Euler's Polyhedron Formula

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Abstract

Euler stated in 1752 that every convex polyhedron satisfied the formula $V - E + F = 2$ where V, E and F are the numbers of its vertices, edges, and faces. For three dimensions, the well-known proof involves removing one face and then flattening the remainder to form a planar graph, which then is iteratively transformed to leave a single triangle. The history of that proof is extensively discussed and elaborated by Imre Lakatos [1], leaving one finally wondering whether the theorem even holds. The formal proof provided here has been ported from HOL Light, where it is credited to Lawrence [2]. The proof generalises Euler's observation from solid polyhedra to convex polytopes of arbitrary dimension.

Contents

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1 Euler's Polyhedron Formula

One of the Famous 100 Theorems, ported from HOL Light

Cited source: Lawrence, J. (1997). A Short Proof of Euler's Relation for Convex Polytopes. *Canadian Mathematical Bulletin*, **40**(4), 471–474.

theory *Euler-Formula*
  imports
    HOL−Analysis.Analysis
begin

Interpret which "side" of a hyperplane a point is on.

definition *hyperplane-side*
  where *hyperplane-side* ≡ $\lambda(a,b)$. λx. *sgn* $(a \cdot x - b)$

Equivalence relation imposed by a hyperplane arrangement.

definition *hyperplane-equiv*
 where *hyperplane-equiv* ≡ $\lambda A\ x\ y.\ \forall h \in A.$ *hyperplane-side h x* = *hyperplane-side h y*

lemma *hyperplane-equiv-refl* [*iff*]: *hyperplane-equiv A x x*
  by (*simp add*: *hyperplane-equiv-def*)

lemma *hyperplane-equiv-sym*:
   hyperplane-equiv A x y ⟷ *hyperplane-equiv A y x*
  by (*auto simp*: *hyperplane-equiv-def*)

lemma *hyperplane-equiv-trans*:
  ⟦*hyperplane-equiv A x y*; *hyperplane-equiv A y z*⟧ ⟹ *hyperplane-equiv A x z*
  by (*auto simp*: *hyperplane-equiv-def*)

lemma *hyperplane-equiv-Un*:
   hyperplane-equiv $(A \cup B)$ *x y* ⟷ *hyperplane-equiv A x y* ∧ *hyperplane-equiv B x y*
  by (*meson Un-iff hyperplane-equiv-def*)

1.1 Cells of a hyperplane arrangement

definition *hyperplane-cell* :: (*'a*::*real-inner* × *real*) *set* ⇒ *'a set* ⇒ *bool*
  where *hyperplane-cell* ≡ $\lambda A\ C.\ \exists x.\ C =$ *Collect* (*hyperplane-equiv A x*)

lemma *hyperplane-cell*: *hyperplane-cell A C* ⟷ (∃ *x*. *C* = {*y*. *hyperplane-equiv A x y*})
  by (*simp add*: *hyperplane-cell-def*)

lemma *not-hyperplane-cell-empty* [*simp*]: ¬ *hyperplane-cell A* {}
  using *hyperplane-cell* **by** *auto*

lemma *nonempty-hyperplane-cell*: *hyperplane-cell A C* ⟹ (*C* ≠ {})

by *auto*

lemma *Union-hyperplane-cells*: $\bigcup$ {*C*. *hyperplane-cell A C*} = *UNIV*
using *hyperplane-cell* **by** *blast*

lemma *disjoint-hyperplane-cells*:
⟦*hyperplane-cell A C1*; *hyperplane-cell A C2*; *C1* ≠ *C2*⟧ ⟹ *disjnt C1 C2*
by (*force simp*: *hyperplane-cell-def disjnt-iff hyperplane-equiv-def*)

lemma *disjoint-hyperplane-cells-eq*:
⟦*hyperplane-cell A C1*; *hyperplane-cell A C2*⟧ ⟹ (*disjnt C1 C2* ⟷ (*C1* ≠ *C2*))
using *disjoint-hyperplane-cells* **by** *auto*

lemma *hyperplane-cell-empty* [*iff*]: *hyperplane-cell* {} *C* ⟷ *C* = *UNIV*
by (*simp add*: *hyperplane-cell hyperplane-equiv-def*)

lemma *hyperplane-cell-singleton-cases*:
assumes *hyperplane-cell* {(*a*,*b*)} *C*
shows *C* = {*x*. *a* · *x* = *b*} ∨ *C* = {*x*. *a* · *x* < *b*} ∨ *C* = {*x*. *a* · *x* > *b*}
proof −
obtain *x* **where** *x*: *C* = {*y*. *hyperplane-side* (*a*, *b*) *x* = *hyperplane-side* (*a*, *b*) *y*}
using *assms* **by** (*auto simp*: *hyperplane-equiv-def hyperplane-cell*)
then show *?thesis*
by (*auto simp*: *hyperplane-side-def sgn-if split*: *if-split-asm*)
qed

lemma *hyperplane-cell-singleton*:
hyperplane-cell {(*a*,*b*)} *C* ⟷
(*if a* = *0 then C* = *UNIV else C* = {*x*. *a* · *x* = *b*} ∨ *C* = {*x*. *a* · *x* < *b*} ∨ *C* = {*x*. *a* · *x* > *b*})
apply (*simp add*: *hyperplane-cell-def hyperplane-equiv-def hyperplane-side-def sgn-if split*: *if-split-asm*)
by (*smt* (*verit*) *Collect-cong gt-ex hyperplane-eq-Ex lt-ex*)

lemma *hyperplane-cell-Un*:
hyperplane-cell (*A* ∪ *B*) *C* ⟷
C ≠ {} ∧
(∃ *C1 C2*. *hyperplane-cell A C1* ∧ *hyperplane-cell B C2* ∧ *C* = *C1* ∩ *C2*)
by (*auto simp*: *hyperplane-cell hyperplane-equiv-def*)

lemma *finite-hyperplane-cells*:
finite A ⟹ *finite* {*C*. *hyperplane-cell A C*}
proof (*induction rule*: *finite-induct*)
case (*insert p A*)
obtain *a b* **where** *peq*: *p* = (*a*,*b*)
by *fastforce*
have *Collect* (*hyperplane-cell* {*p*}) ⊆ {{*x*. *a* · *x* = *b*},{*x*. *a* · *x* < *b*},{*x*. *a* · *x* > *b*}}

using *hyperplane-cell-singleton-cases*
by (*auto simp*: *peq*)
then have ∗: *finite* (*Collect* (*hyperplane-cell* {*p*}))
by (*simp add*: *finite-subset*)
define $\mathcal{C}$ **where** $\mathcal{C}$ ≡ (⋃*C1* ∈ {*C*. *hyperplane-cell A C*}. ⋃*C2* ∈ {*C*. *hyperplane-cell* {*p*} *C*}. {*C1* ∩ *C2*})
have {*a*. *hyperplane-cell* (*insert p A*) *a*} ⊆ $\mathcal{C}$
using *hyperplane-cell-Un* [*of* {*p*} *A*] **by** (*auto simp*: $\mathcal{C}$*-def*)
moreover have *finite* $\mathcal{C}$
using ∗ $\mathcal{C}$*-def insert.IH* **by** *blast*
ultimately show *?case*
using *finite-subset* **by** *blast*
qed *auto*

lemma *finite-restrict-hyperplane-cells*:
finite A ⟹ *finite* {*C*. *hyperplane-cell A C* ∧ *P C*}
by (*simp add*: *finite-hyperplane-cells*)

lemma *finite-set-of-hyperplane-cells*:
⟦*finite A*; ⋀*C*. *C* ∈ $\mathcal{C}$ ⟹ *hyperplane-cell A C*⟧ ⟹ *finite* $\mathcal{C}$
by (*metis finite-hyperplane-cells finite-subset mem-Collect-eq subsetI*)

lemma *pairwise-disjoint-hyperplane-cells*:
(⋀*C*. *C* ∈ $\mathcal{C}$ ⟹ *hyperplane-cell A C*) ⟹ *pairwise disjnt* $\mathcal{C}$
by (*metis disjoint-hyperplane-cells pairwiseI*)

lemma *hyperplane-cell-Int-open-affine*:
assumes *finite A hyperplane-cell A C*
obtains *S T* **where** *open S affine T C* = *S* ∩ *T*
using *assms*
proof (*induction arbitrary*: *thesis C rule*: *finite-induct*)
case *empty*
then show *?case*
by *auto*
next
case (*insert p A thesis C′*)
obtain *a b* **where** *peq*: *p* = (*a*,*b*)
by *fastforce*
obtain *C C1* **where** *C1*: *hyperplane-cell* {(*a*,*b*)} *C1* **and** *C*: *hyperplane-cell A C*
and *C′* ≠ {} **and** *C′*: *C′* = *C1* ∩ *C*
by (*metis hyperplane-cell-Un insert.prems*(*2*) *insert-is-Un peq*)
then obtain *S T* **where** *ST*: *open S affine T C* = *S* ∩ *T*
by (*meson insert.IH*)
show *?case*
proof (*cases a*=*0*)
case *True*
with *insert.prems* **show** *?thesis*
by (*metis C1 Int-commute ST* ‹*C′* = *C1* ∩ *C*› *hyperplane-cell-singleton*

inf-top.right-neutral)
  next
    case *False*
    then consider *C1* = {*x*. *a* · *x* = *b*} | *C1* = {*x*. *a* · *x* < *b*} | *C1* = {*x*. *b* < *a* · *x*}
      by (*metis C1 hyperplane-cell-singleton*)
    then show *?thesis*
    proof *cases*
      case *1*
      then show *thesis*
      by (*metis C′ ST affine-Int affine-hyperplane inf-left-commute insert.prems*(*1*))
    next
      case *2*
      with *ST* **show** *thesis*
          by (*metis Int-assoc C′ insert.prems*(*1*) *open-Int open-halfspace-lt*)
    next
      case *3*
      with *ST* **show** *thesis*
        by (*metis Int-assoc C′ insert.prems*(*1*) *open-Int open-halfspace-gt*)
    qed
  qed
qed

lemma *hyperplane-cell-relatively-open*:
  assumes *finite A hyperplane-cell A C*
  shows *openin* (*subtopology euclidean* (*affine hull C*)) *C*
proof −
  obtain *S T* **where** *open S affine T C* = *S* ∩ *T*
    by (*meson assms hyperplane-cell-Int-open-affine*)
  show *?thesis*
  proof (*cases S* ∩ *T* = {})
    case *True*
    then show *?thesis*
      by (*simp add*: ‹*C* = *S* ∩ *T*›)
  next
    case *False*
    then have *affine hull* (*S* ∩ *T*) = *T*
     by (*metis* ‹*affine T*› ‹*open S*› *affine-hull-affine-Int-open hull-same inf-commute*)
    then show *?thesis*
      using ‹*C* = *S* ∩ *T*› ‹*open S*› *openin-subtopology* **by** *fastforce*
  qed
qed

lemma *hyperplane-cell-relative-interior*:
  ⟦*finite A*; *hyperplane-cell A C*⟧ ⟹ *rel-interior C* = *C*
  by (*simp add*: *hyperplane-cell-relatively-open rel-interior-openin*)

lemma *hyperplane-cell-convex*:
  assumes *hyperplane-cell A C*

shows *convex C*
proof −
obtain *c* **where** *c*: $C = \{y.\ \textit{hyperplane-equiv}\ A\ c\ y\}$
by (*meson assms hyperplane-cell*)
have *convex* ($\bigcap h{\in}A.\ \{y.\ \textit{hyperplane-side}\ h\ c = \textit{hyperplane-side}\ h\ y\}$)
proof (*rule convex-INT*)
fix $h :: {}'a \times \textit{real}$
assume $h \in A$
obtain *a b* **where** *heq*: $h = (a,b)$
by *fastforce*
have [*simp*]: $\{y.\ \neg\ a \cdot c < a \cdot y \wedge a \cdot y = a \cdot c\} = \{y.\ a \cdot y = a \cdot c\}$
$\{y.\ \neg\ b < a \cdot y \wedge a \cdot y \neq b\} = \{y.\ b > a \cdot y\}$
by *auto*
then show *convex* $\{y.\ \textit{hyperplane-side}\ h\ c = \textit{hyperplane-side}\ h\ y\}$
by (*fastforce simp*: *heq hyperplane-side-def sgn-if convex-halfspace-gt convex-halfspace-lt convex-hyperplane cong*: *conj-cong*)
qed
with *c* **show** *?thesis*
by (*simp add*: *hyperplane-equiv-def INTER-eq*)
qed

lemma *hyperplane-cell-Inter*:
assumes $\bigwedge C.\ C \in \mathcal{C} \Longrightarrow \textit{hyperplane-cell}\ A\ C$
and $\mathcal{C} \neq \{\}$ **and** *INT*: $\bigcap\mathcal{C} \neq \{\}$
shows *hyperplane-cell A* ($\bigcap\mathcal{C}$)
proof −
have $\bigcap\mathcal{C} = \{y.\ \textit{hyperplane-equiv}\ A\ z\ y\}$
if $z \in \bigcap\mathcal{C}$ **for** *z*
using *assms that* **by** (*force simp*: *hyperplane-cell hyperplane-equiv-def*)
with *INT hyperplane-cell* **show** *?thesis*
by *fastforce*
qed

lemma *hyperplane-cell-Int*:
$[\![\textit{hyperplane-cell}\ A\ S;\ \textit{hyperplane-cell}\ A\ T;\ S \cap T \neq \{\}]\!] \Longrightarrow \textit{hyperplane-cell}\ A\ (S \cap T)$
by (*metis hyperplane-cell-Un sup.idem*)

