Ordinary Differential Equations

Fabian Immler

March 17, 2025

Abstract

Session `Ordinary-Differential-Equations` formalizes ordinary differential equations (ODEs) and initial value problems. This work comprises proofs for local and global existence of unique solutions (Picard-Lindelöf theorem). Moreover, it contains a formalization of the (continuous or even differentiable) dependency of the flow on initial conditions as the *flow* of ODEs.

Not in the generated document are the following sessions:

- `HOL-ODE-Numerics`: Rigorous numerical algorithms for computing enclosures of solutions based on Runge-Kutta methods and affine arithmetic. Reachability analysis with splitting and reduction at hyperplanes.
- `HOL-ODE-Examples`: Applications of the numerical algorithms to concrete systems of ODEs (e.g., van der Pol and Lorenz attractor).

Contents

1 Auxiliary Lemmas

theory *ODE-Auxiliarities*
imports
  HOL−Analysis.Analysis
  HOL−Library.Float
  List−Index.List-Index
  Affine-Arithmetic.Affine-Arithmetic-Auxiliarities
  Affine-Arithmetic.Executable-Euclidean-Space
begin

instantiation *prod* :: (*zero-neq-one*, *zero-neq-one*) *zero-neq-one*
begin

definition *1* = (*1*, *1*)

instance ⟨*proof*⟩
end

1.1 there is no inner product for type $'a \Rightarrow_L \ 'b$

lemma (**in** *real-inner*) *parallelogram-law*: $(norm\ (x + y))^2 + (norm\ (x - y))^2 = 2 * (norm\ x)^2 + 2 * (norm\ y)^2$
⟨*proof*⟩

locale *no-real-inner*
begin

lift-definition *fstzero*::(*real*∗*real*) $\Rightarrow_L$ (*real*∗*real*) **is** λ(*x*, *y*). (*x*, *0*)
  ⟨*proof*⟩

lemma [*simp*]: *fstzero* (*a*, *b*) = (*a*, *0*)
  ⟨*proof*⟩

lift-definition *zerosnd*::(*real*∗*real*) $\Rightarrow_L$ (*real*∗*real*) **is** λ(*x*, *y*). (*0*, *y*)
  ⟨*proof*⟩

lemma [*simp*]: *zerosnd* (*a*, *b*) = (*0*, *b*)
  ⟨*proof*⟩

lemma *fstzero-add-zerosnd*: *fstzero* + *zerosnd* = *id-blinfun*
  ⟨*proof*⟩

lemma *norm-fstzero-zerosnd*: *norm fstzero* = *1* *norm zerosnd* = *1* *norm* (*fstzero* − *zerosnd*) = *1*
  ⟨*proof*⟩

compare with $(norm\ (?x + ?y))^2 + (norm\ (?x - ?y))^2 = 2 * (norm\ ?x)^2 + 2 * (norm\ ?y)^2$

lemma $(norm\ (fstzero + zerosnd))^2 + (norm\ (fstzero - zerosnd))^2 \neq$
$2 * (norm\ fstzero)^2 + 2 * (norm\ zerosnd)^2$
$\langle proof \rangle$

end

1.2 Topology

1.3 Vector Spaces

lemma *ex-norm-eq-1*: $\exists\, x.\ norm\ (x::'a::\{real\text{-}normed\text{-}vector,\ perfect\text{-}space\}) = 1$
$\langle proof \rangle$

1.4 Reals

1.5 Balls

sometimes $(?y \in ball\ ?x\ ?e) = (dist\ ?x\ ?y < ?e)$ etc. are not good [*simp*] rules (although they are often useful): not sure that inequalities are "simpler" than set membership (distorts automatic reasoning when only sets are involved)

lemmas [*simp del*] = *mem-ball mem-cball mem-sphere mem-ball-0 mem-cball-0*

1.6 Boundedness

lemma *bounded-subset-cboxE*:
assumes $\bigwedge i.\ i \in Basis \Longrightarrow bounded\ ((\lambda x.\ x \cdot i)\ `\ X)$
obtains $a\ b$ **where** $X \subseteq cbox\ a\ b$
$\langle proof \rangle$

lemma
bounded-euclideanI:
assumes $\bigwedge i.\ i \in Basis \Longrightarrow bounded\ ((\lambda x.\ x \cdot i)\ `\ X)$
shows *bounded X*
$\langle proof \rangle$

1.7 Intervals

notation *closed-segment* (‹(*1*{-−−-})›)
notation *open-segment* (‹(*1*{-<−−<-})›)

lemma *min-zero-mult-nonneg-le*: $0 \leq h' \Longrightarrow h' \leq h \Longrightarrow min\ 0\ (h * k::real) \leq h' * k$
$\langle proof \rangle$

lemma *max-zero-mult-nonneg-le*: $0 \leq h' \Longrightarrow h' \leq h \Longrightarrow h' * k \leq max\ 0\ (h * k::real)$
$\langle proof \rangle$

lemmas *closed-segment-eq-real-ivl* = *closed-segment-eq-real-ivl*

lemma *bdd-above-is-intervalI*: *bdd-above I* **if** *is-interval I* $a \leq b$ $a \in I$ $b \notin I$ **for** *I*::*real set*
⟨*proof*⟩

lemma *bdd-below-is-intervalI*: *bdd-below I* **if** *is-interval I* $a \leq b$ $a \notin I$ $b \in I$ **for** *I*::*real set*
⟨*proof*⟩

1.8 Extended Real Intervals

1.9 Euclidean Components

1.10 Operator Norm

1.11 Limits

lemma *eventually-open-cball*:
assumes *open X*
assumes $x \in X$
shows *eventually* (λe. *cball x e* $\subseteq X$) (*at-right 0*)
⟨*proof*⟩

1.12 Continuity

1.13 Derivatives

lemma
if-eventually-has-derivative:
assumes (*f has-derivative* F') (*at x within S*)
assumes $\forall_F$ *x in at x within S*. *P x P x* $x \in S$
shows ((λx. *if P x then f x else g x*) *has-derivative* F') (*at x within S*)
⟨*proof*⟩

lemma *norm-le-in-cubeI*: *norm x* $\leq$ *norm y*
if $\bigwedge i$. $i \in$ *Basis* $\Longrightarrow$ *abs* $(x \cdot i) \leq$ *abs* $(y \cdot i)$ **for** *x y*
⟨*proof*⟩

lemma *has-derivative-partials-euclidean-convexI*:
fixes *f*::*'a*::*euclidean-space* $\Rightarrow$ *'b*::*real-normed-vector*
assumes f': $\bigwedge i\ x\ xi$. $i \in$ *Basis* $\Longrightarrow$ ($\forall j \in$ *Basis*. $x \cdot j \in X\ j$) $\Longrightarrow xi = x \cdot i \Longrightarrow$
((λp. $f\ (x + (p - x \cdot i) *_R i)$) *has-vector-derivative* $f'\ i\ x$) (*at xi within X i*)
assumes *df-cont*: $\bigwedge i$. $i \in$ *Basis* $\Longrightarrow$ ($f'\ i \longrightarrow (f'\ i\ x)$) (*at x within* $\{x. \forall j \in$ *Basis*. $x \cdot j \in X\ j\}$)
assumes $\bigwedge i$. $i \in$ *Basis* $\Longrightarrow x \cdot i \in X\ i$
assumes $\bigwedge i$. $i \in$ *Basis* $\Longrightarrow$ *convex* $(X\ i)$
shows (*f has-derivative* (λh. $\sum j \in$ *Basis*. $(h \cdot j) *_R f'\ j\ x$)) (*at x within* $\{x. \forall j \in$ *Basis*. $x \cdot j \in X\ j\}$)
(**is** - (*at x within ?S*))
⟨*proof*⟩

lemma
frechet-derivative-equals-partial-derivative:
fixes f::$'a$::*euclidean-space* $\Rightarrow$ $'a$
assumes Df: $\bigwedge x.$ (f *has-derivative* Df x) (*at* x)
assumes f': (($\lambda p.$ f (x + (p − x · i) $*_R$ i) · b) *has-real-derivative* f' x i b) (*at* (x · i))
shows Df x i · b = f' x i b
⟨*proof*⟩

1.14 Integration

lemmas *content-real*[*simp*]
lemmas *integrable-continuous*[*intro*, *simp*]
and *integrable-continuous-real*[*intro*, *simp*]

lemma *integral-eucl-le*:
fixes f g::$'a$::*euclidean-space* $\Rightarrow$ $'b$::*ordered-euclidean-space*
assumes f *integrable-on* s
and g *integrable-on* s
and $\bigwedge x.$ $x \in s \Longrightarrow f\ x \leq g\ x$
shows *integral* s f $\leq$ *integral* s g
⟨*proof*⟩

lemma
integral-ivl-bound:
fixes l u::$'a$::*ordered-euclidean-space*
assumes $\bigwedge x\ h'.\ h' \in \{t0\ ..\ h\} \Longrightarrow x \in \{t0\ ..\ h\} \Longrightarrow (h' - t0) *_R f\ x \in \{l\ ..\ u\}$
assumes $t0 \leq h$
assumes *f-int*: f *integrable-on* $\{t0\ ..\ h\}$
shows *integral* $\{t0\ ..\ h\}$ $f \in \{l\ ..\ u\}$
⟨*proof*⟩

lemma
add-integral-ivl-bound:
fixes l u::$'a$::*ordered-euclidean-space*
assumes $\bigwedge x\ h'.\ h' \in \{t0\ ..\ h\} \Longrightarrow x \in \{t0\ ..\ h\} \Longrightarrow (h' - t0) *_R f\ x \in \{l - x0\ ..\ u - x0\}$
assumes $t0 \leq h$
assumes *f-int*: f *integrable-on* $\{t0\ ..\ h\}$
shows $x0$ + *integral* $\{t0\ ..\ h\}$ $f \in \{l\ ..\ u\}$
⟨*proof*⟩

1.15 conditionally complete lattice

1.16 Lists

lemma
Ball-set-Cons[*simp*]: ($\forall\ a{\in}$*set-Cons* x y. P a) $\longleftrightarrow$ ($\forall\ a{\in}x.\ \forall\ b{\in}y.\ P\ (a\#b)$)

⟨*proof*⟩

lemma *set-cons-eq-empty*[*iff*]: *set-Cons a b* = {} ⟷ *a* = {} ∨ *b* = {}
⟨*proof*⟩

lemma *listset-eq-empty-iff*[*iff*]: *listset XS* = {} ⟷ {} ∈ *set XS*
⟨*proof*⟩

lemma *sing-in-sings*[*simp*]: [*x*] ∈ (λ*x*. [*x*]) ‘ *xd* ⟷ *x* ∈ *xd*
⟨*proof*⟩

lemma *those-eq-None-set-iff*: *those xs* = *None* ⟷ *None* ∈ *set xs*
⟨*proof*⟩

lemma *those-eq-Some-lengthD*: *those xs* = *Some ys* ⟹ *length xs* = *length ys*
⟨*proof*⟩

lemma *those-eq-Some-map-Some-iff*: *those xs* = *Some ys* ⟷ (*xs* = *map Some ys*) (**is** *?l* ⟷ *?r*)
⟨*proof*⟩

1.17 Set(sum)

1.18 Max

1.19 Uniform Limit

1.20 Bounded Linear Functions

lift-definition *comp3*::— TODO: name?
('*c*::*real-normed-vector* $\Rightarrow_L$ '*d*::*real-normed-vector*) ⇒ ('*b*::*real-normed-vector* $\Rightarrow_L$ '*c*) $\Rightarrow_L$ '*b* $\Rightarrow_L$ '*d* **is**
λ(*cd*::('*c* $\Rightarrow_L$ '*d*)) (*bc*::'*b* $\Rightarrow_L$ '*c*). (*cd* o_L *bc*)
⟨*proof*⟩

lemma *blinfun-apply-comp3*[*simp*]: *blinfun-apply* (*comp3 a*) *b* = (*a* o_L *b*)
⟨*proof*⟩

lemma *bounded-linear-comp3*[*bounded-linear*]: *bounded-linear comp3*
⟨*proof*⟩

lift-definition *comp12*::— TODO: name?
('*a*::*real-normed-vector* $\Rightarrow_L$ '*c*::*real-normed-vector*) ⇒ ('*b*::*real-normed-vector* $\Rightarrow_L$ '*c*) ⇒ ('*a* × '*b*) $\Rightarrow_L$ '*c*
is λ*f g* (*a*, *b*). *f a* + *g b*
⟨*proof*⟩

lemma *blinfun-apply-comp12*[*simp*]: *blinfun-apply* (*comp12 f g*) *b* = *f* (*fst b*) + *g* (*snd b*)
⟨*proof*⟩

1.21 Order Transitivity Attributes

⟨*ML*⟩

1.22 point reflection

definition *preflect*::*'a*::*real-vector* $\Rightarrow$ *'a* $\Rightarrow$ *'a* **where** *preflect* $\equiv \lambda t0\ t.\ 2 *_R t0 - t$

lemma *preflect-preflect*[*simp*]: *preflect t0* (*preflect t0 t*) = *t*
⟨*proof*⟩

lemma *preflect-preflect-image*[*simp*]: *preflect t0* ‘ *preflect t0* ‘ *S* = *S*
⟨*proof*⟩

lemma *is-interval-preflect*[*simp*]: *is-interval* (*preflect t0* ‘ *S*) $\longleftrightarrow$ *is-interval S*
⟨*proof*⟩

lemma *iv-in-preflect-image*[*intro*, *simp*]: $t0 \in T \Longrightarrow t0 \in$ *preflect t0* ‘ *T*
⟨*proof*⟩

lemma *preflect-tendsto*[*tendsto-intros*]:
fixes *l*::*'a*::*real-normed-vector*
shows $(g \longrightarrow l)\ F \Longrightarrow (h \longrightarrow m)\ F \Longrightarrow ((\lambda x.\ preflect\ (g\ x)\ (h\ x)) \longrightarrow preflect\ l\ m)\ F$
⟨*proof*⟩

lemma *continuous-preflect*[*continuous-intros*]:
fixes *a*::*'a*::*real-normed-vector*
shows *continuous* (*at a within A*) (*preflect t0*)
⟨*proof*⟩

lemma
fixes *t0*::*'a*::*ordered-real-vector*
shows *preflect-le*[*simp*]: $t0 \le$ *preflect t0 b* $\longleftrightarrow b \le t0$
and *le-preflect*[*simp*]: *preflect t0 b* $\le t0 \longleftrightarrow t0 \le b$
and *antimono-preflect*: *antimono* (*preflect t0*)
and *preflect-le-preflect*[*simp*]: *preflect t0 a* $\le$ *preflect t0 b* $\longleftrightarrow b \le a$
and *preflect-eq-cancel*[*simp*]: *preflect t0 a* = *preflect t0 b* $\longleftrightarrow a = b$
⟨*proof*⟩

lemma *preflect-eq-point-iff*[*simp*]: *t0* = *preflect t0 s* $\longleftrightarrow$ *t0* = *s* *preflect t0 s* = *t0* $\longleftrightarrow$ *t0* = *s*
⟨*proof*⟩

lemma *preflect-minus-self*[*simp*]: *preflect t0 s* − *t0* = *t0* − *s*
⟨*proof*⟩

end
theory *MVT-Ex*
imports

HOL−Analysis.Analysis
HOL−Decision-Procs.Approximation
../ODE-Auxiliarities
begin

1.23 (Counter)Example of Mean Value Theorem in Euclidean Space

There is no exact analogon of the mean value theorem in the multivariate case!

lemma *MVT-wrong*: **assumes**
$\bigwedge J\ a\ u\ (f::real*real \Rightarrow real*real).$
$(\bigwedge x.\ FDERIV\ f\ x :> J\ x) \Longrightarrow$
$(\exists\, t \in \{0 <..< 1\}.\ f\ (a + u) - f\ a = J\ (a + t *_R u)\ u)$
shows *False*
⟨*proof*⟩

lemma *MVT-corrected*:
fixes $f::'a::ordered\text{-}euclidean\text{-}space \Rightarrow 'b::euclidean\text{-}space$
assumes *fderiv*: $\bigwedge x.\ x \in D \Longrightarrow (f\ has\text{-}derivative\ J\ x)\ (at\ x\ within\ D)$
assumes *line-in*: $\bigwedge x.\ [\![0 \le x;\ x \le 1]\!] \Longrightarrow a + x *_R u \in D$
shows $(\exists\, t \in Basis \to \{0 <..< 1\}.\ (f\ (a + u) - f\ a) = (\sum i \in Basis.\ (J\ (a + t\ i *_R u)\ u \cdot i) *_R i))$
⟨*proof*⟩

lemma *MVT-ivl*:
fixes $f::'a::ordered\text{-}euclidean\text{-}space \Rightarrow 'b::ordered\text{-}euclidean\text{-}space$
assumes *fderiv*: $\bigwedge x.\ x \in D \Longrightarrow (f\ has\text{-}derivative\ J\ x)\ (at\ x\ within\ D)$
assumes *J-ivl*: $\bigwedge x.\ x \in D \Longrightarrow J\ x\ u \in \{J0\ ..\ J1\}$
assumes *line-in*: $\bigwedge x.\ x \in \{0..1\} \Longrightarrow a + x *_R u \in D$
shows $f\ (a + u) - f\ a \in \{J0..J1\}$
⟨*proof*⟩

lemma *MVT*:
shows
$\bigwedge J\ J0\ J1\ a\ u\ (f::real*real \Rightarrow real*real).$
$(\bigwedge x.\ FDERIV\ f\ x :> J\ x) \Longrightarrow$
$(\bigwedge x.\ J\ x\ u \in \{J0\ ..\ J1\}) \Longrightarrow$
$f\ (a + u) - f\ a \in \{J0\ ..\ J1\}$
⟨*proof*⟩

lemma *MVT-ivl'*:
fixes $f::'a::ordered\text{-}euclidean\text{-}space \Rightarrow 'b::ordered\text{-}euclidean\text{-}space$
assumes *fderiv*: $(\bigwedge x.\ x \in D \Longrightarrow (f\ has\text{-}derivative\ J\ x)\ (at\ x\ within\ D))$
assumes *J-ivl*: $\bigwedge x.\ x \in D \Longrightarrow J\ x\ (a - b) \in \{J0..J1\}$
assumes *line-in*: $\bigwedge x.\ x \in \{0..1\} \Longrightarrow b + x *_R (a - b) \in D$
shows $f\ a \in \{f\ b + J0..f\ b + J1\}$
⟨*proof*⟩

end
theory
Vector-Derivative-On
imports
HOL−Analysis.Analysis
begin

1.24 Vector derivative on a set

definition
has-vderiv-on :: (*real* ⇒ ′*a*::*real-normed-vector*) ⇒ (*real* ⇒ ′*a*) ⇒ *real set* ⇒ *bool*
(**infix** ‹(*has*′-*vderiv*′-*on*)› *50*)
where
(*f has-vderiv-on f*′) *S* ⟷ (∀ *x* ∈ *S*. (*f has-vector-derivative f*′ *x*) (*at x within S*))

lemma *has-vderiv-on-empty*[*intro*, *simp*]: (*f has-vderiv-on f*′) {}
⟨*proof*⟩

lemma *has-vderiv-on-subset*:
assumes (*f has-vderiv-on f*′) *S*
assumes *T* ⊆ *S*
shows (*f has-vderiv-on f*′) *T*
⟨*proof*⟩

lemma *has-vderiv-on-compose*:
assumes (*f has-vderiv-on f*′) (*g* ‘ *T*)
assumes (*g has-vderiv-on g*′) *T*
shows (*f o g has-vderiv-on* (λ*x*. *g*′ *x* $*_R$ *f*′ (*g x*))) *T*
⟨*proof*⟩

lemma *has-vderiv-on-open*:
assumes *open T*
shows (*f has-vderiv-on f*′) *T* ⟷ (∀ *t* ∈ *T*. (*f has-vector-derivative f*′ *t*) (*at t*))
⟨*proof*⟩

lemma *has-vderiv-on-eq-rhs*:— TODO: integrate intro *derivative-eq-intros*
(*f has-vderiv-on g*′) *T* ⟹ (⋀*x*. *x* ∈ *T* ⟹ *g*′ *x* = *f*′ *x*) ⟹ (*f has-vderiv-on f*′) *T*
⟨*proof*⟩

lemma [*THEN has-vderiv-on-eq-rhs*, *derivative-intros*]:
shows *has-vderiv-on-id*: ((λ*x*. *x*) *has-vderiv-on* (λ*x*. *1*)) *T*
and *has-vderiv-on-const*: ((λ*x*. *c*) *has-vderiv-on* (λ*x*. *0*)) *T*
⟨*proof*⟩

