten, Jake Palmer, Jacques Fleuriot

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Abstract

This is a formalisation of Schutz' system of axioms for Minkowski spacetime [1], as well as the results in his third chapter ("Temporal Order on a Path"), with the exception of the second part of Theorem 12. Many results are proven here that cannot be found in Schutz, either preceding the theorem they are needed for, or in their own thematic section.

Contents

theory *TernaryOrdering*
imports *Main Util*

begin

Definition of chains using an ordering on sets of events based on natural numbers, plus some proofs.

1 Totally ordered chains

Based on page 110 of Phil Scott's thesis and the following HOL Light definition:

```
let ORDERING = new_definition
  `ORDERING f X <=> (!n. (FINITE X ==> n < CARD X) ==> f n IN X)
                    /\ (!x. x IN X ==> ?n. (FINITE X ==> n < CARD X)
                        /\ f n = x)
                    /\ !n n' n''. (FINITE X ==> n'' < CARD X)
                          /\ n < n' /\ n' < n''
                          ==> between (f n) (f n') (f n'')`;;
```

I've made it strict for simplicity, and because that's how Schutz's ordering is. It could be made more generic by taking in the function corresponding to $<$ as a paramater. Main difference to Schutz: he has local order, not total (cf Theorem 2 and *ordering2*).

definition *ordering* :: $(nat \Rightarrow 'a) \Rightarrow ('a \Rightarrow 'a \Rightarrow 'a \Rightarrow bool) \Rightarrow 'a\ set \Rightarrow bool$
where
$ordering\ f\ ord\ X \equiv (\forall n.\ (finite\ X \longrightarrow n < card\ X) \longrightarrow f\ n \in X)$
$\wedge\ (\forall x{\in}X.\ (\exists n.\ (finite\ X \longrightarrow n < card\ X) \wedge f\ n = x))$
$\wedge\ (\forall n\ n'\ n''.\ (finite\ X \longrightarrow n'' < card\ X) \wedge n < n' \wedge n' < n''$
$\longrightarrow ord\ (f\ n)\ (f\ n')\ (f\ n''))$

lemma *ordering-ord-ijk*:
assumes *ordering f ord X*
and $i < j \wedge j < k \wedge (finite\ X \longrightarrow k < card\ X)$
shows $ord\ (f\ i)\ (f\ j)\ (f\ k)$
by (*metis ordering-def assms*)

lemma *empty-ordering* [*simp*]: $\exists f.\ ordering\ f\ ord\ \{\}$
by (*simp add*: *ordering-def*)

lemma *singleton-ordering* [*simp*]: $\exists f.\ ordering\ f\ ord\ \{a\}$
apply (*rule-tac* $x = \lambda n.\ a$ **in** *exI*)
by (*simp add*: *ordering-def*)

lemma *two-ordering* [*simp*]: $\exists f.$ *ordering f ord* $\{a,\ b\}$
proof *cases*
  assume $a = b$
  thus *?thesis* **using** *singleton-ordering* **by** *simp*
next
  assume *a-neq-b*: $a \neq b$
  let $?f = \lambda n.$ *if* $n = 0$ *then* a *else* b
  have *ordering1*: $(\forall\, n.\ (finite\ \{a,b\} \longrightarrow n < card\ \{a,b\}) \longrightarrow ?f\ n \in \{a,b\})$ **by** *simp*
  have *ordering2*: $(\forall\, x{\in}\{a,b\}.\ \exists\, n.\ (finite\ \{a,b\} \longrightarrow n < card\ \{a,b\}) \wedge ?f\ n = x)$
    using *a-neq-b all-not-in-conv card-Suc-eq card-0-eq card-gt-0-iff insert-iff lessI* **by** *auto*
  have *ordering3*: $(\forall\, n\ n'\ n''.\ (finite\ \{a,b\} \longrightarrow n'' < card\ \{a,b\}) \wedge n < n' \wedge n' < n''$
    $\longrightarrow ord\ (?f\ n)\ (?f\ n')\ (?f\ n''))$ **using** *a-neq-b* **by** *auto*
  have *ordering ?f ord* $\{a,\ b\}$ **using** *ordering-def ordering1 ordering2 ordering3* **by** *blast*
  thus *?thesis* **by** *auto*
qed

lemma *card-le2-ordering*:
  assumes *finiteX*: *finite X*
    and *card-le2*: $card\ X \leq 2$
  shows $\exists f.$ *ordering f ord X*
proof $-$
  have *card012*: $card\ X = 0 \vee card\ X = 1 \vee card\ X = 2$ **using** *card-le2* **by** *auto*
  have *card0*: $card\ X = 0 \longrightarrow ?thesis$ **using** *finiteX* **by** *simp*
  have *card1*: $card\ X = 1 \longrightarrow ?thesis$ **using** *card-eq-SucD* **by** *fastforce*
  have *card2*: $card\ X = 2 \longrightarrow ?thesis$ **by** (*metis two-ordering card-eq-SucD numeral-2-eq-2*)
  thus *?thesis* **using** *card012 card0 card1 card2* **by** *auto*
qed

lemma *ord-ordered*:
  assumes *abc*: *ord a b c*
    and *abc-neq*: $a \neq b \wedge a \neq c \wedge b \neq c$
  shows $\exists f.$ *ordering f ord* $\{a,b,c\}$
apply (*rule-tac* $x = \lambda n.$ *if* $n = 0$ *then* a *else if* $n = 1$ *then* b *else* c **in** *exI*)
apply (*unfold ordering-def*)
using *abc abc-neq* **by** *auto*

lemma *overlap-ordering*:
  assumes *abc*: *ord a b c*
    and *bcd*: *ord b c d*
    and *abd*: *ord a b d*
    and *acd*: *ord a c d*
    and *abc-neq*: $a \neq b \wedge a \neq c \wedge a \neq d \wedge b \neq c \wedge b \neq d \wedge c \neq d$
  shows $\exists f.$ *ordering f ord* $\{a,b,c,d\}$

proof −
  let *?X* = {*a*,*b*,*c*,*d*}
  let *?f* = *λn. if n = 0 then a else if n = 1 then b else if n = 2 then c else d*
  have *card4*: *card ?X = 4* **using** *abc bcd abd abc-neq* **by** *simp*
  have *ordering1*: ∀ *n*. (*finite ?X* ⟶ *n* < *card ?X*) ⟶ *?f n* ∈ *?X* **by** *simp*
  have *ordering2*: ∀ *x*∈*?X*. ∃ *n*. (*finite ?X* ⟶ *n* < *card ?X*) ∧ *?f n* = *x*
    by (*metis card4 One-nat-def Suc-1 Suc-lessI empty-iff insertE numeral-3-eq-3 numeral-eq-iff*
      numeral-eq-one-iff rel-simps(*51*) *semiring-norm*(*85*) *semiring-norm*(*86*) *semiring-norm*(*87*)
      semiring-norm(*89*) *zero-neq-numeral*)
  have *ordering3*: (∀ *n n′ n″*. (*finite ?X* ⟶ *n″* < *card ?X*) ∧ *n* < *n′* ∧ *n′* < *n″*
                ⟶ *ord* (*?f n*) (*?f n′*) (*?f n″*))
    using *card4 abc bcd abd acd card-0-eq card-insert-if finite.emptyI finite-insert less-antisym*
      less-one less-trans-Suc not-less-eq not-one-less-zero numeral-2-eq-2 **by** *auto*
  have *ordering ?f ord ?X* **using** *ordering1 ordering2 ordering3 ordering-def* **by** *blast*
  thus *?thesis* **by** *auto*
qed

lemma *overlap-ordering-alt1*:
  assumes *abc*: *ord a b c*
    and *bcd*: *ord b c d*
    and *abc-bcd-abd*: ∀ *a b c d*. *ord a b c* ∧ *ord b c d* ⟶ *ord a b d*
    and *abc-bcd-acd*: ∀ *a b c d*. *ord a b c* ∧ *ord b c d* ⟶ *ord a c d*
    and *ord-distinct*: ∀ *a b c*. (*ord a b c* ⟶ *a* ≠ *b* ∧ *a* ≠ *c* ∧ *b* ≠ *c*)
  shows ∃ *f*. *ordering f ord* {*a*,*b*,*c*,*d*}
by (*metis* (*full-types*) *assms overlap-ordering*)

lemma *overlap-ordering-alt2*:
  assumes *abc*: *ord a b c*
    and *bcd*: *ord b c d*
    and *abd*: *ord a b d*
    and *acd*: *ord a c d*
    and *ord-distinct*: ∀ *a b c*. (*ord a b c* ⟶ *a* ≠ *b* ∧ *a* ≠ *c* ∧ *b* ≠ *c*)
  shows ∃ *f*. *ordering f ord* {*a*,*b*,*c*,*d*}
by (*metis assms overlap-ordering*)

lemma *overlap-ordering-alt*:
  assumes *abc*: *ord a b c*
    and *bcd*: *ord b c d*
    and *abc-bcd-abd*: ∀ *a b c d*. *ord a b c* ∧ *ord b c d* ⟶ *ord a b d*
    and *abc-bcd-acd*: ∀ *a b c d*. *ord a b c* ∧ *ord b c d* ⟶ *ord a c d*
    and *abc-neq*: *a* ≠ *b* ∧ *a* ≠ *c* ∧ *a* ≠ *d* ∧ *b* ≠ *c* ∧ *b* ≠ *d* ∧ *c* ≠ *d*
  shows ∃ *f*. *ordering f ord* {*a*,*b*,*c*,*d*}
by (*meson assms overlap-ordering*)

The lemmas below are easy to prove for $X = \{\}$, and if I included that case then I would have to write a conditional definition in place of $\{0..|X| - 1\}$.

lemma *finite-ordering-img*: $[\![X \neq \{\}; \textit{finite } X; \textit{ordering } f \textit{ ord } X]\!] \Longrightarrow f \text{ ` } \{0..\textit{card } X - 1\} = X$
by (*force simp add*: *ordering-def image-def*)

lemma *inf-ordering-img*: $[\![\textit{infinite } X; \textit{ordering } f \textit{ ord } X]\!] \Longrightarrow f \text{ ` } \{0..\} = X$
by (*auto simp add*: *ordering-def image-def*)

lemma *finite-ordering-inv-img*: $[\![X \neq \{\}; \textit{finite } X; \textit{ordering } f \textit{ ord } X]\!] \Longrightarrow f -\text{` } X = \{0..\textit{card } X - 1\}$
apply (*auto simp add*: *ordering-def*)
oops

lemma *inf-ordering-inv-img*: $[\![\textit{infinite } X; \textit{ordering } f \textit{ ord } X]\!] \Longrightarrow f -\text{` } X = \{0..\}$
by (*auto simp add*: *ordering-def image-def*)

lemma *inf-ordering-img-inv-img*: $[\![\textit{infinite } X; \textit{ordering } f \textit{ ord } X]\!] \Longrightarrow f \text{ ` } f -\text{` } X = X$
using *inf-ordering-img* **by** *auto*

lemma *finite-ordering-inj-on*: $[\![\textit{finite } X; \textit{ordering } f \textit{ ord } X]\!] \Longrightarrow \textit{inj-on } f \{0..\textit{card } X - 1\}$
by (*metis finite-ordering-img Suc-diff-1 atLeastAtMost-iff card-atLeastAtMost card-eq-0-iff diff-0-eq-0 diff-zero eq-card-imp-inj-on gr0I inj-onI le-0-eq*)

lemma *finite-ordering-bij*:
  assumes *orderingX*: *ordering f ord X*
    and *finiteX*: *finite X*
    and *non-empty*: $X \neq \{\}$
  shows *bij-betw f* $\{0..\textit{card } X - 1\}$ *X*
proof −
 have *f-image*: $f \text{ ` } \{0..\textit{card } X - 1\} = X$ **by** (*metis orderingX finiteX finite-ordering-img non-empty*)
 thus *?thesis* **by** (*metis inj-on-imp-bij-betw orderingX finiteX finite-ordering-inj-on*)

qed

lemma *inf-ordering-inj'*:
  assumes *infX*: *infinite X*
    and *f-ord*: *ordering f ord X*
    and *ord-distinct*: $\forall a\ b\ c.\ (\textit{ord } a\ b\ c \longrightarrow a \neq b \wedge a \neq c \wedge b \neq c)$
    and *f-eq*: $f\ m = f\ n$
  shows $m = n$

proof (*rule ccontr*)
  assume *m-not-n*: $m \neq n$
  have *betw-3n*: $\forall n\ n'\ n''.\ n < n' \wedge n' < n'' \longrightarrow \textit{ord } (f\ n)\ (f\ n')\ (f\ n'')$
    using *f-ord* **by** (*simp add*: *ordering-def infX*)

```
  thus False
  proof cases
    assume m-less-n: m < n
    then obtain k where n < k by auto
    then have ord (f m) (f n) (f k) using m-less-n betw-3n by simp
    then have f m ≠ f n using ord-distinct by simp
    thus ?thesis using f-eq by simp
  next
    assume ¬ m < n
    then have n-less-m: n < m using m-not-n by simp
    then obtain k where m < k by auto
    then have ord (f n) (f m) (f k) using n-less-m betw-3n by simp
    then have f n ≠ f m using ord-distinct by simp
    thus ?thesis using f-eq by simp
  qed
qed


lemma inf-ordering-inj:
  assumes infinite X
      and ordering f ord X
      and ∀ a b c. (ord a b c ⟶ a ≠ b ∧ a ≠ c ∧ b ≠ c)
  shows inj f
using inf-ordering-inj' assms by (metis injI)
```

The finite case is a little more difficult as I can't just choose some other natural number to form the third part of the betweenness relation and the initial simplification isn't as nice. Note that I cannot prove *inj f* (over the whole type that *f* is defined on, i.e. natural numbers), because I need to capture the *m* and *n* that obey specific requirements for the finite case. In order to prove *inj f*, I would have to extend the definition for ordering to include *m* and *n* beyond *card X*, such that it is still injective. That would probably not be very useful.

```
lemma finite-ordering-inj:
  assumes finiteX: finite X
      and f-ord: ordering f ord X
      and ord-distinct: ∀ a b c. (ord a b c ⟶ a ≠ b ∧ a ≠ c ∧ b ≠ c)
      and m-less-card: m < card X
      and n-less-card: n < card X
      and f-eq: f m = f n
  shows m = n
proof (rule ccontr)
  assume m-not-n: m ≠ n
  have surj-f: ∀ x∈X. ∃ n<card X. f n = x
             using f-ord by (simp add: ordering-def finiteX)
  have betw-3n: ∀ n n' n''. n'' < card X ∧ n < n' ∧ n' < n'' ⟶ ord (f n) (f n')
(f n'')
              using f-ord by (simp add: ordering-def)
```

show *False*
proof *cases*
assume *card-le2*: *card* $X \leq 2$
have *card0*: *card* $X = 0 \longrightarrow$ *False* **using** *m-less-card* **by** *simp*
have *card1*: *card* $X = 1 \longrightarrow$ *False* **using** *m-less-card n-less-card m-not-n* **by** *simp*
have *card2*: *card* $X = 2 \longrightarrow$ *False*
proof (*rule impI*)
assume *card-is-2*: *card* $X = 2$
then have *mn01*: $m = 0 \wedge n = 1 \vee n = 0 \wedge m = 1$ **using** *m-less-card n-less-card m-not-n* **by** *auto*
then have $f\,m \neq f\,n$ **using** *card-is-2 surj-f One-nat-def card-eq-SucD insertCI less-2-cases numeral-2-eq-2* **by** (*metis* (*no-types*, *lifting*))
thus *False* **using** *f-eq* **by** *simp*
qed
show *False* **using** *card0 card1 card2 card-le2* **by** *simp*
next
assume $\neg$ *card* $X \leq 2$
then have *card-ge3*: *card* $X \geq 3$ **by** *simp*
thus *False*
proof *cases*
assume *m-less-n*: $m < n$
then obtain k **where** *k-pos*: $k < m \vee (m < k \wedge k < n) \vee (n < k \wedge k <$ *card* $X)$
using *is-free-nat m-less-n n-less-card card-ge3* **by** *blast*
have *k1*: $k < m \longrightarrow$*ord* $(f\,k)$ $(f\,m)$ $(f\,n)$ **using** *m-less-n n-less-card betw-3n* **by** *simp*
have *k2*: $m < k \wedge k < n \longrightarrow$ *ord* $(f\,m)$ $(f\,k)$ $(f\,n)$ **using** *m-less-n n-less-card betw-3n* **by** *simp*
have *k3*: $n < k \wedge k <$ *card* $X \longrightarrow$ *ord* $(f\,m)$ $(f\,n)$ $(f\,k)$ **using** *m-less-n betw-3n* **by** *simp*
have $f\,m \neq f\,n$ **using** *k1 k2 k3 k-pos ord-distinct* **by** *auto*
thus *False* **using** *f-eq* **by** *simp*
next
assume $\neg\ m < n$
then have *n-less-m*: $n < m$ **using** *m-not-n* **by** *simp*
then obtain k **where** *k-pos*: $k < n \vee (n < k \wedge k < m) \vee (m < k \wedge k <$ *card* $X)$
using *is-free-nat n-less-m m-less-card card-ge3* **by** *blast*
have *k1*: $k < n \longrightarrow$*ord* $(f\,k)$ $(f\,n)$ $(f\,m)$ **using** *n-less-m m-less-card betw-3n* **by** *simp*
have *k2*: $n < k \wedge k < m \longrightarrow$ *ord* $(f\,n)$ $(f\,k)$ $(f\,m)$ **using** *n-less-m m-less-card betw-3n* **by** *simp*
have *k3*: $m < k \wedge k <$ *card* $X \longrightarrow$ *ord* $(f\,n)$ $(f\,m)$ $(f\,k)$ **using** *n-less-m betw-3n* **by** *simp*
have $f\,n \neq f\,m$ **using** *k1 k2 k3 k-pos ord-distinct* **by** *auto*
thus *False* **using** *f-eq* **by** *simp*
qed
qed

```
qed

lemma ordering-inj:
  assumes ordering f ord X
      and ∀ a b c. (ord a b c ⟶ a ≠ b ∧ a ≠ c ∧ b ≠ c)
      and finite X ⟶ m < card X
      and finite X ⟶ n < card X
      and f m = f n
  shows m = n
  using inf-ordering-inj' finite-ordering-inj assms by blast

lemma ordering-sym:
  assumes ord-sym: ⋀a b c. ord a b c ⟹ ord c b a
      and finite X
      and ordering f ord X
  shows ordering (λn. f (card X − 1 − n)) ord X
unfolding ordering-def using assms(2)
  apply auto
 apply (metis ordering-def assms(3) card-0-eq card-gt-0-iff diff-Suc-less gr-implies-not0)
proof −
  fix x
  assume finite X
  assume x ∈ X
  obtain n where finite X ⟶ n < card X and f n = x
    by (metis ordering-def ‹x ∈ X› assms(3))
  have f (card X − ((card X − 1 − n) + 1)) = x
    by (simp add: Suc-leI ‹f n = x› ‹finite X ⟶ n < card X› assms(2))
  thus ∃ n<card X. f (card X − Suc n) = x
     by (metis ‹x ∈ X› add.commute assms(2) card-Diff-singleton card-Suc-Diff1
diff-less-Suc plus-1-eq-Suc)
next
  fix n n' n''
  assume finite X
  assume n'' < card X n < n' n' < n''
  have ord (f (card X − Suc n'')) (f (card X − Suc n')) (f (card X − Suc n))
    using assms(3) unfolding ordering-def
    using ‹n < n'› ‹n' < n''› ‹n'' < card X› diff-less-mono2 by auto
  thus  ord (f (card X − Suc n)) (f (card X − Suc n')) (f (card X − Suc n''))
    using ord-sym by blast
qed

lemma  zero-into-ordering:
  assumes ordering f betw X
  and X ≠ {}
  shows (f 0) ∈ X
    using ordering-def
    by (metis assms card-eq-0-iff gr-implies-not0 linorder-neqE-nat)
```

2 Locally ordered chains

Definitions for Schutz-like chains, with local order only.

definition *ordering2* :: $(nat \Rightarrow 'a) \Rightarrow ('a \Rightarrow 'a \Rightarrow 'a \Rightarrow bool) \Rightarrow 'a\ set \Rightarrow bool$
where
$ordering2\ f\ ord\ X \equiv (\forall\, n.\ (finite\ X \longrightarrow n < card\ X) \longrightarrow f\ n \in X)$
$\wedge\ (\forall\, x{\in}X.\ (\exists\, n.\ (finite\ X \longrightarrow n < card\ X) \wedge f\ n = x))$
$\wedge\ (\forall\, n\ n'\ n''.\ (finite\ X \longrightarrow n'' < card\ X) \wedge Suc\ n = n' \wedge Suc\ n'$
$= n''$
$\longrightarrow ord\ (f\ n)\ (f\ n')\ (f\ n''))$

Analogue to *ordering-ord-ijk*, which is quicker to use in sledgehammer than the definition.

lemma *ordering2-ord-ijk*:
assumes *ordering2 f ord X*
and $Suc\ i = j \wedge Suc\ j = k \wedge (finite\ X \longrightarrow k < card\ X)$
shows $ord\ (f\ i)\ (f\ j)\ (f\ k)$
by (*metis ordering2-def assms*)

end

theory *Minkowski*
imports *Main TernaryOrdering*
begin

Primitives and axioms as given in [1, pp. 9-17].

I've tried to do little to no proofs in this file, and keep that in other files. So, this is mostly locale and other definitions, except where it is nice to prove something about definitional equivalence and the like (plus the intermediate lemmas that are necessary for doing so).

Minkowski spacetime = $(\mathcal{E}, \mathcal{P}, [\ldots])$ except in the notation here I've used $[[\ldots]]$ for $[\ldots]$ as Isabelle uses $[\ldots]$ for lists.

Except where stated otherwise all axioms are exactly as they appear in Schutz97. It is the independent axiomatic system provided in the main body of the book. The axioms O1-O6 are the axioms of order, and largely concern properties of the betweenness relation. I1-I7 are the axioms of incidence. I1-I3 are similar to axioms found in systems for Euclidean geometry. As compared to Hilbert's Foundations (HIn), our incidence axioms (In) are loosely identifiable as I1 $\rightarrow$ HI3, HI8; I2 $\rightarrow$ HI1; I3 $\rightarrow$ HI2. I4 fixes the dimension of the space. I5-I7 are what makes our system non-Galilean, and lead (I think) to Lorentz transforms (together with S?) and the ultimate speed limit. Axioms S and C and the axioms of symmetry and continuity, where the latter is what makes the system second order. Symmetry replaces all of Hilbert's axioms of congruence, when considered in the context of I5-I7.

3 MinkowskiPrimitive: I1-I3

Events $\mathcal{E}$, paths $\mathcal{P}$, and sprays. Sprays only need to refer to $\mathcal{E}$ and $\mathcal{P}$. Axiom *in-path-event* is covered in English by saying "a path is a set of events", but is necessary to have explicitly as an axiom as the types do not force it to be the case.

I think part of why Schutz has I1, together with the trickery $[\![\ \mathcal{E} \neq \{\} \ ]\!] \Longrightarrow \ldots$ in I4, is that then I4 talks *only* about dimension, and results such as *no-empty-paths* can be proved using only existence of elements and unreachable sets. In our case, it's also a question of ordering the sequence of axiom introductions: dimension should really go at the end, since it is not needed for quite a while; but many earlier proofs rely on the set of events being non-empty. It may be nice to have the existence of paths as a separate axiom too, which currently still relies on the axiom of dimension (Schutz has no such axiom either).

locale *MinkowskiPrimitive* =

fixes $\mathcal{E}$ :: *'a set*
and $\mathcal{P}$ :: *('a set) set*
assumes *in-path-event* [*simp*]: $[\![Q \in \mathcal{P};\ a \in Q]\!] \Longrightarrow a \in \mathcal{E}$

and *nonempty-events* [*simp*]: $\mathcal{E} \neq \{\}$

and *events-paths*: $[\![a \in \mathcal{E};\ b \in \mathcal{E};\ a \neq b]\!] \Longrightarrow \exists R{\in}\mathcal{P}.\ \exists S{\in}\mathcal{P}.\ a \in R \wedge b \in S \wedge R \cap S \neq \{\}$

and *eq-paths* [*intro*]: $[\![P \in \mathcal{P};\ Q \in \mathcal{P};\ a \in P;\ b \in P;\ a \in Q;\ b \in Q;\ a \neq b]\!] \Longrightarrow P = Q$
begin

This should be ensured by the additional axiom.

lemma *path-sub-events*:
$Q \in \mathcal{P} \Longrightarrow Q \subseteq \mathcal{E}$
by (*simp add*: *subsetI*)

lemma *paths-sub-power*:
$\mathcal{P} \subseteq Pow\ \mathcal{E}$
by (*simp add*: *path-sub-events subsetI*)

For more terse statements. $a \neq b$ because a and b are being used to identify the path, and $a = b$ would not do that.

abbreviation *path* :: *'a set* ⇒ *'a* ⇒ *'a* ⇒ *bool* **where**
$path\ ab\ a\ b \equiv ab \in \mathcal{P} \wedge a \in ab \wedge b \in ab \wedge a \neq b$

abbreviation *path-ex* :: *'a* ⇒ *'a* ⇒ *bool* **where**
$path\text{-}ex\ a\ b \equiv \exists\,Q.\ path\ Q\ a\ b$

lemma *path-permute*:
$path\ ab\ a\ b = path\ ab\ b\ a$
by *auto*

abbreviation *path-of* :: *'a* ⇒ *'a* ⇒ *'a set* **where**
$path\text{-}of\ a\ b \equiv THE\ ab.\ path\ ab\ a\ b$

lemma *path-of-ex*: $path\ (path\text{-}of\ a\ b)\ a\ b \longleftrightarrow path\text{-}ex\ a\ b$
using *theI'* [**where** $P{=}\lambda x.\ path\ x\ a\ b$] *eq-paths* **by** *blast*

lemma *path-unique*:
assumes *path ab a b* **and** *path ab' a b*
shows $ab = ab'$
using *eq-paths assms* **by** *blast*

4 Primitives: Unreachable Subset (from an Event)

The $Q \in \mathcal{P} \wedge b \in \mathcal{E}$ constraints are necessary as the types as not expressive enough to do it on their own. Schutz's notation is: $Q(b, \emptyset)$.

definition *unreachable-subset* :: $'a\ set \Rightarrow 'a \Rightarrow 'a\ set$ ($\emptyset$ - - [*100*, *100*] *100*) **where**
unreachable-subset $Q\ b \equiv \{x{\in}Q.\ Q \in \mathcal{P} \wedge b \in \mathcal{E} \wedge b \notin Q \wedge \neg(\mathit{path\text{-}ex}\ b\ x)\}$

5 Primitives: Kinematic Triangle

definition *kinematic-triangle* :: $'a \Rightarrow 'a \Rightarrow 'a \Rightarrow bool$ ($\triangle$ - - - [*100*, *100*, *100*] *100*) **where**

$$\begin{aligned}
&\mathit{kinematic\text{-}triangle}\ a\ b\ c \equiv \\
&\quad a \in \mathcal{E} \wedge b \in \mathcal{E} \wedge c \in \mathcal{E} \wedge a \neq b \wedge a \neq c \wedge b \neq c \\
&\quad \wedge (\exists\, Q{\in}\mathcal{P}.\ \exists\, R{\in}\mathcal{P}.\ Q \neq R \wedge (\exists\, S{\in}\mathcal{P}.\ Q \neq S \wedge R \neq S \\
&\qquad\qquad \wedge a \in Q \wedge b \in Q \\
&\qquad\qquad \wedge a \in R \wedge c \in R \\
&\qquad\qquad \wedge b \in S \wedge c \in S))
\end{aligned}$$

A fuller, more explicit equivalent of $\triangle$, to show that the above definition is sufficient.

lemma *tri-full*:

$$\begin{aligned}
&\triangle\ a\ b\ c = (a \in \mathcal{E} \wedge b \in \mathcal{E} \wedge c \in \mathcal{E} \wedge a \neq b \wedge a \neq c \wedge b \neq c \\
&\qquad \wedge (\exists\, Q{\in}\mathcal{P}.\ \exists\, R{\in}\mathcal{P}.\ Q \neq R \wedge (\exists\, S{\in}\mathcal{P}.\ Q \neq S \wedge R \neq S \\
&\qquad\qquad \wedge a \in Q \wedge b \in Q \wedge c \notin Q \\
&\qquad\qquad \wedge a \in R \wedge c \in R \wedge b \notin R \\
&\qquad\qquad \wedge b \in S \wedge c \in S \wedge a \notin S)))
\end{aligned}$$

unfolding *kinematic-triangle-def* **by** (*meson path-unique*)

6 Primitives: SPRAY

It's okay to not require $x \in \mathcal{E}$ because if $x \notin \mathcal{E}$ the *SPRAY* will be empty anyway, and if it's nonempty then $x \in \mathcal{E}$ is derivable.

definition *SPRAY* :: $'a \Rightarrow ('a\ set)\ set$ **where**
$\mathit{SPRAY}\ x \equiv \{R{\in}\mathcal{P}.\ x \in R\}$

definition *spray* :: $'a \Rightarrow 'a\ set$ **where**
$\mathit{spray}\ x \equiv \{y.\ \exists\, R{\in}\mathit{SPRAY}\ x.\ y \in R\}$

definition *is-SPRAY* :: $('a\ set)\ set \Rightarrow bool$ **where**
$\mathit{is\text{-}SPRAY}\ S \equiv \exists\, x{\in}\mathcal{E}.\ S = \mathit{SPRAY}\ x$

definition *is-spray* :: $'a\ set \Rightarrow bool$ **where**
$\mathit{is\text{-}spray}\ S \equiv \exists\, x{\in}\mathcal{E}.\ S = \mathit{spray}\ x$

Some very simple SPRAY and spray lemmas below.

lemma *SPRAY-event*:
  $SPRAY\ x \neq \{\} \Longrightarrow x \in \mathcal{E}$
proof (*unfold SPRAY-def*)
  assume *nonempty-SPRAY*: $\{R \in \mathcal{P}.\ x \in R\} \neq \{\}$
  then have *x-in-path-R*: $\exists\, R \in \mathcal{P}.\ x \in R$ **by** *blast*
  thus $x \in \mathcal{E}$ **using** *in-path-event* **by** *blast*
qed

lemma *SPRAY-nonevent*:
  $x \notin \mathcal{E} \Longrightarrow SPRAY\ x = \{\}$
using *SPRAY-event* **by** *auto*

lemma *SPRAY-path*:
  $P \in SPRAY\ x \Longrightarrow P \in \mathcal{P}$
by (*simp add*: *SPRAY-def*)

lemma *in-SPRAY-path*:
  $P \in SPRAY\ x \Longrightarrow x \in P$
by (*simp add*: *SPRAY-def*)

lemma *source-in-SPRAY*:
  $SPRAY\ x \neq \{\} \Longrightarrow \exists\, P \in SPRAY\ x.\ x \in P$
using *in-SPRAY-path* **by** *auto*

lemma *spray-event*:
  $spray\ x \neq \{\} \Longrightarrow x \in \mathcal{E}$
proof (*unfold spray-def*)
  assume $\{y.\ \exists\, R \in SPRAY\ x.\ y \in R\} \neq \{\}$
  then have $\exists\, y.\ \exists\, R \in SPRAY\ x.\ y \in R$ **by** *simp*
  then have $SPRAY\ x \neq \{\}$ **by** *blast*
  thus $x \in \mathcal{E}$ **using** *SPRAY-event* **by** *simp*
qed

lemma *spray-nonevent*:
  $x \notin \mathcal{E} \Longrightarrow spray\ x = \{\}$
using *spray-event* **by** *auto*

lemma *in-spray-event*:
  $y \in spray\ x \Longrightarrow y \in \mathcal{E}$
proof (*unfold spray-def*)
  assume $y \in \{y.\ \exists\, R{\in}SPRAY\ x.\ y \in R\}$
  then have $\exists\, R{\in}SPRAY\ x.\ y \in R$ **by** (*rule CollectD*)
  then obtain R **where** *path-R*: $R \in \mathcal{P}$
          and *y-inR*: $y \in R$ **using** *SPRAY-path* **by** *auto*
  thus $y \in \mathcal{E}$ **using** *in-path-event* **by** *simp*
qed

lemma *source-in-spray*:
  $spray\ x \neq \{\} \Longrightarrow x \in spray\ x$

proof –
  assume *nonempty-spray*: $spray\ x \neq \{\}$
  have *spray-eq*: $spray\ x = \{y.\ \exists\, R{\in}SPRAY\ x.\ y \in R\}$ **using** *spray-def* **by** *simp*
  then have *ex-in-SPRAY-path*: $\exists\, y.\ \exists\, R{\in}SPRAY\ x.\ y \in R$ **using** *nonempty-spray* **by** *simp*
  show $x \in spray\ x$ **using** *ex-in-SPRAY-path spray-eq source-in-SPRAY* **by** *auto*
qed

7 Primitives: Path (In)dependence

"A subset of three paths of a SPRAY is dependent if there is a path which does not belong to the SPRAY and which contains one event from each of the three paths: we also say any one of the three paths is dependent on the other two. Otherwise the subset is independent." [Schutz97]

The definition of *SPRAY* constrains x, Q, R, S to be in $\mathcal{E}$ and $\mathcal{P}$.

definition *dep3-event* :: $'a\ set \Rightarrow\ 'a\ set \Rightarrow\ 'a\ set \Rightarrow\ 'a \Rightarrow bool$ **where**
  $dep3\text{-}event\ Q\ R\ S\ x \equiv Q \neq R \wedge Q \neq S \wedge R \neq S \wedge Q \in SPRAY\ x \wedge R \in SPRAY\ x \wedge S \in SPRAY\ x$
  $\wedge (\exists\, T{\in}\mathcal{P}.\ T \notin SPRAY\ x \wedge (\exists\, y{\in}Q.\ y \in T) \wedge (\exists\, y{\in}R.\ y \in T) \wedge (\exists\, y{\in}S.\ y \in T))$

definition *dep3-spray* :: $'a\ set \Rightarrow\ 'a\ set \Rightarrow\ 'a\ set \Rightarrow ('a\ set)\ set \Rightarrow bool$ **where**
  $dep3\text{-}spray\ Q\ R\ S\ SPR \equiv \exists\, x.\ SPRAY\ x = SPR \wedge dep3\text{-}event\ Q\ R\ S\ x$

definition *dep3* :: $'a\ set \Rightarrow\ 'a\ set \Rightarrow\ 'a\ set \Rightarrow bool$ **where**
  $dep3\ Q\ R\ S \equiv \exists\, x.\ dep3\text{-}event\ Q\ R\ S\ x$

Some very simple lemmas related to *dep3-event*.

lemma *dep3-nonspray*:
  assumes *dep3-event Q R S x*
    shows $\exists\, P{\in}\mathcal{P}.\ P \notin SPRAY\ x$
  by (*metis assms dep3-event-def*)

lemma *dep3-path*:
  assumes *dep3-QRSx*: *dep3-event Q R S x*
  shows $Q \in \mathcal{P}$ $R \in \mathcal{P}$ $S \in \mathcal{P}$
proof –
  have $\{Q,R,S\} \subseteq SPRAY\ x$ **using** *dep3-event-def* **using** *dep3-QRSx* **by** *simp*
  thus $Q \in \mathcal{P}$ $R \in \mathcal{P}$ $S \in \mathcal{P}$ **using** *SPRAY-path* **by** *auto*
qed

lemma *dep3-is-event*:
  $dep3\text{-}event\ Q\ R\ S\ x \Longrightarrow x \in \mathcal{E}$
using *SPRAY-event dep3-event-def* **by** *auto*

lemma *dep3-event-permute* [*no-atp*]:
  assumes *dep3-event Q R S x*

shows *dep3-event Q S R x dep3-event R Q S x dep3-event R S Q x dep3-event S Q R x dep3-event S R Q x*
using *dep3-event-def assms* **by** *auto*

"We next give recursive definitions of dependence and independence which will be used to characterize the concept of dimension. A path T is dependent on the set of n paths (where $n \geq 3$)

$$S = \{Q_i : i = 1, 2, ..., n; Q_i \in \mathrm{SPRAY} x\}$$

if it is dependent on two paths S_1 and S_2, where each of these two paths is dependent on some subset of $n - 1$ paths from the set S." [Schutz97]

inductive *dep-path* :: $'a\ set \Rightarrow ('a\ set)\ set \Rightarrow\ 'a \Rightarrow bool$ **where**
dep-two: *dep3-event T A B x* $\Longrightarrow$ *dep-path T* $\{A, B\}$ *x*
| *dep-n*: $[\![S \subseteq SPRAY\ x;\ card\ S \geq 3;\ dep\text{-}path\ T\ \{S1, S2\}\ x;$
$S' \subseteq S;\ S'' \subseteq S;\ card\ S' = card\ S - 1;\ card\ S'' = card\ S - 1;$
$dep\text{-}path\ S1\ S'\ x;\ dep\text{-}path\ S2\ S''\ x]\!] \Longrightarrow dep\text{-}path\ T\ S\ x$

"We also say that the set of $n+1$ paths $S \cup \{T\}$ is a dependent set." [Schutz97] Starting from this constructive definition, the below gives an analytical one.

definition *dep-set* :: $('a\ set)\ set \Rightarrow bool$ **where**
dep-set S $\equiv \exists x.\ \exists S' \subseteq S.\ \exists P \in (S - S').$ *dep-path P S' x*

lemma *dependent-superset*:
assumes *dep-set A* **and** $A \subseteq B$
shows *dep-set B*
using *assms(1) assms(2) dep-set-def*
by (*meson Diff-mono dual-order.trans in-mono order-refl*)

lemma *path-in-dep-set*:
assumes *dep3-event P Q R x*
shows *dep-set* $\{P,Q,R\}$
using *dep-two assms dep3-event-def dep-set-def*
by (*metis DiffI insertE insertI1 singletonD subset-insertI*)

lemma *path-in-dep-set2*:
assumes *dep3-event P Q R x*
shows *dep-path P* $\{P,Q,R\}$ *x*
proof
let *?S1* = *Q*
let *?S2* = *R*
let *?S'* = $\{P,R\}$
let *?S''* = $\{P,Q\}$
show $\{P, Q, R\} \subseteq SPRAY\ x$ **using** *assms dep3-event-def* **by** *blast*
show $3 \leq card\ \{P, Q, R\}$ **using** *assms dep3-event-def* **by** *auto*
show *dep-path P* $\{?S1, ?S2\}$ *x* **using** *assms dep3-event-def* **by** (*simp add: dep-two*)
show *?S'* $\subseteq \{P, Q, R\}$ **by** *simp*

show $?S'' \subseteq \{P,\ Q,\ R\}$ **by** *simp*
show $card\ ?S' = card\ \{P,\ Q,\ R\} - 1$ **using** *assms dep3-event-def* **by** *auto*
show $card\ ?S'' = card\ \{P,\ Q,\ R\} - 1$ **using** *assms dep3-event-def* **by** *auto*
show *dep-path ?S1 ?S′ x* **by** (*simp add*: *assms dep3-event-permute*(*2*) *dep-two*)
show *dep-path ?S2 ?S″ x* **using** *assms dep3-event-permute*(*2*,*4*) *dep-two* **by** *blast*
qed

definition *indep-set* :: ($'a\ set$) *set* $\Rightarrow$ *bool* **where**
$indep\text{-}set\ S \equiv \neg(\exists\ T \subseteq S.\ dep\text{-}set\ T)$

8 Primitives: 3-SPRAY

"We now make the following definition which enables us to specify the dimensions of Minkowski space-time. A SPRAY is a 3-SPRAY if: i) it contains four independent paths, and ii) all paths of the SPRAY are dependent on these four paths." [Schutz97]

definition *three-SPRAY* :: $'a \Rightarrow bool$ **where**
$three\text{-}SPRAY\ x \equiv \exists\ S1{\in}\mathcal{P}.\ \exists\ S2{\in}\mathcal{P}.\ \exists\ S3{\in}\mathcal{P}.\ \exists\ S4{\in}\mathcal{P}.$
$S1 \neq S2 \wedge S1 \neq S3 \wedge S1 \neq S4 \wedge S2 \neq S3 \wedge S2 \neq S4 \wedge S3 \neq S4$
$\wedge\ S1 \in SPRAY\ x \wedge S2 \in SPRAY\ x \wedge S3 \in SPRAY\ x \wedge S4 \in SPRAY\ x$
$\wedge\ (indep\text{-}set\ \{S1,\ S2,\ S3,\ S4\})$
$\wedge\ (\forall\ S{\in}SPRAY\ x.\ dep\text{-}path\ S\ \{S1,S2,S3,S4\}\ x)$

Lemma *is-three-SPRAY* says "this set of sets of elements is a set of paths which is a 3-SPRAY". Lemma *three-SPRAY-ge4* just extracts a bit of the definition.

definition *is-three-SPRAY* :: ($'a\ set$) *set* $\Rightarrow$ *bool* **where**
$is\text{-}three\text{-}SPRAY\ SPR \equiv \exists\ x.\ SPR = SPRAY\ x \wedge three\text{-}SPRAY\ x$

lemma *three-SPRAY-ge4*:
assumes *three-SPRAY x*
shows $\exists\ Q1{\in}\mathcal{P}.\ \exists\ Q2{\in}\mathcal{P}.\ \exists\ Q3{\in}\mathcal{P}.\ \exists\ Q4{\in}\mathcal{P}.\ Q1 \neq Q2 \wedge Q1 \neq Q3 \wedge Q1 \neq Q4 \wedge Q2 \neq Q3 \wedge Q2 \neq Q4 \wedge Q3 \neq Q4$
using *assms three-SPRAY-def* **by** *meson*

end

9 MinkowskiBetweenness: O1-O5

In O4, I have removed the requirement that $a \neq d$ in order to prove negative betweenness statements as Schutz does. For example, if we have [*abc*] and [*bca*] we want to conclude [*aba*] and claim "contradiction!", but we can't as long as we mandate that $a \neq d$.

locale *MinkowskiBetweenness* = *MinkowskiPrimitive* +

fixes *betw* :: $'a \Rightarrow 'a \Rightarrow 'a \Rightarrow bool$ ([[- - -]])

assumes *abc-ex-path*: $[[a\ b\ c]] \Longrightarrow \exists\, Q{\in}\mathcal{P}.\ a \in Q \wedge b \in Q \wedge c \in Q$

and *abc-sym*: $[[a\ b\ c]] \Longrightarrow [[c\ b\ a]]$

and *abc-ac-neq*: $[[a\ b\ c]] \Longrightarrow a \neq c$

and *abc-bcd-abd* [*intro*]: $[\![[[a\ b\ c]]; [[b\ c\ d]]]\!] \Longrightarrow [[a\ b\ d]]$

and *some-betw*: $[\![Q \in \mathcal{P}; a \in Q; b \in Q; c \in Q; a \neq b; a \neq c; b \neq c]\!]$
$\Longrightarrow [[a\ b\ c]] \vee [[b\ c\ a]] \vee [[c\ a\ b]]$

begin

The next few lemmas either provide the full axiom from the text derived from a new simpler statement, or provide some very simple fundamental additions which make sense to prove immediately before starting, usually related to set-level things that should be true which fix the type-level ambiguity of 'a.

lemma *betw-events*:
assumes *abc*: $[[a\ b\ c]]$
shows $a \in \mathcal{E} \wedge b \in \mathcal{E} \wedge c \in \mathcal{E}$
proof −
have $\exists\, Q{\in}\mathcal{P}.\ a \in Q \wedge b \in Q \wedge c \in Q$ **using** *abc-ex-path abc* **by** *simp*
thus *?thesis* **using** *in-path-event* **by** *auto*
qed

This shows the shorter version of O5 is equivalent.

lemma *O5-still-O5* [*no-atp*]:
$((Q \in \mathcal{P} \wedge \{a,b,c\} \subseteq Q \wedge a \in \mathcal{E} \wedge b \in \mathcal{E} \wedge c \in \mathcal{E} \wedge a \neq b \wedge a \neq c \wedge b \neq c)$
$\longrightarrow [[a\ b\ c]] \vee [[b\ c\ a]] \vee [[c\ a\ b]])$
$=$
$((Q \in \mathcal{P} \wedge \{a,b,c\} \subseteq Q \wedge a \in \mathcal{E} \wedge b \in \mathcal{E} \wedge c \in \mathcal{E} \wedge a \neq b \wedge a \neq c \wedge b \neq c)$
$\longrightarrow [[a\ b\ c]] \vee [[b\ c\ a]] \vee [[c\ a\ b]] \vee [[c\ b\ a]] \vee [[a\ c\ b]] \vee [[b\ a\ c]])$
by (*auto simp add*: *abc-sym*)

lemma *some-betw-xor*:
$[\![Q \in \mathcal{P}; a \in Q; b \in Q; c \in Q; a \neq b; a \neq c; b \neq c]\!]$
$\Longrightarrow ([[a\ b\ c]] \wedge \neg [[b\ c\ a]] \wedge \neg [[c\ a\ b]])$
$\vee ([[b\ c\ a]] \wedge \neg [[a\ b\ c]] \wedge \neg [[c\ a\ b]])$
$\vee ([[c\ a\ b]] \wedge \neg [[a\ b\ c]] \wedge \neg [[b\ c\ a]])$
by (*meson abc-ac-neq abc-bcd-abd some-betw*)

The lemma *abc-abc-neq* is the full O3 as stated by Schutz.

lemma *abc-abc-neq*:
assumes *abc*: $[[a\ b\ c]]$
shows $a \neq b \wedge a \neq c \wedge b \neq c$
using *abc-sym abc-ac-neq assms abc-bcd-abd* **by** *blast*

lemma *abc-bcd-acd*:
  assumes *abc*: $[[a\ b\ c]]$
    and *bcd*: $[[b\ c\ d]]$
  shows $[[a\ c\ d]]$
proof –
  have *cba*: $[[c\ b\ a]]$ **using** *abc-sym abc* **by** *simp*
  have *dcb*: $[[d\ c\ b]]$ **using** *abc-sym bcd* **by** *simp*
  have $[[d\ c\ a]]$ **using** *abc-bcd-abd dcb cba* **by** *blast*
  thus *?thesis* **using** *abc-sym* **by** *simp*
qed

lemma *abc-only-cba*:
  assumes $[[a\ b\ c]]$
    shows $\neg\ [[b\ a\ c]]\ \neg\ [[a\ c\ b]]\ \neg\ [[b\ c\ a]]\ \neg\ [[c\ a\ b]]$
using *abc-sym abc-abc-neq abc-bcd-abd assms* **by** *blast+*

10 Betweenness: Unreachable Subset Via a Path

definition *unreachable-subset-via* :: $'a\ set \Rightarrow\ 'a \Rightarrow\ 'a\ set \Rightarrow\ 'a \Rightarrow\ 'a\ set$
$(\emptyset$ *- from - via - at -* $[100, 100, 100, 100]\ 100)$ **where**
  unreachable-subset-via $Q\ Qa\ R\ x \equiv \{Qy.\ [[x\ Qy\ Qa]] \wedge (\exists Rw{\in}R.\ Qa \in \emptyset\ Q\ Rw \wedge Qy \in \emptyset\ Q\ Rw)\}$

11 Betweenness: Chains

11.1 Totally ordered chains with indexing

definition *short-ch* :: $'a\ set \Rightarrow bool$ **where**
  short-ch $X \equiv$
    — EITHER two distinct events connected by a path
    $\exists x{\in}X.\ \exists y{\in}X.$ *path-ex* $x\ y \wedge \neg(\exists z{\in}X.\ z{\neq}x \wedge z{\neq}y)$

Infinite sets have card 0, because card gives a natural number always.

definition *long-ch-by-ord* :: $(nat \Rightarrow\ 'a) \Rightarrow\ 'a\ set \Rightarrow bool$ **where**
  long-ch-by-ord $f\ X \equiv$
    — OR at least three events such that any three events are ordered
    $\exists x{\in}X.\ \exists y{\in}X.\ \exists z{\in}X.\ x{\neq}y \wedge y{\neq}z \wedge x{\neq}z \wedge$ *ordering* f *betw* X

Does this restrict chains to lie on paths? Proven in Ch3's Interlude!

definition *ch-by-ord* :: $(nat \Rightarrow\ 'a) \Rightarrow\ 'a\ set \Rightarrow bool$ **where**
  ch-by-ord $f\ X \equiv$ *short-ch* $X \vee$ *long-ch-by-ord* $f\ X$

definition *ch* :: $'a\ set \Rightarrow bool$ **where**
  ch $X \equiv \exists f.$ *ch-by-ord* $f\ X$

Since $f(0)$ is always in the chain, and plays a special role particularly for infinite chains (as the 'endpoint', the non-finite edge) let us fix it straight in the definition. Notice we require both *infinite X* and *long-ch-by-ord*, thus circumventing infinite Isabelle sets having cardinality 0.

definition *semifin-chain*:: (*nat* ⇒ *'a*) ⇒ *'a* ⇒ *'a set* ⇒ *bool* ([-[- ..]-]) **where**
  semifin-chain f x Q ≡
    infinite Q ∧ *long-ch-by-ord f Q*
    ∧ *f 0* = *x*

definition *fin-long-chain*:: (*nat* ⇒ *'a*) ⇒ *'a* ⇒ *'a* ⇒ *'a* ⇒ *'a set* ⇒ *bool*
  ([-[- .. - .. -]-]) **where**
  fin-long-chain f x y z Q ≡
    x≠*y* ∧ *x*≠*z* ∧ *y*≠*z*
    ∧ *finite Q* ∧ *long-ch-by-ord f Q*
    ∧ *f 0* = *x* ∧ *y*∈*Q* ∧ *f* (*card Q* − *1*) = *z*

lemma *index-middle-element*:
  assumes [*f*[*a*..*b*..*c*]*X*]
  shows ∃ *n*. *0*<*n* ∧ *n*<(*card X* − *1*) ∧ *f n* = *b*
proof −
  obtain *n* **where** *n-def*: *n* < *card X f n* = *b*
   by (*metis TernaryOrdering.ordering-def assms fin-long-chain-def long-ch-by-ord-def*)
  have *0*<*n* ∧ *n*<(*card X* − *1*) ∧ *f n* = *b*
    using *assms fin-long-chain-def n-def*
    by (*metis Suc-pred' gr-implies-not0 less-SucE not-gr-zero*)
  thus *?thesis* **by** *blast*
qed

lemma *fin-ch-betw*:
  assumes [*f*[*a*..*b*..*c*]*X*]
  shows [[*a b c*]]
proof −
  obtain *nb* **where** *n-def*: *nb*≠*0* *nb*<*card X* − *1* *f nb* = *b*
    using *assms index-middle-element* **by** *blast*
  have [[(*f 0*) (*f nb*) (*f* (*card X* − *1*))]]
   using *fin-long-chain-def long-ch-by-ord-def assms n-def ordering-ord-ijk zero-less-iff-neq-zero*
    by *fastforce*
  thus *?thesis* **using** *assms fin-long-chain-def n-def*(*3*) **by** *auto*
qed

lemma *chain-sym-obtain*:
  assumes [*f*[*a*..*b*..*c*]*X*]
  obtains *g* **where** [*g*[*c*..*b*..*a*]*X*] **and** *g*=(λ*n*. *f* (*card X* − *1* − *n*))
using *ordering-sym assms*(*1*) **unfolding** *fin-long-chain-def long-ch-by-ord-def*
by (*metis* (*mono-tags*, *lifting*) *abc-sym diff-self-eq-0 diff-zero*)

lemma *chain-sym*:
  assumes [*f*[*a*..*b*..*c*]*X*]
    shows [λ*n*. *f* (*card X* − *1* − *n*)[*c*..*b*..*a*]*X*]
  using *chain-sym-obtain* [**where** *f*=*f* **and** *a*=*a* **and** *b*=*b* **and** *c*=*c* **and** *X*=*X*]
  using *assms*(*1*) **by** *blast*

definition *fin-long-chain-2*:: $'a \Rightarrow 'a \Rightarrow 'a \Rightarrow 'a$ *set* $\Rightarrow$ *bool* **where**
fin-long-chain-2 x y z Q $\equiv \exists f.\ [f[x..y..z]Q]$

definition *fin-chain*:: $(nat \Rightarrow 'a) \Rightarrow 'a \Rightarrow 'a \Rightarrow 'a$ *set* $\Rightarrow$ *bool* ([-[- .. -]-]) **where**
fin-chain f x y Q $\equiv$
($short\text{-}ch\ Q \wedge x{\in}Q \wedge y{\in}Q \wedge x{\neq}y$)
$\vee$ ($\exists\, z{\in}Q.\ [f[x..z..y]Q]$)

lemma *points-in-chain*:
assumes $[f[x..y..z]Q]$
shows $x{\in}Q \wedge y{\in}Q \wedge z{\in}Q$
proof −
have $x{\in}Q$
using *ordering-def assms card-gt-0-iff emptyE fin-long-chain-def long-ch-by-ord-def*
by *metis*
moreover have $y{\in}Q$
using *assms fin-long-chain-def*
by *auto*
moreover have $z{\in}Q$
using *ordering-def assms card-gt-0-iff emptyE fin-long-chain-def long-ch-by-ord-def*
by (*metis* (*no-types*, *hide-lams*) *Suc-diff-1 lessI*)
ultimately show *?thesis*
by *blast*
qed

lemma *ch-long-if-card-ge3*:
assumes *ch X*
and *card X* $\geq$ *3*
shows $\exists f.$ *long-ch-by-ord f X*
proof (*rule ccontr*)
assume $\nexists f.$ *long-ch-by-ord f X*
hence *short-ch X*
using *assms*(*1*) *ch-by-ord-def ch-def*
by *auto*
obtain *x y z* **where** $x{\in}X \wedge y{\in}X \wedge z{\in}X$ **and** $x{\neq}y \wedge y{\neq}z \wedge x{\neq}z$
using *assms*(*2*)
by (*auto simp add*: *card-le-Suc-iff numeral-3-eq-3*)
thus *False*
using ‹*short-ch X*› *short-ch-def*
by *metis*
qed

11.2 Locally ordered chains with indexing

Definition for Schutz-like chains, with local order only.

definition *long-ch-by-ord2* :: $(nat \Rightarrow 'a) \Rightarrow 'a$ *set* $\Rightarrow$ *bool* **where**
long-ch-by-ord2 f X $\equiv$
$\exists\, x{\in}X.\ \exists\, y{\in}X.\ \exists\, z{\in}X.\ x{\neq}y \wedge y{\neq}z \wedge x{\neq}z \wedge$ *ordering2 f betw X*

11.3 Chains using betweenness

Old definitions of chains. Shown equivalent to *fin-long-chain-2* in TemporalOrderOnPath.thy.

definition *chain-with* :: $'a \Rightarrow 'a \Rightarrow 'a \Rightarrow 'a\ set \Rightarrow bool$ ([[.. - .. - .. - ..]-]) **where**
chain-with $x\ y\ z\ X \equiv [[x\ y\ z]] \land x \in X \land y \in X \land z \in X \land (\exists f.\ ordering\ f\ betw\ X)$

definition *finite-chain-with3* :: $'a \Rightarrow 'a \Rightarrow 'a \Rightarrow 'a\ set \Rightarrow bool$ ([[- .. - .. -]-]) **where**
finite-chain-with3 $x\ y\ z\ X \equiv [[..x..y..z..]X] \land \neg(\exists\, w{\in}X.\ [[w\ x\ y]] \lor [[y\ z\ w]])$

lemma *long-chain-betw*: $[[..a..b..c..]X] \Longrightarrow [[a\ b\ c]]$
by (*simp add*: *chain-with-def*)

lemma *finite-chain3-betw*: $[[a..b..c]X] \Longrightarrow [[a\ b\ c]]$
by (*simp add*: *chain-with-def finite-chain-with3-def*)

definition *finite-chain-with2* :: $'a \Rightarrow 'a \Rightarrow 'a\ set \Rightarrow bool$ ([[- .. -]-]) **where**
finite-chain-with2 $x\ z\ X \equiv \exists\, y{\in}X.\ [[x..y..z]X]$

lemma *finite-chain2-betw*: $[[a..c]X] \Longrightarrow \exists\, b.\ [[a\ b\ c]]$
using *finite-chain-with2-def finite-chain3-betw* **by** *meson*

12 Betweenness: Rays and Intervals

"Given any two distinct events a, b of a path we define the segment $(ab) = \{x : [a\ x\ b],\ x \in ab\}$" [Schutz97] Our version is a little different, because it is defined for any a, b of type $'a$. Thus we can have empty set segments, while Schutz can prove (once he proves path density) that segments are never empty.

definition *segment* :: $'a \Rightarrow 'a \Rightarrow 'a\ set$
where *segment* $a\ b \equiv \{x{::}'a.\ \exists\, ab.\ [[a\ x\ b]] \land x{\in}ab \land path\ ab\ a\ b\}$

abbreviation *is-segment* :: $'a\ set \Rightarrow bool$
where *is-segment* $ab \equiv (\exists\, a\ b.\ ab = segment\ a\ b)$

definition *interval* :: $'a \Rightarrow 'a \Rightarrow 'a\ set$
where *interval* $a\ b \equiv insert\ b\ (insert\ a\ (segment\ a\ b))$

abbreviation *is-interval* :: $'a\ set \Rightarrow bool$
where *is-interval* $ab \equiv (\exists\, a\ b.\ ab = interval\ a\ b)$

definition *prolongation* :: $'a \Rightarrow 'a \Rightarrow 'a\ set$
where *prolongation* $a\ b \equiv \{x{::}'a.\ \exists\, ab.\ [[a\ b\ x]] \land x{\in}ab \land path\ ab\ a\ b\}$

abbreviation *is-prolongation* :: $'a\ set \Rightarrow bool$
where *is-prolongation* $ab \equiv \exists\, a\ b.\ ab = prolongation\ a\ b$

I think this is what Schutz actually meant, maybe there is a typo in the text?