1.2 A cell complex is considered to be a union of such cells

definition *hyperplane-cellcomplex*
where *hyperplane-cellcomplex A S* ≡
$\exists \mathcal{T}.\ (\forall\ C \in \mathcal{T}.\ \textit{hyperplane-cell}\ A\ C) \wedge S = \bigcup\mathcal{T}$

lemma *hyperplane-cellcomplex-empty* [*simp*]: *hyperplane-cellcomplex A* {}
using *hyperplane-cellcomplex-def* **by** *auto*

lemma *hyperplane-cell-cellcomplex*:

hyperplane-cell A C $\Longrightarrow$ *hyperplane-cellcomplex A C*
by (*auto simp*: *hyperplane-cellcomplex-def*)

lemma *hyperplane-cellcomplex-Union*:
assumes $\bigwedge S.\ S \in \mathcal{C} \Longrightarrow$ *hyperplane-cellcomplex A S*
shows *hyperplane-cellcomplex A* $(\bigcup\ \mathcal{C})$
proof −
obtain $\mathcal{F}$ **where** $\mathcal{F}$: $\bigwedge S.\ S \in \mathcal{C} \Longrightarrow (\forall\ C \in \mathcal{F}\ S.$ *hyperplane-cell A C*$) \wedge S = \bigcup(\mathcal{F}\ S)$
by (*metis assms hyperplane-cellcomplex-def*)
show *?thesis*
unfolding *hyperplane-cellcomplex-def*
using $\mathcal{F}$ **by** (*fastforce intro*: *exI* [**where** $x{=}\bigcup\ (\mathcal{F}$ *‘* $\mathcal{C})$])
qed

lemma *hyperplane-cellcomplex-Un*:
⟦*hyperplane-cellcomplex A S*; *hyperplane-cellcomplex A T*⟧
$\Longrightarrow$ *hyperplane-cellcomplex A* $(S \cup T)$
by (*smt* (*verit*) *Un-iff Union-Un-distrib hyperplane-cellcomplex-def*)

lemma *hyperplane-cellcomplex-UNIV* [*simp*]: *hyperplane-cellcomplex A UNIV*
by (*metis Union-hyperplane-cells hyperplane-cellcomplex-def mem-Collect-eq*)

lemma *hyperplane-cellcomplex-Inter*:
assumes $\bigwedge S.\ S \in \mathcal{C} \Longrightarrow$ *hyperplane-cellcomplex A S*
shows *hyperplane-cellcomplex A* $(\bigcap \mathcal{C})$
proof (*cases* $\mathcal{C} = \{\}$)
case *True*
then show *?thesis*
by *simp*
next
case *False*
obtain $\mathcal{F}$ **where** $\mathcal{F}$: $\bigwedge S.\ S \in \mathcal{C} \Longrightarrow (\forall\ C \in \mathcal{F}\ S.$ *hyperplane-cell A C*$) \wedge S = \bigcup(\mathcal{F}\ S)$
by (*metis assms hyperplane-cellcomplex-def*)
have $*$: $\mathcal{C} = (\lambda S.\ \bigcup(\mathcal{F}\ S))$ *‘* $\mathcal{C}$
using $\mathcal{F}$ **by** *force*
define U **where** $U \equiv \bigcup\ \{T \in \{\bigcap(g$ *‘* $\mathcal{C})\ |g.\ \forall\ S{\in}\mathcal{C}.\ g\ S \in \mathcal{F}\ S\}.\ T \neq \{\}\}$
have $\bigcap \mathcal{C} = \bigcup\{\bigcap(g$ *‘* $\mathcal{C})\ |g.\ \forall\ S{\in}\mathcal{C}.\ g\ S \in \mathcal{F}\ S\}$
using *False* $\mathcal{F}$ **unfolding** *Inter-over-Union* [*symmetric*]
by *blast*
also have $\ldots = U$
unfolding *U-def*
by *blast*
finally have $\bigcap \mathcal{C} = U$ **.**
have *hyperplane-cellcomplex A U*
using *False* $\mathcal{F}$ **unfolding** *U-def*
apply (*intro hyperplane-cellcomplex-Union hyperplane-cell-cellcomplex*)
by (*auto intro*!: *hyperplane-cell-Inter*)

then show *?thesis*
by (*simp add*: ‹$\bigcap \mathcal{C} = U$›)
qed

lemma *hyperplane-cellcomplex-Int*:
⟦*hyperplane-cellcomplex A S*; *hyperplane-cellcomplex A T*⟧
$\Longrightarrow$ *hyperplane-cellcomplex A* $(S \cap T)$
using *hyperplane-cellcomplex-Inter* [*of* $\{S,T\}$] **by** *force*

lemma *hyperplane-cellcomplex-Compl*:
assumes *hyperplane-cellcomplex A S*
shows *hyperplane-cellcomplex A* $(- S)$
proof −
obtain $\mathcal{C}$ **where** $\mathcal{C}$: $\bigwedge C.\ C \in \mathcal{C} \Longrightarrow$ *hyperplane-cell A C* **and** $S = \bigcup \mathcal{C}$
by (*meson assms hyperplane-cellcomplex-def*)
have *hyperplane-cellcomplex A* $(\bigcap T \in \mathcal{C}.\ -T)$
proof (*intro hyperplane-cellcomplex-Inter*)
fix *C0*
assume $C0 \in$ *uminus* ‘ $\mathcal{C}$
then obtain C **where** C: $C0 = -C$ $C \in \mathcal{C}$
by *auto*
have $*$: $-C = \bigcup \{D.$ *hyperplane-cell A D* $\wedge D \neq C\}$ (**is** - = *?rhs*)
proof
show $- C \subseteq$ *?rhs*
using *hyperplane-cell* **by** *blast*
show *?rhs* $\subseteq - C$
by *clarify* (*meson* ‹$C \in \mathcal{C}$› $\mathcal{C}$ *disjnt-iff disjoint-hyperplane-cells*)
qed
then show *hyperplane-cellcomplex A C0*
by (*metis* (*no-types*, *lifting*) *C*(*1*) *hyperplane-cell-cellcomplex hyperplane-cellcomplex-Union mem-Collect-eq*)
qed
then show *?thesis*
by (*simp add*: ‹$S = \bigcup \mathcal{C}$› *uminus-Sup*)
qed

lemma *hyperplane-cellcomplex-diff*:
⟦*hyperplane-cellcomplex A S*; *hyperplane-cellcomplex A T*⟧
$\Longrightarrow$ *hyperplane-cellcomplex A* $(S - T)$
using *hyperplane-cellcomplex-Inter* [*of* $\{S,-T\}$]
by (*force simp*: *Diff-eq hyperplane-cellcomplex-Compl*)

lemma *hyperplane-cellcomplex-mono*:
assumes *hyperplane-cellcomplex A S* $A \subseteq B$
shows *hyperplane-cellcomplex B S*
proof −
obtain $\mathcal{C}$ **where** $\mathcal{C}$: $\bigwedge C.\ C \in \mathcal{C} \Longrightarrow$ *hyperplane-cell A C* **and** *eq*: $S = \bigcup \mathcal{C}$
by (*meson assms hyperplane-cellcomplex-def*)
show *?thesis*

unfolding *eq*
proof (*intro hyperplane-cellcomplex-Union*)
fix C
assume $C \in \mathcal{C}$
have $\bigwedge x.\ x \in C \Longrightarrow \exists D'.\ (\exists D.\ D' = D \cap C \wedge$ *hyperplane-cell* $(B - A)\ D \wedge D \cap C \neq \{\}) \wedge x \in D'$
unfolding *hyperplane-cell-def* **by** *blast*
then
have *hyperplane-cellcomplex* $(A \cup (B - A))\ C$
unfolding *hyperplane-cellcomplex-def hyperplane-cell-Un*
using $\mathcal{C}$ ‹$C \in \mathcal{C}$› **by** (*fastforce intro*!: *exI* [**where** x= $\{D \cap C\ |D.$ *hyperplane-cell* $(B - A)\ D \wedge D \cap C \neq \{\}\}$])
moreover have $B = A \cup (B - A)$
using ‹$A \subseteq B$› **by** *auto*
ultimately show *hyperplane-cellcomplex* $B\ C$ **by** *simp*
qed
qed

lemma *finite-hyperplane-cellcomplexes*:
assumes *finite* A
shows *finite* $\{C.$ *hyperplane-cellcomplex* $A\ C\}$
proof −
have $\{C.$ *hyperplane-cellcomplex* $A\ C\} \subseteq$ *image* $\bigcup\ \{T.\ T \subseteq \{C.$ *hyperplane-cell* $A\ C\}\}$
by (*force simp*: *hyperplane-cellcomplex-def subset-eq*)
with *finite-hyperplane-cells* **show** *?thesis*
by (*metis assms finite-Collect-subsets finite-surj*)
qed

lemma *finite-restrict-hyperplane-cellcomplexes*:
finite $A \Longrightarrow$ *finite* $\{C.$ *hyperplane-cellcomplex* $A\ C \wedge P\ C\}$
by (*simp add*: *finite-hyperplane-cellcomplexes*)

lemma *finite-set-of-hyperplane-cellcomplex*:
assumes *finite* A $\bigwedge C.\ C \in \mathcal{C} \Longrightarrow$ *hyperplane-cellcomplex* $A\ C$
shows *finite* $\mathcal{C}$
by (*metis assms finite-hyperplane-cellcomplexes mem-Collect-eq rev-finite-subset subsetI*)

lemma *cell-subset-cellcomplex*:
⟦*hyperplane-cell* $A\ C$; *hyperplane-cellcomplex* $A\ S$⟧ $\Longrightarrow C \subseteq S \longleftrightarrow$ ~ *disjnt* $C\ S$
by (*smt* (*verit*) *Union-iff disjnt-iff disjnt-subset1 disjoint-hyperplane-cells-eq hyperplane-cellcomplex-def subsetI*)

1.3 Euler characteristic

definition *Euler-characteristic* :: ('*a*::*euclidean-space* × *real*) *set* ⇒ '*a set* ⇒ *int*
where *Euler-characteristic* $A\ S \equiv$
$(\sum C \mid$ *hyperplane-cell* $A\ C \wedge C \subseteq S.\ (-1)$ ^ *nat* (*aff-dim* C))

lemma *Euler-characteristic-empty* [*simp*]: *Euler-characteristic A* {} = *0*
  by (*simp add*: *sum.neutral Euler-characteristic-def*)

lemma *Euler-characteristic-cell-Union*:
  assumes $\bigwedge C.\ C \in \mathcal{C} \Longrightarrow$ *hyperplane-cell A C*
  shows *Euler-characteristic A* ($\bigcup$ $\mathcal{C}$) = ($\sum C{\in}\mathcal{C}$. (− *1*) ^ *nat* (*aff-dim C*))
proof −
  have $\bigwedge x$. ⟦*hyperplane-cell A x*; $x \subseteq \bigcup \mathcal{C}$⟧ $\Longrightarrow x \in \mathcal{C}$
    by (*metis assms disjnt-Union1 disjnt-subset1 disjoint-hyperplane-cells-eq*)
  then have {*C*. *hyperplane-cell A C* ∧ $C \subseteq \bigcup \mathcal{C}$} = $\mathcal{C}$
    by (*auto simp*: *assms*)
  then show *?thesis*
    by (*auto simp*: *Euler-characteristic-def*)
qed

lemma *Euler-characteristic-cell*:
  hyperplane-cell A C ⟹ *Euler-characteristic A C* = (−*1*) ^(*nat*(*aff-dim C*))
  using *Euler-characteristic-cell-Union* [*of* {*C*}] **by** *force*

lemma *Euler-characteristic-cellcomplex-Un*:
  assumes *finite A hyperplane-cellcomplex A S*
    and *AT*: *hyperplane-cellcomplex A T* **and** *disjnt S T*
  shows *Euler-characteristic A* (*S* ∪ *T*) =
        Euler-characteristic A S + *Euler-characteristic A T*
proof −
  have ∗: {*C*. *hyperplane-cell A C* ∧ *C* ⊆ *S* ∪ *T*} =
       {*C*. *hyperplane-cell A C* ∧ *C* ⊆ *S*} ∪ {*C*. *hyperplane-cell A C* ∧ *C* ⊆ *T*}
    using *cell-subset-cellcomplex* [*OF* - *AT*] **by** (*auto simp*: *disjnt-iff*)
  have ∗∗: {*C*. *hyperplane-cell A C* ∧ *C* ⊆ *S*} ∩ {*C*. *hyperplane-cell A C* ∧ *C* ⊆
T} = {}
    using *assms cell-subset-cellcomplex disjnt-subset1* **by** *fastforce*
  show *?thesis*
  unfolding *Euler-characteristic-def*
   by (*simp add*: *finite-restrict-hyperplane-cells assms* ∗ ∗∗ *flip*: *sum.union-disjoint*)
qed

lemma *Euler-characteristic-cellcomplex-Union*:
  assumes *finite A*
    and $\mathcal{C}$: $\bigwedge C.\ C \in \mathcal{C} \Longrightarrow$ *hyperplane-cellcomplex A C pairwise disjnt* $\mathcal{C}$
  shows *Euler-characteristic A* ($\bigcup$ $\mathcal{C}$) = *sum* (*Euler-characteristic A*) $\mathcal{C}$
proof −
  have *finite* $\mathcal{C}$
    using *assms finite-set-of-hyperplane-cellcomplex* **by** *blast*
  then show *?thesis*
    using $\mathcal{C}$
  proof (*induction rule*: *finite-induct*)
    case *empty*
    then show *?case*

by *auto*
next
case (*insert C* $\mathcal{C}$)
then obtain *disjoint* $\mathcal{C}$ *disjnt C* ($\bigcup$ $\mathcal{C}$)
by (*metis disjnt-Union2 pairwise-insert*)
with *insert* **show** *?case*
by (*simp add*: *Euler-characteristic-cellcomplex-Un hyperplane-cellcomplex-Union* ‹*finite A*›)
qed
qed

lemma *Euler-characteristic*:
fixes *A* :: (*'n*::*euclidean-space* ∗ *real*) *set*
assumes *finite A*
shows *Euler-characteristic A S* =
($\sum$ *d* = *0*..*DIM*(*'n*). (−*1*) ^ *d* ∗ *int* (*card* {*C*. *hyperplane-cell A C* ∧ *C* ⊆ *S* ∧ *aff-dim C* = *int d*}))
(**is** - = *?rhs*)
proof −
have ⋀*T*. ⟦*hyperplane-cell A T*; *T* ⊆ *S*⟧ ⟹ *aff-dim T* ∈ {*0*..*DIM*(*'n*)}
by (*metis atLeastAtMost-iff nle-le order.strict-iff-not aff-dim-negative-iff nonempty-hyperplane-cell aff-dim-le-DIM*)
then have ∗: *aff-dim* ‘ {*C*. *hyperplane-cell A C* ∧ *C* ⊆ *S*} ⊆ *int* ‘ {*0*..*DIM*(*'n*)}
by (*auto simp*: *image-int-atLeastAtMost*)
have *Euler-characteristic A S* = ($\sum$ *y*∈*int* ‘ {*0*..*DIM*(*'n*)}.
$\sum$ *C*∈{*x*. *hyperplane-cell A x* ∧ *x* ⊆ *S* ∧ *aff-dim x* = *y*}. (− *1*) ^ *nat y*)
using *sum.group* [*of* {*C*. *hyperplane-cell A C* ∧ *C* ⊆ *S*} *int* ‘ {*0*..*DIM*(*'n*)} *aff-dim* λ*C*. (−*1*::*int*) ^ *nat*(*aff-dim C*), *symmetric*]
by (*simp add*: *assms Euler-characteristic-def finite-restrict-hyperplane-cells* ∗)
also have . . . = *?rhs*
by (*simp add*: *sum.reindex mult-of-nat-commute*)
finally show *?thesis* **.**
qed