lemma [*THEN has-vderiv-on-eq-rhs*, *derivative-intros*]:
fixes *f*::*real* ⇒ ′*a*::*real-normed-vector*
assumes (*f has-vderiv-on f*′) *T*

shows *has-vderiv-on-uminus*: $((\lambda x.\ - f\ x)$ *has-vderiv-on* $(\lambda x.\ - f'\ x))\ T$
$\langle proof \rangle$

lemma [*THEN has-vderiv-on-eq-rhs*, *derivative-intros*]:
fixes $f\ g$::*real* $\Rightarrow$ *'a*::*real-normed-vector*
assumes $(f$ *has-vderiv-on* $f')\ T$
assumes $(g$ *has-vderiv-on* $g')\ T$
shows *has-vderiv-on-add*: $((\lambda x.\ f\ x + g\ x)$ *has-vderiv-on* $(\lambda x.\ f'\ x + g'\ x))\ T$
and *has-vderiv-on-diff*: $((\lambda x.\ f\ x - g\ x)$ *has-vderiv-on* $(\lambda x.\ f'\ x - g'\ x))\ T$
$\langle proof \rangle$

lemma [*THEN has-vderiv-on-eq-rhs*, *derivative-intros*]:
fixes f::*real* $\Rightarrow$ *real* **and** g::*real* $\Rightarrow$ *'a*::*real-normed-vector*
assumes $(f$ *has-vderiv-on* $f')\ T$
assumes $(g$ *has-vderiv-on* $g')\ T$
shows *has-vderiv-on-scaleR*: $((\lambda x.\ f\ x *_R g\ x)$ *has-vderiv-on* $(\lambda x.\ f\ x *_R g'\ x + f'\ x *_R g\ x))\ T$
$\langle proof \rangle$

lemma [*THEN has-vderiv-on-eq-rhs*, *derivative-intros*]:
fixes $f\ g$::*real* $\Rightarrow$ *'a*::*real-normed-algebra*
assumes $(f$ *has-vderiv-on* $f')\ T$
assumes $(g$ *has-vderiv-on* $g')\ T$
shows *has-vderiv-on-mult*: $((\lambda x.\ f\ x * g\ x)$ *has-vderiv-on* $(\lambda x.\ f\ x * g'\ x + f'\ x * g\ x))\ T$
$\langle proof \rangle$

lemma *has-vderiv-on-ln*[*THEN has-vderiv-on-eq-rhs*, *derivative-intros*]:
fixes g::*real* $\Rightarrow$ *real*
assumes $\bigwedge x.\ x \in s \Longrightarrow 0 < g\ x$
assumes $(g$ *has-vderiv-on* $g')\ s$
shows $((\lambda x.\ ln\ (g\ x))$ *has-vderiv-on* $(\lambda x.\ g'\ x\ /\ g\ x))\ s$
$\langle proof \rangle$

lemma *fundamental-theorem-of-calculus'*:
fixes f :: *real* $\Rightarrow$ *'a*::*banach*
shows $a \le b \Longrightarrow (f$ *has-vderiv-on* $f')\ \{a\ ..\ b\} \Longrightarrow (f'$ *has-integral* $(f\ b - f\ a))\ \{a\ ..\ b\}$
$\langle proof \rangle$

lemma *has-vderiv-on-If*:
assumes $U = S \cup T$
assumes $(f$ *has-vderiv-on* $f')\ (S \cup (closure\ T \cap closure\ S))$
assumes $(g$ *has-vderiv-on* $g')\ (T \cup (closure\ T \cap closure\ S))$
assumes $\bigwedge x.\ x \in closure\ T \Longrightarrow x \in closure\ S \Longrightarrow f\ x = g\ x$
assumes $\bigwedge x.\ x \in closure\ T \Longrightarrow x \in closure\ S \Longrightarrow f'\ x = g'\ x$
shows $((\lambda t.\ if\ t \in S\ then\ f\ t\ else\ g\ t)$ *has-vderiv-on* $(\lambda t.\ if\ t \in S\ then\ f'\ t\ else\ g'\ t))\ U$

⟨*proof*⟩

lemma *mvt-very-simple-closed-segmentE*:
fixes f::*real*⇒*real*
assumes (f *has-vderiv-on* f') (*closed-segment* a b)
obtains y **where** $y \in$ *closed-segment* a b $f\ b - f\ a = (b - a) * f'\ y$
⟨*proof*⟩

lemma *mvt-simple-closed-segmentE*:
fixes f::*real*⇒*real*
assumes (f *has-vderiv-on* f') (*closed-segment* a b)
assumes $a \neq b$
obtains y **where** $y \in$ *open-segment* a b $f\ b - f\ a = (b - a) * f'\ y$
⟨*proof*⟩

lemma *differentiable-bound-general-open-segment*:
fixes a :: *real*
and b :: *real*
and f :: *real* ⇒ *'a*::*real-normed-vector*
and f' :: *real* ⇒ *'a*
assumes *continuous-on* (*closed-segment* a b) f
assumes *continuous-on* (*closed-segment* a b) g
and (f *has-vderiv-on* f') (*open-segment* a b)
and (g *has-vderiv-on* g') (*open-segment* a b)
and $\bigwedge x.\ x \in$ *open-segment* a $b \Longrightarrow$ *norm* $(f'\ x) \leq g'\ x$
shows *norm* $(f\ b - f\ a) \leq$ *abs* $(g\ b - g\ a)$
⟨*proof*⟩

lemma *has-vderiv-on-union*:
assumes (f *has-vderiv-on* g) ($s \cup$ *closure* $s \cap$ *closure* t)
assumes (f *has-vderiv-on* g) ($t \cup$ *closure* $s \cap$ *closure* t)
shows (f *has-vderiv-on* g) ($s \cup t$)
⟨*proof*⟩

lemma *has-vderiv-on-union-closed*:
assumes (f *has-vderiv-on* g) s
assumes (f *has-vderiv-on* g) t
assumes *closed* s *closed* t
shows (f *has-vderiv-on* g) ($s \cup t$)
⟨*proof*⟩

lemma *vderiv-on-continuous-on*: (f *has-vderiv-on* f') $S \Longrightarrow$ *continuous-on* S f
⟨*proof*⟩

lemma *has-vderiv-on-cong*[*cong*]:
assumes $\bigwedge x.\ x \in S \Longrightarrow f\ x = g\ x$
assumes $\bigwedge x.\ x \in S \Longrightarrow f'\ x = g'\ x$
assumes $S = T$
shows (f *has-vderiv-on* f') S = (g *has-vderiv-on* g') T

⟨*proof*⟩

lemma *has-vderiv-eq*:
assumes $(f\ \textit{has-vderiv-on}\ f')\ S$
assumes $\bigwedge x.\ x \in S \Longrightarrow f\ x = g\ x$
assumes $\bigwedge x.\ x \in S \Longrightarrow f'\ x = g'\ x$
assumes $S = T$
shows $(g\ \textit{has-vderiv-on}\ g')\ T$
⟨*proof*⟩

lemma *has-vderiv-on-compose′*:
assumes $(f\ \textit{has-vderiv-on}\ f')\ (g\ `\ T)$
assumes $(g\ \textit{has-vderiv-on}\ g')\ T$
shows $((\lambda x.\ f\ (g\ x))\ \textit{has-vderiv-on}\ (\lambda x.\ g'\ x *_R f'\ (g\ x)))\ T$
⟨*proof*⟩

lemma *has-vderiv-on-compose2*:
assumes $(f\ \textit{has-vderiv-on}\ f')\ S$
assumes $(g\ \textit{has-vderiv-on}\ g')\ T$
assumes $\bigwedge t.\ t \in T \Longrightarrow g\ t \in S$
shows $((\lambda x.\ f\ (g\ x))\ \textit{has-vderiv-on}\ (\lambda x.\ g'\ x *_R f'\ (g\ x)))\ T$
⟨*proof*⟩

lemma *has-vderiv-on-singleton*: $(y\ \textit{has-vderiv-on}\ y')\ \{t0\}$
⟨*proof*⟩

lemma
has-vderiv-on-zero-constant:
assumes *convex s*
assumes $(f\ \textit{has-vderiv-on}\ (\lambda h.\ 0))\ s$
obtains c **where** $\bigwedge x.\ x \in s \Longrightarrow f\ x = c$
⟨*proof*⟩

lemma *bounded-vderiv-on-imp-lipschitz*:
assumes $(f\ \textit{has-vderiv-on}\ f')\ X$
assumes *convex*: *convex X*
assumes $\bigwedge x.\ x \in X \Longrightarrow \textit{norm}\ (f'\ x) \le C\ 0 \le C$
shows $C{-}\textit{lipschitz-on}\ X\ f$
⟨*proof*⟩

end
theory *Interval-Integral-HK*
imports *Vector-Derivative-On*
begin

1.25 interval integral

definition *has-ivl-integral* ::
$(\textit{real} \Rightarrow {'}b{::}\textit{real-normed-vector}) \Rightarrow {'}b \Rightarrow \textit{real} \Rightarrow \textit{real} \Rightarrow \textit{bool}$— TODO: generalize?

(**infixr** ‹*has′-ivl′-integral*› *46*)
where $(f\ \textit{has-ivl-integral}\ y)\ a\ b \longleftrightarrow (\textit{if}\ a \le b\ \textit{then}\ (f\ \textit{has-integral}\ y)\ \{a\ ..\ b\}\ \textit{else}\ (f\ \textit{has-integral}\ -\ y)\ \{b\ ..\ a\})$

definition $\textit{ivl-integral}::\textit{real} \Rightarrow \textit{real} \Rightarrow (\textit{real} \Rightarrow 'a) \Rightarrow 'a::\textit{real-normed-vector}$
where $\textit{ivl-integral}\ a\ b\ f = \textit{integral}\ \{a\ ..\ b\}\ f - \textit{integral}\ \{b\ ..\ a\}\ f$

lemma *integral-emptyI*[*simp*]:
fixes $a\ b::\textit{real}$
shows $a \ge b \Longrightarrow \textit{integral}\ \{a..b\}\ f = 0\ a > b \Longrightarrow \textit{integral}\ \{a..b\}\ f = 0$
⟨*proof*⟩

lemma *ivl-integral-unique*: $(f\ \textit{has-ivl-integral}\ y)\ a\ b \Longrightarrow \textit{ivl-integral}\ a\ b\ f = y$
⟨*proof*⟩

lemma *fundamental-theorem-of-calculus-ivl-integral*:
fixes $f :: \textit{real} \Rightarrow 'a::\textit{banach}$
shows $(f\ \textit{has-vderiv-on}\ f')\ (\textit{closed-segment}\ a\ b) \Longrightarrow (f'\ \textit{has-ivl-integral}\ f\ b - f\ a)\ a\ b$
⟨*proof*⟩

lemma
fixes $f :: \textit{real} \Rightarrow 'a::\textit{banach}$
assumes $f\ \textit{integrable-on}\ (\textit{closed-segment}\ a\ b)$
shows *indefinite-ivl-integral-continuous*:
$\textit{continuous-on}\ (\textit{closed-segment}\ a\ b)\ (\lambda x.\ \textit{ivl-integral}\ a\ x\ f)$
$\textit{continuous-on}\ (\textit{closed-segment}\ b\ a)\ (\lambda x.\ \textit{ivl-integral}\ a\ x\ f)$
⟨*proof*⟩

lemma
fixes $f :: \textit{real} \Rightarrow 'a::\textit{banach}$
assumes $f\ \textit{integrable-on}\ (\textit{closed-segment}\ a\ b)$
assumes $c \in \textit{closed-segment}\ a\ b$
shows *indefinite-ivl-integral-continuous-subset*:
$\textit{continuous-on}\ (\textit{closed-segment}\ a\ b)\ (\lambda x.\ \textit{ivl-integral}\ c\ x\ f)$
⟨*proof*⟩

lemma *real-Icc-closed-segment*: **fixes** $a\ b::\textit{real}$ **shows** $a \le b \Longrightarrow \{a\ ..\ b\} = \textit{closed-segment}\ a\ b$
⟨*proof*⟩

lemma *ivl-integral-zero*[*simp*]: $\textit{ivl-integral}\ a\ a\ f = 0$
⟨*proof*⟩

lemma *ivl-integral-cong*:
assumes $\bigwedge x.\ x \in \textit{closed-segment}\ a\ b \Longrightarrow g\ x = f\ x$
assumes $a = c\ b = d$
shows $\textit{ivl-integral}\ a\ b\ f = \textit{ivl-integral}\ c\ d\ g$
⟨*proof*⟩

lemma *ivl-integral-diff*:
f integrable-on (*closed-segment s t*) $\Longrightarrow$ *g integrable-on* (*closed-segment s t*) $\Longrightarrow$
ivl-integral s t ($\lambda x.$ *f x* $-$ *g x*) = *ivl-integral s t f* $-$ *ivl-integral s t g*
⟨*proof*⟩

lemma *ivl-integral-norm-bound-ivl-integral*:
fixes *f* :: *real* $\Rightarrow$ *'a::banach*
assumes *f integrable-on* (*closed-segment a b*)
and *g integrable-on* (*closed-segment a b*)
and $\bigwedge x.$ *x* $\in$ *closed-segment a b* $\Longrightarrow$ *norm* (*f x*) $\leq$ *g x*
shows *norm* (*ivl-integral a b f*) $\leq$ *abs* (*ivl-integral a b g*)
⟨*proof*⟩

lemma *ivl-integral-norm-bound-integral*:
fixes *f* :: *real* $\Rightarrow$ *'a::banach*
assumes *f integrable-on* (*closed-segment a b*)
and *g integrable-on* (*closed-segment a b*)
and $\bigwedge x.$ *x* $\in$ *closed-segment a b* $\Longrightarrow$ *norm* (*f x*) $\leq$ *g x*
shows *norm* (*ivl-integral a b f*) $\leq$ *integral* (*closed-segment a b*) *g*
⟨*proof*⟩

lemma *norm-ivl-integral-le*:
fixes *f* :: *real* $\Rightarrow$ *real*
assumes *f integrable-on* (*closed-segment a b*)
and *g integrable-on* (*closed-segment a b*)
and $\bigwedge x.$ *x* $\in$ *closed-segment a b* $\Longrightarrow$ *f x* $\leq$ *g x*
and $\bigwedge x.$ *x* $\in$ *closed-segment a b* $\Longrightarrow$ *0* $\leq$ *f x*
shows *abs* (*ivl-integral a b f*) $\leq$ *abs* (*ivl-integral a b g*)
⟨*proof*⟩

lemma *ivl-integral-const* [*simp*]:
shows *ivl-integral a b* ($\lambda x.$ *c*) = (*b* $-$ *a*) $*_R$ *c*
⟨*proof*⟩

lemma *ivl-integral-has-vector-derivative*:
fixes *f* :: *real* $\Rightarrow$ *'a::banach*
assumes *continuous-on* (*closed-segment a b*) *f*
and *x* $\in$ *closed-segment a b*
shows (($\lambda u.$ *ivl-integral a u f*) *has-vector-derivative f x*) (*at x within closed-segment a b*)
⟨*proof*⟩

lemma *ivl-integral-has-vderiv-on*:
fixes *f* :: *real* $\Rightarrow$ *'a::banach*
assumes *continuous-on* (*closed-segment a b*) *f*
shows (($\lambda u.$ *ivl-integral a u f*) *has-vderiv-on f*) (*closed-segment a b*)
⟨*proof*⟩

lemma *ivl-integral-has-vderiv-on-subset-segment*:
  fixes f :: *real* $\Rightarrow$ $'a$::*banach*
  assumes *continuous-on* (*closed-segment* a b) f
    and $c \in$ *closed-segment* a b
  shows ((λu. *ivl-integral* c u f) *has-vderiv-on* f) (*closed-segment* a b)
⟨*proof*⟩

lemma *ivl-integral-has-vector-derivative-subset*:
  fixes f :: *real* $\Rightarrow$ $'a$::*banach*
  assumes *continuous-on* (*closed-segment* a b) f
    and $x \in$ *closed-segment* a b
    and $c \in$ *closed-segment* a b
  shows ((λu. *ivl-integral* c u f) *has-vector-derivative* f x) (*at* x *within closed-segment* a b)
  ⟨*proof*⟩

lemma
  compact-interval-eq-Inf-Sup:
  fixes A::*real set*
  assumes *is-interval* A *compact* A $A \neq \{\}$
  shows $A = \{$*Inf* A .. *Sup* $A\}$
  ⟨*proof*⟩

lemma *ivl-integral-has-vderiv-on-compact-interval*:
  fixes f :: *real* $\Rightarrow$ $'a$::*banach*
  assumes *continuous-on* A f
    and $c \in A$ *is-interval* A *compact* A
  shows ((λu. *ivl-integral* c u f) *has-vderiv-on* f) A
⟨*proof*⟩

lemma *ivl-integral-has-vector-derivative-compact-interval*:
  fixes f :: *real* $\Rightarrow$ $'a$::*banach*
  assumes *continuous-on* A f
    and *is-interval* A *compact* A $x \in A$ $c \in A$
  shows ((λu. *ivl-integral* c u f) *has-vector-derivative* f x) (*at* x *within* A)
  ⟨*proof*⟩

lemma *ivl-integral-combine*:
  fixes f::*real* $\Rightarrow$ $'a$::*banach*
  assumes f *integrable-on* (*closed-segment* a b)
  assumes f *integrable-on* (*closed-segment* b c)
  assumes f *integrable-on* (*closed-segment* a c)
  shows *ivl-integral* a b f + *ivl-integral* b c f = *ivl-integral* a c f
⟨*proof*⟩

lemma *integral-equation-swap-initial-value*:
  fixes x::*real*$\Rightarrow$$'a$::*banach*
  assumes $\bigwedge t$. $t \in$ *closed-segment* $t0$ $t1$ $\Longrightarrow$ $x\ t = x\ t0$ + *ivl-integral* $t0$ t (λt. f t (x t))

assumes t: $t \in$ *closed-segment t0 t1*
assumes *int*: $(\lambda t.\ f\ t\ (x\ t))$ *integrable-on closed-segment t0 t1*
shows $x\ t = x\ t1 + \textit{ivl-integral}\ t1\ t\ (\lambda t.\ f\ t\ (x\ t))$
⟨*proof*⟩

lemma *has-integral-nonpos*:
fixes $f :: {}'n::\textit{euclidean-space} \Rightarrow \textit{real}$
assumes $(f\ \textit{has-integral}\ i)\ s$
and $\forall x{\in}s.\ f\ x \leq 0$
shows $i \leq 0$
⟨*proof*⟩

lemma *has-ivl-integral-nonneg*:
fixes $f :: \textit{real} \Rightarrow \textit{real}$
assumes $(f\ \textit{has-ivl-integral}\ i)\ a\ b$
and $\bigwedge x.\ a \leq x \Longrightarrow x \leq b \Longrightarrow 0 \leq f\ x$
and $\bigwedge x.\ b \leq x \Longrightarrow x \leq a \Longrightarrow f\ x \leq 0$
shows $0 \leq i$
⟨*proof*⟩

lemma *has-ivl-integral-ivl-integral*:
f *integrable-on* $(\textit{closed-segment}\ a\ b) \longleftrightarrow (f\ \textit{has-ivl-integral}\ (\textit{ivl-integral}\ a\ b\ f))\ a$
b
⟨*proof*⟩

lemma *ivl-integral-nonneg*:
fixes $f :: \textit{real} \Rightarrow \textit{real}$
assumes f *integrable-on* $(\textit{closed-segment}\ a\ b)$
and $\bigwedge x.\ a \leq x \Longrightarrow x \leq b \Longrightarrow 0 \leq f\ x$
and $\bigwedge x.\ b \leq x \Longrightarrow x \leq a \Longrightarrow f\ x \leq 0$
shows $0 \leq \textit{ivl-integral}\ a\ b\ f$
⟨*proof*⟩

lemma *ivl-integral-bound*:
fixes $f::\textit{real} \Rightarrow {}'a::\textit{banach}$
assumes *continuous-on* $(\textit{closed-segment}\ a\ b)\ f$
assumes $\bigwedge t.\ t \in (\textit{closed-segment}\ a\ b) \Longrightarrow \textit{norm}\ (f\ t) \leq B$
shows $\textit{norm}\ (\textit{ivl-integral}\ a\ b\ f) \leq B * \textit{abs}\ (b - a)$
⟨*proof*⟩

lemma *ivl-integral-minus-sets*:
fixes $f::\textit{real} \Rightarrow {}'a::\textit{banach}$
shows f *integrable-on* $(\textit{closed-segment}\ c\ a) \Longrightarrow f$ *integrable-on* $(\textit{closed-segment}\ c$
$b) \Longrightarrow f$ *integrable-on* $(\textit{closed-segment}\ a\ b) \Longrightarrow$
$\textit{ivl-integral}\ c\ a\ f - \textit{ivl-integral}\ c\ b\ f = \textit{ivl-integral}\ b\ a\ f$
⟨*proof*⟩