Notice that $b \in ray\ a\ b$ for any a, always. Cf the comment on *segment-def*. Thus $\exists\, ray\ a\ b \neq \{\}$ is no guarantee that a path ab exists.

definition *ray* :: $'a \Rightarrow 'a \Rightarrow 'a\ set$
  where $ray\ a\ b \equiv insert\ b\ (segment\ a\ b \cup prolongation\ a\ b)$

abbreviation *is-ray* :: $'a\ set \Rightarrow bool$
  where $is\text{-}ray\ R \equiv \exists\, a\ b.\ R = ray\ a\ b$

definition *is-ray-on* :: $'a\ set \Rightarrow 'a\ set \Rightarrow bool$
  where $is\text{-}ray\text{-}on\ R\ P \equiv P{\in}\mathcal{P} \wedge R{\subseteq}P \wedge is\text{-}ray\ R$

This is as in Schutz. Notice b is not in the ray through b?

definition *ray-Schutz* :: $'a \Rightarrow 'a \Rightarrow 'a\ set$
  where $ray\text{-}Schutz\ a\ b \equiv insert\ a\ (segment\ a\ b \cup prolongation\ a\ b)$

lemma *ends-notin-segment*: $a \notin segment\ a\ b \wedge b \notin segment\ a\ b$
  using *abc-abc-neq segment-def* **by** *fastforce*

lemma *ends-in-int*: $a \in interval\ a\ b \wedge b \in interval\ a\ b$
  using *interval-def* **by** *auto*

lemma *seg-betw*: $x \in segment\ a\ b \longleftrightarrow [[a\ x\ b]]$
  using *segment-def abc-abc-neq abc-ex-path* **by** *fastforce*

lemma *pro-betw*: $x \in prolongation\ a\ b \longleftrightarrow [[a\ b\ x]]$
  using *prolongation-def abc-abc-neq abc-ex-path* **by** *fastforce*

lemma *seg-sym*: $segment\ a\ b = segment\ b\ a$
  using *abc-sym segment-def* **by** *auto*

lemma *empty-segment*: $segment\ a\ a = \{\}$
  by (*simp add*: *segment-def*)

lemma *int-sym*: $interval\ a\ b = interval\ b\ a$
  by (*simp add*: *insert-commute interval-def seg-sym*)

lemma *seg-path*:
  assumes $x \in segment\ a\ b$
  obtains *ab* **where** *path ab a b* $segment\ a\ b \subseteq ab$
proof –
  obtain *ab* **where** *path ab a b*
    using *abc-abc-neq abc-ex-path assms seg-betw*
    by *meson*
  have $segment\ a\ b \subseteq ab$
    using ‹*path ab a b*› *abc-ex-path path-unique seg-betw*
    by *fastforce*
  thus *?thesis*
    using ‹*path ab a b*› *that* **by** *blast*
qed

lemma *seg-path2*:
  assumes *segment a b* $\neq$ {}
  obtains *ab* **where** *path ab a b segment a b* $\subseteq$ *ab*
  using *assms seg-path* **by** *force*

Path density (theorem 17) will extend this by weakening the assumptions to *segment a b* $\neq$ {}.

lemma *seg-endpoints-on-path*:
  assumes *card* (*segment a b*) $\geq$ *2 segment a b* $\subseteq$ *P P*$\in\mathcal{P}$
  shows *path P a b*
proof −
  have *non-empty*: *segment a b* $\neq$ {} **using** *assms*(*1*) *numeral-2-eq-2* **by** *auto*
  then obtain *ab* **where** *path ab a b segment a b* $\subseteq$ *ab*
    using *seg-path2* **by** *force*
  have *a*$\neq$*b* **by** (*simp add*: ‹*path ab a b*›)
  obtain *x y* **where** *x*$\in$*segment a b y*$\in$*segment a b x*$\neq$*y*
    using *assms*(*1*) *numeral-2-eq-2*
    by (*metis card.infinite card-le-Suc0-iff-eq not-less-eq-eq not-numeral-le-zero*)
  have [[*a x b*]]
    using ‹*x* $\in$ *segment a b*› *seg-betw* **by** *auto*
  have [[*a y b*]]
    using ‹*y* $\in$ *segment a b*› *seg-betw* **by** *auto*
  have *x*$\in$*P* $\wedge$ *y*$\in$*P*
    using ‹*x* $\in$ *segment a b*› ‹*y* $\in$ *segment a b*› *assms*(*2*) **by** *blast*
  have *x*$\in$*ab* $\wedge$ *y*$\in$*ab*
    using ‹*segment a b* $\subseteq$ *ab*› ‹*x* $\in$ *segment a b*› ‹*y* $\in$ *segment a b*› **by** *blast*
  have *ab*=*P*
     using ‹*path ab a b*› ‹*x* $\in$ *P* $\wedge$ *y* $\in$ *P*› ‹*x* $\in$ *ab* $\wedge$ *y* $\in$ *ab*› ‹*x* $\neq$ *y*› *assms*(*3*) *path-unique* **by** *auto*
  thus *?thesis*
    using ‹*path ab a b*› **by** *auto*
qed

lemma *pro-path*:
  assumes *x* $\in$ *prolongation a b*
  obtains *ab* **where** *path ab a b prolongation a b* $\subseteq$ *ab*
proof −
  obtain *ab* **where** *path ab a b*
    using *abc-abc-neq abc-ex-path assms pro-betw*
    by *meson*
  have *prolongation a b* $\subseteq$ *ab*
    using ‹*path ab a b*› *abc-ex-path path-unique pro-betw*
    by *fastforce*
  thus *?thesis*
    using ‹*path ab a b*› *that* **by** *blast*
qed

lemma *ray-cases*:

```
  assumes x ∈ ray a b
  shows [[a x b]] ∨ [[a b x]] ∨ x = b
proof −
  have x∈segment a b ∨ x∈ prolongation a b ∨ x=b
    using assms ray-def by auto
  thus [[a x b]] ∨ [[a b x]] ∨ x = b
    using pro-betw seg-betw by auto
qed

lemma ray-path:
  assumes x ∈ ray a b x≠b
  obtains ab where path ab a b ∧ ray a b ⊆ ab
proof −
  let ?r = ray a b
  have ?r ≠ {b}
    using assms by blast
  have ∃ ab. path ab a b ∧ ray a b ⊆ ab
  proof −
    have betw-cases: [[a x b]] ∨ [[a b x]] using ray-cases assms
      by blast
    then obtain ab where path ab a b
      using abc-abc-neq abc-ex-path by blast
    have ?r ⊆ ab using betw-cases
    proof (rule disjE)
      assume [[a x b]]
      show ?r ⊆ ab
      proof
        fix x assume x∈?r
        show x∈ab
          by (metis ‹path ab a b› ‹x ∈ ray a b› abc-ex-path eq-paths ray-cases)
      qed
    next assume [[a b x]]
      show ?r ⊆ ab
      proof
        fix x assume x∈?r
        show x∈ab
          by (metis ‹path ab a b› ‹x ∈ ray a b› abc-ex-path eq-paths ray-cases)
      qed
    qed
    thus ?thesis
      using ‹path ab a b› by blast
  qed
  thus ?thesis
    using that by blast
qed

end
```

13 MinkowskiChain: O6

O6 supposedly serves the same purpose as Pasch's axiom.

locale *MinkowskiChain* = *MinkowskiBetweenness* +
 assumes *O6*: $[\![Q \in \mathcal{P};\ R \in \mathcal{P};\ S \in \mathcal{P};\ T \in \mathcal{P};\ Q \neq R;\ Q \neq S;\ R \neq S;\ a \in Q{\cap}R \wedge b \in Q{\cap}S \wedge c \in R{\cap}S;$
$\exists\, d{\in}S.\ [[b\ c\ d]] \wedge (\exists\, e{\in}R.\ d \in T \wedge e \in T \wedge [[c\ e\ a]])]\!]$
$\Longrightarrow \exists f{\in}T{\cap}Q.\ \exists X.\ [[a..f..b]X]$
begin

14 Chains: (Closest) Bounds

definition *is-bound-f* :: $'a \Rightarrow 'a\ set \Rightarrow (nat{\Rightarrow}'a) \Rightarrow bool$ **where**
 $is\text{-}bound\text{-}f\ Q_b\ Q\ f \equiv$
 $\forall\, i\ j\ {::}nat.\ [f[(f\ 0)..]Q] \wedge (i{<}j \longrightarrow [[(f\ i)\ (f\ j)\ Q_b]])$

definition *is-bound* :: $'a \Rightarrow 'a\ set \Rightarrow bool$ **where**
 $is\text{-}bound\ Q_b\ Q \equiv$
 $\exists f{::}(nat{\Rightarrow}'a).\ is\text{-}bound\text{-}f\ Q_b\ Q\ f$

Q_b has to be on the same path as the chain Q. This is left implicit in the betweenness condition (as is $Q_b \in \mathcal{E}$). So this is equivalent to Schutz only if we also assume his axioms, i.e. the statement of the continuity axiom is no longer independent of other axioms.

definition *all-bounds* :: $'a\ set \Rightarrow 'a\ set$ **where**
 $all\text{-}bounds\ Q = \{Q_b.\ is\text{-}bound\ Q_b\ Q\}$

definition *bounded* :: $'a\ set \Rightarrow bool$ **where**
 $bounded\ Q \equiv \exists\ Q_b.\ is\text{-}bound\ Q_b\ Q$

Just to make sure Continuity is not too strong.

lemma *bounded-imp-inf*:
 assumes *bounded Q*
 shows *infinite Q*
 using *assms bounded-def is-bound-def is-bound-f-def semifin-chain-def* **by** *blast*

definition *closest-bound-f* :: $'a \Rightarrow 'a\ set \Rightarrow (nat{\Rightarrow}'a) \Rightarrow bool$ **where**
 $closest\text{-}bound\text{-}f\ Q_b\ Q\ f \equiv$
~~Q is an infinite chain indexed by f bound by Qb~~
 $is\text{-}bound\text{-}f\ Q_b\ Q\ f \wedge$
~~Any other bound must be further from the start of the chain than the closest bound~~
 $(\forall\ Q_b'.\ (is\text{-}bound\ Q_b'\ Q \wedge Q_b' \neq Q_b) \longrightarrow [[(f\ 0)\ Q_b\ Q_b']])$

definition *closest-bound* :: $'a \Rightarrow 'a\ set \Rightarrow bool$ **where**

closest-bound Q_b $Q \equiv$
~~*Q is an infinite chain indexed by f bound by* Q_b~~
$\exists f.$ *is-bound-f* Q_b Q f $\wedge$
~~*Any other bound must be further from the start of the chain than the closest bound*~~
$(\forall\ Q_b{}'.\ ($*is-bound* $Q_b{}'$ $Q \wedge Q_b{}' \neq Q_b) \longrightarrow [[(f\ 0)\ Q_b\ Q_b{}']])$

end

15 MinkowskiUnreachable: I5-I7

locale *MinkowskiUnreachable* = *MinkowskiChain* +

assumes *two-in-unreach*: $[\![Q \in \mathcal{P};\ b \in \mathcal{E};\ b \notin Q]\!] \Longrightarrow \exists x{\in}\emptyset\ Q\ b.\ \exists y{\in}\emptyset\ Q\ b.\ x \neq y$

and *I6*: $[\![Q \in \mathcal{P};\ b \notin Q;\ b \in \mathcal{E};\ Qx \in (\emptyset\ Q\ b);\ Qz \in (\emptyset\ Q\ b);\ Qx{\neq}Qz]\!]$
$\Longrightarrow \exists X.\ \exists f.$ *ch-by-ord* $f\ X \wedge f\ 0 = Qx \wedge f\ (card\ X - 1) = Qz$
$\wedge\ (\forall i{\in}\{1\ ..\ card\ X - 1\}.\ (f\ i) \in \emptyset\ Q\ b$
$\wedge\ (\forall Qy{\in}\mathcal{E}.\ [[(f(i{-}1))\ Qy\ (f\ i)]] \longrightarrow Qy \in \emptyset\ Q\ b))$
$\wedge\ ($*short-ch* $X \longrightarrow Qx{\in}X \wedge Qz{\in}X \wedge (\forall Qy{\in}\mathcal{E}.\ [[Qx\ Qy\ Qz]] \longrightarrow Qy \in \emptyset\ Q\ b))$
and *I7*: $[\![Q \in \mathcal{P};\ b \notin Q;\ b \in \mathcal{E};\ Qx \in Q - \emptyset\ Q\ b;\ Qy \in \emptyset\ Q\ b]\!]$
$\Longrightarrow \exists g\ X\ Qn.\ [g[Qx..Qy..Qn]X] \wedge Qn \in Q - \emptyset\ Q\ b$
begin

lemma *card-unreach-geq-2*:
assumes $Q{\in}\mathcal{P}$ $b{\in}\mathcal{E}{-}Q$
shows $2 \leq card\ (\emptyset\ Q\ b) \vee (infinite\ (\emptyset\ Q\ b))$
using *DiffD1 assms*(*1*) *assms*(*2*) *card-le-Suc0-iff-eq two-in-unreach* **by** *fastforce*

end

16 MinkowskiSymmetry: Symmetry

locale *MinkowskiSymmetry* = *MinkowskiUnreachable* +
assumes *Symmetry*: $[\![Q \in \mathcal{P};\ R \in \mathcal{P};\ S \in \mathcal{P};\ Q \neq R;\ Q \neq S;\ R \neq S;$
$x \in Q{\cap}R{\cap}S;\ Q_a \in Q;\ Q_a \neq x;$
$\emptyset\ Q$ *from* Q_a *via* R *at* $x = \emptyset\ Q$ *from* Q_a *via* S *at* $x]\!]$
$\Longrightarrow \exists \vartheta{::}'a{\Rightarrow}'a.$ ~~*i) there is a map* $\vartheta{:}\mathcal{E}{\Rightarrow}\mathcal{E}$~~
bij-betw $(\lambda P.\ \{\vartheta\ y \mid y.\ y{\in}P\})\ \mathcal{P}\ \mathcal{P}$ ~~*ii) which induces a bijection*~~
~~Θ~~
$\wedge\ (y{\in}Q \longrightarrow \vartheta\ y = y)$ ~~*iii)* ϑ *leaves Q invariant*~~
$\wedge\ (\lambda P.\ \{\vartheta\ y \mid y.\ y{\in}P\})\ R = S$ ~~*iv)* Θ *maps R to S*~~

17 MinkowskiContinuity: Continuity

locale *MinkowskiContinuity* = *MinkowskiSymmetry* +
assumes *Continuity*: *bounded* $Q \Longrightarrow (\exists\ Q_b.$ *closest-bound* $Q_b\ Q)$

18 MinkowskiSpacetime: Dimension (I4)

locale *MinkowskiSpacetime* = *MinkowskiContinuity* +

assumes *ex-3SPRAY* [*simp*]: $[\![\mathcal{E} \neq \{\}]\!] \Longrightarrow \exists\, x{\in}\mathcal{E}.\ \mathit{three\text{-}SPRAY}\ x$
begin

There exists an event by *nonempty-events*, and by *ex-3SPRAY* there is a three-SPRAY, which by *three-SPRAY-ge4* means that there are at least four paths.

lemma *four-paths*:
$\exists\, Q1{\in}\mathcal{P}.\ \exists\, Q2{\in}\mathcal{P}.\ \exists\, Q3{\in}\mathcal{P}.\ \exists\, Q4{\in}\mathcal{P}.\ Q1 \neq Q2 \wedge Q1 \neq Q3 \wedge Q1 \neq Q4 \wedge Q2 \neq Q3 \wedge Q2 \neq Q4 \wedge Q3 \neq Q4$
using *nonempty-events ex-3SPRAY three-SPRAY-ge4* **by** *blast*

end

end

theory *TemporalOrderOnPath*
imports *Main Minkowski TernaryOrdering*
begin

In Schutz [1, pp. 18-30], this is "Chapter 3: Temporal order on a path". All theorems are from Schutz, all lemmas are either parts of the Schutz proofs extracted, or additional lemmas which needed to be added, with the exception of the three transitivity lemmas leading to Theorem 9, which are given by Schutz as well. Much of what we'd like to prove about chains with respect to injectivity, surjectivity, bijectivity, is proved in *TernaryOrdering.thy*. Some more things are proved in interlude sections.

Disable list syntax.

no-translations
  [*x*, *xs*] == *x*#[*xs*]
  [*x*] == *x*#[]
no-syntax
  — list Enumeration
  -list :: *args* => *'a list* ([(-)])
no-notation *Cons* (**infixr** # *65*)
no-notation *Nil* ([])

19 Preliminary Results for Primitives

First some proofs that belong in this section but aren't proved in the book or are covered but in a different form or off-handed remark.

context *MinkowskiPrimitive* **begin**

lemma *three-in-set3*:
  assumes *card* $X \geq 3$
  obtains x y z **where** $x \in X$ **and** $y \in X$ **and** $z \in X$ **and** $x \neq y$ **and** $x \neq z$ **and** $y \neq z$
  using *assms* **by** (*auto simp add*: *card-le-Suc-iff numeral-3-eq-3*)

lemma *paths-cross-once*:
  assumes *path-Q*: $Q \in \mathcal{P}$
    and *path-R*: $R \in \mathcal{P}$
    and *Q-neq-R*: $Q \neq R$
    and *QR-nonempty*: $Q \cap R \neq \{\}$
  shows $\exists! a \in \mathcal{E}.\ Q \cap R = \{a\}$
proof −
  have *ab-inQR*: $\exists\, a \in \mathcal{E}.\ a \in Q \cap R$ **using** *QR-nonempty in-path-event path-Q* **by** *auto*
  then obtain a **where** *a-event*: $a \in \mathcal{E}$ **and** *a-inQR*: $a \in Q \cap R$ **by** *auto*
  have $Q \cap R = \{a\}$
  proof (*rule ccontr*)
    assume $Q \cap R \neq \{a\}$

then have $\exists\, b{\in}Q{\cap}R.\ b \neq a$ **using** *a-inQR* **by** *blast*
then have $Q = R$ **using** *eq-paths a-inQR path-Q path-R* **by** *auto*
thus *False* **using** *Q-neq-R* **by** *simp*
qed
thus *?thesis* **using** *a-event* **by** *blast*
qed

lemma *cross-once-notin*:
assumes $Q \in \mathcal{P}$
and $R \in \mathcal{P}$
and $a \in Q$
and $b \in Q$
and $b \in R$
and $a \neq b$
and $Q \neq R$
shows $a \notin R$
using *assms paths-cross-once eq-paths* **by** *meson*

lemma *paths-cross-at*:
assumes *path-Q*: $Q \in \mathcal{P}$ **and** *path-R*: $R \in \mathcal{P}$
and *Q-neq-R*: $Q \neq R$
and *QR-nonempty*: $Q \cap R \neq \{\}$
and *x-inQ*: $x \in Q$ **and** *x-inR*: $x \in R$
shows $Q \cap R = \{x\}$
proof (*rule equalityI*)
show $Q \cap R \subseteq \{x\}$
proof (*rule subsetI*, *rule ccontr*)
fix y
assume *y-in-QR*: $y \in Q \cap R$
and *y-not-in-just-x*: $y \notin \{x\}$
then have *y-neq-x*: $y \neq x$ **by** *simp*
then have $\neg\ (\exists\, z.\ Q \cap R = \{z\})$
by (*meson Q-neq-R path-Q path-R x-inQ x-inR y-in-QR cross-once-notin IntD1 IntD2*)
thus *False* **using** *paths-cross-once* **by** (*meson QR-nonempty Q-neq-R path-Q path-R*)
qed
show $\{x\} \subseteq Q \cap R$ **using** *x-inQ x-inR* **by** *simp*
qed

lemma *events-distinct-paths*:
assumes *a-event*: $a \in \mathcal{E}$
and *b-event*: $b \in \mathcal{E}$
and *a-neq-b*: $a \neq b$
shows $\exists\, R{\in}\mathcal{P}.\ \exists\, S{\in}\mathcal{P}.\ a \in R \wedge b \in S \wedge (R \neq S \longrightarrow (\exists !c{\in}\mathcal{E}.\ R \cap S = \{c\}))$
by (*metis events-paths assms paths-cross-once*)

end
context *MinkowskiBetweenness* **begin**

lemma assumes $[[a\ b\ c]]$ **shows** $\exists f.$ *long-ch-by-ord* f $\{a,b,c\}$
  using *abc-abc-neq ord-ordered long-ch-by-ord-def assms*
  by (*smt insertI1 insert-commute*)

lemma *between-chain*: $[[a\ b\ c]] \Longrightarrow$ *ch* $\{a,b,c\}$
proof −
  assume $[[a\ b\ c]]$
  hence $\exists f.$ *ordering* f *betw* $\{a,b,c\}$
    by (*simp add*: *abc-abc-neq ord-ordered*)
  hence $\exists f.$ *long-ch-by-ord* f $\{a,b,c\}$
    using ‹$[[a\ b\ c]]$› *abc-abc-neq long-ch-by-ord-def* **by** *auto*
  thus *?thesis*
    by (*simp add*: *ch-by-ord-def ch-def*)
qed

lemma *overlap-chain*: $[\![[[a\ b\ c]]; [[b\ c\ d]]]\!] \Longrightarrow$ *ch* $\{a,b,c,d\}$
proof −
  assume $[[a\ b\ c]]$ **and** $[[b\ c\ d]]$
  have $\exists f.$ *ordering* f *betw* $\{a,b,c,d\}$
    proof −
      have *f1*: $[[a\ b\ d]]$
        using ‹$[[a\ b\ c]]$› ‹$[[b\ c\ d]]$› **by** *blast*
      have $[[a\ c\ d]]$
        using ‹$[[a\ b\ c]]$› ‹$[[b\ c\ d]]$› *abc-bcd-acd* **by** *blast*
      then show *?thesis*
      using *f1* **by** (*metis* (*no-types*) ‹$[[a\ b\ c]]$› ‹$[[b\ c\ d]]$› *abc-abc-neq overlap-ordering*)
    qed
    hence $\exists f.$ *long-ch-by-ord* f $\{a,b,c,d\}$
      using ‹$[[a\ b\ c]]$› *abc-abc-neq long-ch-by-ord-def* **by** *auto*
    thus *?thesis*
      by (*simp add*: *ch-by-ord-def ch-def*)
  qed

end

20 3.1 Order on a finite chain

context *MinkowskiBetweenness* **begin**

20.1 Theorem 1

See *Minkowski.abc-only-cba*. Proving it again here to show it can be done following the prose in Schutz.

theorem *theorem1* [*no-atp*]:
  assumes *abc*: $[[a\ b\ c]]$
  shows $[[c\ b\ a]] \wedge \neg\ [[b\ c\ a]] \wedge \neg\ [[c\ a\ b]]$
proof −

have *part-i*: [[*c b a*]] **using** *abc abc-sym* **by** *simp*

have *part-ii*: ¬ [[*b c a*]]
proof (*rule notI*)
  assume [[*b c a*]]
  then have [[*a b a*]] **using** *abc abc-bcd-abd* **by** *blast*
  thus *False* **using** *abc-ac-neq* **by** *blast*
qed

have *part-iii*: ¬ [[*c a b*]]
proof (*rule notI*)
  assume [[*c a b*]]
  then have [[*c a c*]] **using** *abc abc-bcd-abd* **by** *blast*
  thus *False* **using** *abc-ac-neq* **by** *blast*
qed
thus *?thesis* **using** *part-i part-ii part-iii* **by** *auto*
qed

20.2 Theorem 2

The lemma *abc-bcd-acd*, equal to the start of Schutz's proof, is given in *Minkowski* in order to prove some equivalences. Splitting it up into the proof of: "there is a betweenness relation for each ordered triple", and "all events of a chain are distinct" The first part is obvious with total chains (using *ordering*), and will be proved using the local definition as well (*ordering2*), following Schutz' proof. The second part is proved as injectivity of the indexing function (see *index-injective*).

For the case of two-element chains: the elements are distinct by definition, and the statement on ordering is void (respectively, *False* $\Longrightarrow$ P for any P).

theorem *order-finite-chain*:
  assumes *chX*: *long-ch-by-ord f X*
    and *finiteX*: *finite X*
    and *ordered-nats*: $0 \leq (i{::}nat) \wedge i < j \wedge j < l \wedge l < card\ X$
  shows [[(*f i*) (*f j*) (*f l*)]]
  by (*metis chX long-ch-by-ord-def ordered-nats ordering-ord-ijk*)

lemma *thm2-ind1*:
  assumes *chX*: *long-ch-by-ord2 f X*
    and *finiteX*: *finite X*
  shows $\forall j\ i.\ ((i{::}nat) < j \wedge j < card\ X - 1) \longrightarrow$ [[(*f i*) (*f j*) (*f* (*j* + *1*))]]
proof (*rule allI*)+
  let $?P = \lambda\ i\ j.$ [[(*f i*) (*f j*) (*f* (*j*+*1*))]]
  fix *i j*
  show $(i<j \wedge j<card\ X - 1) \longrightarrow\ ?P\ i\ j$
  proof (*induct j*)

```
    case 0
    show ?case by blast
  next
    case (Suc j)
    show ?case
    proof (clarify)
      assume asm: i<Suc j Suc j<card X −1
      have pj: ?P j (Suc j)
        using asm(2) chX less-diff-conv long-ch-by-ord2-def ordering2-def
        by (metis Suc-eq-plus1)
      have i<j ∨ i=j using asm(1)
        by linarith
      thus ?P i (Suc j)
      proof
        assume i=j
        hence Suc i = Suc j ∧ Suc (Suc j) = Suc (Suc j)
          by simp
        thus ?P i (Suc j)
          using pj by auto
      next
        assume i<j
        have j < card X − 1
          using asm(2) by linarith
        thus ?P i (Suc j)
         using ⟨i<j⟩ Suc.hyps asm(1) asm(2) chX finiteX Suc-eq-plus1 abc-bcd-acd
pj
          by presburger
      qed
    qed
  qed
qed

lemma thm2-ind2:
  assumes chX: long-ch-by-ord2 f X
      and finiteX: finite X
    shows ∀ m l. (0<(l−m) ∧ (l−m) < l ∧ l < card X) ⟶ [[(f ((l−m)−1)) (f
(l−m)) (f l)]]
proof (rule allI)+
  fix l m
  let ?P = λ k l. [[(f (k−1)) (f k) (f l)]]
  let ?n = card X
  let ?k = (l::nat)−m
  show 0 < ?k ∧ ?k < l ∧ l < ?n ⟶ ?P ?k l
  proof (induct m)
    case 0
    show ?case by simp
  next
    case (Suc m)
    show ?case
```

proof (*clarify*)
assume *asm*: $0 < l - Suc\ m\ l - Suc\ m < l\ l < ?n$
have $Suc\ m = 1 \lor Suc\ m > 1$ **by** *linarith*
thus $[[(f\ (l - Suc\ m - 1))\ (f\ (l - Suc\ m))\ (f\ l)]]$ (**is** *?goal*)
proof
assume $Suc\ m = 1$
show *?goal*
proof −
have $l - Suc\ m < card\ X$
using *asm*(2) *asm*(3) *less-trans* **by** *blast*
then show *?thesis*
using ‹$Suc\ m = 1$› *asm finiteX thm2-ind1 chX*
using *Suc-eq-plus1 add-diff-inverse-nat diff-Suc-less gr-implies-not-zero less-one plus-1-eq-Suc*
by (*smt long-ch-by-ord2-def ordering2-ord-ijk*)
qed
next
assume $Suc\ m > 1$
show *?goal*
apply (*rule-tac* $a{=}f\ l$ **and** $c{=}f(l - Suc\ m - 1)$ **in** *abc-sym*)
apply (*rule-tac* $a{=}f\ l$ **and** $c{=}f(l{-}Suc\ m)$ **and** $d{=}f(l{-}Suc\ m{-}1)$ **and** $b{=}f(l{-}m)$ **in** *abc-bcd-acd*)
proof −
have $[[(f(l{-}m{-}1))\ (f(l{-}m))\ (f\ l)]]$
using *Suc.hyps* ‹$1 < Suc\ m$› *asm*(1,3) **by** *force*
thus $[[(f\ l)\ (f(l - m))\ (f(l - Suc\ m))]]$
using *abc-sym One-nat-def diff-zero minus-nat.simps*(2)
by *metis*
have $Suc(l - Suc\ m - 1) = l - Suc\ m\ Suc(l - Suc\ m) = l{-}m$
using *Suc-pred asm*(1) **by** *presburger+*
hence $[[(f(l - Suc\ m - 1))\ (f(l - Suc\ m))\ (f(l - m))]]$
using *chX* **unfolding** *long-ch-by-ord2-def ordering2-def*
by (*meson asm*(3) *less-imp-diff-less*)
thus $[[(f(l - m))\ (f(l - Suc\ m))\ (f(l - Suc\ m - 1))]]$
using *abc-sym* **by** *blast*
qed
qed
qed
qed
qed

lemma *thm2-ind2b*:
assumes *chX*: *long-ch-by-ord2 f X*
and *finiteX*: *finite X*
and *ordered-nats*: $0{<}k \land k{<}l \land l < card\ X$
shows $[[(f\ (k{-}1))\ (f\ k)\ (f\ l)]]$
using *thm2-ind2 finiteX chX ordered-nats*
by (*metis diff-diff-cancel less-imp-le*)

This is Theorem 2 properly speaking, except for the "chain elements are distinct" part (which is proved as injectivity of the index later). Follows Schutz fairly well! The statement Schutz proves under (i) is given in *Minkowski-Betweenness.abc-bcd-acd* instead.

theorem *order-finite-chain2*:
  assumes *chX*: *long-ch-by-ord2 f X*
    and *finiteX*: *finite X*
    and *ordered-nats*: $0 \leq (i::nat) \wedge i < j \wedge j < l \wedge l < card\ X$
  shows $[[(f\ i)\ (f\ j)\ (f\ l)]]$
proof −
  let $?n = card\ X - 1$
  have *ord1*: $0 \leq i \wedge i<j \wedge j<?n$
    using *ordered-nats* **by** *linarith*
  have *e2*: $[[(f\ i)\ (f\ j)\ (f\ (j+1))]]$ **using** *thm2-ind1*
    using *Suc-eq-plus1 chX finiteX ord1*
    by *presburger*
  have *e3*: $\forall k.\ 0<k \wedge k<l \longrightarrow [[(f\ (k-1))\ (f\ k)\ (f\ l)]]$
    using *thm2-ind2b chX finiteX ordered-nats*
    by *blast*
  have $j<l-1 \vee j=l-1$
    using *ordered-nats* **by** *linarith*
  thus *?thesis*
  proof
    assume $j<l-1$
    have $[[(f\ j)\ (f\ (j+1))\ (f\ l)]]$
      using *e3 abc-abc-neq ordered-nats*
      using ‹$j < l - 1$› *less-diff-conv* **by** *auto*
    thus *?thesis*
      using *e2 abc-bcd-abd*
      by *blast*
  next
    assume $j=l-1$
    thus *?thesis* **using** *e2*
      using *ordered-nats* **by** *auto*
  qed
qed

lemma *three-in-long-chain2*:
  assumes *long-ch-by-ord2 f X*
  obtains *x y z* **where** $x \in X$ **and** $y \in X$ **and** $z \in X$ **and** $x \neq y$ **and** $x \neq z$ **and** $y \neq z$
  using *assms*(*1*) *long-ch-by-ord2-def* **by** *auto*

lemma *short-ch-card-2*:
  assumes *ch-by-ord f X*
  shows *short-ch X* $\longleftrightarrow$ *card X* $= 2$
  by (*metis assms card-2-iff' ch-by-ord-def long-ch-by-ord-def short-ch-def*)

```
lemma long-chain2-card-geq:
  assumes long-ch-by-ord2 f X and fin: finite X
  shows card X ≥ 3
proof −
  obtain x y z where xyz: x∈X y∈X z∈X and neq: x≠y x≠z y≠z
    using three-in-long-chain2 assms(1) by blast
  let ?S = {x,y,z}
  have ?S ⊆ X
    by (simp add: xyz)
  moreover have card ?S ≥ 3
    using antisym ‹x ≠ y› ‹x ≠ z› ‹y ≠ z› by auto
  ultimately show ?thesis
    by (meson neq fin three-subset)
qed


lemma fin-chain-card-geq-2:
  assumes [f[a..b]X]
  shows card X ≥ 2
  using fin-chain-def apply (cases short-ch X)
  using short-ch-card-2
  apply (metis card-2-iff' dual-order.eq-iff short-ch-def)
  using assms fin-long-chain-def not-less by fastforce


theorem  index-injective:
  fixes i::nat and j::nat
  assumes chX: long-ch-by-ord2 f X
      and finiteX: finite X
      and indices: i<j j<card X
    shows f i ≠ f j
proof (cases)
  assume Suc i < j
  then have [[(f i) (f (Suc(i))) (f j)]]
    using order-finite-chain2 chX finiteX indices(2) by blast
  then show ?thesis
    using abc-abc-neq by blast
next
  assume ¬Suc i < j
  hence Suc i = j
    using Suc-lessI indices(1) by blast
  show ?thesis
  proof (cases)
    assume Suc j = card X
    then have 0<i
    proof −
      have Suc(Suc i) = card X
        by (simp add: ‹Suc i = j› ‹Suc j = card X›)
```

have *card X* $\geq$ *3*
using *assms*(*1*) *finiteX long-chain2-card-geq* **by** *blast*
thus *?thesis*
using ‹*Suc i* = *j*› ‹*Suc j* = *card X*› **by** *linarith*
qed
then have [[(*f 0*) (*f i*) (*f j*)]]
using *assms order-finite-chain2* **by** *blast*
thus *?thesis*
using *abc-abc-neq* **by** *blast*
next
assume ¬*Suc j* = *card X*
then have *Suc j* < *card X*
using *Suc-lessI indices*(*2*) **by** *blast*
then have [[(*f i*) (*f j*) (*f*(*Suc j*))]]
using *chX finiteX indices*(*1*) *order-finite-chain2* **by** *blast*
thus *?thesis*
using *abc-abc-neq* **by** *blast*
qed
qed

end

21 Finite chain equivalence: local ↔ global

context *MinkowskiBetweenness* **begin**

lemma *ch-equiv1*:
assumes *long-ch-by-ord f X finite X*
shows *long-ch-by-ord2 f X*
using *assms*
unfolding *long-ch-by-ord-def long-ch-by-ord2-def ordering-def ordering2-def*
by (*metis lessI*)

lemma *ch-equiv2*:
assumes *long-ch-by-ord2 f X finite X*
shows *long-ch-by-ord f X*
using *order-finite-chain2 assms*
unfolding *long-ch-by-ord-def long-ch-by-ord2-def ordering-def ordering2-def*
apply *safe* **by** *blast*

lemma *ch-equiv*:
assumes *finite X*
shows *long-ch-by-ord f X* ⟷ *long-ch-by-ord2 f X*
using *ch-equiv1 ch-equiv2 assms* **by** *blast*

end

22 Preliminary Results for Kinematic Triangles and Paths/Betweenness

Theorem 3 (collinearity) First we prove some lemmas that will be very helpful.

context *MinkowskiPrimitive* **begin**

lemma *triangle-permutes* [*no-atp*]:
  assumes $\triangle\ a\ b\ c$
  shows $\triangle\ a\ c\ b$ $\triangle\ b\ a\ c$ $\triangle\ b\ c\ a$ $\triangle\ c\ a\ b$ $\triangle\ c\ b\ a$
  using *assms* **by** (*auto simp add*: *kinematic-triangle-def*)+

lemma *triangle-paths* [*no-atp*]:
  assumes *tri-abc*: $\triangle\ a\ b\ c$
  shows *path-ex a b path-ex a c path-ex b c*
using *tri-abc* **by** (*auto simp add*: *kinematic-triangle-def*)+

lemma *triangle-paths-unique*:
  assumes *tri-abc*: $\triangle\ a\ b\ c$
  shows $\exists!ab.\ path\ ab\ a\ b$
  using *path-unique tri-abc triangle-paths*(*1*) **by** *auto*

The definition of the kinematic triangle says that there exist paths that a and b pass through, and a and c pass through etc that are not equal. But we can show there is a *unique* ab that a and b pass through, and assuming there is a path abc that a, b, c pass through, it must be unique. Therefore $ab = abc$ and $ac = abc$, but $ab \neq ac$, therefore *False*. Lemma *tri-three-paths* is not in the books but might simplify some path obtaining.

lemma *triangle-diff-paths*:
  assumes *tri-abc*: $\triangle\ a\ b\ c$
  shows $\neg\ (\exists\ Q\in\mathcal{P}.\ a \in Q \land b \in Q \land c \in Q)$
proof (*rule notI*)
  assume *not-thesis*: $\exists\ Q\in\mathcal{P}.\ a \in Q \land b \in Q \land c \in Q$

  then obtain *abc* **where** *path-abc*: $abc \in \mathcal{P} \land a \in abc \land b \in abc \land c \in abc$ **by** *auto*
  have *abc-neq*: $a \neq b \land a \neq c \land b \neq c$ **using** *tri-abc kinematic-triangle-def* **by** *simp*

  have $\exists\ ab\in\mathcal{P}.\ \exists\ ac\in\mathcal{P}.\ ab \neq ac \land a \in ab \land b \in ab \land a \in ac \land c \in ac$
    using *tri-abc kinematic-triangle-def* **by** *metis*
  then obtain *ab ac* **where** *ab-ac-relate*: $ab \in \mathcal{P} \land ac \in \mathcal{P} \land ab \neq ac \land \{a,b\} \subseteq ab \land \{a,c\} \subseteq ac$
    by *blast*

have $\exists!ab{\in}\mathcal{P}.\ a \in ab \wedge b \in ab$ **using** *tri-abc triangle-paths-unique* **by** *blast*
then have *ab-eq-abc*: $ab = abc$ **using** *path-abc ab-ac-relate* **by** *auto*
have $\exists!ac{\in}\mathcal{P}.\ a \in ac \wedge b \in ac$ **using** *tri-abc triangle-paths-unique* **by** *blast*
then have *ac-eq-abc*: $ac = abc$ **using** *path-abc ab-ac-relate eq-paths abc-neq* **by** *auto*
have $ab = ac$ **using** *ab-eq-abc ac-eq-abc* **by** *simp*
thus *False* **using** *ab-ac-relate* **by** *simp*
qed

lemma *tri-three-paths* [*elim*]:
assumes *tri-abc*: $\triangle\ a\ b\ c$
shows $\exists\, ab\ bc\ ca.\ path\ ab\ a\ b \wedge path\ bc\ b\ c \wedge path\ ca\ c\ a \wedge ab \neq bc \wedge ab \neq ca \wedge bc \neq ca$
using *tri-abc triangle-diff-paths triangle-paths(2,3) triangle-paths-unique*
by *fastforce*

lemma *triangle-paths-neq*:
assumes *tri-abc*: $\triangle\ a\ b\ c$
and *path-ab*: *path ab a b*
and *path-ac*: *path ac a c*
shows $ab \neq ac$
using *assms triangle-diff-paths* **by** *blast*

end
context *MinkowskiBetweenness* **begin**

lemma *abc-ex-path-unique*:
assumes *abc*: $[[a\ b\ c]]$
shows $\exists!Q{\in}\mathcal{P}.\ a \in Q \wedge b \in Q \wedge c \in Q$
proof −
have *a-neq-c*: $a \neq c$ **using** *abc-ac-neq abc* **by** *simp*
have $\exists\, Q{\in}\mathcal{P}.\ a \in Q \wedge b \in Q \wedge c \in Q$ **using** *abc-ex-path abc* **by** *simp*
then obtain *P Q* **where** *path-P*: $P \in \mathcal{P}$ **and** *abc-inP*: $a \in P \wedge b \in P \wedge c \in P$
and *path-Q*: $Q \in \mathcal{P}$ **and** *abc-in-Q*: $a \in Q \wedge b \in Q \wedge c \in Q$ **by** *auto*
then have $P = Q$ **using** *a-neq-c eq-paths* **by** *blast*
thus *?thesis* **using** *eq-paths a-neq-c* **using** *abc-inP path-P* **by** *auto*
qed

lemma *betw-c-in-path*:
assumes *abc*: $[[a\ b\ c]]$
and *path-ab*: *path ab a b*
shows $c \in ab$

using *eq-paths abc-ex-path assms* **by** *blast*

lemma *betw-b-in-path*:
assumes *abc*: $[[a\ b\ c]]$
and *path-ab*: *path ac a c*

shows $b \in ac$
using *assms abc-ex-path-unique path-unique* **by** *blast*

lemma *betw-a-in-path*:
assumes *abc*: $[[a\ b\ c]]$
and *path-ab*: *path bc b c*
shows $a \in bc$
using *assms abc-ex-path-unique path-unique* **by** *blast*

lemma *triangle-not-betw-abc*:
assumes *tri-abc*: $\triangle\ a\ b\ c$
shows $\neg\ [[a\ b\ c]]$
using *tri-abc abc-ex-path triangle-diff-paths* **by** *blast*

lemma *triangle-not-betw-acb*:
assumes *tri-abc*: $\triangle\ a\ b\ c$
shows $\neg\ [[a\ c\ b]]$
by (*simp add*: *tri-abc triangle-not-betw-abc triangle-permutes*(*1*))

lemma *triangle-not-betw-bac*:
assumes *tri-abc*: $\triangle\ a\ b\ c$
shows $\neg\ [[b\ a\ c]]$
by (*simp add*: *tri-abc triangle-not-betw-abc triangle-permutes*(*2*))

lemma *triangle-not-betw-any*:
assumes *tri-abc*: $\triangle\ a\ b\ c$
shows $\neg\ (\exists\, d\in\{a,b,c\}.\ \exists\, e\in\{a,b,c\}.\ \exists f\in\{a,b,c\}.\ [[d\ e\ f]])$
by (*metis abc-ex-path abc-abc-neq empty-iff insertE tri-abc triangle-diff-paths*)

end

23 3.2 First collinearity theorem

theorem (**in** *MinkowskiChain*) *collinearity-alt2*:
assumes *tri-abc*: $\triangle\ a\ b\ c$
and *path-de*: *path de d e*

and *path-ab*: *path ab a b*
and *bcd*: $[[b\ c\ d]]$
and *cea*: $[[c\ e\ a]]$
shows $\exists f\in de\cap ab.\ [[a\ f\ b]]$
proof −
have $\exists f\in ab \cap de.\ \exists X.\ [[a..f..b]X]$
proof −
have *path-ex a c* **using** *tri-abc triangle-paths*(*2*) **by** *auto*
then obtain *ac* **where** *path-ac*: *path ac a c* **by** *auto*
have *path-ex b c* **using** *tri-abc triangle-paths*(*3*) **by** *auto*
then obtain *bc* **where** *path-bc*: *path bc b c* **by** *auto*
have *ab-neq-ac*: $ab \neq ac$ **using** *triangle-paths-neq path-ab path-ac tri-abc* **by**

fastforce
  have *ab-neq-bc*: $ab \neq bc$ **using** *eq-paths ab-neq-ac path-ab path-ac path-bc* **by** *blast*
  have *ac-neq-bc*: $ac \neq bc$ **using** *eq-paths ab-neq-bc path-ab path-ac path-bc* **by** *blast*
  have *d-in-bc*: $d \in bc$ **using** *bcd betw-c-in-path path-bc* **by** *blast*
  have *e-in-ac*: $e \in ac$ **using** *betw-b-in-path cea path-ac* **by** *blast*
  show *?thesis*
   using *O6* [**where** $Q = ab$ **and** $R = ac$ **and** $S = bc$ **and** $T = de$ **and** $a = a$ **and** $b = b$ **and** $c = c$]
      ab-neq-ac ab-neq-bc ac-neq-bc path-ab path-bc path-ac path-de bcd cea d-in-bc e-in-ac
   by *auto*
 qed
 thus *?thesis* **using** *finite-chain3-betw* **by** *blast*
qed

theorem (**in** *MinkowskiChain*) *collinearity-alt*:
 assumes *tri-abc*: $\triangle\ a\ b\ c$
   and *path-de*: *path de d e*
   and *bcd*: $[[b\ c\ d]]$
   and *cea*: $[[c\ e\ a]]$
 shows $\exists\, ab.\ path\ ab\ a\ b \wedge (\exists f{\in}de{\cap}ab.\ [[a\ f\ b]])$
proof −
 have *ex-path-ab*: *path-ex a b*
  using *tri-abc triangle-paths-unique* **by** *blast*
 then obtain *ab* **where** *path-ab*: *path ab a b*
  by *blast*
 have $\exists f{\in}ab \cap de.\ \exists X.\ [[a..f..b]X]$
 proof −
  have *path-ex a c* **using** *tri-abc triangle-paths(2)* **by** *auto*
  then obtain *ac* **where** *path-ac*: *path ac a c* **by** *auto*
  have *path-ex b c* **using** *tri-abc triangle-paths(3)* **by** *auto*
  then obtain *bc* **where** *path-bc*: *path bc b c* **by** *auto*
  have *ab-neq-ac*: $ab \neq ac$ **using** *triangle-paths-neq path-ab path-ac tri-abc* **by** *fastforce*
  have *ab-neq-bc*: $ab \neq bc$ **using** *eq-paths ab-neq-ac path-ab path-ac path-bc* **by** *blast*
  have *ac-neq-bc*: $ac \neq bc$ **using** *eq-paths ab-neq-bc path-ab path-ac path-bc* **by** *blast*
  have *d-in-bc*: $d \in bc$ **using** *bcd betw-c-in-path path-bc* **by** *blast*
  have *e-in-ac*: $e \in ac$ **using** *betw-b-in-path cea path-ac* **by** *blast*
  show *?thesis*
   using *O6* [**where** $Q = ab$ **and** $R = ac$ **and** $S = bc$ **and** $T = de$ **and** $a = a$ **and** $b = b$ **and** $c = c$]
      ab-neq-ac ab-neq-bc ac-neq-bc path-ab path-bc path-ac path-de bcd cea d-in-bc e-in-ac
   by *auto*

qed
thus *?thesis* **using** *finite-chain3-betw path-ab* **by** *fastforce*
qed

theorem (**in** *MinkowskiChain*) *collinearity*:
assumes *tri-abc*: $\triangle\ a\ b\ c$
and *path-de*: *path de d e*
and *bcd*: $[[b\ c\ d]]$
and *cea*: $[[c\ e\ a]]$
shows $(\exists f \in de \cap (path\text{-}of\ a\ b).\ [[a\ f\ b]])$
proof −
let *?ab* = *path-of a b*
have *path-ab*: *path ?ab a b*
using *tri-abc theI′* [*OF triangle-paths-unique*] **by** *blast*
have $\exists f \in ?ab \cap de.\ \exists X.\ [[a..f..b]X]$
proof −
have *path-ex a c* **using** *tri-abc triangle-paths*(*2*) **by** *auto*
then obtain *ac* **where** *path-ac*: *path ac a c* **by** *auto*
have *path-ex b c* **using** *tri-abc triangle-paths*(*3*) **by** *auto*
then obtain *bc* **where** *path-bc*: *path bc b c* **by** *auto*
have *ab-neq-ac*: *?ab* ≠ *ac* **using** *triangle-paths-neq path-ab path-ac tri-abc* **by** *fastforce*
have *ab-neq-bc*: *?ab* ≠ *bc* **using** *eq-paths ab-neq-ac path-ab path-ac path-bc* **by** *blast*
have *ac-neq-bc*: *ac* ≠ *bc* **using** *eq-paths ab-neq-bc path-ab path-ac path-bc* **by** *blast*
have *d-in-bc*: *d* ∈ *bc* **using** *bcd betw-c-in-path path-bc* **by** *blast*
have *e-in-ac*: *e* ∈ *ac* **using** *betw-b-in-path cea path-ac* **by** *blast*
show *?thesis*
using *O6* [**where** *Q* = *?ab* **and** *R* = *ac* **and** *S* = *bc* **and** *T* = *de* **and** *a* = *a* **and** *b* = *b* **and** *c* = *c*]
ab-neq-ac ab-neq-bc ac-neq-bc path-ab path-bc path-ac path-de bcd cea d-in-bc e-in-ac
IntI Int-commute
by (*metis* (*no-types*, *lifting*))
qed
thus *?thesis* **using** *finite-chain3-betw* **by** *blast*
qed

24 Additional results for Paths and Unreachables

context *MinkowskiPrimitive* **begin**

The degenerate case.

lemma *big-bang*:
assumes *no-paths*: $\mathcal{P} = \{\}$
shows $\exists\, a.\ \mathcal{E} = \{a\}$
proof −

have $\exists\, a.\ a \in \mathcal{E}$ **using** *nonempty-events* **by** *blast*
then obtain a **where** *a-event*: $a \in \mathcal{E}$ **by** *auto*
have $\neg\ (\exists\, b{\in}\mathcal{E}.\ b \neq a)$
proof (*rule notI*)
assume $\exists\, b{\in}\mathcal{E}.\ b \neq a$
then have $\exists\, Q.\ Q \in \mathcal{P}$ **using** *events-paths a-event* **by** *auto*
thus *False* **using** *no-paths* **by** *simp*
qed
then have $\forall\, b{\in}\mathcal{E}.\ b = a$ **by** *simp*
thus *?thesis* **using** *a-event* **by** *auto*
qed

lemma *two-events-then-path*:
assumes *two-events*: $\exists\, a{\in}\mathcal{E}.\ \exists\, b{\in}\mathcal{E}.\ a \neq b$
shows $\exists\, Q.\ Q \in \mathcal{P}$
proof –
have $(\forall\, a.\ \mathcal{E} \neq \{a\}) \longrightarrow \mathcal{P} \neq \{\}$ **using** *big-bang* **by** *blast*
then have $\mathcal{P} \neq \{\}$ **using** *two-events* **by** *blast*
thus *?thesis* **by** *blast*
qed

lemma *paths-are-events*: $\forall\, Q{\in}\mathcal{P}.\ \forall\, a{\in}Q.\ a \in \mathcal{E}$
by *simp*

lemma *same-empty-unreach*:
$[\![Q \in \mathcal{P};\ a \in Q]\!] \Longrightarrow \emptyset\ Q\ a = \{\}$
apply (*unfold unreachable-subset-def*)
by *simp*

lemma *same-path-reachable*:
$[\![Q \in \mathcal{P};\ a \in Q;\ b \in Q]\!] \Longrightarrow a \in Q - \emptyset\ Q\ b$
by (*simp add*: *same-empty-unreach*)

If we have two paths crossing and a is on the crossing point, and b is on one of the paths, then a is in the reachable part of the path b is on.

lemma *same-path-reachable2*:
$[\![Q \in \mathcal{P};\ R \in \mathcal{P};\ a \in Q;\ a \in R;\ b \in Q]\!] \Longrightarrow a \in R - \emptyset\ R\ b$
unfolding *unreachable-subset-def* **by** *blast*

lemma *cross-in-reachable*:
assumes *path-Q*: $Q \in \mathcal{P}$
and *a-inQ*: $a \in Q$
and *b-inQ*: $b \in Q$
and *b-inR*: $b \in R$
shows $b \in R - \emptyset\ R\ a$
unfolding *unreachable-subset-def* **using** *a-inQ b-inQ b-inR path-Q* **by** *auto*

lemma *reachable-path*:

assumes *path-Q*: $Q \in \mathcal{P}$
    and *b-event*: $b \in \mathcal{E}$
    and *a-reachable*: $a \in Q - \emptyset\ Q\ b$
  shows $\exists R \in \mathcal{P}.\ a \in R \wedge b \in R$
proof −
  have *a-inQ*: $a \in Q$ **using** *a-reachable* **by** *simp*
  have $Q \notin \mathcal{P} \vee b \notin \mathcal{E} \vee b \in Q \vee (\exists R \in \mathcal{P}.\ b \in R \wedge a \in R)$
    using *a-reachable unreachable-subset-def* **by** *auto*
  then have $b \in Q \vee (\exists R \in \mathcal{P}.\ b \in R \wedge a \in R)$ **using** *path-Q b-event* **by** *simp*
  thus *?thesis*
  proof (*rule disjE*)
    assume $b \in Q$
    thus *?thesis* **using** *a-inQ path-Q* **by** *auto*
  next
    assume $\exists R \in \mathcal{P}.\ b \in R \wedge a \in R$
    thus *?thesis* **using** *conj-commute* **by** *simp*
  qed
qed

end
context *MinkowskiUnreachable* **begin**

First some basic facts about the primitive notions, which seem to belong here. I don't think any/all of these are explicitly proved in Schutz.

lemma *no-empty-paths* [*simp*]:
  assumes $Q \in \mathcal{P}$
  shows $Q \neq \{\}$
proof −
  obtain a **where** $a \in \mathcal{E}$ **using** *nonempty-events* **by** *blast*
  have $a \in Q \vee a \notin Q$ **by** *auto*
  thus *?thesis*
  proof
    assume $a \in Q$
    thus *?thesis* **by** *blast*
  next
    assume $a \notin Q$
    then obtain b **where** $b \in \emptyset\ Q\ a$
      using *two-in-unreach* ‹$a \in \mathcal{E}$› *assms*
      by *blast*
    thus *?thesis*
      using *unreachable-subset-def* **by** *auto*
  qed
qed

lemma *events-ex-path*:
  assumes *ge1-path*: $\mathcal{P} \neq \{\}$
  shows $\forall x \in \mathcal{E}.\ \exists Q \in \mathcal{P}.\ x \in Q$
proof
  fix x

assume *x-event*: $x \in \mathcal{E}$
have $\exists\, Q.\ Q \in \mathcal{P}$ **using** *ge1-path* **using** *ex-in-conv* **by** *blast*
then obtain Q **where** *path-Q*: $Q \in \mathcal{P}$ **by** *auto*
then have $\exists\, y.\ y \in Q$ **using** *no-empty-paths* **by** *blast*
then obtain y **where** *y-inQ*: $y \in Q$ **by** *auto*
then have *y-event*: $y \in \mathcal{E}$ **using** *in-path-event path-Q* **by** *simp*
have $\exists\, P{\in}\mathcal{P}.\ x \in P$
proof *cases*
assume $x = y$
thus *?thesis* **using** *y-inQ path-Q* **by** *auto*
next
assume $x \neq y$
thus *?thesis* **using** *events-paths x-event y-event* **by** *auto*
qed
thus $\exists\, Q{\in}\mathcal{P}.\ x \in Q$ **by** *simp*
qed

lemma *unreach-ge2-then-ge2*:
assumes $\exists\, x{\in}\emptyset\ Q\ b.\ \exists\, y{\in}\emptyset\ Q\ b.\ x \neq y$
shows $\exists\, x{\in}Q.\ \exists\, y{\in}Q.\ x \neq y$
using *assms unreachable-subset-def* **by** *auto*

This lemma just proves that the chain obtained to bound the unreachable set of a path is indeed on that path. Extends I6; requires Theorem 2; used in Theorem 13. Seems to be assumed in Schutz' chain notation in I6.

lemma *chain-on-path-I6*:
assumes *path-Q*: $Q{\in}\mathcal{P}$
and *event-b*: $b{\notin}Q\ b{\in}\mathcal{E}$
and *unreach*: $Q_x \in \emptyset\ Q\ b\ Q_z \in \emptyset\ Q\ b\ Q_x \neq Q_z$
and *X-def*: *ch-by-ord* $f\ X\ f\ 0 = Q_x\ f\ (card\ X - 1) = Q_z$
$(\forall\, i{\in}\{1\ ..\ card\ X - 1\}.\ (f\ i) \in \emptyset\ Q\ b \wedge (\forall\, Q_y{\in}\mathcal{E}.\ [[(f(i{-}1))\ Q_y\ (f\ i)]] \longrightarrow Q_y \in \emptyset\ Q\ b))$
$(short\text{-}ch\ X \longrightarrow Q_x{\in}X \wedge Q_z{\in}X \wedge (\forall\, Q_y{\in}\mathcal{E}.\ [[Q_x\ Q_y\ Q_z]] \longrightarrow Q_y \in \emptyset\ Q\ b))$
shows $X{\subseteq}Q$

proof −
have *in-Q*: $Q_x{\in}Q \wedge Q_z{\in}Q$
using *unreachable-subset-def unreach*$(1,2)$ **by** *blast*
have *fin-X*: *finite* X
using *unreach*(3) *not-less X-def* **by** *fastforce*
{
assume *short-ch* X
hence *?thesis*
by (*metis X-def*(5) *in-Q short-ch-def subsetI unreach*(3))
} moreover {
assume *asm*: *long-ch-by-ord* $f\ X$
have *?thesis*

proof
  fix x **assume** $x \in X$
  then obtain i **where** $f\ i = x\ i < card\ X$
    using *asm* **unfolding** *ch-by-ord-def long-ch-by-ord-def ordering-def*
    using *fin-X* **by** *auto*
  show $x \in Q$
  proof (*cases*)
    assume $x = Q_x \lor x = Q_z$
    thus *?thesis*
      using *in-Q* **by** *blast*
  next
    assume $\neg(x = Q_x \lor x = Q_z)$
    hence $x \neq Q_x\ x \neq Q_z$ **by** *linarith+*
    have $i > 0$
      using *X-def(2)* ‹$x \neq Q_x$› ‹$f\ i = x$› *gr-zeroI* **by** *force*
    have $i < card\ X - 1$
    using *X-def(3)* ‹$f\ i = x$› ‹$i < card\ X$› ‹$x \neq Q_z$› *less-imp-diff-less less-SucE*
      by (*metis Suc-pred′ cancel-comm-monoid-add-class.diff-cancel*)
    have $[[Q_x\ (f\ i)\ Q_z]]$
      using *X-def(2,3)* ‹$0 < i$› ‹$i < card\ X - 1$› *asm fin-X order-finite-chain*
      by *auto*
    thus *?thesis*
      by (*simp add*: ‹$f\ i = x$› *betw-b-in-path in-Q path-Q unreach(3)*)
  qed
qed
}
ultimately show *?thesis*
  using *X-def(1) ch-by-ord-def* **by** *blast*
qed

end

25 Results about Paths as Sets

Note several of the following don't need MinkowskiPrimitive, they are just Set lemmas; nevertheless I'm naming them and writing them this way for clarity.

context *MinkowskiPrimitive* **begin**

lemma *distinct-paths*:
  assumes $Q \in \mathcal{P}$
    and $R \in \mathcal{P}$
    and $d \notin Q$
    and $d \in R$
  shows $R \neq Q$
using *assms* **by** *auto*

lemma *distinct-paths2*:

assumes $Q \in \mathcal{P}$
and $R \in \mathcal{P}$
and $\exists\, d.\ d \notin Q \wedge d \in R$
shows $R \neq Q$
using *assms* **by** *auto*

lemma *external-events-neq*:
$[\![Q \in \mathcal{P};\ a \in Q;\ b \in \mathcal{E};\ b \notin Q]\!] \Longrightarrow a \neq b$
by *auto*

lemma *notin-cross-events-neq*:
$[\![Q \in \mathcal{P};\ R \in \mathcal{P};\ Q \neq R;\ a \in Q;\ b \in R;\ a \notin R{\cap}Q]\!] \Longrightarrow a \neq b$
by *blast*

lemma *nocross-events-neq*:
$[\![Q \in \mathcal{P};\ R \in \mathcal{P};\ a \in Q;\ b \in R;\ R{\cap}Q = \{\}]\!] \Longrightarrow a \neq b$
by *auto*

Given a nonempty path Q, and an external point d, we can find another path R passing through d (by I2 aka *events-paths*). This path is distinct from Q, as it passes through a point external to it.

lemma *external-path*:
assumes *path-Q*: $Q \in \mathcal{P}$
and *a-inQ*: $a \in Q$
and *d-notinQ*: $d \notin Q$
and *d-event*: $d \in \mathcal{E}$
shows $\exists\, R{\in}\mathcal{P}.\ d \in R$
proof −
have *a-neq-d*: $a \neq d$ **using** *a-inQ d-notinQ* **by** *auto*
thus $\exists\, R{\in}\mathcal{P}.\ d \in R$ **using** *events-paths* **by** (*meson a-inQ d-event in-path-event path-Q*)
qed

lemma *distinct-path*:
assumes $Q \in \mathcal{P}$
and $a \in Q$
and $d \notin Q$
and $d \in \mathcal{E}$
shows $\exists\, R{\in}\mathcal{P}.\ R \neq Q$
using *assms external-path* **by** *metis*

lemma *external-distinct-path*:
assumes $Q \in \mathcal{P}$
and $a \in Q$
and $d \notin Q$
and $d \in \mathcal{E}$
shows $\exists\, R{\in}\mathcal{P}.\ R \neq Q \wedge d \in R$
using *assms external-path* **by** *fastforce*

end

26 3.3 Boundedness of the unreachable set

26.1 Theorem 4 (boundedness of the unreachable set)

The same assumptions as I7, different conclusion. This doesn't just give us boundedness, it gives us another event outside of the unreachable set, as long as we have one already. I7 conclusion: $\exists\, X\ Q0\ Qm\ Qn.\ [[Q0\ ..\ Qm\ ..\ Qn]X] \wedge Q0 = ?Qx \wedge Qm = ?Qy \wedge Qn \in ?Q - \emptyset\ ?Q\ ?b$

theorem (**in** *MinkowskiUnreachable*) *unreachable-set-bounded*:
  assumes *path-Q*: $Q \in \mathcal{P}$
    and *b-nin-Q*: $b \notin Q$
    and *b-event*: $b \in \mathcal{E}$
    and *Qx-reachable*: $Qx \in Q - \emptyset\ Q\ b$
    and *Qy-unreachable*: $Qy \in \emptyset\ Q\ b$
  shows $\exists\, Qz{\in}Q - \emptyset\ Q\ b.\ [[Qx\ Qy\ Qz]] \wedge Qx \neq Qz$
  using *assms I7 order-finite-chain fin-long-chain-def*
  by (*metis fin-ch-betw*)

26.2 Theorem 5 (first existence theorem)

The lemma below is used in the contradiction in *external-event*, which is the essential part to Theorem 5(i).

lemma (**in** *MinkowskiUnreachable*) *only-one-path*:
  assumes *path-Q*: $Q \in \mathcal{P}$
    and *all-inQ*: $\forall\, a{\in}\mathcal{E}.\ a \in Q$
    and *path-R*: $R \in \mathcal{P}$
  shows $R = Q$
proof (*rule ccontr*)
  assume $\neg\ R = Q$
  then have *R-neq-Q*: $R \neq Q$ **by** *simp*
  have $\mathcal{E} = Q$
    by (*simp add*: *all-inQ antisym path-Q path-sub-events subsetI*)
  hence $R{\subset}Q$
    using *R-neq-Q path-R path-sub-events* **by** *auto*
  obtain *c* **where** $c{\notin}R$ $c{\in}Q$
    using ‹$R \subset Q$› **by** *blast*
  then obtain *a b* **where** *path R a b*
    using ‹$\mathcal{E} = Q$› *path-R two-in-unreach unreach-ge2-then-ge2* **by** *blast*
  have $a{\in}Q$ $b{\in}Q$
    using ‹$\mathcal{E} = Q$› ‹*path R a b*› *in-path-event* **by** *blast+*
  thus *False* **using** *eq-paths*
    using *R-neq-Q* ‹*path R a b*› *path-Q* **by** *blast*
qed

context *MinkowskiSpacetime* **begin**

Unfortunately, we cannot assume that a path exists without the axiom of dimension.

lemma *external-event*:
  assumes *path-Q*: $Q \in \mathcal{P}$
  shows $\exists\, d{\in}\mathcal{E}.\ d \notin Q$
proof (*rule ccontr*)
  assume $\neg\ (\exists\, d{\in}\mathcal{E}.\ d \notin Q)$
  then have *all-inQ*: $\forall\, d{\in}\mathcal{E}.\ d \in Q$ **by** *simp*
  then have *only-one-path*: $\forall\, P{\in}\mathcal{P}.\ P = Q$ **by** (*simp add*: *only-one-path path-Q*)
  thus *False* **using** *ex-3SPRAY three-SPRAY-ge4 four-paths* **by** *auto*
qed

Now we can prove the first part of the theorem's conjunction. This follows pretty much exactly the same pattern as the book, except it relies on more intermediate lemmas.

theorem *ge2-events*:
  assumes *path-Q*: $Q \in \mathcal{P}$
    and *a-inQ*: $a \in Q$
  shows $\exists\, b{\in}Q.\ b \neq a$
proof −
  have *d-notinQ*: $\exists\, d{\in}\mathcal{E}.\ d \notin Q$ **using** *path-Q external-event* **by** *blast*
  then obtain d **where** $d \in \mathcal{E}$ **and** $d \notin Q$ **by** *auto*
  thus *?thesis* **using** *two-in-unreach* [**where** $Q = Q$ **and** $b = d$] *path-Q unreach-ge2-then-ge2* **by** *metis*
qed

Simple corollary which is easier to use when we don't have one event on a path yet. Anything which uses this implicitly used *no-empty-paths* on top of *ge2-events*.

lemma *ge2-events-lax*:
  assumes *path-Q*: $Q \in \mathcal{P}$
  shows $\exists\, a{\in}Q.\ \exists\, b{\in}Q.\ a \neq b$
proof −
  have $\exists\, a{\in}\mathcal{E}.\ a \in Q$ **using** *path-Q no-empty-paths* **by** (*meson ex-in-conv in-path-event*)
  thus *?thesis* **using** *path-Q ge2-events* **by** *blast*
qed

lemma *ex-crossing-path*:
  assumes *path-Q*: $Q \in \mathcal{P}$
  shows $\exists\, R{\in}\mathcal{P}.\ R \neq Q \wedge (\exists\, c.\ c \in R \wedge c \in Q)$
proof −
  obtain a **where** *a-inQ*: $a \in Q$ **using** *ge2-events-lax path-Q* **by** *blast*
  obtain d **where** *d-event*: $d \in \mathcal{E}$
      and *d-notinQ*: $d \notin Q$ **using** *external-event path-Q* **by** *auto*
  then have $a \neq d$ **using** *a-inQ* **by** *auto*
  then have *ex-through-d*: $\exists\, R{\in}\mathcal{P}.\ \exists\, S{\in}\mathcal{P}.\ a \in R \wedge d \in S \wedge R \cap S \neq \{\}$
    using *events-paths* [**where** $a = a$ **and** $b = d$]
      path-Q a-inQ in-path-event d-event **by** *simp*

then obtain R S **where** *path-R*: $R \in \mathcal{P}$
and *path-S*: $S \in \mathcal{P}$
and *a-inR*: $a \in R$
and *d-inS*: $d \in S$
and *R-crosses-S*: $R \cap S \neq \{\}$ **by** *auto*
have *S-neq-Q*: $S \neq Q$ **using** *d-notinQ d-inS* **by** *auto*
show *?thesis*
proof *cases*
assume $R = Q$
then have $Q \cap S \neq \{\}$ **using** *R-crosses-S* **by** *simp*
thus *?thesis* **using** *S-neq-Q path-S* **by** *blast*
next
assume $R \neq Q$
thus *?thesis* **using** *a-inQ a-inR path-R* **by** *blast*
qed
qed

If we have two paths Q and R with a on Q and b at the intersection of Q and R, then by *two-in-unreach* (I5) and Theorem 4 (boundedness of the unreachable set), there is an unreachable set from a on one side of b on R, and on the other side of that there is an event which is reachable from a by some path, which is the path we want.