1.4 Show that the characteristic is invariant w.r.t. hyperplane arrangement.

lemma *hyperplane-cells-distinct-lemma*:
$\{x.\ a \cdot x = b\} \cap \{x.\ a \cdot x < b\} = \{\} \wedge$
$\{x.\ a \cdot x = b\} \cap \{x.\ a \cdot x > b\} = \{\} \wedge$
$\{x.\ a \cdot x < b\} \cap \{x.\ a \cdot x = b\} = \{\} \wedge$
$\{x.\ a \cdot x < b\} \cap \{x.\ a \cdot x > b\} = \{\} \wedge$
$\{x.\ a \cdot x > b\} \cap \{x.\ a \cdot x = b\} = \{\} \wedge$
$\{x.\ a \cdot x > b\} \cap \{x.\ a \cdot x < b\} = \{\}$
by *auto*

proposition *Euler-characterstic-lemma*:
assumes *finite A* **and** *hyperplane-cellcomplex A S*
shows *Euler-characteristic* (*insert h A*) *S* = *Euler-characteristic A S*

```
proof –
  obtain 𝒞 where 𝒞: ⋀C. C ∈ 𝒞 ⟹ hyperplane-cell A C and S = ⋃𝒞
             and pairwise disjnt 𝒞
    by (meson assms hyperplane-cellcomplex-def pairwise-disjoint-hyperplane-cells)
  obtain a b where h = (a,b)
    by fastforce
  have ⋀C. C ∈ 𝒞 ⟹ hyperplane-cellcomplex A C ∧ hyperplane-cellcomplex (insert (a,b) A) C
      by (meson 𝒞 hyperplane-cell-cellcomplex hyperplane-cellcomplex-mono subset-insertI)
  moreover
  have sum (Euler-characteristic (insert (a,b) A)) 𝒞 = sum (Euler-characteristic A) 𝒞
  proof (rule sum.cong [OF refl])
    fix C
    assume C ∈ 𝒞
    have Euler-characteristic (insert (a, b) A) C = (−1) ^ nat(aff-dim C)
    proof (cases hyperplane-cell (insert (a,b) A) C)
      case True
      then show ?thesis
        using Euler-characteristic-cell by blast
    next
      case False
      with 𝒞[OF ‹C ∈ 𝒞›] have a ≠ 0
          by (smt (verit, ccfv-threshold) hyperplane-cell-Un hyperplane-cell-empty hyperplane-cell-singleton insert-is-Un sup-bot-left)
      have convex C
        using ‹hyperplane-cell A C› hyperplane-cell-convex by blast
      define r where r ≡ (∑D∈{C' ∩ C |C'. hyperplane-cell {(a, b)} C' ∧ C' ∩ C ≠ {}}. (−1::int) ^ nat (aff-dim D))
      have Euler-characteristic (insert (a, b) A) C
          = (∑D | (D ≠ {} ∧
                  (∃C1 C2. hyperplane-cell {(a, b)} C1 ∧ hyperplane-cell A C2 ∧ D = C1 ∩ C2)) ∧ D ⊆ C.
             (− 1) ^ nat (aff-dim D))
      unfolding r-def Euler-characteristic-def insert-is-Un [of - A] hyperplane-cell-Un ..
      also have ... = r
        unfolding r-def
        apply (rule sum.cong [OF - refl])
        using ‹hyperplane-cell A C› disjoint-hyperplane-cells disjnt-iff
        by (smt (verit, ccfv-SIG) Collect-cong Int-iff disjoint-iff subsetD subsetI)
      also have ... = (−1) ^ nat(aff-dim C)
      proof –
        have C ≠ {}
          using ‹hyperplane-cell A C› by auto
        show ?thesis
        proof (cases C ⊆ {x. a · x < b} ∨ C ⊆ {x. a · x > b} ∨ C ⊆ {x. a · x = b})
```

```
    case Csub: True
    with ‹C ≠ {}› have r = sum (λc. (−1) ^ nat (aff-dim c)) {C}
      unfolding r-def
      apply (intro sum.cong [OF - refl])
      by (auto simp: ‹a ≠ 0› hyperplane-cell-singleton)
    also have ... = (−1) ^ nat(aff-dim C)
      by simp
    finally show ?thesis .
  next
    case False
    then obtain u v where uv: u ∈ C ¬ a · u < b v ∈ C ¬ a · v > b
      by blast
    have CInt-ne: C ∩ {x. a · x = b} ≠ {}
    proof (cases a · u = b ∨ a · v = b)
      case True
      with uv show ?thesis
        by blast
    next
      case False
      have a · v < a · u
        using False uv by auto
      define w where w ≡ v + ((b − a · v) / (a · u − a · v)) *R (u − v)
      have **: v + a *R (u − v) = (1 − a) *R v + a *R u for a
        by (simp add: algebra-simps)
      have w ∈ C
        unfolding w-def **
      proof (intro convexD-alt)
      qed (use ‹a · v < a · u› ‹convex C› uv in auto)
      moreover have w ∈ {x. a · x = b}
     using ‹a · v < a · u› by (simp add: w-def inner-add-right inner-diff-right)
      ultimately show ?thesis
        by blast
    qed
    have Cab: C ∩ {x. a · x < b} ≠ {} ∧ C ∩ {x. b < a · x} ≠ {}
    proof −
      obtain u v where u ∈ C a · u = b v ∈ C a · v ≠ b u≠v
        using False ‹C ∩ {x. a · x = b} ≠ {}› by blast
      have openin (subtopology euclidean (affine hull C)) C
          using ‹hyperplane-cell A C› ‹finite A› hyperplane-cell-relatively-open
by blast
      then obtain ε where 0 < ε
           and ε: ⋀x'. ⟦x' ∈ affine hull C; dist x' u < ε⟧ ⟹ x' ∈ C
        by (meson ‹u ∈ C› openin-euclidean-subtopology-iff)
      define ξ where ξ ≡ u − (ε / 2 / norm (v − u)) *R (v − u)
      have ξ ∈ C
      proof (rule ε)
        show ξ ∈ affine hull C
          by (simp add: ξ-def ‹u ∈ C› ‹v ∈ C› hull-inc mem-affine-3-minus2)
      qed (use ξ-def ‹0 < ε› in force)
```

```
      consider a · v < b | a · v > b
        using ‹a · v ≠ b› by linarith
      then show ?thesis
      proof cases
        case 1
        moreover have ξ ∈ {x. b < a · x}
          using 1 ‹0 < ε› ‹a · u = b› divide-less-cancel
          by (fastforce simp: ξ-def algebra-simps)
        ultimately show ?thesis
          using ‹v ∈ C› ‹ξ ∈ C› by blast
      next
        case 2
        moreover have ξ ∈ {x. b > a · x}
          using 2 ‹0 < ε› ‹a · u = b› divide-less-cancel
          by (fastforce simp: ξ-def algebra-simps)
        ultimately show ?thesis
          using ‹v ∈ C› ‹ξ ∈ C› by blast
      qed
    qed
    have r = (∑ C∈{{x. a · x = b} ∩ C, {x. b < a · x} ∩ C, {x. a · x < b}
∩ C}.
              (− 1) ^ nat (aff-dim C))
      unfolding r-def
    proof (intro sum.cong [OF - refl] equalityI)
      show {{x. a · x = b} ∩ C, {x. b < a · x} ∩ C, {x. a · x < b} ∩ C}
        ⊆ {C' ∩ C |C'. hyperplane-cell {(a, b)} C' ∧ C' ∩ C ≠ {}}
        apply clarsimp
            using Cab Int-commute ‹C ∩ {x. a · x = b} ≠ {}› hyper-
plane-cell-singleton ‹a ≠ 0›
        by metis
    qed (auto simp: ‹a ≠ 0› hyperplane-cell-singleton)
    also have . . . = (−1) ^ nat (aff-dim (C ∩ {x. a · x = b}))
                + (−1) ^ nat (aff-dim (C ∩ {x. b < a · x}))
                + (−1) ^ nat (aff-dim (C ∩ {x. a · x < b}))
      using hyperplane-cells-distinct-lemma [of a b] Cab
      by (auto simp: sum.insert-if Int-commute Int-left-commute)
    also have . . . = (− 1) ^ nat (aff-dim C)
    proof −
     have ∗: aff-dim (C ∩ {x. a · x < b}) = aff-dim C ∧ aff-dim (C ∩ {x. a
· x > b}) = aff-dim C
        by (metis Cab open-halfspace-lt open-halfspace-gt aff-dim-affine-hull
                affine-hull-convex-Int-open[OF ‹convex C›])
      obtain S T where open S affine T and Ceq: C = S ∩ T
    by (meson ‹hyperplane-cell A C› ‹finite A› hyperplane-cell-Int-open-affine)
      have affine hull C = affine hull T
        by (metis Ceq ‹C ≠ {}› ‹affine T› ‹open S› affine-hull-affine-Int-open
inf-commute)
      moreover
      have T ∩ ({x. a · x = b} ∩ S) ≠ {}
```

using *Ceq* ‹$C \cap \{x.\ a \cdot x = b\} \neq \{\}$› **by** *blast*
then have *affine hull* $(C \cap \{x.\ a \cdot x = b\})$ = *affine hull* $(T \cap \{x.\ a \cdot x = b\})$
using *affine-hull-affine-Int-open*[*of* $T \cap \{x.\ a \cdot x = b\}$ *S*]
by (*simp add*: *Ceq Int-ac* ‹*affine T*› ‹*open S*› *affine-Int affine-hyperplane*)
ultimately have *aff-dim* (*affine hull C*) = *aff-dim*(*affine hull* $(C \cap \{x.\ a \cdot x = b\})) + 1$
using *CInt-ne False Ceq*
by (*auto simp*: *aff-dim-affine-Int-hyperplane* ‹*affine T*›)
moreover have $0 \leq$ *aff-dim* $(C \cap \{x.\ a \cdot x = b\})$
by (*metis CInt-ne aff-dim-negative-iff linorder-not-le*)
ultimately show *?thesis*
by (*simp add*: $*$ *nat-add-distrib*)
qed
finally show *?thesis* **.**
qed
qed
finally show *Euler-characteristic* (*insert* (*a*, *b*) *A*) *C* = (-1) ^ *nat*(*aff-dim* *C*) **.**
qed
then show *Euler-characteristic* (*insert* (*a*, *b*) *A*) *C* = (*Euler-characteristic A* *C*)
by (*simp add*: *Euler-characteristic-cell* $\mathcal{C}$ ‹$C \in \mathcal{C}$›)
qed
ultimately show *?thesis*
by (*simp add*: *Euler-characteristic-cellcomplex-Union* ‹$S = \bigcup \mathcal{C}$› ‹*disjoint* $\mathcal{C}$› ‹$h = (a,\ b)$› *assms*(*1*))
qed

lemma *Euler-characterstic-invariant-aux*:
assumes *finite B finite A hyperplane-cellcomplex A S*
shows *Euler-characteristic* $(A \cup B)$ *S* = *Euler-characteristic A S*
using *assms*
by (*induction rule*: *finite-induct*) (*auto simp*: *Euler-characterstic-lemma hyperplane-cellcomplex-mono*)

lemma *Euler-characterstic-invariant*:
assumes *finite A finite B hyperplane-cellcomplex A S hyperplane-cellcomplex B S*
shows *Euler-characteristic A S* = *Euler-characteristic B S*
by (*metis Euler-characterstic-invariant-aux assms sup-commute*)

lemma *Euler-characteristic-inclusion-exclusion*:
assumes *finite A finite* $\mathcal{S}$ $\bigwedge K.\ K \in \mathcal{S} \Longrightarrow$ *hyperplane-cellcomplex A K*
shows *Euler-characteristic A* $(\bigcup \mathcal{S}) = (\sum \mathcal{T} \mid \mathcal{T} \subseteq \mathcal{S} \wedge \mathcal{T} \neq \{\}.\ (-\ 1)$ ^ (*card* $\mathcal{T} + 1) *$ *Euler-characteristic A* $(\bigcap \mathcal{T}))$
proof −
interpret *Incl-Excl hyperplane-cellcomplex A Euler-characteristic A*

proof
show *Euler-characteristic A* $(S \cup T)$ = *Euler-characteristic A S* + *Euler-characteristic A T*
if *hyperplane-cellcomplex A S* **and** *hyperplane-cellcomplex A T* **and** *disjnt S T*
for *S T*
using *that Euler-characteristic-cellcomplex-Un assms(1)* **by** *blast*
qed (*use hyperplane-cellcomplex-Int hyperplane-cellcomplex-Un hyperplane-cellcomplex-diff* **in** *auto*)
show *?thesis*
using *restricted assms* **by** *blast*
qed