lemma *ivl-integral-minus-sets'*:
fixes $f::\textit{real} \Rightarrow {}'a::\textit{banach}$

shows f *integrable-on* (*closed-segment* a c) $\Longrightarrow$ f *integrable-on* (*closed-segment* b c) $\Longrightarrow$ f *integrable-on* (*closed-segment* a b) $\Longrightarrow$
ivl-integral a c f $-$ *ivl-integral* b c f $=$ *ivl-integral* a b f
⟨*proof*⟩

end
theory *Gronwall*
imports *Vector-Derivative-On*
begin

1.26 Gronwall

lemma *derivative-quotient-bound*:
assumes *g-deriv-on*: (g *has-vderiv-on* g') $\{a\ ..\ b\}$
assumes *frac-le*: $\bigwedge t.\ t \in \{a\ ..\ b\} \Longrightarrow g'\ t\ /\ g\ t \leq K$
assumes g'*-cont*: *continuous-on* $\{a\ ..\ b\}$ g'
assumes *g-pos*: $\bigwedge t.\ t \in \{a\ ..\ b\} \Longrightarrow g\ t > 0$
assumes *t-in*: $t \in \{a\ ..\ b\}$
shows $g\ t \leq g\ a * exp\ (K * (t - a))$
⟨*proof*⟩

lemma *derivative-quotient-bound-left*:
assumes *g-deriv-on*: (g *has-vderiv-on* g') $\{a\ ..\ b\}$
assumes *frac-ge*: $\bigwedge t.\ t \in \{a\ ..\ b\} \Longrightarrow K \leq g'\ t\ /\ g\ t$
assumes g'*-cont*: *continuous-on* $\{a\ ..\ b\}$ g'
assumes *g-pos*: $\bigwedge t.\ t \in \{a\ ..\ b\} \Longrightarrow g\ t > 0$
assumes *t-in*: $t \in \{a..b\}$
shows $g\ t \leq g\ b * exp\ (K * (t - b))$
⟨*proof*⟩

lemma *gronwall-general*:
fixes g K C a b **and** t::*real*
defines $G \equiv \lambda t.\ C + K * integral\ \{a..t\}\ (\lambda s.\ g\ s)$
assumes *g-le-G*: $\bigwedge t.\ t \in \{a..b\} \Longrightarrow g\ t \leq G\ t$
assumes *g-cont*: *continuous-on* $\{a..b\}$ g
assumes *g-nonneg*: $\bigwedge t.\ t \in \{a..b\} \Longrightarrow 0 \leq g\ t$
assumes *pos*: $0 < C\ K > 0$
assumes $t \in \{a..b\}$
shows $g\ t \leq C * exp\ (K * (t - a))$
⟨*proof*⟩

lemma *gronwall-general-left*:
fixes g K C a b **and** t::*real*
defines $G \equiv \lambda t.\ C + K * integral\ \{t..b\}\ (\lambda s.\ g\ s)$
assumes *g-le-G*: $\bigwedge t.\ t \in \{a..b\} \Longrightarrow g\ t \leq G\ t$
assumes *g-cont*: *continuous-on* $\{a..b\}$ g
assumes *g-nonneg*: $\bigwedge t.\ t \in \{a..b\} \Longrightarrow 0 \leq g\ t$
assumes *pos*: $0 < C\ K > 0$
assumes $t \in \{a..b\}$

shows $g\ t \leq C * exp\ (- K * (t - b))$
⟨*proof*⟩

lemma *gronwall-general-segment*:
fixes $a\ b$::*real*
assumes $\bigwedge t.\ t \in$ *closed-segment* $a\ b \Longrightarrow g\ t \leq C + K *$ *integral* (*closed-segment* $a\ t$) g
and *continuous-on* (*closed-segment* $a\ b$) g
and $\bigwedge t.\ t \in$ *closed-segment* $a\ b \Longrightarrow 0 \leq g\ t$
and $0 < C$
and $0 < K$
and $t \in$ *closed-segment* $a\ b$
shows $g\ t \leq C * exp\ (K * abs\ (t - a))$
⟨*proof*⟩

lemma *gronwall-more-general-segment*:
fixes $a\ b\ c$::*real*
assumes $\bigwedge t.\ t \in$ *closed-segment* $a\ b \Longrightarrow g\ t \leq C + K *$ *integral* (*closed-segment* $c\ t$) g
and *cont*: *continuous-on* (*closed-segment* $a\ b$) g
and $\bigwedge t.\ t \in$ *closed-segment* $a\ b \Longrightarrow 0 \leq g\ t$
and $0 < C$
and $0 < K$
and t: $t \in$ *closed-segment* $a\ b$
and c: $c \in$ *closed-segment* $a\ b$
shows $g\ t \leq C * exp\ (K * abs\ (t - c))$
⟨*proof*⟩

lemma *gronwall*:
fixes $g\ K\ C$ **and** t::*real*
defines $G \equiv \lambda t.\ C + K *$ *integral* $\{0..t\}$ $(\lambda s.\ g\ s)$
assumes *g-le-G*: $\bigwedge t.\ 0 \leq t \Longrightarrow t \leq a \Longrightarrow g\ t \leq G\ t$
assumes *g-cont*: *continuous-on* $\{0..a\}$ g
assumes *g-nonneg*: $\bigwedge t.\ 0 \leq t \Longrightarrow t \leq a \Longrightarrow 0 \leq g\ t$
assumes *pos*: $0 < C\ 0 < K$
assumes $0 \leq t\ t \leq a$
shows $g\ t \leq C * exp\ (K * t)$
⟨*proof*⟩

lemma *gronwall-left*:
fixes $g\ K\ C$ **and** t::*real*
defines $G \equiv \lambda t.\ C + K *$ *integral* $\{t..0\}$ $(\lambda s.\ g\ s)$
assumes *g-le-G*: $\bigwedge t.\ a \leq t \Longrightarrow t \leq 0 \Longrightarrow g\ t \leq G\ t$
assumes *g-cont*: *continuous-on* $\{a..0\}$ g
assumes *g-nonneg*: $\bigwedge t.\ a \leq t \Longrightarrow t \leq 0 \Longrightarrow 0 \leq g\ t$
assumes *pos*: $0 < C\ 0 < K$
assumes $a \leq t\ t \leq 0$
shows $g\ t \leq C * exp\ (- K * t)$
⟨*proof*⟩

end

2 Initial Value Problems

theory *Initial-Value-Problem*
  imports
    ../ODE-Auxiliarities
    ../Library/Interval-Integral-HK
    ../Library/Gronwall
begin

lemma *clamp-le*[*simp*]: $x \leq a \Longrightarrow clamp\ a\ b\ x = a$ **for** x::$'a$::*ordered-euclidean-space*
  ⟨*proof*⟩

lemma *clamp-ge*[*simp*]: $a \leq b \Longrightarrow b \leq x \Longrightarrow clamp\ a\ b\ x = b$ **for** x::$'a$::*ordered-euclidean-space*
  ⟨*proof*⟩

abbreviation *cfuncset* :: $'a$::*topological-space set* ⇒ $'b$::*metric-space set* ⇒ $('a \Rightarrow_C 'b)$ *set*
  (**infixr** ‹$\rightarrow_C$› *60*)
  where $A \rightarrow_C B \equiv PiC\ A\ (\lambda\text{-}.\ B)$

lemma *closed-segment-translation-zero*: $z \in \{z + a{-}{-}z + b\} \longleftrightarrow 0 \in \{a\ {-}{-}\ b\}$
  ⟨*proof*⟩

lemma *closed-segment-subset-interval*: *is-interval* $T \Longrightarrow a \in T \Longrightarrow b \in T \Longrightarrow$ *closed-segment* $a\ b \subseteq T$
  ⟨*proof*⟩

definition *half-open-segment*::$'a$::*real-vector* ⇒ $'a$ ⇒ $'a$ *set* (‹(*1*{-−−<-})›)
  where *half-open-segment* $a\ b = \{a\ {-}{-}\ b\} - \{b\}$

lemma *half-open-segment-real*:
  fixes *a b*::*real*
  shows $\{a\ {-}{-}{<}\ b\} = (\mathit{if}\ a \leq b\ \mathit{then}\ \{a\ ..{<}\ b\}\ \mathit{else}\ \{b\ {<}..\ a\})$
  ⟨*proof*⟩

lemma *closure-half-open-segment*:
  fixes *a b*::*real*
  shows $closure\ \{a\ {-}{-}{<}\ b\} = (\mathit{if}\ a = b\ \mathit{then}\ \{\}\ \mathit{else}\ \{a\ {-}{-}\ b\})$
  ⟨*proof*⟩

lemma *half-open-segment-subset*[*intro*, *simp*]:
  $\{t0{-}{-}{<}t1\} \subseteq \{t0\ {-}{-}\ t1\}$
  $x \in \{t0{-}{-}{<}t1\} \Longrightarrow x \in \{t0\ {-}{-}\ t1\}$
  ⟨*proof*⟩

lemma *half-open-segment-closed-segmentI*:

$t \in \{t0 \ {-}{-}\ t1\} \Longrightarrow t \neq t1 \Longrightarrow t \in \{t0 \ {-}{-}{<}\ t1\}$
⟨*proof*⟩

lemma *islimpt-half-open-segment*:
fixes *t0 t1 s*::*real*
assumes $t0 \neq t1$ $s \in \{t0{-}{-}t1\}$
shows *s islimpt* $\{t0{-}{-}{<}t1\}$
⟨*proof*⟩

lemma
mem-half-open-segment-eventually-in-closed-segment:
fixes *t*::*real*
assumes $t \in \{t0{-}{-}{<}t1'\}$
shows $\forall_F$ *t1′ in at t1′ within* $\{t0{-}{-}{<}t1'\}$. $t \in \{t0{-}{-}t1'\}$
⟨*proof*⟩

lemma *closed-segment-half-open-segment-subsetI*:
fixes *x*::*real* **shows** $x \in \{t0{-}{-}{<}t1\} \Longrightarrow \{t0{-}{-}x\} \subseteq \{t0{-}{-}{<}t1\}$
⟨*proof*⟩

lemma *dist-component-le*:
fixes *x y*::*′a*::*euclidean-space*
assumes $i \in$ *Basis*
shows *dist* $(x \cdot i)$ $(y \cdot i) \leq$ *dist x y*
⟨*proof*⟩

lemma *sum-inner-Basis-one*: $i \in Basis \Longrightarrow (\sum x{\in}Basis.\ x \cdot i) = 1$
⟨*proof*⟩

lemma *cball-in-cbox*:
fixes *y*::*′a*::*euclidean-space*
shows *cball y r* $\subseteq$ *cbox* $(y - r *_R One)$ $(y + r *_R One)$
⟨*proof*⟩

lemma *centered-cbox-in-cball*:
shows *cbox* $(- r *_R One)$ $(r *_R$ *One*::*′a*::*euclidean-space*$) \subseteq$
cball 0 $(sqrt(DIM('a)) * r)$
⟨*proof*⟩

2.1 Solutions of IVPs

definition
solves-ode :: (*real* ⇒ *′a*::*real-normed-vector*) ⇒ (*real* ⇒ *′a* ⇒ *′a*) ⇒ *real set* ⇒ *′a set* ⇒ *bool*
(**infix** ‹(*solves′-ode*)› *50*)
where
(*y solves-ode f*) *T X* ⟷ (*y has-vderiv-on* (λ*t*. *f t* (*y t*))) *T* ∧ *y* ∈ *T* → *X*

lemma *solves-odeI*:

assumes *solves-ode-vderivD*: $(y$ *has-vderiv-on* $(\lambda t.\ f\ t\ (y\ t)))\ T$
and *solves-ode-domainD*: $\bigwedge t.\ t \in T \Longrightarrow y\ t \in X$
shows $(y$ *solves-ode* $f)\ T\ X$
⟨*proof*⟩

lemma *solves-odeD*:
assumes $(y$ *solves-ode* $f)\ T\ X$
shows *solves-ode-vderivD*: $(y$ *has-vderiv-on* $(\lambda t.\ f\ t\ (y\ t)))\ T$
and *solves-ode-domainD*: $\bigwedge t.\ t \in T \Longrightarrow y\ t \in X$
⟨*proof*⟩

lemma *solves-ode-continuous-on*: $(y$ *solves-ode* $f)\ T\ X \Longrightarrow$ *continuous-on* $T\ y$
⟨*proof*⟩

lemma *solves-ode-congI*:
assumes $(x$ *solves-ode* $f)\ T\ X$
assumes $\bigwedge t.\ t \in T \Longrightarrow x\ t = y\ t$
assumes $\bigwedge t.\ t \in T \Longrightarrow f\ t\ (x\ t) = g\ t\ (x\ t)$
assumes $T = S\ X = Y$
shows $(y$ *solves-ode* $g)\ S\ Y$
⟨*proof*⟩

lemma *solves-ode-cong*[*cong*]:
assumes $\bigwedge t.\ t \in T \Longrightarrow x\ t = y\ t$
assumes $\bigwedge t.\ t \in T \Longrightarrow f\ t\ (x\ t) = g\ t\ (x\ t)$
assumes $T = S\ X = Y$
shows $(x$ *solves-ode* $f)\ T\ X \longleftrightarrow (y$ *solves-ode* $g)\ S\ Y$
⟨*proof*⟩

lemma *solves-ode-on-subset*:
assumes $(x$ *solves-ode* $f)\ S\ Y$
assumes $T \subseteq S\ Y \subseteq X$
shows $(x$ *solves-ode* $f)\ T\ X$
⟨*proof*⟩

lemma *preflect-solution*:
assumes $t0 \in T$
assumes *sol*: $((\lambda t.\ x$ (*preflect* $t0\ t))$ *solves-ode* $(\lambda t\ x.\ -\ f$ (*preflect* $t0\ t)\ x))$ (*preflect* $t0$ ‘ $T)\ X$
shows $(x$ *solves-ode* $f)\ T\ X$
⟨*proof*⟩

lemma *solution-preflect*:
assumes $t0 \in T$
assumes *sol*: $(x$ *solves-ode* $f)\ T\ X$
shows $((\lambda t.\ x$ (*preflect* $t0\ t))$ *solves-ode* $(\lambda t\ x.\ -\ f$ (*preflect* $t0\ t)\ x))$ (*preflect* $t0$ ‘ $T)\ X$
⟨*proof*⟩

lemma *solution-eq-preflect-solution*:
assumes $t0 \in T$
shows $(x$ *solves-ode* $f)$ T $X \longleftrightarrow ((\lambda t.\ x\ (preflect\ t0\ t))$ *solves-ode* $(\lambda t\ x.\ -f\ (preflect\ t0\ t)\ x))\ (preflect\ t0\ `\ T)\ X$
⟨*proof*⟩

lemma *shift-autonomous-solution*:
assumes *sol*: $(x$ *solves-ode* $f)$ T X
assumes *auto*: $\bigwedge s\ t.\ s \in T \Longrightarrow f\ s\ (x\ s) = f\ t\ (x\ s)$
shows $((\lambda t.\ x\ (t + t0))$ *solves-ode* $f)$ $((\lambda t.\ t - t0)\ `\ T)$ X
⟨*proof*⟩

lemma *solves-ode-singleton*: $y\ t0 \in X \Longrightarrow (y$ *solves-ode* $f)$ $\{t0\}$ X
⟨*proof*⟩

2.1.1 Connecting solutions

lemma *connection-solves-ode*:
assumes *x*: $(x$ *solves-ode* $f)$ T X
assumes *y*: $(y$ *solves-ode* $g)$ S Y
assumes *conn-T*: *closure* $S \cap$ *closure* $T \subseteq T$
assumes *conn-S*: *closure* $S \cap$ *closure* $T \subseteq S$
assumes *conn-x*: $\bigwedge t.\ t \in$ *closure* $S \Longrightarrow t \in$ *closure* $T \Longrightarrow x\ t = y\ t$
assumes *conn-f*: $\bigwedge t.\ t \in$ *closure* $S \Longrightarrow t \in$ *closure* $T \Longrightarrow f\ t\ (y\ t) = g\ t\ (y\ t)$
shows $((\lambda t.$ *if* $t \in T$ *then* $x\ t$ *else* $y\ t)$ *solves-ode* $(\lambda t.$ *if* $t \in T$ *then* $f\ t$ *else* $g\ t))$ $(T \cup S)$ $(X \cup Y)$
⟨*proof*⟩

lemma
solves-ode-subset-range:
assumes *x*: $(x$ *solves-ode* $f)$ T X
assumes *s*: $x\ `\ T \subseteq Y$
shows $(x$ *solves-ode* $f)$ T Y
⟨*proof*⟩

2.2 unique solution with initial value

definition
usolves-ode-from :: $(real \Rightarrow 'a::real\text{-}normed\text{-}vector) \Rightarrow (real \Rightarrow 'a \Rightarrow 'a) \Rightarrow real \Rightarrow real\ set \Rightarrow 'a\ set \Rightarrow bool$
(‹((-) *usolves′-ode* (-) *from* (-))› [*10*, *10*, *10*] *10*)
— TODO: no idea about mixfix and precedences, check this!
where
$(y$ *usolves-ode* f *from* $t0)$ T $X \longleftrightarrow (y$ *solves-ode* $f)$ T $X \wedge t0 \in T \wedge$ *is-interval* $T \wedge$
$(\forall z\ T'.\ t0 \in T' \wedge$ *is-interval* $T' \wedge T' \subseteq T \wedge (z$ *solves-ode* $f)$ T' $X \longrightarrow z\ t0 = y\ t0 \longrightarrow (\forall t \in T'.\ z\ t = y\ t))$

uniqueness of solution can depend on domain X:

lemma
$((\lambda\text{-}.\ \mathit{0::real})\ \mathit{usolves\text{-}ode}\ (\lambda\text{-}.\ \mathit{sqrt})\ \mathit{from}\ \mathit{0})\ \{\mathit{0..}\}\ \{\mathit{0}\}$
$((\lambda t.\ t^2\ /\ \mathit{4})\ \mathit{solves\text{-}ode}\ (\lambda\text{-}.\ \mathit{sqrt}))\ \{\mathit{0..}\}\ \{\mathit{0..}\}$
$(\lambda t.\ t^2\ /\ \mathit{4})\ \mathit{0} = (\lambda\text{-}.\ \mathit{0::real})\ \mathit{0}$
⟨*proof*⟩

TODO: show that if solution stays in interior, then domain can be enlarged! (?)