lemma *path-past-unreach*:
assumes *path-Q*: $Q \in \mathcal{P}$
and *path-R*: $R \in \mathcal{P}$
and *a-inQ*: $a \in Q$
and *b-inQ*: $b \in Q$
and *b-inR*: $b \in R$
and *Q-neq-R*: $Q \neq R$
and *a-neq-b*: $a \neq b$
shows $\exists S \in \mathcal{P}.\ S \neq Q \wedge a \in S \wedge (\exists c.\ c \in S \wedge c \in R)$
proof −
obtain d **where** *d-event*: $d \in \mathcal{E}$
and *d-notinR*: $d \notin R$ **using** *external-event path-R* **by** *blast*
have *b-reachable*: $b \in R - \emptyset\ R\ a$ **using** *cross-in-reachable path-R a-inQ b-inQ b-inR path-Q* **by** *simp*
have *a-notinR*: $a \notin R$ **using** *cross-once-notin*
Q-neq-R a-inQ a-neq-b b-inQ b-inR path-Q path-R **by** *blast*
then obtain u **where** $u \in \emptyset\ R\ a$
using *two-in-unreach a-inQ in-path-event path-Q path-R* **by** *blast*
then obtain c **where** *c-reachable*: $c \in R - \emptyset\ R\ a$
and *c-neq-b*: $b \neq c$ **using** *unreachable-set-bounded*
[**where** $Q = R$ **and** $Qx = b$ **and** $b = a$ **and** $Qy = u$]
path-R d-event d-notinR
using *a-inQ a-notinR b-reachable in-path-event path-Q* **by** *blast*
then obtain S **where** *S-facts*: $S \in \mathcal{P} \wedge a \in S \wedge (c \in S \wedge c \in R)$ **using** *reachable-path*
by (*metis Diff-iff a-inQ in-path-event path-Q path-R*)

then have $S \neq Q$ **using** *Q-neq-R b-inQ b-inR c-neq-b eq-paths path-R* **by** *blast*
thus *?thesis* **using** *S-facts* **by** *auto*
qed

theorem *ex-crossing-at*:
assumes *path-Q*: $Q \in \mathcal{P}$
and *a-inQ*: $a \in Q$
shows $\exists\, ac{\in}\mathcal{P}.\ ac \neq Q \wedge (\exists\, c.\ c \notin Q \wedge a \in ac \wedge c \in ac)$
proof −
obtain b **where** *b-inQ*: $b \in Q$
and *a-neq-b*: $a \neq b$ **using** *a-inQ ge2-events path-Q* **by** *blast*
have $\exists\, R{\in}\mathcal{P}.\ R \neq Q \wedge (\exists\, e.\ e \in R \wedge e \in Q)$ **by** (*simp add*: *ex-crossing-path path-Q*)
then obtain R e **where** *path-R*: $R \in \mathcal{P}$
and *R-neq-Q*: $R \neq Q$
and *e-inR*: $e \in R$
and *e-inQ*: $e \in Q$ **by** *auto*
thus *?thesis*
proof *cases*
assume *e-eq-a*: $e = a$
then have $\exists\, c.\ c \in \emptyset\ R\ b$ **using** *R-neq-Q a-inQ a-neq-b b-inQ e-inR path-Q path-R*
two-in-unreach path-unique in-path-event **by** *metis*
thus *?thesis* **using** *R-neq-Q e-eq-a e-inR path-Q path-R*
eq-paths ge2-events-lax **by** *metis*
next
assume *e-neq-a*: $e \neq a$

then have $\exists\, S{\in}\mathcal{P}.\ S \neq Q \wedge a \in S \wedge (\exists\, c.\ c \in S \wedge c \in R)$
using *path-past-unreach*
R-neq-Q a-inQ e-inQ e-inR path-Q path-R **by** *auto*
thus *?thesis* **by** (*metis R-neq-Q e-inR e-neq-a eq-paths path-Q path-R*)
qed
qed

lemma *ex-crossing-at-alt*:
assumes *path-Q*: $Q \in \mathcal{P}$
and *a-inQ*: $a \in Q$
shows $\exists\, ac.\ \exists\, c.\ path\ ac\ a\ c \wedge ac \neq Q \wedge c \notin Q$
using *ex-crossing-at assms* **by** *fastforce*

end

27 3.4 Prolongation

context *MinkowskiSpacetime* **begin**

lemma (**in** *MinkowskiPrimitive*) *unreach-on-path*:
  $a \in \emptyset\ Q\ b \Longrightarrow a \in Q$
using *unreachable-subset-def* **by** *simp*

lemma (**in** *MinkowskiUnreachable*) *unreach-equiv*:
  $[\![Q \in \mathcal{P};\ R \in \mathcal{P};\ a \in Q;\ b \in R;\ a \in \emptyset\ Q\ b]\!] \Longrightarrow b \in \emptyset\ R\ a$
  unfolding *unreachable-subset-def* **by** *auto*

theorem *prolong-betw*:
  assumes *path-Q*: $Q \in \mathcal{P}$
    and *a-inQ*: $a \in Q$
    and *b-inQ*: $b \in Q$
    and *ab-neq*: $a \neq b$
  shows $\exists\, c{\in}\mathcal{E}.\ [[a\ b\ c]]$
proof –
  obtain *e ae* **where** *e-event*: $e \in \mathcal{E}$
        and *e-notinQ*: $e \notin Q$
        and *path-ae*: *path ae a e*
    using *ex-crossing-at a-inQ path-Q in-path-event* **by** *blast*
  have $b \notin ae$ **using** *a-inQ ab-neq b-inQ e-notinQ eq-paths path-Q path-ae* **by** *blast*
  then obtain *f* **where** *f-unreachable*: $f \in \emptyset\ ae\ b$
    using *two-in-unreach b-inQ in-path-event path-Q path-ae* **by** *blast*
  then have *b-unreachable*: $b \in \emptyset\ Q\ f$ **using** *unreach-equiv*
    by (*metis* (*mono-tags*, *lifting*) *CollectD b-inQ path-Q unreachable-subset-def*)
  have *a-reachable*: $a \in Q - \emptyset\ Q\ f$
    using *same-path-reachable2* [**where** $Q = ae$ **and** $R = Q$ **and** $a = a$ **and** $b = f$]
      path-ae a-inQ path-Q f-unreachable unreach-on-path **by** *blast*
  thus *?thesis*
    using *unreachable-set-bounded* [**where** $Qy = b$ **and** $Q = Q$ **and** $b = f$ **and** $Qx = a$]
      b-unreachable unreachable-subset-def **by** *auto*
qed

lemma (**in** *MinkowskiSpacetime*) *prolong-betw2*:
  assumes *path-Q*: $Q \in \mathcal{P}$
    and *a-inQ*: $a \in Q$
    and *b-inQ*: $b \in Q$
    and *ab-neq*: $a \neq b$
  shows $\exists\, c{\in}Q.\ [[a\ b\ c]]$
  by (*metis assms betw-c-in-path prolong-betw*)

lemma (**in** *MinkowskiSpacetime*) *prolong-betw3*:
  assumes *path-Q*: $Q \in \mathcal{P}$
    and *a-inQ*: $a \in Q$
    and *b-inQ*: $b \in Q$
    and *ab-neq*: $a \neq b$
  shows $\exists\, c{\in}Q.\ \exists\, d{\in}Q.\ [[a\ b\ c]] \wedge [[a\ b\ d]] \wedge c{\neq}d$
  by (*metis* (*full-types*) *abc-abc-neq abc-bcd-abd a-inQ ab-neq b-inQ path-Q pro-*

```
long-betw2)

lemma finite-path-has-ends:
  assumes Q ∈ 𝒫
      and X ⊆ Q
      and finite X
      and card X ≥ 3
    shows ∃ a∈X. ∃ b∈X. a ≠ b ∧ (∀ c∈X. a ≠ c ∧ b ≠ c ⟶ [[a c b]])
using assms
proof (induct card X − 3 arbitrary: X)
  case 0
  then have card X = 3
    by linarith
  then obtain a b c where X-eq: X = {a, b, c}
    by (metis card-Suc-eq numeral-3-eq-3)
  then have abc-neq: a ≠ b a ≠ c b ≠ c
    by (metis ‹card X = 3› empty-iff insert-iff order-refl three-in-set3)+
  then consider [[a b c]] | [[b c a]] | [[c a b]]
    using some-betw [of Q a b c] 0.prems(1) 0.prems(2) X-eq by auto
  thus ?case
  proof (cases)
    assume [[a b c]]
   thus ?thesis — All d not equal to a or c is just d = b, so it immediately follows.
      using X-eq abc-neq(2) by blast
  next
    assume [[b c a]]
    thus ?thesis
      by (simp add: X-eq abc-neq(1))
  next
    assume [[c a b]]
    thus ?thesis
      using X-eq abc-neq(3) by blast
  qed
next
  case IH: (Suc n)
  obtain Y x where X-eq: X = insert x Y and x ∉ Y
    by (meson IH.prems(4) Set.set-insert three-in-set3)
  then have card Y − 3 = n card Y ≥ 3
    using IH.hyps(2) IH.prems(3) X-eq ‹x ∉ Y› by auto
  then obtain a b where ab-Y: a ∈ Y b ∈ Y a ≠ b
                  and Y-ends: ∀ c∈Y. (a ≠ c ∧ b ≠ c) ⟶ [[a c b]]
    using IH(1) [of Y] IH.prems(1−3) X-eq by auto
  consider [[a x b]] | [[x b a]] | [[b a x]]
    using some-betw [of Q a x b] ab-Y IH.prems(1,2) X-eq ‹x ∉ Y› by auto
  thus ?case
  proof (cases)
    assume [[a x b]]
    thus ?thesis
      using Y-ends X-eq ab-Y by auto
```

next
  assume [[*x b a*]]
  { fix *c*
    assume $c \in X$ $x \neq c$ $a \neq c$
    then have [[*x c a*]]
     by (*smt IH.prems*(*2*) *X-eq Y-ends* ‹[[*x b a*]]› *ab-Y*(*1*) *abc-abc-neq abc-bcd-abd abc-only-cba*(*3*) *abc-sym* ‹$Q \in \mathcal{P}$› *betw-b-in-path insert-iff some-betw subsetD*)
  }
  thus *?thesis*
    using *X-eq* ‹[[*x b a*]]› *ab-Y*(*1*) *abc-abc-neq insert-iff* **by** *force*
next
  assume [[*b a x*]]
  { fix *c*
    assume $c \in X$ $b \neq c$ $x \neq c$
    then have [[*b c x*]]
     by (*smt IH.prems*(*2*) *X-eq Y-ends* ‹[[*b a x*]]› *ab-Y*(*1*) *abc-abc-neq abc-bcd-acd abc-only-cba*(*1*)
       abc-sym ‹$Q \in \mathcal{P}$› *betw-a-in-path insert-iff some-betw subsetD*)
  }
  thus *?thesis*
    using *X-eq* ‹$x \notin Y$› *ab-Y*(*2*) **by** *fastforce*
qed
qed

lemma *obtain-fin-path-ends*:
  assumes *path-X*: $X \in \mathcal{P}$
    and *fin-Q*: *finite Q*
    and *card-Q*: *card* $Q \geq 3$
    and *events-Q*: $Q \subseteq X$
  obtains *a b* **where** $a \neq b$ **and** $a \in Q$ **and** $b \in Q$ **and** $\forall c \in Q.\ (a \neq c \wedge b \neq c) \longrightarrow$ [[*a c b*]]
proof −
  obtain *n* **where** $n \geq 0$ **and** *card* $Q = n+3$
    using *card-Q nat-le-iff-add*
    by *auto*
  then obtain *a b* **where** $a \neq b$ **and** $a \in Q$ **and** $b \in Q$ **and** $\forall c \in Q.\ (a \neq c \wedge b \neq c) \longrightarrow$ [[*a c b*]]
    using *finite-path-has-ends assms* ‹$n \geq 0$›
    by *metis*
  thus *?thesis*
    using *that* **by** *auto*
qed

lemma *path-card-nil*:
  assumes $Q \in \mathcal{P}$
  shows *card* $Q = 0$
proof (*rule ccontr*)

```
  assume card Q ≠ 0
  obtain n where n = card Q
    by auto
  hence n≥1
    using ‹card Q ≠ 0› by linarith
  then consider (n1) n=1 | (n2) n=2 | (n3) n≥3
    by linarith
  thus False
  proof (cases)
    case n1
    thus ?thesis
      using One-nat-def card-Suc-eq ge2-events-lax singletonD assms(1)
      by (metis ‹n = card Q›)
  next
    case n2
    then obtain a b where a≠b and a∈Q and b∈Q
      using ge2-events-lax assms(1) by blast
    then obtain c where c∈Q and c≠a and c≠b
      using prolong-betw2 by (metis abc-abc-neq assms(1))
    hence card Q ≠ 2
      by (metis ‹a ∈ Q› ‹a ≠ b› ‹b ∈ Q› card-2-iff')
    thus False
      using ‹n = card Q› ‹n = 2› by blast
  next
    case n3
    have fin-Q: finite Q
    proof -
      have (0::nat) ≠ 1
        by simp
      then show ?thesis
        by (meson ‹card Q ≠ 0› card.infinite)
    qed
    have card-Q: card Q ≥ 3
      using ‹n = card Q› n3 by blast
    have Q⊆Q by simp
    then obtain a b where a∈Q and b∈Q and a≠b
        and acb: ∀ c∈Q. (c≠a ∧ c≠b) ⟶ [[a c b]]
      using obtain-fin-path-ends card-Q fin-Q assms(1)
      by metis
    then obtain x where [[a b x]] and x∈Q
      using prolong-betw2 assms(1) by blast
    thus False
      by (metis acb abc-abc-neq abc-only-cba(2))
  qed
qed


theorem infinite-paths:
  assumes P∈𝒫
```

shows *infinite P*
proof
assume *fin-P*: *finite P*
have $P \neq \{\}$
by (*simp add*: *assms*)
hence $card\ P \neq 0$
by (*simp add*: *fin-P*)
moreover have $\neg(card\ P \geq 1)$
using *path-card-nil*
by (*simp add*: *assms*)
ultimately show *False*
by *simp*
qed

end

28 3.5 Second collinearity theorem

We start with a useful betweenness lemma.

lemma (**in** *MinkowskiBetweenness*) *some-betw2*:
assumes *path-Q*: $Q \in \mathcal{P}$
and *a-inQ*: $a \in Q$
and *b-inQ*: $b \in Q$
and *c-inQ*: $c \in Q$
shows $a = b \vee a = c \vee b = c \vee [[a\ b\ c]] \vee [[b\ c\ a]] \vee [[c\ a\ b]]$
using *a-inQ b-inQ c-inQ path-Q some-betw* **by** *blast*

lemma (**in** *MinkowskiPrimitive*) *paths-tri*:
assumes *path-ab*: *path ab a b*
and *path-bc*: *path bc b c*
and *path-ca*: *path ca c a*
and *a-notin-bc*: $a \notin bc$
shows $\triangle\ a\ b\ c$
proof −
have *abc-events*: $a \in \mathcal{E} \wedge b \in \mathcal{E} \wedge c \in \mathcal{E}$
using *path-ab path-bc path-ca in-path-event* **by** *auto*
have *abc-neq*: $a \neq b \wedge a \neq c \wedge b \neq c$
using *path-ab path-bc path-ca* **by** *auto*
have *paths-neq*: $ab \neq bc \wedge ab \neq ca \wedge bc \neq ca$
using *a-notin-bc cross-once-notin path-ab path-bc path-ca* **by** *blast*
show *?thesis*
unfolding *kinematic-triangle-def*
using *abc-events abc-neq paths-neq path-ab path-bc path-ca*
by *auto*
qed

lemma (**in** *MinkowskiPrimitive*) *paths-tri2*:

assumes *path-ab*: *path ab a b*
and *path-bc*: *path bc b c*
and *path-ca*: *path ca c a*
and *ab-neq-bc*: $ab \neq bc$
shows $\triangle$ *a b c*
by (*meson ab-neq-bc cross-once-notin path-ab path-bc path-ca paths-tri*)

Schutz states it more like $[\![tri\text{-}abc; bcd; cea]\!] \Longrightarrow (path\ de\ d\ e \longrightarrow \exists f{\in}de.\ [[a\ f\ b]]{\wedge}[[d\ e\ f]])$. Equivalent up to usage of *impI*.

theorem (**in** *MinkowskiChain*) *collinearity2*:
assumes *tri-abc*: $\triangle$ *a b c*
and *bcd*: [[*b c d*]]
and *cea*: [[*c e a*]]
and *path-de*: *path de d e*
shows $\exists f{\in}de.$ [[*a f b*]] $\wedge$ [[*d e f*]]
proof −
obtain *ab* **where** *path-ab*: *path ab a b* **using** *tri-abc triangle-paths-unique* **by** *blast*
then obtain *f* **where** *afb*: [[*a f b*]]
and *f-in-de*: $f \in de$ **using** *collinearity tri-abc path-de path-ab bcd cea* **by** *blast*

obtain *af* **where** *path-af*: *path af a f* **using** *abc-abc-neq afb betw-b-in-path path-ab* **by** *blast*
have [[*d e f*]]
proof −
have *def-in-de*: $d \in de \wedge e \in de \wedge f \in de$ **using** *path-de f-in-de* **by** *simp*
then have *five-poss*:$f = d \vee f = e \vee$ [[*e f d*]] $\vee$ [[*f d e*]] $\vee$ [[*d e f*]]
using *path-de some-betw2* **by** *blast*
have $f = d \vee f = e \longrightarrow (\exists Q{\in}\mathcal{P}.\ a \in Q \wedge b \in Q \wedge c \in Q)$
by (*metis abc-abc-neq afb bcd betw-a-in-path betw-b-in-path cea path-ab*)
then have *f-neq-d-e*: $f \neq d \wedge f \neq e$ **using** *tri-abc*
using *triangle-diff-paths* **by** *simp*
then consider [[*e f d*]] | [[*f d e*]] | [[*d e f*]] **using** *five-poss* **by** *linarith*
thus *?thesis*
proof (*cases*)
assume *efd*: [[*e f d*]]
obtain *dc* **where** *path-dc*: *path dc d c* **using** *abc-abc-neq abc-ex-path bcd* **by** *blast*
obtain *ce* **where** *path-ce*: *path ce c e* **using** *abc-abc-neq abc-ex-path cea* **by** *blast*
have $dc{\neq}ce$
using *bcd betw-a-in-path betw-c-in-path cea path-ce path-dc tri-abc triangle-diff-paths*
by *blast*
hence $\triangle$ *d c e*
using *paths-tri2 path-ce path-dc path-de* **by** *blast*
then obtain *x* **where** *x-in-af*: $x \in af$
and *dxc*: [[*d x c*]]

using *collinearity*
[**where** $a = d$ **and** $b = c$ **and** $c = e$ **and** $d = a$ **and** $e = f$ **and** $de = af$]
cea efd path-dc path-af **by** *blast*
then have *x-in-dc*: $x \in dc$ **using** *betw-b-in-path path-dc* **by** *blast*
then have $x = b$ **using** *eq-paths* **by** (*metis path-af path-dc afb bcd tri-abc x-in-af*
betw-a-in-path betw-c-in-path triangle-diff-paths)
then have [[*d b c*]] **using** *dxc* **by** *simp*
then have *False* **using** *bcd abc-only-cba* [**where** $a = b$ **and** $b = c$ **and** $c = d$] **by** *simp*
thus *?thesis* **by** *simp*
next
assume *fde*: [[*f d e*]]
obtain *bd* **where** *path-bd*: *path bd b d* **using** *abc-abc-neq abc-ex-path bcd* **by** *blast*
obtain *ea* **where** *path-ea*: *path ea e a* **using** *abc-abc-neq abc-ex-path-unique cea* **by** *blast*
obtain *fe* **where** *path-fe*: *path fe f e* **using** *f-in-de f-neq-d-e path-de* **by** *blast*
have $fe \neq ea$
using *tri-abc afb cea path-ea path-fe*
by (*metis abc-abc-neq betw-a-in-path betw-c-in-path triangle-paths-neq*)
hence $\triangle$ *e a f*
by (*metis path-unique path-af path-ea path-fe paths-tri2*)
then obtain *y* **where** *y-in-bd*: $y \in bd$
and *eya*: [[*e y a*]] **thm** *collinearity*
using *collinearity*
[**where** $a = e$ **and** $b = a$ **and** $c = f$ **and** $d = b$ **and** $e = d$ **and** $de = bd$]
afb fde path-bd path-ea **by** *blast*
then have $y = c$ **by** (*metis* (*mono-tags*, *lifting*)
afb bcd cea path-bd tri-abc
abc-ac-neq betw-b-in-path path-unique triangle-paths(*2*)
triangle-paths-neq)
then have [[*e c a*]] **using** *eya* **by** *simp*
then have *False* **using** *cea abc-only-cba* [**where** $a = c$ **and** $b = e$ **and** $c = a$] **by** *simp*
thus *?thesis* **by** *simp*
next
assume [[*d e f*]]
thus *?thesis* **by** *assumption*
qed
qed
thus *?thesis* **using** *afb f-in-de* **by** *blast*
qed

29 3.6 Order on a path - Theorems 8 and 9

context *MinkowskiSpacetime* **begin**

29.1 Theorem 8 (as in Veblen (1911) Theorem 6)

Note $a'b'c'$ don't necessarily form a triangle, as there still needs to be paths between them.

theorem (**in** *MinkowskiChain*) *tri-betw-no-path*:
  assumes *tri-abc*: $\triangle\ a\ b\ c$
    and *ab′c*: $[[a\ b'\ c]]$
    and *bc′a*: $[[b\ c'\ a]]$
    and *ca′b*: $[[c\ a'\ b]]$
  shows $\neg\ (\exists\ Q\in\mathcal{P}.\ a' \in Q \wedge b' \in Q \wedge c' \in Q)$
proof −
  have *abc-a′b′c′-neq*: $a \neq a' \wedge a \neq b' \wedge a \neq c'$
    $\wedge\ b \neq a' \wedge b \neq b' \wedge b \neq c'$
    $\wedge\ c \neq a' \wedge c \neq b' \wedge c \neq c'$
    using *abc-ac-neq*
      by (*metis ab′c abc-abc-neq bc′a ca′b tri-abc triangle-not-betw-abc triangle-permutes*(*4*))
  show *?thesis*
  proof (*rule notI*)
    assume *path-a′b′c′*: $\exists\ Q\in\mathcal{P}.\ a' \in Q \wedge b' \in Q \wedge c' \in Q$
    consider $[[a'\ b'\ c']]\ |\ [[b'\ c'\ a']]\ |\ [[c'\ a'\ b']]$ **using** *some-betw*
      by (*smt abc-a′b′c′-neq path-a′b′c′ bc′a ca′b ab′c tri-abc*
        abc-ex-path cross-once-notin triangle-diff-paths)
    thus *False*
    proof (*cases*)
      assume *a′b′c′*: $[[a'\ b'\ c']]$
      then have *c′b′a′*: $[[c'\ b'\ a']]$ **using** *abc-sym* **by** *simp*
      have *nopath-a′c′b*: $\neg\ (\exists\ Q\in\mathcal{P}.\ a' \in Q \wedge c' \in Q \wedge b \in Q)$
      proof (*rule notI*)
        assume $\exists\ Q\in\mathcal{P}.\ a' \in Q \wedge c' \in Q \wedge b \in Q$
        then obtain Q **where** *path-Q*: $Q \in \mathcal{P}$
          and *a′-inQ*: $a' \in Q$
          and *c′-inQ*: $c' \in Q$
          and *b-inQ*: $b \in Q$ **by** *blast*
        then have *ac-inQ*: $a \in Q \wedge c \in Q$ **using** *eq-paths*
          by (*metis abc-a′b′c′-neq ca′b bc′a betw-a-in-path betw-c-in-path*)
        thus *False* **using** *b-inQ path-Q tri-abc triangle-diff-paths* **by** *blast*
      qed
      then have *tri-a′bc′*: $\triangle\ a'\ b\ c'$
        by (*smt bc′a ca′b path-a′b′c′ paths-tri abc-ex-path-unique*)
      obtain *ab′* **where** *path-ab′*: *path ab′ a b′* **using** *ab′c abc-a′b′c′-neq abc-ex-path* **by** *blast*
      obtain *a′b* **where** *path-a′b*: *path a′b a′ b* **using** *tri-a′bc′ triangle-paths*(*1*) **by** *blast*
      then have $\exists\, x\in a'b.\ [[a'\ x\ b]] \wedge [[a\ b'\ x]]$
        using *collinearity2* [**where** $a = a'$ **and** $b = b$ **and** $c = c'$ **and** $e = b'$ **and** $d = a$ **and** $de = ab'$]
          bc′a betw-b-in-path c′b′a′ path-ab′ tri-a′bc′ **by** *blast*
      then obtain x **where** *x-in-a′b*: $x \in a'b$

and $a'xb$: $[[a'\ x\ b]]$
and $ab'x$: $[[a\ b'\ x]]$ **by** *blast*

have *c-in-ab′*: $c \in ab'$ **using** *ab′c betw-c-in-path path-ab′* **by** *auto*
have *c-in-a′b*: $c \in a'b$ **using** *ca′b betw-a-in-path path-a′b* **by** *auto*
have *ab′-a′b-distinct*: $ab' \neq a'b$
using *c-in-a′b path-a′b path-ab′ tri-abc triangle-diff-paths* **by** *blast*
have $ab' \cap a'b = \{c\}$
using *paths-cross-at ab′-a′b-distinct c-in-a′b c-in-ab′ path-a′b path-ab′* **by** *auto*
then have $x = c$ **using** *ab′x path-ab′ x-in-a′b betw-c-in-path* **by** *auto*
then have $[[a'\ c\ b]]$ **using** *a′xb* **by** *auto*
thus *False* **using** *ca′b abc-only-cba* **by** *blast*
next
assume *b′c′a′*: $[[b'\ c'\ a']]$
then have *a′c′b′*: $[[a'\ c'\ b']]$ **using** *abc-sym* **by** *simp*
have *nopath-a′cb′*: $\neg\ (\exists\, Q{\in}\mathcal{P}.\ a' \in Q \wedge c \in Q \wedge b' \in Q)$
proof (*rule notI*)
assume $\exists\, Q{\in}\mathcal{P}.\ a' \in Q \wedge c \in Q \wedge b' \in Q$
then obtain Q **where** *path-Q*: $Q \in \mathcal{P}$
and *a′-inQ*: $a' \in Q$
and *c-inQ*: $c \in Q$
and *b′-inQ*: $b' \in Q$ **by** *blast*
then have *ab-inQ*: $a \in Q \wedge b \in Q$
using *eq-paths*
by (*metis ab′c abc-a′b′c′-neq betw-a-in-path betw-c-in-path ca′b*)
thus *False* **using** *c-inQ path-Q tri-abc triangle-diff-paths* **by** *blast*
qed
then have *tri-a′cb′*: $\triangle\ a'\ c\ b'$
by (*smt ab′c abc-ex-path-unique b′c′a′ ca′b paths-tri*)
obtain bc' **where** *path-bc′*: *path* $bc'\ b\ c'$
using *abc-a′b′c′-neq abc-ex-path-unique bc′a*
by *blast*
obtain $b'c$ **where** *path-b′c*: *path* $b'c\ b'\ c$ **using** *tri-a′cb′ triangle-paths*(*3*) **by** *blast*
then have $\exists\, x{\in}b'c.\ [[b'\ x\ c]] \wedge [[b\ c'\ x]]$
using *collinearity2* [**where** $a = b'$ **and** $b = c$ **and** $c = a'$
and $e = c'$ **and** $d = b$ **and** $de = bc'$]
bc′a betw-b-in-path a′c′b′ path-bc′ tri-a′cb′
by (*meson ca′b triangle-permutes*(*5*))
then obtain x **where** *x-in-b′c*: $x \in b'c$
and *b′xc*: $[[b'\ x\ c]]$
and *bc′x*: $[[b\ c'\ x]]$ **by** *blast*
have *a-in-bc′*: $a \in bc'$ **using** *bc′a betw-c-in-path path-bc′* **by** *blast*
have *a-in-b′c*: $a \in b'c$ **using** *ab′c betw-a-in-path path-b′c* **by** *blast*
have *bc′-b′c-distinct*: $bc' \neq b'c$
using *a-in-bc′ path-b′c path-bc′ tri-abc triangle-diff-paths* **by** *blast*
have $bc' \cap b'c = \{a\}$
using *paths-cross-at bc′-b′c-distinct a-in-b′c a-in-bc′ path-b′c path-bc′* **by**

auto
then have $x = a$ **using** *bc'x betw-c-in-path path-bc' x-in-b'c* **by** *auto*
then have $[[b'\ a\ c]]$ **using** *b'xc* **by** *auto*
thus *False* **using** *ab'c abc-only-cba* **by** *blast*
next
assume *c'a'b'*: $[[c'\ a'\ b']]$
then have *b'a'c'*: $[[b'\ a'\ c']]$ **using** *abc-sym* **by** *simp*
have *nopath-c'ab'*: $\neg\ (\exists\, Q{\in}\mathcal{P}.\ c' \in Q \wedge a \in Q \wedge b' \in Q)$
proof (*rule notI*)
assume $\exists\, Q{\in}\mathcal{P}.\ c' \in Q \wedge a \in Q \wedge b' \in Q$
then obtain Q **where** *path-Q*: $Q \in \mathcal{P}$
and *c'-inQ*: $c' \in Q$
and *a-inQ*: $a \in Q$
and *b'-inQ*: $b' \in Q$ **by** *blast*
then have *bc-inQ*: $b \in Q \wedge c \in Q$
using *eq-paths ab'c abc-a'b'c'-neq bc'a betw-a-in-path betw-c-in-path* **by** *blast*
thus *False* **using** *a-inQ path-Q tri-abc triangle-diff-paths* **by** *blast*
qed
then have *tri-a'cb'*: $\triangle\ b'\ a\ c'$
by (*smt bc'a abc-ex-path-unique c'a'b' ab'c paths-tri*)
obtain *ca'* **where** *path-ca'*: *path ca' c a'*
using *abc-a'b'c'-neq abc-ex-path-unique ca'b*
by *blast*
obtain *c'a* **where** *path-c'a*: *path c'a c' a* **using** *tri-a'cb' triangle-paths(3)* **by** *blast*
then have $\exists\, x{\in}c'a.\ [[c'\ x\ a]] \wedge [[c\ a'\ x]]$
using *collinearity2* [**where** $a = c'$ **and** $b = a$ **and** $c = b'$
and $e = a'$ **and** $d = c$ **and** $de = ca'$]
ab'c b'a'c' betw-b-in-path path-ca' tri-a'cb' triangle-permutes(5) **by** *blast*
then obtain x **where** *x-in-c'a*: $x \in c'a$
and *c'xa*: $[[c'\ x\ a]]$
and *ca'x*: $[[c\ a'\ x]]$ **by** *blast*
have *b-in-ca'*: $b \in ca'$ **using** *betw-c-in-path ca'b path-ca'* **by** *blast*
have *b-in-c'a*: $b \in c'a$ **using** *bc'a betw-a-in-path path-c'a* **by** *auto*
have *ca'-c'a-distinct*: $ca' \neq c'a$
using *b-in-c'a path-c'a path-ca' tri-abc triangle-diff-paths* **by** *blast*
have $ca' \cap c'a = \{b\}$
using *b-in-c'a b-in-ca' ca'-c'a-distinct path-c'a path-ca' paths-cross-at* **by** *auto*
then have $x = b$ **using** *betw-c-in-path ca'x path-ca' x-in-c'a* **by** *auto*
then have $[[c'\ b\ a]]$ **using** *c'xa* **by** *auto*
thus *False* **using** *abc-only-cba bc'a* **by** *blast*
qed
qed
qed

29.2 Theorem 9

We now begin working on the transitivity lemmas needed to prove Theorem 9. Multiple lemmas below obtain primed variables (e.g. d'). These are starred in Schutz (e.g. $d*$), but that notation is already reserved in Isabelle.

lemma *unreachable-bounded-path-only*:
assumes *d′-def*: $d' \notin \emptyset\ ab\ e\ \ d' \in ab\ \ d' \neq e$
and *e-event*: $e \in \mathcal{E}$
and *path-ab*: $ab \in \mathcal{P}$
and *e-notin-S*: $e \notin ab$
shows $\exists\, d'e.\ path\ d'e\ d'\ e$
proof (*rule ccontr*)
assume $\neg(\exists\, d'e.\ path\ d'e\ d'\ e)$
hence $\neg(\exists\, R \in \mathcal{P}.\ d' \in R \wedge e \in R \wedge d' \neq e)$
by *blast*
hence $\neg(\exists\, R \in \mathcal{P}.\ \ e \in R \wedge d' \in R)$
using *d′-def*(*3*) **by** *blast*
moreover have $ab \in \mathcal{P} \wedge e \in \mathcal{E} \wedge e \notin ab$
by (*simp add*: *e-event e-notin-S path-ab*)
ultimately have $d' \in \emptyset\ ab\ e$
unfolding *unreachable-subset-def* **using** *d′-def*(*2*)
by *blast*
thus *False*
using *d′-def*(*1*) **by** *auto*
qed

lemma *unreachable-bounded-path*:
assumes *S-neq-ab*: $S \neq ab$
and *a-inS*: $a \in S$
and *e-inS*: $e \in S$
and *e-neq-a*: $e \neq a$
and *path-S*: $S \in \mathcal{P}$
and *path-ab*: *path ab a b*
and *path-be*: *path be b e*
and *no-de*: $\neg(\exists\, de.\ path\ de\ d\ e)$
and *abd*: $[[a\ b\ d]]$
obtains $d'\ d'e$ **where** $d' \in ab \wedge path\ d'e\ d'\ e \wedge [[b\ d\ d']]$
proof −
have *e-event*: $e \in \mathcal{E}$
using *e-inS path-S* **by** *auto*
have $e \notin ab$
using *S-neq-ab a-inS e-inS e-neq-a eq-paths path-S path-ab* **by** *auto*
have $ab \in \mathcal{P} \wedge e \notin ab$
using *S-neq-ab a-inS e-inS e-neq-a eq-paths path-S path-ab*
by *auto*
have $b \in ab - \emptyset\ ab\ e$
using *cross-in-reachable path-ab path-be*
by *blast*
have $d \in \emptyset\ ab\ e$

using *no-de abd path-ab e-event* ‹$e \notin ab$›
betw-c-in-path unreachable-bounded-path-only
by *blast*
have $\exists\, d'\ d'e.\ d' \in ab \wedge path\ d'e\ d'\ e \wedge [[b\ d\ d']]$
proof −
obtain d' **where** $[[b\ d\ d']]$ $d' \in ab$ $d' \notin \emptyset\ ab\ e$ $b \neq d'$ $e \neq d'$
using *unreachable-set-bounded* ‹$b \in ab - \emptyset\ ab\ e$› ‹$d \in \emptyset\ ab\ e$› *e-event* ‹$e \notin ab$›
path-ab
by (*metis DiffE*)
then obtain $d'e$ **where** *path* $d'e\ d'\ e$
using *unreachable-bounded-path-only e-event* ‹$e \notin ab$› *path-ab*
by *blast*
thus *?thesis*
using ‹$[[b\ d\ d']]$› ‹$d' \in ab$›
by *blast*
qed
thus *?thesis*
using *that* **by** *blast*
qed

This lemma collects the first three paragraphs of Schutz' proof of Theorem 9 - Lemma 1. Several case splits need to be considered, but have no further importance outside of this lemma: thus we parcel them away from the main proof.

lemma *exist-c′d′-alt*:
assumes *abc*: $[[a\ b\ c]]$
and *abd*: $[[a\ b\ d]]$
and *dbc*: $[[d\ b\ c]]$
and *c-neq-d*: $c \neq d$
and *path-ab*: *path ab a b*
and *path-S*: $S \in \mathcal{P}$
and *a-inS*: $a \in S$
and *e-inS*: $e \in S$
and *e-neq-a*: $e \neq a$
and *S-neq-ab*: $S \neq ab$
and *path-be*: *path be b e*
shows $\exists\, c'\ d'.\ \exists\, d'e\ c'e.\ c' \in ab \wedge d' \in ab$
$\wedge [[a\ b\ d']] \wedge [[c'\ b\ a]] \wedge [[c'\ b\ d']]$
$\wedge\ path\ d'e\ d'\ e \wedge path\ c'e\ c'\ e$
proof (*cases*)
assume $\exists\, de.\ path\ de\ d\ e$
then obtain *de* **where** *path de d e*
by *blast*
hence $[[a\ b\ d]] \wedge d \in ab$
using *abd betw-c-in-path path-ab* **by** *blast*
thus *?thesis*
proof (*cases*)
assume $\exists\, ce.\ path\ ce\ c\ e$
then obtain *ce* **where** *path ce c e* **by** *blast*

```
      have c ∈ ab
        using abc betw-c-in-path path-ab by blast
      thus ?thesis
        using ‹[[a b d]] ∧ d ∈ ab› ‹∃ ce. path ce c e› ‹c ∈ ab› ‹path de d e› abc abc-sym
dbc
        by blast
    next
      assume ¬(∃ ce. path ce c e)
      obtain c' c'e where c'∈ab ∧ path c'e c' e ∧ [[b c c']]
        using unreachable-bounded-path [where ab=ab and e=e and b=b and d=c
and a=a and S=S and be=be]
          S-neq-ab ‹¬(∃ ce. path ce c e)› a-inS abc e-inS e-neq-a path-S path-ab path-be
      by (metis (mono-tags, lifting))
      hence [[a b c']] ∧ [[d b c']]
        using abc dbc by blast
      hence [[c' b a]] ∧ [[c' b d]]
        using theorem1 by blast
      thus ?thesis
        using ‹[[a b d]] ∧ d ∈ ab› ‹c' ∈ ab ∧ path c'e c' e ∧ [[b c c']]› ‹path de d e›
        by blast
    qed
  next
    assume ¬ (∃ de. path de d e)
    obtain d' d'e where d'-in-ab: d' ∈ ab
                    and bdd': [[b d d']]
                    and path d'e d' e
      using unreachable-bounded-path [where ab=ab and e=e and b=b and d=d
and a=a and S=S and be=be]
        S-neq-ab ‹∄ de. path de d e› a-inS abd e-inS e-neq-a path-S path-ab path-be
      by (metis (mono-tags, lifting))
    hence [[a b d']] using abd by blast
    thus ?thesis
    proof (cases)
      assume ∃ ce. path ce c e
      then obtain ce where path ce c e by blast
      have c ∈ ab
        using abc betw-c-in-path path-ab by blast
      thus ?thesis
        using ‹[[a b d']]› ‹d' ∈ ab› ‹path ce c e› ‹c ∈ ab› ‹path d'e d' e› abc abc-sym dbc
        by (meson abc-bcd-acd bdd')
    next
      assume ¬(∃ ce. path ce c e)
      obtain c' c'e where c'∈ab ∧ path c'e c' e ∧ [[b c c']]
        using unreachable-bounded-path [where ab=ab and e=e and b=b and d=c
and a=a and S=S and be=be]
          S-neq-ab ‹¬(∃ ce. path ce c e)› a-inS abc e-inS e-neq-a path-S path-ab path-be
      by (metis (mono-tags, lifting))
      hence [[a b c']] ∧ [[d b c']]
        using abc dbc by blast
```

hence $[[c'\ b\ a]] \wedge [[c'\ b\ d]]$
using *theorem1* **by** *blast*
thus *?thesis*
using ‹$[[a\ b\ d']]$› ‹$c' \in ab \wedge path\ c'e\ c'\ e \wedge [[b\ c\ c']]$› ‹$path\ d'e\ d'\ e$› bdd' d'*-in-ab*
by *blast*
qed
qed

lemma *exist-*$c'd'$:
assumes *abc*: $[[a\ b\ c]]$
and *abd*: $[[a\ b\ d]]$
and *dbc*: $[[d\ b\ c]]$
and *path-S*: *path S a e*
and *path-be*: *path be b e*
and *S-neq-ab*: $S \neq$ *path-of a b*
shows $\exists\, c'\ d'.\ [[a\ b\ d']] \wedge [[c'\ b\ a]] \wedge [[c'\ b\ d']] \wedge$ *path-ex* $d'\ e \wedge$ *path-ex* $c'\ e$
proof (*cases path-ex d e*)
let *?ab* = *path-of a b*
have *path-ex a b*
using *abc abc-abc-neq abc-ex-path* **by** *blast*
hence *path-ab*: *path ?ab a b* **using** *path-of-ex* **by** *simp*
have $c \neq d$ **using** *abc-ac-neq dbc* **by** *blast*
{
case *True*
then obtain *de* **where** *path de d e*
by *blast*
hence $[[a\ b\ d]] \wedge d \in ?ab$
using *abd betw-c-in-path path-ab* **by** *blast*
thus *?thesis*
proof (*cases path-ex c e*)
case *True*
then obtain *ce* **where** *path ce c e* **by** *blast*
have $c \in ?ab$
using *abc betw-c-in-path path-ab* **by** *blast*
thus *?thesis*
using ‹$[[a\ b\ d]] \wedge d \in ?ab$› ‹$\exists\, ce.\ path\ ce\ c\ e$› ‹$c \in ?ab$› ‹*path de d e*› *abc abc-sym dbc*
by *blast*
next
case *False*
obtain $c'\ c'e$ **where** $c' \in ?ab \wedge path\ c'e\ c'\ e \wedge [[b\ c\ c']]$
using *unreachable-bounded-path* [**where** *ab*=*?ab* **and** *e*=*e* **and** *b*=*b* **and** *d*=*c* **and** *a*=*a* **and** *S*=*S* **and** *be*=*be*]
S-neq-ab ‹$\neg(\exists\, ce.\ path\ ce\ c\ e)$› *abc path-S path-ab path-be*
by (*metis* (*mono-tags*, *lifting*))
hence $[[a\ b\ c']] \wedge [[d\ b\ c']]$
using *abc dbc* **by** *blast*

hence $[[c' \ b \ a]] \wedge [[c' \ b \ d]]$
using *theorem1* **by** *blast*
thus *?thesis*
using ‹$[[a \ b \ d]] \wedge d \in$ *?ab*› ‹$c' \in$ *?ab* $\wedge$ *path* $c'e \ c' \ e \wedge [[b \ c \ c']]$› ‹*path de d e*›
by *blast*
qed
} {
case *False*
obtain $d' \ d'e$ **where** d'-*in-ab*: $d' \in$ *?ab*
and *bdd'*: $[[b \ d \ d']]$
and *path* $d'e \ d' \ e$
using *unreachable-bounded-path* [**where** *ab*=*?ab* **and** *e*=*e* **and** *b*=*b* **and** *d*=*d* **and** *a*=*a* **and** *S*=*S* **and** *be*=*be*]
S-neq-ab ‹¬*path-ex d e*› *abd path-S path-ab path-be*
by (*metis* (*mono-tags*, *lifting*))
hence $[[a \ b \ d']]$ **using** *abd* **by** *blast*
thus *?thesis*
proof (*cases path-ex c e*)
case *True*
then obtain *ce* **where** *path ce c e* **by** *blast*
have $c \in$ *?ab*
using *abc betw-c-in-path path-ab* **by** *blast*
thus *?thesis*
using ‹$[[a \ b \ d']]$› ‹$d' \in$ *?ab*› ‹*path ce c e*› ‹$c \in$ *?ab*› ‹*path* $d'e \ d' \ e$› *abc abc-sym dbc*
by (*meson abc-bcd-acd bdd'*)
next
case *False*
obtain $c' \ c'e$ **where** $c' \in$*?ab* $\wedge$ *path* $c'e \ c' \ e \wedge [[b \ c \ c']]$
using *unreachable-bounded-path* [**where** *ab*=*?ab* **and** *e*=*e* **and** *b*=*b* **and** *d*=*c* **and** *a*=*a* **and** *S*=*S* **and** *be*=*be*]
S-neq-ab ‹¬(*path-ex c e*)› *abc path-S path-ab path-be*
by (*metis* (*mono-tags*, *lifting*))
hence $[[a \ b \ c']] \wedge [[d \ b \ c']]$
using *abc dbc* **by** *blast*
hence $[[c' \ b \ a]] \wedge [[c' \ b \ d]]$
using *theorem1* **by** *blast*
thus *?thesis*
using ‹$[[a \ b \ d']]$› ‹$c' \in$ *?ab* $\wedge$ *path* $c'e \ c' \ e \wedge [[b \ c \ c']]$› ‹*path* $d'e \ d' \ e$› *bdd'* d'-*in-ab*
by *blast*
qed
}
qed

lemma *exist-f'-alt*:
assumes *path-ab*: *path ab a b*
and *path-S*: $S \in \mathcal{P}$

and *a-inS*: $a \in S$
and *e-inS*: $e \in S$
and *e-neq-a*: $e \neq a$
and *f-def*: $[[e\ c'\ f]]\ f{\in}c'e$
and *S-neq-ab*: $S \neq ab$
and *c'd'-def*: $c'{\in}ab \wedge d'{\in}ab$
$\wedge [[a\ b\ d']] \wedge [[c'\ b\ a]] \wedge [[c'\ b\ d']]$
$\wedge$ *path* $d'e\ d'\ e \wedge$ *path* $c'e\ c'\ e$
shows $\exists f'. \exists f'b. [[e\ c'\ f']] \wedge$ *path* $f'b\ f'\ b$
proof (*cases*)
assume $\exists\, bf.$ *path* $bf\ b\ f$
thus *?thesis*
using ‹$[[e\ c'\ f]]$› **by** *blast*
next
assume $\neg(\exists\, bf.$ *path* $bf\ b\ f)$
hence $f \in \emptyset\ c'e\ b$
using *assms*(*1*−*5*,*7*−*9*) *abc-abc-neq betw-events eq-paths unreachable-bounded-path-only*
by *metis*
moreover have $c' \in c'e - \emptyset\ c'e\ b$
using *c'd'-def cross-in-reachable path-ab* **by** *blast*
moreover have $b{\in}\mathcal{E} \wedge b{\notin}c'e$
using ‹$f \in \emptyset\ c'e\ b$› *betw-events c'd'-def same-empty-unreach* **by** *auto*
ultimately obtain f' **where** *f'-def*: $[[c'\ f\ f']]\ f'{\in}c'e\ f'{\notin}\ \emptyset\ c'e\ b\ c'{\neq}f'\ b{\neq}f'$
using *unreachable-set-bounded c'd'-def*
by (*metis DiffE*)
hence $[[e\ c'\ f']]$
using ‹$[[e\ c'\ f]]$› **by** *blast*
moreover obtain $f'b$ **where** *path* $f'b\ f'\ b$
using ‹$b \in \mathcal{E} \wedge b \notin c'e$› *c'd'-def f'-def*(*2*,*3*) *unreachable-bounded-path-only*
by *blast*
ultimately show *?thesis* **by** *blast*
qed

lemma *exist-f'*:
assumes *path-ab*: *path* $ab\ a\ b$
and *path-S*: *path* $S\ a\ e$
and *f-def*: $[[e\ c'\ f]]$
and *S-neq-ab*: $S \neq ab$
and *c'd'-def*: $[[a\ b\ d']]\ [[c'\ b\ a]]\ [[c'\ b\ d']]$
path $d'e\ d'\ e$ *path* $c'e\ c'\ e$
shows $\exists f'. [[e\ c'\ f']] \wedge$ *path-ex* $f'\ b$
proof (*cases*)
assume *path-ex* $b\ f$
thus *?thesis*
using *f-def* **by** *blast*
next
assume *no-path*: $\neg($*path-ex* $b\ f)$
have *path-S-2*: $S \in \mathcal{P}\ a \in S\ e \in S\ e \neq a$
using *path-S* **by** *auto*

have $f{\in}c'e$
using *betw-c-in-path f-def* $c'd'$*-def*(*5*) **by** *blast*
have $c'{\in}$ *ab* $d'{\in}$ *ab*
using *betw-a-in-path betw-c-in-path* $c'd'$*-def*(*1*,*2*) *path-ab* **by** *blast*+
have $f \in \emptyset\ c'e\ b$
using *no-path assms*(*1*,*4*−*9*) *path-S-2* ‹$f{\in}c'e$› ‹$c'{\in}ab$› ‹$d'{\in}ab$›
abc-abc-neq betw-events eq-paths unreachable-bounded-path-only
by *metis*
moreover have $c' \in c'e - \emptyset\ c'e\ b$
using $c'd'$*-def cross-in-reachable path-ab* ‹$c' \in ab$› **by** *blast*
moreover have $b{\in}\mathcal{E} \wedge b{\notin}c'e$
using ‹$f \in \emptyset\ c'e\ b$› *betw-events* $c'd'$*-def same-empty-unreach* **by** *auto*
ultimately obtain f' **where** f'*-def*: $[[c'\ f\ f']]$ $f'{\in}c'e$ $f'{\notin}\ \emptyset\ c'e\ b$ $c'{\neq}f'$ $b{\neq}f'$
using *unreachable-set-bounded* $c'd'$*-def*
by (*metis DiffE*)
hence $[[e\ c'\ f']]$
using ‹$[[e\ c'\ f]]$› **by** *blast*
moreover obtain $f'b$ **where** *path* $f'b\ f'\ b$
using ‹$b \in \mathcal{E} \wedge b \notin c'e$› $c'd'$*-def* f'*-def*(*2*,*3*) *unreachable-bounded-path-only*
by *blast*
ultimately show *?thesis* **by** *blast*
qed

lemma *abc-abd-bcdbdc*:
assumes *abc*: $[[a\ b\ c]]$
and *abd*: $[[a\ b\ d]]$
and *c-neq-d*: $c \neq d$
shows $[[b\ c\ d]] \vee [[b\ d\ c]]$
proof −
have $\neg\ [[d\ b\ c]]$
proof (*rule notI*)
assume *dbc*: $[[d\ b\ c]]$
obtain *ab* **where** *path-ab*: *path ab a b*
using *abc-abc-neq abc-ex-path-unique abc* **by** *blast*
obtain *S* **where** *path-S*: $S \in \mathcal{P}$
and *S-neq-ab*: $S \neq ab$
and *a-inS*: $a \in S$
using *ex-crossing-at path-ab*
by *auto*

have $\exists\, e{\in}S.\ e \neq a \wedge (\exists\, be{\in}\mathcal{P}.\ path\ be\ b\ e)$
proof −
have *b-notinS*: $b \notin S$ **using** *S-neq-ab a-inS path-S path-ab path-unique* **by**
blast
then obtain *x y z* **where** *x-in-unreach*: $x \in \emptyset\ S\ b$
and *y-in-unreach*: $y \in \emptyset\ S\ b$
and *x-neq-y*: $x \neq y$
and *z-in-reach*: $z \in S - \emptyset\ S\ b$

using *two-in-unreach* [**where** $Q = S$ **and** $b = b$]
in-path-event path-S path-ab a-inS cross-in-reachable
by *blast*
then obtain w **where** *w-in-reach*: $w \in S - \emptyset\ S\ b$
and *w-neq-z*: $w \neq z$
using *unreachable-set-bounded* [**where** $Q = S$ **and** $b = b$ **and** $Qx = z$ **and** $Qy = x$]
b-notinS in-path-event path-S path-ab **by** *blast*
thus *?thesis* **by** (*metis DiffD1 b-notinS in-path-event path-S path-ab reachable-path z-in-reach*)
qed
then obtain e be **where** *e-inS*: $e \in S$
and *e-neq-a*: $e \neq a$
and *path-be*: *path be b e*
by *blast*
have *path-ae*: *path S a e*
using *a-inS e-inS e-neq-a path-S* **by** *auto*
have *S-neq-ab-2*: $S \neq$ *path-of a b*
using *S-neq-ab cross-once-notin path-ab path-of-ex* **by** *blast*

have $\exists\, c'\ d'.$
$c' \in ab \wedge d' \in ab$
$\wedge$ [[$a\ b\ d'$]] $\wedge$ [[$c'\ b\ a$]] $\wedge$ [[$c'\ b\ d'$]]
$\wedge$ *path-ex* $d'\ e$ $\wedge$ *path-ex* $c'\ e$
using *exist-c′d′* [**where** $a{=}a$ **and** $b{=}b$ **and** $c{=}c$ **and** $d{=}d$ **and** $e{=}e$ **and** $be{=}be$ **and** $S{=}S$]
using *assms*$(1{-}2)$ *dbc e-neq-a path-ae path-be S-neq-ab-2*
using *abc-sym betw-a-in-path path-ab* **by** *blast*
then obtain $c'\ d'\ d'e\ c'e$
where *c′d′-def*: $c' \in ab \wedge d' \in ab$
$\wedge$ [[$a\ b\ d'$]] $\wedge$ [[$c'\ b\ a$]] $\wedge$ [[$c'\ b\ d'$]]
$\wedge$ *path* $d'e\ d'\ e$ $\wedge$ *path* $c'e\ c'\ e$
by *blast*

obtain f **where** *f-def*: $f \in c'e$ [[$e\ c'\ f$]]
using *c′d′-def prolong-betw2* **by** *blast*
then obtain $f'\ f'b$ **where** *f′-def*: [[$e\ c'\ f'$]] $\wedge$ *path* $f'b\ f'\ b$
using *exist-f′*
[**where** $e{=}e$ **and** $c'{=}c'$ **and** $b{=}b$ **and** $f{=}f$ **and** $S{=}S$ **and** $ab{=}ab$ **and** $d'{=}d'$ **and** $a{=}a$ **and** $c'e{=}c'e$]
using *path-ab path-S a-inS e-inS e-neq-a f-def S-neq-ab c′d′-def*
by *blast*

obtain *ae* **where** *path-ae*: *path ae a e* **using** *a-inS e-inS e-neq-a path-S* **by** *blast*
have *tri-aec*: $\triangle\ a\ e\ c'$

by (*smt cross-once-notin S-neq-ab a-inS abc abc-abc-neq abc-ex-path e-inS e-neq-a path-S path-ab c'd'-def paths-tri*)

then obtain h **where** *h-in-f'b*: $h \in f'b$
and *ahe*: $[[a\ h\ e]]$
and *f'bh*: $[[f'\ b\ h]]$
using *collinearity2* [**where** $a = a$ **and** $b = e$ **and** $c = c'$ **and** $d = f'$ **and** $e = b$ **and** $de = f'b$]
f'-def c'd'-def f'-def **by** *blast*
have *tri-dec*: $\triangle\ d'\ e\ c'$
using *cross-once-notin S-neq-ab a-inS abc abc-abc-neq abc-ex-path e-inS e-neq-a path-S path-ab c'd'-def paths-tri* **by** *smt*
then obtain g **where** *g-in-f'b*: $g \in f'b$
and *d'ge*: $[[d'\ g\ e]]$
and *f'bg*: $[[f'\ b\ g]]$
using *collinearity2* [**where** $a = d'$ **and** $b = e$ **and** $c = c'$ **and** $d = f'$ **and** $e = b$ **and** $de = f'b$]
f'-def c'd'-def **by** *blast*
have $\triangle\ e\ a\ d'$ **by** (*smt betw-c-in-path paths-tri2 S-neq-ab a-inS abc-ac-neq abd e-inS e-neq-a c'd'-def path-S path-ab*)
thus *False*
using *tri-betw-no-path* [**where** $a = e$ **and** $b = a$ **and** $c = d'$ **and** $b' = g$ **and** $a' = b$ **and** $c' = h$]
f'-def c'd'-def h-in-f'b g-in-f'b abd d'ge ahe abc-sym
by *blast*
qed
thus *?thesis*
by (*smt abc abc-abc-neq abc-ex-path abc-sym abd c-neq-d cross-once-notin some-betw*)
qed

lemma *abc-abd-acdadc*:
assumes *abc*: $[[a\ b\ c]]$
and *abd*: $[[a\ b\ d]]$
and *c-neq-d*: $c \neq d$
shows $[[a\ c\ d]] \lor [[a\ d\ c]]$
proof −
have *cba*: $[[c\ b\ a]]$ **using** *abc-sym abc* **by** *simp*
have *dba*: $[[d\ b\ a]]$ **using** *abc-sym abd* **by** *simp*

have *dcb-over-cba*: $[[d\ c\ b]] \land [[c\ b\ a]] \Longrightarrow [[d\ c\ a]]$ **by** *auto*
have *cdb-over-dba*: $[[c\ d\ b]] \land [[d\ b\ a]] \Longrightarrow [[c\ d\ a]]$ **by** *auto*

have *bcdbdc*: $[[b\ c\ d]] \lor [[b\ d\ c]]$ **using** *abc abc-abd-bcdbdc abd c-neq-d* **by** *auto*
then have *dcb-or-cdb*: $[[d\ c\ b]] \lor [[c\ d\ b]]$ **using** *abc-sym* **by** *blast*
then have $[[d\ c\ a]] \lor [[c\ d\ a]]$ **using** *abc-only-cba dcb-over-cba cdb-over-dba cba dba* **by** *blast*
thus *?thesis* **using** *abc-sym* **by** *auto*

qed

lemma *abc-acd-bcd*:
  assumes *abc*: $[[a\ b\ c]]$
    and *acd*: $[[a\ c\ d]]$
  shows $[[b\ c\ d]]$
proof −
  have *path-abc*: $\exists\, Q{\in}\mathcal{P}.\ a \in Q \wedge b \in Q \wedge c \in Q$ **using** *abc* **by** (*simp add*: *abc-ex-path*)
  have *path-acd*: $\exists\, Q{\in}\mathcal{P}.\ a \in Q \wedge c \in Q \wedge d \in Q$ **using** *acd* **by** (*simp add*: *abc-ex-path*)
  then have $\exists\, Q{\in}\mathcal{P}.\ b \in Q \wedge c \in Q \wedge d \in Q$ **using** *path-abc abc-abc-neq acd cross-once-notin* **by** *metis*

  then have *bcd3*: $[[b\ c\ d]] \vee [[b\ d\ c]] \vee [[c\ b\ d]]$ **by** (*metis abc abc-only-cba*(*1*,*2*) *acd some-betw2*)
  show *?thesis*
  proof (*rule ccontr*)
    assume $\neg\ [[b\ c\ d]]$
    then have $[[b\ d\ c]] \vee [[c\ b\ d]]$ **using** *bcd3* **by** *simp*
    thus *False*
    proof (*rule disjE*)
      assume $[[b\ d\ c]]$
      then have $[[c\ d\ b]]$ **using** *abc-sym* **by** *simp*
      then have $[[a\ c\ b]]$ **using** *acd abc-bcd-abd* **by** *blast*
      thus *False* **using** *abc abc-only-cba* **by** *blast*
    next
      assume *cbd*: $[[c\ b\ d]]$
      have *cba*: $[[c\ b\ a]]$ **using** *abc abc-sym* **by** *blast*
      have *a-neq-d*: $a \neq d$ **using** *abc-ac-neq acd* **by** *auto*
      then have $[[c\ a\ d]] \vee [[c\ d\ a]]$ **using** *abc-abd-acdadc cbd cba* **by** *simp*
      thus *False* **using** *abc-only-cba acd* **by** *blast*
    qed
  qed
qed

A few lemmas that don't seem to be proved by Schutz, but can be proven now, after Lemma 3. These sometimes avoid us having to construct a chain explicitly.

lemma *abd-bcd-abc*:
  assumes *abd*: $[[a\ b\ d]]$
    and *bcd*: $[[b\ c\ d]]$
  shows $[[a\ b\ c]]$
proof −
  have *dcb*: $[[d\ c\ b]]$ **using** *abc-sym bcd* **by** *simp*
  have *dba*: $[[d\ b\ a]]$ **using** *abc-sym abd* **by** *simp*
  have $[[c\ b\ a]]$ **using** *abc-acd-bcd dcb dba* **by** *blast*
  thus *?thesis* **using** *abc-sym* **by** *simp*

qed

lemma *abc-acd-abd*:
  assumes *abc*: [[*a b c*]]
    and *acd*: [[*a c d*]]
   shows [[*a b d*]]
  using *abc abc-acd-bcd acd* **by** *blast*

lemma *abd-acd-abcacb*:
  assumes *abd*: [[*a b d*]]
    and *acd*: [[*a c d*]]
    and *bc*: *b*≠*c*
   shows [[*a b c*]] ∨ [[*a c b*]]
proof −
  obtain *P* **where** *P-def*: *P*∈𝒫 *a*∈*P* *b*∈*P* *d*∈*P*
   using *abd abc-ex-path* **by** *blast*
  hence *c*∈*P*
   using *acd abc-abc-neq betw-b-in-path* **by** *blast*
  have ¬[[*b a c*]]
   using *abc-only-cba abd acd* **by** *blast*
  thus *?thesis*
   by (*metis P-def*(*1*−*3*) ‹*c* ∈ *P*› *abc-abc-neq abc-sym abd acd bc some-betw*)
qed

lemma *abe-ade-bcd-ace*:
  assumes *abe*: [[*a b e*]]
    and *ade*: [[*a d e*]]
    and *bcd*: [[*b c d*]]
   shows [[*a c e*]]
proof −
  have *abdadb*: [[*a b d*]] ∨ [[*a d b*]]
   using *abc-ac-neq abd-acd-abcacb abe ade bcd* **by** *auto*
  thus *?thesis*
  proof
   assume [[*a b d*]] **thus** *?thesis*
    by (*meson abc-acd-abd abc-sym ade bcd*)
  next assume [[*a d b*]] **thus** *?thesis*
    by (*meson abc-acd-abd abc-sym abe bcd*)
  qed
qed

Now we start on Theorem 9. Based on Veblen (1904) Lemma 2 p357.

lemma (**in** *MinkowskiBetweenness*) *chain3*:
  assumes *path-Q*: *Q* ∈ 𝒫
    and *a-inQ*: *a* ∈ *Q*
    and *b-inQ*: *b* ∈ *Q*
    and *c-inQ*: *c* ∈ *Q*
    and *abc-neq*: *a* ≠ *b* ∧ *a* ≠ *c* ∧ *b* ≠ *c*
  shows *ch* {*a*,*b*,*c*}

proof –
  have *abc-betw*: $[[a\ b\ c]] \vee [[a\ c\ b]] \vee [[b\ a\ c]]$
    using *assms* **by** (*meson in-path-event abc-sym some-betw insert-subset*)
  have *ch1*: $[[a\ b\ c]] \longrightarrow ch\ \{a,b,c\}$
    using *abc-abc-neq ch-by-ord-def ch-def ord-ordered between-chain* **by** *auto*
  have *ch2*: $[[a\ c\ b]] \longrightarrow ch\ \{a,c,b\}$
    using *abc-abc-neq ch-by-ord-def ch-def ord-ordered between-chain* **by** *auto*
  have *ch3*: $[[b\ a\ c]] \longrightarrow ch\ \{b,a,c\}$
    using *abc-abc-neq ch-by-ord-def ch-def ord-ordered between-chain* **by** *auto*
  show *?thesis*
    using *abc-betw ch1 ch2 ch3* **by** (*metis insert-commute*)
qed

The book introduces Theorem 9 before the above three lemmas but can only complete the proof once they are proven. This doesn't exactly say it the same way as the book, as the book gives the ordering (abcd) explicitly (for arbitrarily named events), but is equivalent.

theorem *chain4*:
  assumes *path-Q*: $Q \in \mathcal{P}$
    and *inQ*: $a \in Q\ b \in Q\ c \in Q\ d \in Q$
    and *abcd-neq*: $a \neq b \wedge a \neq c \wedge a \neq d \wedge b \neq c \wedge b \neq d \wedge c \neq d$
  shows $ch\ \{a,b,c,d\}$
proof –
  obtain $a'\ b'\ c'$ **where** *a′-pick*: $a' \in \{a,b,c,d\}$
    and *b′-pick*: $b' \in \{a,b,c,d\}$
    and *c′-pick*: $c' \in \{a,b,c,d\}$
    and *a′b′c′*: $[[a'\ b'\ c']]$
    using *some-betw* **by** (*metis inQ*(*1*,*2*,*4*) *abcd-neq insert-iff path-Q*)
  then obtain d' **where** *d′-neq*: $d' \neq a' \wedge d' \neq b' \wedge d' \neq c'$
    and *d′-pick*: $d' \in \{a,b,c,d\}$
    using *insert-iff abcd-neq* **by** *metis*
  have *all-picked-on-path*: $a' \in Q\ b' \in Q\ c' \in Q\ d' \in Q$
    using *a′-pick b′-pick c′-pick d′-pick inQ* **by** *blast+*
  consider $[[d'\ a'\ b']] \mid [[a'\ d'\ b']] \mid [[a'\ b'\ d']]$
    using *some-betw abc-only-cba all-picked-on-path*(*1*,*2*,*4*)
    by (*metis a′b′c′ d′-neq path-Q*)
  then have *picked-chain*: $ch\ \{a',b',c',d'\}$
  proof (*cases*)
    assume $[[d'\ a'\ b']]$
    thus *?thesis* **using** *a′b′c′ overlap-chain* **by** (*metis* (*full-types*) *insert-commute*)
  next
    assume *a′d′b′*: $[[a'\ d'\ b']]$
    then have $[[d'\ b'\ c']]$ **using** *abc-acd-bcd a′b′c′* **by** *blast*
    thus *?thesis* **using** *a′d′b′ overlap-chain* **by** (*metis* (*full-types*) *insert-commute*)
  next
    assume *a′b′d′*: $[[a'\ b'\ d']]$
    then have *two-cases*: $[[b'\ c'\ d']] \vee [[b'\ d'\ c']]$ **using** *abc-abd-bcdbdc a′b′c′ d′-neq*
by *blast*

have *case1*: $[[b'\ c'\ d']] \Longrightarrow$ *?thesis* **using** $a'b'c'$ *overlap-chain* **by** *blast*
have *case2*: $[[b'\ d'\ c']] \Longrightarrow$ *?thesis*
using *abc-only-cba abc-acd-bcd* $a'b'd'$ *overlap-chain*
by (*metis* (*full-types*) *insert-commute*)
show *?thesis* **using** *two-cases case1 case2* **by** *blast*
qed
have $\{a',b',c',d'\} = \{a,b,c,d\}$
proof (*rule Set.set-eqI*, *rule iffI*)
fix x
assume $x \in \{a',b',c',d'\}$
thus $x \in \{a,b,c,d\}$ **using** a'*-pick* b'*-pick* c'*-pick* d'*-pick* **by** *auto*
next
fix x
assume *x-pick*: $x \in \{a,b,c,d\}$
have $a' \neq b' \wedge a' \neq c' \wedge a' \neq d' \wedge b' \neq c' \wedge c' \neq d'$
using $a'b'c'$ *abc-abc-neq* d'*-neq* **by** *blast*
thus $x \in \{a',b',c',d'\}$
using a'*-pick* b'*-pick* c'*-pick* d'*-pick* *x-pick* d'*-neq* **by** *auto*
qed
thus *?thesis* **using** *picked-chain* **by** *simp*
qed

end

30 Interlude - Chains and Equivalences

This section is meant for our alternative definitions of chains, and proofs of equivalence. If we want to regain full independence of our axioms, we probably need to shuffle a few things around. Some of this may be redundant, but is kept for compatibility with legacy proofs.