1.5 Euler-type relation for full-dimensional proper polyhedral cones

lemma *Euler-polyhedral-cone*:
fixes *S* :: *'n::euclidean-space set*
assumes *polyhedron S conic S* **and** *intS*: *interior S* ≠ {} **and** *S* ≠ *UNIV*
shows $(\sum d = 0..DIM('n).\ (-\ 1)\ \hat{}\ d * int\ (card\ \{f.\ f\ face\text{-}of\ S \wedge aff\text{-}dim\ f = int\ d\})) = 0$ (**is** *?lhs = 0*)
proof −
have [*simp*]: *affine hull S = UNIV*
by (*simp add*: *affine-hull-nonempty-interior intS*)
with ‹*polyhedron S*›
obtain *H* **where** *finite H*
and *Seq*: $S = \bigcap H$
and *Hex*: $\bigwedge h.\ h \in H \Longrightarrow \exists\, a\ b.\ a \neq 0 \wedge h = \{x.\ a \cdot x \le b\}$
and *Hsub*: $\bigwedge \mathcal{G}.\ \mathcal{G} \subset H \Longrightarrow S \subset \bigcap \mathcal{G}$
by (*fastforce simp*: *polyhedron-Int-affine-minimal*)
have $0 \in S$
using *assms(2) conic-contains-0 intS interior-empty* **by** *blast*
have ∗: $\exists\, a.\ a \neq 0 \wedge h = \{x.\ a \cdot x \le 0\}$ **if** $h \in H$ **for** *h*
proof −
obtain *a b* **where** $a \neq 0$ **and** *ab*: $h = \{x.\ a \cdot x \le b\}$
using *Hex* [*OF* ‹$h \in H$›] **by** *blast*
have $0 \in \bigcap H$
using *Seq* ‹$0 \in S$› **by** *force*
then have $0 \in h$
using *that* **by** *blast*
consider $b=0 \mid b < 0 \mid b > 0$
by *linarith*
then
show *?thesis*
proof *cases*
case *1*
then show *?thesis*
using ‹$a \neq 0$› *ab* **by** *blast*
next
case *2*

```
    then show ?thesis
      using ‹0 ∈ h› ab by auto
  next
    case 3
    have S ⊂ ⋂(H − {h})
      using Hsub [of H − {h}] that by auto
    then obtain x where x: x ∈ ⋂(H − {h}) and x ∉ S
      by auto
    define ε where ε ≡ min (1/2) (b / (a · x))
    have b < a · x
      using ‹x ∉ S› ab x by (fastforce simp: ‹S = ⋂H›)
    with 3 have 0 < a · x
      by auto
    with 3 have 0 < ε
      by (simp add: ε-def)
    have ε < 1
      using ε-def by linarith
    have ε ∗ (a · x) ≤ b
      unfolding ε-def using ‹0 < a · x› pos-le-divide-eq by fastforce
    have x = inverse ε ∗R ε ∗R x
      using ‹0 < ε› by force
    moreover
    have ε ∗R x ∈ S
    proof −
      have  ε ∗R x ∈ h
        by (simp add: ‹ε ∗ (a · x) ≤ b› ab)
      moreover have ε ∗R x ∈ ⋂(H − {h})
      proof −
        have ε ∗R x ∈ k if x ∈ k k ∈ H k ≠ h for k
        proof −
          obtain a′ b′ where a′≠0 k = {x. a′ · x ≤ b′}
            using Hex ‹k ∈ H› by blast
          have (0 ≤ a′ · x ⟹ a′ · ε ∗R x ≤ a′ · x)
            by (metis ‹ε < 1› inner-scaleR-right order-less-le pth-1 real-scaleR-def
scaleR-right-mono)
          moreover have (0 ≤ −(a′ · x) ⟹ 0 ≤ −(a′ · ε ∗R x))
            using ‹0 < ε› mult-le-0-iff order-less-imp-le by auto
          ultimately
          have a′ · x ≤ b′ ⟹ a′ · ε ∗R x ≤ b′
           by (smt (verit) InterD ‹0 ∈ ⋂H› ‹k = {x. a′ · x ≤ b′}› inner-zero-right
mem-Collect-eq that(2))
          then show ?thesis
            using ‹k = {x. a′ · x ≤ b′}› ‹x ∈ k› by fastforce
        qed
        with x show ?thesis
          by blast
      qed
      ultimately show ?thesis
        using Seq by blast
```

qed
with ‹*conic S*› **have** $inverse\ \varepsilon *_R \varepsilon *_R x \in S$
by (*meson* ‹$0 < \varepsilon$› *conic-def inverse-nonnegative-iff-nonnegative order-less-le*)
ultimately show *?thesis*
using ‹$x \notin S$› **by** *presburger*
qed
qed
then obtain *fa* **where** *fa*: $\bigwedge h.\ h \in H \Longrightarrow fa\ h \neq 0 \wedge h = \{x.\ fa\ h \cdot x \leq 0\}$
by *metis*
define *fa-le-0* **where** $fa\text{-}le\text{-}0 \equiv \lambda h.\ \{x.\ fa\ h \cdot x \leq 0\}$
have *fa′*: $\bigwedge h.\ h \in H \Longrightarrow fa\text{-}le\text{-}0\ h = h$
using *fa fa-le-0-def* **by** *blast*
define *A* **where** $A \equiv (\lambda h.\ (fa\ h, 0{::}real))$ ‘ H
have *finite A*
using ‹*finite H*› **by** (*simp add*: *A-def*)
then have *?lhs = Euler-characteristic A S*
proof −
have [*simp*]: $card\ \{f.\ f\ face\text{-}of\ S \wedge aff\text{-}dim\ f = int\ d\} = card\ \{C.\ hyperplane\text{-}cell\ A\ C \wedge C \subseteq S \wedge aff\text{-}dim\ C = int\ d\}$
if *finite A* **and** $d \leq card\ (Basis{::}'n\ set)$
for $d :: nat$
proof (*rule bij-betw-same-card*)
have *hyper1*: $hyperplane\text{-}cell\ A\ (rel\text{-}interior\ f) \wedge rel\text{-}interior\ f \subseteq S$
$\wedge\ aff\text{-}dim\ (rel\text{-}interior\ f) = d \wedge closure\ (rel\text{-}interior\ f) = f$
if *f face-of S aff-dim f = d* **for** *f*
proof −
have *1*: $closure(rel\text{-}interior\ f) = f$
proof −
have $closure(rel\text{-}interior\ f) = closure\ f$
by (*meson convex-closure-rel-interior face-of-imp-convex that*(*1*))
also have $\ldots = f$
by (*meson assms*(*1*) *closure-closed face-of-polyhedron-polyhedron polyhedron-imp-closed that*(*1*))
finally show *?thesis* **.**
qed
then have *2*: $aff\text{-}dim\ (rel\text{-}interior\ f) = d$
by (*metis closure-aff-dim that*(*2*))
have $f \neq \{\}$
using *aff-dim-negative-iff* [*of f*] **by** (*simp add*: *that*(*2*))
obtain *J0* **where** $J0 \subseteq H$ **and** *J0*: $f = \bigcap\ (fa\text{-}le\text{-}0$ ‘ $H) \cap (\bigcap h \in J0.\ \{x.\ fa\ h \cdot x = 0\})$
proof (*cases f = S*)
case *True*
have $S = \bigcap\ (fa\text{-}le\text{-}0$ ‘ $H)$
using *Seq fa* **by** (*auto simp*: *fa-le-0-def*)
then show *?thesis*
using *True that* **by** *blast*
next
case *False*

have *fexp*: $f = \bigcap\{S \cap \{x.\ fa\ h \cdot x = 0\} \mid h.\ h \in H \wedge f \subseteq S \cap \{x.\ fa\ h \cdot x = 0\}\}$
proof (*rule face-of-polyhedron-explicit*)
show $S = affine\ hull\ S \cap \bigcap\ H$
by (*simp add*: *Seq hull-subset inf.absorb2*)
qed (*auto simp*: *False* ‹$f \neq \{\}$› ‹*f face-of S*› ‹*finite H*› *Hsub fa*)
show *?thesis*
proof
have $*$: $\bigwedge x\ h.\ [\![x \in f;\ h \in H]\!] \Longrightarrow fa\ h \cdot x \leq 0$
using *Seq fa face-of-imp-subset* ‹*f face-of S*› **by** *fastforce*
show $f = \bigcap\ (fa\text{-}le\text{-}0\ `\ H) \cap (\bigcap h \in \{h \in H.\ \ f \subseteq S \cap \{x.\ fa\ h \cdot x = 0\}\}.\ \{x.\ fa\ h \cdot x = 0\})$
(**is** $f = ?I$)
proof
show $f \subseteq ?I$
using ‹*f face-of S*› *fa face-of-imp-subset* **by** (*force simp*: $*$ *fa-le-0-def*)
show $?I \subseteq f$
apply (*subst* (*2*) *fexp*)
apply (*clarsimp simp*: $*$ *fa-le-0-def*)
by (*metis Inter-iff Seq fa mem-Collect-eq*)
qed
qed *blast*
qed
define H' **where** $H' = (\lambda h.\ \{x.\ -(fa\ h) \cdot x \leq 0\})\ `\ H$
have $\exists J.\ finite\ J \wedge J \subseteq H \cup H' \wedge f = affine\ hull\ f \cap \bigcap J$
proof (*intro exI conjI*)
let $?J = H \cup image\ (\lambda h.\ \{x.\ -(fa\ h) \cdot x \leq 0\})\ J0$
show *finite* (*?J*::*'n set set*)
using ‹$J0 \subseteq H$› ‹*finite H*› *finite-subset* **by** *fastforce*
show $?J \subseteq H \cup H'$
using ‹$J0 \subseteq H$› **by** (*auto simp*: *H'-def*)
have $f = \bigcap ?J$
proof
show $f \subseteq \bigcap ?J$
unfolding *J0* **by** (*auto simp*: *fa'*)
have $\bigwedge x\ j.\ [\![j \in J0;\ \forall h{\in}H.\ x \in h;\ \forall j{\in}J0.\ 0 \leq fa\ j \cdot x]\!] \Longrightarrow fa\ j \cdot x = 0$
by (*metis* ‹$J0 \subseteq H$› *fa in-mono inf.absorb2 inf.orderE mem-Collect-eq*)
then show $\bigcap ?J \subseteq f$
unfolding *J0* **by** (*auto simp*: *fa'*)
qed
then show $f = affine\ hull\ f \cap \bigcap ?J$
by (*simp add*: *Int-absorb1 hull-subset*)
qed
then have $**$: $\exists n\ J.\ finite\ J \wedge card\ J = n \wedge J \subseteq H \cup H' \wedge f = affine\ hull\ f \cap \bigcap J$
by *blast*
obtain *J nJ* **where** *J*: *finite J* $card\ J = nJ$ $J \subseteq H \cup H'$ **and** *feq*: $f = affine\ hull\ f \cap \bigcap J$
and *minJ*: $\bigwedge m\ J'.\ [\![finite\ J';\ m < nJ;\ card\ J' = m;\ J' \subseteq H \cup H']\!] \Longrightarrow f$

$\neq$ *affine hull* $f \cap \bigcap J'$
using *exists-least-iff* [*THEN iffD1*, *OF* $**$] **by** *metis*
have *FF*: $f \subset$ (*affine hull* $f \cap \bigcap J'$) **if** $J' \subset J$ **for** J'
proof $-$
have $f \neq$ *affine hull* $f \cap \bigcap J'$
using *minJ*
by (*metis J finite-subset psubset-card-mono psubset-imp-subset psubset-subset-trans that*)
then show *?thesis*
by (*metis Int-subset-iff Inter-Un-distrib feq hull-subset inf-sup-ord*(*2*) *psubsetI sup.absorb4 that*)
qed
have $\exists\, a.\ \{x.\ a \cdot x \leq 0\} = h \wedge (h \in H \wedge a = fa\ h \vee (\exists\, h'.\ h' \in H \wedge a = -(fa\ h')))$
if $h \in J$ **for** h
proof $-$
have $h \in H \cup H'$
using ‹$J \subseteq H \cup H'$› *that* **by** *blast*
then show *?thesis*
proof
show *?thesis* **if** $h \in H$
using *that fa* **by** *blast*
next
assume $h \in H'$
then obtain h' **where** $h' \in H$ $h = \{x.\ 0 \leq fa\ h' \cdot x\}$
by (*auto simp*: *H'-def*)
then show *?thesis*
by (*force simp*: *intro*!: *exI*[**where** $x = -\ (fa\ h')$])
qed
qed
then obtain *ga*
where *ga-h*: $\bigwedge h.\ h \in J \Longrightarrow h = \{x.\ ga\ h \cdot x \leq 0\}$
and *ga-fa*: $\bigwedge h.\ h \in J \Longrightarrow h \in H \wedge ga\ h = fa\ h \vee (\exists\, h'.\ h' \in H \wedge ga\ h = -(fa\ h'))$
by *metis*
have *3*: *hyperplane-cell A* (*rel-interior f*)
proof $-$
have *D*: *rel-interior* $f = \{x \in f.\ \forall\, h{\in}J.\ ga\ h \cdot x < 0\}$
proof (*rule rel-interior-polyhedron-explicit* [*OF* ‹*finite J*› *feq*])
show $ga\ h \neq 0 \wedge h = \{x.\ ga\ h \cdot x \leq 0\}$ **if** $h \in J$ **for** h
using *that fa ga-fa ga-h* **by** *force*
qed (*auto simp*: *FF*)
have *H*: $h \in H \wedge ga\ h = fa\ h$ **if** $h \in J$ **for** h
proof $-$
obtain z **where** z: $z \in$ *rel-interior* f
using *1* ‹$f \neq \{\}$› **by** *force*
then have $z \in f \wedge z \in S$
using *D* ‹*f face-of S*› *face-of-imp-subset* **by** *blast*
then show *?thesis*