lemma *usolves-odeD*:
assumes $(y\ \mathit{usolves\text{-}ode}\ f\ \mathit{from}\ t0)\ T\ X$
shows $(y\ \mathit{solves\text{-}ode}\ f)\ T\ X$
and $t0 \in T$
and *is-interval* T
and $\bigwedge z\ T'\ t.\ t0 \in T' \Longrightarrow \mathit{is\text{-}interval}\ T' \Longrightarrow T' \subseteq T \Longrightarrow (z\ \mathit{solves\text{-}ode}\ f)\ T'\ X \Longrightarrow z\ t0 = y\ t0 \Longrightarrow t \in T' \Longrightarrow z\ t = y\ t$
⟨*proof*⟩

lemma *usolves-ode-rawI*:
assumes $(y\ \mathit{solves\text{-}ode}\ f)\ T\ X\ t0 \in T\ \mathit{is\text{-}interval}\ T$
assumes $\bigwedge z\ T'\ t.\ t0 \in T' \Longrightarrow \mathit{is\text{-}interval}\ T' \Longrightarrow T' \subseteq T \Longrightarrow (z\ \mathit{solves\text{-}ode}\ f)\ T'\ X \Longrightarrow z\ t0 = y\ t0 \Longrightarrow t \in T' \Longrightarrow z\ t = y\ t$
shows $(y\ \mathit{usolves\text{-}ode}\ f\ \mathit{from}\ t0)\ T\ X$
⟨*proof*⟩

lemma *usolves-odeI*:
assumes $(y\ \mathit{solves\text{-}ode}\ f)\ T\ X\ t0 \in T\ \mathit{is\text{-}interval}\ T$
assumes *usol*: $\bigwedge z\ t.\ \{t0\ \text{--}\ t\} \subseteq T \Longrightarrow (z\ \mathit{solves\text{-}ode}\ f)\ \{t0\ \text{--}\ t\}\ X \Longrightarrow z\ t0 = y\ t0 \Longrightarrow z\ t = y\ t$
shows $(y\ \mathit{usolves\text{-}ode}\ f\ \mathit{from}\ t0)\ T\ X$
⟨*proof*⟩

lemma *is-interval-singleton*[*intro*,*simp*]: *is-interval* $\{t0\}$
⟨*proof*⟩

lemma *usolves-ode-singleton*: $x\ t0 \in X \Longrightarrow (x\ \mathit{usolves\text{-}ode}\ f\ \mathit{from}\ t0)\ \{t0\}\ X$
⟨*proof*⟩

lemma *usolves-ode-congI*:
assumes x: $(x\ \mathit{usolves\text{-}ode}\ f\ \mathit{from}\ t0)\ T\ X$
assumes $\bigwedge t.\ t \in T \Longrightarrow x\ t = y\ t$
assumes $\bigwedge t\ y.\ t \in T \Longrightarrow y \in X \Longrightarrow f\ t\ y = g\ t\ y$— TODO: weaken this assumption?!
assumes $t0 = s0$
assumes $T = S$
assumes $X = Y$
shows $(y\ \mathit{usolves\text{-}ode}\ g\ \mathit{from}\ s0)\ S\ Y$
⟨*proof*⟩

lemma *usolves-ode-cong*[*cong*]:
assumes $\bigwedge t.\ t \in T \Longrightarrow x\ t = y\ t$
assumes $\bigwedge t\ y.\ t \in T \Longrightarrow y \in X \Longrightarrow f\ t\ y = g\ t\ y$— TODO: weaken this assumption?!
assumes $t0 = s0$
assumes $T = S$
assumes $X = Y$
shows $(x$ *usolves-ode f from* $t0)\ T\ X \longleftrightarrow (y$ *usolves-ode g from* $s0)\ S\ Y$
⟨*proof*⟩

lemma *shift-autonomous-unique-solution*:
assumes *usol*: $(x$ *usolves-ode f from* $t0)\ T\ X$
assumes *auto*: $\bigwedge s\ t\ x.\ x \in X \Longrightarrow f\ s\ x = f\ t\ x$
shows $((\lambda t.\ x\ (t + t0 - t1))$ *usolves-ode f from* $t1)\ ((+)\ (t1 - t0)\ \text{‘}\ T)\ X$
⟨*proof*⟩

lemma *three-intervals-lemma*:
fixes $a\ b\ c$::*real*
assumes *a*: $a \in A - B$
and *b*: $b \in B - A$
and *c*: $c \in A \cap B$
and *iA*: *is-interval* A **and** *iB*: *is-interval* B
and *aI*: $a \in I$
and *bI*: $b \in I$
and *iI*: *is-interval* I
shows $c \in I$
⟨*proof*⟩

lemma *connection-usolves-ode*:
assumes *x*: $(x$ *usolves-ode f from* $tx)\ T\ X$
assumes *y*: $\bigwedge t.\ t \in$ *closure* $S \cap$ *closure* $T \Longrightarrow (y$ *usolves-ode g from* $t)\ S\ X$
assumes *conn-T*: *closure* $S \cap$ *closure* $T \subseteq T$
assumes *conn-S*: *closure* $S \cap$ *closure* $T \subseteq S$
assumes *conn-t*: $t \in$ *closure* $S \cap$ *closure* T
assumes *conn-x*: $\bigwedge t.\ t \in$ *closure* $S \Longrightarrow t \in$ *closure* $T \Longrightarrow x\ t = y\ t$
assumes *conn-f*: $\bigwedge t\ x.\ t \in$ *closure* $S \Longrightarrow t \in$ *closure* $T \Longrightarrow x \in X \Longrightarrow f\ t\ x = g\ t\ x$
shows $((\lambda t.$ *if* $t \in T$ *then* $x\ t$ *else* $y\ t)$ *usolves-ode* $(\lambda t.$ *if* $t \in T$ *then* $f\ t$ *else* $g\ t)$ *from* $tx)\ (T \cup S)\ X$
⟨*proof*⟩

lemma *usolves-ode-union-closed*:
assumes *x*: $(x$ *usolves-ode f from* $tx)\ T\ X$
assumes *y*: $\bigwedge t.\ t \in$ *closure* $S \cap$ *closure* $T \Longrightarrow (x$ *usolves-ode f from* $t)\ S\ X$
assumes *conn-T*: *closure* $S \cap$ *closure* $T \subseteq T$
assumes *conn-S*: *closure* $S \cap$ *closure* $T \subseteq S$
assumes *conn-t*: $t \in$ *closure* $S \cap$ *closure* T
shows $(x$ *usolves-ode f from* $tx)\ (T \cup S)\ X$
⟨*proof*⟩

lemma *usolves-ode-solves-odeI*:
  assumes (x *usolves-ode* f *from* tx) T X
  assumes (y *solves-ode* f) T X y $tx = x$ tx
  shows (y *usolves-ode* f *from* tx) T X
  ⟨*proof*⟩

lemma *usolves-ode-subset-range*:
  assumes x: (x *usolves-ode* f *from* $t0$) T X
  assumes r: x ‘ $T \subseteq Y$ **and** $Y \subseteq X$
  shows (x *usolves-ode* f *from* $t0$) T Y
⟨*proof*⟩

2.3 ivp on interval

context
  fixes $t0$ $t1$::*real* **and** T
  defines $T \equiv$ *closed-segment* $t0$ $t1$
begin

lemma *is-solution-ext-cont*:
  continuous-on T $x \Longrightarrow$ (*ext-cont* x (*min* $t0$ $t1$) (*max* $t0$ $t1$) *solves-ode* f) T X =
(x *solves-ode* f) T X
  ⟨*proof*⟩

lemma *solution-fixed-point*:
  fixes x:: *real* ⇒ ′*a*::*banach*
  assumes x: (x *solves-ode* f) T X **and** t: $t \in T$
  shows x $t0$ + *ivl-integral* $t0$ t ($\lambda t.$ f t (x t)) = x t
⟨*proof*⟩

lemma *solution-fixed-point-left*:
  fixes x:: *real* ⇒ ′*a*::*banach*
  assumes x: (x *solves-ode* f) T X **and** t: $t \in T$
  shows x $t1$ − *ivl-integral* t $t1$ ($\lambda t.$ f t (x t)) = x t
⟨*proof*⟩

lemma *solution-fixed-pointI*:
  fixes x:: *real* ⇒ ′*a*::*banach*
  assumes *cont-f*: *continuous-on* ($T \times X$) ($\lambda(t, x).$ f t x)
  assumes *cont-x*: *continuous-on* T x
  assumes *defined*: $\bigwedge t.$ $t \in T \Longrightarrow x$ $t \in X$
  assumes *fp*: $\bigwedge t.$ $t \in T \Longrightarrow x$ $t = x$ $t0$ + *ivl-integral* $t0$ t ($\lambda t.$ f t (x t))
  shows (x *solves-ode* f) T X
⟨*proof*⟩

end

lemma *solves-ode-half-open-segment-continuation*:

fixes f::*real* ⇒ *'a* ⇒ *'a*::*banach*
assumes *ode*: (x *solves-ode* f) {*t0* −−< *t1*} X
assumes *continuous*: *continuous-on* ({*t0* −− *t1*} × X) (λ(t, x). f t x)
assumes *compact* X
assumes *t0* ≠ *t1*
obtains l **where**
(x ⟶ l) (*at t1 within* {*t0* −−< *t1*})
((λt. *if* t = *t1 then* l *else* x t) *solves-ode* f) {*t0* −− *t1*} X
⟨*proof*⟩

2.4 Picard-Lindeloef on set of functions into closed set

locale *continuous-rhs* = **fixes** T X f
assumes *continuous*: *continuous-on* (T × X) (λ(t, x). f t x)
begin

lemma *continuous-rhs-comp*[*continuous-intros*]:
assumes [*continuous-intros*]: *continuous-on* S g
assumes [*continuous-intros*]: *continuous-on* S h
assumes g ‘ S ⊆ T
assumes h ‘ S ⊆ X
shows *continuous-on* S (λx. f (g x) (h x))
⟨*proof*⟩

end

locale *global-lipschitz* =
fixes T X f **and** L::*real*
assumes *lipschitz*: ⋀t. t ∈ T ⟹ L−*lipschitz-on* X (λx. f t x)

locale *closed-domain* =
fixes X **assumes** *closed*: *closed* X

locale *interval* = **fixes** T::*real set*
assumes *interval*: *is-interval* T
begin

lemma *closed-segment-subset-domain*: *t0* ∈ T ⟹ t ∈ T ⟹ *closed-segment t0* t ⊆ T
⟨*proof*⟩

lemma *closed-segment-subset-domainI*: *t0* ∈ T ⟹ t ∈ T ⟹ s ∈ *closed-segment t0* t ⟹ s ∈ T
⟨*proof*⟩

lemma *convex*[*intro*, *simp*]: *convex* T
and *connected*[*intro*, *simp*]: *connected* T
⟨*proof*⟩

end

locale *nonempty-set* = **fixes** *T* **assumes** *nonempty-set*: $T \neq \{\}$

locale *compact-interval* = *interval* + *nonempty-set T* +
  assumes *compact-time*: *compact T*
begin

definition *tmin* = *Inf T*
definition *tmax* = *Sup T*

lemma
  shows *tmin*: $t \in T \Longrightarrow tmin \leq t$ $tmin \in T$
    and *tmax*: $t \in T \Longrightarrow t \leq tmax$ $tmax \in T$
  ⟨*proof*⟩

lemma *tmin-le-tmax*[*intro*, *simp*]: $tmin \leq tmax$
  ⟨*proof*⟩

lemma *T-def*: $T = \{tmin\ ..\ tmax\}$
  ⟨*proof*⟩

lemma *mem-T-I*[*intro*, *simp*]: $tmin \leq t \Longrightarrow t \leq tmax \Longrightarrow t \in T$
  ⟨*proof*⟩

end

locale *self-mapping* = *interval T* **for** *T* +
  fixes *t0*::*real* **and** *x0 f X*
  assumes *iv-defined*: $t0 \in T$ $x0 \in X$
  assumes *self-mapping*:
    $\bigwedge x\ t.\ t \in T \Longrightarrow x\ t0 = x0 \Longrightarrow x \in closed\text{-}segment\ t0\ t \rightarrow X \Longrightarrow$
      $continuous\text{-}on\ (closed\text{-}segment\ t0\ t)\ x \Longrightarrow x\ t0 + ivl\text{-}integral\ t0\ t\ (\lambda t.\ f\ t\ (x\ t)) \in X$
begin

sublocale *nonempty-set T* ⟨*proof*⟩

lemma *closed-segment-iv-subset-domain*: $t \in T \Longrightarrow closed\text{-}segment\ t0\ t \subseteq T$
  ⟨*proof*⟩

end

locale *unique-on-closed* =
  compact-interval T +
  self-mapping T t0 x0 f X +
  continuous-rhs T X f +
  closed-domain X +
  global-lipschitz T X f L **for** *t0*::*real* **and** *T* **and** *x0*::*'a*::*banach* **and** *f X L*

begin

lemma *T-split*: $T = \{tmin .. t0\} \cup \{t0 .. tmax\}$
  ⟨*proof*⟩

lemma *L-nonneg*: $0 \le L$
  ⟨*proof*⟩

Picard Iteration

definition *P-inner* **where** *P-inner x t = x0 + ivl-integral t0 t (λt. f t (x t))*

definition P::(*real* $\Rightarrow_C$ *'a*) $\Rightarrow$ (*real* $\Rightarrow_C$ *'a*)
  where *P x = (SOME g::real*$\Rightarrow_C$ *'a.*
    $(\forall t \in T.$ *g t = P-inner x t*$) \wedge$
    $(\forall t \le tmin.$ *g t = P-inner x tmin*$) \wedge$
    $(\forall t \ge tmax.$ *g t = P-inner x tmax*$))$

lemma *cont-P-inner-ivl*:
  $x \in T \to_C X \Longrightarrow$ *continuous-on* $\{tmin..tmax\}$ (*P-inner* (*apply-bcontfun x*))
  ⟨*proof*⟩

lemma *P-inner-t0*[*simp*]: *P-inner g t0 = x0*
  ⟨*proof*⟩

lemma *t0-cs-tmin-tmax*: $t0 \in \{tmin{-}{-}tmax\}$ **and** *cs-tmin-tmax-subset*: $\{tmin{-}{-}tmax\}$ $\subseteq T$
  ⟨*proof*⟩

lemma
  P-eqs:
  assumes $x \in T \to_C X$
  shows *P-eq-P-inner*: $t \in T \Longrightarrow$ *P x t = P-inner x t*
    and *P-le-tmin*: $t \le tmin \Longrightarrow$ *P x t = P-inner x tmin*
    and *P-ge-tmax*: $t \ge tmax \Longrightarrow$ *P x t = P-inner x tmax*
  ⟨*proof*⟩

lemma *P-if-eq*:
  $x \in T \to_C X \Longrightarrow$
    P x t = (if tmin $\le$ *t* $\wedge$ *t* $\le$ *tmax then P-inner x t else if t* $\ge$ *tmax then P-inner x tmax else P-inner x tmin)*
  ⟨*proof*⟩

lemma *dist-P-le*:
  assumes *y*: $y \in T \to_C X$ **and** *z*: $z \in T \to_C X$
  assumes *le*: $\bigwedge t.\ tmin \le t \Longrightarrow t \le tmax \Longrightarrow$ *dist* (*P-inner y t*) (*P-inner z t*) $\le R$
  assumes $0 \le R$
  shows *dist* (*P y t*) (*P z t*) $\le R$
  ⟨*proof*⟩

lemma *P-def'*:
  assumes $t \in T$
  assumes *fixed-point* $\in T \to_C X$
  shows (*P fixed-point*) $t = x0 + $ *ivl-integral t0 t* (λx. *f x* (*fixed-point x*))
  ⟨*proof*⟩

definition *iter-space* = *PiC T* ((λ-. *X*)(*t0*:={*x0*}))

lemma *iter-spaceI*:
  assumes $g \in T \to_C X$ g $t0 = x0$
  shows $g \in$ *iter-space*
  ⟨*proof*⟩

lemma *iter-spaceD*:
  assumes $g \in$ *iter-space*
  shows $g \in T \to_C X$ *apply-bcontfun g t0* = *x0*
  ⟨*proof*⟩

lemma *const-in-iter-space*: *const-bcontfun x0* $\in$ *iter-space*
  ⟨*proof*⟩

lemma *closed-iter-space*: *closed iter-space*
  ⟨*proof*⟩

lemma *iter-space-notempty*: *iter-space* $\neq$ {}
  ⟨*proof*⟩

lemma *clamp-in-eq*[*simp*]: **fixes** *a x b*::*real* **shows** $a \leq x \Longrightarrow x \leq b \Longrightarrow$ *clamp a b x* = *x*
  ⟨*proof*⟩

lemma *P-self-mapping*:
  assumes *in-space*: $g \in$ *iter-space*
  shows *P g* $\in$ *iter-space*
⟨*proof*⟩

lemma *continuous-on-T*: *continuous-on* {*tmin* .. *tmax*} *g* $\Longrightarrow$ *continuous-on T g*
  ⟨*proof*⟩

lemma *T-closed-segment-subsetI*[*intro*, *simp*]: $t \in$ {*tmin*−−*tmax*} $\Longrightarrow t \in T$
  and *T-subsetI*[*intro*, *simp*]: *tmin* $\leq t \Longrightarrow t \leq$ *tmax* $\Longrightarrow t \in T$
  ⟨*proof*⟩

lemma *t0-mem-closed-segment*[*intro*, *simp*]: *t0* $\in$ {*tmin*−−*tmax*}
  ⟨*proof*⟩

lemma *tmin-le-t0*[*intro*, *simp*]: *tmin* $\leq$ *t0*
  and *tmax-ge-t0*[*intro*, *simp*]: *tmax* $\geq$ *t0*

⟨*proof*⟩

lemma *apply-bcontfun-solution-fixed-point*:
assumes *ode*: (*apply-bcontfun x solves-ode f*) *T X*
assumes *iv*: *x t0* = *x0*
assumes *t*: *t* ∈ *T*
shows *P x t* = *x t*
⟨*proof*⟩

lemma
solution-in-iter-space:
assumes *ode*: (*apply-bcontfun z solves-ode f*) *T X*
assumes *iv*: *z t0* = *x0*
shows *z* ∈ *iter-space* (**is** *?z* ∈ -)
⟨*proof*⟩

end

locale *unique-on-bounded-closed* = *unique-on-closed* +
assumes *lipschitz-bound*: ⋀*s t*. *s* ∈ *T* ⟹ *t* ∈ *T* ⟹ *abs* (*s* − *t*) ∗ *L* < *1*
begin

lemma *lipschitz-bound-maxmin*: (*tmax* − *tmin*) ∗ *L* < *1*
⟨*proof*⟩

lemma *lipschitz-P*:
shows ((*tmax* − *tmin*) ∗ *L*)−*lipschitz-on iter-space P*
⟨*proof*⟩

lemma *fixed-point-unique*: ∃!*x*∈*iter-space*. *P x* = *x*
⟨*proof*⟩

definition *fixed-point* **where**
fixed-point = (*THE x*. *x* ∈ *iter-space* ∧ *P x* = *x*)

lemma *fixed-point'*:
fixed-point ∈ *iter-space* ∧ *P fixed-point* = *fixed-point*
⟨*proof*⟩

lemma *fixed-point*:
fixed-point ∈ *iter-space P fixed-point* = *fixed-point*
⟨*proof*⟩

lemma *fixed-point-equality'*: *x* ∈ *iter-space* ∧ *P x* = *x* ⟹ *fixed-point* = *x*
⟨*proof*⟩

lemma *fixed-point-equality*: *x* ∈ *iter-space* ⟹ *P x* = *x* ⟹ *fixed-point* = *x*
⟨*proof*⟩

lemma *fixed-point-iv*: *fixed-point* $t0 = x0$
and *fixed-point-domain*: $x \in T \Longrightarrow$ *fixed-point* $x \in X$
⟨*proof*⟩

lemma *fixed-point-has-vderiv-on*: (*fixed-point has-vderiv-on* ($\lambda t.\ f\ t$ (*fixed-point* t)))
T
⟨*proof*⟩

lemma *fixed-point-solution*:
shows (*fixed-point solves-ode* f) T X
⟨*proof*⟩

2.4.1 Unique solution

lemma *solves-ode-equals-fixed-point*:
assumes *ode*: (x *solves-ode* f) T X
assumes *iv*: $x\ t0 = x0$
assumes t: $t \in T$
shows $x\ t =$ *fixed-point* t
⟨*proof*⟩

lemma *solves-ode-on-closed-segment-equals-fixed-point*:
assumes *ode*: (x *solves-ode* f) $\{t0\ {-}{-}\ t1'\}$ X
assumes *iv*: $x\ t0 = x0$
assumes *subset*: $\{t0{-}{-}t1'\} \subseteq T$
assumes *t-mem*: $t \in \{t0{-}{-}t1'\}$
shows $x\ t =$ *fixed-point* t
⟨*proof*⟩

lemma *unique-solution*:
assumes *ivp1*: (x *solves-ode* f) T X $x\ t0 = x0$
assumes *ivp2*: (y *solves-ode* f) T X $y\ t0 = x0$
assumes $t \in T$
shows $x\ t = y\ t$
⟨*proof*⟩

lemma *fixed-point-usolves-ode*: (*fixed-point usolves-ode* f *from* $t0$) T X
⟨*proof*⟩

end

lemma *closed-segment-Un*:
fixes a b c::*real*
assumes $b \in$ *closed-segment* a c
shows *closed-segment* a b $\cup$ *closed-segment* b c = *closed-segment* a c
⟨*proof*⟩

lemma *closed-segment-closed-segment-subset*:

fixes s::*real* **and** i::*nat*
assumes $s \in$ *closed-segment a b*
assumes $a \in$ *closed-segment c d* $b \in$ *closed-segment c d*
shows $s \in$ *closed-segment c d*
⟨*proof*⟩

context *unique-on-closed* **begin**

context— solution until t1
fixes *t1*::*real*
assumes *mem-t1*: $t1 \in T$
begin

lemma *subdivide-count-ex*: $\exists n.\ L * abs\ (t1 - t0)\ /\ (Suc\ n) < 1$
⟨*proof*⟩

definition *subdivide-count* $= (SOME\ n.\ L * abs\ (t1 - t0)\ /\ Suc\ n < 1)$

lemma *subdivide-count*: $L * abs\ (t1 - t0)\ /\ Suc\ subdivide\text{-}count < 1$
⟨*proof*⟩

lemma *subdivide-lipschitz*:
assumes $|s - t| \leq abs\ (t1 - t0)\ /\ Suc\ subdivide\text{-}count$
shows $|s - t| * L < 1$
⟨*proof*⟩

lemma *subdivide-lipschitz-lemma*:
assumes *st*: $s \in \{a -- b\}$ $t \in \{a -- b\}$
assumes $abs\ (b - a) \leq abs\ (t1 - t0)\ /\ Suc\ subdivide\text{-}count$
shows $|s - t| * L < 1$
⟨*proof*⟩