Three definitions are given (cf ‘Betweenness: Chains‘ in Minkowski.thy): - one relying on explicit betweenness conditions - one relying on a total ordering and explicit indexing - one equivalent to the above except for use of the weaker, local-only ordering2

context *MinkowskiChain* **begin**

30.1 Proofs for totally ordered index-chains

30.1.1 General results

lemma *inf-chain-is-long*:
assumes *semifin-chain* $f\ x\ X$
shows *long-ch-by-ord* $f\ X \wedge f\ 0 = x \wedge$ *infinite* X
proof −
have *infinite* $X \longrightarrow$ *card* $X \neq 2$ **using** *card.infinite* **by** *simp*
hence *semifin-chain* $f\ x\ X \longrightarrow$ *long-ch-by-ord* $f\ X$

using *long-ch-by-ord-def semifin-chain-def short-ch-def*
by *simp*
thus *?thesis* **using** *assms semifin-chain-def* **by** *blast*
qed

A reassurance that the starting point x is implied.

lemma *long-inf-chain-is-semifin*:
assumes *long-ch-by-ord f X* $\wedge$ *infinite X*
shows $\exists$ x. $[f[x..]X]$
by (*simp add*: *assms semifin-chain-def*)

lemma *endpoint-in-semifin*:
assumes *semifin-chain f x X*
shows $x \in X$
using *assms semifin-chain-def zero-into-ordering inf-chain-is-long long-ch-by-ord-def*
by (*metis finite.emptyI*)

lemma *three-in-long-chain*:
assumes *long-ch-by-ord f X* **and** *fin*: *finite X*
obtains x y z **where** $x \in X$ **and** $y \in X$ **and** $z \in X$ **and** $x \neq y$ **and** $x \neq z$ **and** $y \neq z$
using *assms*(*1*) *long-ch-by-ord-def* **by** *auto*

30.1.2 Index-chains lie on paths

lemma *all-aligned-on-semifin-chain*:
assumes $[f[x..]X]$
and a: $y \in X$ **and** b:$z \in X$ **and** xy: $x \neq y$ **and** xz: $x \neq z$ **and** yz: $y \neq z$
shows $[[x\ y\ z]] \vee [[x\ z\ y]]$
proof −
obtain n_y n_z **where** $f\ n_y = y$ **and** $f\ n_z = z$
by (*metis TernaryOrdering.ordering-def a assms*(*1*) *b inf-chain-is-long long-ch-by-ord-def*)
have $(0 < n_y \wedge n_y < n_z) \vee (0 < n_z \wedge n_z < n_y)$
using ‹$f\ n_y = y$› ‹$f\ n_z = z$› *assms less-linear semifin-chain-def xy xz yz* **by**
auto
hence $[[(f\ 0)\ (f\ n_y)\ (f\ n_z)]] \vee [[(f\ 0)\ (f\ n_z)\ (f\ n_y)]]$
using *ordering-def assms*(*1*) *long-ch-by-ord-def semifin-chain-def*
by (*metis long-ch-by-ord-def*)
thus $[[x\ y\ z]] \vee [[x\ z\ y]]$
using ‹$f\ n_y = y$› ‹$f\ n_z = z$› *assms semifin-chain-def* **by** *auto*
qed

lemma *semifin-chain-on-path*:
assumes $[f[x..]X]$
shows $\exists P \in \mathcal{P}.\ X \subseteq P$
proof −
obtain y **where** $y \in X$ **and** $y \neq x$
using *assms inf-chain-is-long*
by (*metis Diff-iff all-not-in-conv finite-Diff2 finite-insert infinite-imp-nonempty*

insert-iff)
  have *path-exists*: $\exists P \in \mathcal{P}$. *path* $P\ x\ y$
  proof −
    obtain e **where** $e \in X$ **and** $e \neq x$ **and** $e \neq y$ **and** $[[x\ y\ e]] \vee [[x\ e\ y]]$
      using *all-aligned-on-semifin-chain inf-chain-is-long long-ch-by-ord-def assms*
            ordering-def lessI ‹$y \in X$› ‹$y \neq x$› *finite.emptyI finite-insert*
            finite-subset insert-iff subsetI
      by *smt*
    obtain P **where** *path* $P\ x\ y$
      using ‹$[[x\ y\ e]] \vee [[x\ e\ y]]$› *abc-abc-neq abc-ex-path*
      by *blast*
    show *?thesis*
      using ‹*path* $P\ x\ y$›
      by *blast*
  qed
  obtain P **where** *path* $P\ x\ y$
    using *path-exists*
    by *blast*
  have $X \subseteq P$
  proof
    fix e
    assume $e \in X$
    show $e \in P$
    proof −
      have $e=x \vee e=y \vee (e \neq x \wedge e \neq y)$ **by** *auto*
      moreover { **assume** $e \neq x \wedge e \neq y$
        have $[[x\ y\ e]] \vee [[x\ e\ y]]$
          using *all-aligned-on-semifin-chain assms*
                ‹$e \in X$› ‹$e \neq x \wedge e \neq y$› ‹$y \in X$› ‹$y \neq x$›
          by *blast*
        hence *?thesis*
          using ‹*path* $P\ x\ y$› *abc-ex-path path-unique*
          by *blast*
      } **moreover** { **assume** $e=x$
        have *?thesis*
          by (*simp add*: ‹$e = x$› ‹*path* $P\ x\ y$›)
      } **moreover** { **assume** $e=y$
        have $e \in P$
          by (*simp add*: ‹$e = y$› ‹*path* $P\ x\ y$›)
      }
      ultimately show *?thesis* **by** *blast*
    qed
  qed
  thus *?thesis*
    using ‹*path* $P\ x\ y$›
    by *blast*
qed

lemma *card2-either-elt1-or-elt2*:
  assumes *card* $X = 2$ **and** $x{\in}X$ **and** $y{\in}X$ **and** $x{\neq}y$
    and $z{\in}X$ **and** $z{\neq}x$
  shows $z{=}y$
by (*metis assms card-2-iff'*)

lemma *short-chain-on-path*:
  assumes *short-ch X*
  shows $\exists\, P{\in}\mathcal{P}.\ X{\subseteq}P$
proof −
  obtain *x y* **where** $x{\neq}y$ **and** $x{\in}X$ **and** $y{\in}X$
    using *assms short-ch-def* **by** *auto*
  obtain *P* **where** *path P x y*
    using ‹$x \in X$› ‹$x \neq y$› ‹$y \in X$› *assms short-ch-def*
    by *metis*
  have $X{\subseteq}P$
  proof
    fix *z*
    assume $z{\in}X$
    show $z{\in}P$
    proof *cases*
      assume $z{=}x$
      show $z{\in}P$ **using** ‹*path P x y*› **by** (*simp add*: ‹$z{=}x$›)
    next
      assume $z{\neq}x$
      have $z{=}y$
        using ‹$x{\in}X$› ‹$y{\in}X$› ‹$z{\neq}x$› ‹$z{\in}X$› ‹$x{\neq}y$› *assms short-ch-def*
        by *metis*
      thus $z{\in}P$ **using** ‹*path P x y*› **by** (*simp add*: ‹$z{=}y$›)
    qed
  qed
  thus *?thesis*
    using ‹*path P x y*› **by** *blast*
qed

lemma *all-aligned-on-long-chain*:
  assumes *long-ch-by-ord f X* **and** *finite X*
  and *a*: $x{\in}X$ **and** *b*: $y{\in}X$ **and** *c*:$z{\in}X$ **and** *xy*: $x{\neq}y$ **and** *xz*: $x{\neq}z$ **and** *yz*: $y{\neq}z$
shows $[[x\ y\ z]] \vee [[x\ z\ y]] \vee [[z\ x\ y]]$
proof −
  obtain n_x n_y n_z **where** *fx*: $f\ n_x = x$ **and** *fy*: $f\ n_y = y$ **and** *fz*: $f\ n_z = z$
          and *xx*: $n_x <$ *card X* **and** *yy*: $n_y <$ *card X* **and** *zz*: $n_z <$ *card X*
  proof −
    assume *a1*: $\bigwedge n_x\ n_y\ n_z.\ [\![f\ n_x = x;\ f\ n_y = y;\ f\ n_z = z;\ n_x < card\ X;\ n_y < card\ X;\ n_z < card\ X]\!] \Longrightarrow thesis$
    obtain *nn* :: $'a\ set \Rightarrow (nat \Rightarrow 'a) \Rightarrow 'a \Rightarrow nat$ **where**
      $\bigwedge a\ A\ f\ p\ pa.\ (a \notin A \vee \neg\ ordering\ f\ p\ A \vee f\ (nn\ A\ f\ a) = a)$
            $\wedge\ (infinite\ A \vee a \notin A \vee \neg\ ordering\ f\ pa\ A \vee nn\ A\ f\ a < card\ A)$

by (*metis* (*no-types*) *ordering-def*)
then show *?thesis*
using *a1* by (*metis a assms*(*1*) *assms*(*2*) *b c long-ch-by-ord-def*)
qed
have *less-or*: $(n_x<n_y \wedge n_y<n_z) \vee (n_x<n_z \wedge n_z<n_y) \vee (n_z<n_x \wedge n_x<n_y) \vee (n_z<n_y \wedge n_y<n_x) \vee (n_y<n_z \wedge n_z<n_x) \vee (n_y<n_x \wedge n_x<n_z)$
using *fx fy fz assms less-linear*
by *metis*
have *int-imp-1*: $(n_x<n_y \wedge n_y<n_z) \wedge$ *long-ch-by-ord f X* $\wedge\ n_z <$ *card X* $\longrightarrow$ [[$(f\ n_x)$ $(f\ n_y)$ $(f\ n_z)$]]
using *assms long-ch-by-ord-def ordering-def*
by *metis*
hence [[$(f\ n_x)$ $(f\ n_y)$ $(f\ n_z)$]] $\vee$ [[$(f\ n_x)$ $(f\ n_z)$ $(f\ n_y)$]] $\vee$ [[$(f\ n_z)$ $(f\ n_x)$ $(f\ n_y)$]] $\vee$ [[$(f\ n_z)$ $(f\ n_y)$ $(f\ n_x)$]] $\vee$ [[$(f\ n_y)$ $(f\ n_z)$ $(f\ n_x)$]] $\vee$ [[$(f\ n_y)$ $(f\ n_x)$ $(f\ n_z)$]]
proof −
have *f1*: $\bigwedge n\ na\ nb.\ \neg\ n < na \vee \neg\ nb < n \vee \neg\ na <$ *card X* $\vee$ [[(*f nb*) (*f n*) (*f na*)]]
by (*metis* (*no-types*) *ordering-def* ‹*long-ch-by-ord f X*› *long-ch-by-ord-def*)
then have *f2*: $\neg\ n_z < n_y \vee \neg\ n_x < n_z \vee$ [[*x z y*]]
using *fx fy fz yy*
by *blast*
have $\neg\ n_x < n_y \vee \neg\ n_z < n_x \vee$ [[*z x y*]]
using *f1 fx fy fz yy* by *blast*
then show *?thesis*
using *f2 f1 fx fy fz less-or xx zz* by *auto*
qed
hence [[*x y z*]] $\vee$ [[*x z y*]] $\vee$ [[*z x y*]] $\vee$
[[*z y x*]] $\vee$ [[*y z x*]] $\vee$ [[*y x z*]]
using *fx fy fz assms semifin-chain-def long-ch-by-ord-def*
by *metis*
thus *?thesis*
using *abc-sym*
by *blast*
qed

lemma *long-chain-on-path*:
assumes *long-ch-by-ord f X* and *finite X*
shows $\exists P\in\mathcal{P}.\ X\subseteq P$
proof −
obtain *x y* where $x\in X$ and $y\in X$ and $y\neq x$
using *long-ch-by-ord-def assms*
by (*metis* (*mono-tags*, *hide-lams*))
obtain *z* where $z\in X$ and $x\neq z$ and $y\neq z$
using *long-ch-by-ord-def assms*
by *metis*
have [[*x y z*]] $\vee$ [[*x z y*]] $\vee$ [[*z x y*]]
using *all-aligned-on-long-chain assms*
using ‹$x \in X$› ‹$x \neq z$› ‹$y \in X$› ‹$y \neq x$› ‹$y \neq z$› ‹$z \in X$›

by *auto*
then have *path-exists*: $\exists P \in \mathcal{P}.\ path\ P\ x\ y$
using *all-aligned-on-long-chain abc-ex-path*
by (*metis* ‹$y \neq x$›)
obtain P **where** *path* $P\ x\ y$
using *path-exists*
by *blast*
have $X \subseteq P$
proof
fix e
assume $e \in X$
show $e \in P$
proof −
have $e=x \vee e=y \vee (e \neq x \wedge e \neq y)$ **by** *auto*
moreover {
assume $e \neq x \wedge e \neq y$
have $[[x\ y\ e]] \vee [[x\ e\ y]] \vee [[e\ x\ y]]$
using *all-aligned-on-long-chain all-aligned-on-long-chain assms*
‹$e \in X$› ‹$e \neq x \wedge e \neq y$› ‹$y \in X$› ‹$y \neq x$› ‹$x \in X$›
by *metis*
hence *?thesis*
using ‹*path* $P\ x\ y$› *abc-ex-path path-unique*
by *blast*
}
moreover {
assume $e=x$
have *?thesis*
by (*simp add*: ‹$e = x$› ‹*path* $P\ x\ y$›)
}
moreover {
assume $e=y$
have $e \in P$
by (*simp add*: ‹$e = y$› ‹*path* $P\ x\ y$›)
}
ultimately show *?thesis* **by** *blast*
qed
qed
thus *?thesis*
using ‹*path* $P\ x\ y$›
by *blast*
qed

Notice that this whole proof would be unnecessary if including path-belongingness in the definition, as Schutz does. This would also keep path-belongingness independent of axiom O1 and O4, thus enabling an independent statement of axiom O6, which perhaps we now lose. In exchange, our definition is slightly weaker (for *card* $X \geq 3$ and *infinite* X).

lemma *chain-on-path*:
assumes *ch-by-ord* $f\ X$

shows $\exists P \in \mathcal{P}.\ X \subseteq P$
using *assms ch-by-ord-def*
using *semifin-chain-on-path long-chain-on-path short-chain-on-path long-inf-chain-is-semifin*
by *meson*

30.1.3 More general results

lemma *ch-some-betw*: $[\![x \in X;\ y \in X;\ z \in X;\ x \neq y;\ x \neq z;\ y \neq z;\ ch\ X]\!]$
$\Longrightarrow [[x\ y\ z]] \vee [[y\ x\ z]] \vee [[y\ z\ x]]$
proof −
assume *asm*: $x \in X\ y \in X\ z \in X\ x \neq y\ x \neq z\ y \neq z\ ch\ X$
{
fix f **assume** *f-def*: *long-ch-by-ord* $f\ X$
assume *evts*: $x \in X\ y \in X\ z \in X\ x \neq y\ x \neq z\ y \neq z$
assume *ords*: $\neg\ [[x\ y\ z]]\ \neg\ [[y\ z\ x]]$
obtain P **where** $X \subseteq P\ P \in \mathcal{P}$
using *chain-on-path f-def ch-by-ord-def*
by *meson*
have $[[y\ x\ z]]$
proof −
have *f1*: $\forall A\ Aa\ a.\ \neg\ A \subseteq Aa \vee (a{::}'a) \notin A \vee a \in Aa$
by *blast*
have *f2*: $y \in P$
using $\langle X \subseteq P \rangle$ *evts*(*2*) **by** *blast*
have *f3*: $x \in P$
using *f1* **by** (*metis* $\langle X \subseteq P \rangle$ *evts*(*1*))
have $z \in P$
using $\langle X \subseteq P \rangle$ *evts*(*3*) **by** *blast*
then show *?thesis*
using *f3 f2* **by** (*metis some-betw-xor* $\langle P \in \mathcal{P} \rangle$ *abc-sym evts*(*4*,*5*,*6*) *ords*)
qed
}
thus *?thesis*
unfolding *ch-def long-ch-by-ord-def ch-by-ord-def ordering-def short-ch-def*
using *asm ch-by-ord-def ch-def short-ch-def*
by (*metis* $\langle \bigwedge f.\ [\![$*long-ch-by-ord* $f\ X;\ x \in X;\ y \in X;\ z \in X;\ x \neq y;\ x \neq z;\ y \neq z;$
$\neg\ [[x\ y\ z]];\ \neg\ [[y\ z\ x]]]\!] \Longrightarrow [[y\ x\ z]] \rangle$)
qed

lemma *ch-all-betw-f*:
assumes $[f[x..yy..z]X]$ **and** $y \in X$ **and** $y \neq x$ **and** $y \neq z$
shows $[[x\ y\ z]]$
proof (*rule ccontr*)
assume *asm*: $\neg\ [[x\ y\ z]]$
obtain Q **where** $Q \in \mathcal{P}$ **and** $x \in Q \wedge y \in Q \wedge z \in Q$
using *chain-on-path assms ch-by-ord-def asm fin-ch-betw fin-long-chain-def*
by *auto*
hence $[[x\ y\ z]] \vee [[y\ x\ z]] \vee [[y\ z\ x]]$

using *some-betw assms*
by (*metis abc-sym fin-long-chain-def*)
hence $[[y\ x\ z]] \vee [[x\ z\ y]]$
using *asm abc-sym*
by *blast*
thus *False*
using *fin-long-chain-def long-ch-by-ord-def asm assms fin-ch-betw*
by (*metis* (*no-types*, *hide-lams*))
qed

lemma *get-fin-long-ch-bounds*:
assumes *long-ch-by-ord f X*
and *finite X*
shows $\exists x{\in}X.\ \exists y{\in}X.\ \exists z{\in}X.\ [f[x..y..z]X]$
proof −
obtain x **where** $x = f\ 0$ **by** *simp*
obtain z **where** $z = f\ (card\ X - 1)$ **by** *simp*
obtain y **where** *y-def*: $y{\neq}x \wedge y{\neq}z \wedge y{\in}X$
by (*metis assms*(*1*) *long-ch-by-ord-def*)
have $x{\in}X$
using *ordering-def* ‹$x = f\ 0$› *assms*(*1*) *long-ch-by-ord-def*
by (*metis card-gt-0-iff equals0D*)
have $z{\in}X$
using *ordering-def* ‹$z = f\ (card\ X - 1)$› *assms*(*1*) *long-ch-by-ord-def*
by (*metis card-gt-0-iff equals0D Suc-diff-1 lessI*)
obtain n **where** $n{<}card\ X$ **and** $f\ n = y$
using *ordering-def y-def long-ch-by-ord-def assms*
by *metis*
have $n{>}0$
using *y-def* ‹$f\ n = y$› ‹$x = f\ 0$›
using *neq0-conv* **by** *blast*
moreover have $n{<}card\ X - 1$
using *y-def* ‹$f\ n = y$› ‹$n < card\ X$› ‹$z = f\ (card\ X - 1)$› *assms*(*2*)
by (*metis card.remove card-Diff-singleton less-SucE*)
ultimately have $[f[x..y..z]X]$
using *long-ch-by-ord-def y-def* ‹$x = f\ 0$› ‹$z = f\ (card\ X - 1)$› *abc-abc-neq assms ordering-ord-ijk*
unfolding *fin-long-chain-def*
by (*metis* (*no-types*, *lifting*) *card-gt-0-iff diff-less equals0D zero-less-one*)
thus *?thesis*
using *points-in-chain*
by *blast*
qed

lemma *get-fin-long-ch-bounds2*:
assumes *long-ch-by-ord f X*
and *finite X*
obtains $x\ y\ z\ n_x\ n_y\ n_z$

where $x \in X \wedge y \in X \wedge z \in X \wedge [f[x..y..z]X] \wedge f\ n_x = x \wedge f\ n_y = y \wedge f\ n_z = z$
by (*meson assms*(*1*) *assms*(*2*) *fin-long-chain-def get-fin-long-ch-bounds index-middle-element*)

lemma *long-ch-card-ge3*:
assumes *ch-by-ord f X finite X*
shows *long-ch-by-ord f X* $\longleftrightarrow$ *card X* $\geq$ *3*
proof
assume *long-ch-by-ord f X*
then obtain *a b c* **where** $[f[a..b..c]X]$
using *get-fin-long-ch-bounds assms*(*2*) **by** *blast*
thus *3* $\leq$ *card X*
by (*metis* (*no-types*, *hide-lams*) *One-nat-def card-eq-0-iff diff-Suc-1 empty-iff fin-long-chain-def index-middle-element leI less-3-cases less-one*)
next
assume *3* $\leq$ *card X*
hence $\neg$*short-ch X*
using *assms*(*1*) *short-ch-card-2* **by** *auto*
thus *long-ch-by-ord f X*
using *assms*(*1*) *ch-by-ord-def* **by** *auto*
qed

lemma *chain-bounds-unique*:
assumes $[f[a..b..c]X]$ $[g[x..y..z]X]$
shows $(a=x \wedge c=z) \vee (a=z \wedge c=x)$
proof –
have $\forall p \in X.\ (a = p \vee p = c) \vee [[a\ p\ c]]$
using *assms*(*1*) *ch-all-betw-f* **by** *force*
then show *?thesis*
by (*metis* (*full-types*) *abc-abc-neq abc-bcd-abd abc-sym assms*(*1*,*2*) *ch-all-betw-f points-in-chain*)
qed

lemma *chain-bounds-unique2*:
assumes $[f[a..c]X]$ $[g[x..z]X]$ *card X* $\geq$ *3*
shows $(a=x \wedge c=z) \vee (a=z \wedge c=x)$
using *chain-bounds-unique*
by (*metis abc-ac-neq assms*(*1*,*2*) *ch-all-betw-f fin-chain-def points-in-chain short-ch-def*)

30.2 Chain Equivalences

30.2.1 Betweenness-chains and strong index-chains

lemma *equiv-chain-1a*:
assumes $[[..a..b..c..]X]$
shows $\exists f.$ *ch-by-ord f X* $\wedge\ a \in X \wedge b \in X \wedge c \in X \wedge a \neq b \wedge a \neq c \wedge b \neq c$
proof –
have *in-X*: $a \in X \wedge b \in X \wedge c \in X$
using *assms chain-with-def* **by** *auto*
have *all-neq*: $a \neq c \wedge a \neq b \wedge b \neq c$
using *abc-abc-neq assms chain-with-def* **by** *auto*

obtain *f* **where** *ordering f betw X*
  using *assms chain-with-def* **by** *auto*
hence *long-ch-by-ord f X*
  using *in-X all-neq long-ch-by-ord-def* **by** *blast*
hence *ch-by-ord f X*
  by (*simp add*: *ch-by-ord-def*)
thus *?thesis*
  using *all-neq in-X* **by** *blast*
qed

lemma *equiv-chain-1b*:
  assumes $ch\text{-}by\text{-}ord\ f\ X \wedge a{\in}X \wedge b{\in}X \wedge c{\in}X \wedge a{\neq}b \wedge a{\neq}c \wedge b{\neq}c \wedge [[a\ b\ c]]$
  shows $[[..a..b..c..]X]$
  using *assms chain-with-def ch-by-ord-def*
  by (*metis long-ch-by-ord-def short-ch-def*)

lemma *equiv-chain-1*:
  $[[..a..b..c..]X] \longleftrightarrow (\exists f.\ ch\text{-}by\text{-}ord\ f\ X \wedge a{\in}X \wedge b{\in}X \wedge c{\in}X \wedge a{\neq}b \wedge a{\neq}c \wedge b{\neq}c \wedge [[a\ b\ c]])$
  using *equiv-chain-1a equiv-chain-1b long-chain-betw*
  by *meson*

lemma *index-order*:
  assumes *chain-with x y z X*
    and *ch-by-ord f X* **and** $f\ a = x$ **and** $f\ b = y$ **and** $f\ c = z$
    and $finite\ X \longrightarrow a{<}card\ X$ **and** $finite\ X \longrightarrow b{<}card\ X$ **and** $finite\ X \longrightarrow c{<}card\ X$
  shows $(a{<}b \wedge b{<}c) \vee (c{<}b \wedge b{<}a)$
proof (*rule ccontr*)
  assume *a1*: $\neg (a < b \wedge b < c \vee c < b \wedge b < a)$
  hence $(a{\geq}b \vee b{\geq}c) \wedge (c{\geq}b \vee b{\geq}a)$
    by *auto*
  have *all-neq*: $x{\neq}y \wedge x{\neq}z \wedge y{\neq}z$
    using *assms*(*1*) *equiv-chain-1* **by** *blast*
  hence *is-long*: *long-ch-by-ord f X*
    by (*metis assms*(*1*) *assms*(*2*) *ch-by-ord-def equiv-chain-1 short-ch-def*)
  have $a{\neq}b \wedge a{\neq}c \wedge b{\neq}c$
    using *assms*(*3*) *assms*(*4*) *assms*(*5*) *all-neq* **by** *blast*
  hence $(a{>}b \vee b{>}c) \wedge (c{>}b \vee b{>}a)$
    using *a1 linorder-neqE-nat* **by** *blast*
  hence $(a{>}b \wedge c{>}b) \vee (b{>}c \wedge b{>}a)$
    using *not-less-iff-gr-or-eq* **by** *blast*
  have $a{>}c \vee c{>}a$
    using $\langle a \neq b \wedge a \neq c \wedge b \neq c\rangle$ **by** *auto*
  hence $(a{>}c \wedge c{>}b) \vee (a{>}c \wedge b{>}a) \vee (a{>}b \wedge c{>}a) \vee (b{>}c \wedge c{>}a)$
    using $\langle(b < a \vee c < b) \wedge (b < c \vee a < b)\rangle$ **by** *blast*

hence *o1*: $(b<c \wedge c<a) \vee (c<a \wedge a<b) \vee (b<a \wedge a<c) \vee (a<c \wedge c<b)$
  by *blast*
have $(b<c \wedge c<a) \longrightarrow [[y\ z\ x]]$
  using *assms ordering-ord-ijk long-ch-by-ord-def is-long*
  by *metis*
moreover have $(c<a \wedge a<b) \longrightarrow [[z\ x\ y]]$
  using *assms ordering-ord-ijk long-ch-by-ord-def is-long*
  by *metis*
moreover have $(b<a \wedge a<c) \longrightarrow [[y\ x\ z]]$
  using *assms ordering-ord-ijk long-ch-by-ord-def is-long*
  by *metis*
moreover have $(a<c \wedge c<b) \longrightarrow [[x\ z\ y]]$
  using *assms ordering-ord-ijk long-ch-by-ord-def is-long*
  by *metis*
ultimately have $[[y\ z\ x]] \vee [[z\ x\ y]] \vee [[y\ x\ z]] \vee [[x\ z\ y]]$
  using *assms long-ch-by-ord-def is-long o1*
  by *metis*
thus *False*
  by (*meson abc-only-cba assms*(*1*) *chain-with-def*)
qed

lemma *old-fin-chain-finite*:
assumes *finite-chain-with3 x y z X*
shows *finite X*
proof (*rule ccontr*)
assume *infinite X*
have $x \in X$
  using *assms finite-chain-with3-def chain-with-def* **by** *simp*
have $y \in X$
  using *assms finite-chain-with3-def chain-with-def* **by** *simp*
have $z \in X$
  using *assms finite-chain-with3-def chain-with-def* **by** *simp*
obtain *f* **where** *ch-by-ord f X*
  using *assms equiv-chain-1 finite-chain-with3-def*
  by *auto*
obtain *a* **where** $f\ a = x$
  using *equiv-chain-1 ordering-def* ‹*ch-by-ord f X*› *assms*
  by (*metis ch-by-ord-def finite-chain-with3-def long-ch-by-ord-def short-ch-def*)
obtain *c* **where** $f\ c = z$ **and** $a \neq c$
  using *equiv-chain-1 ordering-def* ‹*ch-by-ord f X*› ‹$f\ a = x$› *assms*
  using *ch-by-ord-def finite-chain-with3-def long-ch-by-ord-def short-ch-def*
  by *metis*
obtain *b* **where** $f\ b = y$ **and** $a \neq b$ **and** $b \neq c$
  using *equiv-chain-1 ordering-def* ‹*ch-by-ord f X*› ‹$f\ a = x$› ‹$f\ c = z$› *assms*
  using *ch-by-ord-def finite-chain-with3-def long-ch-by-ord-def short-ch-def*
  by *metis*
obtain *n* **where** $a<n$ **and** $c<n$
  using ‹*ch-by-ord f X*› ‹$f\ a = x$› ‹$f\ c = z$› *assms equiv-chain-1* ‹*infinite X*›

using *ch-by-ord-def finite-chain-with3-def long-ch-by-ord-def short-ch-def*
by (*metis less-Suc-eq-le not-le not-less-iff-gr-or-eq*)
have $[[x\ y\ z]]$
using *assms chain-with-def finite-chain-with3-def* **by** *auto*
hence $(a<b \wedge b<c) \vee (c<b \wedge b<a)$
using ‹$f\ a = x$› ‹$f\ b = y$› ‹$f\ c = z$› ‹*ch-by-ord f X*› ‹$x{\in}X$› ‹$y{\in}X$› ‹$z{\in}X$› *index-order*
using ‹*infinite X*› *assms finite-chain-with3-def*
by *blast*
hence $(a<b \wedge b<c \wedge c<n) \vee (c<b \wedge b<a \wedge a<n)$
using ‹$a{\neq}c$› ‹$a{\neq}b$› ‹$b{\neq}c$› ‹$a<n$› ‹$c<n$› *less-linear*
by *blast*
hence *acn-can*: $(b<c \wedge c<n) \vee (b<a \wedge a<n)$
by *blast*
have $f\ n \in X$
by (*metis ordering-def* ‹*ch-by-ord f X*› ‹*infinite X*› *assms ch-by-ord-def equiv-chain-1 finite-chain-with3-def long-ch-by-ord-def short-ch-def*)
hence *outside*: $[[y\ z\ (f\ n)]] \vee [[(f\ n)\ x\ y]]$
using *acn-can* ‹*ch-by-ord f X*› ‹$f\ a = x$› ‹$f\ c = z$› ‹*infinite X*› *assms equiv-chain-1 abc-sym*
using *ch-by-ord-def finite-chain-with3-def long-ch-by-ord-def ordering-ord-ijk short-ch-def*
by (*metis* ‹$f\ b = y$›)
thus *False*
using ‹$f\ n \in X$› *assms finite-chain-with3-def*
by *blast*
qed

lemma *index-from-with3*:
assumes *finite-chain-with3 a b c X*
shows $\exists f.\ (f\ 0 = a \vee f\ 0 = c) \wedge$ *ch-by-ord f X*
proof −
obtain *f* **where** *ch-by-ord f X*
using *assms equiv-chain-1 finite-chain-with3-def*
by *auto*
have *no-elt*: $\neg(\exists\, w{\in}X.\ [[w\ a\ b]] \vee [[b\ c\ w]])$
using *assms finite-chain-with3-def*
by *blast*
obtain n_a n_b **where** $f\ n_a = a$ **and** $n_a <$ *card X*
and $f\ n_b = b$ **and** $n_b <$ *card X*
using *assms old-fin-chain-finite ch-by-ord-def ordering-def*
using ‹*ch-by-ord f X*› *equiv-chain-1 finite-chain-with3-def long-ch-by-ord-def short-ch-def*
by *metis*
obtain n_c **where** $f\ n_c = c$ **and** $n_c <$ *card X*
using *assms old-fin-chain-finite ch-by-ord-def ordering-def*
using ‹*ch-by-ord f X*› *equiv-chain-1 finite-chain-with3-def long-ch-by-ord-def short-ch-def*
by *metis*

have $a{\neq}b \wedge b{\neq}c \wedge a{\neq}c$
using *assms equiv-chain-1 finite-chain-with3-def* **by** *auto*
have $a{\neq}b \longrightarrow n_a{\neq}n_b \wedge b{\neq}c \longrightarrow n_a{\neq}n_c \wedge a{\neq}c \longrightarrow n_b{\neq}n_c$
using $\langle f\ n_a = a\rangle$ $\langle f\ n_b = b\rangle$ $\langle f\ n_c = c\rangle$ **by** *blast*
hence $n_a{\neq}n_b \wedge n_a{\neq}n_c \wedge n_b{\neq}n_c$
using $\langle a \neq b \wedge b \neq c \wedge a \neq c\rangle$ $\langle f\ n_a = a\rangle$ $\langle f\ n_b = b\rangle$ $\langle f\ n_c = c\rangle$
by *auto*
have $n_a = 0 \vee n_c = 0$
proof (*rule ccontr*)
assume $\neg\ (n_a = 0 \vee n_c = 0)$
hence *not-0*: $n_a \neq 0 \wedge n_c \neq 0$
by *linarith*
then obtain p **where** $f\ 0 = p$
by *simp*
hence $p{\in}X$
using $\langle$*ch-by-ord f X*$\rangle$ $\langle n_a <$ *card X*$\rangle$ *assms card-0-eq ch-by-ord-def zero-into-ordering*
using *equiv-chain-1 finite-chain-with3-def inf.strict-coboundedI2 inf.strict-order-iff less-one long-ch-by-ord-def old-fin-chain-finite short-ch-def*
by *metis*
have $n_a{<}n_c \vee n_c{<}n_a$
using $\langle n_a \neq n_b \wedge n_a \neq n_c \wedge n_b \neq n_c\rangle$ *less-linear* **by** *blast*
{
assume $n_a < n_c$
hence $n_a < n_b$
using *index-order* $\langle$*ch-by-ord f X*$\rangle$ $\langle f\ n_a = a\rangle$ $\langle f\ n_b = b\rangle$ $\langle f\ n_c = c\rangle$ $\langle n_c <$ *card X*$\rangle$
using *finite-chain-with3-def assms*
by *fastforce*
have $0{<}n_a \wedge n_a{<}n_b$
using *index-order* $\langle n_a < n_b\rangle$ *not-0*
by *blast*
hence $[[p\ a\ b]]$
using $\langle$*ch-by-ord f X*$\rangle$ $\langle f\ 0{=}p\rangle$ $\langle f\ n_a{=}a\rangle$ $\langle f\ n_b{=}b\rangle$ $\langle n_b{<}$*card X*$\rangle$ *assms equiv-chain-1 short-ch-def*
by (*metis ch-by-ord-def finite-chain-with3-def long-ch-by-ord-def ordering-ord-ijk*)
hence *False*
using *finite-chain-with3-def* $\langle p{\in}X\rangle$
by (*metis no-elt*)
}
moreover {
assume $n_c < n_a$
hence $n_c < n_b$
using *index-order* $\langle$*ch-by-ord f X*$\rangle$ $\langle f\ n_a = a\rangle$ $\langle f\ n_b = b\rangle$ $\langle f\ n_c = c\rangle$ $\langle n_a <$ *card X*$\rangle$
using *finite-chain-with3-def assms*
by *fastforce*
have $0{<}n_c \wedge n_c{<}n_b$
using *index-order* $\langle n_c < n_b\rangle$ *not-0*

by *blast*
hence $[[p\ c\ b]]$
using ‹*ch-by-ord f X*› ‹*f 0=p*› ‹$f\ n_c$=*c*› ‹$f\ n_b$=*b*› ‹n_b<*card X*› *assms equiv-chain-1 short-ch-def*
using *ch-by-ord-def finite-chain-with3-def long-ch-by-ord-def ordering-ord-ijk*
by *metis*
hence $[[b\ c\ p]]$
by (*simp add*: *abc-sym*)
hence *False*
using *finite-chain-with3-def* ‹*p*∈*X*›
by (*metis no-elt*)
}
ultimately show *False*
using ‹$n_a < n_c \lor n_c < n_a$› **by** *blast*
qed
thus *?thesis*
using ‹*ch-by-ord f X*› ‹$f\ n_a = a$› ‹$f\ n_c = c$›
by *blast*
qed

lemma (**in** *MinkowskiSpacetime*) *with3-and-index-is-fin-chain*:
assumes *f 0* = *a* **and** *ch-by-ord f X* **and** *finite-chain-with3 a b c X*
shows [*f*[*a*..*b*..*c*]*X*]
proof −
have *finite X*
using *ordering-def assms old-fin-chain-finite*
by *auto*
moreover have *long-ch-by-ord f X*
using *assms*(*2*) *assms*(*3*) *ch-by-ord-def equiv-chain-1 finite-chain-with3-def short-ch-def*
by *metis*
moreover have $a{\neq}b \land a{\neq}c \land b{\neq}c \land f\ 0 = a \land b{\in}X$
using *assms*(*1*) *assms*(*3*) *equiv-chain-1 finite-chain-with3-def*
by *auto*
moreover have *f* (*card X* − *1*) = *c*
proof −
obtain *n* **where** *f n* = *c* **and** *n* < *card X*
using *ordering-def equiv-chain-1 finite-chain-with3-def long-ch-by-ord-def*
by (*metis assms*(*3*) *calculation*(*1*,*2*))
{
assume *n* < *card X* − *1*
then obtain *m* **where** *n*<*m* **and** *m*<*card X* **by** *simp*
hence $[[a\ c\ (f\ m)]] \land (f\ m){\in}X$
proof −
have *f1*: *TernaryOrdering.ordering f betw X*
using ‹*long-ch-by-ord f X*› *long-ch-by-ord-def* **by** *blast*
have *f2*: ∀*f A p na*. ((*p* (*f na*::′*a*) (*f n*) (*f m*) ∨ ¬ *m* < *card A*) ∨ ¬ *ordering f p A*)

```
                              ∨ ¬ na < n
            by (metis ordering-def ‹n < m›)
          have f m ∈ X
            using f1 by (simp add: ordering-def ‹m < card X›)
          then show ?thesis
            using f2 f1 ‹a≠b ∧ a≠c ∧ b≠c ∧ f 0 = a ∧ b∈X› ‹f n = c› ‹m < card
X›
            using gr-implies-not0 linorder-neqE-nat
            by (metis (no-types))
        qed
      hence [[b c (f m)]] using abc-acd-bcd
        by (meson assms(3) chain-with-def finite-chain-with3-def)
      hence False
        using assms(3) ‹[[a c (f m)]] ∧ f m ∈ X›
        by (metis finite-chain-with3-def)
    }
    hence n = card X − 1
      using ‹n < card X› by fastforce
    thus ?thesis
      using ‹f n = c› by blast
  qed
  ultimately show ?thesis
    by (simp add: fin-long-chain-def)
qed


lemma (in MinkowskiSpacetime) g-from-with3:
  assumes finite-chain-with3 a b c X
  obtains g where [g[a..b..c]X] ∨ [g[c..b..a]X]
proof −
  have old-chain-sym: finite-chain-with3 c b a X
    by (metis abc-sym assms chain-with-def finite-chain-with3-def)
  obtain f where f-def: (f 0 = a ∨ f 0 = c) ∧ ch-by-ord f X
    using index-from-with3 assms
    by blast
  hence f 0 = a ⟶ [f[a..b..c]X]
    using with3-and-index-is-fin-chain f-def assms
    by simp
  moreover have f 0 = c ⟶ [f[c..b..a]X]
    using with3-and-index-is-fin-chain f-def assms old-chain-sym
    by simp
  ultimately show ?thesis
    using f-def that
    by auto
qed


lemma (in MinkowskiSpacetime) equiv-chain-2a:
  assumes finite-chain-with3 a b c X
```

obtains *f* **where** $[f[a..b..c]X]$
proof −
obtain *g* **where** $[g[a..b..c]X] \vee [g[c..b..a]X]$
using *assms g-from-with3* **by** *blast*
thus *?thesis*
proof
assume $[g[a..b..c]X]$
show *?thesis*
using ‹$[g[a\ ..\ b\ ..\ c]X]$› *that*
by *blast*
next
assume $[g[c..b..a]X]$
show *?thesis*
using ‹$[g[c\ ..\ b\ ..\ a]X]$› *chain-sym that*
by *blast*
qed
qed

lemma *equiv-chain-2b*:
assumes $[f[a..b..c]X]$
shows *finite-chain-with3 a b c X*
proof −
have *aligned*: $[[a\ b\ c]]$
using *assms fin-ch-betw*
by *auto*
hence *some-chain*: $[[..a..b..c..]X]$
using *assms ch-by-ord-def equiv-chain-1b fin-long-chain-def points-in-chain*
by *metis*
have $\neg(\exists\, w{\in}X.\ [[w\ a\ b]] \vee [[b\ c\ w]])$
proof (*safe*)
fix *w* **assume** $w{\in}X$
{
assume *case1*: $[[w\ a\ b]]$
then obtain *n* **where** $f\ n = w$ **and** $n{<}card\ X$
using ‹$w{\in}X$› *abc-bcd-abd abc-only-cba aligned assms fin-ch-betw fin-long-chain-def*
by (*metis* (*no-types*, *hide-lams*))
have $f\ 0 = a$
using *assms fin-long-chain-def*
by *blast*
hence $n < 0$
proof −
have *f1*: $f\ (card\ X - 1) = c$
by (*meson MinkowskiBetweenness.fin-long-chain-def MinkowskiBetweenness-axioms assms*)
have $\neg\ [[a\ w\ c]]$
by (*meson abc-bcd-abd abc-only-cba assms case1 fin-ch-betw*)
thus *?thesis*
using *f1 fin-long-chain-def* ‹$w \in X$› *abc-only-cba assms case1 fin-ch-betw*

by (*metis* (*no-types*))
qed
thus *False*
by *simp*
}
moreover {
assume *case2*: [[*b c w*]]
then obtain *n* **where** *f n* = *w* **and** *n*<*card X*
using ‹*w*∈*X*› *ordering-def abc-bcd-abd abc-only-cba aligned assms fin-ch-betw*
using *fin-long-chain-def long-ch-by-ord-def*
by *metis*
have *f* (*card X* − *1*) = *c*
using *assms fin-long-chain-def*
by *blast*
have ¬ [[*a w c*]]
using *abc-bcd-abd abc-only-cba assms case2 fin-ch-betw abc-bcd-acd*
by *meson*
hence *n* > *card X* − *1*
using ‹¬ [[*a w c*]]› ‹*w* ∈ *X*› *abc-only-cba assms case2 fin-ch-betw*
unfolding *fin-long-chain-def*
by (*metis* (*no-types*))
thus *False*
using ‹*n* < *card X*›
by *linarith*
}
qed
thus *?thesis*
by (*simp add*: *finite-chain-with3-def some-chain*)
qed

lemma (**in** *MinkowskiSpacetime*) *equiv-chain-2*:
∃ *f*. [*f*[*a*..*b*..*c*]*X*] ⟷ [[*a*..*b*..*c*]*X*]
using *equiv-chain-2a equiv-chain-2b*
by *meson*

end

31 Results for segments, rays and chains

context *MinkowskiChain* **begin**

lemma *inside-not-bound*:
assumes [*f*[*a*..*b*..*c*]*X*]
and *j*<*card X*
shows *j*>*0* ⟹ *f j* ≠ *a j*<*card X* − *1* ⟹ *f j* ≠ *c*
proof −
have *bound-indices*: *f 0* = *a* ∧ *f* (*card X* − *1*) = *c*
using *assms*(*1*) *fin-long-chain-def* **by** *auto*

show *f j* ≠ *a* **if** *j*>*0*
proof (*cases*)
assume *f j* = *c*
then have [[(*f 0*) (*f j*) *b*]] ∨ [[(*f 0*) *b* (*f j*)]]
using *assms*(*1*) *fin-ch-betw fin-long-chain-def*
by *metis*
thus *?thesis* **using** *abc-abc-neq bound-indices* **by** *blast*
next
assume *f j* ≠ *c*
then have [[(*f 0*) (*f j*) *c*]] ∨ [[(*f 0*) *c* (*f j*)]]
using *assms fin-ch-betw*
unfolding *fin-long-chain-def long-ch-by-ord-def ordering-def*
by (*metis abc-abc-neq assms that ch-all-betw-f nat-neq-iff*)
thus *?thesis*
using *abc-abc-neq bound-indices* **by** *blast*
qed
show *f j* ≠ *c* **if** *j*<*card X* − *1*
proof (*cases*)
assume *f j* = *a*
show *?thesis*
using ‹*f j* = *a*› *assms*(*1*) *fin-long-chain-def*
by *blast*
next
assume *f j* ≠ *a*
have *0* < *card X*
using *assms*(*2*) **by** *linarith*
hence [[*a* (*f j*) (*f* (*card X* − *1*))]] ∨ [[(*f j*) *a* (*f* (*card X* − *1*))]]
using *assms fin-ch-betw fin-long-chain-def order-finite-chain*
by (*metis* ‹*f j* ≠ *a*› *diff-less le-numeral-extra*(*1*−*3*) *neq0-conv that*)
thus *f j* ≠ *c*
using *abc-abc-neq bound-indices* **by** *auto*
qed
qed

lemma *some-betw2*:
assumes [*f*[*a*..*b*..*c*]*X*]
and *j*<*card X j*>*0 f j* ≠ *b*
shows [[*a b* (*f j*)]] ∨ [[*a* (*f j*) *b*]]
proof −
obtain *ab* **where** *ab-def*: *path ab a b X*⊆*ab*
by (*metis fin-long-chain-def long-chain-on-path assms*(*1*) *points-in-chain subsetD*)
have *bound-indices*: *f 0* = *a* ∧ *f* (*card X* − *1*) = *c*
using *assms*(*1*) *fin-long-chain-def* **by** *auto*
have *f j* ≠ *a*
using *inside-not-bound*(*1*) *assms*(*1*) *assms*(*2*) *assms*(*3*)
by *blast*
have ¬[[(*f j*) *a b*]]

using *abc-bcd-abd abc-only-cba assms*(*1*,*2*) *fin-ch-betw fin-long-chain-def*
by (*metis ordering-def ch-all-betw-f long-ch-by-ord-def*)
thus [[*a b* (*f j*)]] ∨ [[*a* (*f j*) *b*]]
using *some-betw* [**where** *Q*=*ab* **and** *a*=*a* **and** *b*=*b* **and** *c*=*f j*]
using *ab-def assms*(*4*) ‹*f j* ≠ *a*›
by (*metis ordering-def abc-sym assms*(*1*,*2*) *fin-long-chain-def long-ch-by-ord-def subsetD*)
qed

lemma *i-le-j-events-neq1*:
assumes [*f*[*a*..*b*..*c*]*X*]
and *i*<*j j*<*card X f j* ≠ *b*
shows *f i* ≠ *f j*
proof −
have *in-X*: *f i* ∈ *X* ∧ *f j* ∈ *X*
by (*metis ordering-def assms*(*1*,*2*,*3*) *fin-long-chain-def less-trans long-ch-by-ord-def*)
have *bound-indices*: *f 0* = *a* ∧ *f* (*card X* − *1*) = *c*
using *assms*(*1*) *fin-long-chain-def* **by** *auto*
obtain *ab* **where** *ab-def*: *path ab a b X*⊆*ab*
by (*metis fin-long-chain-def long-chain-on-path assms*(*1*) *points-in-chain subsetD*)
show *?thesis*
proof (*cases*)
assume *f i* = *a*
hence [[*a* (*f j*) *b*]] ∨ [[*a b* (*f j*)]]
using *some-betw2 assms* **by** *blast*
thus *?thesis*
using ‹*f i* = *a*› *abc-abc-neq* **by** *blast*
next assume *f i* ≠ *a*
hence [[*a* (*f i*) (*f j*)]]
using *assms*(*1*,*2*,*3*) *ch-equiv fin-long-chain-def order-finite-chain2*
by (*metis gr-implies-not-zero le-numeral-extra*(*3*) *less-linear*)
thus *?thesis*
using *abc-abc-neq* **by** *blast*
qed
qed

lemma *i-le-j-events-neq*:
assumes [*f*[*a*..*b*..*c*]*X*]
and *i*<*j j*<*card X*
shows *f i* ≠ *f j*
proof −
have *in-X*: *f i* ∈ *X* ∧ *f j* ∈ *X*
by (*metis ordering-def assms*(*1*,*2*,*3*) *fin-long-chain-def less-trans long-ch-by-ord-def*)
have *bound-indices*: *f 0* = *a* ∧ *f* (*card X* − *1*) = *c*
using *assms*(*1*) *fin-long-chain-def* **by** *auto*
obtain *ab* **where** *ab-def*: *path ab a b X*⊆*ab*
by (*metis fin-long-chain-def long-chain-on-path assms*(*1*) *points-in-chain subsetD*)

show *?thesis*
proof (*cases*)
assume *f i* = *a*
show *?thesis*
proof (*cases*)
assume (*f j*) = *b*
thus *?thesis*
by (*simp add*: ‹(*f i*) = *a*› *ab-def*(*1*))
next assume (*f j*) ≠ *b*
have [[*a* (*f j*) *b*]] ∨ [[*a b* (*f j*)]]
using *some-betw2 assms* ‹(*f j*) ≠ *b*› **by** *blast*
thus *?thesis*
using ‹(*f i*) = *a*› *abc-abc-neq* **by** *blast*
qed
next assume (*f i*) ≠ *a*
hence [[*a* (*f i*) (*f j*)]]
using *assms*(*1*,*2*,*3*) *ch-equiv fin-long-chain-def order-finite-chain2*
by (*metis gr-implies-not-zero le-numeral-extra*(*3*) *less-linear*)
thus *?thesis*
using *abc-abc-neq* **by** *blast*
qed
qed

lemma *indices-neq-imp-events-neq*:
assumes [*f*[*a*..*b*..*c*]*X*]
and *i*≠*j j*<*card X i*<*card X*
shows *f i* ≠ *f j*
by (*metis assms i-le-j-events-neq less-linear*)

lemma *index-order2*:
assumes [*f*[*x*..*y*..*z*]*X*] **and** *f a* = *x* **and** *f b* = *y* **and** *f c* = *z*
and *finite X* ⟶ *a* < *card X* **and** *finite X* ⟶ *b* < *card X* **and** *finite X* ⟶ *c* < *card X*
shows (*a*<*b* ∧ *b*<*c*) ∨ (*c*<*b* ∧ *b*<*a*)
using *index-order* [**where** *x*=*x* **and** *y*=*y* **and** *z*=*z* **and** *a*=*a* **and** *b*=*b* **and** *c*=*c* **and** *f*=*f* **and** *X*=*X*]
by (*metis assms ch-by-ord-def equiv-chain-2b fin-long-chain-def finite-chain-with3-def*)

lemma *index-order3*:
assumes [[*x y z*]] **and** *f a* = *x* **and** *f b* = *y* **and** *f c* = *z* **and** *long-ch-by-ord f X*
and *finite X* ⟶ *a* < *card X* **and** *finite X* ⟶ *b* < *card X* **and** *finite X* ⟶ *c* < *card X*
shows (*a*<*b* ∧ *b*<*c*) ∨ (*c*<*b* ∧ *b*<*a*)
using *index-order2* [**where** *x*=*x* **and** *y*=*y* **and** *z*=*z* **and** *a*=*a* **and** *b*=*b* **and** *c*=*c* **and** *f*=*f* **and** *X*=*X*]
using *assms long-ch-by-ord-def ordering-ord-ijk*
by (*smt abc-abc-neq abc-only-cba*(*1*−*3*) *linorder-neqE-nat*)

end

context *MinkowskiSpacetime* **begin**

lemma *bound-on-path*:
  assumes $Q\in\mathcal{P}$ $[f[(f\ 0)..]X]$ $X\subseteq Q$ *is-bound-f b X f*
  shows $b\in Q$
proof −
  obtain *a c* **where** $a\in X$ $c\in X$ $[[a\ c\ b]]$
    using *assms*(*4*)
   by (*metis ordering-def inf-chain-is-long is-bound-f-def long-ch-by-ord-def zero-less-one*)
  thus *?thesis*
    using *abc-abc-neq assms*(*1*) *assms*(*3*) *betw-c-in-path* **by** *blast*
qed

lemma *pro-basis-change*:
  assumes $[[a\ b\ c]]$
  shows *prolongation a c* = *prolongation b c* (**is** *?ac=?bc*)
proof
  show *?ac* ⊆ *?bc*
  proof
    fix *x* **assume** *x*∈*?ac*
    hence $[[a\ c\ x]]$
      by (*simp add*: *pro-betw*)
    hence $[[b\ c\ x]]$
      using *assms abc-acd-bcd* **by** *blast*
    thus *x*∈*?bc*
      using *abc-abc-neq pro-betw* **by** *blast*
  qed
  show *?bc* ⊆ *?ac*
  proof
    fix *x* **assume** *x*∈*?bc*
    hence $[[b\ c\ x]]$
      by (*simp add*: *pro-betw*)
    hence $[[a\ c\ x]]$
      using *assms abc-bcd-acd* **by** *blast*
    thus *x*∈*?ac*
      using *abc-abc-neq pro-betw* **by** *blast*
  qed
qed

lemma *adjoining-segs-exclusive*:
  assumes $[[a\ b\ c]]$
  shows *segment a b* ∩ *segment b c* = {}
proof (*cases*)
  assume *segment a b* = {} **thus** *?thesis* **by** *blast*
next
  assume *segment a b* ≠ {}
  have *x*∈*segment a b* ⟶ *x*∉*segment b c* **for** *x*

proof
  fix x **assume** $x\in segment\ a\ b$
  hence $[[a\ x\ b]]$ **by** (*simp add*: *seg-betw*)
  have $\neg[[a\ b\ x]]$ **by** (*meson* ‹$[[a\ x\ b]]$› *abc-only-cba*)
  have $\neg[[b\ x\ c]]$
    using ‹$\neg\ [[a\ b\ x]]$› *abd-bcd-abc assms* **by** *blast*
  thus $x\notin segment\ b\ c$
    by (*simp add*: *seg-betw*)
qed
thus *?thesis* **by** *blast*
qed

end

32 3.6 Order on a path - Theorems 10 and 11

context *MinkowskiSpacetime* **begin**

32.1 Theorem 10 (based on Veblen (1904) theorem 10).

lemma (**in** *MinkowskiBetweenness*) *two-event-chain*:
  assumes *finiteX*: *finite X*
    and *path-Q*: $Q \in \mathcal{P}$
    and *events-X*: $X \subseteq Q$
    and *card-X*: $card\ X = 2$
  shows *ch X*
proof −
  obtain *a b* **where** *X-is*: $X=\{a,b\}$
    using *card-le-Suc-iff numeral-2-eq-2*
    by (*meson card-2-iff card-X*)
  have *no-c*: $\neg(\exists\, c\in\{a,b\}.\ c\neq a \wedge c\neq b)$
    by *blast*
  have $a\neq b \wedge a\in Q\ \&\ b\in Q$
    using *X-is card-X events-X* **by** *force*
  hence *short-ch* $\{a,b\}$
    using *path-Q short-ch-def no-c* **by** *blast*
  thus *?thesis*
    by (*simp add*: *X-is ch-by-ord-def ch-def*)
qed

lemma (**in** *MinkowskiBetweenness*) *three-event-chain*:
  assumes *finiteX*: *finite X*
    and *path-Q*: $Q \in \mathcal{P}$
    and *events-X*: $X \subseteq Q$
    and *card-X*: $card\ X = 3$
  shows *ch X*
proof −
  obtain *a b c* **where** *X-is*: $X=\{a,b,c\}$
    using *numeral-3-eq-3 card-X* **by** (*metis card-Suc-eq*)

then have *all-neq*: $a \neq b \wedge a \neq c \wedge b \neq c$
using *card-X numeral-2-eq-2 numeral-3-eq-3*
by (*metis Suc-n-not-le-n insert-absorb2 insert-commute set-le-two*)
have *in-path*: $a \in Q \wedge b \in Q \wedge c \in Q$
using *X-is events-X* **by** *blast*
hence $[[a\ b\ c]] \vee [[b\ c\ a]] \vee [[c\ a\ b]]$
using *some-betw all-neq path-Q* **by** *auto*
thus *ch X*
using *between-chain X-is all-neq chain3 in-path path-Q* **by** *auto*
qed

This is case (i) of the induction in Theorem 10.

lemma *chain-append-at-left-edge*:
assumes *long-ch-Y*: $[f[a_1..a..a_n]Y]$
and *bY*: $[[b\ a_1\ a_n]]$
fixes *g* **defines** *g-def*: $g \equiv (\lambda j{::}nat.\ \mathit{if}\ j \geq 1\ \mathit{then}\ f\ (j-1)\ \mathit{else}\ b)$
shows $[g[b\ ..\ a_1\ ..\ a_n](insert\ b\ Y)]$
proof −
let $?X = insert\ b\ Y$
have $b \notin Y$
by (*metis abc-ac-neq abc-only-cba*(*1*) *bY ch-all-betw-f long-ch-Y*)
have *bound-indices*: $f\ 0 = a_1 \wedge f\ (card\ Y - 1) = a_n$
using *long-ch-Y* **by** (*simp add*: *fin-long-chain-def*)
have *fin-Y*: $card\ Y \geq 3$
using *fin-long-chain-def long-ch-Y numeral-2-eq-2*
by (*metis ch-by-ord-def long-ch-card-ge3*)
hence *num-ord*: $0 \leq (0{::}nat) \wedge 0 < (1{::}nat) \wedge 1 < card\ Y - 1 \wedge card\ Y - 1 < card\ Y$
by *linarith*
hence $[[a_1\ (f\ 1)\ a_n]]$
using *order-finite-chain fin-long-chain-def long-ch-Y*
by *auto*

Schutz has a step here that says $[b\ a_1\ a_2\ a_n]$ is a chain (using Theorem 9). We have no easy way of denoting an ordered 4-element chain, so we skip this step using an ordering lemma from our script for 3.6, which Schutz doesn't list.

hence $[[b\ a_1\ (f\ 1)]]$
using *bY abd-bcd-abc* **by** *blast*
have *ordering2 g betw ?X*
proof −
{
fix *n* **assume** *finite* $?X \longrightarrow n < card\ ?X$
have $g\ n \in ?X$
apply (*cases* $n \geq 1$)
prefer *2* **apply** (*simp add*: *g-def*)
proof
assume $1 \leq n\ g\ n \notin Y$
hence $g\ n = f(n-1)$ **unfolding** *g-def* **by** *auto*

hence $g\ n \in Y$
proof (*cases* $n = card\ ?X - 1$)
case *True*
thus *?thesis*
using ‹$b \notin Y$› *card.insert diff-Suc-1 fin-long-chain-def long-ch-Y points-in-chain*
by (*metis* ‹$g\ n = f\ (n - 1)$›)
next
case *False*
hence $n < card\ Y$
using *points-in-chain* ‹$finite\ ?X \longrightarrow n < card\ ?X$› ‹$g\ n = f\ (n - 1)$› ‹$g\ n \notin Y$› ‹$b \notin Y$›
by (*metis card.insert fin-long-chain-def finite-insert long-ch-Y not-less-simps*(*1*))
hence $n{-}1 < card\ Y - 1$
using ‹$1 \leq n$› *diff-less-mono* **by** *blast*
hence $f(n{-}1) \in Y$
using *long-ch-Y* **unfolding** *fin-long-chain-def long-ch-by-ord-def ordering-def*
by (*meson less-trans num-ord*)
thus *?thesis*
using ‹$g\ n = f\ (n - 1)$› **by** *presburger*
qed
hence *False* **using** ‹$g\ n \notin Y$› **by** *auto*
thus $g\ n = b$ **by** *simp*
qed
} moreover {
fix $n\ n'\ n''$ **assume** ($finite\ ?X \longrightarrow n'' < card\ ?X$) $Suc\ n = n' \wedge Suc\ n' = n''$
hence $[[(g\ n)\ (g\ n')\ (g\ n'')]]$
using ‹$b \notin Y$› ‹$[[b\ a_1\ (f\ 1)]]$› *g-def long-ch-Y ordering-ord-ijk*
by (*smt* (*verit, ccfv-threshold*) *fin-long-chain-def long-ch-by-ord-def One-nat-def card.insert diff-Suc-Suc diff-diff-cancel diff-is-0-eq finite-insert nat-less-le not-less not-less-eq-eq*)
} moreover {
fix x **assume** $x \in ?X$ $x = b$
have ($finite\ ?X \longrightarrow 0 < card\ ?X$) $\wedge$ $g\ 0 = x$
by (*simp add*: ‹$b \notin Y$› ‹$x = b$› *g-def*)
} moreover {
fix x **assume** $x \in ?X$ $x \neq b$
hence $\exists n.$ ($finite\ ?X \longrightarrow n < card\ ?X$) $\wedge$ $g\ n = x$
proof −
obtain n **where** $f\ n = x$ $n < card\ Y$
using ‹$x \in ?X$› ‹$x \neq b$›
by (*metis ordering-def fin-long-chain-def insert-iff long-ch-Y long-ch-by-ord-def*)
have ($finite\ ?X \longrightarrow n{+}1 < card\ ?X$) $g(n{+}1) = x$
apply (*simp add*: ‹$b \notin Y$› ‹$n < card\ Y$›)
by (*simp add*: ‹$f\ n = x$› *g-def*)
thus *?thesis* **by** *auto*
qed
}
ultimately show *?thesis*

unfolding *ordering2-def*
by *smt*
qed
hence *long-ch-by-ord2 g ?X*
unfolding *long-ch-by-ord2-def*
using *points-in-chain fin-long-chain-def* ‹$b \notin Y$›
by (*metis abc-abc-neq bY insert-iff long-ch-Y points-in-chain*)
hence *long-ch-by-ord g ?X*
using *ch-equiv fin-Y*
by (*meson fin-long-chain-def finite-insert long-ch-Y*)
thus *?thesis*
unfolding *fin-long-chain-def*
using *bound-indices* ‹$b \notin Y$› *g-def num-ord points-in-chain long-ch-Y fin-long-chain-def*
by (*metis card.insert diff-Suc-1 finite-insert insert-iff less-trans nat-less-le*)
qed

This is case (iii) of the induction in Theorem 10. Schutz says merely "The proof for this case is similar to that for Case (i)." Thus I feel free to use a result on symmetry, rather than going through the pain of Case (i) (*chain-append-at-left-edge*) again.

lemma *chain-append-at-right-edge*:
assumes *long-ch-Y*: $[f[a_1..a..a_n]Y]$
and *Yb*: $[[a_1\ a_n\ b]]$
fixes g **defines** *g-def*: $g \equiv (\lambda j{::}nat.\ if\ j \le (card\ Y - 1)\ then\ f\ j\ else\ b)$
shows $[g[a_1\ ..\ a_n\ ..\ b](insert\ b\ Y)]$
proof −
let $?X = insert\ b\ Y$
have $b \notin Y$
by (*metis Yb abc-abc-neq abc-only-cba*(*2*) *ch-all-betw-f long-ch-Y*)
have *fin-X*: *finite ?X*
using *fin-long-chain-def long-ch-Y* **by** *blast*
have *fin-Y*: $card\ Y \ge 3$
by (*meson ch-by-ord-def fin-long-chain-def long-ch-Y long-ch-card-ge3*)
have $a_1 \in Y \land a_n \in Y \land a \in Y$
using *long-ch-Y points-in-chain* **by** *blast*
have $a_1 \neq a \land a \neq a_n \land a_1 \neq a_n$
using *fin-long-chain-def long-ch-Y* **by** *auto*
have $Suc\ (card\ Y) = card\ ?X$
using ‹$b \notin Y$› *fin-X fin-long-chain-def long-ch-Y* **by** *auto*
obtain *f2* **where** *f2-def*: $[f2[a_n..a..a_1]Y]$ $f2 = (\lambda n.\ f\ (card\ Y - 1 - n))$
using *chain-sym long-ch-Y* **by** *blast*
obtain *g2* **where** *g2-def*: $g2 = (\lambda j{::}nat.\ if\ j \ge 1\ then\ f2\ (j-1)\ else\ b)$
by *simp*
have $[[b\ a_n\ a_1]]$
using *abc-sym Yb* **by** *blast*
hence *g2-ord-X*: $[g2[b\ ..\ a_n\ ..\ a_1]?X]$
using *chain-append-at-left-edge* [**where** $a_1 = a_n$ **and** $a_n = a_1$ **and** $f = f2$]
fin-X ‹$b \notin Y$› *f2-def g2-def*
by *blast*

then obtain *g1* **where** *g1-def*: $[g1[a_1..a_n..b]?X]$ $g1{=}(\lambda n.\ g2\ (card\ ?X - 1 - n))$
using *chain-sym* **by** *blast*
have *sYX*: $(card\ Y) = (card\ ?X) - 1$
using *assms(2,3) fin-long-chain-def long-ch-Y* ‹*Suc* (*card Y*) = *card ?X*› **by** *linarith*
have *g1=g*
unfolding *g1-def g2-def f2-def g-def*
proof
fix *n*
show (
if $1 \leq card\ ?X - 1 - n$ *then*
$f\ (card\ Y - 1 - (card\ ?X - 1 - n - 1))$
else b
) = (
if $n \leq card\ Y - 1$ *then*
f n
else b
) (**is** *?lhs=?rhs*)
proof (*cases*)
assume $n \leq card\ ?X - 2$
show *?lhs=?rhs*
using ‹$n \leq card\ ?X - 2$› *fin-long-chain-def long-ch-Y sYX*
by (*metis Suc-1 Suc-diff-1 Suc-diff-le card-gt-0-iff diff-Suc-eq-diff-pred diff-commute*
diff-diff-cancel equals0D less-one nat.simps(3) not-less)
next
assume $\neg\ n \leq card\ ?X - 2$
thus *?lhs=?rhs*
by (*metis* ‹*Suc* (*card Y*) = *card ?X*› *Suc-1 diff-Suc-1 diff-Suc-eq-diff-pred diff-diff-cancel*
diff-is-0-eq′ nat-le-linear not-less-eq-eq)
qed
qed
thus *?thesis*
using *g1-def(1)* **by** *blast*
qed

lemma *S-is-dense*:
assumes *long-ch-Y*: $[f[a_1..a..a_n]Y]$
and *S-def*: $S = \{k{::}nat.\ [[a_1\ (f\ k)\ b]] \wedge k < card\ Y\}$
and *k-def*: $S{\neq}\{\}$ $k = Max\ S$
and *k′-def*: $k'{>}0$ $k'{<}k$
shows $k' \in S$
proof −
have $k{\in}S$ **using** *k-def Max-in S-def*
by (*metis finite-Collect-conjI finite-Collect-less-nat*)
show $k' \in S$

proof (*rule ccontr*)
  assume $\neg k' \in S$
  hence $[[a_1\ b\ (f\ k')]]$
    using *order-finite-chain S-def abc-acd-bcd abc-bcd-acd abc-sym long-ch-Y*
    by (*smt fin-long-chain-def* ‹$0 < k'$› ‹$k \in S$› ‹$k' < k$› *le-numeral-extra*(*3*)
      less-trans mem-Collect-eq)
  have $[[a_1\ (f\ k)\ b]]$
    using *S-def* ‹$k \in S$› **by** *blast*
  have $[[(f\ k)\ b\ (f\ k')]]$
    using *abc-acd-bcd* ‹$[[a_1\ b\ (f\ k')]]$› ‹$[[a_1\ (f\ k)\ b]]$› **by** *blast*
  have $k' < card\ Y$
    using *S-def* ‹$k \in S$› ‹$k' < k$› *less-trans* **by** *blast*
  thus *False*
    using *abc-bcd-abd order-finite-chain S-def abc-only-cba*(*2*) *long-ch-Y*
     ‹$0 < k'$› ‹$[[(f\ k)\ b\ (f\ k')]]$› ‹$k \in S$› ‹$k' < k$›
    unfolding *fin-long-chain-def*
    by (*metis* (*mono-tags*, *lifting*) *le-numeral-extra*(*3*) *mem-Collect-eq*)
qed
qed

lemma *smallest-k-ex*:
  assumes *long-ch-Y*: $[f[a_1..a..a_n]Y]$
    and *Y-def*: $b \notin Y$
    and *Yb*: $[[a_1\ b\ a_n]]$
  shows $\exists k>0.\ [[a_1\ b\ (f\ k)]] \wedge k < card\ Y \wedge \neg(\exists k'<k.\ [[a_1\ b\ (f\ k')]])$
proof –

  have *bound-indices*: $f\ 0 = a_1 \wedge f\ (card\ Y - 1) = a_n$
    using *fin-long-chain-def long-ch-Y* **by** *auto*
  have *fin-Y*: *finite Y*
    using *fin-long-chain-def long-ch-Y* **by** *blast*
  have *card-Y*: $card\ Y \geq 3$
    using *fin-long-chain-def long-ch-Y points-in-chain*
   by (*metis* (*no-types*, *lifting*) *One-nat-def antisym card2-either-elt1-or-elt2 diff-is-0-eq'*
     not-less-eq-eq numeral-2-eq-2 numeral-3-eq-3)