using *ga-fa* [*OF that*]
by (*smt* (*verit*, *del-insts*) *D InterE Seq fa inner-minus-left mem-Collect-eq that z*)
qed
then obtain *K* **where** *K* ⊆ *H*
and *K*: *f* = ⋂ (*fa-le-0* ‘ *H*) ∩ (⋂ *h* ∈ *K*. {*x*. *fa h* · *x* = *0*})
using *J0* ‹*J0* ⊆ *H*› **by** *blast*
have *E*: *rel-interior f* = {*x*. (∀ *h* ∈ *H*. *fa h* · *x* ≤ *0*) ∧ (∀ *h* ∈ *K*. *fa h* · *x* = *0*) ∧ (∀ *h* ∈ *J*. *ga h* · *x* < *0*)}
unfolding *D* **by** (*simp add*: *K fa-le-0-def*)
have *relif*: *rel-interior f* ≠ {}
using *1* ‹*f* ≠ {}› **by** *force*
with *E* **have** *disjnt J K*
using *H disjnt-iff* **by** *fastforce*
define *IFJK* **where** *IFJK* ≡ λ*h*. *if h* ∈ *J then* {*x*. *fa h* · *x* < *0*}
else if h ∈ *K then* {*x*. *fa h* · *x* = *0*}
else if rel-interior f ⊆ {*x*. *fa h* · *x* = *0*}
then {*x*. *fa h* · *x* = *0*}
else {*x*. *fa h* · *x* < *0*}
have *relint-f*: *rel-interior f* = ⋂(*IFJK* ‘ *H*)
proof
have *A*: *False*
if *x*: *x* ∈ *rel-interior f* **and** *y*: *y* ∈ *rel-interior f* **and** *less0*: *fa h* · *y* < *0*
and *fa0*: *fa h* · *x* = *0* **and** *h* ∈ *H h* ∉ *J h* ∉ *K* **for** *x h y*
proof −
obtain ε **where** *x* ∈ *f* ε>*0*
and ε: ⋀*t*. ⟦*dist x t* ≤ ε; *t* ∈ *affine hull f*⟧ ⟹ *t* ∈ *f*
using *x* **by** (*force simp*: *mem-rel-interior-cball*)
then have *y* ≠ *x*
using *fa0 less0* **by** *force*
define *x'* **where** *x'* ≡ *x* + (ε / *norm*(*y* − *x*)) $*_R$ (*x* − *y*)
have *x* ∈ *affine hull f* ∧ *y* ∈ *affine hull f*
by (*metis* ‹*x* ∈ *f*› *hull-inc mem-rel-interior-cball y*)
moreover have *dist x x'* ≤ ε
using ‹*0* < ε› ‹*y* ≠ *x*› **by** (*simp add*: *x'-def divide-simps dist-norm norm-minus-commute*)
ultimately have *x'* ∈ *f*
by (*simp add*: ε *mem-affine-3-minus x'-def*)
have *x'* ∈ *S*
using ‹*f face-of S*› ‹*x'* ∈ *f*› *face-of-imp-subset* **by** *auto*
then have *x'* ∈ *h*
using *Seq that*(*5*) **by** *blast*
then have *x'* ∈ {*x*. *fa h* · *x* ≤ *0*}
using *fa that*(*5*) **by** *blast*
moreover have ε / *norm* (*y* − *x*) ∗ −(*fa h* · *y*) > *0*
using ‹*0* < ε› ‹*y* ≠ *x*› *less0* **by** (*simp add*: *field-split-simps*)
ultimately show *?thesis*
by (*simp add*: *x'-def fa0 inner-diff-right inner-right-distrib*)
qed

show *rel-interior f* ⊆ ⋂(*IFJK* ' *H*)
unfolding *IFJK-def* **by** (*smt* (*verit*, *ccfv-SIG*) *A E H INT-I in-mono mem-Collect-eq subsetI*)
show ⋂(*IFJK* ' *H*) ⊆ *rel-interior f*
using ‹*K* ⊆ *H*› ‹*disjnt J K*›
apply (*clarsimp simp add*: *ball-Un E H disjnt-iff IFJK-def*)
apply (*smt* (*verit*, *del-insts*) *IntI Int-Collect subsetD*)
done
qed
obtain *z* **where** *zrelf*: *z* ∈ *rel-interior f*
using *relif* **by** *blast*
moreover
have *H*: *z* ∈ *IFJK h* ⟹ (*x* ∈ *IFJK h*) = (*hyperplane-side* (*fa h*, *0*) *z* = *hyperplane-side* (*fa h*, *0*) *x*) **for** *h x*
using *zrelf* **by** (*auto simp*: *IFJK-def hyperplane-side-def sgn-if split*: *if-split-asm*)
then have *z* ∈ ⋂(*IFJK* ' *H*) ⟹ (*x* ∈ ⋂(*IFJK* ' *H*)) = *hyperplane-equiv A z x* **for** *x*
unfolding *A-def Inter-iff hyperplane-equiv-def ball-simps* **using** *H* **by** *blast*
then have *x* ∈ *rel-interior f* ⟷ *hyperplane-equiv A z x* **for** *x*
using *relint-f zrelf* **by** *presburger*
ultimately show *?thesis*
by (*metis equalityI hyperplane-cell mem-Collect-eq subset-iff*)
qed
have *4*: *rel-interior f* ⊆ *S*
by (*meson face-of-imp-subset order-trans rel-interior-subset that*(*1*))
show *?thesis*
using *1 2 3 4* **by** *blast*
qed
have *hyper2*: (*closure c face-of S* ∧ *aff-dim* (*closure c*) = *d*) ∧ *rel-interior* (*closure c*) = *c*
if *c*: *hyperplane-cell A c* **and** *c* ⊆ *S aff-dim c* = *d* **for** *c*
proof (*intro conjI*)
obtain *J* **where** *J* ⊆ *H* **and** *J*: *c* = (⋂*h* ∈ *J*. {*x*. (*fa h*) · *x* < *0*}) ∩ (⋂*h* ∈ (*H* − *J*). {*x*. (*fa h*) · *x* = *0*})
proof −
obtain *z* **where** *z*: *c* = {*y*. ∀ *x* ∈ *H*. *sgn* (*fa x* · *y*) = *sgn* (*fa x* · *z*)}
using *c* **by** (*force simp*: *hyperplane-cell A-def hyperplane-equiv-def hyperplane-side-def*)
show *thesis*
proof
let *?J* = {*h* ∈ *H*. *sgn*(*fa h* · *z*) = −*1*}
have *1*: *fa h* · *x* < *0*
if ∀ *h*∈*H*. *sgn* (*fa h* · *x*) = *sgn* (*fa h* · *z*) **and** *h* ∈ *H* **and** *sgn* (*fa h* · *z*) = − *1* **for** *x h*
using *that* **by** (*metis sgn-1-neg*)
have *2*: *sgn* (*fa h* · *z*) = − *1*
if ∀ *h*∈*H*. *sgn* (*fa h* · *x*) = *sgn* (*fa h* · *z*) **and** *h* ∈ *H* **and** *fa h* · *x* ≠ *0*

for x h
proof −
have $[\![0 < fa\ h \cdot x;\ 0 < fa\ h \cdot z]\!] \Longrightarrow False$
using *that fa* **by** (*smt* (*verit*, *del-insts*) *Inter-iff Seq* ‹*c* ⊆ *S*› *mem-Collect-eq subset-iff z*)
then show *?thesis*
by (*metis that sgn-if sgn-zero-iff*)
qed
have *3*: $sgn\ (fa\ h \cdot x) = sgn\ (fa\ h \cdot z)$
if $h \in H$ **and** $\forall h.\ h \in H \wedge sgn\ (fa\ h \cdot z) = -\ 1 \longrightarrow fa\ h \cdot x < 0$
and $\forall h{\in}H - \{h \in H.\ sgn\ (fa\ h \cdot z) = -\ 1\}.\ fa\ h \cdot x = 0$
for x h
using *that 2* **by** (*metis* (*mono-tags*, *lifting*) *Diff-iff mem-Collect-eq sgn-neg*)
show $c = (\bigcap h \in ?J.\ \{x.\ fa\ h \cdot x < 0\}) \cap (\bigcap h{\in}H - ?J.\ \{x.\ fa\ h \cdot x = 0\})$
unfolding *z* **by** (*auto intro*: *1 2 3*)
qed *auto*
qed
have *finite J*
using ‹*J* ⊆ *H*› ‹*finite H*› *finite-subset* **by** *blast*
show *closure c face-of S*
proof −
have *cc*: $closure\ c = closure\ (\bigcap h{\in}J.\ \{x.\ fa\ h \cdot x < 0\}) \cap closure\ (\bigcap h{\in}H - J.\ \{x.\ fa\ h \cdot x = 0\})$
unfolding *J*
proof (*rule closure-Int-convex*)
show $convex\ (\bigcap h{\in}J.\ \{x.\ fa\ h \cdot x < 0\})$
by (*simp add*: *convex-INT convex-halfspace-lt*)
show $convex\ (\bigcap h{\in}H - J.\ \{x.\ fa\ h \cdot x = 0\})$
by (*simp add*: *convex-INT convex-hyperplane*)
have *o1*: $open\ (\bigcap h{\in}J.\ \{x.\ fa\ h \cdot x < 0\})$
by (*metis open-INT*[*OF* ‹*finite J*›] *open-halfspace-lt*)
have *o2*: $openin\ (top\text{-}of\text{-}set\ (affine\ hull\ (\bigcap h{\in}H - J.\ \{x.\ fa\ h \cdot x = 0\})))\ (\bigcap h{\in}H - J.\ \{x.\ fa\ h \cdot x = 0\})$
proof −
have $affine\ (\bigcap h{\in}H - J.\ \{n.\ fa\ h \cdot n = 0\})$
using *affine-hyperplane* **by** *auto*
then show *?thesis*
by (*metis* (*no-types*) *affine-hull-eq openin-subtopology-self*)
qed
show $rel\text{-}interior\ (\bigcap h{\in}J.\ \{x.\ fa\ h \cdot x < 0\}) \cap rel\text{-}interior\ (\bigcap h{\in}H - J.\ \{x.\ fa\ h \cdot x = 0\}) \neq \{\}$
by (*metis nonempty-hyperplane-cell c rel-interior-open o1 rel-interior-openin o2 J*)
qed
have *clo-im-J*: $closure\ `\ ((\lambda h.\ \{x.\ fa\ h \cdot x < 0\})\ `\ J) = (\lambda h.\ \{x.\ fa\ h \cdot x \le 0\})\ `\ J$
using ‹*J* ⊆ *H*› **by** (*force simp*: *image-comp fa*)

have *cleq*: *closure* ($\bigcap$*h*∈*H* − *J*. {*x*. *fa h* · *x* = *0*}) = ($\bigcap$*h*∈*H* − *J*. {*x*. *fa h* · *x* = *0*})
by (*intro closure-closed*) (*blast intro*: *closed-hyperplane*)
have ∗∗: ($\bigcap$*h*∈*J*. {*x*. *fa h* · *x* ≤ *0*}) ∩ ($\bigcap$*h*∈*H* − *J*. {*x*. *fa h* · *x* = *0*}) *face-of S*
if ($\bigcap$*h*∈*J*. {*x*. *fa h* · *x* < *0*}) ≠ {}
proof (*cases J*=*H*)
case *True*
have [*simp*]: ($\bigcap$*x*∈*H*. {*xa*. *fa x* · *xa* ≤ *0*}) = $\bigcap$ *H*
using *fa* **by** *auto*
show *?thesis*
using ‹*polyhedron S*› **by** (*simp add*: *Seq True polyhedron-imp-convex face-of-refl*)
next
case *False*
have ∗∗: ($\bigcap$*h*∈*J*. {*n*. *fa h* · *n* ≤ *0*}) ∩ ($\bigcap$*h*∈*H* − *J*. {*x*. *fa h* · *x* = *0*}) =
($\bigcap$*h*∈*H* − *J*. *S* ∩ {*x*. *fa h* · *x* = *0*}) (**is** *?L* = *?R*)
proof
show *?L* ⊆ *?R*
by *clarsimp* (*smt* (*verit*) *DiffI InterI Seq fa mem-Collect-eq*)
show *?R* ⊆ *?L*
using *False Seq* ‹*J* ⊆ *H*› *fa* **by** *blast*
qed
show *?thesis*
unfolding ∗∗
proof (*rule face-of-Inter*)
show (λ*h*. *S* ∩ {*x*. *fa h* · *x* = *0*}) ‘ (*H* − *J*) ≠ {}
using *False* ‹*J* ⊆ *H*› **by** *blast*
show *T face-of S*
if *T*: *T* ∈ (λ*h*. *S* ∩ {*x*. *fa h* · *x* = *0*}) ‘ (*H* − *J*) **for** *T*
proof −
obtain *h* **where** *h*: *T* = *S* ∩ {*x*. *fa h* · *x* = *0*} **and** *h* ∈ *H h* ∉ *J*
using *T* **by** *auto*
have *S* ∩ {*x*. *fa h* · *x* = *0*} *face-of S*
proof (*rule face-of-Int-supporting-hyperplane-le*)
show *convex S*
by (*simp add*: *assms*(*1*) *polyhedron-imp-convex*)
show *fa h* · *x* ≤ *0* **if** *x* ∈ *S* **for** *x*
using *that Seq fa* ‹*h* ∈ *H*› **by** *auto*
qed
then show *?thesis*
using *h* **by** *blast*
qed
qed
qed
have ∗: $\bigwedge$*S*. *S* ∈ (λ*h*. {*x*. *fa h* · *x* < *0*}) ‘ *J* ⟹ *convex S* ∧ *open S*
using *convex-halfspace-lt open-halfspace-lt* **by** *fastforce*
show *?thesis*