definition *step* $= (t1 - t0)\ /\ Suc\ subdivide\text{-}count$

lemma *last-step*: $t0 + real\ (Suc\ subdivide\text{-}count) * step = t1$
⟨*proof*⟩

lemma *step-in-segment*:
assumes $0 \leq i$ $i \leq real\ (Suc\ subdivide\text{-}count)$
shows $t0 + i * step \in closed\text{-}segment\ t0\ t1$
⟨*proof*⟩

lemma *subset-T1*:
fixes s::*real* **and** i::*nat*
assumes $s \in closed\text{-}segment\ t0\ (t0 + i * step)$
assumes $i \leq Suc\ subdivide\text{-}count$
shows $s \in \{t0 -- t1\}$
⟨*proof*⟩

lemma *subset-T*: $\{t0 \;{-}{-}\; t1\} \subseteq T$ **and** *subset-TI*: $s \in \{t0 \;{-}{-}\; t1\} \Longrightarrow s \in T$
⟨*proof*⟩

primrec *psolution*::$nat \Rightarrow real \Rightarrow 'a$ **where**
psolution 0 t = *x0*
| *psolution* (*Suc i*) *t* = *unique-on-bounded-closed.fixed-point*
(*t0* + *real i* ∗ *step*) {*t0* + *real i* ∗ *step* −− *t0* + *real* (*Suc i*) ∗ *step*}
(*psolution i* (*t0* + *real i* ∗ *step*)) *f X t*

definition *psolutions t* = *psolution* (*LEAST i*. *t* ∈ *closed-segment* (*t0* + *real* (*i* − *1*) ∗ *step*) (*t0* + *real i* ∗ *step*)) *t*

lemma *psolutions-usolves-until-step*:
assumes *i-le*: *i* ≤ *Suc subdivide-count*
shows (*psolutions usolves-ode f from t0*) (*closed-segment t0* (*t0* + *real i* ∗ *step*)) *X*
⟨*proof*⟩

lemma *psolutions-usolves-ode*: (*psolutions usolves-ode f from t0*) {*t0* −− *t1*} *X*
⟨*proof*⟩

end

definition *solution t* = (*if t* ≤ *t0 then psolutions tmin t else psolutions tmax t*)

lemma *solution-eq-left*: *tmin* ≤ *t* ⟹ *t* ≤ *t0* ⟹ *solution t* = *psolutions tmin t*
⟨*proof*⟩

lemma *solution-eq-right*: *t0* ≤ *t* ⟹ *t* ≤ *tmax* ⟹ *solution t* = *psolutions tmax t*
⟨*proof*⟩

lemma *solution-usolves-ode*: (*solution usolves-ode f from t0*) *T X*
⟨*proof*⟩

lemma *solution-solves-ode*: (*solution solves-ode f*) *T X*
⟨*proof*⟩

lemma *solution-iv*[*simp*]: *solution t0* = *x0*
⟨*proof*⟩

end

2.5 Picard-Lindeloef for $X = UNIV$

locale *unique-on-strip* =
compact-interval T +
continuous-rhs T UNIV f +
global-lipschitz T UNIV f L

for *t0* **and** *T* **and** *f*::*real* ⇒ ′*a* ⇒ ′*a*::*banach* **and** *L* +
assumes *iv-time*: *t0* ∈ *T*
begin

sublocale *unique-on-closed t0 T x0 f UNIV L* **for** *x0*
⟨*proof*⟩

end

2.6 Picard-Lindeloef on cylindric domain

locale *solution-in-cylinder* =
continuous-rhs T cball x0 b f +
compact-interval T
for *t0 T x0 b* **and** *f*::*real* ⇒ ′*a* ⇒ ′*a*::*banach* +
fixes *X B*
defines *X* ≡ *cball x0 b*
assumes *initial-time-in*: *t0* ∈ *T*
assumes *norm-f*: ⋀*x t*. *t* ∈ *T* ⟹ *x* ∈ *X* ⟹ *norm* (*f t x*) ≤ *B*
assumes *b-pos*: *b* ≥ *0*
assumes *e-bounded*: ⋀*t*. *t* ∈ *T* ⟹ *dist t t0* ≤ *b* / *B*
begin

lemmas *cylinder* = *X-def*

lemma *B-nonneg*: *B* ≥ *0*
⟨*proof*⟩

lemma *in-bounds-derivativeI*:
assumes *t* ∈ *T*
assumes *init*: *x t0* = *x0*
assumes *cont*: *continuous-on* (*closed-segment t0 t*) *x*
assumes *solves*: (*x has-vderiv-on* (λ*s*. *f s* (*y s*))) (*open-segment t0 t*)
assumes *y-bounded*: ⋀ξ. ξ ∈ *closed-segment t0 t* ⟹ *x* ξ ∈ *X* ⟹ *y* ξ ∈ *X*
shows *x t* ∈ *cball x0* (*B* ∗ *abs* (*t* − *t0*))
⟨*proof*⟩

lemma *in-bounds-derivative-globalI*:
assumes *t* ∈ *T*
assumes *init*: *x t0* = *x0*
assumes *cont*: *continuous-on* (*closed-segment t0 t*) *x*
assumes *solves*: (*x has-vderiv-on* (λ*s*. *f s* (*y s*))) (*open-segment t0 t*)
assumes *y-bounded*: ⋀ξ. ξ ∈ *closed-segment t0 t* ⟹ *x* ξ ∈ *X* ⟹ *y* ξ ∈ *X*
shows *x t* ∈ *X*
⟨*proof*⟩

lemma *integral-in-bounds*:
assumes *t* ∈ *T x t0* = *x0 x* ∈ {*t0* −− *t*} → *X*
assumes *cont*[*continuous-intros*]: *continuous-on* ({*t0* −− *t*}) *x*

shows $x\ t0 + ivl\text{-}integral\ t0\ t\ (\lambda t.\ f\ t\ (x\ t)) \in X$ (**is** - + ?ix $t \in X$)
⟨*proof*⟩

lemma *solves-in-cone*:
assumes $t \in T$
assumes *init*: $x\ t0 = x0$
assumes *cont*: *continuous-on* (*closed-segment t0 t*) *x*
assumes *solves*: (x *has-vderiv-on* ($\lambda s.\ f\ s\ (x\ s)$)) (*open-segment t0 t*)
shows $x\ t \in cball\ x0\ (B * abs\ (t - t0))$
⟨*proof*⟩

lemma *is-solution-in-cone*:
assumes $t \in T$
assumes *sol*: (x *solves-ode f*) (*closed-segment t0 t*) Y **and** *iv*: $x\ t0 = x0$
shows $x\ t \in cball\ x0\ (B * abs\ (t - t0))$
⟨*proof*⟩

lemma *cone-subset-domain*:
assumes $t \in T$
shows $cball\ x0\ (B * |t - t0|) \subseteq X$
⟨*proof*⟩

lemma *is-solution-in-domain*:
assumes $t \in T$
assumes *sol*: (x *solves-ode f*) (*closed-segment t0 t*) Y **and** *iv*: $x\ t0 = x0$
shows $x\ t \in X$
⟨*proof*⟩

lemma *solves-ode-on-subset-domain*:
assumes *sol*: (x *solves-ode f*) $S\ Y$ **and** *iv*: $x\ t0 = x0$
and *ivl*: $t0 \in S$ *is-interval* $S\ S \subseteq T$
shows (x *solves-ode f*) $S\ X$
⟨*proof*⟩

lemma *usolves-ode-on-subset*:
assumes *x*: (x *usolves-ode f from t0*) $T\ X$ **and** *iv*: $x\ t0 = x0$
assumes $t0 \in S$ *is-interval* $S\ S \subseteq T\ X \subseteq Y$
shows (x *usolves-ode f from t0*) $S\ Y$
⟨*proof*⟩

lemma *usolves-ode-on-superset-domain*:
assumes (x *usolves-ode f from t0*) $T\ X$ **and** *iv*: $x\ t0 = x0$
assumes $X \subseteq Y$
shows (x *usolves-ode f from t0*) $T\ Y$
⟨*proof*⟩

end

locale *unique-on-cylinder* =

solution-in-cylinder t0 T x0 b f X B +
global-lipschitz T X f L
for *t0 T x0 b X f B L*
begin

sublocale *unique-on-closed t0 T x0 f X L*
⟨*proof*⟩

end

locale *derivative-on-prod* =
fixes *T X* **and** *f*::*real* ⇒ *'a*::*banach* ⇒ *'a* **and** *f'*:: *real* × *'a* ⇒ (*real* × *'a*) ⇒ *'a*
assumes *f'*: $\bigwedge$*tx*. *tx* ∈ *T* × *X* ⟹ ((λ(*t*, *x*). *f t x*) *has-derivative* (*f' tx*)) (*at tx within* (*T* × *X*))
begin

lemma *f'-comp*[*derivative-intros*]:
(*g has-derivative g'*) (*at s within S*) ⟹ (*h has-derivative h'*) (*at s within S*) ⟹
s ∈ *S* ⟹ ($\bigwedge$*x*. *x* ∈ *S* ⟹ *g x* ∈ *T*) ⟹ ($\bigwedge$*x*. *x* ∈ *S* ⟹ *h x* ∈ *X*) ⟹
((λ*x*. *f* (*g x*) (*h x*)) *has-derivative* (λ*y*. *f'* (*g s*, *h s*) (*g' y*, *h' y*))) (*at s within S*)
⟨*proof*⟩

lemma *derivative-on-prod-subset*:
assumes *X'* ⊆ *X*
shows *derivative-on-prod T X' f f'*
⟨*proof*⟩

end

end
theory *Picard-Lindeloef-Qualitative*
imports *Initial-Value-Problem*
begin

2.7 Picard-Lindeloef On Open Domains

2.7.1 Local Solution with local Lipschitz

lemma *cball-eq-closed-segment-real*:
fixes *x e*::*real*
shows *cball x e* = (*if e* ≥ *0 then* {*x* − *e* −− *x* + *e*} *else* {})
⟨*proof*⟩

lemma *cube-in-cball*:
fixes *x y* :: *'a*::*euclidean-space*
assumes *r* > *0*
assumes $\bigwedge$*i*. *i*∈ *Basis* ⟹ *dist* (*x* · *i*) (*y* · *i*) ≤ *r* / *sqrt*(*DIM*(*'a*))
shows *y* ∈ *cball x r*
⟨*proof*⟩

lemma *cbox-in-cball′*:
  fixes x::′a::*euclidean-space*
  assumes $0 < r$
  shows $\exists\, b > 0.\ b \leq r \wedge (\exists\, B.\ B = (\sum i{\in}Basis.\ b *_R i) \wedge (\forall\, y \in cbox\ (x - B)\ (x + B).\ y \in cball\ x\ r))$
⟨*proof*⟩

lemma *Pair1-in-Basis*: $i \in Basis \Longrightarrow (i,\ 0) \in Basis$
 and *Pair2-in-Basis*: $i \in Basis \Longrightarrow (0,\ i) \in Basis$
  ⟨*proof*⟩

lemma *le-real-sqrt-sumsq′* [*simp*]: $y \leq sqrt\ (x * x + y * y)$
  ⟨*proof*⟩

lemma *cball-Pair-split-subset*: $cball\ (a,\ b)\ c \subseteq cball\ a\ c \times cball\ b\ c$
  ⟨*proof*⟩

lemma *cball-times-subset*: $cball\ a\ (c/2) \times cball\ b\ (c/2) \subseteq cball\ (a,\ b)\ c$
⟨*proof*⟩

lemma *eventually-bound-pairE*:
  assumes *isCont* $f\ (t0,\ x0)$
  obtains B **where**
    $B \geq 1$
    eventually $(\lambda e.\ \forall\, x \in cball\ t0\ e \times cball\ x0\ e.\ norm\ (f\ x) \leq B)\ (at\text{-}right\ 0)$
⟨*proof*⟩

lemma
  eventually-in-cballs:
  assumes $d > 0\ c > 0$
  shows *eventually* $(\lambda e.\ cball\ t0\ (c * e) \times (cball\ x0\ e) \subseteq cball\ (t0,\ x0)\ d)\ (at\text{-}right\ 0)$
  ⟨*proof*⟩

lemma *cball-eq-sing′*:
  fixes x :: ′a::{*metric-space*,*perfect-space*}
  shows $cball\ x\ e = \{y\} \longleftrightarrow e = 0 \wedge x = y$
  ⟨*proof*⟩

locale *ll-on-open* = *interval* T **for** T +
  fixes f::*real* ⇒ ′a::{*banach*, *heine-borel*} ⇒ ′a **and** X
  assumes *local-lipschitz*: *local-lipschitz* $T\ X\ f$
  assumes *cont*: $\bigwedge x.\ x \in X \Longrightarrow continuous\text{-}on\ T\ (\lambda t.\ f\ t\ x)$
  assumes *open-domain*[*intro*!, *simp*]: *open* T *open* X
begin

all flows on closed segments

definition *csols* **where**

csols t0 x0 = {(*x*, *t1*). {*t0*−−*t1*} ⊆ *T* ∧ *x t0* = *x0* ∧ (*x solves-ode f*) {*t0*−−*t1*} *X*}

the maximal existence interval

definition *existence-ivl t0 x0* = (⋃(*x*, *t1*)∈*csols t0 x0* . {*t0*−−*t1*})

witness flow

definition *csol t0 x0* = (*SOME csol*. ∀ *t* ∈ *existence-ivl t0 x0*. (*csol t*, *t*) ∈ *csols t0 x0*)

unique flow

definition *flow* **where** *flow t0 x0* = (λ*t*. *if t* ∈ *existence-ivl t0 x0 then csol t0 x0 t t else 0*)

end

locale *ll-on-open-it* =
general?:— TODO: why is this qualification necessary? It seems only because of *ll-on-open-it T f X*
ll-on-open + **fixes** *t0*::*real*
— if possible, all development should be done with *t0* as explicit parameter for initial time: then it can be instantiated with *0* for autonomous ODEs

context *ll-on-open* **begin**

sublocale *ll-on-open-it* **where** *t0* = *t0* **for** *t0* ⟨*proof*⟩

sublocale *continuous-rhs T X f*
⟨*proof*⟩

end

context *ll-on-open-it* **begin**

lemma *ll-on-open-rev*[*intro*, *simp*]: *ll-on-open* (*preflect t0* ‘ *T*) (λ*t*. − *f* (*preflect t0 t*)) *X*
⟨*proof*⟩

lemma *eventually-lipschitz*:
assumes *t0* ∈ *T x0* ∈ *X c* > *0*
obtains *L* **where**
eventually (λ*u*. ∀ *t'* ∈ *cball t0* (*c* ∗ *u*) ∩ *T*.
L−*lipschitz-on* (*cball x0 u* ∩ *X*) (λ*y*. *f t' y*)) (*at-right 0*)
⟨*proof*⟩

lemmas *continuous-on-Times-f* = *continuous*
lemmas *continuous-on-f* = *continuous-rhs-comp*

lemma

lipschitz-on-compact:
assumes *compact* K $K \subseteq T$
assumes *compact* Y $Y \subseteq X$
obtains L **where** $\bigwedge t.\ t \in K \Longrightarrow L$*−lipschitz-on* Y $(f\ t)$
⟨*proof*⟩

lemma *csols-empty-iff*: *csols t0 x0* $= \{\} \longleftrightarrow$ *t0* $\notin T \vee$ *x0* $\notin X$
⟨*proof*⟩

lemma *csols-notempty*: *t0* $\in T \Longrightarrow$ *x0* $\in X \Longrightarrow$ *csols t0 x0* $\neq \{\}$
⟨*proof*⟩

lemma *existence-ivl-empty-iff* [*simp*]: *existence-ivl t0 x0* $= \{\} \longleftrightarrow$ *t0* $\notin T \vee$ *x0* $\notin$ X
⟨*proof*⟩

lemma *existence-ivl-empty1* [*simp*]: *t0* $\notin T \Longrightarrow$ *existence-ivl t0 x0* $= \{\}$
and *existence-ivl-empty2* [*simp*]: *x0* $\notin X \Longrightarrow$ *existence-ivl t0 x0* $= \{\}$
⟨*proof*⟩

lemma *flow-undefined*:
shows *t0* $\notin T \Longrightarrow$ *flow t0 x0* $= (\lambda$-. *0*)
x0 $\notin X \Longrightarrow$ *flow t0 x0* $= (\lambda$-. *0*)
⟨*proof*⟩

lemma (**in** *ll-on-open*) *flow-eq-in-existence-ivlI*:
assumes $\bigwedge u.$ *x0* $\in X \Longrightarrow u \in$ *existence-ivl t0 x0* $\longleftrightarrow g\ u \in$ *existence-ivl s0 x0*
assumes $\bigwedge u.$ *x0* $\in X \Longrightarrow u \in$ *existence-ivl t0 x0* $\Longrightarrow$ *flow t0 x0 u* $=$ *flow s0 x0* $(g\ u)$
shows *flow t0 x0* $= (\lambda t.$ *flow s0 x0* $(g\ t))$
⟨*proof*⟩

2.7.2 Global maximal flow with local Lipschitz

lemma *local-unique-solution*:
assumes *iv-defined*: *t0* $\in T$ *x0* $\in X$
obtains *et ex B L*
where *et* > 0 $0 <$ *ex cball t0 et* $\subseteq T$ *cball x0 ex* $\subseteq X$
unique-on-cylinder t0 (*cball t0 et*) *x0 ex f B L*
⟨*proof*⟩

lemma *mem-existence-ivl-iv-defined*:
assumes $t \in$ *existence-ivl t0 x0*
shows *t0* $\in T$ *x0* $\in X$
⟨*proof*⟩

lemma *csol-mem-csols*:
assumes $t \in$ *existence-ivl t0 x0*

shows $(csol\ t0\ x0\ t,\ t) \in csols\ t0\ x0$
⟨*proof*⟩

lemma *csol*:
assumes $t \in existence\text{-}ivl\ t0\ x0$
shows $t \in T\ \{t0{-}{-}t\} \subseteq T\ csol\ t0\ x0\ t\ t0 = x0\ (csol\ t0\ x0\ t\ solves\text{-}ode\ f)\ \{t0{-}{-}t\}\ X$
⟨*proof*⟩

lemma *existence-ivl-initial-time-iff*[*simp*]: $t0 \in existence\text{-}ivl\ t0\ x0 \longleftrightarrow t0 \in T \wedge x0 \in X$
⟨*proof*⟩

lemma *existence-ivl-initial-time*: $t0 \in T \Longrightarrow x0 \in X \Longrightarrow t0 \in existence\text{-}ivl\ t0\ x0$
⟨*proof*⟩

lemmas *mem-existence-ivl-subset* = *csol*(*1*)

lemma *existence-ivl-subset*:
$existence\text{-}ivl\ t0\ x0 \subseteq T$
⟨*proof*⟩

lemma *is-interval-existence-ivl*[*intro*, *simp*]: *is-interval* (*existence-ivl t0 x0*)
⟨*proof*⟩

lemma *connected-existence-ivl*[*intro*, *simp*]: *connected* (*existence-ivl t0 x0*)
⟨*proof*⟩

lemma *in-existence-between-zeroI*:
$t \in existence\text{-}ivl\ t0\ x0 \Longrightarrow s \in \{t0\ {-}{-}\ t\} \Longrightarrow s \in existence\text{-}ivl\ t0\ x0$
⟨*proof*⟩

lemma *segment-subset-existence-ivl*:
assumes $s \in existence\text{-}ivl\ t0\ x0\ t \in existence\text{-}ivl\ t0\ x0$
shows $\{s\ {-}{-}\ t\} \subseteq existence\text{-}ivl\ t0\ x0$
⟨*proof*⟩

lemma *flow-initial-time-if*: $flow\ t0\ x0\ t0 = (if\ t0 \in T \wedge x0 \in X\ then\ x0\ else\ 0)$
⟨*proof*⟩

lemma *flow-initial-time*[*simp*]: $t0 \in T \Longrightarrow x0 \in X \Longrightarrow flow\ t0\ x0\ t0 = x0$
⟨*proof*⟩

lemma *open-existence-ivl*[*intro*, *simp*]: *open* (*existence-ivl t0 x0*)
⟨*proof*⟩

lemma *csols-unique*:
assumes $(x,\ t1) \in csols\ t0\ x0$
assumes $(y,\ t2) \in csols\ t0\ x0$

shows $\forall\, t \in \{t0\ {-}{-}\ t1\} \cap \{t0\ {-}{-}\ t2\}.\ x\ t = y\ t$
⟨*proof*⟩

lemma *csol-unique*:
assumes *t1*: $t1 \in$ *existence-ivl t0 x0*
assumes *t2*: $t2 \in$ *existence-ivl t0 x0*
assumes *t*: $t \in \{t0\ {-}{-}\ t1\}$ $t \in \{t0\ {-}{-}\ t2\}$
shows *csol t0 x0 t1 t* = *csol t0 x0 t2 t*
⟨*proof*⟩