We consider all indices of chain elements between a_1 and b, and find the maximal one.

  let $?S = \{k::nat.\ [[a_1\ (f\ k)\ b]] \wedge k < card\ Y\}$
  obtain S **where** *S-def*: $S=?S$
    by *simp*
  have $S \subseteq \{0..card\ Y\}$
    using *S-def* **by** *auto*
  hence *finite S*
    using *finite-subset* **by** *blast*

  show *?thesis*
  proof (*cases*)

assume $S=\{\}$
show *?thesis*
proof
show $(0::nat)<1 \wedge [[a_1\ b\ (f\ 1)]] \wedge 1 < card\ Y \wedge \neg (\exists k'::nat.\ k' < 1 \wedge [[a_1$
$b\ (f\ k')]])$
proof (*rule conjI4*)
show $(0::nat)<1$ **by** *simp*
show $1 < card\ Y$
using *Yb abc-ac-neq bound-indices not-le* **by** *fastforce*

show $\neg (\exists k'::nat.\ k' < 1 \wedge [[a_1\ b\ (f\ k')]])$
using *abc-abc-neq bound-indices*
by *blast*
show $[[a_1\ b\ (f\ 1)]]$
proof −
have $f\ 1 \in Y$
by (*metis ordering-def diff-0-eq-0 fin-long-chain-def less-one long-ch-Y*
long-ch-by-ord-def nat-neq-iff)

hence $[[a_1\ (f\ 1)\ a_n]]$
using *bound-indices long-ch-Y*
unfolding *fin-long-chain-def long-ch-by-ord-def ordering-def*
by (*smt One-nat-def card.remove card-Diff1-less card-Diff-singleton*
diff-is-0-eq′
le-eq-less-or-eq less-SucE neq0-conv zero-less-diff zero-less-one)
hence $[[a_1\ b\ (f\ 1)]] \vee [[a_1\ (f\ 1)\ b]] \vee [[b\ a_1\ (f\ 1)]]$
using *abc-ex-path-unique some-betw abc-sym*
by (*smt Y-def Yb* ‹$f\ 1 \in Y$› *abc-abc-neq cross-once-notin*)
thus $[[a_1\ b\ (f\ 1)]]$

proof −
have $\forall n.\ \neg ([[a_1\ (f\ n)\ b]] \wedge n < card\ Y)$
using *S-def* ‹$S = \{\}$›
by *blast*
then have $[[a_1\ b\ (f\ 1)]] \vee \neg [[a_n\ (f\ 1)\ b]] \wedge \neg [[a_1\ (f\ 1)\ b]]$
using *bound-indices abc-sym abd-bcd-abc Yb*
by (*metis* (*no-types*) *diff-is-0-eq′ nat-le-linear nat-less-le*)
then show *?thesis*
using *abc-bcd-abd abc-sym*
by (*meson* ‹$[[a_1\ b\ (f\ 1)]] \vee [[a_1\ (f\ 1)\ b]] \vee [[b\ a_1\ (f\ 1)]]$› ‹$[[a_1\ (f\ 1)\ a_n]]$›)
qed
qed
qed
qed
next assume $\neg S=\{\}$
obtain k **where** $k = Max\ S$
by *simp*
hence $k \in S$ **using** *Max-in*
by (*simp add:* ‹$S \neq \{\}$› ‹*finite S*›)

```
have k≥1
proof (rule ccontr)
  assume ¬ 1 ≤ k
  hence k=0 by simp
  have [[a₁ (f k) b]]
    using ‹k∈S› S-def
    by blast
  thus False
    using bound-indices ‹k = 0› abc-abc-neq
    by blast
qed

show ?thesis
proof
  let ?k = k+1
  show 0<?k ∧ [[a₁ b (f ?k)]] ∧ ?k < card Y ∧ ¬ (∃k'::nat. k' < ?k ∧ [[a₁ b
(f k')]])
  proof (rule conjI4)
    show (0::nat)<?k by simp
    show ?k < card Y
     by (metis (no-types, lifting) S-def Yb ‹k ∈ S› abc-only-cba(2) add.commute
      add-diff-cancel-right' bound-indices less-SucE mem-Collect-eq nat-add-left-cancel-less
          plus-1-eq-Suc)
    show [[a₁ b (f ?k)]]
    proof -
      have f ?k ∈ Y
        using ‹k + 1 < card Y›
        by (metis ordering-def fin-long-chain-def long-ch-Y long-ch-by-ord-def)
      have [[a₁ (f ?k) aₙ]] ∨ f ?k = aₙ
        using bound-indices long-ch-Y ‹k + 1 < card Y›
        unfolding fin-long-chain-def long-ch-by-ord-def ordering-def
     by (metis (no-types, lifting) Suc-lessI add.commute add-gr-0 card-Diff1-less
          card-Diff-singleton less-diff-conv plus-1-eq-Suc zero-less-one)
      thus  [[a₁ b (f ?k)]]
      proof (rule disjE)
        assume [[a₁ (f ?k) aₙ]]
        hence f ?k ≠ aₙ
          by (simp add: abc-abc-neq)
        hence [[a₁ b (f ?k)]] ∨ [[a₁ (f ?k) b]] ∨ [[b a₁ (f ?k)]]
          using abc-ex-path-unique some-betw abc-sym ‹[[a₁ (f ?k) aₙ]]›
            ‹f ?k ∈ Y› Yb abc-abc-neq assms(3) cross-once-notin
          by (smt Y-def)
        moreover have ¬ [[a₁ (f ?k) b]]
        proof
          assume [[a₁ (f ?k) b]]
          hence ?k ∈ S
            using S-def ‹[[a₁ (f ?k) b]]› ‹k + 1 < card Y› by blast
          hence ?k ≤ k
            by (simp add: ‹finite S› ‹k = Max S›)
```

thus *False*
by *linarith*
qed
moreover have $\neg$ $[[b\ a_1\ (f\ ?k)]]$
using *Yb* ‹$[[a_1\ (f\ ?k)\ a_n]]$› *abc-only-cba*
by *blast*
ultimately show $[[a_1\ b\ (f\ ?k)]]$
by *blast*
next assume $f\ ?k = a_n$
show *?thesis*
using *Yb* ‹$f\ (k + 1) = a_n$› **by** *blast*
qed
qed
show $\neg(\exists k'::nat.\ k' < k + 1 \wedge [[a_1\ b\ (f\ k')]])$
proof
assume $\exists k'::nat.\ k' < k + 1 \wedge [[a_1\ b\ (f\ k')]]$
then obtain k' **where** k'-*def*: $k'{>}0$ $k' < k + 1$ $[[a_1\ b\ (f\ k')]]$
using *abc-ac-neq bound-indices neq0-conv*
by *blast*
hence $k'{<}k$
using *S-def* ‹$k \in S$› *abc-only-cba*(2) *less-SucE* **by** *fastforce*
hence $k'{\in}S$
using *S-is-dense long-ch-Y S-def* ‹$\neg S=\{\}$› ‹$k = Max\ S$› ‹$k'{>}0$›
by *blast*
thus *False*
using *S-def abc-only-cba*(2) k'-*def*(3) **by** *blast*
qed
qed
qed
qed
qed

lemma *greatest-k-ex*:
assumes *long-ch-Y*: $[f[a_1..a..a_n]Y]$
and *Y-def*: $b \notin Y$
and *Yb*: $[[a_1\ b\ a_n]]$
shows $\exists k.\ [[(f\ k)\ b\ a_n]] \wedge k < card\ Y - 1 \wedge \neg(\exists k'{<}card\ Y.\ k'{>}k \wedge [[(f\ k')\ b\ a_n]])$
proof −

have *bound-indices*: $f\ 0 = a_1 \wedge f\ (card\ Y - 1) = a_n$
using *fin-long-chain-def long-ch-Y* **by** *auto*
have *fin-Y*: *finite Y*
using *fin-long-chain-def long-ch-Y* **by** *blast*
have *card-Y*: $card\ Y \geq 3$
using *fin-long-chain-def long-ch-Y points-in-chain*
by (*metis* (*no-types*, *lifting*) *One-nat-def antisym card2-either-elt1-or-elt2 diff-is-0-eq'*

```
        not-less-eq-eq numeral-2-eq-2 numeral-3-eq-3)
```

Again we consider all indices of chain elements between a_1 and b.

```
  let ?S = {k::nat. [[aₙ (f k) b]] ∧ k < card Y}
  obtain S where S-def: S=?S
    by simp
  have S⊆{0..card Y}
    using S-def by auto
  hence finite S
    using finite-subset by blast

  show ?thesis
  proof (cases)
    assume S={}
    show ?thesis
    proof
      let ?n = card Y − 2
      show [[(f ?n) b aₙ]] ∧ ?n < card Y − 1 ∧ ¬(∃ k'<card Y. k'>?n ∧ [[(f k') b
aₙ]])
      proof (rule conjI3)
        show ?n < card Y − 1
          using Yb abc-ac-neq bound-indices not-le by fastforce
      next show ¬(∃ k'<card Y. k'>?n ∧ [[(f k') b aₙ]])
          using abc-abc-neq bound-indices
            by (metis One-nat-def Suc-diff-le Suc-leD Suc-lessI card-Y diff-Suc-1
diff-Suc-Suc
              not-less-eq numeral-2-eq-2 numeral-3-eq-3)
      next show [[(f ?n) b aₙ]]
        proof −
          have f ?n ∈ Y
          by (metis ordering-def diff-less fin-long-chain-def gr-implies-not0 long-ch-Y
              long-ch-by-ord-def neq0-conv not-less-eq numeral-2-eq-2)
          hence [[a₁ (f ?n) aₙ]]
            using bound-indices long-ch-Y
            unfolding fin-long-chain-def long-ch-by-ord-def ordering-def
            using card-Y by force
          hence [[aₙ b (f ?n)]] ∨ [[aₙ (f ?n) b]] ∨ [[b aₙ (f ?n)]]
            using abc-ex-path-unique some-betw abc-sym
            by (smt Y-def Yb ‹f ?n ∈ Y› abc-abc-neq cross-once-notin)
          thus [[(f ?n) b aₙ]]
          proof −
            have ∀ n. ¬ ([[aₙ (f n) b]] ∧ n < card Y)
              using S-def ‹S = {}›
              by blast
            then have [[aₙ b (f ?n)]] ∨ ¬ [[a₁ (f ?n) b]] ∧ ¬ [[aₙ (f ?n) b]]
              using bound-indices abc-sym abd-bcd-abc Yb
             by (metis (no-types, lifting) ‹f (card Y − 2) ∈ Y› card-gt-0-iff diff-less
empty-iff fin-Y zero-less-numeral)
            then show ?thesis
```

          using *abc-bcd-abd abc-sym*
          by (*meson* ‹$[[a_n\ b\ (f\ ?n)]] \vee [[a_n\ (f\ ?n)\ b]] \vee [[b\ a_n\ (f\ ?n)]]$› ‹$[[a_1\ (f\ ?n)\ a_n]]$›)
        qed
      qed
    qed
  qed
 next assume $\neg S=\{\}$
  obtain k **where** $k = Min\ S$
   by *simp*
  hence $k \in S$ **using** *Max-in*
   by (*simp add*: ‹$S \neq \{\}$› ‹*finite S*›)

  show *?thesis*
  proof
   let $?k = k-1$
   show $[[(f\ ?k)\ b\ a_n]] \wedge ?k < card\ Y - 1 \wedge \neg (\exists k'<card\ Y.\ ?k < k' \wedge [[(f\ k')\ b\ a_n]])$
   proof (*rule conjI3*)
    show $?k < card\ Y - 1$
     using *S-def* ‹$k \in S$› *less-imp-diff-less card-Y*
      by (*metis* (*no-types*, *lifting*) *One-nat-def diff-is-0-eq′ diff-less-mono lessI less-le-trans*
       mem-Collect-eq nat-le-linear numeral-3-eq-3 zero-less-diff)
    show $[[(f\ ?k)\ b\ a_n]]$
    proof −
     have $f\ ?k \in Y$
      using ‹$k - 1 < card\ Y - 1$› *long-ch-Y long-ch-by-ord-def ordering-def*
      by (*metis diff-less fin-long-chain-def less-trans neq0-conv zero-less-one*)
     have $[[a_1\ (f\ ?k)\ a_n]] \vee f\ ?k = a_1$
      using *bound-indices long-ch-Y* ‹$k - 1 < card\ Y - 1$›
      unfolding *fin-long-chain-def long-ch-by-ord-def ordering-def*
    by (*smt S-def* ‹$k \in S$› *add-diff-inverse-nat card-Diff1-less card-Diff-singleton*
       less-numeral-extra(*4*) *less-trans mem-Collect-eq nat-add-left-cancel-less*
        neq0-conv zero-less-diff)
     thus $[[(f\ ?k)\ b\ a_n]]$
     proof (*rule disjE*)
      assume $[[a_1\ (f\ ?k)\ a_n]]$
      hence $f\ ?k \neq a_1$
       using *abc-abc-neq* **by** *blast*
      hence $[[a_n\ b\ (f\ ?k)]] \vee [[a_n\ (f\ ?k)\ b]] \vee [[b\ a_n\ (f\ ?k)]]$
       using *abc-ex-path-unique some-betw abc-sym* ‹$[[a_1\ (f\ ?k)\ a_n]]$›
        ‹$f\ ?k \in Y$› *Yb abc-abc-neq assms*(*3*) *cross-once-notin*
       by (*smt Y-def*)
      moreover have $\neg\ [[a_n\ (f\ ?k)\ b]]$
      proof
       assume $[[a_n\ (f\ ?k)\ b]]$
       hence $?k \in S$
        using *S-def* ‹$[[a_n\ (f\ ?k)\ b]]$› ‹$k - 1 < card\ Y - 1$›

by *simp*
hence $?k \geq k$
by (*simp add*: ‹*finite S*› ‹$k = Min\ S$›)
thus *False*
using ‹$f\ (k - 1) \neq a_1$› *fin-long-chain-def long-ch-Y*
by *auto*
qed
moreover have $\neg$ [[$b\ a_n\ (f\ ?k)$]]
using *Yb* ‹[[$a_1\ (f\ ?k)\ a_n$]]› *abc-only-cba*(2) *abc-bcd-acd*
by *blast*
ultimately show [[$(f\ ?k)\ b\ a_n$]]
using *abc-sym* **by** *auto*
next assume $f\ ?k = a_1$
show *?thesis*
using *Yb* ‹$f\ (k - 1) = a_1$› **by** *blast*
qed
qed
show $\neg(\exists\, k'{<}card\ Y.\ k{-}1 < k' \wedge$ [[$(f\ k')\ b\ a_n$]])
proof
assume $\exists\, k'{<}card\ Y.\ k{-}1 < k' \wedge$ [[$(f\ k')\ b\ a_n$]]
then obtain k' **where** k'-*def*: $k'{<}card\ Y\ {-}1\ k' > k - 1$ [[$a_n\ b\ (f\ k')$]]
using *abc-ac-neq bound-indices neq0-conv*
by (*metis Suc-diff-1 abc-sym gr-implies-not0 less-SucE*)
hence $k'{>}k$
using *S-def* ‹$k \in S$› *abc-only-cba*(2) *less-SucE*
by (*metis* (*no-types*, *lifting*) *add-diff-inverse-nat less-one mem-Collect-eq not-less-eq plus-1-eq-Suc*)
hence $k'{\in}S$
using *S-is-dense long-ch-Y S-def* ‹$\neg S{=}\{\}$› ‹$k = Min\ S$› ‹$k'{<}card\ Y - 1$›
by (*smt Yb* ‹$k \in S$› *abc-acd-bcd abc-only-cba*(3) *card-Diff1-less card-Diff-singleton fin-long-chain-def* k'-*def*(3) *less-le mem-Collect-eq neq0-conv order-finite-chain*)
thus *False*
using *S-def abc-only-cba*(2) k'-*def*(3)
by *blast*
qed
qed
qed
qed
qed

lemma *get-closest-chain-events*:
assumes *long-ch-Y*: [f[a_0..a..a_n] Y]
and *x-def*: $x{\notin}Y$ [[$a_0\ x\ a_n$]]
obtains $n_b\ n_c\ b\ c$
where $b{=}f\ n_b$ $c{=}f\ n_c$ [[$b\ x\ c$]] $b{\in}Y$ $c{\in}Y$ $n_b = n_c - 1$ $n_c{<}card\ Y$ $n_c{>}0$
$\neg(\exists\, k < card\ Y.$ [[$(f\ k)\ x\ a_n$]] $\wedge k{>}n_b)$ $\neg(\exists\, k{<}n_c.$ [[$a_0\ x\ (f\ k)$]])
proof –

have $\exists\ n_b\ n_c\ b\ c.\ b{=}f\ n_b \wedge c{=}f\ n_c \wedge [[b\ x\ c]] \wedge b{\in}Y \wedge c{\in}Y \wedge n_b = n_c - 1 \wedge n_c{<}card\ Y \wedge n_c{>}0$
$\wedge \neg(\exists k < card\ Y.\ [[(f\ k)\ x\ a_n]] \wedge k{>}n_b) \wedge \neg(\exists k < n_c.\ [[a_0\ x\ (f\ k)]])$
proof −
have *bound-indices*: $f\ 0 = a_0 \wedge f\ (card\ Y - 1) = a_n$
using *fin-long-chain-def long-ch-Y* **by** *auto*
have *finite* Y
using *fin-long-chain-def long-ch-Y* **by** *blast*
obtain P **where** *P-def*: $P{\in}\mathcal{P}\ \ Y{\subseteq}P$
using *chain-on-path long-ch-Y*
unfolding *fin-long-chain-def ch-by-ord-def*
by *blast*
hence $x{\in}P$
using *betw-b-in-path x-def(2) long-ch-Y points-in-chain*
by (*metis abc-abc-neq in-mono*)
obtain n_c **where** *nc-def*: $\neg(\exists k.\ [[a_0\ x\ (f\ k)]] \wedge k{<}n_c)\ [[a_0\ x\ (f\ n_c)]]\ n_c{<}card\ Y\ n_c{>}0$
using *smallest-k-ex* [**where** $a_1{=}a_0$ **and** $a{=}a$ **and** $a_n{=}a_n$ **and** $b{=}x$ **and** $f{=}f$ **and** $Y{=}Y$]
long-ch-Y x-def
by *blast*
then obtain c **where** *c-def*: $c{=}f\ n_c\ \ c{\in}Y$
using *long-ch-Y long-ch-by-ord-def fin-long-chain-def*
by (*metis ordering-def*)
have *c-goal*: $c{=}f\ n_c \wedge c{\in}Y \wedge n_c{<}card\ Y \wedge n_c{>}0 \wedge \neg(\exists k < card\ Y.\ [[a_0\ x\ (f\ k)]] \wedge k{<}n_c)$
using *c-def nc-def(1,3,4)* **by** *blast*
obtain n_b **where** *nb-def*: $\neg(\exists k < card\ Y.\ [[(f\ k)\ x\ a_n]] \wedge k{>}n_b)\ [[(f\ n_b)\ x\ a_n]]\ n_b{<}card\ Y{-}1$
using *greatest-k-ex* [**where** $a_1{=}a_0$ **and** $a{=}a$ **and** $a_n{=}a_n$ **and** $b{=}x$ **and** $f{=}f$ **and** $Y{=}Y$]
long-ch-Y x-def
by *blast*
hence $n_b{<}card\ Y$
by *linarith*
then obtain b **where** *b-def*: $b{=}f\ n_b\ \ b{\in}Y$
using *nb-def long-ch-Y long-ch-by-ord-def fin-long-chain-def ordering-def*
by *metis*
have $[[b\ x\ c]]$
proof −
have $[[b\ x\ a_n]]$
using *b-def(1) nb-def(2)* **by** *blast*
have $[[a_0\ x\ c]]$
using *c-def(1) nc-def(2)* **by** *blast*
moreover have $\forall a.\ [[a\ x\ b]] \vee \neg\ [[a\ a_n\ x]]$
using $\langle[[b\ x\ a_n]]\rangle$ *abc-bcd-acd*
by (*metis* (*full-types*) *abc-sym*)
moreover have $\forall a.\ [[a\ x\ b]] \vee \neg\ [[a_n\ a\ x]]$
using $\langle[[b\ x\ a_n]]\rangle$ **by** (*meson abc-acd-bcd abc-sym*)

moreover have $a_n = c \longrightarrow [[b\ x\ c]]$
using ‹$[[b\ x\ a_n]]$› **by** *meson*
ultimately show *?thesis*
using *abc-abd-bcdbdc abc-sym x-def(2)*
by *meson*
qed
have $n_b<n_c$
using ‹$[[b\ x\ c]]$› ‹$n_c<card\ Y$› ‹$n_b<card\ Y$› ‹$c = f\ n_c$› ‹$b = f\ n_b$›
by (*smt*
‹$\bigwedge thesis.\ (\bigwedge n_b.\ [\![\neg\ (\exists\, k<card\ Y.\ [[(f\ k)\ x\ a_n]] \wedge n_b < k);\ [[(f\ n_b)\ x\ a_n]];\ n_b < card\ Y - 1]\!]$
$\Longrightarrow thesis) \Longrightarrow thesis$› *abc-abd-acdadc abc-ac-neq abc-only-cba diff-less fin-long-chain-def le-antisym le-trans less-imp-le-nat less-numeral-extra(1) linorder-neqE-nat long-ch-Y nb-def(2) nc-def(4) order-finite-chain*)
have $n_b = n_c - 1$
proof (*rule ccontr*)
assume $n_b \neq n_c - 1$
have $n_b<n_c-1$
using ‹$n_b \neq n_c - 1$› ‹$n_b<n_c$› **by** *linarith*
hence $[[(f\ n_b)\ (f(n_c-1))\ (f\ n_c)]]$
using ‹$n_b \neq n_c - 1$› *fin-long-chain-def long-ch-Y nc-def(3) order-finite-chain*
by *auto*
have $\neg[[a_0\ x\ (f(n_c-1))]]$
using *nc-def(1,4) diff-less less-numeral-extra(1)*
by *blast*
have $n_c-1\neq 0$
using ‹$n_b < n_c$› ‹$n_b \neq n_c - 1$› **by** *linarith*
hence $f(n_c-1)\neq a_0 \wedge a_0\neq x$
using *bound-indices*
by (*metis* ‹$[[(f\ n_b)\ (f\ (n_c - 1))\ (f\ n_c)]]$› *abc-abc-neq abd-bcd-abc b-def(1,2) ch-all-betw-f*
long-ch-Y nb-def(2) nc-def(2))
have $x\neq f(n_c-1)$
using *x-def(1) nc-def(3) long-ch-Y*
unfolding *fin-long-chain-def long-ch-by-ord-def ordering-def*
by (*metis less-imp-diff-less*)
hence $[[a_0\ (f\ (n_c-1))\ x]]$
using *some-betw P-def(1,2) abc-abc-neq abc-acd-bcd abc-bcd-acd abc-sym b-def(1,2)*
c-def(1,2) ch-all-betw-f in-mono long-ch-Y nc-def(2) betw-b-in-path
by (*smt* ‹$[[(f\ n_b)\ (f\ (n_c-1))\ (f\ n_c)]]$› ‹$\neg\ [[a_0\ x\ (f\ (n_c-1))]]$› ‹$x \in P$› ‹$f(n_c-1)\neq a_0 \wedge a_0\neq x$›)
hence $[[(f(n_c-1))\ x\ a_n]]$
using *abc-acd-bcd x-def(2)* **by** *blast*
thus *False* **using** *nb-def(1)*
using ‹$n_b < n_c - 1$› *less-imp-diff-less nc-def(3)*
by *blast*
qed
have *b-goal*: $b=f\ n_b \wedge b\in Y \wedge n_b=n_c-1 \wedge \neg(\exists\, k < card\ Y.\ [[(f\ k)\ x\ a_n]] \wedge$

$k>n_b$)
      using *b-def nb-def(1) nb-def(3)* ‹$n_b=n_c-1$› **by** *blast*
    thus *?thesis*
      using ‹[[$b\ x\ c$]]› *c-goal*
      using ‹n_b < *card* Y› *nc-def(1)* **by** *auto*
  qed
  thus *?thesis*
    using *that* **by** *auto*
qed

This is case (ii) of the induction in Theorem 10.

lemma *chain-append-inside*:
  assumes *long-ch-Y*: [f[a_1..a..a_n] Y]
      and *Y-def*: $b \notin Y$
      and *Yb*: [[a_1 b a_n]]
      and *k-def*: [[a_1 b (f k)]] k < *card* Y ¬(∃ k'. (*0*::*nat*)<k' ∧ k'<k ∧ [[a_1 b (f k')]])
    fixes g
   defines *g-def*: g ≡ (λj::*nat*. *if* (j≤$k-1$) *then* f j *else* (*if* (j=k) *then* b *else* f ($j-1$)))
    shows [g[a_1 .. b .. a_n]*insert* b Y]
proof −
  let *?X* = *insert* b Y
  have *fin-X*: *finite ?X*
    by (*meson fin-long-chain-def finite.insertI long-ch-Y*)
  have *bound-indices*: f *0* = a_1 ∧ f (*card* Y − *1*) = a_n
    using *fin-long-chain-def long-ch-Y*
    by *auto*
  have *fin-Y*: *finite* Y
    using *fin-long-chain-def long-ch-Y* **by** *blast*
  have *f-def*: *long-ch-by-ord* f Y
    using *fin-long-chain-def long-ch-Y* **by** *blast*
  have ‹$a_1 \neq a_n \land a_1 \neq b \land b \neq a_n$›
    using *Yb abc-abc-neq* **by** *blast*
  have $k \neq 0$
    using *abc-abc-neq bound-indices k-def*
    by *metis*

  have *b-middle*: [[(f ($k-1$)) b (f k)]]
  proof (*cases*)
    assume k=*1* **show** [[(f ($k-1$)) b (f k)]]
      using ‹[[a_1 b (f k)]]› ‹k = *1*› *bound-indices* **by** *auto*
  next assume $k \neq 1$ **show** [[(f ($k-1$)) b (f k)]]
    proof −
      have [[a_1 (f ($k-1$)) (f k)]] **using** *bound-indices*
        using ‹k < *card* Y› ‹$k \neq 0$› ‹$k \neq 1$› *long-ch-Y fin-Y order-finite-chain*
        unfolding *fin-long-chain-def*
        by *auto*

In fact, the comprehension below gives the order of elements too. Our notation and Theorem 9 are too weak to say that just now.

have *ch-with-b*: *ch* $\{a_1, (f\ (k-1)), b, (f\ k)\}$ **using** *chain4*
using *k-def(1) abc-ex-path-unique between-chain cross-once-notin*
by (*smt* ‹$[[a_1\ (f\ (k - 1))\ (f\ k)]]$› *abc-abc-neq insert-absorb2*)

have $f\ (k-1) \neq b \wedge (f\ k) \neq (f\ (k-1)) \wedge b \neq (f\ k)$
using *abc-abc-neq f-def k-def(2) Y-def*
by (*metis ordering-def* ‹$[[a_1\ (f\ (k - 1))\ (f\ k)]]$› *less-imp-diff-less long-ch-by-ord-def*)
hence *some-ord-bk*: $[[(f\ (k-1))\ b\ (f\ k)]] \vee [[b\ (f\ (k-1))\ (f\ k)]] \vee [[(f\ (k-1))\ (f\ k)\ b]]$
using *chain-on-path ch-with-b some-betw Y-def* **unfolding** *ch-def*
by (*metis abc-sym insert-subset*)
thus $[[(f\ (k-1))\ b\ (f\ k)]]$
proof −
have $\neg\ [[a_1\ (f\ k)\ b]]$
by (*simp add*: ‹$[[a_1\ b\ (f\ k)]]$› *abc-only-cba(2)*)
thus *?thesis*
using *some-ord-bk k-def abc-bcd-acd abd-bcd-abc bound-indices*
by (*metis diff-is-0-eq′ diff-less less-imp-diff-less less-irrefl-nat not-less zero-less-diff zero-less-one* ‹$[[a_1\ b\ (f\ k)]]$› ‹$[[a_1\ (f\ (k - 1))\ (f\ k)]]$›)
qed
qed
qed

let $?case1 \vee ?case2 = k-2 \geq 0 \vee k+1 \leq card\ Y\ -1$

have *b-right*: $[[(f\ (k-2))\ (f\ (k-1))\ b]]$ **if** $k \geq 2$
proof −
have $k-1 < (k::nat)$
using ‹$k \neq 0$› *diff-less zero-less-one* **by** *blast*
hence $k-2 < k-1$
using ‹$2 \leq k$› **by** *linarith*
have $[[(f\ (k-2))\ (f\ (k-1))\ (f\ k)]]$
using *f-def k-def(2)* ‹$k-2 < k-1$› ‹$k-1 < k$› **unfolding** *long-ch-by-ord-def ordering-def*
by *blast*
thus $[[(f\ (k-2))\ (f\ (k-1))\ b]]$
using ‹$[[(f\ (k - 1))\ b\ (f\ k)]]$› *abd-bcd-abc*
by *blast*
qed

have *b-left*: $[[b\ (f\ k)\ (f\ (k+1))]]$ **if** $k+1 \leq card\ Y\ -1$
proof −
have $[[(f\ (k-1))\ (f\ k)\ (f\ (k+1))]]$
using ‹$k \neq 0$› *f-def fin-Y order-finite-chain that*
by *auto*
thus $[[b\ (f\ k)\ (f\ (k+1))]]$
using ‹$[[(f\ (k - 1))\ b\ (f\ k)]]$› *abc-acd-bcd*

by *blast*
qed

have *ordering2 g betw ?X*
proof −
have ∀ *n*. (*finite ?X* ⟶ *n* < *card ?X*) ⟶ *g n* ∈ *?X*
proof (*clarify*)
fix *n* **assume** *finite ?X* ⟶ *n* < *card ?X g n* ∉ *Y*
consider *n*≤*k*−*1* | *n*≥*k*+*1* | *n*=*k*
by *linarith*
thus *g n* = *b*
proof (*cases*)
assume *n* ≤ *k* − *1*
thus *g n* = *b*
using *f-def k-def*(*2*) *Y-def*(*1*) *long-ch-by-ord-def ordering-def g-def*
by (*metis* ‹*g n* ∉ *Y*› ‹*k* ≠ *0*› *diff-less le-less less-one less-trans not-le*)
next
assume *k* + *1* ≤ *n*
show *g n* = *b*
proof −

have *f n* ∈ *Y* ∨ ¬(*n* < *card Y*) **for** *n*
by (*metis ordering-def f-def long-ch-by-ord-def*)
then show *g n* = *b*
using ‹*finite ?X* ⟶ *n* < *card ?X*› *fin-Y g-def Y-def* ‹*g n* ∉ *Y*› ‹*k* + *1*
≤ *n*›
not-less not-less-simps(*1*) *not-one-le-zero*
by *fastforce*
qed
next
assume *n*=*k*
thus *g n* = *b*
using *Y-def* ‹*k* ≠ *0*› *g-def*
by *auto*
qed
qed
moreover have ∀ *x*∈*?X*. ∃ *n*. (*finite ?X* ⟶ *n* < *card ?X*) ∧ *g n* = *x*
proof
fix *x* **assume** *x*∈*?X*
show ∃ *n*. (*finite ?X* ⟶ *n* < *card ?X*) ∧ *g n* = *x*
proof (*cases*)
assume *x*∈*Y*
show *?thesis*
proof −
obtain *ix* **where** *f ix* = *x ix* < *card Y*
using ‹*x* ∈ *Y*› *f-def fin-Y*
unfolding *long-ch-by-ord-def ordering-def*
by *auto*
have *ix*≤*k*−*1* ∨ *ix*≥*k*

```
          by linarith
        thus ?thesis
        proof
          assume ix≤k−1
          hence g ix = x
            using ‹f ix = x› g-def by auto
          moreover have finite ?X ⟶ ix < card ?X
            using Y-def ‹ix < card Y› by auto
          ultimately show ?thesis by metis
        next assume ix≥k
          hence g (ix+1) = x
            using ‹f ix = x› g-def by auto
          moreover have finite ?X ⟶ ix+1 < card ?X
            using Y-def ‹ix < card Y› by auto
          ultimately show ?thesis by metis
        qed
      qed
    next assume x∉Y
      hence x=b
        using Y-def ‹x ∈ ?X› by blast
      thus ?thesis
     using Y-def ‹k ≠ 0› k-def(2) ordered-cancel-comm-monoid-diff-class.le-diff-conv2
g-def
        by auto
    qed
  qed
  moreover have ∀ n n′ n″. (finite ?X ⟶ n″ < card ?X) ∧ Suc n = n′ ∧ Suc
n′ = n″
        ⟶ [[(g n) (g (Suc n)) (g (Suc (Suc n)))]]
  proof (clarify)
    fix n n′ n″ assume  a: (finite ?X ⟶ (Suc (Suc n)) < card ?X)
```

Introduce the two-case splits used later.

```
    have  cases-sn: Suc n≤k−1 ∨ Suc n=k if n≤k−1
      using ‹k ≠ 0› that by linarith
    have cases-ssn: Suc(Suc n)≤k−1 ∨ Suc(Suc n)=k if n≤k−1 Suc n≤k−1
      using that(2) by linarith

    consider n≤k−1 | n≥k+1 | n=k
      by linarith
    then show [[(g n) (g (Suc n)) (g (Suc (Suc n)))]]
    proof (cases)
      assume n≤k−1 show ?thesis
        using cases-sn
      proof (rule disjE)
        assume Suc n ≤ k − 1
        show ?thesis using cases-ssn
        proof (rule disjE)
          show  n ≤ k − 1 using ‹n ≤ k − 1› by blast
```

```
          show ‹Suc n ≤ k − 1› using ‹Suc n ≤ k − 1› by blast
        next
          assume Suc (Suc n) ≤ k − 1
          thus ?thesis
           using ‹Suc n ≤ k − 1› ‹k ≠ 0› ‹n ≤ k − 1› ordering-ord-ijk f-def g-def
k-def(2)
            by (metis (no-types, lifting) add-diff-inverse-nat lessI less-Suc-eq-le
              less-imp-le-nat less-le-trans less-one long-ch-by-ord-def plus-1-eq-Suc)
        next
          assume Suc (Suc n) = k
          thus ?thesis
            using b-right g-def by force
        qed
      next
        assume Suc n = k
        show ?thesis
          using b-middle ‹Suc n = k› ‹n ≤ k − 1› g-def
          by auto
      next show n ≤ k−1 using ‹n ≤ k − 1› by blast
      qed
    next assume n≥k+1 show ?thesis
      proof −
        have g n = f (n−1)
          using ‹k + 1 ≤ n› less-imp-diff-less g-def
          by auto
        moreover have g (Suc n) = f (n)
          using ‹k + 1 ≤ n› g-def by auto
        moreover have g (Suc (Suc n)) = f (Suc n)
          using ‹k + 1 ≤ n› g-def by auto
        moreover have n−1<n ∧ n<Suc n
          using ‹k + 1 ≤ n› by auto
        moreover have finite Y ⟶ Suc n < card Y
          using Y-def a by auto
        ultimately show ?thesis
          using f-def unfolding long-ch-by-ord-def ordering-def
          by auto
      qed
    next assume n=k
      show ?thesis
        using ‹k ≠ 0› ‹n = k› b-left g-def Y-def(1) a assms(3) fin-Y
        by auto
    qed
  qed
  ultimately show ordering2 g betw ?X
    unfolding ordering2-def
    by presburger
 qed
 hence long-ch-by-ord2 g ?X
  using Y-def f-def long-ch-by-ord2-def long-ch-by-ord-def
```

by *auto*
thus $[g[a_1..b..a_n]\,?X]$
unfolding *fin-long-chain-def*
using *ch-equiv fin-X* ‹$a_1 \neq a_n \wedge a_1 \neq b \wedge b \neq a_n$› *bound-indices k-def*(*2*) *Y-def g-def*
by *simp*
qed

lemma *card4-eq*:
assumes *card X* = *4*
shows $\exists\, a\ b\ c\ d.\ a \neq b \wedge a \neq c \wedge a \neq d \wedge b \neq c \wedge b \neq d \wedge c \neq d \wedge X = \{a, b, c, d\}$
proof −
obtain $a\ X'$ **where** X = *insert* $a\ X'$ **and** $a \notin X'$
by (*metis Suc-eq-numeral assms card-Suc-eq*)
then have *card* X' = *3*
by (*metis add-2-eq-Suc′ assms card-eq-0-iff card-insert-if diff-Suc-1 finite-insert numeral-3-eq-3 numeral-Bit0 plus-nat.add-0 zero-neq-numeral*)
then obtain $b\ X''$ **where** X' = *insert* $b\ X''$ **and** $b \notin X''$
by (*metis card-Suc-eq numeral-3-eq-3*)
then have *card* X'' = *2*
by (*metis Suc-eq-numeral* ‹*card* X' = *3*› *card.infinite card-insert-if finite-insert pred-numeral-simps*(*3*) *zero-neq-numeral*)
then have $\exists\, c\ d.\ c \neq d \wedge X'' = \{c, d\}$
by (*meson card-2-iff*)
thus *?thesis*
using ‹X = *insert* $a\ X'$› ‹X' = *insert* $b\ X''$› ‹$a \notin X'$› ‹$b \notin X''$› **by** *blast*
qed

theorem *path-finsubset-chain*:
assumes $Q \in \mathcal{P}$
and $X \subseteq Q$
and *card* $X \geq$ *2*
shows *ch X*
proof −
have *finite X*
using *assms*(*3*) *not-numeral-le-zero* **by** *fastforce*
consider *card X* = *2* | *card X* = *3* | *card* $X \geq$ *4*
using ‹*card* $X \geq$ *2*› **by** *linarith*
thus *?thesis*
proof (*cases*)
assume *card X* = *2*
thus *?thesis*
using ‹*finite X*› *assms two-event-chain* **by** *blast*
next
assume *card X* = *3*
thus *?thesis*

using ‹*finite X*› *assms three-event-chain* **by** *blast*
next
assume *card* $X \geq 4$
thus *?thesis*
using *assms*(*1*,*2*) ‹*finite X*›
proof (*induct card* $X - 4$ *arbitrary*: *X*)
case *0*
then have *card* $X = 4$
by *auto*
then have $\exists\, a\ b\ c\ d.\ a \neq b \wedge a \neq c \wedge a \neq d \wedge b \neq c \wedge b \neq d \wedge c \neq d \wedge X = \{a,\ b,\ c,\ d\}$
using *card4-eq* **by** *fastforce*
thus *?case*
using *0.prems*(*3*) *assms*(*1*) *chain4* **by** *auto*
next
case *IH*: (*Suc n*)

then obtain *Y b* **where** *X-eq*: $X =$ *insert b Y* **and** $b \notin Y$
by (*metis Diff-iff card-eq-0-iff finite.cases insertI1 insert-Diff-single not-numeral-le-zero*)
have *card* $Y \geq 4$ $n =$ *card* $Y - 4$
using *IH.hyps*(*2*) *IH.prems*(*4*) *X-eq* ‹$b \notin Y$› **by** *auto*
then have *ch Y*
using *IH*(*1*) [*of Y*] *IH.prems*(*3*,*4*) *X-eq assms*(*1*) **by** *auto*

then obtain *f* **where** *f-ords*: *long-ch-by-ord f Y*
using *ch-long-if-card-ge3* ‹$4 \leq$ *card Y*› **by** *fastforce*
then obtain a_1 *a* a_n **where** *long-ch-Y*: $[f[a_1..a..a_n]Y]$
using ‹$4 \leq$ *card Y*› *get-fin-long-ch-bounds* **by** *fastforce*
hence *bound-indices*: $f\ 0 = a_1 \wedge f\ (card\ Y - 1) = a_n$
by (*simp add*: *fin-long-chain-def*)
have $a_1 \neq a_n \wedge a_1 \neq b \wedge b \neq a_n$
using ‹$b \notin Y$› *abc-abc-neq fin-ch-betw long-ch-Y points-in-chain* **by** *blast*
moreover have $a_1 \in Q \wedge a_n \in Q \wedge b \in Q$
using *IH.prems*(*3*) *X-eq long-ch-Y points-in-chain* **by** *auto*
ultimately consider $[[b\ a_1\ a_n]] \mid [[a_1\ a_n\ b]] \mid [[a_n\ b\ a_1]]$
using *some-betw* [*of Q b* a_1 a_n] ‹$Q \in \mathcal{P}$› **by** *blast*
thus *ch X*
proof (*cases*)

assume $[[b\ a_1\ a_n]]$
have *X-eq'*: $X = Y \cup \{b\}$
using *X-eq* **by** *auto*
let $?g = \lambda j.\ if\ j \geq 1\ then\ f\ (j - 1)\ else\ b$
have $[?g[b..a_1..a_n]X]$
using *chain-append-at-left-edge IH.prems*(*4*) *X-eq'* ‹$[[b\ a_1\ a_n]]$› ‹$b \notin Y$› *long-ch-Y X-eq*
by *presburger*
thus *ch X*
using *ch-by-ord-def ch-def fin-long-chain-def* **by** *auto*

next

assume $[[a_1\ a_n\ b]]$
let *?g* $= \lambda j.$ *if* $j \leq$ (*card* $X - 2$) *then* $f\ j$ *else* b
have $[?g[a_1..a_n..b]X]$
using *chain-append-at-right-edge IH.prems*(*4*) *X-eq* ‹$[[a_1\ a_n\ b]]$› ‹$b \notin Y$› *long-ch-Y*
by *auto*
thus *ch X*
unfolding *ch-def ch-by-ord-def* **using** *fin-long-chain-def* **by** *auto*
next

assume $[[a_n\ b\ a_1]]$
then have $[[a_1\ b\ a_n]]$
by (*simp add*: *abc-sym*)
obtain k **where**
k-def: $[[a_1\ b\ (f\ k)]]$ $k <$ *card* Y $\neg (\exists k'.\ 0 < k' \wedge k' < k \wedge [[a_1\ b\ (f\ k')]])$
using ‹$[[a_1\ b\ a_n]]$› ‹$b \notin Y$› *long-ch-Y smallest-k-ex* **by** *blast*
obtain g **where** $g = (\lambda j{::}nat.$ *if* $j \leq k - 1$
then $f\ j$
else if $j = k$
then b *else* $f\ (j - 1))$
by *simp*
hence $[g[a_1..b..a_n]X]$
using *chain-append-inside* [*of* $f\ a_1\ a\ a_n\ Y\ b\ k$] *IH.prems*(*4*) *X-eq*
‹$[[a_1\ b\ a_n]]$› ‹$b \notin Y$› *k-def long-ch-Y*
by *auto*
thus *ch X*
using *ch-by-ord-def ch-def fin-long-chain-def* **by** *auto*
qed
qed
qed
qed

lemma *path-finsubset-chain2*:
assumes $Q \in \mathcal{P}$ **and** $X \subseteq Q$ **and** *card* $X \geq 2$
obtains $f\ a\ b$ **where** $[f[a..b]X]$
proof −
have *finX*: *finite X*
by (*metis assms*(*3*) *card.infinite rel-simps*(*28*))
have *ch-X*: *ch X*
using *path-finsubset-chain*[*OF assms*] **by** *blast*
obtain $f\ a\ b$ **where** *f-def*: $[f[a..b]X]$ $a{\in}X \wedge b{\in}X$
using *assms finX ch-X ch-some-betw get-fin-long-ch-bounds ch-long-if-card-ge3*
by (*metis ch-by-ord-def ch-def fin-chain-def short-ch-def*)
thus *?thesis*
using *that* **by** *auto*
qed

32.2 Theorem 11

Notice this case is so simple, it doesn't even require the path density larger sets of segments rely on for fixing their cardinality.

lemma *segmentation-ex-N2*:
  assumes *path-P*: $P \in \mathcal{P}$
    and *Q-def*: $\mathit{finite}\ (Q::'a\ set)\ \mathit{card}\ Q = N\ Q \subseteq P\ N=2$
    and *f-def*: $[f[a..b]Q]$
    and *S-def*: $S = \{\mathit{segment}\ a\ b\}$
    and *P1-def*: $P1 = \mathit{prolongation}\ b\ a$
    and *P2-def*: $P2 = \mathit{prolongation}\ a\ b$
  shows $P = ((\bigcup S) \cup P1 \cup P2 \cup Q) \wedge$
      $\mathit{card}\ S = (N-1) \wedge (\forall x \in S.\ \mathit{is\text{-}segment}\ x) \wedge$
        $P1 \cap P2=\{\} \wedge (\forall x \in S.\ (x \cap P1=\{\} \wedge x \cap P2=\{\} \wedge (\forall y \in S.\ x \neq y \longrightarrow$
$x \cap y=\{\})))$
proof –
  have $a \in Q \wedge b \in Q \wedge a \neq b$
    by (*metis f-def fin-chain-def fin-long-chain-def points-in-chain*)
  hence $Q=\{a,b\}$
    using *assms*(*3*,*5*)
   by (*smt card-2-iff insert-absorb insert-commute insert-iff singleton-insert-inj-eq*)
  have $a \in P \wedge b \in P$
    using ‹$Q=\{a,b\}$› *assms*(*4*) **by** *auto*
  have $a \neq b$ **using** ‹$Q=\{a,b\}$›
    using ‹$N = 2$› *assms*(*3*) **by** *force*
  obtain *s* **where** *s-def*: $s = \mathit{segment}\ a\ b$ **by** *simp*
  let $?S = \{s\}$
  have $P = ((\bigcup \{s\}) \cup P1 \cup P2 \cup Q) \wedge$
      $\mathit{card}\ \{s\} = (N-1) \wedge (\forall x \in \{s\}.\ \mathit{is\text{-}segment}\ x) \wedge$
        $P1 \cap P2=\{\} \wedge (\forall x \in \{s\}.\ (x \cap P1=\{\} \wedge x \cap P2=\{\} \wedge (\forall y \in \{s\}.\ x \neq y \longrightarrow$
$x \cap y=\{\})))$
  proof (*rule conjI*)
    { fix *x* **assume** $x \in P$
      have $[[a\ x\ b]] \vee [[b\ a\ x]] \vee [[a\ b\ x]] \vee x=a \vee x=b$
        using ‹$a \in P \wedge b \in P$› *some-betw path-P* ‹$a \neq b$›
        by (*meson* ‹$x \in P$› *abc-sym*)
      then have $x \in s \vee x \in P1 \vee x \in P2 \vee x=a \vee x=b$
        using *pro-betw seg-betw P1-def P2-def s-def* ‹$Q = \{a, b\}$›
        by *auto*
      hence $x \in (\bigcup \{s\}) \cup P1 \cup P2 \cup Q$
        using ‹$Q = \{a, b\}$› **by** *auto*
    } moreover {
      fix *x* **assume** $x \in (\bigcup \{s\}) \cup P1 \cup P2 \cup Q$
      hence $x \in s \vee x \in P1 \vee x \in P2 \vee x=a \vee x=b$
        using ‹$Q = \{a, b\}$› **by** *blast*
      hence $[[a\ x\ b]] \vee [[b\ a\ x]] \vee [[a\ b\ x]] \vee x=a \vee x=b$
        using *s-def P1-def P2-def*
        unfolding *segment-def prolongation-def*
        by *auto*

hence $x{\in}P$
  using ‹$a \in P \wedge b \in P$› ‹$a \neq b$› *betw-b-in-path betw-c-in-path path-P*
  by *blast*
}
ultimately show *union-P*: $P = ((\bigcup\{s\}) \cup P1 \cup P2 \cup Q)$
  by *blast*
show *card* $\{s\} = (N{-}1) \wedge (\forall x{\in}\{s\}.\ \textit{is-segment } x) \wedge P1{\cap}P2{=}\{\} \wedge$
   $(\forall x{\in}\{s\}.\ (x{\cap}P1{=}\{\} \wedge x{\cap}P2{=}\{\} \wedge (\forall y{\in}\{s\}.\ x{\neq}y \longrightarrow x{\cap}y{=}\{\})))$
proof (*safe*)
  show *card* $\{s\} = N - 1$
    using ‹$Q = \{a, b\}$› ‹$a \neq b$› *assms*(*3*) **by** *auto*
  show *is-segment s*
    using *s-def* **by** *blast*
  show $\bigwedge x.\ x \in P1 \Longrightarrow x \in P2 \Longrightarrow x \in \{\}$
  proof −
    fix x **assume** $x{\in}P1$ $x{\in}P2$
    show $x{\in}\{\}$
      using *P1-def P2-def* ‹$x \in P1$› ‹$x \in P2$› *abc-only-cba pro-betw*
      by *metis*
  qed
  show $\bigwedge x\ xa.\ xa \in s \Longrightarrow xa \in P1 \Longrightarrow xa \in \{\}$
  proof −
    fix x xa **assume** $xa{\in}s$ $xa{\in}P1$
    show $xa{\in}\{\}$
      using *abc-only-cba seg-betw pro-betw P1-def* ‹$xa \in P1$› ‹$xa \in s$› *s-def*
      by (*metis*)
  qed
  show $\bigwedge x\ xa.\ xa \in s \Longrightarrow xa \in P2 \Longrightarrow xa \in \{\}$
  proof −
    fix x xa **assume** $xa{\in}s$ $xa{\in}P2$
    show $xa{\in}\{\}$
      using *abc-only-cba seg-betw pro-betw*
      by (*metis P2-def* ‹$xa \in P2$› ‹$xa \in s$› *s-def*)
  qed
qed
qed
thus *?thesis*
  by (*simp add*: *S-def s-def*)
qed

lemma *int-split-to-segs*:
  assumes *f-def*: $[f[a..b..c]Q]$
  fixes S **defines** *S-def*: $S \equiv \{\textit{segment } (f\ i)\ (f(i{+}1)) \mid i.\ i{<}\textit{card } Q{-}1\}$
  shows *interval a c* $= (\bigcup S) \cup Q$
proof
  let $?N = \textit{card } Q$
  have *f-def-2*: $a{\in}Q \wedge b{\in}Q \wedge c{\in}Q$

using *f-def points-in-chain* **by** *blast*
hence $?N \geq 3$
by (*meson ch-by-ord-def f-def fin-long-chain-def long-ch-card-ge3*)
have *bound-indices*: $f\ 0 = a \wedge f\ (card\ Q - 1) = c$
using *f-def fin-long-chain-def* **by** *auto*
let $?i = ?u = interval\ a\ c = (\bigcup S) \cup Q$
show $?i \subseteq ?u$
proof
fix p **assume** $p \in ?i$
show $p \in ?u$
proof (*cases*)
assume $p \in Q$ **thus** *?thesis* **by** *blast*
next assume $p \notin Q$
hence $p \neq a \wedge p \neq c$
using *f-def f-def-2* **by** *blast*
hence $[[a\ p\ c]]$
using *seg-betw* ‹$p \in interval\ a\ c$› *interval-def*
by *auto*
then obtain $n_y\ n_z\ y\ z$
where *yz-def*: $y = f\ n_y$ $z = f\ n_z$ $[[y\ p\ z]]$ $y \in Q$ $z \in Q$ $n_y = n_z - 1$ $n_z < card\ Q$
$\neg(\exists k < card\ Q.\ [[(f\ k)\ p\ c]] \wedge k > n_y)$ $\neg(\exists k < n_z.\ [[a\ p\ (f\ k)]])$
using *get-closest-chain-events* [**where** $f = f$ **and** $x = p$ **and** $Y = Q$ **and** $a_n = c$ **and** $a_0 = a$ **and** $a = b$]
f-def ‹$p \notin Q$›
by *metis*
have $n_y < card\ Q - 1$
using *yz-def*(*6*,*7*) *f-def index-middle-element*
by *fastforce*
let $?s = segment\ (f\ n_y)\ (f\ n_z)$
have $p \in ?s$
using ‹$[[y\ p\ z]]$› *abc-abc-neq seg-betw yz-def*(*1*,*2*)
by *blast*
have $n_z = n_y + 1$
using *yz-def*(*6*)
by (*metis abc-abc-neq add.commute add-diff-inverse-nat less-one yz-def*(*1*,*2*,*3*) *zero-diff*)
hence $?s \in S$
using *S-def* ‹$n_y < card\ Q - 1$› *assms*(*2*)
by *blast*
hence $p \in \bigcup S$
using ‹$p \in ?s$› **by** *blast*
thus *?thesis* **by** *blast*
qed
qed
show $?u \subseteq ?i$
proof
fix p **assume** $p \in ?u$
hence $p \in \bigcup S \vee p \in Q$ **by** *blast*
thus $p \in ?i$

proof
  assume $p \in Q$
  then consider $p=a|p=c|[[a\ p\ c]]$
    using *ch-all-betw-f f-def* **by** *blast*
  thus *?thesis*
  proof (*cases*)
    assume $p=a$
    thus *?thesis* **by** (*simp add*: *interval-def*)
  next assume $p=c$
    thus *?thesis* **by** (*simp add*: *interval-def*)
  next assume $[[a\ p\ c]]$
    thus *?thesis* **using** *interval-def seg-betw* **by** *auto*
  qed
next assume $p \in \bigcup S$
  then obtain s **where** $p \in s$ $s \in S$
    by *blast*
  then obtain y **where** $s = segment\ (f\ y)\ (f\ (y+1))$ $y < ?N-1$
    using *S-def* **by** *blast*
  hence $y+1 < ?N$ **by** (*simp add*: *assms*(*2*))
  hence *fy-in-Q*: $(f\ y) \in Q \wedge f\ (y+1) \in Q$
    using *f-def* **unfolding** *fin-long-chain-def long-ch-by-ord-def ordering-def*
    by (*meson add-lessD1*)
  have $[[a\ (f\ y)\ c]] \vee y=0$
    using ‹$y < ?N - 1$› *assms*(*2*) *f-def fin-long-chain-def order-finite-chain* **by**
auto
  moreover have $[[a\ (f\ (y+1))\ c]] \vee y = ?N-2$
    using ‹$y + 1 < card\ Q$› *assms*(*2*) *f-def fin-long-chain-def order-finite-chain*
  by (*smt One-nat-def Suc-diff-1 Suc-eq-plus1 diff-Suc-eq-diff-pred gr-implies-not0*
      lessI less-Suc-eq-le linorder-neqE-nat not-le numeral-2-eq-2)
  ultimately consider $y=0|y=?N-2|([[a\ (f\ y)\ c]] \wedge [[a\ (f\ (y+1))\ c]])$
    by *linarith*
  hence $[[a\ p\ c]]$
  proof (*cases*)
    assume $y=0$
    hence $f\ y = a$
      by (*simp add*: *bound-indices*)
    hence $[[a\ p\ (f(y+1))]]$
      using ‹$p \in s$› ‹$s = segment\ (f\ y)\ (f\ (y + 1))$› *seg-betw*
      by *auto*
    moreover have $[[a\ (f(y+1))\ c]]$
      using ‹$[[a\ (f(y+1))\ c]] \vee y = ?N - 2$› ‹$y = 0$› ‹$?N \geq 3$›
      by *linarith*
    ultimately show $[[a\ p\ c]]$
      using *abc-acd-abd* **by** *blast*
  next
    assume $y=?N-2$
    hence $f\ (y+1) = c$
      using *bound-indices* ‹$?N \geq 3$› *numeral-2-eq-2 numeral-3-eq-3*
        by (*metis One-nat-def Suc-diff-le add.commute add-leD2 diff-Suc-Suc*

plus-1-eq-Suc)
hence $[[(f\ y)\ p\ c]]$
using $\langle p \in s\rangle$ $\langle s = segment\ (f\ y)\ (f\ (y + 1))\rangle$ *seg-betw*
by *auto*
moreover have $[[a\ (f\ y)\ c]]$
using $\langle[[a\ (f\ y)\ c]] \vee y = 0\rangle$ $\langle y = ?N - 2\rangle$ $\langle ?N\geq 3\rangle$
by *linarith*
ultimately show $[[a\ p\ c]]$
by (*meson abc-acd-abd abc-sym*)
next
assume $[[a\ (f\ y)\ c]] \wedge [[a\ (f(y+1))\ c]]$
thus $[[a\ p\ c]]$
using *abe-ade-bcd-ace* [**where** $a=a$ **and** $b=f\ y$ **and** $d=f\ (y+1)$ **and** $e=c$ **and** $c=p$]
using $\langle p \in s\rangle$ $\langle s = segment\ (f\ y)\ (f(y+1))\rangle$ *seg-betw*
by *auto*
qed
thus *?thesis*
using *interval-def seg-betw* **by** *auto*
qed
qed
qed

lemma *path-is-union*:
assumes *path-P*: $P\in\mathcal{P}$
and *Q-def*: *finite* $(Q::'a\ set)$ $card\ Q = N$ $Q\subseteq P$ $N\geq 3$
and *f-def*: $a\in Q \wedge b\in Q \wedge c\in Q$ $[f[a..b..c]Q]$
and *S-def*: $S = \{s.\ \exists i<(N-1).\ s = segment\ (f\ i)\ (f\ (i+1))\}$
and *P1-def*: $P1 = prolongation\ b\ a$
and *P2-def*: $P2 = prolongation\ b\ c$
shows $P = ((\bigcup S) \cup P1 \cup P2 \cup Q)$
proof −

have *in-P*: $a\in P \wedge b\in P \wedge c\in P$
using *assms*(4) *f-def* **by** *blast*
have *bound-indices*: $f\ 0 = a \wedge f\ (card\ Q - 1) = c$
using *f-def fin-long-chain-def* **by** *auto*
have *points-neq*: $a\neq b \wedge b\neq c \wedge a\neq c$
using *f-def fin-long-chain-def* **by** *auto*

The proof in two parts: subset inclusion one way, then the other.