unfolding *cc*
apply (*simp add*: ∗ *closure-Inter-convex-open*)
by (*metis* ∗∗ *cleq clo-im-J image-image*)
qed
show *aff-dim* (*closure c*) = *int d*
by (*simp add*: *that*)
show *rel-interior* (*closure c*) = *c*
by (*metis* ‹*finite A*› *c convex-rel-interior-closure hyperplane-cell-convex hyperplane-cell-relative-interior*)
qed
have *rel-interior* ‘ {*f*. *f face-of S* ∧ *aff-dim f* = *int d*}
= {*C*. *hyperplane-cell A C* ∧ *C* ⊆ *S* ∧ *aff-dim C* = *int d*}
using *hyper1 hyper2* **by** *fastforce*
then show *bij-betw* (*rel-interior*) {*f*. *f face-of S* ∧ *aff-dim f* = *int d*} {*C*. *hyperplane-cell A C* ∧ *C* ⊆ *S* ∧ *aff-dim C* = *int d*}
unfolding *bij-betw-def inj-on-def* **by** (*metis* (*mono-tags*) *hyper1 mem-Collect-eq*)

qed
show *?thesis*
by (*simp add*: *Euler-characteristic* ‹*finite A*›)
qed
also have . . . = *0*
proof −
have *A*: *hyperplane-cellcomplex A* (− *h*) **if** *h* ∈ *H* **for** *h*
proof (*rule hyperplane-cellcomplex-mono* [*OF hyperplane-cell-cellcomplex*])
have − *h* = {*x*. *fa h* · *x* = *0*} ∨ − *h* = {*x*. *fa h* · *x* < *0*} ∨ − *h* = {*x*. *0* < *fa h* · *x*}
by (*smt* (*verit*, *ccfv-SIG*) *Collect-cong Collect-neg-eq fa that*)
then show *hyperplane-cell* {(*fa h*,*0*)} (− *h*)
by (*simp add*: *hyperplane-cell-singleton fa that*)
show {(*fa h*,*0*)} ⊆ *A*
by (*simp add*: *A-def that*)
qed
then have $\bigwedge$*h*. *h* ∈ *H* ⟹ *hyperplane-cellcomplex A h*
using *hyperplane-cellcomplex-Compl* **by** *fastforce*
then have *hyperplane-cellcomplex A S*
by (*simp add*: *Seq hyperplane-cellcomplex-Inter*)
then have *D*: *Euler-characteristic A* (*UNIV*::′*n set*) =
Euler-characteristic A (⋂ *H*) + *Euler-characteristic A* (− ⋂ *H*)
using *Euler-characteristic-cellcomplex-Un*
by (*metis Compl-partition Diff-cancel Diff-eq Seq* ‹*finite A*› *disjnt-def hyperplane-cellcomplex-Compl*)
have *Euler-characteristic A UNIV* = *Euler-characteristic* {} (*UNIV*::′*n set*)
by (*simp add*: *Euler-characterstic-invariant* ‹*finite A*›)
then have *E*: *Euler-characteristic A UNIV* = (−*1*) ^ (*DIM*(′*n*))
by (*simp add*: *Euler-characteristic-cell*)
have *DD*: *Euler-characteristic A* (⋂ (*uminus* ‘ *J*)) = (− *1*) ^ *DIM*(′*n*)
if *J* ≠ {} *J* ⊆ *H* **for** *J*
proof −

```
    define B where B ≡ (λh. (fa h,0::real)) ` J
    then have B ⊆ A
      by (simp add: A-def image-mono that)
    have ∃x. y = −x if y ∈ ⋂ (uminus ` H) for y::'n — Weirdly, the assumption
is not used
      by (metis add.inverse-inverse)
    moreover have −x ∈ ⋂ (uminus ` H) ⟷ x ∈ interior S for x
    proof −
      have 1: interior S = {x ∈ S. ∀h∈H. fa h · x < 0}
        using rel-interior-polyhedron-explicit [OF ‹finite H› - fa]
        by (metis (no-types, lifting) inf-top-left  Hsub Seq ‹affine hull S = UNIV›
rel-interior-interior)
      have 2: ⋀x y. ⟦y ∈ H; ∀h∈H. fa h · x < 0; − x ∈ y⟧ ⟹ False
        by (smt (verit, best) fa inner-minus-right mem-Collect-eq)
      show ?thesis
        apply (simp add: 1)
        by (smt (verit) 2 ∗ fa Inter-iff Seq inner-minus-right mem-Collect-eq)
    qed
    ultimately have INT-Compl-H: ⋂ (uminus ` H) = uminus ` interior S
      by blast
    obtain z where z: z ∈ ⋂ (uminus ` J)
      using ‹J ⊆ H› ‹⋂ (uminus ` H) = uminus ` interior S› intS by fastforce
    have ⋂ (uminus ` J) = Collect (hyperplane-equiv B z) (is ?L = ?R)
    proof
      show ?L ⊆ ?R
        using fa ‹J ⊆ H› z
        by (fastforce simp: hyperplane-equiv-def hyperplane-side-def B-def set-eq-iff
)
      show ?R ⊆ ?L
        using z ‹J ⊆ H› apply (clarsimp simp add: hyperplane-equiv-def hyper-
plane-side-def B-def)
        by (metis fa in-mono mem-Collect-eq sgn-le-0-iff)
    qed
    then have hyper-B: hyperplane-cell B (⋂ (uminus ` J))
      by (metis hyperplane-cell)
    have Euler-characteristic A (⋂ (uminus ` J)) = Euler-characteristic B (⋂
(uminus ` J))
    proof (rule Euler-characterstic-invariant [OF ‹finite A›])
      show finite B
        using ‹B ⊆ A› ‹finite A› finite-subset by blast
      show hyperplane-cellcomplex A (⋂ (uminus ` J))
      by (meson ‹B ⊆ A› hyper-B hyperplane-cell-cellcomplex hyperplane-cellcomplex-mono)
      show hyperplane-cellcomplex B (⋂ (uminus ` J))
        by (simp add: hyper-B hyperplane-cell-cellcomplex)
    qed
    also have ... = (− 1) ^ nat (aff-dim (⋂ (uminus ` J)))
      using Euler-characteristic-cell hyper-B by blast
    also have ... = (− 1) ^ DIM('n)
    proof −
```

have *affine hull* $\bigcap$ (*uminus* ' *H*) = *UNIV*
by (*simp add*: *INT-Compl-H affine-hull-nonempty-interior intS interior-negations*)
then have *affine hull* $\bigcap$ (*uminus* ' *J*) = *UNIV*
by (*metis Inf-superset-mono hull-mono subset-UNIV subset-antisym subset-image-iff that*(*2*))
with *aff-dim-eq-full* **show** *?thesis*
by (*metis nat-int*)
qed
finally show *?thesis* **.**
qed
have *EE*: ($\sum\mathcal{T}$ | $\mathcal{T} \subseteq$ *uminus* ' *H* $\wedge$ $\mathcal{T}\neq\{\}$. (−*1*) ^ (*card* $\mathcal{T}$ + *1*) ∗ *Euler-characteristic A* ($\bigcap\mathcal{T}$))
= ($\sum\mathcal{T}$ | $\mathcal{T} \subseteq$ *uminus* ' *H* $\wedge$ $\mathcal{T} \neq \{\}$. (−*1*) ^(*card* $\mathcal{T}$ + *1*) ∗ (− *1*) ^ *DIM*('*n*))
by (*intro sum.cong* [*OF refl*]) (*fastforce simp*: *subset-image-iff intro*!: *DD*)
also have . . . = (−*1*) ^ *DIM*('*n*)
proof −
have *A*: ($\sum$ *y* = *1*..*card H*. $\sum$ *t*∈{*x* ∈ {$\mathcal{T}$. $\mathcal{T} \subseteq$ *uminus* ' *H* $\wedge$ $\mathcal{T} \neq \{\}$}. *card x* = *y*}. (− *1*) ^(*card t* + *1*))
= ($\sum\mathcal{T}$∈{$\mathcal{T}$. $\mathcal{T} \subseteq$ *uminus* ' *H* $\wedge$ $\mathcal{T} \neq \{\}$}. (− *1*) ^(*card* $\mathcal{T}$ + *1*))
proof (*rule sum.group*)
have $\bigwedge$*C*. ⟦*C* ⊆ *uminus* ' *H*; *C* ≠ {}⟧ ⟹ *Suc 0* ≤ *card C* ∧ *card C* ≤ *card H*
by (*meson* ‹*finite H*› *card-eq-0-iff finite-surj le-zero-eq not-less-eq-eq surj-card-le*)
then show *card* ' {$\mathcal{T}$. $\mathcal{T} \subseteq$ *uminus* ' *H* $\wedge$ $\mathcal{T} \neq \{\}$} ⊆ {*1*..*card H*}
by *force*
qed (*auto simp*: ‹*finite H*›)

have ($\sum$ *n* = *Suc 0*..*card H*. − (*int* (*card* {*x*. *x* ⊆ *uminus* ' *H* ∧ *x* ≠ {} ∧ *card x* = *n*}) ∗ (− *1*) ^ *n*))
= ($\sum$ *n* = *Suc 0*..*card H*. (−*1*) ^(*Suc n*) ∗ (*card H choose n*))
proof (*rule sum.cong* [*OF refl*])
fix *n*
assume *n* ∈ {*Suc 0*..*card H*}
then have {$\mathcal{T}$. $\mathcal{T} \subseteq$ *uminus* ' *H* $\wedge$ $\mathcal{T} \neq \{\}$ ∧ *card* $\mathcal{T}$ = *n*} = {$\mathcal{T}$. $\mathcal{T} \subseteq$ *uminus* ' *H* ∧ *card* $\mathcal{T}$ = *n*}
by *auto*
then have *card*{$\mathcal{T}$. $\mathcal{T} \subseteq$ *uminus* ' *H* $\wedge$ $\mathcal{T} \neq \{\}$ ∧ *card* $\mathcal{T}$ = *n*} = *card* (*uminus* ' *H*) *choose n*
by (*simp add*: ‹*finite H*› *n-subsets*)
also have . . . = *card H choose n*
by (*metis card-image double-complement inj-on-inverseI*)
finally
show − (*int* (*card* {$\mathcal{T}$. $\mathcal{T} \subseteq$ *uminus* ' *H* $\wedge$ $\mathcal{T} \neq \{\}$ ∧ *card* $\mathcal{T}$ = *n*}) ∗ (− *1*) ^ *n*) = (− *1*) ^ *Suc n* ∗ *int* (*card H choose n*)
by *simp*
qed

also have ... = − ($\sum k = Suc\ 0..card\ H.\ (-1)\ \hat{}\ k * (card\ H\ choose\ k)$)
by (*simp add*: *sum-negf*)
also have ... = $1 - (\sum k{=}0..card\ H.\ (-1)\ \hat{}\ k * (card\ H\ choose\ k))$
using *atLeastSucAtMost-greaterThanAtMost* **by** (*simp add*: *sum.head* [*of 0*])
also have ... = $1 - 0\ \hat{}\ card\ H$
using *binomial-ring* [*of* −*1 1*::*int card H*] **by** (*simp add*: *mult.commute atLeast0AtMost*)
also have ... = *1*
using *Seq* ‹*finite H*› ‹$S \neq UNIV$› *card-0-eq* **by** *auto*
finally have *C*: ($\sum n = Suc\ 0..card\ H.\ -\ (int\ (card\ \{x.\ x \subseteq uminus\ `\ H \wedge x \neq \{\} \wedge card\ x = n\}) * (-\ 1)\ \hat{}\ n)) = (1::int)$ **.**

have ($\sum \mathcal{T} \mid \mathcal{T} \subseteq uminus\ `\ H \wedge \mathcal{T} \neq \{\}.\ (-\ 1)\ \hat{}(card\ \mathcal{T} + 1)) = (1::int)$
unfolding *A* [*symmetric*] **by** (*simp add*: *C*)
then show *?thesis*
by (*simp flip*: *sum-distrib-right power-Suc*)
qed
finally have ($\sum \mathcal{T} \mid \mathcal{T} \subseteq uminus\ `\ H \wedge \mathcal{T}{\neq}\{\}.\ (-1)\ \hat{}\ (card\ \mathcal{T} + 1) * Euler\text{-}characteristic\ A\ (\bigcap \mathcal{T}))$
$= (-1)\ \hat{}\ DIM('n)$ **.**
then have *Euler-characteristic A* ($\bigcup$ (*uminus* ‘ *H*)) = $(-1)\ \hat{}(DIM('n))$
using *Euler-characteristic-inclusion-exclusion* [*OF* ‹*finite A*›]
by (*smt* (*verit*) *A Collect-cong* ‹*finite H*› *finite-imageI image-iff sum.cong*)
then show *?thesis*
using *D E* **by** (*simp add*: *uminus-Inf Seq*)
qed
finally show *?thesis* **.**
qed