lemma *flow-vderiv-on-left*:
(*flow t0 x0 has-vderiv-on* ($\lambda x.$ *f x* (*flow t0 x0 x*))) (*existence-ivl t0 x0* $\cap$ {..*t0*})
⟨*proof*⟩

lemma *flow-vderiv-on-right*:
(*flow t0 x0 has-vderiv-on* ($\lambda x.$ *f x* (*flow t0 x0 x*))) (*existence-ivl t0 x0* $\cap$ {*t0*..})
⟨*proof*⟩

lemma *flow-usolves-ode*:
assumes *iv-defined*: $t0 \in T$ $x0 \in X$
shows (*flow t0 x0 usolves-ode f from t0*) (*existence-ivl t0 x0*) *X*
⟨*proof*⟩

lemma *flow-solves-ode*: $t0 \in T \Longrightarrow x0 \in X \Longrightarrow$ (*flow t0 x0 solves-ode f*) (*existence-ivl t0 x0*) *X*
⟨*proof*⟩

lemma *equals-flowI*:
assumes $t0 \in T'$
is-interval T'
$T' \subseteq$ *existence-ivl t0 x0*
(*z solves-ode f*) T' *X*
z t0 = *flow t0 x0 t0* $t \in T'$
shows *z t* = *flow t0 x0 t*
⟨*proof*⟩

lemma *existence-ivl-maximal-segment*:
assumes (*x solves-ode f*) $\{t0\ {-}{-}\ t\}$ *X x t0* = *x0*
assumes $\{t0\ {-}{-}\ t\} \subseteq T$
shows $t \in$ *existence-ivl t0 x0*
⟨*proof*⟩

lemma *existence-ivl-maximal-interval*:
assumes (*x solves-ode f*) *S X x t0* = *x0*
assumes $t0 \in S$ *is-interval S* $S \subseteq T$
shows $S \subseteq$ *existence-ivl t0 x0*
⟨*proof*⟩

lemma *maximal-existence-flow*:

assumes *sol*: $(x$ *solves-ode* $f)$ K X **and** *iv*: x $t0 = x0$
assumes *is-interval* K
assumes $t0 \in K$
assumes $K \subseteq T$
shows $K \subseteq$ *existence-ivl* $t0$ $x0$ $\bigwedge t.$ $t \in K \Longrightarrow$ *flow* $t0$ $x0$ $t = x$ t
$\langle proof \rangle$

lemma *maximal-existence-flowI*:
assumes $(x$ *has-vderiv-on* $(\lambda t.$ f t $(x$ $t)))$ K
assumes $\bigwedge t.$ $t \in K \Longrightarrow x$ $t \in X$
assumes x $t0 = x0$
assumes K: *is-interval* K $t0 \in K$ $K \subseteq T$
shows $K \subseteq$ *existence-ivl* $t0$ $x0$ $\bigwedge t.$ $t \in K \Longrightarrow$ *flow* $t0$ $x0$ $t = x$ t
$\langle proof \rangle$

lemma *flow-in-domain*: $t \in$ *existence-ivl* $t0$ $x0 \Longrightarrow$ *flow* $t0$ $x0$ $t \in X$
$\langle proof \rangle$

lemma (**in** *ll-on-open*)
assumes $t \in$ *existence-ivl* s x
assumes $x \in X$
assumes *auto*: $\bigwedge s$ t $x.$ $x \in X \Longrightarrow f$ s $x = f$ t x
assumes $T = UNIV$
shows *mem-existence-ivl-shift-autonomous1*: $t - s \in$ *existence-ivl* 0 x
and *flow-shift-autonomous1*: *flow* s x $t =$ *flow* 0 x $(t - s)$
$\langle proof \rangle$

lemma (**in** *ll-on-open*)
assumes $t - s \in$ *existence-ivl* 0 x
assumes $x \in X$
assumes *auto*: $\bigwedge s$ t $x.$ $x \in X \Longrightarrow f$ s $x = f$ t x
assumes $T = UNIV$
shows *mem-existence-ivl-shift-autonomous2*: $t \in$ *existence-ivl* s x
and *flow-shift-autonomous2*: *flow* s x $t =$ *flow* 0 x $(t - s)$
$\langle proof \rangle$

lemma
flow-eq-rev:
assumes $t \in$ *existence-ivl* $t0$ $x0$
shows *preflect* $t0$ $t \in$ *ll-on-open.existence-ivl* $($*preflect* $t0$ ‘ $T)$ $(\lambda t.$ $-$ f $($*preflect* $t0$ $t))$ X $t0$ $x0$
flow $t0$ $x0$ $t =$ *ll-on-open.flow* $($*preflect* $t0$ ‘ $T)$ $(\lambda t.$ $-$ f $($*preflect* $t0$ $t))$ X $t0$ $x0$ $($*preflect* $t0$ $t)$
$\langle proof \rangle$

lemma (**in** *ll-on-open*)
shows *rev-flow-eq*: $t \in$ *ll-on-open.existence-ivl* $($*preflect* $t0$ ‘ $T)$ $(\lambda t.$ $-$ f $($*preflect* $t0$ $t))$ X $t0$ $x0 \Longrightarrow$
ll-on-open.flow $($*preflect* $t0$ ‘ $T)$ $(\lambda t.$ $-$ f $($*preflect* $t0$ $t))$ X $t0$ $x0$ $t =$ *flow* $t0$ $x0$

(*preflect t0 t*)
and *mem-rev-existence-ivl-eq*:
t ∈ *ll-on-open.existence-ivl* (*preflect t0* ‘ *T*) (λ*t*. − *f* (*preflect t0 t*)) *X t0 x0* ⟷ *preflect t0 t* ∈ *existence-ivl t0 x0*
⟨*proof*⟩

lemma
shows *rev-existence-ivl-eq*: *ll-on-open.existence-ivl* (*preflect t0* ‘ *T*) (λ*t*. − *f* (*preflect t0 t*)) *X t0 x0* = *preflect t0* ‘ *existence-ivl t0 x0*
and *existence-ivl-eq-rev*: *existence-ivl t0 x0* = *preflect t0* ‘ *ll-on-open.existence-ivl* (*preflect t0* ‘ *T*) (λ*t*. − *f* (*preflect t0 t*)) *X t0 x0*
⟨*proof*⟩

end

end

3 Bounded Linear Operator

theory *Bounded-Linear-Operator*
imports
HOL−Analysis.Analysis
begin

typedef (**overloaded**) *'a blinop* = *UNIV*::(*'a*, *'a*) *blinfun set*
⟨*proof*⟩

setup-lifting *type-definition-blinop*

lift-definition *blinop-apply*::(*'a*::*real-normed-vector*) *blinop* ⇒ *'a* ⇒ *'a* **is** *blinfun-apply* ⟨*proof*⟩
lift-definition *Blinop*::(*'a*::*real-normed-vector* ⇒ *'a*) ⇒ *'a blinop* **is** *Blinfun* ⟨*proof*⟩

no-notation *vec-nth* (**infixl** ‹$› *90*)
notation *blinop-apply* (**infixl** ‹$› *999*)
declare [[*coercion blinop-apply* :: (*'a*::*real-normed-vector*) *blinop* ⇒ *'a* ⇒ *'a*]]

instantiation *blinop* :: (*real-normed-vector*) *real-normed-vector*
begin

lift-definition *norm-blinop* :: *'a blinop* ⇒ *real* **is** *norm* ⟨*proof*⟩

lift-definition *minus-blinop* :: *'a blinop* ⇒ *'a blinop* ⇒ *'a blinop* **is** *minus* ⟨*proof*⟩

lift-definition *dist-blinop* :: *'a blinop* ⇒ *'a blinop* ⇒ *real* **is** *dist* ⟨*proof*⟩

definition *uniformity-blinop* :: (*'a blinop* × *'a blinop*) *filter* **where**
uniformity-blinop = (*INF e*∈{*0*<..}. *principal* {(*x*, *y*). *dist x y* < *e*})

definition *open-blinop* :: *'a blinop set* ⇒ *bool* **where**
open-blinop U = (∀ *x*∈*U*. ∀$_F$ (*x'*, *y*) *in uniformity*. *x'* = *x* ⟶ *y* ∈ *U*)

lift-definition *uminus-blinop* :: *'a blinop* ⇒ *'a blinop* **is** *uminus* ⟨*proof*⟩

lift-definition *zero-blinop* :: *'a blinop* **is** *0* ⟨*proof*⟩

lift-definition *plus-blinop* :: *'a blinop* ⇒ *'a blinop* ⇒ *'a blinop* **is** *plus* ⟨*proof*⟩

lift-definition *scaleR-blinop*::*real* ⇒ *'a blinop* ⇒ *'a blinop* **is** *scaleR* ⟨*proof*⟩

lift-definition *sgn-blinop* :: *'a blinop* ⇒ *'a blinop* **is** *sgn* ⟨*proof*⟩

instance
⟨*proof*⟩
end

lemma *bounded-bilinear-blinop-apply*: *bounded-bilinear* ($)
⟨*proof*⟩

interpretation *blinop*: *bounded-bilinear* ($)
⟨*proof*⟩

lemma *blinop-eqI*: (⋀*i*. *x* $ *i* = *y* $ *i*) ⟹ *x* = *y*
⟨*proof*⟩

lemmas *bounded-linear-apply-blinop*[*intro*, *simp*] = *blinop.bounded-linear-left*
declare *blinop.tendsto*[*tendsto-intros*]
declare *blinop.FDERIV*[*derivative-intros*]
declare *blinop.continuous*[*continuous-intros*]
declare *blinop.continuous-on*[*continuous-intros*]

instance *blinop* :: (*banach*) *banach*
⟨*proof*⟩

instance *blinop* :: (*euclidean-space*) *heine-borel*
⟨*proof*⟩

instantiation *blinop*::({*real-normed-vector*, *perfect-space*}) *real-normed-algebra-1*
begin

lift-definition *one-blinop*::*'a blinop* **is** *id-blinfun* ⟨*proof*⟩
lemma *blinop-apply-one-blinop*[*simp*]: *1* $ *x* = *x*
⟨*proof*⟩

lift-definition *times-blinop* :: *'a blinop* ⇒ *'a blinop* ⇒ *'a blinop* **is** *blinfun-compose*
⟨*proof*⟩

lemma *blinop-apply-times-blinop*[*simp*]: $(f * g)$ \$ $x = f$ \$ $(g$ \$ $x)$
⟨*proof*⟩

instance
⟨*proof*⟩
end

lemmas *bounded-bilinear-bounded-uniform-limit-intros*[*uniform-limit-intros*] =
bounded-bilinear.bounded-uniform-limit[*OF Bounded-Linear-Operator.bounded-bilinear-blinop-apply*]
bounded-bilinear.bounded-uniform-limit[*OF Bounded-Linear-Function.bounded-bilinear-blinfun-apply*]
bounded-bilinear.bounded-uniform-limit[*OF Bounded-Linear-Operator.blinop.flip*]
bounded-bilinear.bounded-uniform-limit[*OF Bounded-Linear-Function.blinfun.flip*]
bounded-linear.uniform-limit[*OF blinop.bounded-linear-right*]
bounded-linear.uniform-limit[*OF blinop.bounded-linear-left*]
bounded-linear.uniform-limit[*OF bounded-linear-apply-blinop*]

no-notation
blinop-apply (**infixl** ‹\$› *999*)
notation *vec-nth* (**infixl** ‹\$› *90*)

end

4 Multivariate Taylor

theory *Multivariate-Taylor*
imports
HOL−Analysis.Analysis
../ODE-Auxiliarities
begin

no-notation *vec-nth* (**infixl** ‹\$› *90*)
notation *blinfun-apply* (**infixl** ‹\$› *999*)

lemma
fixes f::$'a$::*real-normed-vector* $\Rightarrow$ $'b$::*banach*
and Df::$'a \Rightarrow nat \Rightarrow 'a \Rightarrow 'a \Rightarrow 'b$
assumes $n > 0$
assumes *Df-Nil*: $\bigwedge a\ x.\ Df\ a\ 0\ H\ H = f\ a$
assumes *Df-Cons*: $\bigwedge a\ i\ d.\ a \in$ *closed-segment* $X\ (X + H) \Longrightarrow i < n \Longrightarrow$
$((\lambda a.\ Df\ a\ i\ H\ H)$ *has-derivative* $(Df\ a\ (Suc\ i)\ H))$ (*at* a *within* G)
assumes *cs*: *closed-segment* $X\ (X + H) \subseteq G$
defines $i \equiv \lambda x.$
$((1 - x)\ \hat{}\ (n - 1)\ /\ fact\ (n - 1)) *_R Df\ (X + x *_R H)\ n\ H\ H$
shows *multivariate-Taylor-has-integral*:
(i *has-integral* $f\ (X + H) - (\sum i{<}n.\ (1\ /\ fact\ i) *_R Df\ X\ i\ H\ H))\ \{0..1\}$
and *multivariate-Taylor*:
$f\ (X + H) = (\sum i{<}n.\ (1\ /\ fact\ i) *_R Df\ X\ i\ H\ H) +$ *integral* $\{0..1\}\ i$
and *multivariate-Taylor-integrable*:
i *integrable-on* $\{0..1\}$

$\langle proof \rangle$

4.1 Symmetric second derivative

lemma *symmetric-second-derivative-aux*:
  assumes *first-fderiv*[*derivative-intros*]:
    $\bigwedge a.\ a \in G \Longrightarrow (f\ \textit{has-derivative}\ (f'\ a))\ (\textit{at}\ a\ \textit{within}\ G)$
  assumes *second-fderiv*[*derivative-intros*]:
    $\bigwedge i.\ ((\lambda x.\ f'\ x\ i)\ \textit{has-derivative}\ (\lambda j.\ f''\ j\ i))\ (\textit{at}\ a\ \textit{within}\ G)$
  assumes $i \neq j\ i \neq 0\ j \neq 0$
  assumes $a \in G$
  assumes $\bigwedge s\ t.\ s \in \{0..1\} \Longrightarrow t \in \{0..1\} \Longrightarrow a + s *_R i + t *_R j \in G$
  shows $f''\ j\ i = f''\ i\ j$
$\langle proof \rangle$

locale *second-derivative-within* =
  fixes $f\ f'\ f''\ a\ G$
  assumes *first-fderiv*[*derivative-intros*]:
    $\bigwedge a.\ a \in G \Longrightarrow (f\ \textit{has-derivative blinfun-apply}\ (f'\ a))\ (\textit{at}\ a\ \textit{within}\ G)$
  assumes *in-G*: $a \in G$
  assumes *second-fderiv*[*derivative-intros*]:
    $(f'\ \textit{has-derivative blinfun-apply}\ f'')\ (\textit{at}\ a\ \textit{within}\ G)$
begin

lemma *symmetric-second-derivative-within*:
  assumes $a \in G$
  assumes $\bigwedge s\ t.\ s \in \{0..1\} \Longrightarrow t \in \{0..1\} \Longrightarrow a + s *_R i + t *_R j \in G$
  shows $f''\ i\ j = f''\ j\ i$
  $\langle proof \rangle$

end

locale *second-derivative* =
  fixes $f::'a::\textit{real-normed-vector} \Rightarrow\ 'b::\textit{banach}$
    and $f' ::\ 'a \Rightarrow\ 'a \Rightarrow_L\ 'b$
    and $f'' ::\ 'a \Rightarrow_L\ 'a \Rightarrow_L\ 'b$
    and $a ::\ 'a$
    and $G ::\ 'a\ \textit{set}$
  assumes *first-fderiv*[*derivative-intros*]:
    $\bigwedge a.\ a \in G \Longrightarrow (f\ \textit{has-derivative}\ f'\ a)\ (\textit{at}\ a)$
  assumes *in-G*: $a \in \textit{interior}\ G$
  assumes *second-fderiv*[*derivative-intros*]:
    $(f'\ \textit{has-derivative}\ f'')\ (\textit{at}\ a)$
begin

lemma *symmetric-second-derivative*:
  assumes $a \in \textit{interior}\ G$
  shows $f''\ i\ j = f''\ j\ i$
$\langle proof \rangle$

end

lemma
uniform-explicit-remainder-Taylor-1:
fixes $f::'a::\{banach,heine\text{-}borel,perfect\text{-}space\} \Rightarrow 'b::banach$
assumes f'[*derivative-intros*]: $\bigwedge x.\ x \in G \Longrightarrow (f\ has\text{-}derivative\ blinfun\text{-}apply\ (f'\ x))\ (at\ x)$
assumes f'-*cont*: $\bigwedge x.\ x \in G \Longrightarrow isCont\ f'\ x$
assumes *open* G
assumes $J \neq \{\}$ *compact* J $J \subseteq G$
assumes $e > 0$
obtains d R
where $d > 0$
$\bigwedge x\ z.\ f\ z = f\ x + f'\ x\ (z - x) + R\ x\ z$
$\bigwedge x\ y.\ x \in J \Longrightarrow y \in J \Longrightarrow dist\ x\ y < d \Longrightarrow norm\ (R\ x\ y) \leq e * dist\ x\ y$
continuous-on $(G \times G)$ $(\lambda(a,\ b).\ R\ a\ b)$
⟨*proof*⟩

TODO: rename, duplication?

locale *second-derivative-within'* =
fixes $f\ f'\ f''\ a\ G$
assumes *first-fderiv*[*derivative-intros*]:
$\bigwedge a.\ a \in G \Longrightarrow (f\ has\text{-}derivative\ f'\ a)\ (at\ a\ within\ G)$
assumes *in-G*: $a \in G$
assumes *second-fderiv*[*derivative-intros*]:
$\bigwedge i.\ ((\lambda x.\ f'\ x\ i)\ has\text{-}derivative\ f''\ i)\ (at\ a\ within\ G)$
begin

lemma *symmetric-second-derivative-within*:
assumes $a \in G$ *open* G
assumes $\bigwedge s\ t.\ s \in \{0..1\} \Longrightarrow t \in \{0..1\} \Longrightarrow a + s *_R i + t *_R j \in G$
shows $f''\ i\ j = f''\ j\ i$
⟨*proof*⟩

end

locale *second-derivative-on-open* =
fixes $f::'a::real\text{-}normed\text{-}vector \Rightarrow 'b::banach$
and $f' :: 'a \Rightarrow 'a \Rightarrow 'b$
and $f'' :: 'a \Rightarrow 'a \Rightarrow 'b$
and $a :: 'a$
and $G :: 'a\ set$
assumes *first-fderiv*[*derivative-intros*]:
$\bigwedge a.\ a \in G \Longrightarrow (f\ has\text{-}derivative\ f'\ a)\ (at\ a)$
assumes *in-G*: $a \in G$ **and** *open-G*: *open* G
assumes *second-fderiv*[*derivative-intros*]:
$((\lambda x.\ f'\ x\ i)\ has\text{-}derivative\ f''\ i)\ (at\ a)$
begin

lemma *symmetric-second-derivative*:
  assumes $a \in G$
  shows $f''\ i\ j = f''\ j\ i$
⟨*proof*⟩

end

no-notation
  blinfun-apply (**infixl** ‹$› *999*)
notation *vec-nth* (**infixl** ‹$› *90*)

end

5 Flow

theory *Flow*
imports
  Picard-Lindeloef-Qualitative
  HOL−Library.Diagonal-Subsequence
  ../Library/Bounded-Linear-Operator
  ../Library/Multivariate-Taylor
  ../Library/Interval-Integral-HK
begin