{ fix x **assume** $x\in P$
have $[[a\ x\ c]] \vee [[b\ a\ x]] \vee [[b\ c\ x]] \vee x=a \vee x=c$
using *in-P some-betw path-P points-neq* $\langle x \in P\rangle$ *abc-sym*
by (*metis* (*full-types*) *abc-acd-bcd ch-all-betw-f f-def*)
then have $(\exists s\in S.\ x\in s) \vee x\in P1 \vee x\in P2 \vee x\in Q$
proof (*cases*)
assume $[[a\ x\ c]]$

hence *only-axc*: $\neg([[b\ a\ x]] \vee [[b\ c\ x]] \vee x{=}a \vee x{=}c)$
using *abc-only-cba*
by (*meson abc-bcd-abd abc-sym f-def fin-ch-betw*)
have $x \in$ *interval a c*
using ‹[[*a x c*]]› *interval-def seg-betw* **by** *auto*
hence $x{\in}Q \vee x{\in}\bigcup S$
using *int-split-to-segs S-def assms*(*2*,*3*,*5*) *f-def*
by *blast*
thus *?thesis* **by** *blast*
next assume $\neg[[a\ x\ c]]$
hence $[[b\ a\ x]] \vee [[b\ c\ x]] \vee x{=}a \vee x{=}c$
using ‹$[[a\ x\ c]] \vee [[b\ a\ x]] \vee [[b\ c\ x]] \vee x = a \vee x = c$› **by** *blast*
hence $x{\in}P1 \vee x{\in}P2 \vee x{\in}Q$
using *P1-def P2-def f-def pro-betw* **by** *auto*
thus *?thesis* **by** *blast*
qed
hence $x \in (\bigcup S) \cup P1 \cup P2 \cup Q$ **by** *blast*
} moreover {
fix *x* **assume** $x \in (\bigcup S) \cup P1 \cup P2 \cup Q$
hence $(\exists\, s{\in}S.\ x{\in}s) \vee x{\in}P1 \vee x{\in}P2 \vee x{\in}Q$
by *blast*
hence $x{\in}\bigcup S \vee [[b\ a\ x]] \vee [[b\ c\ x]] \vee x{\in}Q$
using *S-def P1-def P2-def*
unfolding *segment-def prolongation-def*
by *auto*
hence $x{\in}P$
proof (*cases*)
assume $x{\in}\bigcup S$
have $S = \{segment\ (f\ i)\ (f(i{+}1)) \mid i.\ i{<}N{-}1\}$
using *S-def* **by** *blast*
hence $x{\in}$*interval a c*
using *int-split-to-segs* [*OF f-def*(*2*)] *assms* ‹$x{\in}\bigcup S$›
by (*simp add*: *UnCI*)
hence $[[a\ x\ c]] \vee x{=}a \vee x{=}c$
using *interval-def seg-betw* **by** *auto*
thus *?thesis*
proof (*rule disjE*)
assume $x{=}a \vee x{=}c$
thus *?thesis*
using *in-P* **by** *blast*
next
assume $[[a\ x\ c]]$
thus *?thesis*
using *betw-b-in-path in-P path-P points-neq* **by** *blast*
qed
next assume $x{\notin}\bigcup S$
hence $[[b\ a\ x]] \vee [[b\ c\ x]] \vee x{\in}Q$
using ‹$x \in \bigcup S \vee [[b\ a\ x]] \vee [[b\ c\ x]] \vee x \in Q$›
by *blast*

```
    thus ?thesis
      using assms(4) betw-c-in-path in-P path-P points-neq
      by blast
  qed
 }
 ultimately show P = ((⋃S) ∪ P1 ∪ P2 ∪ Q)
  by blast
qed


lemma inseg-axc:
 assumes path-P: P∈𝒫
    and Q-def: finite (Q::'a set) card Q = N Q⊆P N≥3
    and f-def: a∈Q ∧ b∈Q ∧ c∈Q [f[a..b..c]Q]
    and S-def: S = {s. ∃i<(N−1). s = segment (f i) (f (i+1))}
    and x-def: x∈s s∈S
  shows [[a x c]]
proof −
 have inseg-neq-ac: x≠a ∧ x≠c if x∈s s∈S for x s
 proof
  show x≠a
  proof (rule notI)
    assume x=a
    obtain n where s-def: s = segment (f n) (f (n+1)) n<N−1
      using S-def ‹s ∈ S› by blast
    have f n ∈ Q
      using f-def ‹n < N − 1› fin-long-chain-def long-ch-by-ord-def ordering-def
      by (metis assms(3) diff-diff-cancel less-imp-diff-less less-irrefl-nat not-less)
    hence [[a (f n) c]]
      using f-def fin-long-chain-def assms(3) order-finite-chain seg-betw that(1)
      using ‹n < N − 1› ‹s = segment (f n) (f (n + 1))› ‹x = a›
    by (metis abc-abc-neq add-lessD1 ch-all-betw-f inside-not-bound(2) less-diff-conv)
    moreover have [[(f(n)) x (f(n+1))]]
      using ‹x∈s› seg-betw s-def(1) by simp
    ultimately show False
       using ‹x=a› abc-only-cba(1) assms(3) f-def fin-long-chain-def s-def(2)
order-finite-chain
      by (metis le-numeral-extra(3) less-add-one less-diff-conv neq0-conv)
  qed

  show x≠c
  proof (rule notI)
    assume x=c
    obtain n where s-def: s = segment (f n) (f (n+1)) n<N−1
      using S-def ‹s ∈ S› by blast
    hence n+1<N by simp
    have [[(f(n)) x (f(n+1))]]
      using ‹x∈s› seg-betw s-def(1) by simp
    have f (n) ∈ Q
```

using *f-def* ‹$n+1 < N$› *fin-long-chain-def long-ch-by-ord-def ordering-def*
by (*metis add-lessD1 assms*(*3*))
have $f\ (n+1) \in Q$
using *f-def* ‹$n+1 < N$› *fin-long-chain-def long-ch-by-ord-def ordering-def*
by (*metis assms*(*3*))
have $f(n+1) \neq c$
using ‹$x=c$› ‹$[[(f(n))\ x\ (f(n+1))]]$› *abc-abc-neq*
by *blast*
hence $[[a\ (f(n+1))\ c]]$
using *f-def fin-long-chain-def assms*(*3*) *order-finite-chain seg-betw that*(*1*)
abc-abc-neq abc-only-cba ch-all-betw-f
by (*metis* ‹$[[(f\ n)\ x\ (f\ (n + 1))]]$› ‹$f\ (n + 1) \in Q$› ‹$f\ n \in Q$› ‹$x = c$›)
thus *False*
using ‹$x=c$› ‹$[[(f(n))\ x\ (f(n+1))]]$› *assms*(*3*) *f-def s-def*(*2*)
abc-only-cba(*1*) *fin-long-chain-def order-finite-chain*
by (*metis* ‹$f\ n \in Q$› *abc-bcd-acd abc-only-cba*(*1*,*2*) *ch-all-betw-f*)
qed
qed

show $[[a\ x\ c]]$
proof −
have $x \in interval\ a\ c$
using *int-split-to-segs* [*OF f-def*(*2*)] *S-def assms*(*2*,*3*,*5*) *x-def*
by *blast*
have $x \neq a \wedge x \neq c$ **using** *inseg-neq-ac*
using *x-def* **by** *auto*
thus *?thesis*
using *seg-betw* ‹$x \in interval\ a\ c$› *interval-def*
by *auto*
qed
qed

lemma *disjoint-segmentation*:
assumes *path-P*: $P \in \mathcal{P}$
and *Q-def*: *finite* (Q::'a *set*) $card\ Q = N$ $Q \subseteq P$ $N \geq 3$
and *f-def*: $a \in Q \wedge b \in Q \wedge c \in Q$ $[f[a..b..c]Q]$
and *S-def*: $S = \{s.\ \exists i<(N-1).\ s = segment\ (f\ i)\ (f\ (i+1))\}$
and *P1-def*: $P1 = prolongation\ b\ a$
and *P2-def*: $P2 = prolongation\ b\ c$
shows $P1 \cap P2 = \{\} \wedge (\forall x \in S.\ (x \cap P1 = \{\} \wedge x \cap P2 = \{\} \wedge (\forall y \in S.\ x \neq y \longrightarrow x \cap y = \{\})))$
proof (*rule conjI*)
show $P1 \cap P2 = \{\}$
proof (*safe*)
fix x **assume** $x \in P1$ $x \in P2$
show $x \in \{\}$
using *abc-only-cba pro-betw P1-def P2-def*
by (*metis* ‹$x \in P1$› ‹$x \in P2$› *abc-bcd-abd f-def*(*2*) *fin-ch-betw*)

qed

show $\forall x\in S.\ (x\cap P1=\{\} \wedge x\cap P2=\{\} \wedge (\forall y\in S.\ x\neq y \longrightarrow x\cap y=\{\}))$
proof (*rule ballI*)
fix *s* **assume** $s\in S$
show $s \cap P1 = \{\} \wedge s \cap P2 = \{\} \wedge (\forall y\in S.\ s \neq y \longrightarrow s \cap y = \{\})$
proof (*rule conjI3*, *rule-tac*[*3*] *ballI*, *rule-tac*[*3*] *impI*)
show $s\cap P1=\{\}$
proof (*safe*)
fix *x* **assume** $x\in s$ $x\in P1$
hence $[[a\ x\ c]]$
using *inseg-axc* ‹$s \in S$› *assms* **by** *blast*
thus $x\in\{\}$
by (*metis P1-def* ‹$x \in P1$› *abc-bcd-abd abc-only-cba*(*1*) *f-def*(*2*) *fin-ch-betw pro-betw*)
qed
show $s\cap P2=\{\}$
proof (*safe*)
fix *x* **assume** $x\in s$ $x\in P2$
hence $[[a\ x\ c]]$
using *inseg-axc* ‹$s \in S$› *assms* **by** *blast*
thus $x\in\{\}$
by (*metis P2-def* ‹$x \in P2$› *abc-bcd-acd abc-only-cba*(*2*) *f-def*(*2*) *fin-ch-betw pro-betw*)
qed
fix *r* **assume** $r\in S$ $s\neq r$
show $s\cap r=\{\}$
proof (*safe*)
fix *y* **assume** $y \in r$ $y \in s$
obtain *n m* **where** *rs-def*: $r = segment\ (f\ n)\ (f(n+1))$ $s = segment\ (f\ m)\ (f(m+1))$
$n\neq m$ $n<N-1$ $m<N-1$
using *S-def* ‹$r \in S$› ‹$s \neq r$› ‹$s \in S$› **by** *blast*
have *y-betw*: $[[(f\ n)\ y\ (f(n+1))]] \wedge [[(f\ m)\ y\ (f(m+1))]]$
using *seg-betw* ‹$y\in r$› ‹$y\in s$› *rs-def*(*1*,*2*) **by** *simp*
have *False*
proof (*cases*)
assume $n<m$
have $[[(f\ n)\ (f\ m)\ (f(m+1))]]$
using ‹$n < m$› *assms*(*3*) *f-def fin-long-chain-def order-finite-chain rs-def*(*5*) **by** *auto*
have $n+1<m$
using ‹$[[(f\ n)\ (f\ m)\ (f(m + 1))]]$› ‹$n < m$› *abc-only-cba*(*2*) *abd-bcd-abc y-betw*
by (*metis Suc-eq-plus1 Suc-leI le-eq-less-or-eq*)
hence $[[(f\ n)\ (f(n+1))\ (f\ m)]]$
using *f-def assms*(*3*) *rs-def*(*5*)
unfolding *fin-long-chain-def long-ch-by-ord-def ordering-def*
by (*metis add-lessD1 less-add-one less-diff-conv*)

hence $[[(f\ n)\ (f(n+1))\ y]]$
using ‹$[[(f\ n)\ (f\ m)\ (f(m + 1))]]$› *abc-acd-abd abd-bcd-abc y-betw*
by *blast*
thus *?thesis*
using *abc-only-cba y-betw* **by** *blast*
next
assume $\neg n<m$
hence $n>m$ **using** *nat-neq-iff rs-def(3)* **by** *blast*
have $[[(f\ m)\ (f\ n)\ (f(n+1))]]$
using ‹$n > m$› *assms(3) f-def fin-long-chain-def order-finite-chain rs-def(4)* **by** *auto*
hence $m+1<n$
using ‹$n > m$› *abc-only-cba(2) abd-bcd-abc y-betw*
by (*metis Suc-eq-plus1 Suc-leI le-eq-less-or-eq*)
hence $[[(f\ m)\ (f(m+1))\ (f\ n)]]$
using *f-def assms(3) rs-def(4)*
unfolding *fin-long-chain-def long-ch-by-ord-def ordering-def*
by (*metis add-lessD1 less-add-one less-diff-conv*)
hence $[[(f\ m)\ (f(m+1))\ y]]$
using ‹$[[(f\ m)\ (f\ n)\ (f(n + 1))]]$› *abc-acd-abd abd-bcd-abc y-betw*
by *blast*
thus *?thesis*
using *abc-only-cba y-betw* **by** *blast*
qed
thus $y\in\{\}$ **by** *blast*
qed
qed
qed
qed

lemma *segmentation-ex-Nge3*:
assumes *path-P*: $P\in\mathcal{P}$
and *Q-def*: *finite* $(Q::'a\ set)$ *card* $Q = N$ $Q\subseteq P$ $N\geq 3$
and *f-def*: $a\in Q \wedge b\in Q \wedge c\in Q$ $[f[a..b..c]Q]$
and *S-def*: $S = \{s.\ \exists i<(N-1).\ s = segment\ (f\ i)\ (f\ (i+1))\}$
and *P1-def*: $P1 = prolongation\ b\ a$
and *P2-def*: $P2 = prolongation\ b\ c$
shows $P = ((\bigcup S) \cup P1 \cup P2 \cup Q) \wedge$
$(\forall x\in S.\ is\text{-}segment\ x) \wedge$
$P1\cap P2=\{\} \wedge (\forall x\in S.\ (x\cap P1=\{\} \wedge x\cap P2=\{\} \wedge (\forall y\in S.\ x\neq y \longrightarrow x\cap y=\{\})))$
proof −
have $P = ((\bigcup S) \cup P1 \cup P2 \cup Q) \wedge$
$(\forall x\in S.\ is\text{-}segment\ x) \wedge P1\cap P2=\{\} \wedge$
$(\forall x\in S.\ (x\cap P1=\{\} \wedge x\cap P2=\{\} \wedge (\forall y\in S.\ x\neq y \longrightarrow x\cap y=\{\})))$
proof (*rule conjI3*)
show $P = ((\bigcup S) \cup P1 \cup P2 \cup Q)$
using *path-is-union assms*

by *blast*
show $\forall x{\in}S.$ *is-segment* x
proof
fix s **assume** $s{\in}S$
thus *is-segment* s **using** *S-def* **by** *auto*
qed
show $P1{\cap}P2{=}\{\} \wedge (\forall x{\in}S.\ x \cap P1 = \{\} \wedge x \cap P2 = \{\} \wedge (\forall y{\in}S.\ x \neq y \longrightarrow x \cap y = \{\}))$
using *assms disjoint-segmentation*
[**where** $P{=}P$ **and** $Q{=}Q$ **and** $N{=}N$ **and** $a{=}a$ **and** $b{=}b$ **and** $c{=}c$ **and** $f{=}f$ **and** $S{=}S$]
by *presburger*
qed
then show *?thesis* **by** *auto*
qed

We define *disjoint* to be the same as in HOL-Library.DisjointSets. This saves importing a lot of baggage we don't need. The two lemmas below are just for safety.

abbreviation *disjoint*
where *disjoint* $A \equiv (\forall a{\in}A.\ \forall b{\in}A.\ a \neq b \longrightarrow a \cap b = \{\})$

lemma
fixes S:: (*'a set*) *set* **and** $P1$:: *'a set* **and** $P2$:: *'a set*
assumes $\forall x{\in}S.\ (x{\cap}P1{=}\{\} \wedge x{\cap}P2{=}\{\} \wedge (\forall y{\in}S.\ x{\neq}y \longrightarrow x{\cap}y{=}\{\}))$ $P1{\cap}P2{=}\{\}$
shows *disjoint* $(S{\cup}\{P1,P2\})$
proof (*rule ballI*)
let $?U = S{\cup}\{P1,P2\}$
fix a **assume** $a{\in}?U$
then consider $(aS)\, a{\in}S \mid (a1)\, a{=}P1 \mid (a2)\, a{=}P2$
by *fastforce*
thus $\forall b{\in}?U.\ a \neq b \longrightarrow a \cap b = \{\}$
proof *cases*
case *aS*
{ **fix** b **assume** $b{\in}?U$ $a{\neq}b$
then consider $b{\in}S \mid b{=}P1 \mid b{=}P2$
by *fastforce*
hence $a{\cap}b{=}\{\}$
apply *cases*
apply (*simp add*: ‹$a \in S$› ‹$a \neq b$› *assms*)
apply (*meson* ‹$a \in S$› *assms*)
by (*simp add*: ‹$a \in S$› *assms*)
}
thus *?thesis*
by *meson*
next
case *a1*
{ **fix** b **assume** $b{\in}?U$ $a{\neq}b$
then consider $b{\in}S \mid b{=}P2$

```
      using a1 by fastforce
    hence a∩b={}
      apply cases
      apply (metis a1 assms(1) inf-commute)
      by (simp add: a1 assms(2))
  }
  thus ?thesis
    by meson
next
  case a2
  { fix b assume b∈?U a≠b
    then consider b∈S|b=P1
      using a2 by fastforce
    hence a∩b={}
      apply cases
      apply (metis a2 assms(1) inf-commute)
      by (simp add: a2 assms(2) inf-commute)
  }
  thus ?thesis
    by meson
qed
qed
lemma
  fixes S:: ('a set) set and P1:: 'a set and P2:: 'a set
  assumes disjoint (S∪{P1,P2}) P1∉S P2∉S P1≠P2
  shows ∀x∈S. (x∩P1={} ∧ x∩P2={} ∧ (∀y∈S. x≠y ⟶ x∩y={})) P1∩P2={}
proof (rule ballI)
  show P1∩P2={}
    using assms(1,4) by simp
  fix x assume x∈S
  show x∩P1={} ∧ x∩P2={} ∧ (∀y∈S. x≠y ⟶ x∩y={})
  proof (rule conjI, rule-tac[2] conjI, rule-tac[3] ballI, rule-tac[3] impI)
    show x∩P1={}
      using ‹x ∈ S› assms(1,2) by fastforce
    show x∩P2={}
      using ‹x ∈ S› assms(1,3) by fastforce
    fix y assume y∈S x≠y
    thus x∩y={}
      by (simp add: ‹x ∈ S› assms(1))
  qed
qed
```

Schutz says "As in the proof of the previous theorem [...]" - does he mean to imply that this should really be proved as induction? I can see that quite easily, induct on N, and add a segment by either splitting up a segment or taking a piece out of a prolongation. But I think that might be too much trouble.

```
theorem show-segmentation:
  assumes path-P: P∈𝒫
```

```
    and Q-def: Q⊆P
    and f-def: [f[a..b]Q]
  fixes P1 defines P1-def: P1 ≡ prolongation b a
  fixes P2 defines P2-def: P2 ≡ prolongation a b
  fixes S  defines S-def: S ≡ if card Q=2 then {segment a b}
                             else {segment (f i) (f (i+1)) | i. i<card Q−1}
  shows P = ((⋃S) ∪ P1 ∪ P2 ∪ Q) (∀x∈S. is-segment x)
      disjoint (S∪{P1,P2}) P1≠P2 P1∉S P2∉S
proof −
  have card-Q: card Q ≥ 2
    using fin-chain-card-geq-2 f-def by blast
  have finite Q
    by (metis card.infinite card-Q rel-simps(28))

  have ch-Q: ch Q
    using Q-def card-Q path-P path-finsubset-chain [where X=Q and Q=P]
    by blast
  have f-def-2: a∈Q ∧ b∈Q
    using f-def points-in-chain fin-chain-def by auto
  have a≠b
    using f-def fin-chain-def fin-long-chain-def by auto
  {
    assume card Q = 2
    hence S={segment a b}
      by (simp add: S-def)
    have P = ((⋃S) ∪ P1 ∪ P2 ∪ Q) (∀x∈S. is-segment x) P1∩P2={}
        (∀x∈S. (x∩P1={} ∧ x∩P2={} ∧ (∀y∈S. x≠y ⟶ x∩y={})))
      using assms ch-Q ‹finite Q› segmentation-ex-N2
        [where P=P and Q=Q and N=card Q]
      by (metis (no-types, lifting) ‹card Q = 2›)+
  } moreover {
    assume card Q ≠ 2
    hence card Q ≥ 3
      using card-Q by auto
    then obtain c where c-def: [f[a..c..b]Q]
      using assms(3,5) ‹a≠b›
      by (metis f-def fin-chain-def short-ch-def three-in-set3)
    have pro-equiv: P1 = prolongation c a ∧ P2 = prolongation c b
      using pro-basis-change
      using P1-def P2-def abc-sym c-def fin-ch-betw by auto
    have S-def2: S = {s. ∃i<(card Q−1). s = segment (f i) (f (i+1))}
      using S-def ‹card Q ≥ 3› by auto
    have P = ((⋃S) ∪ P1 ∪ P2 ∪ Q) (∀x∈S. is-segment x) P1∩P2={}
        (∀x∈S. (x∩P1={} ∧ x∩P2={} ∧ (∀y∈S. x≠y ⟶ x∩y={})))
      using f-def-2 assms ch-Q ‹card Q ≥ 3› c-def pro-equiv
        segmentation-ex-Nge3 [where P=P and Q=Q and N=card Q and S=S
and a=a and b=c and c=b and f=f]
      using points-in-chain ‹finite Q› S-def2 by presburger+
  }
```

ultimately have *old-thesis*: $P = ((\bigcup S) \cup P1 \cup P2 \cup Q)$ $(\forall x{\in}S.\ is\text{-}segment\ x)$ $P1{\cap}P2{=}\{\}$
$(\forall x{\in}S.\ (x{\cap}P1{=}\{\} \wedge x{\cap}P2{=}\{\} \wedge (\forall y{\in}S.\ x{\neq}y \longrightarrow x{\cap}y{=}\{\})))$ **by** *meson+*
thus *disjoint* $(S{\cup}\{P1,P2\})$ $P1{\neq}P2$ $P1{\notin}S$ $P2{\notin}S$
$P = ((\bigcup S) \cup P1 \cup P2 \cup Q)$ $(\forall x{\in}S.\ is\text{-}segment\ x)$
apply (*simp add*: *Int-commute*)
apply (*metis P2-def Un-iff old-thesis*(*1*,*3*) ‹$a \neq b$› *disjoint-iff f-def-2 path-P pro-betw prolong-betw2*)
apply (*metis P1-def Un-iff old-thesis*(*1*,*4*) ‹$a \neq b$› *disjoint-iff f-def-2 path-P pro-betw prolong-betw3*)
apply (*metis P2-def Un-iff old-thesis*(*1*,*4*) ‹$a \neq b$› *disjoint-iff f-def-2 path-P pro-betw prolong-betw*)
using *old-thesis*(*1*,*2*) **by** *linarith+*
qed

theorem *segmentation*:
assumes *path-P*: $P{\in}\mathcal{P}$
and *Q-def*: *card* $Q{\geq}2$ $Q{\subseteq}P$
shows $\exists S\ P1\ P2.\ P = ((\bigcup S) \cup P1 \cup P2 \cup Q) \wedge$
disjoint $(S{\cup}\{P1,P2\}) \wedge P1{\neq}P2 \wedge P1{\notin}S \wedge P2{\notin}S \wedge$
$(\forall x{\in}S.\ is\text{-}segment\ x) \wedge is\text{-}prolongation\ P1 \wedge is\text{-}prolongation\ P2$
proof −
let *?N* = *card Q*
obtain *f a b* **where** *f-def*: $[f[a..b]Q]$
using *path-finsubset-chain2*[*OF path-P Q-def*(*2*,*1*)]
by *metis*
let *?S* = *if ?N=2 then* {*segment a b*} *else* {*segment* (*f i*) (*f* (*i+1*)) | *i*. *i<card Q−1*}
let *?P1* = *prolongation b a*
let *?P2* = *prolongation a b*
have *from-seg*: $P = ((\bigcup ?S) \cup ?P1 \cup ?P2 \cup Q)$ $(\forall x{\in}?S.\ is\text{-}segment\ x)$
disjoint $(?S{\cup}\{?P1,?P2\})$ $?P1{\neq}?P2$ $?P1{\notin}?S$ $?P2{\notin}?S$
using *show-segmentation*[*OF path-P Q-def*(*2*) ‹$[f[a..b]Q]$›]
by *force+*
thus *?thesis*
by *blast*
qed

end

33 Chains are unique up to reversal

lemma (**in** *MinkowskiSpacetime*) *chain-remove-at-right-edge*:
assumes $[f[a..c]X]$ f $(card\ X - 2) = p$ $3 \leq card\ X$ $X = insert\ c\ Y$ $c{\notin}Y$
shows $[f[a..p]Y]$

proof −

have *lch-X*: *long-ch-by-ord f X*
using *assms*(*1*,*3*) *fin-chain-def fin-long-chain-def ch-by-ord-def short-ch-card-2*
by *fastforce*
have *p*∈*X*
by (*metis ordering-def assms*(*2*,*3*) *card.empty card-gt-0-iff diff-less lch-X long-ch-by-ord-def not-numeral-le-zero zero-less-numeral*)
have *bound-ind*: *f 0* = *a* ∧ *f* (*card X* − *1*) = *c*
using *lch-X assms*(*1*,*3*) **unfolding** *fin-chain-def fin-long-chain-def*
by (*metis* (*no-types*, *hide-lams*) *One-nat-def Suc-1 ch-by-ord-def diff-Suc-Suc less-Suc-eq-le neq0-conv numeral-3-eq-3 short-ch-card-2 zero-less-diff*)

have [[*a p c*]]
proof −
have *card X* − *2* < *card X* − *1*
using ‹*3* ≤ *card X*› **by** *auto*
moreover have *card X* − *2* > *0*
using ‹*3* ≤ *card X*› **by** *linarith*
ultimately show *?thesis*
using *assms*(*2*) *lch-X bound-ind* ‹*3* ≤ *card X*› **unfolding** *long-ch-by-ord-def ordering-def*
by (*metis One-nat-def diff-Suc-less less-le-trans zero-less-numeral*)
qed
hence *p*≠*c*
using *abc-abc-neq* **by** *blast*
hence *p*∈*Y*
using ‹*p* ∈ *X*› *assms*(*4*) **by** *blast*

show *?thesis*
proof (*cases*)
assume *3* = *card X*
hence *2* = *card Y*
by (*metis assms*(*4*,*5*) *card.insert card.infinite diff-Suc-1 finite-insert nat.simps*(*3*) *numeral-2-eq-2 numeral-3-eq-3*)
have *a*≠*p*
using ‹[[*a p c*]]› *abc-abc-neq* **by** *auto*
moreover have *a*∈*Y* ∧ *p*∈*Y*
using ‹[[*a p c*]]› ‹*p* ∈ *Y*› *abc-abc-neq assms*(*1*,*4*) *fin-chain-def points-in-chain*
by *fastforce*
moreover have *short-ch Y*
proof −
obtain *ap* **where** *path ap a p*
using ‹[[*a p c*]]› *abc-ex-path-unique calculation*(*1*) **by** *blast*
hence ∃ *Q*. *path Q a p*
by *blast*
moreover have ¬ (∃ *z*∈*Y*. *z* ≠ *a* ∧ *z* ≠ *p*)
using ‹*2* = *card Y*› ‹*a* ∈ *Y* ∧ *p* ∈ *Y*› ‹*a* ≠ *p*›
by (*metis card-2-iff'*)

ultimately show *?thesis*
unfolding *short-ch-def* **using** ‹$a \in Y \wedge p \in Y$›
by *blast*
qed
ultimately show *?thesis* **unfolding** *fin-chain-def* **by** *blast*
next
assume $3 \neq card\ X$
hence $4 \leq card\ X$
using *assms*(*3*) **by** *auto*

obtain *b* **where** $b = f\ 1$ **by** *simp*
have $\exists\, b.\ [f[a..b..p]Y]$
proof
have [[*a b p*]]
using *bound-ind* ‹$b = f\ 1$› ‹$3 \neq card\ X$› *assms*(*2*,*3*) *lch-X order-finite-chain*
by *fastforce*
hence *all-neq*: $b{\neq}a \wedge b{\neq}p \wedge a{\neq}p$
using *abc-abc-neq* **by** *blast*
have $b{\in}X$
using ‹$b = f\ 1$› *lch-X assms*(*3*) **unfolding** *long-ch-by-ord-def ordering-def*
by *force*
hence $b{\in}Y$
using ‹[[*a b p*]]› ‹[[*a p c*]]› *abc-only-cba*(*2*) *assms*(*4*) **by** *blast*

have *ordering f betw Y*
unfolding *ordering-def*
proof (*safe*)
show $\bigwedge n.$ *infinite* $Y \Longrightarrow f\ n \in Y$
using *assms*(*3*) *assms*(*4*) **by** *auto*
show $\bigwedge n.\ n < card\ Y \Longrightarrow f\ n \in Y$
using *assms*(*3*,*4*,*5*) *bound-ind lch-X*
unfolding *long-ch-by-ord-def ordering-def*
using *get-fin-long-ch-bounds indices-neq-imp-events-neq*
by (*smt Suc-less-eq add-leD1 cancel-comm-monoid-add-class.diff-cancel card-Diff1-less*
card-Diff-singleton card-eq-0-iff card-insert-disjoint gr-implies-not0 insert-iff lch-X
le-add-diff-inverse less-SucI numeral-3-eq-3 plus-1-eq-Suc zero-less-diff)
{
fix *x* **assume** $x{\in}Y$
hence $x{\in}X$
using *assms*(*4*) **by** *blast*
then obtain *n* **where** $n < card\ X\ f\ n = x$
using *lch-X* **unfolding** *long-ch-by-ord-def ordering-def*
using *assms*(*3*) **by** *auto*
show $\exists\, n.$ (*finite* $Y \longrightarrow n < card\ Y) \wedge f\ n = x$
proof
show (*finite* $Y \longrightarrow n < card\ Y) \wedge f\ n = x$
using ‹$f\ n = x$› ‹$n < card\ X$› ‹$x \in Y$› *assms*(*4*,*5*) *bound-ind*

by (*metis Diff-insert-absorb card.remove card-Diff-singleton finite.insertI insertI1 less-SucE*)
qed
}
fix $n\ n'\ n''$
assume $(n::nat)<n'\ n'<n''$
{
assume *infinite Y*
show $[[(f\ n)\ (f\ n')\ (f\ n'')]]$
using ‹$\bigwedge n$. *infinite* $Y \Longrightarrow f\ n \in Y$› ‹*infinite* Y› *assms*(5) *bound-ind* **by** *blast*
} {
assume $n'' <$ *card* Y
show $[[(f\ n)\ (f\ n')\ (f\ n'')]]$
using ‹$n < n'$› ‹$n' < n''$› ‹$n'' <$ *card* Y› *assms*(4,5) *lch-X order-finite-chain*
using ‹*infinite* $Y \Longrightarrow [[(f\ n)\ (f\ n')\ (f\ n'')]]$› **by** *fastforce*
}
qed
hence *lch-Y*: *long-ch-by-ord f Y*
using ‹$[[a\ p\ c]]$› ‹$b \in Y$› ‹$p \in X$› *abc-abc-neq all-neq assms*(4) *bound-ind long-ch-by-ord-def zero-into-ordering*
by *fastforce*

show $[f[a..b..p]Y]$
using *all-neq lch-Y bound-ind* ‹$b{\in}Y$› *assms*(2,3,4,5) **unfolding** *fin-long-chain-def*
by (*metis Diff-insert-absorb One-nat-def add-leD1 card.infinite finite-insert plus-1-eq-Suc diff-diff-left card-Diff-singleton not-one-le-zero insertI1 numeral-2-eq-2 numeral-3-eq-3*)
qed

thus *?thesis* **unfolding** *fin-chain-def*
using *points-in-chain* **by** *blast*
qed
qed

lemma (**in** *MinkowskiChain*) *fin-long-ch-imp-fin-ch*:
assumes $[f[a..b..c]X]$
shows $[f[a..c]X]$
using *assms fin-chain-def points-in-chain* **by** *auto*

If we ever want to have chains less strongly identified by endpoints, this result should generalise - a, c, x, z are only used to identify reversal/no-reversal cases.

lemma (**in** *MinkowskiSpacetime*) *chain-unique-induction-ax*:
assumes *card* $X \geq 3$
and $i <$ *card* X
and $[f[a..c]X]$

and $[g[x..z]X]$
and $a = x \vee c = z$
shows $f\ i = g\ i$
using *assms*
proof (*induct card X − 3 arbitrary*: *X a c x z*)
case *Nil*: *0*
have $card\ X = 3$
using *Nil.hyps Nil.prems*(*1*) **by** *auto*

obtain *b* **where** *f-ch*: $[f[a..b..c]X]$
by (*metis Nil.prems*(*1*,*3*) *fin-chain-def short-ch-def three-in-set3*)
obtain *y* **where** *g-ch*: $[g[x..y..z]X]$
using *Nil.prems fin-chain-def short-ch-card-2*
by (*metis Suc-n-not-le-n ch-by-ord-def numeral-2-eq-2 numeral-3-eq-3*)

have $i=1 \vee i=0 \vee i=2$
using ‹$card\ X = 3$› *Nil.prems*(*2*) **by** *linarith*
thus *?case*
proof (*rule disjE*)
assume $i=1$
hence $f\ i = b \wedge g\ i = y$
using *index-middle-element f-ch g-ch* ‹$card\ X = 3$› *numeral-3-eq-3*
by (*metis One-nat-def add-diff-cancel-left′ less-SucE not-less-eq plus-1-eq-Suc*)
have $f\ i = g\ i$
proof (*rule ccontr*)
assume $f\ i \neq g\ i$
hence $g\ i \neq b$
by (*simp add*: ‹$f\ i = b \wedge g\ i = y$›)
have $g\ i \in X$
using ‹$f\ i = b \wedge g\ i = y$› *g-ch points-in-chain* **by** *blast*
hence $(g\ i = a \vee g\ i = c)$
using ‹$g\ i \neq b$› ‹$card\ X = 3$› *points-in-chain*
by (*smt f-ch card2-either-elt1-or-elt2 card-Diff-singleton diff-Suc-1*
fin-long-chain-def insert-Diff insert-iff numeral-2-eq-2 numeral-3-eq-3)
hence $\neg\ [[a\ (g\ i)\ c]]$
using *abc-abc-neq* **by** *blast*
hence $g\ i \notin X$
using ‹$f\ i{=}b \wedge g\ i{=}y$› ‹$g\ i{=}a \vee g\ i{=}c$› *f-ch g-ch chain-bounds-unique*
fin-long-chain-def
by *blast*
thus *False*
by (*simp add*: ‹$g\ i \in X$›)
qed
thus *?thesis*
by (*simp add*: ‹$card\ X = 3$› ‹$i = 1$›)
next
assume $i = 0 \vee i = 2$
show *?thesis*
using *Nil.prems*(*5*) ‹$card\ X = 3$› ‹$i = 0 \vee i = 2$› *chain-bounds-unique f-ch*

g-ch
by (*metis diff-Suc-1 fin-long-chain-def numeral-2-eq-2 numeral-3-eq-3*)
qed
next
case *IH*: (*Suc n*)
have *lch-fX*: *long-ch-by-ord f X*
using *ch-by-ord-def fin-chain-def fin-long-chain-def long-ch-card-ge3 IH*(*3*,*5*)
by *fastforce*
have *lch-gX*: *long-ch-by-ord g X*
using *IH*(*3*,*6*) *ch-by-ord-def fin-chain-def fin-long-chain-def long-ch-card-ge3*
by *fastforce*
have *fin-X*: *finite X*
using *IH*(*4*) *le-0-eq* **by** *fastforce*

have *ch-by-ord f X*
using *lch-fX* **unfolding** *ch-by-ord-def* **by** *blast*
have *card* $X \geq 4$
using *IH.hyps*(*2*) **by** *linarith*

obtain *b* **where** *f-ch*: [*f*[*a..b..c*]*X*]
using ‹*ch-by-ord f X*› *IH*(*3*,*5*) *fin-chain-def short-ch-card-2*
by *auto*
obtain *y* **where** *g-ch*: [*g*[*x..y..z*]*X*]
using ‹*ch-by-ord f X*› *IH.prems*(*1*,*4*) *fin-chain-def short-ch-card-2*
by *auto*

obtain *p* **where** *p-def*: $p = f$ (*card* $X - 2$) **by** *simp*
have [[*a p c*]]
proof −
have *card* $X - 2 <$ *card* $X - 1$
using ‹$4 \leq$ *card X*› **by** *auto*
moreover have *card* $X - 2 > 0$
using ‹$3 \leq$ *card X*› **by** *linarith*
ultimately show *?thesis*
using *f-ch p-def* **unfolding** *fin-long-chain-def long-ch-by-ord-def ordering-def*
by (*metis card-Diff1-less card-Diff-singleton*)
qed
hence $p \neq c \wedge p \neq a$
using *abc-abc-neq* **by** *blast*

obtain *Y* **where** *Y-def*: $X =$ *insert c Y* $c \notin Y$
using *f-ch points-in-chain*
by (*meson mk-disjoint-insert*)
hence *fin-Y*: *finite Y*
using *f-ch fin-long-chain-def* **by** *auto*
hence $n =$ *card* $Y - 3$
using ‹*Suc n* = *card X* − *3*› ‹*X* = *insert c Y*› ‹$c \notin Y$› *card-insert-if*
by *auto*
hence *card-Y*: *card* $Y = n + 3$

using *Y-def(1) Y-def(2) fin-Y IH.hyps(2)* **by** *fastforce*
have *card Y = card X − 1*
using *Y-def(1,2) fin-X* **by** *auto*
have *p∈Y*
using ‹*X = insert c Y*› ‹[[*a p c*]]› *abc-abc-neq lch-fX p-def IH.prems(1,3) Y-def(2)*
by (*metis chain-remove-at-right-edge fin-chain-def points-in-chain*)
have [*f*[*a..p*]*Y*]
using *chain-remove-at-right-edge* [**where** *f=f* **and** *a=a* **and** *c=c* **and** *X=X* **and** *p=p* **and** *Y=Y*]
using *fin-long-ch-imp-fin-ch* [**where** *f=f* **and** *a=a* **and** *c=c* **and** *b=b* **and** *X=X*]
using *f-ch p-def* ‹*card X ≥ 3*› *Y-def*
by *blast*
hence *ch-fY*: *long-ch-by-ord f Y*
unfolding *fin-chain-def*
using *card-Y ch-by-ord-def fin-Y fin-long-chain-def long-ch-card-ge3*
by *force*

have *p-closest*: ¬ (∃ *q*∈*X*. [[*p q c*]])
proof
assume (∃ *q*∈*X*. [[*p q c*]])
then obtain *q* **where** *q*∈*X* [[*p q c*]] **by** *blast*
then obtain *j* **where** *j < card X f j = q*
using *lch-fX lch-gX fin-X points-in-chain* ‹*p≠c ∧ p≠a*›
by (*metis ordering-def long-ch-by-ord-def*)
have *j > card X − 2 ∧ j < card X − 1*
proof −
have *j > card X − 2 ∧ j < card X − 1 ∨ j < card X − 2 ∧ j > card X − 1*
using *index-order3* [**where** *b=j* **and** *a=card X − 2* **and** *c=card X − 1*]
using ‹[[*p q c*]]› ‹*f j = q*› ‹*j < card X*› *f-ch p-def*
by (*metis* (*no-types*, *lifting*) *One-nat-def card-gt-0-iff diff-less empty-iff fin-long-chain-def lessI zero-less-numeral*)
thus *?thesis* **by** *linarith*
qed
thus *False* **by** *linarith*
qed

have *g* (*card X − 2*) = *p*
proof (*rule ccontr*)
assume *asm-false*: *g* (*card X − 2*) ≠ *p*
obtain *j* **where** *g j = p j < card X − 1 j>0*
using ‹*X = insert c Y*› ‹*p∈Y*› *points-in-chain* ‹*p≠c ∧ p≠a*›
by (*metis* (*no-types*, *hide-lams*) *chain-bounds-unique f-ch fin-long-chain-def g-ch index-middle-element insert-iff*)
hence *j < card X − 2*
using *asm-false le-eq-less-or-eq* **by** *fastforce*
hence *j < card Y − 1*
by (*simp add*: *Y-def(1,2) fin-Y*)

obtain d **where** $d = g$ $(card\ X - 2)$ **by** *simp*
have $[[p\ d\ z]]$
proof $-$
have $card\ X - 1 > card\ X - 2$
using ‹$j < card\ X - 1$› **by** *linarith*
thus *?thesis*
using *lch-gX* ‹$j < card\ Y - 1$› ‹$card\ Y = card\ X - 1$› ‹$d = g$ $(card\ X - 2)$› ‹$g\ j = p$›
unfolding *long-ch-by-ord-def ordering-def*
by (*metis* (*mono-tags*, *lifting*) *One-nat-def card-Diff1-less card-Diff-singleton diff-diff-left fin-long-chain-def g-ch numeral-2-eq-2 plus-1-eq-Suc*)
qed
moreover have $d \in X$
using *lch-gX* ‹$d = g$ $(card\ X - 2)$› **unfolding** *long-ch-by-ord-def ordering-def*
by *auto*
ultimately show *False*
using *p-closest abc-sym IH.prems*(*5*) *chain-bounds-unique f-ch g-ch*
by *blast*
qed

hence *ch-gY*: *long-ch-by-ord g Y*
using *IH.prems*(*1*,*4*,*5*) *g-ch f-ch ch-fY card-Y ch-by-ord-def chain-remove-at-right-edge fin-Y*
by (*metis Y-def chain-bounds-unique fin-chain-def fin-long-chain-def long-ch-card-ge3*)

have $f\ i \in Y \lor f\ i = c$
by (*metis ordering-def* ‹$X = insert\ c\ Y$› ‹$i < card\ X$› *lch-fX insert-iff long-ch-by-ord-def*)
thus $f\ i = g\ i$
proof (*rule disjE*)
assume $f\ i \in Y$
hence $f\ i \neq c$
using ‹$c \notin Y$› **by** *blast*
hence $i < card\ Y$
using ‹$X = insert\ c\ Y$› ‹$c \notin Y$› *IH*(*3*,*4*) *f-ch fin-Y fin-long-chain-def not-less-less-Suc-eq*
by *fastforce*
hence $3 \leq card\ Y$
using *card-Y le-add2* **by** *presburger*
show $f\ i = g\ i$
using *IH*(*1*) [*of Y*]
using ‹$n = card\ Y - 3$› ‹$3 \leq card\ Y$› ‹$i < card\ Y$›
using *Y-def card-Y chain-remove-at-right-edge le-add2*
by (*metis IH.prems*(*1*,*3*,*4*,*5*) *chain-bounds-unique2*)
next
assume $f\ i = c$
show *?thesis*
using *IH.prems*(*2*,*5*) ‹$f\ i = c$› *chain-bounds-unique f-ch g-ch indices-neq-imp-events-neq*
by (*metis* ‹$card\ Y = card\ X - 1$› *Y-def card-insert-disjoint fin-Y fin-long-chain-def lessI*)
qed

qed

I'm really impressed *sledgehammer/smt* can solve this if I just tell them "Use symmetry!".

lemma (**in** *MinkowskiSpacetime*) *chain-unique-induction-cx*:
  assumes *card X* $\geq$ *3*
    and $i <$ *card X*
    and $[f[a..c]X]$
    and $[g[x..z]X]$
    and $c = x \lor a = z$
   shows $f\ i = g$ (*card X* $-$ i $-$ *1*)
  using *chain-sym chain-unique-induction-ax*
  by (*smt* (*verit*, *best*) *assms diff-right-commute fin-chain-def fin-long-ch-imp-fin-ch*)

This lemma has to exclude two-element chains again, because no order exists within them. Alternatively, the result is trivial: any function that assigns one element to index 0 and the other to 1 can be replaced with the (unique) other assignment, without destroying any (trivial, since ternary) "ordering" of the chain. This could be made generic over the ordering similar to *chain-sym* relying on *ordering-sym*.

lemma (**in** *MinkowskiSpacetime*) *chain-unique-upto-rev-cases*:
  assumes *ch-f*: $[f[a..c]X]$
    and *ch-g*: $[g[x..z]X]$
    and *card-X*: *card X* $\geq$ *3*
    and *valid-index*: $i <$ *card X*
  shows ((a=x $\lor$ c=z) $\longrightarrow$ ($f\ i = g\ i$)) ((a=z $\lor$ c=x) $\longrightarrow$ ($f\ i = g$ (*card X* $-$ i $-$ *1*)))
proof $-$
  obtain n **where** *n-def*: $n =$ *card X* $-$ *3*
   by *blast*
  hence *valid-index-2*: $i < n + 3$
   by (*simp add*: *card-X valid-index*)

  show ((a=x $\lor$ c=z) $\longrightarrow$ ($f\ i = g\ i$))
   using *card-X ch-f ch-g chain-unique-induction-ax valid-index* **by** *blast*
  show ((a=z $\lor$ c=x) $\longrightarrow$ ($f\ i = g$ (*card X* $-$ i $-$ *1*)))
   using *assms*(*3*) *ch-f ch-g chain-unique-induction-cx valid-index* **by** *blast*
qed

lemma (**in** *MinkowskiSpacetime*) *chain-unique-upto-rev*:
  assumes $[f[a..c]X]$ $[g[x..z]X]$ *card X* $\geq$ *3* $i <$ *card X*
  shows $f\ i = g\ i \lor f\ i = g$ (*card X* $-$ i $-$ *1*) a=$x$$\land$$c$=$z$ $\lor$ c=$x$$\land$$a$=$z$
proof $-$
  have (a=x $\lor$ c=z) $\lor$ (a=z $\lor$ c=x)
   using *chain-bounds-unique*
   by (*metis assms*(*1*,*2*) *fin-chain-def points-in-chain short-ch-def*)
  thus $f\ i = g\ i \lor f\ i = g$ (*card X* $-$ i $-$ *1*)
   using *assms*(*3*) ‹$i <$ *card X*› *assms chain-unique-upto-rev-cases* **by** *blast*

thus $(a{=}x{\wedge}c{=}z) \vee (c{=}x{\wedge}a{=}z)$
by (*meson assms*(*1−3*) *chain-bounds-unique2*)
qed

34 Subchains

context *MinkowskiSpacetime* **begin**

lemma *f-img-is-subset*:
assumes $[f[(f\ 0)\ ..]X]$ $i{\geq}0$ $j{>}i$ $Y{=}f`\{i..j\}$
shows $Y{\subseteq}X$
proof
fix *x* **assume** $x{\in}Y$
then obtain *n* **where** $n{\in}\{i..j\}$ $f\ n = x$
using *assms*(*4*) **by** *blast*
hence $f\ n \in X$
by (*metis ordering-def assms*(*1*) *inf-chain-is-long long-ch-by-ord-def*)
thus $x{\in}X$
using ‹$f\ n = x$› **by** *blast*
qed

lemma *f-inj-on-index-subset*:
assumes $[f[(f\ 0)\ ..]X]$ $i{\geq}0$ $j{>}i$ $Y{=}f`\{i..j\}$
shows *inj-on f* $\{i..j\}$
unfolding *inj-on-def*
proof (*safe*)
fix *x y* **assume** $x{\in}\{i..j\}$ $y{\in}\{i..j\}$ $f\ x = f\ y$
show $x{=}y$
proof (*rule ccontr*)
assume $x{\neq}y$
let $?P = \lambda r\ s.\ f\ r \neq f\ s$
{
assume $x{\leq}y$
hence $x{<}y$
using ‹$x \neq y$› *le-imp-less-or-eq* **by** *blast*
obtain *n* **where** $n{>}y$ **by** *blast*
hence $[[(f\ x)(f\ y)(f\ n)]]$
using *assms*(*1*) ‹$x{<}y$› *inf-chain-is-long long-ch-by-ord-def ordering-ord-ijk*
by *fastforce*
hence $?P\ x\ y$
using *abc-abc-neq* **by** *blast*
} moreover {
assume $x{>}y$
obtain *n* **where** $n{>}x$ **by** *blast*
hence $[[(f\ y)(f\ x)(f\ n)]]$
using *assms*(*1*) ‹$x{>}y$› *inf-chain-is-long long-ch-by-ord-def ordering-ord-ijk*
by *fastforce*

hence *?P y x*
using *abc-abc-neq* **by** *blast*
}
ultimately show *False*
using *not-le-imp-less* ‹*f x* = *f y*› **by** *auto*
qed
qed

lemma *f-bij-on-index-subset*:
assumes [*f*[(*f 0*) ..]*X*] *i*≥*0* *j*>*i* *Y*=*f*‘{*i..j*}
shows *bij-betw f* {*i..j*} *Y*
using *f-inj-on-index-subset*
by (*metis assms inj-on-imp-bij-betw*)

lemma *only-one-index*:
assumes [*f*[(*f 0*) ..]*X*] *i*≥*0* *j*>*i* *Y*=*f*‘{*i..j*} *f n* ∈ *Y*
shows *n*∈{*i..j*}
proof −
obtain *m* **where** *m*∈{*i..j*} *f m* = *f n*
using *assms*(*4*) *assms*(*5*) **by** *auto*
have *inj-on f* {*i..j*}
using *assms*(*1*,*3*) *f-inj-on-index-subset* **by** *blast*
have *m* = *n*
proof (*rule ccontr*)
assume *m*≠*n*
obtain *l* **where** *f l* ∈ *X* *l*≠*m* *l*≠*n*
using *assms*(*1*) *inf-chain-is-long*
by (*metis ordering-def le-eq-less-or-eq lessI long-ch-by-ord-def not-less-eq-eq*)
hence [[(*f l*)(*f m*)(*f n*)]] ∨ [[(*f m*)(*f l*)(*f n*)]] ∨ [[(*f l*)(*f n*)(*f m*)]]
using ‹*f m* = *f n*› ‹*m*≠*n*›
using *abc-abc-neq assms*(*1*) *inf-chain-is-long inf-ordering-inj′ long-ch-by-ord-def*
by *blast*
thus *False*
using ‹*f m* = *f n*› *abc-abc-neq* **by** *auto*
qed
thus *?thesis*
using ‹*m* ∈ {*i..j*}› **by** *blast*
qed

lemma *f-one-to-one-on-index-subset*:
assumes [*f*[(*f 0*) ..]*X*] *i*≥*0* *j*>*i* *Y*=*f*‘{*i..j*} *y*∈*Y*
shows ∃!*k*∈{*i..j*}. *f k* = *y* *f k* = *y* ⟶ *k*∈{*i..j*}
using *f-inj-on-index-subset only-one-index assms image-iff inj-on-eq-iff* **apply** *metis*
using *assms*(*1*,*3*,*4*,*5*) *only-one-index* **by** *blast*

```
lemma card-of-subchain:
  assumes [f[(f 0) ..]X] i≥0 j>i Y=f‘{i..j}
  shows card Y = card {i..j} card Y = j−i+1
proof −
  show card Y = card {i..j}
    by (metis assms bij-betw-same-card f-bij-on-index-subset)
  thus card Y = j−i+1
    using card-Collect-nat
    by (simp add: assms(3))
qed


lemma fin-long-subchain-of-semifin:
  assumes [f[(f 0) ..]X] i≥0 j>i+1 Y=f‘{i..j}
    g = (λn. f(n+i))
  shows [g[(f i)..(f j)]Y]
proof −
  obtain k where k=i+1 by simp
  hence ind-ord: i<k ∧ k<j using assms(3) by simp
  have [g[(f i) .. (f k) .. (f j)]Y]
  proof −
    have f i ≠ f k ∧ f i ≠ f j ∧ f k ≠ f j
    proof −
      have [[(f i) (f k) (f j)]]
       using assms(1) ind-ord long-ch-by-ord-def ordering-ord-ijk semifin-chain-def
        by fastforce
      thus ?thesis
        using abc-abc-neq by blast
    qed
    moreover have finite Y
    proof −
      have inj f
        using inf-ordering-inj [where ord=betw] abc-abc-neq
        using assms(1) long-ch-by-ord-def semifin-chain-def by auto
      hence card Y ≤ card {i..j}
        using assms(4) inf-ordering-inj
        using card-image-le by blast
      have finite {i..j}
        by simp
      thus finite Y
        by (simp add: assms(4))
    qed
    moreover have long-ch-by-ord g Y
    proof −
      obtain x y z where x=f i y=f k z=f j
        by auto
      have x∈Y ∧ y∈Y ∧ z∈Y ∧ x ≠ y ∧ y ≠ z ∧ x ≠ z
        using ‹x = f i› ‹y = f k› ‹z = f j› assms(4) calculation(1) ind-ord by auto
```

```
      moreover have ordering g betw Y
        unfolding ordering-def
      proof (rule conjI3)
        show ∀ n. (finite Y ⟶ n < card Y) ⟶ g n ∈ Y
          apply (safe) apply (auto simp add: ‹finite Y›)
        proof -
          fix n assume n<card Y
          then obtain n' where n+i = n' n'∈{i..j}
          proof -
            assume asm: ⋀n'. ⟦n + i = n'; n' ∈ {i..j}⟧ ⟹ thesis
            have n < card {i..j}
               by (metis ‹n < card Y› assms(4) card-image-le finite-atLeastAtMost
less-le-trans)
            thus ?thesis
              using asm by simp
          qed
          show g n ∈ Y
            using ‹n + i = n'› ‹n' ∈ {i..j}› assms(4,5) by blast
        qed
        show ∀ x∈Y. ∃ n. (finite Y ⟶ n < card Y) ∧ g n = x
        proof (rule ballI)
          fix x assume x∈Y
          hence x∈X
            using f-img-is-subset assms(1,4)
            by (metis ordering-def imageE inf-chain-is-long long-ch-by-ord-def)
          then obtain n where f n = x
            using ‹x ∈ Y› assms(4) by blast
          have n∈{i..j} using only-one-index
            by (metis ‹f n = x› ‹x ∈ Y› assms(1,2,4) ind-ord less-trans)
          show ∃ n. (finite Y ⟶ n < card Y) ∧ g n = x
          proof (rule exI, rule conjI)
            have n−i≥0
              by blast
            have g (n−i) = f (n−i+i)
              using assms(5) by blast
            show g (n−i) = x
            proof (cases)
              assume n−i>0
              thus ?thesis
                by (simp add: ‹f n = x› ‹g (n − i) = f (n − i + i)›)
            next assume ¬n−i>0
              hence n−i=0 by blast
              thus ?thesis
                using ‹n∈{i..j}› ‹f n = x› ‹g (n − i) = f (n − i + i)› by auto
            qed
            show finite Y ⟶ (n−i) < card Y
            proof
              assume finite Y
              show n−i<card Y
```

using *card-of-subchain*
using ‹$n \in \{i..j\}$› *assms*(*1*,*4*) *ind-ord* **by** *auto*
qed
qed
qed
show $\forall n\ n'\ n''.$ (*finite* $Y \longrightarrow n'' <$ *card* Y) $\wedge$ $n{<}n' \wedge n'{<}n'' \longrightarrow [[(g\ n)(g\ n')(g\ n'')]]$
apply (*safe*) **using** ‹*finite* Y› **apply** *blast*
proof −
fix $l\ m\ n$
assume $l{<}m\ m{<}n\ n{<}$*card* Y
hence $l{+}i{<}m{+}i\ m{+}i{<}n{+}i$
apply *simp* **by** (*simp add*: ‹$m < n$›)
hence $[[(f(l{+}i))(f(m{+}i))(f(n{+}i))]]$
using *assms*(*1*) *inf-chain-is-long long-ch-by-ord-def ordering-ord-ijk* **by** *fastforce*
thus $[[(g\ l)(g\ m)(g\ n)]]$
using *assms*(*5*) **by** *blast*
qed
qed
ultimately show *?thesis*
using *long-ch-by-ord-def* **by** *auto*
qed
moreover have $g\ 0 = f\ i \wedge f\ k \in Y \wedge g$ (*card* $Y - 1$) $= f\ j$
using *card-of-subchain assms*(*1*,*4*,*5*) *ind-ord less-imp-le-nat*
by *force*
ultimately show *?thesis*
using *fin-long-chain-def* **by** *blast*
qed
thus *?thesis*
using *fin-long-ch-imp-fin-ch* **by** *blast*
qed

end

35 Extensions of results to infinite chains

context *MinkowskiSpacetime* **begin**

lemma *i-neq-j-imp-events-neq-inf*:
assumes $[f[(f\ 0)..]X]$ $i{\neq}j$
shows $f\ i \neq f\ j$
proof −
let $?P = \lambda\ i\ j.\ i{\neq}j \longrightarrow f\ i \neq f\ j$
{
fix $i\ j$ **assume** $(i{::}nat){\leq}j$
have $?P\ i\ j$
proof (*cases*)
assume $i{<}j$

then obtain *k* **where** *k*>*j* **by** *blast*
hence [[(*f i*)(*f j*)(*f k*)]]
using ‹*i* < *j*› *assms*(*1*) *inf-chain-is-long long-ch-by-ord-def ordering-ord-ijk*
by *fastforce*
thus *?P i j*
using *abc-abc-neq* **by** *blast*
next
assume ¬*i*<*j* **hence** *i*=*j* **using** ‹*i* ≤ *j*› **by** *auto*
show *?P i j* **by** (*simp add*: ‹*i* = *j*›)
qed
} moreover {
fix *i j* **assume** *?P j i*
hence *?P i j* **by** *auto*
}
ultimately show *?thesis*
by (*metis assms*(*2*) *leI less-imp-le-nat*)
qed

lemma *i-neq-j-imp-events-neq*:
assumes *long-ch-by-ord f X i*≠*j finite X* ⟶ (*i*<*card X* ∧ *j*<*card X*)
shows *f i* ≠ *f j*
using *i-neq-j-imp-events-neq-inf indices-neq-imp-events-neq*
by (*meson assms get-fin-long-ch-bounds semifin-chain-def*)

lemma *inf-chain-origin-unique*:
assumes [*f*[*f 0*..]*X*] [*g*[*g 0*..]*X*]
shows *f 0* = *g 0*
proof (*rule ccontr*)
assume *f 0* ≠ *g 0*
obtain *P* **where** *P*∈𝒫 *X*⊆*P*
using *assms*(*1*) *semifin-chain-on-path* **by** *blast*
obtain *x* **where** *x* = *g 1* **by** *simp*
hence *x*≠*g 0*
using *assms*(*2*) *i-neq-j-imp-events-neq-inf zero-neq-one* **by** *blast*
have *x*∈*X*
by (*metis ordering-def* ‹*x* = *g 1*› *assms*(*2*) *inf-chain-is-long long-ch-by-ord-def*)
have *x*=*f 0* ∨ *x*≠*f 0* **by** *auto*
thus *False*
proof (*rule disjE*)
assume *x*=*f 0*
hence [[(*g 0*)(*f 0*)(*g 2*)]]
using ‹*x*=*g 1*› ‹*x*=*f 0*› *assms*(*2*) *inf-chain-is-long long-ch-by-ord-def ordering-ord-ijk*
by *fastforce*
then obtain *m n* **where** *f m* = *g 0 f n* = *g 2*
by (*metis ordering-def assms*(*1*) *assms*(*2*) *inf-chain-is-long long-ch-by-ord-def*)
hence [[(*f m*)(*f 0*)(*f n*)]]

by (*simp add*: ‹[[(*g 0*)(*f 0*)(*g 2*)]]›)
hence $m{\neq}n$
using *abc-abc-neq* **by** *blast*
have $m{>}0 \wedge n{>}0$
using ‹[[(*f m*)(*f 0*)(*f n*)]]› *abc-abc-neq neq0-conv* **by** *blast*
hence $(0{<}m \wedge m{<}n) \vee (0{<}n \wedge n{<}m)$
using ‹$m \neq n$› **by** *auto*
thus *False*
using ‹[[(*f m*)(*f 0*)(*f n*)]]› *assms*(*1*) *index-order3 inf-chain-is-long* **by** *blast*
next
assume $x{\neq}f\ 0$

have *fn*: $\forall n.\ f\ n \in X$
by (*metis* (*no-types*) *ordering-def assms*(*1*) *inf-chain-is-long long-ch-by-ord-def*)
have *gn*: $\forall n.\ g\ n \in X$
by (*metis ordering-def assms*(*2*) *inf-chain-is-long long-ch-by-ord-def*)

have [[(*g 0*)*x*(*f 0*)]]
proof −
have [[(*f 0*)(*g 0*)*x*]] ∨ [[(*g 0*)(*f 0*)*x*]] ∨ [[(*g 0*)*x*(*f 0*)]]
using ‹$f\ 0 \neq g\ 0$› ‹$x \neq f\ 0$› ‹$x \neq g\ 0$› *all-aligned-on-semifin-chain*
by (*metis ordering-def* ‹$x \in X$› *assms inf-chain-is-long long-ch-by-ord-def*)
moreover have ¬[[(*f 0*)(*g 0*)*x*]]
using *abc-only-cba*(*1*,*3*) *all-aligned-on-semifin-chain assms*(*2*) *fn*
by (*metis* ‹$x{\in}X$› ‹$x{\neq}f\ 0$› ‹$x{\neq}g\ 0$›)
moreover have ¬[[(*g 0*)(*f 0*)*x*]]
using *fn gn* ‹$x \in X$› ‹$x \neq g\ 0$›
by (*metis* (*no-types*) *abc-only-cba*(*1*,*2*,*4*) *all-aligned-on-semifin-chain assms*(*1*))
ultimately show *?thesis* **by** *blast*
qed

obtain *m m′* **where** $g\ m' = f\ 0\ m = Suc\ m'$
using *ordering-def assms inf-chain-is-long long-ch-by-ord-def* **by** *metis*
hence [[(*g 0*)(*f 0*)(*g m*)]]
by (*metis Suc-le-eq* ‹$f\ 0 \neq g\ 0$› *assms*(*2*) *inf-chain-is-long lessI linorder-neqE-nat long-ch-by-ord-def not-le ordering-ord-ijk zero-less-Suc*)
then obtain *n p* **where** $f\ n = g\ 0\ f\ p = g\ m$
by (*metis abc-abc-neq abc-only-cba*(*1*,*4*) *all-aligned-on-semifin-chain assms*(*1*)
gn)
hence $m{<}0 \vee n{<}0$
using *all-aligned-on-semifin-chain assms*(*1*) ‹[[(*g 0*)(*f 0*)(*g m*)]]›
by (*metis abc-abc-neq abc-only-cba*(*1*,*4*) *fn*)
thus *False* **by** *simp*
qed
qed

lemma *inf-chain-unique*:

assumes $[f[f\ 0..]X]$ $[g[g\ 0..]X]$
shows $\forall\, i{::}nat.\ f\ i = g\ i$
proof –
{
assume *asm*: $[f[f\ 0..]X]$ $[g[f\ 0..]X]$
have $\forall\, i{::}nat.\ f\ i = g\ i$
proof
fix $i{::}nat$
show $f\ i = g\ i$
proof (*induct i*)
show $f\ 0 = g\ 0$
using *asm*(*2*) *inf-chain-is-long* **by** *fastforce*
fix i **assume** $f\ i = g\ i$
show $f\ (Suc\ i) = g\ (Suc\ i)$
proof (*rule ccontr*)
assume $f\ (Suc\ i) \neq g\ (Suc\ i)$
let $?i = Suc\ i$
have $f\ 0{\in}X \wedge g?i{\in}X \wedge f?i{\in}X$
by (*metis ordering-def assms*(*1*) *assms*(*2*) *inf-chain-is-long long-ch-by-ord-def*)
hence $[[(f\ 0)(f\ ?i)(g\ ?i)]] \vee [[(f\ 0)(g\ ?i)(f\ ?i)]] \vee [[(f\ ?i)(f\ 0)(g\ ?i)]]$
using *all-aligned-on-semifin-chain assms*(*1*,*2*) *i-neq-j-imp-events-neq-inf*
by (*metis* ‹$f?i \neq g?i$› ‹$f\ 0 = g\ 0$›)
hence $[[(f\ 0)(f\ ?i)(g\ ?i)]] \vee [[(f\ 0)(g\ ?i)(f\ ?i)]]$
using *all-aligned-on-semifin-chain asm*(*2*)
by (*metis* ‹$f\ 0 \in X \wedge g\ (Suc\ i) \in X \wedge f\ (Suc\ i) \in X$› *abc-abc-neq*)
have $([[(f\ 0)(f\ i)(f\ ?i)]] \wedge [[(f\ 0)(g\ i)(g\ ?i)]]) \vee i{=}0$
using *long-ch-by-ord-def ordering-ord-ijk asm*(*1*,*2*)
by (*metis Suc-inject Suc-lessI Suc-less-eq inf-chain-is-long lessI zero-less-Suc*)
thus *False*
proof (*rule disjE*)
assume $i{=}0$
have $[[(g\ 0)(f\ 1)(g\ 1)]]$
proof –
obtain x **where** $x = g\ 1$ **by** *simp*
hence $x{\in}X$
using ‹$f\ 0 \in X \wedge g\ (Suc\ i) \in X \wedge f\ (Suc\ i) \in X$› ‹$i = 0$› **by** *force*
then obtain m **where** $f\ m = x$
by (*metis ordering-def assms*(*1*) *inf-chain-is-long long-ch-by-ord-def*)
hence $f\ m = g\ 1$
using ‹$x = g\ 1$› **by** *blast*
have $m{>}1$
using *assms*(*2*) *i-neq-j-imp-events-neq-inf* ‹$f?i \neq g?i$›
by (*metis One-nat-def Suc-lessI* ‹$f\ 0 = g\ 0$› ‹$f\ m = x$› ‹$i = 0$› ‹$x = g\ 1$› *neq0-conv*)
thus $[[(g\ 0)(f\ 1)(g\ 1)]]$
using ‹$[[(f\ 0)(f?i)(g?i)]] \vee [[(f\ 0)(g?i)(f?i)]]$› ‹$f\ 0 = g\ 0$› ‹$f\ m = x$› ‹$i{=}0$› ‹$x = g\ 1$›
by (*metis One-nat-def assms*(*1*) *gr-implies-not-zero index-order3 inf-chain-is-long order.asym*)

qed
have $f\ 1 \in X$
using ‹$f\ 0 \in X \wedge g\ (Suc\ i) \in X \wedge f\ (Suc\ i) \in X$› ‹$i = 0$› **by** *auto*
then obtain m' **where** $g\ m' = f\ 1$
by (*metis ordering-def assms*(*2*) *inf-chain-is-long long-ch-by-ord-def*)
hence $[[(g\ 0)(g\ m')(g\ 1)]]$
using ‹$[[(g\ 0)(f\ 1)(g\ 1)]]$› **by** *auto*
have $[[(g\ 0)(g\ 1)(g\ m')]]$
proof −
have $m' \neq 1 \wedge m' \neq 0$
using ‹$[[(g\ 0)(g\ m')(g\ 1)]]$› **by** (*meson abc-abc-neq*)
hence $m'>1$ **by** *auto*
thus $[[(g\ 0)(g\ 1)(g\ m')]]$
using ‹$[[(g\ 0)(g\ m')(g\ 1)]]$› *assms*(*2*) *index-order3 inf-chain-is-long*
by *blast*
qed
thus *False*
using ‹$[[(g\ 0)(g\ m')(g\ 1)]]$› *abc-only-cba*(*2*) **by** *blast*
next
assume $[[(f\ 0)(f\ i)(f\ ?i)]] \wedge [[(f\ 0)(g\ i)(g\ ?i)]]$
have $[[(g\ 0)(f\ ?i)(g\ ?i)]]$
proof −
obtain x **where** $x = g\ ?i$ **by** *simp*
hence $x \in X$
by (*simp add*: ‹$f\ 0 \in X \wedge g\ (Suc\ i) \in X \wedge f\ (Suc\ i) \in X$›)
then obtain m **where** $f\ m = x$
by (*metis ordering-def assms*(*1*) *inf-chain-is-long long-ch-by-ord-def*)
hence $f\ m = g\ ?i$
using ‹$x = g\ ?i$› **by** *blast*
have $m>?i$
using *assms*(*2*) *i-neq-j-imp-events-neq-inf* ‹$f?i \neq g?i$›
by (*metis Suc-lessI* ‹$[[(f\ 0)(f\ i)(f\ ?i)]] \wedge [[(f\ 0)(g\ i)(g\ ?i)]]$› ‹$f\ i = g\ i$›
‹$f\ m = x$›
‹$x = g\ (Suc\ i)$› *assms*(*1*) *index-order3 less-nat-zero-code*
semifin-chain-def)
thus $[[(g\ 0)(f\ ?i)(g\ ?i)]]$
using ‹$[[(f\ 0)(f?i)(g?i)]] \vee [[(f\ 0)(g?i)(f?i)]]$› ‹$f\ 0 = g\ 0$› ‹$f\ m = x$› ‹$x$
$= g\ ?i$›
by (*metis assms*(*1*) *gr-implies-not-zero index-order3 inf-chain-is-long*
order.asym)
qed
obtain m **where** $g\ m = f\ ?i$
using ‹$(f\ 0) \in X \wedge g?i \in X \wedge f?i \in X$› *assms*(*2*)
by (*metis ordering-def inf-chain-is-long long-ch-by-ord-def*)
hence $[[(g\ i)(g\ m)(g\ ?i)]]$
using *abc-acd-bcd* ‹$[[(f\ 0)(f\ i)(f?i)]] \wedge [[(f\ 0)(g\ i)(g\ ?i)]]$› ‹$[[(g\ 0)(f\ ?i)(g$
$?i)]]$›
by (*metis* ‹$f\ 0 = g\ 0$› ‹$f\ i = g\ i$›)
have $[[(g\ i)(g\ ?i)(g\ m)]]$

proof −
have *m>?i*
using ‹[[(*g i*)(*g m*)(*g ?i*)]]› *assms*(*2*) *index-order3 inf-chain-is-long* **by** *fastforce*
thus *?thesis*
using *assms*(*2*) *inf-chain-is-long long-ch-by-ord-def ordering-ord-ijk* **by** *fastforce*
qed
thus *False*
using ‹[[(*g i*)(*g m*)(*g ?i*)]]› *abc-only-cba* **by** *blast*
qed
qed
qed
qed
}
moreover have *f 0* = *g 0* **using** *inf-chain-origin-unique assms* **by** *blast*
ultimately show *?thesis* **using** *assms* **by** *auto*
qed

end

36 Interlude: betw4 and WLOG

36.1 betw4 - strict and non-strict, basic lemmas

context *MinkowskiBetweenness* **begin**

Define additional notation for non-strict ordering - cf Schutz' monograph [1, p. 27].