1.6 Euler-Poincare relation for special $(n - 1)$-dimensional polytope

lemma *Euler-Poincare-lemma*:
fixes *p* :: *'n*::*euclidean-space set*
assumes $DIM('n) \geq 2$ *polytope p i* ∈ *Basis* **and** *affp*: *affine hull p* = $\{x.\ x \cdot i = 1\}$
shows ($\sum d = 0..DIM('n) - 1.\ (-1)\ \hat{}\ d * int\ (card\ \{f.\ f\ face\text{-}of\ p \wedge aff\text{-}dim\ f = int\ d\})) = 1$
proof −
have *aff-dim p* = *aff-dim* $\{x.\ i \cdot x = 1\}$
by (*metis* (*no-types*, *lifting*) *Collect-cong aff-dim-affine-hull affp inner-commute*)
also have ... = *int* $(DIM('n) - 1)$
using *aff-dim-hyperplane* [*of i 1*] ‹*i* ∈ *Basis*› **by** *fastforce*
finally have *AP*: *aff-dim p* = *int* $(DIM('n) - 1)$ **.**
show *?thesis*
proof (*cases p* = {})
case *True*
with *AP* **show** *?thesis* **by** *simp*
next

case *False*
define S **where** $S \equiv$ *conic hull p*
have *1*: (*conic hull f*) $\cap$ $\{x.\ x \cdot i = 1\} = f$ **if** $f \subseteq \{x.\ x \cdot i = 1\}$ **for** f
using *that*
by (*smt* (*verit*, *ccfv-threshold*) *affp conic-hull-Int-affine-hull hull-hull inner-zero-left mem-Collect-eq*)
obtain K **where** *finite K* **and** K: p = *convex hull K*
by (*meson assms*(*2*) *polytope-def*)
then have *convex-cone hull K* = *conic hull* (*convex hull K*)
using *False convex-cone-hull-separate-nonempty* **by** *auto*
then have *polyhedron S*
using *polyhedron-convex-cone-hull*
by (*simp add*: *S-def* ‹*polytope p*› *polyhedron-conic-hull-polytope*)
then have *convex S*
by (*simp add*: *polyhedron-imp-convex*)
then have *conic S*
by (*simp add*: *S-def conic-conic-hull*)
then have $0 \in S$
by (*simp add*: *False S-def*)
have $S \neq$ *UNIV*
proof
assume S = *UNIV*
then have *conic hull p* $\cap$ $\{x.\ x{\cdot}i = 1\} = p$
by (*metis 1 affp hull-subset*)
then have *bounded* $\{x.\ x \cdot i = 1\}$
using *S-def* ‹S = *UNIV*› *assms*(*2*) *polytope-imp-bounded* **by** *auto*
then obtain B **where** $B{>}0$ **and** B: $\bigwedge x.\ x \in \{x.\ x \cdot i = 1\} \Longrightarrow$ *norm* $x \leq B$
using *bounded-normE* **by** *blast*
define x **where** $x \equiv (\sum b{\in}Basis.\ (\text{if } b{=}i \text{ then } 1 \text{ else } B{+}1) *_R b)$
obtain j **where** j: $j \in$ *Basis* $j{\neq}i$
using ‹$DIM('n) \geq 2$›
by (*metis DIM-complex DIM-ge-Suc0 card-2-iff′ card-le-Suc0-iff-eq euclidean-space-class.finite-Basis le-antisym*)
have $B{+}1 \leq |x \cdot j|$
using j **by** (*simp add*: *x-def*)
also have $\ldots \leq$ *norm* x
using *Basis-le-norm j* **by** *blast*
finally have *norm* $x > B$
by *simp*
moreover have $x \cdot i = 1$
by (*simp add*: *x-def* ‹$i \in$ *Basis*›)
ultimately show *False*
using B **by** *force*
qed
have $S \neq \{\}$
by (*metis False S-def empty-subsetI equalityI hull-subset*)
have $\bigwedge c\ x.\ [\![0 < c;\ x \in p;\ x \neq 0]\!] \Longrightarrow 0 < (c *_R x) \cdot i$
by (*metis* (*mono-tags*) *Int-Collect Int-iff affp hull-inc inner-commute inner-scaleR-right mult.right-neutral*)

then have *doti-gt0*: *0* < *x* · *i* **if** *S*: *x* ∈ *S* **and** *x* ≠ *0* **for** *x*
  using *that* **by** (*auto simp*: *S-def conic-hull-explicit*)
have ⋀*a*. {*a*} *face-of S* ⟹ *a* = *0*
  using ‹*conic S*› *conic-contains-0 face-of-conic* **by** *blast*
moreover have {*0*} *face-of S*
proof −
  have ⋀*a b u*. ⟦*a* ∈ *S*; *b* ∈ *S*; *a* ≠ *b*; *u* < *1*; *0* < *u*; (*1* − *u*) $*_R$ *a* + *u* $*_R$ *b* = *0*⟧ ⟹ *False*
    using *conic-def euclidean-all-zero-iff inner-left-distrib scaleR-eq-0-iff*
    by (*smt* (*verit*, *del-insts*) *doti-gt0* ‹*conic S*› ‹*i* ∈ *Basis*›)
  then show *?thesis*
    by (*auto simp*: *in-segment face-of-singleton extreme-point-of-def* ‹*0* ∈ *S*›)
qed
ultimately have *face-0*: {*f*. *f face-of S* ∧ (∃ *a*. *f* = {*a*})} = {{*0*}}
  by *auto*
have *interior S* ≠ {}
proof
  assume *interior S* = {}
  then obtain *a b* **where** *a* ≠ *0* **and** *ab*: *S* ⊆ {*x*. *a* · *x* = *b*}
    by (*metis* ‹*convex S*› *empty-interior-subset-hyperplane*)
  have {*x*. *x* · *i* = *1*} ⊆ {*x*. *a* · *x* = *b*}
    by (*metis S-def ab affine-hyperplane affp hull-inc subset-eq subset-hull*)
  moreover have ¬ {*x*. *x* · *i* = *1*} ⊂ {*x*. *a* · *x* = *b*}
    using *aff-dim-hyperplane* [*of a b*]
    by (*metis AP* ‹*a* ≠ *0*› *aff-dim-eq-full-gen affine-hyperplane affp hull-subset less-le-not-le subset-hull*)
  ultimately have *S* ⊆ {*x*. *x* · *i* = *1*}
    using *ab* **by** *auto*
  with ‹*S* ≠ {}› **show** *False*
    using ‹*conic S*› *conic-contains-0* **by** *fastforce*
qed
then have (∑ *d* = *0*..*DIM*(*'n*). (−*1*) ^ *d* ∗ *int* (*card* {*f*. *f face-of S* ∧ *aff-dim f* = *int d*})) = *0*
  using *Euler-polyhedral-cone* ‹*S* ≠ *UNIV*› ‹*conic S*› ‹*polyhedron S*› **by** *blast*
then have *1* + (∑ *d* = *1*..*DIM*(*'n*). (−*1*) ^ *d* ∗ (*card* {*f*. *f face-of S* ∧ *aff-dim f* = *d*})) = *0*
  by (*simp add*: *sum.atLeast-Suc-atMost aff-dim-eq-0 face-0*)
moreover have (∑ *d* = *1*..*DIM*(*'n*). (−*1*) ^ *d* ∗ (*card* {*f*. *f face-of S* ∧ *aff-dim f* = *d*}))
  = − (∑ *d* = *0*..*DIM*(*'n*) − *1*. (−*1*) ^ *d* ∗ *int* (*card* {*f*. *f face-of p* ∧ *aff-dim f* = *int d*}))
proof −
  have (∑ *d* = *1*..*DIM*(*'n*). (−*1*) ^ *d* ∗ (*card* {*f*. *f face-of S* ∧ *aff-dim f* = *d*}))
    = (∑ *d* = *Suc 0*..*Suc* (*DIM*(*'n*)−*1*). (−*1*) ^ *d* ∗ (*card* {*f*. *f face-of S* ∧ *aff-dim f* = *d*}))
    by *auto*
  also have ... = − (∑ *d* = *0*..*DIM*(*'n*) − *1*. (−*1*) ^ *d* ∗ *card* {*f*. *f face-of S* ∧ *aff-dim f* = *1* + *int d*})
    unfolding *sum.atLeast-Suc-atMost-Suc-shift* **by** (*simp add*: *sum-negf*)

also have ... = $-$ ($\sum d = 0..DIM('n) - 1.\ (-1)$ ^ $d * card\ \{f.\ f\ face\text{-}of\ p \wedge aff\text{-}dim\ f = int\ d\}$)
proof $-$
{ **fix** *d*
assume $d \leq DIM('n) - Suc\ 0$
have *conic-face-p*: (*conic hull f*) *face-of S* **if** *f face-of p* **for** *f*
proof (*cases f*={})
case *False*
have $\{c *_R x\ |c\ x.\ 0 \leq c \wedge x \in f\} \subseteq \{c *_R x\ |c\ x.\ 0 \leq c \wedge x \in p\}$
using *face-of-imp-subset that* **by** *blast*
moreover
have *convex* $\{c *_R x\ |c\ x.\ 0 \leq c \wedge x \in f\}$
by (*metis* (*no-types*) *cone-hull-expl convex-cone-hull face-of-imp-convex that*)
moreover
have $(\exists c\ x.\ ca *_R a = c *_R x \wedge 0 \leq c \wedge x \in f) \wedge (\exists c\ x.\ cb *_R b = c *_R x \wedge 0 \leq c \wedge x \in f)$
if $\forall a{\in}p.\ \forall b{\in}p.\ (\exists x{\in}f.\ x \in open\text{-}segment\ a\ b) \longrightarrow a \in f \wedge b \in f$
and $0 \leq ca\ a \in p\ 0 \leq cb\ b \in p$
and $0 \leq cx\ x \in f$ **and** *oseg*: $cx *_R x \in open\text{-}segment\ (ca *_R a)\ (cb *_R b)$
for *ca a cb b cx x*
proof $-$
have *ai*: $a \cdot i = 1$ **and** *bi*: $b \cdot i = 1$
using *affp hull-inc that*(*3*,*5*) **by** *fastforce+*
have *xi*: $x \cdot i = 1$
using *affp that* ‹*f face-of p*› *face-of-imp-subset hull-subset* **by** *fastforce*
show *?thesis*
proof (*cases* $cx *_R x = 0$)
case *True*
then show *?thesis*
using ‹{*0*} *face-of S*› *face-ofD* ‹*conic S*› *that*
by (*smt* (*verit*, *best*) *S-def conic-def hull-subset insertCI singletonD subsetD*)
next
case *False*
then have $cx \neq 0\ x \neq 0$
by *auto*
obtain *u* **where** $0 < u\ u < 1$ **and** *u*: $cx *_R x = (1 - u) *_R (ca *_R a) + u *_R (cb *_R b)$
using *oseg in-segment*(*2*) **by** *metis*
show *?thesis*
proof (*cases* $x = a$)
case *True*
then have *ua*: $(cx - (1 - u) * ca) *_R a = (u * cb) *_R b$
using *u* **by** (*simp add*: *algebra-simps*)
then have $(cx - (1 - u) * ca) * 1 = u * cb * 1$
by (*metis ai bi inner-scaleR-left*)
then have $a{=}b \vee cb = 0$

```
        using ua ‹0 < u› by force
      then show ?thesis
        by (metis True scaleR-zero-left that(2) that(4) that(7))
    next
      case False
      show ?thesis
      proof (cases x = b)
        case True
        then have ub: (cx − (u ∗ cb)) ∗R b = ((1 − u) ∗ ca) ∗R a
          using u by (simp add: algebra-simps)
        then have (cx − (u ∗ cb)) ∗ 1 = ((1 − u) ∗ ca) ∗ 1
          by (metis ai bi inner-scaleR-left)
        then have a=b ∨ ca = 0
          using ‹u < 1› ub by auto
        then show ?thesis
          using False True that(4) that(7) by auto
      next
        case False
        have cx > 0
          using ‹cx ≠ 0› ‹0 ≤ cx› by linarith
        have False if ca = 0
        proof −
          have cx = u ∗ cb
        by (metis add-0 bi inner-real-def inner-scaleR-left real-inner-1-right
scale-eq-0-iff that u xi)
          then show False
            using ‹x ≠ b› ‹cx ≠ 0› that u by force
        qed
        with ‹0 ≤ ca› have ca > 0
          by force
        have aff: x ∈ affine hull p ∧ a ∈ affine hull p ∧ b ∈ affine hull p
          using affp xi ai bi by blast
        show ?thesis
        proof (cases cb=0)
          case True
          have u': cx ∗R x = ((1 − u) ∗ ca) ∗R a
            using u by (simp add: True)
          then have cx = ((1 − u) ∗ ca)
            by (metis ai inner-scaleR-left mult.right-neutral xi)
          then show ?thesis
            using True u' ‹cx ≠ 0› ‹ca ≥ 0› ‹x ∈ f› by auto
        next
          case False
          with ‹cb ≥ 0› have cb > 0
            by linarith
          { have False if a=b
            proof −
              have ∗: cx ∗R x = ((1 − u) ∗ ca + u ∗ cb) ∗R b
                using u that by (simp add: algebra-simps)
```