TODO: extend theorems for dependence on initial time

5.1 simp rules for integrability (TODO: move)

lemma *blinfun-ext*: $x = y \longleftrightarrow (\forall i.\ \textit{blinfun-apply}\ x\ i = \textit{blinfun-apply}\ y\ i)$
  ⟨*proof*⟩

notation *id-blinfun* (‹1_L›)

lemma *blinfun-inverse-left*:
  fixes $f{::}'a{::}\textit{euclidean-space} \Rightarrow_L 'a$ **and** f'
  shows $f\ o_L\ f' = 1_L \longleftrightarrow f'\ o_L\ f = 1_L$
  ⟨*proof*⟩

lemma *onorm-zero-blinfun*[*simp*]: $\textit{onorm}\ (\textit{blinfun-apply}\ 0) = 0$
  ⟨*proof*⟩

lemma *blinfun-compose-1-left*[*simp*]: $x\ o_L\ 1_L = x$
  and *blinfun-compose-1-right*[*simp*]: $1_L\ o_L\ y = y$
  ⟨*proof*⟩

named-theorems *integrable-on-simps*

lemma *integrable-on-refl-ivl*[*intro*, *simp*]: *g integrable-on* {*b* .. (*b*::′*b*::*ordered-euclidean-space*)}
and *integrable-on-refl-closed-segment*[*intro*, *simp*]: *h integrable-on closed-segment a a*
⟨*proof*⟩

lemma *integrable-const-ivl-closed-segment*[*intro*, *simp*]: ($\lambda x.\ c$) *integrable-on closed-segment a* (*b*::*real*)
⟨*proof*⟩

lemma *integrable-ident-ivl*[*intro*, *simp*]: ($\lambda x.\ x$) *integrable-on closed-segment a* (*b*::*real*)
and *integrable-ident-cbox*[*intro*, *simp*]: ($\lambda x.\ x$) *integrable-on cbox a* (*b*::*real*)
⟨*proof*⟩

lemma *content-closed-segment-real*:
fixes *a b*::*real*
shows *content* (*closed-segment a b*) = *abs* ($b - a$)
⟨*proof*⟩

lemma *integral-const-closed-segment*:
fixes *a b*::*real*
shows *integral* (*closed-segment a b*) ($\lambda x.\ c$) = *abs* ($b - a$) $*_R$ *c*
⟨*proof*⟩

lemmas [*integrable-on-simps*] =
integrable-on-empty — empty
integrable-on-refl integrable-on-refl-ivl integrable-on-refl-closed-segment — singleton
integrable-const integrable-const-ivl integrable-const-ivl-closed-segment — constant
ident-integrable-on integrable-ident-ivl integrable-ident-cbox — identity

lemma *integrable-cmul-real*:
fixes *K*::*real*
shows *f integrable-on X* $\Longrightarrow$ ($\lambda x.\ K * f\ x$) *integrable-on X*
⟨*proof*⟩

lemmas [*integrable-on-simps*] =
integrable-0
integrable-neg
integrable-cmul
integrable-cmul-real
integrable-on-cmult-iff
integrable-on-cmult-left
integrable-on-cmult-right
integrable-on-cmult-iff
integrable-on-cmult-left-iff
integrable-on-cmult-right-iff
integrable-on-cdivide-iff
integrable-diff
integrable-add

integrable-sum

lemma *dist-cancel-add1*: *dist* $(t0 + et)$ *t0* = *norm et*
⟨*proof*⟩

lemma *double-nonneg-le*:
fixes *a*::*real*
shows $a * 2 \leq b \Longrightarrow a \geq 0 \Longrightarrow a \leq b$
⟨*proof*⟩

5.2 Nonautonomous IVP on maximal existence interval

context *ll-on-open-it*
begin

context
fixes *x0*
assumes *iv-defined*: $t0 \in T$ $x0 \in X$
begin

lemmas *closed-segment-iv-subset-domain* = *closed-segment-subset-domainI*[*OF iv-defined*(*1*)]

lemma
local-unique-solutions:
obtains *t u L*
where
$0 < t$ $0 < u$
cball t0 t ⊆ *existence-ivl t0 x0*
cball x0 $(2 * u) \subseteq X$
$\bigwedge t'.\ t' \in$ *cball t0 t* ⟹ *L*−*lipschitz-on* (*cball x0* $(2 * u)$) (*f* t')
$\bigwedge x.\ x \in$ *cball x0 u* ⟹ (*flow t0 x usolves-ode f from t0*) (*cball t0 t*) (*cball x u*)
$\bigwedge x.\ x \in$ *cball x0 u* ⟹ *cball x u* ⊆ *X*
⟨*proof*⟩

lemma *Picard-iterate-mem-existence-ivlI*:
assumes $t \in T$
assumes *compact C* $x0 \in C$ $C \subseteq X$
assumes $\bigwedge y\ s.\ s \in \{t0 -- t\} \Longrightarrow y\ t0 = x0 \Longrightarrow y \in \{t0--s\} \to C \Longrightarrow$ *continuous-on* $\{t0--s\}$ $y \Longrightarrow$
x0 + *ivl-integral t0 s* $(\lambda t.\ f\ t\ (y\ t)) \in C$
shows $t \in$ *existence-ivl t0 x0* $\bigwedge s.\ s \in \{t0 -- t\} \Longrightarrow$ *flow t0 x0 s* $\in C$
⟨*proof*⟩

lemma *flow-has-vderiv-on*: (*flow t0 x0 has-vderiv-on* $(\lambda t.$ *f t* (*flow t0 x0 t*))) (*existence-ivl t0 x0*)
⟨*proof*⟩

lemmas *flow-has-vderiv-on-compose*[*derivative-intros*] =
has-vderiv-on-compose2[*OF flow-has-vderiv-on*, *THEN has-vderiv-on-eq-rhs*]

end

lemma *unique-on-intersection*:
  assumes *sols*: $(x$ *solves-ode* $f)$ U X $(y$ *solves-ode* $f)$ V X
  assumes *iv-mem*: $t0 \in U$ $t0 \in V$ **and** *subs*: $U \subseteq T$ $V \subseteq T$
  assumes *ivls*: *is-interval* U *is-interval* V
  assumes *iv*: $x\ t0 = y\ t0$
  assumes *mem*: $t \in U$ $t \in V$
  shows $x\ t = y\ t$
⟨*proof*⟩

lemma *unique-solution*:
  assumes *sols*: $(x$ *solves-ode* $f)$ U X $(y$ *solves-ode* $f)$ U X
  assumes *iv-mem*: $t0 \in U$ **and** *subs*: $U \subseteq T$
  assumes *ivls*: *is-interval* U
  assumes *iv*: $x\ t0 = y\ t0$
  assumes *mem*: $t \in U$
  shows $x\ t = y\ t$
  ⟨*proof*⟩

lemma
  assumes *s*: $s \in$ *existence-ivl* $t0$ $x0$
  assumes *t*: $t + s \in$ *existence-ivl* s (*flow* $t0$ $x0$ s)
  shows *flow-trans*: *flow* $t0$ $x0$ $(s + t) =$ *flow* s (*flow* $t0$ $x0$ s) $(s + t)$
    and *existence-ivl-trans*: $s + t \in$ *existence-ivl* $t0$ $x0$
⟨*proof*⟩

lemma
  assumes *t*: $t \in$ *existence-ivl* $t0$ $x0$
  shows *flows-reverse*: *flow* t (*flow* $t0$ $x0$ t) $t0 = x0$
    and *existence-ivl-reverse*: $t0 \in$ *existence-ivl* t (*flow* $t0$ $x0$ t)
⟨*proof*⟩

lemma *flow-has-derivative*:
  assumes $t \in$ *existence-ivl* $t0$ $x0$
  shows (*flow* $t0$ $x0$ *has-derivative* $(\lambda i.\ i *_R f\ t$ (*flow* $t0$ $x0$ t))) (*at* t)
⟨*proof*⟩

lemma *flow-has-vector-derivative*:
  assumes $t \in$ *existence-ivl* $t0$ $x0$
  shows (*flow* $t0$ $x0$ *has-vector-derivative* $f\ t$ (*flow* $t0$ $x0$ t)) (*at* t)
  ⟨*proof*⟩

lemma *flow-has-vector-derivative-at-0*:
  assumes$t \in$ *existence-ivl* $t0$ $x0$
  shows $((\lambda h.$ *flow* $t0$ $x0$ $(t + h))$ *has-vector-derivative* $f\ t$ (*flow* $t0$ $x0$ t)) (*at* 0)
⟨*proof*⟩

lemma
  assumes $t \in$ *existence-ivl t0 x0*
  shows *closed-segment-subset-existence-ivl*: *closed-segment t0 t* $\subseteq$ *existence-ivl t0 x0*
    and *ivl-subset-existence-ivl*: $\{t0 .. t\} \subseteq$ *existence-ivl t0 x0*
    and *ivl-subset-existence-ivl'*: $\{t .. t0\} \subseteq$ *existence-ivl t0 x0*
  ⟨*proof*⟩

lemma *flow-fixed-point*:
  assumes *t*: $t \in$ *existence-ivl t0 x0*
  shows *flow t0 x0 t* = *x0* + *ivl-integral t0 t* (λt. *f t* (*flow t0 x0 t*))
⟨*proof*⟩

lemma *flow-continuous*: $t \in$ *existence-ivl t0 x0* $\Longrightarrow$ *continuous* (*at t*) (*flow t0 x0*)
  ⟨*proof*⟩

lemma *flow-tendsto*: $t \in$ *existence-ivl t0 x0* $\Longrightarrow$ (*ts* $\longrightarrow$ *t*) *F* $\Longrightarrow$
    ((λs. *flow t0 x0* (*ts s*)) $\longrightarrow$ *flow t0 x0 t*) *F*
  ⟨*proof*⟩

lemma *flow-continuous-on*: *continuous-on* (*existence-ivl t0 x0*) (*flow t0 x0*)
  ⟨*proof*⟩

lemma *flow-continuous-on-intro*:
  continuous-on s g $\Longrightarrow$
  ($\bigwedge$*xa*. *xa* $\in$ *s* $\Longrightarrow$ *g xa* $\in$ *existence-ivl t0 x0*) $\Longrightarrow$
  continuous-on s (λ*xa*. *flow t0 x0* (*g xa*))
  ⟨*proof*⟩

lemma *f-flow-continuous*:
  assumes $t \in$ *existence-ivl t0 x0*
  shows *isCont* (λt. *f t* (*flow t0 x0 t*)) *t*
  ⟨*proof*⟩

lemma *exponential-initial-condition*:
  assumes *y0*: $t \in$ *existence-ivl t0 y0*
  assumes *z0*: $t \in$ *existence-ivl t0 z0*
  assumes $Y \subseteq X$
  assumes *remain*: $\bigwedge s$. $s \in$ *closed-segment t0 t* $\Longrightarrow$ *flow t0 y0 s* $\in Y$
    $\bigwedge s$. $s \in$ *closed-segment t0 t* $\Longrightarrow$ *flow t0 z0 s* $\in Y$
  assumes *lipschitz*: $\bigwedge s$. $s \in$ *closed-segment t0 t* $\Longrightarrow$ *K*−*lipschitz-on Y* (*f s*)
  shows *norm* (*flow t0 y0 t* − *flow t0 z0 t*) $\le$ *norm* (*y0* − *z0*) $*$ *exp* ((*K* + *1*) $*$ *abs* (*t* − *t0*))
⟨*proof*⟩

lemma
  existence-ivl-cballs:
  assumes *iv-defined*: *t0* $\in$ *T x0* $\in$ *X*

obtains $t\ u\ L$
where
$\bigwedge y.\ y \in cball\ x0\ u \Longrightarrow cball\ t0\ t \subseteq existence\text{-}ivl\ t0\ y$
$\bigwedge s\ y.\ y \in cball\ x0\ u \Longrightarrow s \in cball\ t0\ t \Longrightarrow flow\ t0\ y\ s \in cball\ y\ u$
$L{-}lipschitz\text{-}on\ (cball\ t0\ t \times cball\ x0\ u)\ (\lambda(t,\ x).\ flow\ t0\ x\ t)$
$\bigwedge y.\ y \in cball\ x0\ u \Longrightarrow cball\ y\ u \subseteq X$
$0 < t\ 0 < u$
⟨*proof*⟩

context
fixes *x0*
assumes *iv-defined*: $t0 \in T\ x0 \in X$
begin

lemma *existence-ivl-notempty*: $existence\text{-}ivl\ t0\ x0 \neq \{\}$
⟨*proof*⟩

lemma *initial-time-bounds*:
shows $bdd\text{-}above\ (existence\text{-}ivl\ t0\ x0) \Longrightarrow t0 < Sup\ (existence\text{-}ivl\ t0\ x0)$ (**is** *?a* $\Longrightarrow$ -)
and $bdd\text{-}below\ (existence\text{-}ivl\ t0\ x0) \Longrightarrow Inf\ (existence\text{-}ivl\ t0\ x0) < t0$ (**is** *?b* $\Longrightarrow$ -)
⟨*proof*⟩

lemma
flow-leaves-compact-ivl-right:
assumes *bdd*: $bdd\text{-}above\ (existence\text{-}ivl\ t0\ x0)$
defines $b \equiv Sup\ (existence\text{-}ivl\ t0\ x0)$
assumes $b \in T$
assumes *compact K*
assumes $K \subseteq X$
obtains t **where** $t \geq t0\ t \in existence\text{-}ivl\ t0\ x0\ flow\ t0\ x0\ t \notin K$
⟨*proof*⟩

lemma
flow-leaves-compact-ivl-left:
assumes *bdd*: $bdd\text{-}below\ (existence\text{-}ivl\ t0\ x0)$
defines $b \equiv Inf\ (existence\text{-}ivl\ t0\ x0)$
assumes $b \in T$
assumes *compact K*
assumes $K \subseteq X$
obtains t **where** $t \leq t0\ t \in existence\text{-}ivl\ t0\ x0\ flow\ t0\ x0\ t \notin K$
⟨*proof*⟩

lemma
sup-existence-maximal:
assumes $\bigwedge t.\ t0 \leq t \Longrightarrow t \in existence\text{-}ivl\ t0\ x0 \Longrightarrow flow\ t0\ x0\ t \in K$
assumes $compact\ K\ K \subseteq X$
assumes $bdd\text{-}above\ (existence\text{-}ivl\ t0\ x0)$

shows Sup ($existence\text{-}ivl\ t0\ x0$) $\notin T$
⟨*proof*⟩

lemma
inf-existence-minimal:
assumes $\bigwedge t.\ t \leq t0 \Longrightarrow t \in existence\text{-}ivl\ t0\ x0 \Longrightarrow flow\ t0\ x0\ t \in K$
assumes $compact\ K\ K \subseteq X$
assumes $bdd\text{-}below\ (existence\text{-}ivl\ t0\ x0)$
shows $Inf\ (existence\text{-}ivl\ t0\ x0) \notin T$
⟨*proof*⟩

end

lemma
subset-mem-compact-implies-subset-existence-interval:
assumes *ivl*: $t0 \in T'$ $is\text{-}interval\ T'\ T' \subseteq T$
assumes *iv-defined*: $x0 \in X$
assumes *mem-compact*: $\bigwedge t.\ t \in T' \Longrightarrow t \in existence\text{-}ivl\ t0\ x0 \Longrightarrow flow\ t0\ x0\ t$
$\in K$
assumes *K*: $compact\ K\ K \subseteq X$
shows $T' \subseteq existence\text{-}ivl\ t0\ x0$
⟨*proof*⟩

lemma
mem-compact-implies-subset-existence-interval:
assumes *iv-defined*: $t0 \in T\ x0 \in X$
assumes *mem-compact*: $\bigwedge t.\ t \in T \Longrightarrow t \in existence\text{-}ivl\ t0\ x0 \Longrightarrow flow\ t0\ x0\ t$
$\in K$
assumes *K*: $compact\ K\ K \subseteq X$
shows $T \subseteq existence\text{-}ivl\ t0\ x0$
⟨*proof*⟩

lemma
global-right-existence-ivl-explicit:
assumes $b \geq t0$
assumes *b*: $b \in existence\text{-}ivl\ t0\ x0$
obtains $d\ K$ **where** $d > 0\ K > 0$
$ball\ x0\ d \subseteq X$
$\bigwedge y.\ y \in ball\ x0\ d \Longrightarrow b \in existence\text{-}ivl\ t0\ y$
$\bigwedge t\ y.\ y \in ball\ x0\ d \Longrightarrow t \in \{t0\ ..\ b\} \Longrightarrow$
$dist\ (flow\ t0\ x0\ t)\ (flow\ t0\ y\ t) \leq dist\ x0\ y * exp\ (K * abs\ (t - t0))$
⟨*proof*⟩

lemma
global-left-existence-ivl-explicit:
assumes $b \leq t0$
assumes *b*: $b \in existence\text{-}ivl\ t0\ x0$
assumes *iv-defined*: $t0 \in T\ x0 \in X$
obtains $d\ K$ **where** $d > 0\ K > 0$

ball x0 d $\subseteq$ *X*
$\bigwedge$*y*. *y* $\in$ *ball x0 d* $\Longrightarrow$ *b* $\in$ *existence-ivl t0 y*
$\bigwedge$*t y*. *y* $\in$ *ball x0 d* $\Longrightarrow$ *t* $\in$ {*b* .. *t0*} $\Longrightarrow$ *dist* (*flow t0 x0 t*) (*flow t0 y t*) $\leq$ *dist x0 y* $*$ *exp* (*K* $*$ *abs* (*t* $-$ *t0*))
⟨*proof*⟩

lemma
global-existence-ivl-explicit:
assumes *a*: *a* $\in$ *existence-ivl t0 x0*
assumes *b*: *b* $\in$ *existence-ivl t0 x0*
assumes *le*: *a* $\leq$ *b*
obtains *d K* **where** *d* $>$ *0 K* $>$ *0*
ball x0 d $\subseteq$ *X*
$\bigwedge$*y*. *y* $\in$ *ball x0 d* $\Longrightarrow$ *a* $\in$ *existence-ivl t0 y*
$\bigwedge$*y*. *y* $\in$ *ball x0 d* $\Longrightarrow$ *b* $\in$ *existence-ivl t0 y*
$\bigwedge$*t y*. *y* $\in$ *ball x0 d* $\Longrightarrow$ *t* $\in$ {*a* .. *b*} $\Longrightarrow$
dist (*flow t0 x0 t*) (*flow t0 y t*) $\leq$ *dist x0 y* $*$ *exp* (*K* $*$ *abs* (*t* $-$ *t0*))
⟨*proof*⟩

lemma *eventually-exponential-separation*:
assumes *a*: *a* $\in$ *existence-ivl t0 x0*
assumes *b*: *b* $\in$ *existence-ivl t0 x0*
assumes *le*: *a* $\leq$ *b*
obtains *K* **where** *K* $>$ *0* $\forall_F$ *y in at x0*. $\forall$ *t*$\in${*a*..*b*}. *dist* (*flow t0 x0 t*) (*flow t0 y t*) $\leq$ *dist x0 y* $*$ *exp* (*K* $*$ $|$*t* $-$ *t0*$|$)
⟨*proof*⟩

lemma *eventually-mem-existence-ivl*:
assumes *b*: *b* $\in$ *existence-ivl t0 x0*
shows $\forall_F$ *x in at x0*. *b* $\in$ *existence-ivl t0 x*
⟨*proof*⟩

lemma *uniform-limit-flow*:
assumes *a*: *a* $\in$ *existence-ivl t0 x0*
assumes *b*: *b* $\in$ *existence-ivl t0 x0*
assumes *le*: *a* $\leq$ *b*
shows *uniform-limit* {*a* .. *b*} (*flow t0*) (*flow t0 x0*) (*at x0*)
⟨*proof*⟩

lemma *eventually-at-fst*:
assumes *eventually P* (*at* (*fst x*))
assumes *P* (*fst x*)
shows *eventually* (λ*h*. *P* (*fst h*)) (*at x*)
⟨*proof*⟩

lemma *eventually-at-snd*:
assumes *eventually P* (*at* (*snd x*))
assumes *P* (*snd x*)
shows *eventually* (λ*h*. *P* (*snd h*)) (*at x*)