abbreviation *nonstrict-betw-right* :: *'a* ⇒ *'a* ⇒ *'a* ⇒ *bool* ([[- - -⟧) **where**
nonstrict-betw-right a b c ≡ [[*a b c*]] ∨ *b* = *c*

abbreviation *nonstrict-betw-left* :: *'a* ⇒ *'a* ⇒ *'a* ⇒ *bool* (⟦- - -]]) **where**
nonstrict-betw-left a b c ≡ [[*a b c*]] ∨ *b* = *a*

abbreviation *nonstrict-betw-both* :: *'a* ⇒ *'a* ⇒ *'a* ⇒ *bool* **where**
nonstrict-betw-both a b c ≡ *nonstrict-betw-left a b c* ∨ *nonstrict-betw-right a b c*

abbreviation *betw4* :: *'a* ⇒ *'a* ⇒ *'a* ⇒ *'a* ⇒ *bool* ([[- - - -]]) **where**
betw4 a b c d ≡ [[*a b c*]] ∧ [[*b c d*]]

abbreviation *nonstrict-betw-right4* :: *'a* ⇒ *'a* ⇒ *'a* ⇒ *'a* ⇒ *bool* ([[- - - -⟧) **where**
nonstrict-betw-right4 a b c d ≡ *betw4 a b c d* ∨ *c* = *d*

abbreviation *nonstrict-betw-left4* :: *'a* ⇒ *'a* ⇒ *'a* ⇒ *'a* ⇒ *bool* (⟦- - - -]]) **where**
nonstrict-betw-left4 a b c d ≡ *betw4 a b c d* ∨ *a* = *b*

abbreviation *nonstrict-betw-both4* :: *'a* ⇒ *'a* ⇒ *'a* ⇒ *'a* ⇒ *bool* **where**

nonstrict-betw-both4 a b c d ≡ *nonstrict-betw-left4 a b c d* ∨ *nonstrict-betw-right4 a b c d*

lemma *betw4-strong*:
assumes *betw4 a b c d*
shows [[*a b d*]] ∧ [[*a c d*]]
using *abc-bcd-acd assms* **by** *blast*

lemma *betw4-imp-neq*:
assumes *betw4 a b c d*
shows $a \neq b \wedge a \neq c \wedge a \neq d \wedge b \neq c \wedge b \neq d \wedge c \neq d$
using *abc-only-cba assms* **by** *blast*

end
context *MinkowskiSpacetime* **begin**

lemma *betw4-weak*:
fixes *a b c d* :: *'a*
assumes [[*a b c*]] ∧ [[*a c d*]]
∨ [[*a b c*]] ∧ [[*b c d*]]
∨ [[*a b d*]] ∧ [[*b c d*]]
∨ [[*a b d*]] ∧ [[*b c d*]]
shows *betw4 a b c d*
using *abc-acd-bcd abd-bcd-abc assms* **by** *blast*

lemma *betw4-sym*:
fixes *a*::*'a* **and** *b*::*'a* **and** *c*::*'a* **and** *d*::*'a*
shows *betw4 a b c d* ⟷ *betw4 d c b a*
using *abc-sym* **by** *blast*

lemma *abcd-dcba-only*:
fixes *a*::*'a* **and** *b*::*'a* **and** *c*::*'a* **and** *d*::*'a*
assumes *betw4 a b c d*
shows ¬*betw4 a b d c* ¬*betw4 a c b d* ¬*betw4 a c d b* ¬*betw4 a d b c* ¬*betw4 a d c b*
¬*betw4 b a c d* ¬*betw4 b a d c* ¬*betw4 b c a d* ¬*betw4 b c d a* ¬*betw4 b d c a* ¬*betw4 b d a c*
¬*betw4 c a b d* ¬*betw4 c a d b* ¬*betw4 c b a d* ¬*betw4 c b d a* ¬*betw4 c d a b* ¬*betw4 c d b a*
¬*betw4 d a b c* ¬*betw4 d a c b* ¬*betw4 d b a c* ¬*betw4 d b c a* ¬*betw4 d c a b*
using *abc-only-cba assms* **by** *blast+*

lemma *some-betw4a*:
fixes *a*::*'a* **and** *b*::*'a* **and** *c*::*'a* **and** *d*::*'a* **and** *P*
assumes $P \in \mathcal{P}$ $a \in P$ $b \in P$ $c \in P$ $d \in P$ $a \neq b \wedge a \neq c \wedge a \neq d \wedge b \neq c \wedge b \neq d \wedge c \neq d$
and ¬(*betw4 a b c d* ∨ *betw4 a b d c* ∨ *betw4 a c b d* ∨ *betw4 a c d b* ∨ *betw4 a d b c* ∨ *betw4 a d c b*)

shows *betw4 b a c d* ∨ *betw4 b a d c* ∨ *betw4 b c a d* ∨ *betw4 b d a c* ∨ *betw4 c a b d* ∨ *betw4 c b a d*
by (*smt abc-bcd-acd abc-sym abd-bcd-abc assms some-betw-xor*)

lemma *some-betw4b*:
fixes *a*::'*a* **and** *b*::'*a* **and** *c*::'*a* **and** *d*::'*a* **and** *P*
assumes *P*∈𝒫 *a*∈*P* *b*∈*P* *c*∈*P* *d*∈*P* *a*≠*b* ∧ *a*≠*c* ∧ *a*≠*d* ∧ *b*≠*c* ∧ *b*≠*d* ∧ *c*≠*d*
and ¬(*betw4 b a c d* ∨ *betw4 b a d c* ∨ *betw4 b c a d* ∨ *betw4 b d a c* ∨ *betw4 c a b d* ∨ *betw4 c b a d*)
shows *betw4 a b c d* ∨ *betw4 a b d c* ∨ *betw4 a c b d* ∨ *betw4 a c d b* ∨ *betw4 a d b c* ∨ *betw4 a d c b*
by (*smt abc-bcd-acd abc-sym abd-bcd-abc assms some-betw-xor*)

lemma *abd-acd-abcdacbd*:
fixes *a*::'*a* **and** *b*::'*a* **and** *c*::'*a* **and** *d*::'*a*
assumes *abd*: [[*a b d*]] **and** *acd*: [[*a c d*]] **and** *b*≠*c*
shows *betw4 a b c d* ∨ *betw4 a c b d*
proof −
obtain *P* **where** *P*∈𝒫 *a*∈*P* *b*∈*P* *d*∈*P*
using *abc-ex-path abd* **by** *blast*
have *c*∈*P*
using ‹*P* ∈ 𝒫› ‹*a* ∈ *P*› ‹*d* ∈ *P*› *abc-abc-neq acd betw-b-in-path* **by** *blast*
have ¬[[*b d c*]]
using *abc-sym abcd-dcba-only*(*5*) *abd acd* **by** *blast*
hence [[*b c d*]] ∨ [[*c b d*]]
using *abc-abc-neq abc-sym abd acd assms*(*3*) *some-betw*
by (*metis* ‹*P* ∈ 𝒫› ‹*b* ∈ *P*› ‹*c* ∈ *P*› ‹*d* ∈ *P*›)
thus *?thesis*
using *abd acd betw4-weak* **by** *blast*
qed

end

36.2 WLOG for two general symmetric relations of two elements on a single path

context *MinkowskiBetweenness* **begin**

This first one is really just trying to get a hang of how to write these things. If you have a relation that does not care which way round the "endpoints" (if Q is the interval-relation) go, then anything you want to prove about both undistinguished endpoints, follows from a proof involving a single endpoint.

lemma *wlog-sym-element*:
assumes *symmetric-rel*: $\bigwedge a\ b\ I.\ Q\ I\ a\ b \Longrightarrow Q\ I\ b\ a$
and *one-endpoint*: $\bigwedge a\ b\ x\ I.\ [\![Q\ I\ a\ b;\ x{=}a]\!] \Longrightarrow P\ x\ I$
shows *other-endpoint*: $\bigwedge a\ b\ x\ I.\ [\![Q\ I\ a\ b;\ x{=}b]\!] \Longrightarrow P\ x\ I$
using *assms* **by** *fastforce*

This one gives the most pertinent case split: a proof involving e.g. an element of an interval must consider the edge case and the inside case.

lemma *wlog-element*:
  assumes *symmetric-rel*: $\bigwedge a\ b\ I.\ Q\ I\ a\ b \Longrightarrow Q\ I\ b\ a$
    and *one-endpoint*: $\bigwedge a\ b\ x\ I.\ [\![Q\ I\ a\ b;\ x{=}a]\!] \Longrightarrow P\ x\ I$
    and *neither-endpoint*: $\bigwedge a\ b\ x\ I.\ [\![Q\ I\ a\ b;\ x{\in}I;\ (x{\neq}a \wedge x{\neq}b)]\!] \Longrightarrow P\ x\ I$
  shows *any-element*: $\bigwedge x\ I.\ [\![x{\in}I;\ (\exists\ a\ b.\ Q\ I\ a\ b)]\!] \Longrightarrow P\ x\ I$
  by (*metis assms*)

Summary of the two above. Use for early case splitting in proofs. Doesn't need P to be symmetric - the context in the conclusion is explicitly symmetric.

lemma *wlog-two-sets-element*:
  assumes *symmetric-Q*: $\bigwedge a\ b\ I.\ Q\ I\ a\ b \Longrightarrow Q\ I\ b\ a$
    and *case-split*: $\bigwedge a\ b\ c\ d\ x\ I\ J.\ [\![Q\ I\ a\ b;\ Q\ J\ c\ d]\!] \Longrightarrow$
      $(x{=}a \vee x{=}c \longrightarrow P\ x\ I\ J) \wedge (\neg(x{=}a \vee x{=}b \vee x{=}c \vee x{=}d) \longrightarrow P\ x\ I\ J)$
  shows $\bigwedge x\ I\ J.\ [\![\exists\ a\ b.\ Q\ I\ a\ b;\ \exists\ a\ b.\ Q\ J\ a\ b]\!] \Longrightarrow P\ x\ I\ J$
  by (*smt case-split symmetric-Q*)

Now we start on the actual result of interest. First we assume the events are all distinct, and we deal with the degenerate possibilities after.

lemma *wlog-endpoints-distinct1*:
  assumes *symmetric-Q*: $\bigwedge a\ b\ I.\ Q\ I\ a\ b \Longrightarrow Q\ I\ b\ a$
    and $\bigwedge I\ J\ a\ b\ c\ d.\ [\![Q\ I\ a\ b;\ Q\ J\ c\ d;\ betw4\ a\ b\ c\ d]\!] \Longrightarrow P\ I\ J$
  shows $\bigwedge I\ J\ a\ b\ c\ d.\ [\![Q\ I\ a\ b;\ Q\ J\ c\ d;$
      $betw4\ b\ a\ c\ d \vee betw4\ a\ b\ d\ c \vee betw4\ b\ a\ d\ c \vee betw4\ d\ c\ b\ a]\!] \Longrightarrow P\ I\ J$
  by (*meson abc-sym assms*(*2*) *symmetric-Q*)

lemma *wlog-endpoints-distinct2*:
  assumes *symmetric-Q*: $\bigwedge a\ b\ I.\ Q\ I\ a\ b \Longrightarrow Q\ I\ b\ a$
    and $\bigwedge I\ J\ a\ b\ c\ d.\ [\![Q\ I\ a\ b;\ Q\ J\ c\ d;\ betw4\ a\ c\ b\ d]\!] \Longrightarrow P\ I\ J$
  shows $\bigwedge I\ J\ a\ b\ c\ d.\ [\![Q\ I\ a\ b;\ Q\ J\ c\ d;$
      $betw4\ b\ c\ a\ d \vee betw4\ a\ d\ b\ c \vee betw4\ b\ d\ a\ c \vee betw4\ d\ b\ c\ a]\!] \Longrightarrow P\ I\ J$
  by (*meson abc-sym assms*(*2*) *symmetric-Q*)

lemma *wlog-endpoints-distinct3*:
  assumes *symmetric-Q*: $\bigwedge a\ b\ I.\ Q\ I\ a\ b \Longrightarrow Q\ I\ b\ a$
    and *symmetric-P*: $\bigwedge I\ J.\ [\![\exists\ a\ b.\ Q\ I\ a\ b;\ \exists\ a\ b.\ Q\ J\ a\ b;\ P\ I\ J]\!] \Longrightarrow P\ J\ I$
    and $\bigwedge I\ J\ a\ b\ c\ d.\ [\![Q\ I\ a\ b;\ Q\ J\ c\ d;\ betw4\ a\ c\ d\ b]\!] \Longrightarrow P\ I\ J$
  shows $\bigwedge I\ J\ a\ b\ c\ d.\ [\![Q\ I\ a\ b;\ Q\ J\ c\ d;$
      $betw4\ a\ d\ c\ b \vee betw4\ b\ c\ d\ a \vee betw4\ b\ d\ c\ a \vee betw4\ c\ a\ b\ d]\!] \Longrightarrow P\ I\ J$
  by (*meson assms*)

lemma (**in** *MinkowskiSpacetime*) *wlog-endpoints-distinct4*:
  fixes Q:: $('a\ set) \Rightarrow 'a \Rightarrow 'a \Rightarrow bool$
    and P:: $('a\ set) \Rightarrow ('a\ set) \Rightarrow bool$
    and A:: $('a\ set)$
  assumes *path-A*: $A{\in}\mathcal{P}$

and *symmetric-Q*: $\bigwedge a\ b\ I.\ Q\ I\ a\ b \Longrightarrow Q\ I\ b\ a$
and *Q-implies-path*: $\bigwedge a\ b\ I.\ [\![I{\subseteq}A;\ Q\ I\ a\ b]\!] \Longrightarrow b{\in}A \wedge a{\in}A$
and *symmetric-P*: $\bigwedge I\ J.\ [\![\exists\ a\ b.\ Q\ I\ a\ b;\ \exists\ a\ b.\ Q\ J\ a\ b;\ P\ I\ J]\!] \Longrightarrow P\ J\ I$
and $\bigwedge I\ J\ a\ b\ c\ d.$
$[\![Q\ I\ a\ b;\ Q\ J\ c\ d;\ I{\subseteq}A;\ J{\subseteq}A;\ betw4\ a\ b\ c\ d \vee betw4\ a\ c\ b\ d \vee betw4\ a\ c$
$d\ b]\!] \Longrightarrow P\ I\ J$
shows $\bigwedge I\ J\ a\ b\ c\ d.\ [\![Q\ I\ a\ b;\ Q\ J\ c\ d;\ I{\subseteq}A;\ J{\subseteq}A;$
$a{\neq}b \wedge a{\neq}c \wedge a{\neq}d \wedge b{\neq}c \wedge b{\neq}d \wedge c{\neq}d]\!] \Longrightarrow P\ I\ J$
proof −
fix $I\ J\ a\ b\ c\ d$
assume *asm*: $Q\ I\ a\ b\ Q\ J\ c\ d\ I \subseteq A\ J \subseteq A$
$a{\neq}b \wedge a{\neq}c \wedge a{\neq}d \wedge b{\neq}c \wedge b{\neq}d \wedge c{\neq}d$
have *endpoints-on-path*: $a{\in}A\ b{\in}A\ c{\in}A\ d{\in}A$
using *Q-implies-path asm* **by** *blast+*
show $P\ I\ J$
proof (*cases*)
assume $betw4\ b\ a\ c\ d \vee betw4\ b\ a\ d\ c \vee betw4\ b\ c\ a\ d \vee$
$betw4\ b\ d\ a\ c \vee betw4\ c\ a\ b\ d \vee betw4\ c\ b\ a\ d$
then consider $betw4\ b\ a\ c\ d | betw4\ b\ a\ d\ c | betw4\ b\ c\ a\ d |$
$betw4\ b\ d\ a\ c | betw4\ c\ a\ b\ d | betw4\ c\ b\ a\ d$
by *linarith*
thus $P\ I\ J$
apply (*cases*)
apply (*metis*(*mono-tags*) *asm*(*1*−*4*) *assms*(*5*) *symmetric-Q*)+
apply (*metis asm*(*1*−*4*) *assms*(*4*,*5*))
by (*metis asm*(*1*−*4*) *assms*(*2*,*4*,*5*) *symmetric-Q*)
next
assume $\neg(betw4\ b\ a\ c\ d \vee betw4\ b\ a\ d\ c \vee betw4\ b\ c\ a\ d \vee$
$betw4\ b\ d\ a\ c \vee betw4\ c\ a\ b\ d \vee betw4\ c\ b\ a\ d)$
hence $betw4\ a\ b\ c\ d \vee betw4\ a\ b\ d\ c \vee betw4\ a\ c\ b\ d \vee$
$betw4\ a\ c\ d\ b \vee betw4\ a\ d\ b\ c \vee betw4\ a\ d\ c\ b$
using *some-betw4b* [**where** $P{=}A$ **and** $a{=}a$ **and** $b{=}b$ **and** $c{=}c$ **and** $d{=}d$]
using *endpoints-on-path asm path-A* **by** *simp*
then consider $betw4\ a\ b\ c\ d | betw4\ a\ b\ d\ c | betw4\ a\ c\ b\ d |$
$betw4\ a\ c\ d\ b | betw4\ a\ d\ b\ c | betw4\ a\ d\ c\ b$
by *linarith*
thus $P\ I\ J$
apply (*cases*)
by (*metis asm*(*1*−*4*) *assms*(*5*) *symmetric-Q*)+
qed
qed

lemma (**in** *MinkowskiSpacetime*) *wlog-endpoints-distinct'*:
assumes $A \in \mathcal{P}$
and $\bigwedge a\ b\ I.\ Q\ I\ a\ b \Longrightarrow Q\ I\ b\ a$
and $\bigwedge a\ b\ I.\ [\![I \subseteq A;\ Q\ I\ a\ b]\!] \Longrightarrow a \in A$
and $\bigwedge I\ J.\ [\![\exists\ a\ b.\ Q\ I\ a\ b;\ \exists\ a\ b.\ Q\ J\ a\ b;\ P\ I\ J]\!] \Longrightarrow P\ J\ I$
and $\bigwedge I\ J\ a\ b\ c\ d.$

$\llbracket Q\ I\ a\ b;\ Q\ J\ c\ d;\ I{\subseteq}A;\ J{\subseteq}A;\ betw4\ a\ b\ c\ d \vee betw4\ a\ c\ b\ d \vee betw4\ a\ c\ d\ b\rrbracket \Longrightarrow P\ I\ J$
and $Q\ I\ a\ b$
and $Q\ J\ c\ d$
and $I \subseteq A$
and $J \subseteq A$
and $a \neq b\ a \neq c\ a \neq d\ b \neq c\ b \neq d\ c \neq d$
shows $P\ I\ J$
proof −
{
let *?R* = $(\lambda I.\ (\exists\ a\ b.\ Q\ I\ a\ b))$
have $\bigwedge I\ J.\ \llbracket ?R\ I;\ ?R\ J;\ P\ I\ J\rrbracket \Longrightarrow P\ J\ I$
using *assms(4)* **by** *blast*
}
thus *?thesis*
using *wlog-endpoints-distinct4*
[**where** $P=P$ **and** $Q=Q$ **and** $A=A$ **and** $I=I$ **and** $J=J$ **and** $a=a$ **and** $b=b$ **and** $c=c$ **and** $d=d$]
by (*smt assms(1−3,5−)*)
qed

lemma (**in** *MinkowskiSpacetime*) *wlog-endpoints-distinct*:
assumes *path-A*: $A{\in}\mathcal{P}$
and *symmetric-Q*: $\bigwedge a\ b\ I.\ Q\ I\ a\ b \Longrightarrow Q\ I\ b\ a$
and *Q-implies-path*: $\bigwedge a\ b\ I.\ \llbracket I{\subseteq}A;\ Q\ I\ a\ b\rrbracket \Longrightarrow b{\in}A \wedge a{\in}A$
and *symmetric-P*: $\bigwedge I\ J.\ \llbracket \exists\ a\ b.\ Q\ I\ a\ b;\ \exists\ a\ b.\ Q\ J\ a\ b;\ P\ I\ J\rrbracket \Longrightarrow P\ J\ I$
and $\bigwedge I\ J\ a\ b\ c\ d.$
$\llbracket Q\ I\ a\ b;\ Q\ J\ c\ d;\ I{\subseteq}A;\ J{\subseteq}A;\ betw4\ a\ b\ c\ d \vee betw4\ a\ c\ b\ d \vee betw4\ a\ c\ d\ b\rrbracket \Longrightarrow P\ I\ J$
shows $\bigwedge I\ J\ a\ b\ c\ d.\ \llbracket Q\ I\ a\ b;\ Q\ J\ c\ d;\ I{\subseteq}A;\ J{\subseteq}A;$
$a{\neq}b \wedge a{\neq}c \wedge a{\neq}d \wedge b{\neq}c \wedge b{\neq}d \wedge c{\neq}d\rrbracket \Longrightarrow P\ I\ J$
by (*smt* (*verit*, *ccfv-SIG*) *assms some-betw4b*)

lemma *wlog-endpoints-degenerate1*:
assumes *symmetric-Q*: $\bigwedge a\ b\ I.\ Q\ I\ a\ b \Longrightarrow Q\ I\ b\ a$
and *symmetric-P*: $\bigwedge I\ J.\ \llbracket \exists\ a\ b.\ Q\ I\ a\ b;\ \exists\ a\ b.\ Q\ I\ a\ b;\ P\ I\ J\rrbracket \Longrightarrow P\ J\ I$

and *two*: $\bigwedge I\ J\ a\ b\ c\ d.\ \llbracket Q\ I\ a\ b;\ Q\ J\ c\ d;$
$(a{=}b \wedge b{=}c \wedge c{=}d) \vee (a{=}b \wedge b{\neq}c \wedge c{=}d)\rrbracket \Longrightarrow P\ I\ J$

and *one*: $\bigwedge I\ J\ a\ b\ c\ d.\ \llbracket Q\ I\ a\ b;\ Q\ J\ c\ d;$
$(a{=}b \wedge b{=}c \wedge c{\neq}d) \vee (a{=}b \wedge b{\neq}c \wedge c{\neq}d \wedge a{\neq}d)\rrbracket \Longrightarrow P\ I\ J$

and *no*: $\bigwedge I\ J\ a\ b\ c\ d.\ \llbracket Q\ I\ a\ b;\ Q\ J\ c\ d;$
$(a{\neq}b \wedge b{\neq}c \wedge c{\neq}d \wedge a{=}d) \vee (a{\neq}b \wedge b{=}c \wedge c{\neq}d \wedge a{=}d)\rrbracket \Longrightarrow P\ I\ J$
shows $\bigwedge I\ J\ a\ b\ c\ d.\ \llbracket Q\ I\ a\ b;\ Q\ J\ c\ d;\ \neg(a{\neq}b \wedge b{\neq}c \wedge c{\neq}d \wedge a{\neq}d \wedge a{\neq}c \wedge b{\neq}d)\rrbracket \Longrightarrow P\ I\ J$

by (*metis assms*)

lemma *wlog-endpoints-degenerate2*:
assumes *symmetric-Q*: $\bigwedge a\ b\ I.\ Q\ I\ a\ b \Longrightarrow Q\ I\ b\ a$
and *Q-implies-path*: $\bigwedge a\ b\ I\ A.\ [\![I{\subseteq}A;\ A{\in}\mathcal{P};\ Q\ I\ a\ b]\!] \Longrightarrow b{\in}A \wedge a{\in}A$
and *symmetric-P*: $\bigwedge I\ J.\ [\![\exists\ a\ b.\ Q\ I\ a\ b;\ \exists\ a\ b.\ Q\ J\ a\ b;\ P\ I\ J]\!] \Longrightarrow P\ J\ I$
and $\bigwedge I\ J\ a\ b\ c\ d\ A.\ [\![Q\ I\ a\ b;\ Q\ J\ c\ d;\ I{\subseteq}A;\ J{\subseteq}A;\ A{\in}\mathcal{P};$
$[[a\ b\ c]] \wedge a{=}d]\!] \Longrightarrow P\ I\ J$
and $\bigwedge I\ J\ a\ b\ c\ d\ A.\ [\![Q\ I\ a\ b;\ Q\ J\ c\ d;\ I{\subseteq}A;\ J{\subseteq}A;\ A{\in}\mathcal{P};$
$[[b\ a\ c]] \wedge a{=}d]\!] \Longrightarrow P\ I\ J$
shows $\bigwedge I\ J\ a\ b\ c\ d\ A.\ [\![Q\ I\ a\ b;\ Q\ J\ c\ d;\ I{\subseteq}A;\ J{\subseteq}A;\ A{\in}\mathcal{P};$
$a{\neq}b \wedge b{\neq}c \wedge c{\neq}d \wedge a{=}d]\!] \Longrightarrow P\ I\ J$
proof –
have *last-case*: $\bigwedge I\ J\ a\ b\ c\ d\ A.\ [\![Q\ I\ a\ b;\ Q\ J\ c\ d;\ I{\subseteq}A;\ J{\subseteq}A;\ A{\in}\mathcal{P};$
$[[b\ c\ a]] \wedge a{=}d]\!] \Longrightarrow P\ I\ J$
using *assms*(*1*,*3*–*5*) **by** (*metis abc-sym*)
thus $\bigwedge I\ J\ a\ b\ c\ d\ A.\ [\![Q\ I\ a\ b;\ Q\ J\ c\ d;\ I{\subseteq}A;\ J{\subseteq}A;\ A{\in}\mathcal{P};$
$a{\neq}b \wedge b{\neq}c \wedge c{\neq}d \wedge a{=}d]\!] \Longrightarrow P\ I\ J$
by (*smt* (*z3*) *abc-sym assms*(*2*,*4*,*5*) *some-betw*)
qed

lemma *wlog-endpoints-degenerate*:
assumes *path-A*: $A{\in}\mathcal{P}$
and *symmetric-Q*: $\bigwedge a\ b\ I.\ Q\ I\ a\ b \Longrightarrow Q\ I\ b\ a$
and *Q-implies-path*: $\bigwedge a\ b\ I.\ [\![I{\subseteq}A;\ Q\ I\ a\ b]\!] \Longrightarrow b{\in}A \wedge a{\in}A$
and *symmetric-P*: $\bigwedge I\ J.\ [\![\exists\ a\ b.\ Q\ I\ a\ b;\ \exists\ a\ b.\ Q\ J\ a\ b;\ P\ I\ J]\!] \Longrightarrow P\ J\ I$
and $\bigwedge I\ J\ a\ b\ c\ d.\ [\![Q\ I\ a\ b;\ Q\ J\ c\ d;\ I{\subseteq}A;\ J{\subseteq}A]\!]$
$\Longrightarrow ((a{=}b \wedge b{=}c \wedge c{=}d) \longrightarrow P\ I\ J) \wedge ((a{=}b \wedge b{\neq}c \wedge c{=}d) \longrightarrow P\ I\ J)$
$\wedge ((a{=}b \wedge b{=}c \wedge c{\neq}d) \longrightarrow P\ I\ J) \wedge ((a{=}b \wedge b{\neq}c \wedge c{\neq}d \wedge a{\neq}d) \longrightarrow$
$P\ I\ J)$
$\wedge ((a{\neq}b \wedge b{=}c \wedge c{\neq}d \wedge a{=}d) \longrightarrow P\ I\ J)$
$\wedge (([[a\ b\ c]] \wedge a{=}d) \longrightarrow P\ I\ J) \wedge (([[b\ a\ c]] \wedge a{=}d) \longrightarrow P\ I\ J)$
shows $\bigwedge I\ J\ a\ b\ c\ d.\ [\![Q\ I\ a\ b;\ Q\ J\ c\ d;\ I{\subseteq}A;\ J{\subseteq}A;$
$\neg(a{\neq}b \wedge b{\neq}c \wedge c{\neq}d \wedge a{\neq}d \wedge a{\neq}c \wedge b{\neq}d)]\!] \Longrightarrow P\ I\ J$
proof –

We first extract some of the assumptions of this lemma into the form of other WLOG lemmas' assumptions.

have *ord1*: $\bigwedge I\ J\ a\ b\ c\ d.\ [\![Q\ I\ a\ b;\ Q\ J\ c\ d;\ I{\subseteq}A;\ J{\subseteq}A;$
$[[a\ b\ c]] \wedge a{=}d]\!] \Longrightarrow P\ I\ J$
using *assms*(*5*) **by** *auto*
have *ord2*: $\bigwedge I\ J\ a\ b\ c\ d.\ [\![Q\ I\ a\ b;\ Q\ J\ c\ d;\ I{\subseteq}A;\ J{\subseteq}A;$
$[[b\ a\ c]] \wedge a{=}d]\!] \Longrightarrow P\ I\ J$
using *assms*(*5*) **by** *auto*
have *last-case*: $\bigwedge I\ J\ a\ b\ c\ d.\ [\![Q\ I\ a\ b;\ Q\ J\ c\ d;\ I{\subseteq}A;\ J{\subseteq}A;$
$a{\neq}b \wedge b{\neq}c \wedge c{\neq}d \wedge a{=}d]\!] \Longrightarrow P\ I\ J$
using *ord1 ord2 wlog-endpoints-degenerate2 symmetric-P symmetric-Q Q-implies-path path-A*

by (*metis abc-sym some-betw*)
show $\bigwedge I\ J\ a\ b\ c\ d.\ [\![Q\ I\ a\ b;\ Q\ J\ c\ d;\ I{\subseteq}A;\ J{\subseteq}A;$
$\neg(a{\neq}b \wedge b{\neq}c \wedge c{\neq}d \wedge a{\neq}d \wedge a{\neq}c \wedge b{\neq}d)]\!] \Longrightarrow P\ I\ J$
proof −

Fix the sets on the path, and obtain the assumptions of *wlog-endpoints-degenerate1*.

fix $I\ J$
assume *asm1*: $I{\subseteq}A\ J{\subseteq}A$
have *two*: $\bigwedge a\ b\ c\ d.\ [\![Q\ I\ a\ b;\ Q\ J\ c\ d;\ a{=}b \wedge b{=}c \wedge c{=}d]\!] \Longrightarrow P\ I\ J$
$\bigwedge a\ b\ c\ d.\ [\![Q\ I\ a\ b;\ Q\ J\ c\ d;\ a{=}b \wedge b{\neq}c \wedge c{=}d]\!] \Longrightarrow P\ I\ J$
using ‹$J \subseteq A$› ‹$I \subseteq A$› *path-A assms*(5) **by** *blast+*
have *one*: $\bigwedge\ a\ b\ c\ d.\ [\![Q\ I\ a\ b;\ Q\ J\ c\ d;\ a{=}b \wedge b{=}c \wedge c{\neq}d]\!] \Longrightarrow P\ I\ J$
$\bigwedge\ a\ b\ c\ d.\ [\![Q\ I\ a\ b;\ Q\ J\ c\ d;\ a{=}b \wedge b{\neq}c \wedge c{\neq}d \wedge a{\neq}d]\!] \Longrightarrow P\ I\ J$
using ‹$I \subseteq A$› ‹$J \subseteq A$› *path-A assms*(5) **by** *blast+*
have *no*: $\bigwedge\ a\ b\ c\ d.\ [\![Q\ I\ a\ b;\ Q\ J\ c\ d;\ a{\neq}b \wedge b{\neq}c \wedge c{\neq}d \wedge a{=}d]\!] \Longrightarrow P\ I\ J$
$\bigwedge\ a\ b\ c\ d.\ [\![Q\ I\ a\ b;\ Q\ J\ c\ d;\ a{\neq}b \wedge b{=}c \wedge c{\neq}d \wedge a{=}d]\!] \Longrightarrow P\ I\ J$
using ‹$I \subseteq A$› ‹$J \subseteq A$› *path-A last-case* **apply** *blast*
using ‹$I \subseteq A$› ‹$J \subseteq A$› *path-A assms*(5) **by** *auto*

Now unwrap the remaining object logic and finish the proof.

fix $a\ b\ c\ d$
assume *asm2*: $Q\ I\ a\ b\ Q\ J\ c\ d\ \neg(a{\neq}b \wedge b{\neq}c \wedge c{\neq}d \wedge a{\neq}d \wedge a{\neq}c \wedge b{\neq}d)$
show $P\ I\ J$
using *two* [**where** $a{=}a$ **and** $b{=}b$ **and** $c{=}c$ **and** $d{=}d$]
using *one* [**where** $a{=}a$ **and** $b{=}b$ **and** $c{=}c$ **and** $d{=}d$]
using *no* [**where** $a{=}a$ **and** $b{=}b$ **and** $c{=}c$ **and** $d{=}d$]
using *wlog-endpoints-degenerate1*
[**where** $I{=}I$ **and** $J{=}J$ **and** $a{=}a$ **and** $b{=}b$ **and** $c{=}c$ **and** $d{=}d$ **and** $P{=}P$
and $Q{=}Q$]
using *asm1 asm2 symmetric-P last-case assms*(5) *symmetric-Q*

by *smt*
qed
qed

end

36.3 WLOG for two intervals

context *MinkowskiBetweenness* **begin**

This section just specifies the results for a generic relation Q in the previous section to the interval relation.

lemma *wlog-two-interval-element*:
assumes $\bigwedge x\ I\ J.\ [\![\textit{is-interval}\ I;\ \textit{is-interval}\ J;\ P\ x\ J\ I]\!] \Longrightarrow P\ x\ I\ J$
and $\bigwedge a\ b\ c\ d\ x\ I\ J.\ [\![I = \textit{interval}\ a\ b;\ J = \textit{interval}\ c\ d]\!] \Longrightarrow$
$(x{=}a \vee x{=}c \longrightarrow P\ x\ I\ J) \wedge (\neg(x{=}a \vee x{=}b \vee x{=}c \vee x{=}d) \longrightarrow P\ x\ I\ J)$
shows $\bigwedge x\ I\ J.\ [\![\textit{is-interval}\ I;\ \textit{is-interval}\ J]\!] \Longrightarrow P\ x\ I\ J$

by (*metis assms*(*2*) *int-sym*)

lemma (**in** *MinkowskiSpacetime*) *wlog-interval-endpoints-distinct*:
assumes $\bigwedge I\ J.\ [\![\mathit{is\text{-}interval}\ I;\ \mathit{is\text{-}interval}\ J;\ P\ I\ J]\!] \Longrightarrow P\ J\ I$
$\bigwedge I\ J\ a\ b\ c\ d.\ [\![I = \mathit{interval}\ a\ b;\ J = \mathit{interval}\ c\ d]\!]$
$\Longrightarrow (\mathit{betw4}\ a\ b\ c\ d \longrightarrow P\ I\ J) \wedge (\mathit{betw4}\ a\ c\ b\ d \longrightarrow P\ I\ J) \wedge (\mathit{betw4}\ a\ c\ d\ b \longrightarrow P\ I\ J)$
shows $\bigwedge I\ J\ Q\ a\ b\ c\ d.\ [\![I = \mathit{interval}\ a\ b;\ J = \mathit{interval}\ c\ d;\ I{\subseteq}Q;\ J{\subseteq}Q;\ Q{\in}\mathcal{P};$
$a{\neq}b \wedge a{\neq}c \wedge a{\neq}d \wedge b{\neq}c \wedge b{\neq}d \wedge c{\neq}d]\!] \Longrightarrow P\ I\ J$
proof −
let $?Q = \lambda\ I\ a\ b.\ I = \mathit{interval}\ a\ b$

fix $I\ J\ A\ a\ b\ c\ d$
assume *asm*: $?Q\ I\ a\ b\ ?Q\ J\ c\ d\ I{\subseteq}A\ J{\subseteq}A\ A{\in}\mathcal{P}\ a{\neq}b \wedge a{\neq}c \wedge a{\neq}d \wedge b{\neq}c \wedge b{\neq}d \wedge c{\neq}d$
show $P\ I\ J$
proof (*rule wlog-endpoints-distinct*)
show $\bigwedge a\ b\ I.\ ?Q\ I\ a\ b \Longrightarrow ?Q\ I\ b\ a$
by (*simp add*: *int-sym*)
show $\bigwedge a\ b\ I.\ I \subseteq A \Longrightarrow ?Q\ I\ a\ b \Longrightarrow b \in A \wedge a \in A$
by (*simp add*: *ends-in-int subset-iff*)
show $\bigwedge I\ J.\ \mathit{is\text{-}interval}\ I \Longrightarrow \mathit{is\text{-}interval}\ J \Longrightarrow P\ I\ J \Longrightarrow P\ J\ I$
using *assms*(*1*) **by** *blast*
show $\bigwedge I\ J\ a\ b\ c\ d.\ [\![?Q\ I\ a\ b;\ ?Q\ J\ c\ d;\ \mathit{betw4}\ a\ b\ c\ d \vee \mathit{betw4}\ a\ c\ b\ d \vee \mathit{betw4}\ a\ c\ d\ b]\!]$
$\Longrightarrow P\ I\ J$
by (*meson assms*(*2*))
show $I = \mathit{interval}\ a\ b\ J = \mathit{interval}\ c\ d\ I{\subseteq}A\ J{\subseteq}A\ A{\in}\mathcal{P}$
$a{\neq}b \wedge a{\neq}c \wedge a{\neq}d \wedge b{\neq}c \wedge b{\neq}d \wedge c{\neq}d$
using *asm* **by** *simp+*
qed
qed

lemma *wlog-interval-endpoints-degenerate*:
assumes *symmetry*: $\bigwedge I\ J.\ [\![\mathit{is\text{-}interval}\ I;\ \mathit{is\text{-}interval}\ J;\ P\ I\ J]\!] \Longrightarrow P\ J\ I$
and $\bigwedge I\ J\ a\ b\ c\ d\ Q.\ [\![I = \mathit{interval}\ a\ b;\ J = \mathit{interval}\ c\ d;\ I{\subseteq}Q;\ J{\subseteq}Q;\ Q{\in}\mathcal{P}]\!]$
$\Longrightarrow ((a{=}b \wedge b{=}c \wedge c{=}d) \longrightarrow P\ I\ J) \wedge ((a{=}b \wedge b{\neq}c \wedge c{=}d) \longrightarrow P\ I\ J)$
$\wedge ((a{=}b \wedge b{=}c \wedge c{\neq}d) \longrightarrow P\ I\ J) \wedge ((a{=}b \wedge b{\neq}c \wedge c{\neq}d \wedge a{\neq}d) \longrightarrow P\ I\ J)$
$\wedge ((a{\neq}b \wedge b{=}c \wedge c{\neq}d \wedge a{=}d) \longrightarrow P\ I\ J)$
$\wedge (([[a\ b\ c]] \wedge a{=}d) \longrightarrow P\ I\ J) \wedge (([[b\ a\ c]] \wedge a{=}d) \longrightarrow P\ I\ J)$
shows $\bigwedge I\ J\ a\ b\ c\ d\ Q.\ [\![I = \mathit{interval}\ a\ b;\ J = \mathit{interval}\ c\ d;\ I{\subseteq}Q;\ J{\subseteq}Q;\ Q{\in}\mathcal{P};$
$\neg(a{\neq}b \wedge b{\neq}c \wedge c{\neq}d \wedge a{\neq}d \wedge a{\neq}c \wedge b{\neq}d)]\!] \Longrightarrow P\ I\ J$
proof −
let $?Q = \lambda\ I\ a\ b.\ I = \mathit{interval}\ a\ b$

fix $I\ J\ a\ b\ c\ d\ A$

assume *asm*: $?Q\ I\ a\ b\ ?Q\ J\ c\ d\ I{\subseteq}A\ J{\subseteq}A\ A{\in}\mathcal{P}\ \neg(a{\neq}b \wedge b{\neq}c \wedge c{\neq}d \wedge a{\neq}d \wedge a{\neq}c \wedge b{\neq}d)$
show $P\ I\ J$
proof (*rule wlog-endpoints-degenerate*)
show $\bigwedge a\ b\ I.\ ?Q\ I\ a\ b \Longrightarrow ?Q\ I\ b\ a$
by (*simp add*: *int-sym*)
show $\bigwedge a\ b\ I.\ I \subseteq A \Longrightarrow ?Q\ I\ a\ b \Longrightarrow b \in A \wedge a \in A$
by (*simp add*: *ends-in-int subset-iff*)
show $\bigwedge I\ J.$ *is-interval* $I \Longrightarrow$ *is-interval* $J \Longrightarrow P\ I\ J \Longrightarrow P\ J\ I$
using *symmetry* **by** *blast*
show $I =$ *interval* $a\ b\ J =$ *interval* $c\ d\ I{\subseteq}A\ J{\subseteq}A\ A{\in}\mathcal{P}$
$\neg\ (a{\neq}b \wedge b{\neq}c \wedge c{\neq}d \wedge a{\neq}d \wedge a{\neq}c \wedge b{\neq}d)$
using *asm* **by** *auto+*
show $\bigwedge I\ J\ a\ b\ c\ d.\ [\![?Q\ I\ a\ b;\ ?Q\ J\ c\ d;\ I \subseteq A;\ J \subseteq A]\!] \Longrightarrow$
$(a = b \wedge b = c \wedge c = d \longrightarrow P\ I\ J) \wedge$
$(a = b \wedge b \neq c \wedge c = d \longrightarrow P\ I\ J) \wedge$
$(a = b \wedge b = c \wedge c \neq d \longrightarrow P\ I\ J) \wedge$
$(a = b \wedge b \neq c \wedge c \neq d \wedge a \neq d \longrightarrow P\ I\ J) \wedge$
$(a \neq b \wedge b = c \wedge c \neq d \wedge a = d \longrightarrow P\ I\ J) \wedge$
$([[a\ b\ c]] \wedge a = d \longrightarrow P\ I\ J) \wedge ([[b\ a\ c]] \wedge a = d \longrightarrow P\ I\ J)$
using *assms*(*2*) ‹$A{\in}\mathcal{P}$› **by** *auto*
qed
qed

end

37 Interlude: Intervals, Segments, Connectedness

context *MinkowskiSpacetime* **begin**

In this secion, we apply the WLOG lemmas from the previous section in order to reduce the number of cases we need to consider when thinking about two arbitrary intervals on a path. This is used to prove that the (countable) intersection of intervals is an interval. These results cannot be found in Schutz, but he does use them (without justification) in his proof of Theorem 12 (even for uncountable intersections).

lemma *int-of-ints-is-interval-neq*:
assumes $I1 =$ *interval* $a\ b\ I2 =$ *interval* $c\ d\ I1{\subseteq}P\ I2{\subseteq}P\ P{\in}\mathcal{P}\ I1{\cap}I2 \neq \{\}$
and *events-neq*: $a{\neq}b\ a{\neq}c\ a{\neq}d\ b{\neq}c\ b{\neq}d\ c{\neq}d$
shows *is-interval* $(I1 \cap I2)$
proof −
have *on-path*: $a{\in}P \wedge b{\in}P \wedge c{\in}P \wedge d{\in}P$
using *assms*(*1*−*4*) *interval-def* **by** *auto*

let $?prop = \lambda\ I\ J.$ *is-interval* $(I{\cap}J) \vee (I{\cap}J) = \{\}$

have *symmetry*: $(\bigwedge I\ J.$ *is-interval* $I \Longrightarrow$ *is-interval* $J \Longrightarrow ?prop\ I\ J \Longrightarrow ?prop\ J\ I)$

```
    by (simp add: Int-commute)

  {
    fix I J a b c d
    assume I = interval a b J = interval c d
    have (betw4 a b c d ⟶ ?prop I J)
         (betw4 a c b d ⟶ ?prop I J)
         (betw4 a c d b ⟶ ?prop I J)
    proof (rule-tac [!] impI)
      assume betw4 a b c d
      have I∩J = {}
      proof (rule ccontr)
        assume I∩J≠{}
        then obtain x where x∈I∩J
          by blast
        show False
        proof (cases)
          assume x≠a ∧ x≠b ∧ x≠c ∧ x≠d
          hence [[a x b]] [[c x d]]
            using ‹I=interval a b› ‹x∈I∩J› ‹J=interval c d› ‹x∈I∩J›
            by (simp add: interval-def seg-betw)+
          thus False
            by (meson ‹betw4 a b c d› abc-only-cba(3) abc-sym abd-bcd-abc)
        next
          assume ¬(x≠a ∧ x≠b ∧ x≠c ∧ x≠d)
          thus False
                 using interval-def seg-betw ‹I = interval a b› ‹J = interval c d›
abcd-dcba-only(21)
                ‹x ∈ I ∩ J› ‹betw4 a b c d› abc-bcd-abd abc-bcd-acd abc-only-cba(1,2)
            by (metis (full-types) insert-iff Int-iff)
        qed
      qed
      thus ?prop I J by simp
    next
      assume betw4 a c b d
      then have a ≠ b ∧ a ≠ c ∧ a ≠ d ∧ b ≠ c ∧ b ≠ d ∧ c ≠ d
        using betw4-imp-neq by blast
      have I∩J = interval c b
      proof (safe)
        fix x
        assume x ∈ interval c b
        {
          assume x=b ∨ x=c
          hence x∈I
            using ‹betw4 a c b d› ‹I = interval a b› interval-def seg-betw by auto
          have x∈J
            using ‹x=b ∨ x=c›
            using ‹betw4 a c b d› ‹J = interval c d› interval-def seg-betw by auto
          hence x∈I ∧ x∈J using ‹x ∈ I› by blast
```

```
      } moreover {
        assume ¬(x=b ∨ x=c)
        hence [[c x b]]
          using ‹x∈interval c b› unfolding interval-def segment-def by simp
        hence [[a x b]]
          by (meson ‹betw4 a c b d› abc-acd-abd abc-sym)
        have [[c x d]]
          using ‹betw4 a c b d› ‹[[c x b]]› abc-acd-abd by blast
        have x∈I x∈J
          using ‹I = interval a b› ‹[[a x b]]› ‹J = interval c d› ‹[[c x d]]›
                interval-def seg-betw by auto
      }
      ultimately show x∈I x∈J by blast+
    next
      fix x
      assume x∈I x∈J
      show x ∈ interval c b
      proof (cases)
        assume not-eq: x≠a ∧ x≠b ∧ x≠c ∧ x≠d
        have [[a x b]] [[c x d]]
          using ‹x∈I› ‹I = interval a b›  ‹x∈J› ‹J = interval c d›
                not-eq unfolding interval-def segment-def by blast+
        hence [[c x b]]
          by (meson ‹betw4 a c b d› abc-bcd-acd betw4-weak)
        thus ?thesis
          unfolding interval-def segment-def using seg-betw segment-def by auto
      next
        assume not-not-eq: ¬(x≠a ∧ x≠b ∧ x≠c ∧ x≠d)
        {
          assume x=a
          have ¬[[d a c]]
            using ‹betw4 a c b d› abcd-dcba-only(9) by blast
          hence a ∉ interval c d unfolding interval-def segment-def
            using abc-sym ‹a ≠ b ∧ a ≠ c ∧ a ≠ d ∧ b ≠ c ∧ b ≠ d ∧ c ≠ d› by
blast
          hence False using ‹x∈J› ‹J = interval c d› ‹x=a› by blast
        } moreover {
          assume x=d
          have ¬[[a d b]] using ‹betw4 a c b d› abc-sym abcd-dcba-only(9) by blast
          hence d∉interval a b unfolding interval-def segment-def
            using ‹a ≠ b ∧ a ≠ c ∧ a ≠ d ∧ b ≠ c ∧ b ≠ d ∧ c ≠ d› by blast
          hence False using ‹x∈I› ‹x=d› ‹I = interval a b› by blast
        }
        ultimately show ?thesis
          using interval-def not-not-eq by auto
      qed
    qed
    thus ?prop I J by auto
  next
```

assume *betw4 a c d b*
have *I*∩*J* = *interval c d*
proof (*safe*)
fix *x*
assume *x* ∈ *interval c d*
{
assume *x*≠*c* ∧ *x*≠*d*
have *x* ∈ *J*
by (*simp add*: ‹*J* = *interval c d*› ‹*x* ∈ *interval c d*›)
have [[*c x d*]]
using ‹*x* ∈ *interval c d*› ‹*x* ≠ *c* ∧ *x* ≠ *d*› *interval-def seg-betw* **by** *auto*
have [[*a x b*]]
by (*meson* ‹*betw4 a c d b*› ‹[[*c x d*]]› *abc-bcd-abd abc-sym abe-ade-bcd-ace*)
have *x* ∈ *I*
using ‹*I* = *interval a b*› ‹[[*a x b*]]› *interval-def seg-betw* **by** *auto*
hence *x*∈*I* ∧ *x*∈*J* **by** (*simp add*: ‹*x* ∈ *J*›)
} moreover {
assume ¬ (*x*≠*c* ∧ *x*≠*d*)
hence *x*∈*I* ∧ *x*∈*J*
by (*metis* ‹*I* = *interval a b*› ‹*J* = *interval c d*› ‹*betw4 a c d b*› ‹*x* ∈ *interval c d*›
abc-bcd-abd abc-bcd-acd insertI2 interval-def seg-betw)
}
ultimately show *x*∈*I* *x*∈*J* **by** *blast+*
next
fix *x*
assume *x*∈*I* *x*∈*J*
show *x* ∈ *interval c d*
using ‹*J* = *interval c d*› ‹*x* ∈ *J*› **by** *auto*
qed
thus *?prop I J* **by** *auto*
qed
}

then show *is-interval* (*I1*∩*I2*)
using *wlog-interval-endpoints-distinct*
[**where** *P*=*?prop* **and** *I*=*I1* **and** *J*=*I2* **and** *Q*=*P* **and** *a*=*a* **and** *b*=*b* **and** *c*=*c* **and** *d*=*d*]
using *symmetry assms* **by** *simp*
qed

lemma *int-of-ints-is-interval-deg*:
assumes *I* = *interval a b* *J* = *interval c d* *I*∩*J* ≠ {} *I*⊆*P* *J*⊆*P* *P*∈𝒫
and *events-deg*: ¬(*a*≠*b* ∧ *b*≠*c* ∧ *c*≠*d* ∧ *a*≠*d* ∧ *a*≠*c* ∧ *b*≠*d*)
shows *is-interval* (*I* ∩ *J*)
proof −

let *?p* = λ *I J*. (*is-interval* (*I* ∩ *J*) ∨ *I*∩*J* = {})

have *symmetry*: $\bigwedge I\ J.\ [\![is\text{-}interval\ I;\ is\text{-}interval\ J;\ ?p\ I\ J]\!] \Longrightarrow ?p\ J\ I$
by (*simp add*: *inf-commute*)

have *degen-cases*: $\bigwedge I\ J\ a\ b\ c\ d\ Q.\ [\![I = interval\ a\ b;\ J = interval\ c\ d;\ I \subseteq Q;$ $J \subseteq Q;\ Q \in \mathcal{P}]\!]$
$\Longrightarrow ((a=b \wedge b=c \wedge c=d) \longrightarrow ?p\ I\ J) \wedge ((a=b \wedge b \neq c \wedge c=d) \longrightarrow ?p\ I$ $J)$
$\wedge ((a=b \wedge b=c \wedge c \neq d) \longrightarrow ?p\ I\ J) \wedge ((a=b \wedge b \neq c \wedge c \neq d \wedge a \neq d)$ $\longrightarrow ?p\ I\ J)$
$\wedge ((a \neq b \wedge b=c \wedge c \neq d \wedge a=d) \longrightarrow ?p\ I\ J)$
$\wedge (([[a\ b\ c]] \wedge a=d) \longrightarrow ?p\ I\ J) \wedge (([[b\ a\ c]] \wedge a=d) \longrightarrow ?p\ I\ J)$
proof −
fix $I\ J\ a\ b\ c\ d\ Q$
assume $I = interval\ a\ b\ J = interval\ c\ d\ I \subseteq Q\ J \subseteq Q\ Q \in \mathcal{P}$
show $((a=b \wedge b=c \wedge c=d) \longrightarrow ?p\ I\ J) \wedge ((a=b \wedge b \neq c \wedge c=d) \longrightarrow ?p\ I\ J)$
$\wedge ((a=b \wedge b=c \wedge c \neq d) \longrightarrow ?p\ I\ J) \wedge ((a=b \wedge b \neq c \wedge c \neq d \wedge a \neq d)$ $\longrightarrow ?p\ I\ J)$
$\wedge ((a \neq b \wedge b=c \wedge c \neq d \wedge a=d) \longrightarrow ?p\ I\ J)$
$\wedge (([[a\ b\ c]] \wedge a=d) \longrightarrow ?p\ I\ J) \wedge (([[b\ a\ c]] \wedge a=d) \longrightarrow ?p\ I\ J)$
proof (*intro conjI7 impI*)
assume $a = b \wedge b = c \wedge c = d$ **thus** $?p\ I\ J$
using ‹$I = interval\ a\ b$› ‹$J = interval\ c\ d$› **by** *auto*
next
assume $a = b \wedge b \neq c \wedge c = d$ **thus** $?p\ I\ J$
using ‹$J = interval\ c\ d$› *empty-segment interval-def* **by** *auto*
next
assume $a = b \wedge b = c \wedge c \neq d$ **thus** $?p\ I\ J$
using ‹$I = interval\ a\ b$› *empty-segment interval-def* **by** *auto*
next
assume $a = b \wedge b \neq c \wedge c \neq d \wedge a \neq d$ **thus** $?p\ I\ J$
using ‹$I = interval\ a\ b$› *empty-segment interval-def* **by** *auto*
next
assume $a \neq b \wedge b = c \wedge c \neq d \wedge a = d$ **thus** $?p\ I\ J$
using ‹$I = interval\ a\ b$› ‹$J = interval\ c\ d$› *int-sym* **by** *auto*
next
assume $[[a\ b\ c]] \wedge a = d$ **show** $?p\ I\ J$
proof (*cases*)
assume $I \cap J = \{\}$ **thus** *?thesis* **by** *simp*
next
assume $I \cap J \neq \{\}$
have $I \cap J = interval\ a\ b$
proof (*safe*)
fix x **assume** $x \in I\ x \in J$
thus $x \in interval\ a\ b$
using ‹$I = interval\ a\ b$› **by** *blast*
next
fix x **assume** $x \in interval\ a\ b$
show $x \in I$

```
          by (simp add: ‹I = interval a b› ‹x ∈ interval a b›)
        have [[d b c]]
          using ‹[[a b c]] ∧ a = d› by blast
        have [[a x b]] ∨ x=a ∨ x=b
          using ‹I = interval a b› ‹x ∈ I› interval-def seg-betw by auto
        consider [[d x c]]|x=a ∨ x=b
         using ‹[[a b c]] ∧ a = d› ‹[[a x b]] ∨ x = a ∨ x = b› abc-acd-abd by blast
        thus x∈J
        proof (cases)
          case 1
          then show ?thesis
               by (simp add: ‹J = interval c d› abc-abc-neq abc-sym interval-def
seg-betw)
        next
          case 2
          then have x ∈ interval c d
            using ‹[[a b c]] ∧ a = d› int-sym interval-def seg-betw
            by force
          then show ?thesis
            using ‹J = interval c d› by blast
        qed
      qed
      thus ?p I J by blast
    qed
  next
    assume [[b a c]] ∧ a = d show ?p I J
    proof (cases)
      assume I∩J = {} thus ?thesis by simp
    next
      assume I∩J ≠ {}
      have I∩J = {a}
      proof (safe)
        fix x assume x∈I x∈J x∉{}
        have cxd: [[c x d]] ∨ x=c ∨ x=d
          using ‹J = interval c d› ‹x ∈ J› interval-def seg-betw by auto
        consider [[a x b]]|x=a|x=b
          using ‹I = interval a b› ‹x ∈ I› interval-def seg-betw by auto
        then show x=a
        proof (cases)
          assume [[a x b]]
          hence betw4 b x d c
            using ‹[[b a c]] ∧ a = d› abc-acd-bcd abc-sym by meson
          hence False
            using cxd abc-abc-neq by blast
          thus ?thesis by simp
        next
          assume x=b
          hence [[b d c]]
            using ‹[[b a c]] ∧ a = d› by blast
```

hence *False*
using *cxd* ‹$x = b$› *abc-abc-neq* **by** *blast*
thus *?thesis*
by *simp*
next
assume $x{=}a$ **thus** $x{=}a$ **by** *simp*
qed
next
show $a{\in}I$
by (*simp add*: ‹I = *interval a b*› *ends-in-int*)
show $a{\in}J$
by (*simp add*: ‹J = *interval c d*› ‹$[[b\ a\ c]] \wedge a = d$› *ends-in-int*)
qed
thus *?p I J*
by (*simp add*: *empty-segment interval-def*)
qed
qed
qed

have *?p I J*
using *wlog-interval-endpoints-degenerate*
[**where** $P{=}?p$ **and** $I{=}I$ **and** $J{=}J$ **and** $a{=}a$ **and** $b{=}b$ **and** $c{=}c$ **and** $d{=}d$ **and** $Q{=}P$]
using *degen-cases*
using *symmetry assms*
by *smt*

thus *?thesis*
using *assms*(*3*) **by** *blast*
qed

lemma *int-of-ints-is-interval*:
assumes *is-interval I is-interval J* $I{\subseteq}P$ $J{\subseteq}P$ $P{\in}\mathcal{P}$ $I{\cap}J \neq \{\}$
shows *is-interval* ($I \cap J$)
using *int-of-ints-is-interval-neq int-of-ints-is-interval-deg*
by (*meson assms*)

lemma *int-of-ints-is-interval2*:
assumes $\forall\, x{\in}S.$ (*is-interval* $x \wedge x{\subseteq}P$) $P{\in}\mathcal{P}$ $\bigcap S \neq \{\}$ *finite S* $S{\neq}\{\}$
shows *is-interval* ($\bigcap S$)
proof −
obtain *n* **where** n = *card S*
by *simp*
consider $n{=}0|n{=}1|n{\geq}2$
by *linarith*
thus *?thesis*
proof (*cases*)

```
    assume n=0
    then have False
      using ‹n = card S› assms(4,5) by simp
    thus ?thesis
      by simp
  next
    assume n=1
    then obtain I where S = {I}
      using ‹n = card S› card-1-singletonE by auto
    then have ⋂ S = I
      by simp
    moreover have is-interval I
      by (simp add: ‹S = {I}› assms(1))
    ultimately show ?thesis
      by blast
  next
    assume 2≤n
    obtain m where m+2=n
      using ‹2 ≤ n› le-add-diff-inverse2 by blast
    have ind: ⋀S. ⟦∀ x∈S. (is-interval x ∧ x⊆P); P∈𝒫; ⋂ S ≠ {}; finite S; S≠{};
m+2=card S⟧
      ⟹ is-interval (⋂ S)
    proof (induct m)
      case 0
      then have card S = 2
        by auto
      then obtain I J where S={I,J} I≠J
        by (meson card-2-iff)
      then have I∈S J∈S
        by blast+
      then have is-interval I is-interval J I⊆P J⊆P
          by (simp add: 0.prems(1))+
      also have I∩J ≠ {}
        using ‹S={I,J}› 0.prems(3) by force
      then have is-interval(I∩J)
       using assms(2) calculation int-of-ints-is-interval[where I=I and J=J and
P=P]
        by fastforce
      then show ?case
        by (simp add: ‹S = {I, J}›)
    next
      case (Suc m)
      obtain S' I where I∈S S = insert I S' I∉S'
        using Suc.prems(4,5) by (metis Set.set-insert finite.simps insertI1)
      then have is-interval (⋂ S')
      proof –
        have m+2 = card S'
          using Suc.prems(4,6) ‹S = insert I S'› ‹I∉S'› by auto
        moreover have ∀ x∈S'. is-interval x ∧ x ⊆ P
```

by (*simp add*: *Suc.prems*(*1*) ‹S = *insert* I S'›)
moreover have $\bigcap\ S' \neq \{\}$
using *Suc.prems*(*3*) ‹S = *insert* I S'› **by** *auto*
moreover have *finite* S'
using *Suc.prems*(*4*) ‹S = *insert* I S'› **by** *auto*
ultimately show *?thesis*
using *assms*(*2*) *Suc*(*1*) [**where** S=S'] **by** *fastforce*
qed
then have *is-interval* $((\bigcap S') \cap I)$
proof (*rule int-of-ints-is-interval*)
show *is-interval* I
by (*simp add*: *Suc.prems*(*1*) ‹$I \in S$›)
show $\bigcap S' \subseteq P$
using ‹$I \notin S'$› ‹S = *insert* I S'› *Suc.prems*(*1*,*4*,*6*) *Inter-subset*
by (*metis Suc-n-not-le-n card.empty card-insert-disjoint finite-insert le-add2 numeral-2-eq-2 subset-eq subset-insertI*)
show $I \subseteq P$
by (*simp add*: *Suc.prems*(*1*) ‹$I \in S$›)
show $P \in \mathcal{P}$
using *assms*(*2*) **by** *auto*
show $\bigcap S' \cap I \neq \{\}$
using *Suc.prems*(*3*) ‹S = *insert* I S'› **by** *auto*
qed
thus *?case*
using ‹S = *insert* I S'› **by** (*simp add*: *inf.commute*)
qed
then show *?thesis*
using ‹$m + 2 = n$› ‹n = *card* S› *assms* **by** *blast*
qed
qed

end

38 3.7 Continuity and the monotonic sequence property

context *MinkowskiSpacetime* **begin**

This section only includes a proof of the first part of Theorem 12, as well as some results that would be useful in proving part (ii).

theorem *two-rays*:
assumes *path-Q*: $Q \in \mathcal{P}$
and *event-a*: $a \in Q$
shows $\exists R\ L.$ (*is-ray-on* R Q $\wedge$ *is-ray-on* L Q
$\wedge\ Q - \{a\} \subseteq (R \cup L)$ ~~events of Q excl. a belong to two rays~~
$\wedge\ (\forall r \in R.\ \forall l \in L.\ [[l\ a\ r]])$ ~~a is betw any "a" of one ray and any "a" of the other~~

```
        ∧ (∀x∈R. ∀y∈R. ¬ [[x a y]])      — but a is not betw any two events ...
        ∧ (∀x∈L. ∀y∈L. ¬ [[x a y]]))     — ... of the same ray
proof –
```