then have *cx* = ((*1* − *u*) ∗ *ca* + *u* ∗ *cb*)
by (*metis xi bi inner-scaleR-left mult.right-neutral*)
with ‹*x* ≠ *b*› ‹*cx* ≠ *0*› ∗ **show** *False*
by *force*
qed
}
moreover
have $cx *_R x /_R cx = (((1 - u) * ca) *_R a + (cb * u) *_R b) /_R cx$
using *u* **by** *simp*
then have *xeq*: $x = ((1-u) * ca / cx) *_R a + (cb * u / cx) *_R b$
by (*simp add*: ‹*cx* ≠ *0*› *divide-inverse-commute scaleR-right-distrib*)
then have *proj*: *1* = ((*1*−*u*) ∗ *ca* / *cx*) + (*cb* ∗ *u* / *cx*)
using *ai bi xi* **by** (*simp add*: *inner-left-distrib*)
then have *eq*: *cx* + *ca* ∗ *u* = *ca* + *cb* ∗ *u*
using ‹*cx* > *0*› **by** (*simp add*: *field-simps*)
have $\exists u>0.\ u < 1 \wedge x = (1 - u) *_R a + u *_R b$
proof (*intro exI conjI*)
show *0* < *inverse cx* ∗ *u* ∗ *cb*
by (*simp add*: ‹*0* < *cb*› ‹*0* < *cx*› ‹*0* < *u*›)
show *inverse cx* ∗ *u* ∗ *cb* < *1*
using *proj* ‹*0* < *ca*› ‹*0* < *cx*› ‹*u* < *1*› **by** (*simp add*: *divide-simps*)
show $x = (1 - inverse\ cx * u * cb) *_R a + (inverse\ cx * u * cb) *_R b$
using *eq* ‹*cx* ≠ *0*› **by** (*simp add*: *xeq field-simps*)
qed
ultimately show *?thesis*
using *that* **by** (*metis in-segment*(*2*))
qed
qed
qed
qed
qed
ultimately show *?thesis*
using *that* **by** (*auto simp*: *S-def conic-hull-explicit face-of-def*)
qed *auto*
moreover
have *conic-hyperplane-eq*: *conic hull* (*f* ∩ {*x*. *x* · *i* = *1*}) = *f*
if *f face-of S 0* < *aff-dim f* **for** *f*
proof
show *conic hull* (*f* ∩ {*x*. *x* · *i* = *1*}) ⊆ *f*
by (*metis* ‹*conic S*› *face-of-conic inf-le1 subset-hull that*(*1*))
have $\exists c\ x'.\ x = c *_R x' \wedge 0 \le c \wedge x' \in f \wedge x' \cdot i = 1$ **if** *x* ∈ *f* **for** *x*
proof (*cases x=0*)
case *True*
obtain *y* **where** *y* ∈ *f y* ≠ *0*
by (*metis* ‹*0* < *aff-dim f*› *aff-dim-sing aff-dim-subset insertCI linorder-not-le subset-iff*)

```
    then have y · i > 0
      using ‹f face-of S› doti-gt0 face-of-imp-subset by blast
    then have y /R (y · i) ∈ f ∧ (y /R (y · i)) · i = 1
    using ‹conic S› ‹f face-of S› ‹y ∈ f› conic-def face-of-conic by fastforce
    then show ?thesis
      using True by fastforce
  next
    case False
    then have x · i > 0
      using ‹f face-of S› doti-gt0 face-of-imp-subset that by blast
    then have x /R (x · i) ∈ f ∧ (x /R (x · i)) · i = 1
    using ‹conic S› ‹f face-of S› ‹x ∈ f› conic-def face-of-conic by fastforce
    then show ?thesis
      by (metis ‹0 < x · i› divideR-right eucl-less-le-not-le)
  qed
  then show f ⊆ conic hull (f ∩ {x. x · i = 1})
    by (auto simp: conic-hull-explicit)
qed

have conic-face-S: conic hull f face-of S
  if f face-of S for f
  by (metis ‹conic S› face-of-conic hull-same that)

have aff-1d: aff-dim (conic hull f) = aff-dim f + 1 (is ?lhs = ?rhs)
  if f face-of p and f ≠ {} for f
proof (rule order-antisym)
  have ?lhs ≤ aff-dim(affine hull (insert 0 (affine hull f)))
  proof (intro aff-dim-subset hull-minimal)
    show f ⊆ affine hull insert 0 (affine hull f)
      by (metis hull-insert hull-subset insert-subset)
    show conic (affine hull insert 0 (affine hull f))
      by (metis affine-hull-span-0 conic-span hull-inc insertI1)
  qed
  also have ... ≤ ?rhs
    by (simp add: aff-dim-insert)
  finally show ?lhs ≤ ?rhs .
  have aff-dim f < aff-dim (conic hull f)
  proof (intro aff-dim-psubset psubsetI)
    show affine hull f ⊆ affine hull (conic hull f)
      by (simp add: hull-mono hull-subset)
    have 0 ∉ affine hull f
      using affp face-of-imp-subset hull-mono that(1) by fastforce
    moreover have 0 ∈ affine hull (conic hull f)
      by (simp add: ‹f ≠ {}› hull-inc)
    ultimately show affine hull f ≠ affine hull (conic hull f)
      by auto
  qed
  then show ?rhs ≤ ?lhs
    by simp
```

```
  qed

  have face-S-imp-face-p: ⋀f. f face-of S ⟹ f ∩ {x. x · i = 1} face-of p
    by (metis 1 S-def affp convex-affine-hull face-of-slice hull-subset)

  have conic-eq-f: conic hull f ∩ {x. x · i = 1} = f
    if f face-of p for f
    by (metis 1 affp face-of-imp-subset hull-subset le-inf-iff that)

  have dim-f-hyperplane: aff-dim (f ∩ {x. x · i = 1}) = int d
    if f face-of S aff-dim f = 1 + int d for f
  proof −
    have conic f
      using ‹conic S› face-of-conic that(1) by blast
    then have 0 ∈ f
      using conic-contains-0 that by force
    moreover have ¬ f ⊆ {0}
      using subset-singletonD that(2) by fastforce
    ultimately obtain y where y: y ∈ f y ≠ 0
      by blast
    then have y · i > 0
      using doti-gt0 face-of-imp-subset that(1) by blast
     have aff-dim (conic hull (f ∩ {x. x · i = 1})) = aff-dim (f ∩ {x. x · i
= 1}) + 1
    proof (rule aff-1d)
      show f ∩ {x. x · i = 1} face-of p
        by (simp add: face-S-imp-face-p that(1))
      have inverse(y · i) *R y ∈ f
        using ‹0 < y · i› ‹conic S› conic-mul face-of-conic that(1) y(1) by
fastforce
      moreover have inverse(y · i) *R y ∈ {x. x · i = 1}
        using ‹y · i > 0› by (simp add: field-simps)
      ultimately show f ∩ {x. x · i = 1} ≠ {}
        by blast
    qed
    then show ?thesis
      by (simp add: conic-hyperplane-eq that)
  qed
  have card {f. f face-of S ∧ aff-dim f = 1 + int d}
     = card {f. f face-of p ∧ aff-dim f = int d}
  proof (intro bij-betw-same-card bij-betw-imageI)
    show inj-on (λf. f ∩ {x. x · i = 1}) {f. f face-of S ∧ aff-dim f = 1 +
int d}
  by (smt (verit) conic-hyperplane-eq inj-on-def mem-Collect-eq of-nat-less-0-iff)

    show (λf. f ∩ {x. x · i = 1}) ‘ {f. f face-of S ∧ aff-dim f = 1 + int d}
= {f. f face-of p ∧ aff-dim f = int d}
      using aff-1d conic-eq-f conic-face-p
      by (fastforce simp: image-iff face-S-imp-face-p dim-f-hyperplane)
```

qed
}
then show *?thesis*
by *force*
qed
finally show *?thesis* **.**
qed
ultimately show *?thesis*
by *auto*
qed
qed

corollary *Euler-poincare-special*:
fixes *p* :: *'n::euclidean-space set*
assumes *2* $\leq$ *DIM('n) polytope p i* $\in$ *Basis* **and** *affp*: *affine hull p* = {*x. x* $\cdot$ *i* = *0*}
shows ($\sum$ *d* = *0..DIM('n)* $-$ *1*. ($-$*1*) ^ *d* $*$ *card* {*f. f face-of p* $\wedge$ *aff-dim f* = *d*}) = *1*
proof $-$
{ fix *d*
have *eq*: *image((+) i)* ' {*f. f face-of p*} $\cap$ *image((+) i)* ' {*f. aff-dim f* = *int d*}
= *image((+) i)* ' {*f. f face-of p*} $\cap$ {*f. aff-dim f* = *int d*}
by (*auto simp*: *aff-dim-translation-eq*)
have *card* {*f. f face-of p* $\wedge$ *aff-dim f* = *int d*} = *card* (*image((+) i)* ' {*f. f face-of p* $\wedge$ *aff-dim f* = *int d*})
by (*simp add*: *inj-on-image card-image*)
also have ... = *card* (*image((+) i)* ' {*f. f face-of p*} $\cap$ {*f. aff-dim f* = *int d*})
by (*simp add*: *Collect-conj-eq image-Int inj-on-image eq*)
also have ... = *card* {*f. f face-of* (+) *i* ' *p* $\wedge$ *aff-dim f* = *int d*}
by (*simp add*: *Collect-conj-eq faces-of-translation*)
finally have *card* {*f. f face-of p* $\wedge$ *aff-dim f* = *int d*} = *card* {*f. f face-of* (+) *i* ' *p* $\wedge$ *aff-dim f* = *int d*} **.**
}
then
have ($\sum$ *d* = *0..DIM('n)* $-$ *1*. ($-$*1*) ^ *d* $*$ *card* {*f. f face-of p* $\wedge$ *aff-dim f* = *d*})
= ($\sum$ *d* = *0..DIM('n)* $-$ *1*. ($-$*1*) ^ *d* $*$ *card* {*f. f face-of* (+) *i* ' *p* $\wedge$ *aff-dim f* = *int d*})
by *simp*
also have ... = *1*
proof (*rule Euler-Poincare-lemma*)
have $\bigwedge$*x*. ⟦*i* $\in$ *Basis*; *x* $\cdot$ *i* = *1*⟧ $\Longrightarrow$ $\exists$ *y. y* $\cdot$ *i* = *0* $\wedge$ *x* = *y* + *i*
by (*metis add-cancel-left-left eq-diff-eq inner-diff-left inner-same-Basis*)
then show *affine hull* (+) *i* ' *p* = {*x. x* $\cdot$ *i* = *1*}
using ‹*i* $\in$ *Basis*› **unfolding** *affine-hull-translation affp* **by** (*auto simp*: *algebra-simps*)
qed (*use assms polytope-translation-eq* **in** *auto*)
finally show *?thesis* **.**
qed

1.7 Now Euler-Poincare for a general full-dimensional polytope

theorem *Euler-Poincare-full*:
fixes p :: $'n$::*euclidean-space set*
assumes *polytope p aff-dim p* = *DIM*($'n$)
shows $(\sum d = 0..DIM('n).\ (-1)\ \hat{}\ d * (card\ \{f.\ f\ face\text{-}of\ p \wedge aff\text{-}dim\ f = d\}))$ $= 1$
proof −
define *augm*:: $'n \Rightarrow 'n \times real$ **where** $augm \equiv \lambda x.\ (x,0)$
define *S* **where** $S \equiv augm$ ` *p*
obtain i::$'n$ **where** i: $i \in Basis$
by (*meson SOME-Basis*)
have *bounded-linear augm*
by (*auto simp*: *augm-def bounded-linearI'*)
then have *polytope S*
unfolding *S-def* **using** *polytope-linear-image* ‹*polytope p*› *bounded-linear.linear* **by** *blast*
have *face-pS*: $\bigwedge F.\ F$ *face-of p* $\longleftrightarrow$ *augm* ` *F face-of S*
using *S-def* ‹*bounded-linear augm*› *augm-def bounded-linear.linear face-of-linear-image inj-on-def* **by** *blast*
have *aff-dim-eq*[*simp*]: *aff-dim* (*augm* ` *F*) = *aff-dim F* **for** *F*
using ‹*bounded-linear augm*› *aff-dim-injective-linear-image bounded-linear.linear*

unfolding *augm-def inj-on-def* **by** *blast*
have ∗: {*F*. *F face-of S* ∧ *aff-dim F* = *int d*} = (*image augm*) ` {*F*. *F face-of p* ∧ *aff-dim F* = *int d*}
(**is** *?lhs* = *?rhs*) **for** *d*
proof
have $\bigwedge G$. ⟦*G face-of S*; *aff-dim G* = *int d*⟧
$\Longrightarrow \exists F$. *F face-of p* ∧ *aff-dim F* = *int d* ∧ *G* = *augm* ` *F*
by (*metis face-pS S-def aff-dim-eq face-of-imp-subset subset-imageE*)
then show *?lhs* ⊆ *?rhs*
by (*auto simp*: *image-iff*)
qed (*auto simp*: *image-iff face-pS*)
have *ceqc*: *card* {*f*. *f face-of S* ∧ *aff-dim f* = *int d*} = *card* {*f*. *f face-of p* ∧ *aff-dim f* = *int d*} **for** *d*
unfolding ∗
by (*rule card-image*) (*auto simp*: *inj-on-def augm-def*)
have $(\sum d = 0..DIM('n \times real) - 1.\ (-\ 1)\ \hat{}\ d * int\ (card\ \{f.\ f\ face\text{-}of\ S \wedge aff\text{-}dim\ f = int\ d\})) = 1$
proof (*rule Euler-poincare-special*)
show $2 \le DIM('n \times real)$
by *auto*
have *snd0*: $(a,\ b) \in affine\ hull\ S \Longrightarrow b = 0$ **for** *a b*
using *S-def* ‹*bounded-linear augm*› *affine-hull-linear-image augm-def* **by** *blast*
moreover have $\bigwedge a.\ (a,\ 0) \in affine\ hull\ S$
using *S-def* ‹*bounded-linear augm*› *aff-dim-eq-full affine-hull-linear-image assms*(*2*) *augm-def* **by** *blast*
ultimately show $affine\ hull\ S = \{x.\ x \cdot (0::'n,\ 1::real) = 0\}$

    by *auto*
  qed (*auto simp*: ‹*polytope S*› *Basis-prod-def*)
  then show *?thesis*
    by (*simp add*: *ceqc*)
qed

In particular, the Euler relation in 3 dimensions

corollary *Euler-relation*:
  fixes *p* :: *'n*::*euclidean-space set*
  assumes *polytope p aff-dim p* = *3 DIM*(*'n*) = *3*
  shows (*card* {*v*. *v face-of p* ∧ *aff-dim v* = *0*} + *card* {*f*. *f face-of p* ∧ *aff-dim f* = *2*}) − *card* {*e*. *e face-of p* ∧ *aff-dim e* = *1*} = *2*
proof −
  have ⋀*x*. ⟦*x face-of p*; *aff-dim x* = *3*⟧ ⟹ *x* = *p*
    using *assms* **by** (*metis face-of-aff-dim-lt less-irrefl polytope-imp-convex*)
  then have *3*: {*f*. *f face-of p* ∧ *aff-dim f* = *3*} = {*p*}
    using *assms* **by** (*auto simp*: *face-of-refl polytope-imp-convex*)
  have (∑ *d* = *0*..*3*. (−*1*) ^ *d* ∗ *int* (*card* {*f*. *f face-of p* ∧ *aff-dim f* = *int d*})) = *1*
    using *Euler-Poincare-full* [*of p*] *assms* **by** *simp*
  then show *?thesis*
    by (*simp add*: *sum.atLeast0-atMost-Suc-shift numeral-3-eq-3 3*)
qed

end

References

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