Schutz here uses Theorem 6, but we don't need it.

```
  obtain b where b∈ℰ and b∈Q and b≠a
    using event-a ge2-events in-path-event path-Q by blast
  let ?L = {x. [[x a b]]}
  let ?R = {y. [[a y b]] ∨ [[a b y]]}
  have Q = ?L ∪ {a} ∪ ?R
  proof –
    have inQ: ∀x∈Q. [[x a b]] ∨ x=a ∨ [[a x b]] ∨ [[a b x]]
      by (meson ‹b ∈ Q› ‹b ≠ a› abc-sym event-a path-Q some-betw)
    show ?thesis
    proof (safe)
      fix x
      assume x ∈ Q x ≠ a ¬ [[x a b]] ¬ [[a x b]] b ≠ x
      then show [[a b x]]
        using inQ by blast
    next
      fix x
      assume [[x a b]]
      then show x ∈ Q
        by (simp add: ‹b ∈ Q› abc-abc-neq betw-a-in-path event-a path-Q)
    next
      show a ∈ Q
        by (simp add: event-a)
    next
      fix x
      assume [[a x b]]
      then show  x ∈ Q
        by (simp add: ‹b ∈ Q› abc-abc-neq betw-b-in-path event-a path-Q)
    next
      fix x
      assume [[a b x]]
      then show  x ∈ Q
        by (simp add: ‹b ∈ Q› abc-abc-neq betw-c-in-path event-a path-Q)
    next
      show b ∈ Q using ‹b ∈ Q› .
    qed
  qed
  have disjointLR: ?L ∩ ?R = {}
    using abc-abc-neq abc-only-cba by blast

  have wxyz-ord: nonstrict-betw-right4 x a y b ∨ nonstrict-betw-right4 x a b y
      ∧ (([[w x a]] ∧ [[x a y]]) ∨ ([[x w a]] ∧ [[w a y]]))
      ∧ (([[x a y]] ∧ [[a y z]]) ∨ ([[x a z]] ∧ [[a z y]]))
    if x∈?L w∈?L y∈?R z∈?R w≠x y≠z for x w y z
    using path-finsubset-chain order-finite-chain2
```

by (*smt abc-abd-bcdbdc abc-bcd-abd abc-sym abd-bcd-abc mem-Collect-eq that*)

obtain *x y* **where** $x \in ?L$ $y \in ?R$
by (*metis* (*mono-tags*) ‹$b \in Q$› ‹$b \neq a$› *abc-sym event-a mem-Collect-eq path-Q prolong-betw2*)
obtain *w* **where** $w \in ?L$ $w \neq x$
by (*metis* ‹$b \in Q$› ‹$b \neq a$› *abc-sym event-a mem-Collect-eq path-Q prolong-betw3*)

obtain *z* **where** $z \in ?R$ $y \neq z$
by (*metis* (*mono-tags*) ‹$b \in Q$› ‹$b \neq a$› *event-a mem-Collect-eq path-Q prolong-betw3*)

have *is-ray-on ?R Q* $\wedge$
is-ray-on ?L Q $\wedge$
$Q - \{a\} \subseteq ?R \cup ?L$ $\wedge$
$(\forall r \in ?R.\ \forall l \in ?L.\ [[l\ a\ r]])$ $\wedge$
$(\forall x \in ?R.\ \forall y \in ?R.\ \neg\ [[x\ a\ y]])$ $\wedge$
$(\forall x \in ?L.\ \forall y \in ?L.\ \neg\ [[x\ a\ y]])$
proof (*rule conjI6*)
show *is-ray-on ?L Q*
proof (*unfold is-ray-on-def*, *safe*)
show $Q \in \mathcal{P}$
by (*simp add*: *path-Q*)
next
fix *x*
assume $[[x\ a\ b]]$
then show $x \in Q$
using ‹$b \in Q$› ‹$b \neq a$› *betw-a-in-path event-a path-Q* **by** *blast*
next
show *is-ray* $\{x.\ [[x\ a\ b]]\}$
proof −
have $[[x\ a\ b]]$
using ‹$x \in ?L$› **by** *simp*
have $?L = ray\ a\ x$
proof
show $ray\ a\ x \subseteq ?L$
proof
fix *e* **assume** $e \in ray\ a\ x$
show $e \in ?L$
using *wxyz-ord ray-cases abc-bcd-abd abd-bcd-abc abc-sym*
by (*metis* ‹$[[x\ a\ b]]$› ‹$e \in ray\ a\ x$› *mem-Collect-eq*)
qed
show $?L \subseteq ray\ a\ x$
proof
fix *e* **assume** $e \in ?L$
hence $[[e\ a\ b]]$
by *simp*
show $e \in ray\ a\ x$
proof (*cases*)

```
          assume e=x
          thus ?thesis
            by (simp add: ray-def)
        next
          assume e≠x
          hence [[e x a]] ∨ [[x e a]] using wxyz-ord
            by (meson ‹[[e a b]]› ‹[[x a b]]› abc-abd-bcdbdc abc-sym)
          thus e∈ray a x
            by (metis Un-iff abc-sym insertCI pro-betw ray-def seg-betw)
        qed
      qed
    qed
    thus is-ray ?L by auto
  qed
qed

show is-ray-on ?R Q
proof (unfold is-ray-on-def, safe)
  show Q ∈ 𝒫
    by (simp add: path-Q)
next
  fix x
  assume [[a x b]]
  then show x ∈ Q
    by (simp add: ‹b ∈ Q› abc-abc-neq betw-b-in-path event-a path-Q)
next
  fix x
  assume [[a b x]]
  then show x ∈ Q
    by (simp add: ‹b ∈ Q› abc-abc-neq betw-c-in-path event-a path-Q)
next
  show b ∈ Q using ‹b ∈ Q› .
next
  show is-ray {y. [[a y b]] ∨ [[a b y]]}
  proof −
    have [[a y b]] ∨ [[a b y]] ∨ y=b
      using ‹y∈?R› by blast
    have ?R = ray a y
    proof
      show ray a y ⊆ ?R
      proof
        fix e assume e∈ray a y
        hence [[a e y]] ∨ [[a y e]] ∨ y=e
          using ray-cases by auto
        show e∈?R
        proof −
          { assume e ≠ b
            have (e ≠ y ∧ e ≠ b) ∧ [[w a y]] ∨ [[a e b]] ∨ [[a b e⟧
             using ‹[[a y b]] ∨ [[a b y]] ∨ y = b› ‹w ∈ {x. [[x a b]]}› abd-bcd-abc by
```

blast

```
          hence [[a e b]] ∨ [[a b e]]
            using abc-abd-bcdbdc abc-bcd-abd abd-bcd-abc
            by (metis ‹[[a e y]] ∨ [[a y e]]› ‹w ∈ ?L› mem-Collect-eq)
        }
        thus ?thesis
          by blast
      qed
    qed
    show ?R ⊆ ray a y
    proof
      fix e assume e∈?R
      hence aeb-cases: [[a e b]] ∨ [[a b e]] ∨ e=b
        by blast
      hence aey-cases: [[a e y]] ∨ [[a y e]] ∨ e=y
        using abc-abd-bcdbdc abc-bcd-abd abd-bcd-abc
       by (metis ‹[[a y b]] ∨ [[a b y]] ∨ y = b› ‹x ∈ {x. [[x a b]]}› mem-Collect-eq)
      show e∈ray a y
      proof –
        {
          assume e=b
          hence ?thesis
            using ‹[[a y b]] ∨ [[a b y]] ∨ y = b› ‹b ≠ a› pro-betw ray-def seg-betw
by auto
        } moreover {
          assume [[a e b]] ∨ [[a b e]]
          assume y≠e
          hence [[a e y]] ∨ [[a y e]]
            using aey-cases by auto
          hence e∈ray a y
            unfolding ray-def using abc-abc-neq pro-betw seg-betw by auto
        } moreover {
          assume [[a e b]] ∨ [[a b e]]
          assume y=e
          have e∈ray a y
            unfolding ray-def by (simp add: ‹y = e›)
        }
        ultimately show ?thesis
          using aeb-cases by blast
      qed
    qed
  qed
  thus is-ray ?R by auto
 qed
qed
 show (∀ r∈?R. ∀ l∈?L. [[l a r]])
  using abd-bcd-abc by blast
 show ∀ x∈?R. ∀ y∈?R. ¬ [[x a y]]
  by (smt abc-ac-neq abc-bcd-abd abd-bcd-abc mem-Collect-eq)
```

show $\forall x\in ?L.\ \forall y\in ?L.\ \neg$ [[x a y]]
  using *abc-abc-neq abc-abd-bcdbdc abc-only-cba* **by** *blast*
show $Q-\{a\} \subseteq ?R \cup ?L$
  using ‹$Q = \{x.$ [[x a b]]$\} \cup \{a\} \cup \{y.$ [[a y b]] $\vee$ [[a b y]]$\}$› **by** *blast*
qed
thus *?thesis*
  by (*metis* (*mono-tags*, *lifting*))
qed

The definition *closest-to* in prose: Pick any $r \in R$. The closest event c is such that there is no closer event in L, i.e. all other events of L are further away from r. Thus in L, c is the element closest to R.

definition *closest-to* :: ($'a$ *set*) $\Rightarrow$ $'a$ $\Rightarrow$ ($'a$ *set*) $\Rightarrow$ *bool*
  where *closest-to* L c $R \equiv c\in L \wedge (\forall r\in R.\ \forall l\in L-\{c\}.$ [[l c r]])

lemma *int-on-path*:
  assumes $l\in L$ $r\in R$ $Q\in\mathcal{P}$
    and *partition*: $L\subseteq Q$ $L\neq\{\}$ $R\subseteq Q$ $R\neq\{\}$ $L\cup R=Q$
  shows *interval* l $r \subseteq Q$
proof
  fix x **assume** $x\in$ *interval* l r
  thus $x\in Q$
    unfolding *interval-def segment-def*
    using *betw-b-in-path partition*(*5*) ‹$Q\in\mathcal{P}$› *seg-betw* ‹$l \in L$› ‹$r \in R$›
    by *blast*
qed

lemma *ray-of-bounds1*:
  assumes $Q\in\mathcal{P}$ [f[(f *0*)..]X] $X\subseteq Q$ *closest-bound* c X *is-bound-f* b X f $b\neq c$
  assumes *is-bound-f* x X f
  shows $x=b \vee x=c \vee$ [[c x b]] $\vee$ [[c b x]]
proof −
  have $x\in Q$
   using *bound-on-path assms*(*1*,*3*,*7*) **unfolding** *all-bounds-def is-bound-def is-bound-f-def*
    by *auto*
  {
    assume $x=b$
    hence *?thesis* **by** *blast*
  } moreover {
    assume $x=c$
    hence *?thesis* **by** *blast*
  } moreover {
    assume $x\neq b$ $x\neq c$
    hence *?thesis*
      by (*meson abc-abd-bcdbdc assms*(*4*,*5*,*6*,*7*) *closest-bound-def is-bound-def*)
  }
  ultimately show *?thesis* **by** *blast*

qed

lemma *ray-of-bounds2*:
  assumes $Q \in \mathcal{P}$ $[f[(f\ 0)..]X]$ $X \subseteq Q$ *closest-bound-f c X f is-bound-f b X f* $b \neq c$
  assumes $x=b \vee x=c \vee [[c\ x\ b]] \vee [[c\ b\ x]]$
  shows *is-bound-f x X f*
proof –
  have $x \in Q$
    using *assms*(*1*,*3*,*4*,*5*,*6*,*7*) *betw-b-in-path betw-c-in-path bound-on-path*
    using *closest-bound-f-def is-bound-f-def* **by** *metis*
  {
    assume $x=b$
    hence *?thesis*
      by (*simp add*: *assms*(*5*))
  } moreover {
    assume $x=c$
    hence *?thesis* **using** *assms*(*4*)
      by (*simp add*: *closest-bound-f-def*)
  } moreover {
    assume $[[c\ x\ b]]$
    hence *?thesis* **unfolding** *is-bound-f-def*
    proof (*safe*)
      fix *i j*::*nat*
      show $[f[f\ 0..]X]$
        by (*simp add*: *assms*(*2*))
      assume $i<j$
      hence $[[(f\ i)(f\ j)b]]$
        using *assms*(*5*) *is-bound-f-def* **by** *blast*
      hence $[[(f\ j)\ b\ c]] \vee [[(f\ j)\ c\ b]]$
         using ‹$i < j$› *abc-abd-bcdbdc assms*(*4*,*6*) *closest-bound-f-def is-bound-f-def*
by *auto*
      thus $[[(f\ i)(f\ j)(x)]]$
        by (*meson* ‹$[[c\ x\ b]]$› ‹$[[(f\ i)(f\ j)b]]$› *abc-bcd-acd abc-sym abd-bcd-abc*)
    qed
  } moreover {
    assume $[[c\ b\ x]]$
    hence *?thesis* **unfolding** *is-bound-f-def*
    proof (*safe*)
      fix *i j*::*nat*
      show $[f[f\ 0..]X]$
        by (*simp add*: *assms*(*2*))
      assume $i<j$
      hence $[[(f\ i)(f\ j)b]]$
        using *assms*(*5*) *is-bound-f-def* **by** *blast*
      hence $[[(f\ j)\ b\ c]] \vee [[(f\ j)\ c\ b]]$
         using ‹$i < j$› *abc-abd-bcdbdc assms*(*4*,*6*) *closest-bound-f-def is-bound-f-def*
by *auto*
      thus $[[(f\ i)(f\ j)(x)]]$

proof −
  have $(c = b) \vee [[(f\ 0)\ c\ b]]$
    using *assms*(*4*,*5*) *closest-bound-f-def is-bound-def* **by** *auto*
  hence $[[(f\,j)\ b\ c]] \longrightarrow [[x(f\,j)(f\,i)]]$
    by (*metis abc-bcd-acd abc-only-cba*(*2*) *assms*(*5*) *is-bound-f-def neq0-conv*)
  thus *?thesis*
  using ‹$[[c\ b\ x]]$› ‹$[[(f\,i)(f\,j)b]]$› ‹$[[(f\,j)\ b\ c]] \vee [[(f\,j)\ c\ b]]$› *abc-bcd-acd abc-sym*
    by *blast*
qed
qed
}
ultimately show *?thesis* **using** *assms*(*7*) **by** *blast*
qed

lemma *ray-of-bounds3*:
assumes $Q \in \mathcal{P}$ $[f[(f\ 0)..]X]$ $X \subseteq Q$ *closest-bound-f c X f is-bound-f b X f* $b \neq c$
shows *all-bounds X* = *insert c* (*ray c b*)
proof
let *?B* = *all-bounds X*
let *?C* = *insert c* (*ray c b*)
show *?B* ⊆ *?C*
proof
fix *x* **assume** *x*∈*?B*
hence *is-bound x X*
by (*simp add*: *all-bounds-def*)
hence $x=b \vee x=c \vee [[c\ x\ b]] \vee [[c\ b\ x]]$
using *ray-of-bounds1 abc-abd-bcdbdc assms*(*4*,*5*,*6*)
by (*meson closest-bound-f-def is-bound-def*)
thus *x*∈*?C*
using *pro-betw ray-def seg-betw* **by** *auto*
qed
show *?C* ⊆ *?B*
proof
fix *x* **assume** *x*∈*?C*
hence $x=b \vee x=c \vee [[c\ x\ b]] \vee [[c\ b\ x]]$
using *pro-betw ray-def seg-betw* **by** *auto*
hence *is-bound x X*
unfolding *is-bound-def* **using** *ray-of-bounds2 assms*
by *blast*
thus *x*∈*?B*
by (*simp add*: *all-bounds-def*)
qed
qed

lemma *ray-of-bounds*:
assumes $[f[(f\ 0)..]X]$ *closest-bound-f c X f is-bound-f b X f* $b \neq c$
shows *all-bounds X* = *insert c* (*ray c b*)

using *ray-of-bounds3 assms semifin-chain-on-path* by *blast*

lemma *int-in-closed-ray*:
assumes *path ab a b*
shows *interval a b* $\subset$ *insert a* (*ray a b*)
proof
let *?i* = *interval a b*
show *interval a b* $\neq$ *insert a* (*ray a b*)
proof −
obtain *c* **where** [[*a b c*]] **using** *prolong-betw2*
using *assms* **by** *blast*
hence *c*∈*ray a b*
using *abc-abc-neq pro-betw ray-def* **by** *auto*
have *c*∉*interval a b*
using ‹[[*a b c*]]› *abc-abc-neq abc-only-cba*(*2*) *interval-def seg-betw* **by** *auto*
thus *?thesis*
using ‹*c* ∈ *ray a b*› **by** *blast*
qed
show *interval a b* $\subseteq$ *insert a* (*ray a b*)
using *interval-def ray-def* **by** *auto*
qed

lemma *bound-any-f*:
assumes *Q*∈$\mathcal{P}$ [*f*[(*f 0*)..]*X*] *X*⊆*Q is-bound c X*
shows *is-bound-f c X f*
proof −
obtain *g* **where** *is-bound-f c X g* [*g*[*g 0*..]*X*]
using *assms*(*4*) *is-bound-def is-bound-f-def* **by** *blast*
show *?thesis*
unfolding *is-bound-f-def*
proof (*safe*)
fix *i j*::*nat*
show [*f*[*f 0* ..]*X*] **by** (*simp add*: *assms*(*2*))
assume *i*<*j*
have [[(*g i*)(*g j*)*c*]]
using ‹*i* < *j*› ‹*is-bound-f c X g*› *is-bound-f-def* **by** *blast*
thus [[(*f i*)(*f j*)*c*]]
using *inf-chain-unique* ‹[*g*[*g 0* ..]*X*]› *assms*(*2*) **by** *force*
qed
qed

lemma *closest-bound-any-f*:
assumes *Q*∈$\mathcal{P}$ [*f*[(*f 0*)..]*X*] *X*⊆*Q closest-bound c X*
shows *closest-bound-f c X f*
proof (*unfold closest-bound-f-def*, *safe*)
show *is-bound-f c X f*

using *bound-any-f assms closest-bound-def is-bound-def* **by** *blast*
next
fix $Q_b{}'$
assume *is-bound* $Q_b{}'$ X $Q_b{}' \neq c$
then show $[[(f\ 0)\ c\ Q_b{}']]$
by (*metis* (*full-types*) *assms*(*2*,*4*) *closest-bound-def inf-chain-unique is-bound-f-def*)
qed

end

39 3.8 Connectedness of the unreachable set

context *MinkowskiSpacetime* **begin**

39.1 Theorem 13 (Connectedness of the Unreachable Set)

theorem *unreach-connected*:
assumes *path-Q*: $Q \in \mathcal{P}$
and *event-b*: $b \notin Q$ $b \in \mathcal{E}$
and *unreach*: $Q_x \in \emptyset\ Q\ b$ $Q_z \in \emptyset\ Q\ b$ $Q_x \neq Q_z$
and *xyz*: $[[Q_x\ Q_y\ Q_z]]$
shows $Q_y \in \emptyset\ Q\ b$
proof −

First we obtain the chain from I6.

have *in-Q*: $Q_x \in Q \wedge Q_y \in Q \wedge Q_z \in Q$
using *betw-b-in-path path-Q unreach*(*1*,*2*,*3*) *unreach-on-path xyz* **by** *blast*
hence *event-y*: $Q_y \in \mathcal{E}$
using *in-path-event path-Q* **by** *blast*
obtain *X f* **where** *X-def*: *ch-by-ord f X* $f\ 0 = Q_x$ $f\ (card\ X - 1) = Q_z$
$(\forall i \in \{1\ ..\ card\ X - 1\}.\ (f\ i) \in \emptyset\ Q\ b \wedge (\forall Qy \in \mathcal{E}.\ [[(f\ (i - 1))\ Qy\ (f\ i)]] \longrightarrow$
$Qy \in \emptyset\ Q\ b))$
short-ch $X \longrightarrow Q_x \in X \wedge Q_z \in X \wedge (\forall Q_y \in \mathcal{E}.\ [[Q_x\ Q_y\ Q_z]] \longrightarrow Q_y \in \emptyset\ Q\ b)$
using *I6* [*OF assms*(*1*−*6*)] **by** *blast*
hence *fin-X*: *finite X*
using *unreach*(*3*) *not-less* **by** *fastforce*
obtain *N* **where** $N = card\ X$ $N \geq 2$
using *X-def*(*2*,*3*) *unreach*(*3*) **by** *fastforce*

Then we have to manually show the bounds, defined via indices only, are in the obtained chain. This step made me add the two-element-chain-case to I6 in *Minkowski.thy*; this case is referenced here as *X-def*(*5*).

let $?a = f\ 0$
let $?d = f\ (card\ X - 1)$
{
assume $card\ X = 2$
hence *short-ch X* $?a \in X \wedge ?d \in X$ $?a \neq ?d$
using *X-def* ‹$card\ X = 2$› *short-ch-card-2* *unreach*(*3*) **by** *blast+*

}
hence $[f[Q_x..Q_z]X]$
unfolding *fin-chain-def*
by (*metis X-def*(*1*−*3*,*5*) *ch-by-ord-def fin-X fin-long-chain-def get-fin-long-ch-bounds unreach*(*3*))

Further on, we split the proof into two cases, namely the split Schutz absorbs into his non-strict ordering. Just below is the statement we use *disjE* with.

have *y-cases*: $Q_y \in X \vee Q_y \notin X$ **by** *blast*
have *y-int*: $Q_y \in$ *interval* Q_x Q_z
using *interval-def seg-betw xyz* **by** *auto*
have *X-in-Q*: $X \subseteq Q$
using *chain-on-path-I6* [**where** *Q*=*Q* **and** *X*=*X*] *X-def event-b path-Q unreach*
by *blast*

show *?thesis*
proof (*cases*)

As usual, we treat short chains separately, and they have their own clause in I6.

assume *N*=*2*
thus *?thesis*
using *X-def*(*1*,*5*) *xyz* ‹*N* = *card X*› *event-y short-ch-card-2* **by** *auto*
next

This is where Schutz obtains the chain from Theorem 11. We instead use the chain we already have with only a part of Theorem 11, namely *int-split-to-segs*. *?S* is defined like in *segmentation*.

assume *N*≠*2*
hence *N*≥*3* **using** ‹*2* ≤ *N*› **by** *auto*
have *2*≤*card X* **using** ‹*2* ≤ *N*› ‹*N* = *card X*› **by** *blast*
show *?thesis* **using** *y-cases*
proof (*rule disjE*)
assume $Q_y \in X$
then obtain *i* **where** *i-def*: *i*<*card X* Q_y = *f i*
using *X-def*(*1*)
unfolding *ch-by-ord-def long-ch-by-ord-def ordering-def*
by (*metis X-def*(*5*) *abc-abc-neq fin-X short-ch-def xyz*)
have *i*≠*0* ∧ *i*≠*card X* − *1*
using *X-def*(*2*,*3*)
by (*metis abc-abc-neq i-def*(*2*) *xyz*)
hence *i*∈{*1*..*card X* −*1*}
using *i-def*(*1*) **by** *fastforce*
thus *?thesis* **using** *X-def*(*4*) *i-def*(*2*) **by** *metis*
next
assume $Q_y \notin X$

let *?S* = *if card X* = *2 then* {*segment ?a ?d*} *else* {*segment* (*f i*) (*f*(*i*+*1*)) | *i*. *i*<*card X* − *1*}

```
      have Q_y∈⋃ ?S
      proof -
        obtain c where [f[Q_x..c..Q_z]X]
        using X-def(1) ‹N = card X› ‹N≠2› ‹[f[Q_x..Q_z]X]› fin-chain-def short-ch-card-2
by auto
        have interval Q_x Q_z = ⋃ ?S ∪ X
          using int-split-to-segs [OF ‹[f[Q_x..c..Q_z]X]›] by auto
        thus ?thesis
          using ‹Q_y∉X› y-int by blast
      qed
      then obtain s where s∈?S Q_y∈s by blast

      have ∃ i. i∈{1..(card X)−1} ∧ [[(f(i−1)) Q_y (f i)]]
      proof -
        obtain i' where i'-def: i' < N−1 s = segment (f i') (f (i' + 1))
          using ‹Q_y∈s› ‹s∈?S› ‹N=card X›
          by (smt ‹2 ≤ N› ‹N ≠ 2› le-antisym mem-Collect-eq not-less)
        show ?thesis
        proof (rule exI, rule conjI)
          show (i'+1) ∈ {1..card X − 1}
            using i'-def(1)
            by (simp add: ‹N = card X›)
          show [[(f((i'+1) − 1)) Q_y (f(i'+1))]]
            using i'-def(2) ‹Q_y∈s› seg-betw by simp
        qed
      qed
      then obtain i where i-def: i∈{1..(card X)−1} [[(f(i−1)) Q_y (f i)]]
        by blast

      show ?thesis
        by (meson X-def(4) i-def event-y)
    qed
  qed
qed
```

39.2 Theorem 14 (Second Existence Theorem)

```
lemma union-of-bounded-sets-is-bounded:
  assumes ∀x∈A. [[a x b]] ∀x∈B. [[c x d]] A⊆Q B⊆Q Q∈𝒫
    card A > 1 ∨ infinite A card B > 1 ∨ infinite B
  shows ∃l∈Q. ∃u∈Q. ∀x∈A∪B. [[l x u]]
proof -
  let ?P = λ A B. ∃l∈Q. ∃u∈Q. ∀x∈A∪B. [[l x u]]
  let ?I = λ A a b. (card A > 1 ∨ infinite A) ∧ (∀x∈A. [[a x b]])
  let ?R = λA. ∃a b. ?I A a b

  have on-path: ⋀a b A. A ⊆ Q ⟹ ?I A a b ⟹ b ∈ Q ∧ a ∈ Q
  proof -
```

fix *a b A* **assume** $A \subseteq Q$ *?I A a b*
show $b \in Q \wedge a \in Q$
proof (*cases*)
assume *card A* $\leq$ *1* $\wedge$ *finite A*
thus *?thesis*
using ‹*?I A a b*› **by** *auto*
next
assume $\neg$ (*card A* $\leq$ *1* $\wedge$ *finite A*)
hence *asmA*: *card A* $>$ *1* $\vee$ *infinite A*
by *linarith*
then obtain *x y* **where** $x \in A$ $y \in A$ $x \neq y$
proof
assume *1* $<$ *card A* $\bigwedge x\ y.\ [\![x \in A;\ y \in A;\ x \neq y]\!] \Longrightarrow$ *thesis*
then show *?thesis*
by (*metis One-nat-def Suc-le-eq card-le-Suc-iff insert-iff*)
next
assume *infinite A* $\bigwedge x\ y.\ [\![x \in A;\ y \in A;\ x \neq y]\!] \Longrightarrow$ *thesis*
then show *?thesis*
using *infinite-imp-nonempty* **by** (*metis finite-insert finite-subset singletonI subsetI*)
qed
have $x \in Q$ $y \in Q$
using ‹$A \subseteq Q$› ‹$x \in A$› ‹$y \in A$› **by** *auto*
have [[*a x b*]] [[*a y b*]]
by (*simp add*: ‹(*1* $<$ *card A* $\vee$ *infinite A*) $\wedge$ ($\forall x \in A$. [[*a x b*]])› ‹$x \in A$› ‹$y \in A$›)+
hence *betw4 a x y b* $\vee$ *betw4 a y x b*
using ‹$x \neq y$› *abd-acd-abcdacbd* **by** *blast*
hence $a \in Q \wedge b \in Q$
using ‹$Q \in \mathcal{P}$› ‹$x \in Q$› ‹$x \neq y$› ‹$x \in Q$› ‹$y \in Q$› *betw-a-in-path betw-c-in-path* **by** *blast*
thus *?thesis* **by** *simp*
qed
qed

show *?thesis*
proof (*cases*)
assume $a \neq b \wedge a \neq c \wedge a \neq d \wedge b \neq c \wedge b \neq d \wedge c \neq d$
show *?P A B*
proof (*rule-tac P=?P* **and** *A=Q* **in** *wlog-endpoints-distinct*)

First, some technicalities: the relations P, I, R have the symmetry required.

show $\bigwedge a\ b\ I.$ *?I I a b* $\Longrightarrow$ *?I I b a* **using** *abc-sym* **by** *blast*
show $\bigwedge a\ b\ A.\ A \subseteq Q \Longrightarrow$ *?I A a b* $\Longrightarrow b \in Q \wedge a \in Q$ **using** *on-path assms(5)* **by** *blast*
show $\bigwedge I\ J.$ *?R I* $\Longrightarrow$ *?R J* $\Longrightarrow$ *?P I J* $\Longrightarrow$ *?P J I* **by** (*simp add*: *Un-commute*)

Next, the lemma/case assumptions have to be repeated for Isabelle.

show *?I A a b ?I B c d* $A \subseteq Q$ $B \subseteq Q$ $Q \in \mathcal{P}$

using *assms* **by** *simp+*
show $a{\neq}b \wedge a{\neq}c \wedge a{\neq}d \wedge b{\neq}c \wedge b{\neq}d \wedge c{\neq}d$
using ‹$a{\neq}b \wedge a{\neq}c \wedge a{\neq}d \wedge b{\neq}c \wedge b{\neq}d \wedge c{\neq}d$› **by** *simp*

Finally, the important bit: proofs for the necessary cases of betweenness.

show *?P I J*
if *?I I a b ?I J c d* $I{\subseteq}Q$ $J{\subseteq}Q$
and *betw4 a b c d* ∨ *betw4 a c b d* ∨ *betw4 a c d b*
for *I J a b c d*
proof −
consider *betw4 a b c d*|*betw4 a c b d*|*betw4 a c d b*
using ‹*betw4 a b c d* ∨ *betw4 a c b d* ∨ *betw4 a c d b*› **by** *fastforce*
thus *?thesis*
proof (*cases*)
assume *asm*: *betw4 a b c d* **show** *?P I J*
proof −
have $\forall x\in I\cup J$. [[*a x d*]]
by (*metis Un-iff asm betw4-strong betw4-weak that*(*1*) *that*(*2*))
moreover have $a{\in}Q$ $d{\in}Q$
using *assms*(*5*) *on-path that*(*1*−*4*) **by** *blast+*
ultimately show *?thesis* **by** *blast*
qed
next
assume *betw4 a c b d* **show** *?P I J*
proof −
have $\forall x\in I\cup J$. [[*a x d*]]
by (*metis Un-iff* ‹*betw4 a c b d*› *abc-bcd-abd abc-bcd-acd betw4-weak that*(*1*,*2*))
moreover have $a{\in}Q$ $d{\in}Q$
using *assms*(*5*) *on-path that*(*1*−*4*) **by** *blast+*
ultimately show *?thesis* **by** *blast*
qed
next
assume *betw4 a c d b* **show** *?P I J*
proof −
have $\forall x\in I\cup J$. [[*a x b*]]
using ‹*betw4 a c d b*› *abc-bcd-abd abc-bcd-acd abe-ade-bcd-ace*
by (*meson UnE that*(*1*,*2*))
moreover have $a{\in}Q$ $b{\in}Q$
using *assms*(*5*) *on-path that*(*1*−*4*) **by** *blast+*
ultimately show *?thesis* **by** *blast*
qed
qed
qed
qed
next
assume $\neg(a{\neq}b \wedge a{\neq}c \wedge a{\neq}d \wedge b{\neq}c \wedge b{\neq}d \wedge c{\neq}d)$

show *?P A B*

proof (*rule-tac* $P=?P$ **and** $A=Q$ **in** *wlog-endpoints-degenerate*)

This case follows the same pattern as above: the next five *show* statements are effectively bookkeeping.

show $\bigwedge a\ b\ I.\ ?I\ I\ a\ b \Longrightarrow ?I\ I\ b\ a$ **using** *abc-sym* **by** *blast*
show $\bigwedge a\ b\ A.\ A \subseteq Q \Longrightarrow ?I\ A\ a\ b \Longrightarrow b \in Q \wedge a \in Q$ **using** *on-path* $\langle Q{\in}\mathcal{P}\rangle$ **by** *blast*
show $\bigwedge I\ J.\ ?R\ I \Longrightarrow ?R\ J \Longrightarrow ?P\ I\ J \Longrightarrow ?P\ J\ I$ **by** (*simp add*: *Un-commute*)

show $?I\ A\ a\ b\ ?I\ B\ c\ d\ A{\subseteq}Q\ B{\subseteq}Q\ Q{\in}\mathcal{P}$
using *assms* **by** *simp+*
show $\neg\ (a \neq b \wedge b \neq c \wedge c \neq d \wedge a \neq d \wedge a \neq c \wedge b \neq d)$
using $\langle\neg\ (a \neq b \wedge a \neq c \wedge a \neq d \wedge b \neq c \wedge b \neq d \wedge c \neq d)\rangle$ **by** *blast*

Again, this is the important bit: proofs for the necessary cases of degeneracy.

show $(a = b \wedge b = c \wedge c = d \longrightarrow ?P\ I\ J) \wedge (a = b \wedge b \neq c \wedge c = d \longrightarrow ?P\ I\ J) \wedge$
$(a = b \wedge b = c \wedge c \neq d \longrightarrow ?P\ I\ J) \wedge (a = b \wedge b \neq c \wedge c \neq d \wedge a \neq d \longrightarrow ?P\ I\ J) \wedge$
$(a \neq b \wedge b = c \wedge c \neq d \wedge a = d \longrightarrow ?P\ I\ J) \wedge$
$([[a\ b\ c]] \wedge a = d \longrightarrow ?P\ I\ J) \wedge ([[b\ a\ c]] \wedge a = d \longrightarrow ?P\ I\ J)$
if $?I\ I\ a\ b\ ?I\ J\ c\ d\ I \subseteq Q\ J \subseteq Q$
for $I\ J\ a\ b\ c\ d$
proof (*rule conjI7*, *rule-tac*[*1*−*7*] *impI*)
assume $a = b \wedge b = c \wedge c = d$
show $\exists\, l{\in}Q.\ \exists\, u{\in}Q.\ \forall\, x{\in}I \cup J.\ [[l\ x\ u]]$
using $\langle a = b \wedge b = c \wedge c = d\rangle$ *abc-ac-neq* *assms*(*5*) *ex-crossing-path* *that*(*1*,*2*)
by *fastforce*
next
assume $a = b \wedge b \neq c \wedge c = d$
show $\exists\, l{\in}Q.\ \exists\, u{\in}Q.\ \forall\, x{\in}I \cup J.\ [[l\ x\ u]]$
using $\langle a = b \wedge b \neq c \wedge c = d\rangle$ *abc-ac-neq* *assms*(*5*) *ex-crossing-path* *that*(*1*,*2*)
by (*metis Un-iff*)
next
assume $a = b \wedge b = c \wedge c \neq d$
hence $\forall\, x{\in}\ I{\cup}J.\ [[c\ x\ d]]$
using *abc-abc-neq* *that*(*1*,*2*) **by** *fastforce*
moreover have $c{\in}Q\ d{\in}Q$
using *on-path* $\langle a = b \wedge b = c \wedge c \neq d\rangle$ *that*(*1*,*3*) *abc-abc-neq* **by** *metis+*
ultimately show $\exists\, l{\in}Q.\ \exists\, u{\in}Q.\ \forall\, x{\in}I \cup J.\ [[l\ x\ u]]$ **by** *blast*
next
assume $a = b \wedge b \neq c \wedge c \neq d \wedge a \neq d$
hence $\forall\, x{\in}\ I{\cup}J.\ [[c\ x\ d]]$
using *abc-abc-neq* *that*(*1*,*2*) **by** *fastforce*
moreover have $c{\in}Q\ d{\in}Q$
using *on-path* $\langle a = b \wedge b \neq c \wedge c \neq d \wedge a \neq d\rangle$ *that*(*1*,*3*) *abc-abc-neq* **by** *metis+*

ultimately show $\exists l{\in}Q.\ \exists u{\in}Q.\ \forall x{\in}I \cup J.\ [[l\ x\ u]]$ **by** *blast*
next
assume $a \neq b \wedge b = c \wedge c \neq d \wedge a = d$
hence $\forall x{\in}\ I{\cup}J.\ [[c\ x\ d]]$
using *abc-sym that(1,2)* **by** *auto*
moreover have $c{\in}Q\ d{\in}Q$
using *on-path* ‹$a \neq b \wedge b = c \wedge c \neq d \wedge a = d$› *that(1,3) abc-abc-neq* **by** *metis+*
ultimately show $\exists l{\in}Q.\ \exists u{\in}Q.\ \forall x{\in}I \cup J.\ [[l\ x\ u]]$ **by** *blast*
next
assume $[[a\ b\ c]] \wedge a = d$
hence $\forall x{\in}\ I{\cup}J.\ [[c\ x\ d]]$
by (*metis UnE abc-acd-abd abc-sym that(1,2)*)
moreover have $c{\in}Q\ d{\in}Q$
using *on-path that(2,4)* **by** *blast+*
ultimately show $\exists l{\in}Q.\ \exists u{\in}Q.\ \forall x{\in}I \cup J.\ [[l\ x\ u]]$ **by** *blast*
next
assume $[[b\ a\ c]] \wedge a = d$
hence $\forall x{\in}\ I{\cup}J.\ [[c\ x\ b]]$
using *abc-sym abd-bcd-abc betw4-strong that(1,2)* **by** (*metis Un-iff*)
moreover have $c{\in}Q\ b{\in}Q$
using *on-path that* **by** *blast+*
ultimately show $\exists l{\in}Q.\ \exists u{\in}Q.\ \forall x{\in}I \cup J.\ [[l\ x\ u]]$ **by** *blast*
qed
qed
qed
qed

lemma *union-of-bounded-sets-is-bounded2*:
assumes $\forall x{\in}A.\ [[a\ x\ b]]\ \forall x{\in}B.\ [[c\ x\ d]]\ A{\subseteq}Q\ B{\subseteq}Q\ Q{\in}\mathcal{P}$
$1{<}card\ A \vee infinite\ A\ \ 1{<}card\ B \vee infinite\ B$
shows $\exists l{\in}Q{-}(A{\cup}B).\ \exists u{\in}Q{-}(A{\cup}B).\ \forall x{\in}A{\cup}B.\ [[l\ x\ u]]$
using *assms union-of-bounded-sets-is-bounded*
[**where** $A{=}A$ **and** $a{=}a$ **and** $b{=}b$ **and** $B{=}B$ **and** $c{=}c$ **and** $d{=}d$ **and** $Q{=}Q$]
by (*metis Diff-iff abc-abc-neq*)

Schutz proves a mildly stronger version of this theorem than he states. Namely, he gives an additional condition that has to be fulfilled by the bounds y, z in the proof ($y,z{\notin}\emptyset\ \ Q\ ab$). This condition is trivial given *abc-abc-neq*. His stating it in the proof makes me wonder whether his (strictly speaking) undefined notion of bounded set is somehow weaker than the version using strict betweenness in his theorem statement and used here in Isabelle. This would make sense, given the obvious analogy with sets on the real line.

theorem *second-existence-thm-1*:
assumes *path-Q*: $Q{\in}\mathcal{P}$
and *events*: $a{\notin}Q\ b{\notin}Q$

and *reachable*: *path-ex a q1 path-ex b q2 q1*∈*Q q2*∈*Q*
shows ∃ *y*∈*Q*. ∃ *z*∈*Q*. (∀ *x*∈∅ *Q a*. [[*y x z*]]) ∧ (∀ *x*∈∅ *Q b*. [[*y x z*]])
proof −

Slightly annoying: Schutz implicitly extends *bounded* to sets, so his statements are neater.

have ∃ *q*∈*Q*. *q*∉(∅ *Q a*) ∃ *q*∈*Q*. *q*∉(∅ *Q b*)
using *cross-in-reachable reachable* **by** *blast*+

This is a helper statement for obtaining bounds in both directions of both unreachable sets. Notice this needs Theorem 13 right now, Schutz claims only Theorem 4. I think this is necessary?

have *get-bds*: ∃ *la*∈*Q*. ∃ *ua*∈*Q*. *la*∉∅ *Q a* ∧ *ua*∉∅ *Q a* ∧ (∀ *x*∈∅ *Q a*. [[*la x ua*]])
if *asm*: *a*∉*Q path-ex a q q*∈*Q*
for *a q*
proof −
obtain *Qy* **where** *Qy*∈∅ *Q a*
using *asm(2)* ‹*a* ∉ *Q*› *in-path-event path-Q two-in-unreach* **by** *blast*
then obtain *la* **where** *la* ∈ *Q* − ∅ *Q a*
using *asm(2,3) cross-in-reachable* **by** *blast*
then obtain *ua* **where** *ua* ∈ *Q* − ∅ *Q a* [[*la Qy ua*]] *la* ≠ *ua*
using *unreachable-set-bounded* [**where** *Q*=*Q* **and** *b*=*a* **and** *Qx*=*la* **and** *Qy*=*Qy*]
using ‹*Qy* ∈ ∅ *Q a*› *asm in-path-event path-Q* **by** *blast*
have *la* ∉ ∅ *Q a* ∧ *ua* ∉ ∅ *Q a* ∧ (∀ *x*∈∅ *Q a*. (*x*≠*la* ∧ *x*≠*ua*) ⟶ [[*la x ua*]])
proof (*intro conjI*)
show *la* ∉ ∅ *Q a*
using ‹*la* ∈ *Q* − ∅ *Q a*› **by** *force*
next
show *ua* ∉ ∅ *Q a*
using ‹*ua* ∈ *Q* − ∅ *Q a*› **by** *force*
next show ∀ *x*∈∅ *Q a*. *x* ≠ *la* ∧ *x* ≠ *ua* ⟶ [[*la x ua*]]
proof (*safe*)
fix *x* **assume** *x*∈∅ *Q a x*≠*la x*≠*ua*
{
assume *x*=*Qy* **hence** [[*la x ua*]] **by** (*simp add*: ‹[[*la Qy ua*]]›)
} moreover {
assume *x*≠*Qy*
have [[*Qy x la*]] ∨ [[*la Qy x*]]
proof −
{ assume [[*x la Qy*]]
hence *la*∈∅ *Q a*
using *unreach-connected* ‹*Qy*∈∅ *Q a*›‹*x*∈∅ *Q a*›‹*x*≠*Qy*› *in-path-event path-Q that* **by** *blast*
hence *False*
using ‹*la* ∈ *Q* − ∅ *Q a*› **by** *blast* **}**
thus [[*Qy x la*]] ∨ [[*la Qy x*]]
using *some-betw* [**where** *Q*=*Q* **and** *a*=*x* **and** *b*=*la* **and** *c*=*Qy*] *path-Q unreach-on-path*

using ‹$Qy \in \emptyset\ Q\ a$› ‹$la \in Q - \emptyset\ Q\ a$› ‹$x \in \emptyset\ Q\ a$› ‹$x \neq Qy$› ‹$x \neq la$› **by** *force*
qed
hence [[*la x ua*]]

proof
assume [[*Qy x la*]]
thus *?thesis* **using** ‹[[*la Qy ua*]]› *abc-acd-abd abc-sym* **by** *blast*
next
assume [[*la Qy x*]]
hence [[*la x ua*]] $\vee$ [[*la ua x*]]
using ‹[[*la Qy ua*]]› ‹$x \neq ua$› *abc-abd-acdadc* **by** *auto*
have $\neg$[[*la ua x*]]
using *unreach-connected that abc-abc-neq abc-acd-bcd in-path-event path-Q*
by (*metis DiffD2* ‹$Qy \in \emptyset\ Q\ a$› ‹[[*la Qy ua*]]› ‹$ua \in Q - \emptyset\ Q\ a$› ‹$x \in \emptyset\ Q\ a$›)
show *?thesis*
using ‹[[*la x ua*]] $\vee$ [[*la ua x*]]› ‹$\neg$ [[*la ua x*]]› **by** *linarith*
qed
}
ultimately show [[*la x ua*]] **by** *blast*
qed
qed
thus *?thesis* **using** ‹$la \in Q - \emptyset\ Q\ a$› ‹$ua \in Q - \emptyset\ Q\ a$› **by** *force*
qed

have $\exists\, y{\in}Q.\ \exists\, z{\in}Q.\ (\forall\, x{\in}(\emptyset\ Q\ a)\cup(\emptyset\ Q\ b).$ [[*y x z*]])
proof −
obtain *la ua* **where** $\forall\, x{\in}\emptyset\ Q\ a.$ [[*la x ua*]]
using *events*(*1*) *get-bds reachable*(*1*,*3*) **by** *blast*
obtain *lb ub* **where** $\forall\, x{\in}\emptyset\ Q\ b.$ [[*lb x ub*]]
using *events*(*2*) *get-bds reachable*(*2*,*4*) **by** *blast*
have $\emptyset\ Q\ a \subseteq Q$ $\emptyset\ Q\ b \subseteq Q$
by (*simp add*: *subsetI unreach-on-path*)+
moreover have $1 < card\ (\emptyset\ Q\ a) \vee infinite\ (\emptyset\ Q\ a)$
using *two-in-unreach events*(*1*) *in-path-event path-Q reachable*(*1*)
by (*metis One-nat-def card-le-Suc0-iff-eq not-less*)
moreover have $1 < card\ (\emptyset\ Q\ b) \vee infinite\ (\emptyset\ Q\ b)$
using *two-in-unreach events*(*2*) *in-path-event path-Q reachable*(*2*)
by (*metis One-nat-def card-le-Suc0-iff-eq not-less*)
ultimately show *?thesis*
using *union-of-bounded-sets-is-bounded* [**where** $Q{=}Q$ **and** $A{=}\emptyset\ Q\ a$ **and** $B{=}\emptyset\ Q\ b$]
using *get-bds assms* ‹$\forall\, x{\in}\emptyset\ Q\ a.$ [[*la x ua*]]› ‹$\forall\, x{\in}\emptyset\ Q\ b.$ [[*lb x ub*]]›
by *blast*
qed

then obtain *y z* **where** $y{\in}Q$ $z{\in}Q$ $(\forall\, x{\in}(\emptyset\ Q\ a)\cup(\emptyset\ Q\ b).$ [[*y x z*]])
by *blast*

```
  show ?thesis
  proof (rule bexI)+
    show y∈Q by (simp add: ‹y ∈ Q›)
    show z∈Q by (simp add: ‹z ∈ Q›)
    show (∀x∈∅ Q a. [[z x y]]) ∧ (∀x∈∅ Q b. [[z x y]])
      by (simp add: ‹∀x∈∅ Q a ∪ ∅ Q b. [[y x z]]› abc-sym)
  qed
qed


theorem second-existence-thm-2:
  assumes path-Q: Q∈𝒫
      and events: a∉Q b∉Q c∈Q d∈Q c≠d
      and reachable: ∃P∈𝒫. ∃q∈Q. path P a q ∃P∈𝒫. ∃q∈Q. path P b q
    shows ∃e∈Q. ∃ae∈𝒫. ∃be∈𝒫. path ae a e ∧ path be b e ∧ [[c d e]]
proof −
  obtain y z where bounds-yz: (∀x∈∅ Q a. [[z x y]]) ∧ (∀x∈∅ Q b. [[z x y]])
             and yz-inQ: y∈Q z∈Q
    using second-existence-thm-1 [where Q=Q and a=a and b=b]
    using path-Q events(1,2) reachable by blast
  have y∉(∅ Q a)∪(∅ Q b) z∉(∅ Q a)∪(∅ Q b)
   by (meson Un-iff ‹(∀x∈∅ Q a. [[z x y]]) ∧ (∀x∈∅ Q b. [[z x y]])› abc-abc-neq)+
  let ?P = λe ae be. (e∈Q ∧ path ae a e ∧ path be b e ∧ [[c d e]])

  have exist-ay: ∃ay. path ay a y
    if a∉Q ∃P∈𝒫. ∃q∈Q. path P a q y∉(∅ Q a) y∈Q
    for a y
    using in-path-event path-Q that unreachable-bounded-path-only
    by blast

  have [[c d y]] ∨ ⟦y c d]] ∨ [[c y d⟧
    by (meson ‹y ∈ Q› abc-sym events(3−5) path-Q some-betw)
  moreover have [[c d z]] ∨ ⟦z c d]] ∨ [[c z d⟧
    by (meson ‹z ∈ Q› abc-sym events(3−5) path-Q some-betw)
  ultimately consider [[c d y]] | [[c d z]] |
                   ((⟦y c d]] ∨ [[c y d⟧) ∧ (⟦z c d]] ∨ [[c z d⟧))
    by auto
  thus ?thesis
  proof (cases)
    assume [[c d y]]
    have y∉(∅ Q a) y∉(∅ Q b)
      using ‹y ∉ ∅ Q a ∪ ∅ Q b› by blast+
    then obtain ay yb where path ay a y path yb b y
      using ‹y∈Q› exist-ay events(1,2) reachable(1,2) by blast
    have ?P y ay yb
      using ‹[[c d y]]› ‹path ay a y› ‹path yb b y› ‹y ∈ Q› by blast
    thus ?thesis by blast
  next
    assume [[c d z]]
```

have $z \notin (\emptyset\ Q\ a)$ $z \notin (\emptyset\ Q\ b)$
  using ‹$z \notin \emptyset\ Q\ a \cup \emptyset\ Q\ b$› **by** *blast+*
then obtain *az bz* **where** *path az a z path bz b z*
  using ‹$z \in Q$› *exist-ay events(1,2) reachable(1,2)* **by** *blast*
have *?P z az bz*
  using ‹$[[c\ d\ z]]$› ‹*path az a z*› ‹*path bz b z*› ‹$z \in Q$› **by** *blast*
thus *?thesis* **by** *blast*
next
assume $([\![y\ c\ d]] \lor [[c\ y\ d]\!]) \land ([\![z\ c\ d]] \lor [[c\ z\ d]\!])$
have $\exists\, e.\ [[c\ d\ e]]$
  using *prolong-betw*
  using *events(3−5) path-Q* **by** *blast*
then obtain *e* **where** $[[c\ d\ e]]$ **by** *auto*
have $\neg[[y\ e\ z]]$
proof (*rule notI*)

Notice Theorem 10 is not needed for this proof, and does not seem to help *sledgehammer*. I think this is because it cannot be easily/automatically reconciled with non-strict notation.

assume $[[y\ e\ z]]$
moreover consider $([\![y\ c\ d]] \land [\![z\ c\ d]]) \mid ([\![y\ c\ d]] \land [[c\ z\ d]\!]) \mid$
  $([[c\ y\ d]\!] \land [\![z\ c\ d]]) \mid ([[c\ y\ d]\!] \land [[c\ z\ d]\!])$
  using ‹$([\![y\ c\ d]] \lor [[c\ y\ d]\!]) \land ([\![z\ c\ d]] \lor [[c\ z\ d]\!])$› **by** *linarith*
ultimately show *False*
  by (*smt* ‹$[[c\ d\ e]]$› *abc-ac-neq betw4-strong betw4-weak*)
qed
have $e \in Q$
  using ‹$[[c\ d\ e]]$› *betw-c-in-path events(3−5) path-Q* **by** *blast*
have $e \notin \emptyset\ Q\ a$ $e \notin \emptyset\ Q\ b$
  using *bounds-yz* ‹$\neg\ [[y\ e\ z]]$› *abc-sym* **by** *blast+*
hence *ex-aebe*: $\exists\, ae\ be.\ path\ ae\ a\ e \land path\ be\ b\ e$
  using ‹$e \in Q$› *events(1,2) in-path-event path-Q reachable(1,2) unreachable-bounded-path-only*
  by *metis*
thus *?thesis*
  using ‹$[[c\ d\ e]]$› ‹$e \in Q$› **by** *blast*
qed
qed

The assumption $Q{\neq}R$ in Theorem 14(iii) is somewhat implicit in Schutz. If $Q{=}R$, $\emptyset\ Q\ a$ is empty, so the third conjunct of the conclusion is meaningless.

theorem *second-existence-thm-3*:
assumes *paths*: $Q \in \mathcal{P}$ $R \in \mathcal{P}$ $Q \neq R$
  and *events*: $x \in Q$ $x \in R$ $a \in R$ $a \neq x$ $b \notin Q$
  and *reachable*: $\exists\, P \in \mathcal{P}.\ \exists\, q \in Q.\ path\ P\ b\ q$
shows $\exists\, e \in \mathcal{E}.\ \exists\, ae \in \mathcal{P}.\ \exists\, be \in \mathcal{P}.\ path\ ae\ a\ e \land path\ be\ b\ e \land (\forall\, y \in \emptyset\ Q\ a.\ [[x\ y\ e]])$
proof −
have $a \notin Q$
  using *events(1−4) paths eq-paths* **by** *blast*

hence $\emptyset\ Q\ a \neq \{\}$
by (*metis events*(*3*) *ex-in-conv in-path-event paths*(*1*,*2*) *two-in-unreach*)

then obtain d **where** $d \in \emptyset\ Q\ a$
by *blast*
have $x \neq d$
using ‹$d \in \emptyset\ Q\ a$› *cross-in-reachable events*(*1*) *events*(*2*) *events*(*3*) *paths*(*2*) **by** *auto*
have $d \in Q$
using ‹$d \in \emptyset\ Q\ a$› *unreach-on-path* **by** *blast*

have $\exists\, e \in Q.\ \exists\, ae\ be.\ [[x\ d\ e]] \wedge path\ ae\ a\ e \wedge path\ be\ b\ e$
using *second-existence-thm-2* [**where** $c=x$ **and** $Q=Q$ **and** $a=a$ **and** $b=b$ **and** $d=d$]
using ‹$a \notin Q$› ‹$d \in Q$› ‹$x \neq d$› *events*(*1*−*3*,*5*) *paths*(*1*,*2*) *reachable* **by** *blast*
then obtain $e\ ae\ be$ **where** *conds*: $[[x\ d\ e]] \wedge path\ ae\ a\ e \wedge path\ be\ b\ e$ **by** *blast*
have $\forall\, y \in (\emptyset\ Q\ a).\ [[x\ y\ e]]$
proof
fix y **assume** $y \in (\emptyset\ Q\ a)$
hence $y \in Q$
using *unreach-on-path* **by** *blast*
show $[[x\ y\ e]]$
proof (*rule ccontr*)
assume $\neg[[x\ y\ e]]$
then consider $y=x \mid y=e \mid [[y\ x\ e]] \mid [[x\ e\ y]]$
by (*metis* ‹$d \in Q$› ‹$y \in Q$› *abc-abc-neq abc-sym betw-c-in-path conds events*(*1*) *paths*(*1*) *some-betw*)
thus *False*
proof (*cases*)
assume $y=x$ **thus** *False*
using ‹$y \in \emptyset\ Q\ a$› *events*(*2*,*3*) *paths*(*1*,*2*) *same-empty-unreach unreach-equiv unreach-on-path*
by *blast*
next
assume $y=e$ **thus** *False*
by (*metis* ‹$y \in Q$› *assms*(*1*) *conds empty-iff same-empty-unreach unreach-equiv* ‹$y \in \emptyset\ Q\ a$›)
next
assume $[[y\ x\ e]]$
hence $[[y\ x\ d]]$
using *abd-bcd-abc conds* **by** *blast*
hence $x \in (\emptyset\ Q\ a)$
using *unreach-connected* [**where** $Q=Q$ **and** $Q_x=y$ **and** $Q_y=x$ **and** $Q_z=d$ **and** $b=a$]
using ‹$\neg[[x\ y\ e]]$› ‹$a \notin Q$› ‹$d \in \emptyset\ Q\ a$› ‹$y \in \emptyset\ Q\ a$› *conds in-path-event paths*(*1*) **by** *blast*
thus *False*
using *empty-iff events*(*2*,*3*) *paths*(*1*,*2*) *same-empty-unreach unreach-equiv unreach-on-path*

```
        by metis
      next
        assume [[x e y]]
        hence [[d e y]]
          using abc-acd-bcd conds by blast
        hence e∈(∅ Q a)
          using unreach-connected [where Q=Q and Q_x=y and Q_y=e and Q_z=d
and b=a]
          using ‹a ∉ Q› ‹d ∈ ∅ Q a› ‹y ∈ ∅ Q a›
            abc-abc-neq abc-sym events(3) in-path-event paths(1,2)
          by blast
        thus False
            by (metis conds empty-iff paths(1) same-empty-unreach unreach-equiv
unreach-on-path)
      qed
    qed
  qed
  thus ?thesis
    using conds in-path-event by blast
qed


end
```

40 Theorem 11 - with path density assumed

```
locale MinkowskiDense = MinkowskiSpacetime +
  assumes path-dense: path ab a b ⟹ ∃x. [[a x b]]
begin
```

Path density: if a and b are connected by a path, then the segment between them is nonempty. Since Schutz insists on the number of segments in his segmentation (Theorem 11), we prove it here, showcasing where his missing assumption of path density fits in (it is used three times in *number-of-segments*, once in each separate meaningful ordering case).

```
lemma segment-nonempty:
  assumes path ab a b
  obtains x where x ∈ segment a b
  using path-dense by (metis seg-betw assms)


lemma number-of-segments:
  assumes path-P: P∈𝒫
      and Q-def: Q⊆P
      and f-def: [f[a..b..c]Q]
    shows card {segment (f i) (f (i+1)) | i. i<(card Q−1)} = card Q − 1
proof −
  let ?S = {segment (f i) (f (i+1)) | i. i<(card Q−1)}
```

```
let ?N = card Q
let ?g = λ i. segment (f i) (f (i+1))
have ?N ≥ 3
  by (meson ch-by-ord-def f-def fin-long-chain-def long-ch-card-ge3)
have ?g ‘ {0..?N−2} = ?S
proof (safe)
  fix i assume i∈{(0::nat)..?N−2}
  show ∃ ia. segment (f i) (f (i+1)) = segment (f ia) (f (ia+1)) ∧ ia<card Q
− 1
  proof
    have i<?N−1
      using assms ‹i∈{(0::nat)..?N−2}› ‹?N≥3›
        by (metis One-nat-def Suc-diff-Suc atLeastAtMost-iff le-less-trans lessI
less-le-trans
          less-trans numeral-2-eq-2 numeral-3-eq-3)
    then show segment (f i) (f (i + 1)) = segment (f i) (f (i + 1)) ∧ i<?N−1
      by blast
  qed
next
  fix x i assume i < card Q − 1
  let ?s = segment (f i) (f (i + 1))
  show ?s ∈ ?g ‘ {0..?N − 2}
  proof −
    have i∈{0..?N−2}
      using ‹i < card Q − 1› by force
    thus ?thesis by blast
  qed
qed
moreover have inj-on ?g {0..?N−2}
proof
  fix i j assume asm: i∈{0..?N−2} j∈{0..?N−2} ?g i = ?g j
  show i=j
  proof (rule ccontr)
    assume i≠j
    hence f i ≠ f j
      using asm(1,2) f-def assms(3) indices-neq-imp-events-neq
        [where X=Q and f=f and a=a and b=b and c=c and i=i and j=j]
      by auto
    show False
    proof (cases)
      assume j=i+1
      hence [[(f i) (f j) (f (j+1))]]
        using asm(2) assms fin-long-chain-def order-finite-chain ‹?N≥3›
     by (metis (no-types, lifting) One-nat-def Suc-diff-Suc Suc-less-eq add.commute
          add-leD2 atLeastAtMost-iff card.remove card-Diff-singleton less-Suc-eq-le
            less-add-one numeral-2-eq-2 numeral-3-eq-3 plus-1-eq-Suc)
      obtain e where e∈?g j using segment-nonempty abc-ex-path asm(3)
        by (metis ‹[[(f i) (f j) (f (j + 1))]]› ‹f i ≠ f j› ‹j = i + 1›)
      hence e∈?g i
```

using *asm*(*3*) **by** *blast*
have [[(*f i*) (*f j*) *e*]]
using *abd-bcd-abc* ‹[[(*f i*) (*f j*) (*f* (*j* + *1*))]]›
by (*meson* ‹*e* ∈ *segment* (*f j*) (*f* (*j* + *1*))› *seg-betw*)
thus *False*
using ‹*e* ∈ *segment* (*f i*) (*f* (*i* + *1*))› ‹*j* = *i* + *1*› *abc-only-cba*(*2*) *seg-betw*
by *auto*
next assume *j*≠*i*+*1*
have *i* < *card Q* ∧ *j* < *card Q* ∧ (*i*+*1*) < *card Q*
using *add-mono-thms-linordered-field*(*3*) *asm*(*1*,*2*) *assms* ‹*?N*≥*3*› **by** *auto*
hence *f i* ∈ *Q* ∧ *f j* ∈ *Q* ∧ *f* (*i*+*1*) ∈ *Q*
using *f-def* **unfolding** *fin-long-chain-def long-ch-by-ord-def ordering-def*
by *blast*
hence *f i* ∈ *P* ∧ *f j* ∈ *P* ∧ *f* (*i*+*1*) ∈ *P*
using *path-is-union assms*
by (*simp add*: *subset-iff*)
then consider [[(*f i*) (*f*(*i*+*1*)) (*f j*)]] | [[(*f i*) (*f j*) (*f*(*i*+*1*))]] |
[[(*f*(*i*+*1*)) (*f i*) (*f j*)]]
using *some-betw path-P f-def indices-neq-imp-events-neq*
‹*f i* ≠ *f j*› ‹*i* < *card Q* ∧ *j* < *card Q* ∧ *i* + *1* < *card Q*› ‹*j* ≠ *i* + *1*›
by (*metis abc-sym less-add-one less-irrefl-nat*)
thus *False*
proof (*cases*)
assume [[(*f*(*i*+*1*)) (*f i*) (*f j*)]]
then obtain *e* **where** *e*∈*?g i* **using** *segment-nonempty*
by (*metis* ‹*f i* ∈ *P* ∧ *f j* ∈ *P* ∧ *f* (*i* + *1*) ∈ *P*› *abc-abc-neq path-P*)
hence [[*e* (*f j*) (*f*(*j*+*1*))]]
using ‹[[(*f*(*i*+*1*)) (*f i*) (*f j*)]]›
by (*smt abc-acd-abd abc-acd-bcd abc-only-cba abc-sym asm*(*3*) *seg-betw*)
moreover have *e*∈*?g j*
using ‹*e* ∈ *?g i*› *asm*(*3*) **by** *blast*
ultimately show *False*
by (*simp add*: *abc-only-cba*(*1*) *seg-betw*)
next
assume [[(*f i*) (*f j*) (*f*(*i*+*1*))]]
thus *False*
using *abc-abc-neq* [**where** *b*=*f j* **and** *a*=*f i* **and** *c*=*f*(*i*+*1*)] *asm*(*3*)
seg-betw [**where** *x*=*f j*]
using *ends-notin-segment* **by** *blast*
next
assume [[(*f i*) (*f*(*i*+*1*)) (*f j*)]]
then obtain *e* **where** *e*∈*?g i* **using** *segment-nonempty*
by (*metis* ‹*f i* ∈ *P* ∧ *f j* ∈ *P* ∧ *f* (*i* + *1*) ∈ *P*› *abc-abc-neq path-P*)
hence [[*e* (*f j*) (*f*(*j*+*1*))]]
proof −
have *f* (*i*+*1*) ≠ *f j*
using ‹[[(*f i*) (*f*(*i*+*1*)) (*f j*)]]› *abc-abc-neq* **by** *presburger*
then show *?thesis*
using ‹*e* ∈ *segment* (*f i*) (*f* (*i*+*1*))› ‹[[(*f i*) (*f*(*i*+*1*)) (*f j*)]]› *asm*(*3*)

seg-betw
```
              by (metis (no-types) abc-abc-neq abc-acd-abd abc-acd-bcd abc-sym)
          qed
          moreover have e∈?g j
            using ‹e ∈ ?g i› asm(3) by blast
          ultimately show False
            by (simp add: abc-only-cba(1) seg-betw)
        qed
      qed
    qed
  qed
  ultimately have bij-betw ?g {0..?N−2} ?S
    using inj-on-imp-bij-betw by fastforce
  thus ?thesis
    using assms(2) bij-betw-same-card numeral-2-eq-2 numeral-3-eq-3 ‹?N≥3›
   by (metis (no-types, lifting) One-nat-def Suc-diff-Suc card-atLeastAtMost le-less-trans
       less-Suc-eq-le minus-nat.diff-0 not-less not-numeral-le-zero)
qed

theorem segmentation-card:
  assumes path-P: P∈𝒫
      and Q-def: Q⊆P
      and f-def: [f[a..b]Q]
    fixes P1 defines P1-def: P1 ≡ prolongation b a
    fixes P2 defines P2-def: P2 ≡ prolongation a b
    fixes S defines S-def: S ≡ (if card Q=2 then {segment a b} else {segment (f
i) (f (i+1)) | i. i<card Q−1})
    shows P = ((⋃S) ∪ P1 ∪ P2 ∪ Q)

          card S = (card Q−1) ∧ (∀x∈S. is-segment x)



          disjoint (S∪{P1,P2}) P1≠P2 P1∉S P2∉S

proof −
  let ?N = card Q
  have 2 ≤ card Q
    using f-def fin-chain-card-geq-2 by blast
  have seg-facts: P = (⋃S ∪ P1 ∪ P2 ∪ Q) (∀x∈S. is-segment x)
    disjoint (S∪{P1,P2}) P1≠P2 P1∉S P2∉S
    using show-segmentation [OF path-P Q-def f-def]
    using P1-def P2-def S-def by fastforce+
  show P = ⋃S ∪ P1 ∪ P2 ∪ Q by (simp add: seg-facts(1))
  show disjoint (S∪{P1,P2}) P1≠P2 P1∉S P2∉S
    using seg-facts(3−6) by blast+
  have card S = (?N−1)
  proof (cases)
    assume ?N=2
```

hence *card S* = *1*
by (*simp add*: *S-def*)
thus *?thesis*
by (*simp add*: ‹*?N* = *2*›)
next
assume *?N*≠*2*
hence *?N*≥*3*
using ‹*2* ≤ *card Q*› **by** *linarith*
then obtain *c* **where** [*f*[*a*..*c*..*b*]*Q*]
using *assms ch-by-ord-def fin-chain-def short-ch-card-2* ‹*2* ≤ *card Q*› ‹*card Q* ≠ *2*›
by *force*
show *?thesis*
using *number-of-segments* [*OF assms*(*1*,*2*) ‹[*f*[*a*..*c*..*b*]*Q*]›]
using *S-def* ‹*card Q* ≠ *2*› **by** *presburger*
qed
thus *card S* = *card Q* − *1* ∧ *Ball S is-segment*
using *seg-facts*(*2*) **by** *blast*
qed

end

end

References

[1] J. W. Schutz. *Independent Axioms for Minkowski Space-Time.* CRC Press, Oct. 1997.