⟨*proof*⟩

lemma
shows *open-state-space*: *open* (*Sigma X* (*existence-ivl t0*))
and *flow-continuous-on-state-space*:
continuous-on (*Sigma X* (*existence-ivl t0*)) (λ(*x*, *t*). *flow t0 x t*)
⟨*proof*⟩

lemmas *flow-continuous-on-compose*[*continuous-intros*] =
continuous-on-compose-Pair[*OF flow-continuous-on-state-space*]

lemma *flow-isCont-state-space*: *t* ∈ *existence-ivl t0 x0* ⟹ *isCont* (λ(*x*, *t*). *flow t0 x t*) (*x0*, *t*)
⟨*proof*⟩

lemma
flow-absolutely-integrable-on[*integrable-on-simps*]:
assumes *s* ∈ *existence-ivl t0 x0*
shows (λ*x*. *norm* (*flow t0 x0 x*)) *integrable-on closed-segment t0 s*
⟨*proof*⟩

lemma *existence-ivl-eq-domain*:
assumes *iv-defined*: *t0* ∈ *T x0* ∈ *X*
assumes *bnd*: ⋀*tm tM t x*. *tm* ∈ *T* ⟹ *tM* ∈ *T* ⟹ ∃ *M*. ∃ *L*. ∀ *t* ∈ {*tm* .. *tM*}. ∀ *x* ∈ *X*. *norm* (*f t x*) ≤ *M* + *L* ∗ *norm x*
assumes *is-interval T X* = *UNIV*
shows *existence-ivl t0 x0* = *T*
⟨*proof*⟩

lemma *flow-unique*:
assumes *t* ∈ *existence-ivl t0 x0*
assumes *phi t0* = *x0*
assumes ⋀*t*. *t* ∈ *existence-ivl t0 x0* ⟹ (*phi has-vector-derivative f t* (*phi t*)) (*at t*)
assumes ⋀*t*. *t* ∈ *existence-ivl t0 x0* ⟹ *phi t* ∈ *X*
shows *flow t0 x0 t* = *phi t*
⟨*proof*⟩

lemma *flow-unique-on*:
assumes *t* ∈ *existence-ivl t0 x0*
assumes *phi t0* = *x0*
assumes (*phi has-vderiv-on* (λ*t*. *f t* (*phi t*))) (*existence-ivl t0 x0*)
assumes ⋀*t*. *t* ∈ *existence-ivl t0 x0* ⟹ *phi t* ∈ *X*
shows *flow t0 x0 t* = *phi t*
⟨*proof*⟩

end — *local-lipschitz T X f*

locale *two-ll-on-open* =

F: *ll-on-open* $T1\ F\ X$ + G: *ll-on-open* $T2\ G\ X$
for $F\ T1\ G\ T2\ X\ J\ x0$ +
fixes e::*real* **and** K
assumes *t0-in-J*: $0 \in J$
assumes *J-subset*: $J \subseteq F.existence\text{-}ivl\ 0\ x0$
assumes *J-ivl*: *is-interval* J
assumes *F-lipschitz*: $\bigwedge t.\ t \in J \Longrightarrow K\text{--}lipschitz\text{-}on\ X\ (F\ t)$
assumes *K-pos*: $0 < K$
assumes *F-G-norm-ineq*: $\bigwedge t\ x.\ t \in J \Longrightarrow x \in X \Longrightarrow norm\ (F\ t\ x - G\ t\ x) < e$
begin

context begin

lemma *F-iv-defined*: $0 \in T1$ $x0 \in X$
⟨*proof*⟩

lemma *e-pos*: $0 < e$
⟨*proof*⟩ **definition** *flow0* t = F.*flow* $0\ x0\ t$
qualified definition $Y\ t = G$.*flow* $0\ x0\ t$

lemma *norm-X-Y-bound*:
shows $\forall t \in J \cap G.existence\text{-}ivl\ 0\ x0.\ norm\ (flow0\ t - Y\ t) \leq e\ /\ K * (exp(K * |t|) - 1)$
⟨*proof*⟩

end

end

locale *auto-ll-on-open* =
fixes f::'a::{*banach*, *heine-borel*} ⇒ 'a **and** X
assumes *auto-local-lipschitz*: *local-lipschitz UNIV* X (λ-::*real*. f)
assumes *auto-open-domain*[*intro*!, *simp*]: *open* X
begin

autonomous flow and existence interval

definition *flow0* $x0\ t$ = *ll-on-open.flow UNIV* (λ-. f) $X\ 0\ x0\ t$

definition *existence-ivl0* $x0$ = *ll-on-open.existence-ivl UNIV* (λ-. f) $X\ 0\ x0$

sublocale *ll-on-open-it UNIV* λ-. $f\ X\ 0$
rewrites *flow* = ($\lambda t0\ x0\ t.$ *flow0* $x0\ (t - t0)$)
and *existence-ivl* = ($\lambda t0\ x0.$ (+) $t0$ ‘ *existence-ivl0* $x0$)
and (+) 0 = (λx::*real*. x)
and $s - 0 = s$
and $(\lambda x.\ x)$ ‘ $S = S$
and $s \in (+)\ t$ ‘ $S \longleftrightarrow s - t \in (S$::*real set*)
and $P\ (s + t - s) = P\ (t$::*real*)— TODO: why does just the equation not work?

and $P\ (t + s - s) = P\ t$— TODO: why does just the equation not work?
⟨*proof*⟩

lemma *existence-ivl-zero*: $x0 \in X \Longrightarrow 0 \in$ *existence-ivl0* $x0$ ⟨*proof*⟩

lemmas [*continuous-intros del*] = *continuous-on-f*
lemmas *continuous-on-f-comp*[*continuous-intros*] = *continuous-on-f*[*OF continuous-on-const - subset-UNIV*]

lemma
flow-in-compact-right-existence:
assumes $\bigwedge t.\ 0 \leq t \Longrightarrow t \in$ *existence-ivl0* $x \Longrightarrow$ *flow0* $x\ t \in K$
assumes *compact* $K\ K \subseteq X$
assumes $x \in X\ t \geq 0$
shows $t \in$ *existence-ivl0* x
⟨*proof*⟩

lemma
flow-in-compact-left-existence:
assumes $\bigwedge t.\ t \leq 0 \Longrightarrow t \in$ *existence-ivl0* $x \Longrightarrow$ *flow0* $x\ t \in K$
assumes *compact* $K\ K \subseteq X$
assumes $x \in X\ t \leq 0$
shows $t \in$ *existence-ivl0* x
⟨*proof*⟩

end

locale *compact-continuously-diff* =
derivative-on-prod $T\ X\ f\ \lambda(t, x).\ f'\ x\ o_L$ *snd-blinfun*
for $T\ X$ **and** f::*real* ⇒ ′*a*::{*banach*,*perfect-space*,*heine-borel*} ⇒ ′*a*
and f'::′*a* ⇒ (′*a*, ′*a*) *blinfun* +
assumes *compact-domain*: *compact* X
assumes *convex*: *convex* X
assumes *nonempty-domains*: $T \neq \{\}\ X \neq \{\}$
assumes *continuous-derivative*: *continuous-on* $X\ f'$
begin

lemma *ex-onorm-bound*:
$\exists B.\ \forall x \in X.$ *norm* $(f'\ x) \leq B$
⟨*proof*⟩

definition *onorm-bound* = (*SOME* $B.\ \forall x \in X.$ *norm* $(f'\ x) \leq B$)

lemma *onorm-bound*: **assumes** $x \in X$ **shows** *norm* $(f'\ x) \leq$ *onorm-bound*
⟨*proof*⟩

sublocale *closed-domain* X
⟨*proof*⟩

sublocale *global-lipschitz T X f onorm-bound*
⟨*proof*⟩

end — *compact X*

locale *unique-on-compact-continuously-diff* = *self-mapping* +
  compact-interval T +
  compact-continuously-diff T X f
begin

sublocale *unique-on-closed t0 T x0 f X onorm-bound*
  ⟨*proof*⟩

end

locale *c1-on-open* =
  fixes f::'a::{*banach*, *perfect-space*, *heine-borel*} ⇒ 'a **and** f' X
  assumes *open-dom*[*simp*]: *open X*
  assumes *derivative-rhs*:
    $\bigwedge x.\ x \in X \Longrightarrow$ (f *has-derivative blinfun-apply* (f' x)) (*at x*)
  assumes *continuous-derivative*: *continuous-on X* f'
begin

lemmas *continuous-derivative-comp*[*continuous-intros*] =
  continuous-on-compose2[*OF continuous-derivative*]

lemma *derivative-tendsto*[*tendsto-intros*]:
  assumes [*tendsto-intros*]: ($g \longrightarrow l$) F
    and $l \in X$
  shows (($\lambda x.\ f'$ (g x)) $\longrightarrow f'$ l) F
  ⟨*proof*⟩

lemma *c1-on-open-rev*[*intro*, *simp*]: *c1-on-open* $(-f)$ $(-f')$ X
  ⟨*proof*⟩

lemma *derivative-rhs-compose*[*derivative-intros*]:
  ((g *has-derivative* g') (*at x within s*)) $\Longrightarrow g\ x \in X \Longrightarrow$
    (($\lambda x.\ f$ (g x)) *has-derivative*
      ($\lambda xa.$ *blinfun-apply* (f' (g x)) (g' xa)))
    (*at x within s*)
  ⟨*proof*⟩

sublocale *auto-ll-on-open*
⟨*proof*⟩

end — $?x \in X \Longrightarrow$ (f *has-derivative blinfun-apply* (f' $?x$)) (*at* $?x$)

locale *c1-on-open-euclidean* = *c1-on-open f f' X*
  for f::'a::*euclidean-space* ⇒ - **and** f' X

begin
lemma *c1-on-open-euclidean-anchor*: *True* ⟨*proof*⟩

definition *vareq x0 t* = *f'* (*flow0 x0 t*)

interpretation *var*: *ll-on-open existence-ivl0 x0 vareq x0 UNIV*
⟨*proof*⟩

context begin

lemma *continuous-on-A*[*continuous-intros*]:
assumes *continuous-on S a*
assumes *continuous-on S b*
assumes $\bigwedge s.\ s \in S \Longrightarrow a\ s \in X$
assumes $\bigwedge s.\ s \in S \Longrightarrow b\ s \in$ *existence-ivl0* (*a s*)
shows *continuous-on S* (*λs. vareq* (*a s*) (*b s*))
⟨*proof*⟩

lemmas [*intro*] = *mem-existence-ivl-iv-defined*

context
fixes *x0*::*'a*
begin

lemma *flow0-defined*: *xa* ∈ *existence-ivl0 x0* ⟹ *flow0 x0 xa* ∈ *X*
⟨*proof*⟩

lemma *continuous-on-flow0*: *continuous-on* (*existence-ivl0 x0*) (*flow0 x0*)
⟨*proof*⟩

lemmas *continuous-on-flow0-comp*[*continuous-intros*] = *continuous-on-compose2*[*OF continuous-on-flow0*]

lemma *varexivl-eq-exivl*:
assumes *t* ∈ *existence-ivl0 x0*
shows *var.existence-ivl x0 t a* = *existence-ivl0 x0*
⟨*proof*⟩

definition *vector-Dflow u0 t* ≡ *var.flow x0 0 u0 t*

qualified abbreviation *Y z t* ≡ *flow0* (*x0* + *z*) *t*

Linearity of the solution to the variational equation. TODO: generalize this and some other things for arbitrary linear ODEs

lemma *vector-Dflow-linear*:
assumes *t* ∈ *existence-ivl0 x0*
shows *vector-Dflow* ($\alpha *_R a + \beta *_R b$) *t* = $\alpha *_R$ *vector-Dflow a t* + $\beta *_R$ *vector-Dflow b t*
⟨*proof*⟩

lemma *linear-vector-Dflow*:
assumes $t \in$ *existence-ivl0 x0*
shows *linear* (λz. *vector-Dflow z t*)
⟨*proof*⟩

lemma *bounded-linear-vector-Dflow*:
assumes $t \in$ *existence-ivl0 x0*
shows *bounded-linear* (λz. *vector-Dflow z t*)
⟨*proof*⟩

lemma *vector-Dflow-continuous-on-time*: *x0* $\in X \Longrightarrow$ *continuous-on* (*existence-ivl0 x0*) (λt. *vector-Dflow z t*)
⟨*proof*⟩

proposition *proposition-17-6-weak*:
— from "Differential Equations, Dynamical Systems, and an Introduction to Chaos", Hirsch/Smale/Devaney
assumes $t \in$ *existence-ivl0 x0*
shows (λy. (*Y* (*y* $-$ *x0*) *t* $-$ *flow0 x0 t* $-$ *vector-Dflow* (*y* $-$ *x0*) *t*) $/_R$ *norm* (*y* $-$ *x0*)) $-$ *x0* $\rightarrow$ *0*
⟨*proof*⟩

lemma *local-lipschitz-A*:
OT $\subseteq$ *existence-ivl0 x0* $\Longrightarrow$ *local-lipschitz OT* (*OS*::($'a \Rightarrow_L\ 'a$) *set*) (λt. (o_L) (*vareq x0 t*))
⟨*proof*⟩

lemma *total-derivative-ll-on-open*:
ll-on-open (*existence-ivl0 x0*) (λt. *blinfun-compose* (*vareq x0 t*)) (*UNIV*::($'a \Rightarrow_L\ 'a$) *set*)
⟨*proof*⟩

end

end

sublocale *mvar*: *ll-on-open existence-ivl0 x0* λt. *blinfun-compose* (*vareq x0 t*) *UNIV*::($'a \Rightarrow_L\ 'a$) *set* **for** *x0*
⟨*proof*⟩

lemma *mvar-existence-ivl-eq-existence-ivl*[*simp*]:— TODO: unify with *?t* $\in$ *existence-ivl0 ?x0.0* $\Longrightarrow$ *var.existence-ivl ?x0.0 ?t ?a* = *existence-ivl0 ?x0.0*
assumes $t \in$ *existence-ivl0 x0*
shows *mvar.existence-ivl x0 t* = (λ-. *existence-ivl0 x0*)
⟨*proof*⟩

lemma
assumes $t \in$ *existence-ivl0 x0*

shows *continuous-on* (*UNIV* × *existence-ivl0 x0*) (λ(*x*, *ta*). *mvar.flow x0 t x ta*)
⟨*proof*⟩

definition *Dflow x0* = *mvar.flow x0 0 id-blinfun*

lemma *var-eq-mvar*:
assumes *t0* ∈ *existence-ivl0 x0*
assumes *t* ∈ *existence-ivl0 x0*
shows *var.flow x0 t0 i t* = *mvar.flow x0 t0 id-blinfun t i*
⟨*proof*⟩

lemma *Dflow-zero*[*simp*]: *x* ∈ *X* ⟹ *Dflow x 0* = 1_L
⟨*proof*⟩

5.3 Differentiability of the flow0

U t, i.e. the solution of the variational equation, is the space derivative at the initial value *x0*.

lemma *flow-dx-derivative*:
assumes *t* ∈ *existence-ivl0 x0*
shows ((λ*x0*. *flow0 x0 t*) *has-derivative* (λ*z*. *vector-Dflow x0 z t*)) (*at x0*)
⟨*proof*⟩

lemma *flow-dx-derivative-blinfun*:
assumes *t* ∈ *existence-ivl0 x0*
shows ((λ*x*. *flow0 x t*) *has-derivative Blinfun* (λ*z*. *vector-Dflow x0 z t*)) (*at x0*)
⟨*proof*⟩

definition *flowderiv x0 t* = *comp12* (*Dflow x0 t*) (*blinfun-scaleR-left* (*f* (*flow0 x0 t*)))

lemma *flowderiv-eq*: *flowderiv x0 t* (ξ_1, ξ_2) = (*Dflow x0 t*) ξ_1 + ξ_2 $*_R$ *f* (*flow0 x0 t*)
⟨*proof*⟩

lemma *W-continuous-on*: *continuous-on* (*Sigma X existence-ivl0*) (λ(*x0*, *t*). *Dflow x0 t*)
— TODO: somewhere here is hidden continuity wrt rhs of ODE, extract it!
⟨*proof*⟩

lemma *W-continuous-on-comp*[*continuous-intros*]:
assumes *h*: *continuous-on S h* **and** *g*: *continuous-on S g*
shows ($\bigwedge$*s*. *s* ∈ *S* ⟹ *h s* ∈ *X*) ⟹ ($\bigwedge$*s*. *s* ∈ *S* ⟹ *g s* ∈ *existence-ivl0* (*h s*)) ⟹
continuous-on S (λ*s*. *Dflow* (*h s*) (*g s*))
⟨*proof*⟩

lemma *f-flow-continuous-on*: *continuous-on* (*Sigma X existence-ivl0*) (λ(*x0*, *t*). *f* (*flow0 x0 t*))

⟨*proof*⟩

lemma
flow-has-space-derivative:
assumes $t \in$ *existence-ivl0 x0*
shows ((λ*x0*. *flow0 x0 t*) *has-derivative Dflow x0 t*) (*at x0*)
⟨*proof*⟩

lemma
flow-has-flowderiv:
assumes $t \in$ *existence-ivl0 x0*
shows ((λ(*x0*, *t*). *flow0 x0 t*) *has-derivative flowderiv x0 t*) (*at* (*x0*, *t*) *within S*)
⟨*proof*⟩

lemma *flow0-comp-has-derivative*:
assumes *h*: *h s* ∈ *existence-ivl0* (*g s*)
assumes [*derivative-intros*]: (*g has-derivative g′*) (*at s within S*)
assumes [*derivative-intros*]: (*h has-derivative h′*) (*at s within S*)
shows ((λ*x*. *flow0* (*g x*) (*h x*)) *has-derivative* (λ*x*. *blinfun-apply* (*flowderiv* (*g s*) (*h s*)) (*g′ x*, *h′ x*)))
(*at s within S*)
⟨*proof*⟩

lemma *flowderiv-continuous-on*: *continuous-on* (*Sigma X existence-ivl0*) (λ(*x0*, *t*). *flowderiv x0 t*)
⟨*proof*⟩

lemma *flowderiv-continuous-on-comp*[*continuous-intros*]:
assumes *continuous-on S x*
assumes *continuous-on S t*
assumes $\bigwedge s.\ s \in S \Longrightarrow x\ s \in X$ $\bigwedge s.\ s \in S \Longrightarrow t\ s \in$ *existence-ivl0* (*x s*)
shows *continuous-on S* (λ*xa*. *flowderiv* (*x xa*) (*t xa*))
⟨*proof*⟩

lemmas [*intro*] = *flow-in-domain*

lemma *vareq-trans*: *t0* ∈ *existence-ivl0 x0* ⟹ *t* ∈ *existence-ivl0* (*flow0 x0 t0*) ⟹
vareq (*flow0 x0 t0*) *t* = *vareq x0* (*t0* + *t*)
⟨*proof*⟩

lemma *diff-existence-ivl-trans*:
t0 ∈ *existence-ivl0 x0* ⟹ *t* ∈ *existence-ivl0 x0* ⟹ *t* − *t0* ∈ *existence-ivl0* (*flow0 x0 t0*) **for** *t*
⟨*proof*⟩

lemma *has-vderiv-on-blinfun-compose-right*[*derivative-intros*]:
assumes (*g has-vderiv-on g′*) *T*
assumes $\bigwedge x.\ x \in T \Longrightarrow gd'\ x = g'\ x\ o_L\ d$
shows ((λ*x*. $g\ x\ o_L\ d$) *has-vderiv-on gd′*) *T*

⟨*proof*⟩

lemma *has-vderiv-on-blinfun-compose-left*[*derivative-intros*]:
assumes (g *has-vderiv-on* g') T
assumes $\bigwedge x.\ x \in T \Longrightarrow gd'\ x = d\ o_L\ g'\ x$
shows (($\lambda x.\ d\ o_L\ g\ x$) *has-vderiv-on* gd') T
⟨*proof*⟩

lemma *mvar-flow-shift*:
assumes $t0 \in$ *existence-ivl0* $x0$ $t1 \in$ *existence-ivl0* $x0$
shows *mvar.flow* $x0$ $t0$ d $t1$ = *Dflow* (*flow0* $x0$ $t0$) ($t1 - t0$) o_L d
⟨*proof*⟩

lemma *Dflow-trans*:
assumes $h \in$ *existence-ivl0* $x0$
assumes $i \in$ *existence-ivl0* (*flow0* $x0$ h)
shows *Dflow* $x0$ ($h + i$) = *Dflow* (*flow0* $x0$ h) i o_L (*Dflow* $x0$ h)
⟨*proof*⟩

lemma *Dflow-trans-apply*:
assumes $h \in$ *existence-ivl0* $x0$
assumes $i \in$ *existence-ivl0* (*flow0* $x0$ h)
shows *Dflow* $x0$ ($h + i$) $d0$ = *Dflow* (*flow0* $x0$ h) i (*Dflow* $x0$ h $d0$)
⟨*proof*⟩

end — *True*

end

6 Upper and Lower Solutions

theory *Upper-Lower-Solution*
imports *Flow*
begin

Following Walter [1] in section 9

lemma *IVT-min*:
fixes f :: *real* ⇒ *'b* :: {*linorder-topology*,*real-normed-vector*,*ordered-real-vector*}
— generalize?
assumes y: $f\ a \le y$ $y \le f\ b$ $a \le b$
assumes $*$: *continuous-on* $\{a\ ..\ b\}$ f
notes [*continuous-intros*] = $*$[*THEN continuous-on-subset*]
obtains x **where** $a \le x$ $x \le b$ $f\ x = y$ $\bigwedge x'.\ a \le x' \Longrightarrow x' < x \Longrightarrow f\ x' < y$
⟨*proof*⟩

lemma *filtermap-at-left-shift*: *filtermap* ($\lambda x.\ x - d$) (*at-left* a) = *at-left* ($a - d$::*real*)
⟨*proof*⟩

context
fixes $v\ v'\ w\ w'$::*real* $\Rightarrow$ *real* **and** *t0 t1 e*::*real*
assumes v': (v *has-vderiv-on* v') $\{t0 <..\ t1\}$
and w': (w *has-vderiv-on* w') $\{t0 <..\ t1\}$
assumes *pos-ivl*: $t0 < t1$
assumes *e-pos*: $e > 0$ **and** *e-in*: $t0 + e \leq t1$
assumes *less*: $\bigwedge t.\ t0 < t \Longrightarrow t < t0 + e \Longrightarrow v\ t < w\ t$
begin

lemma *first-intersection-crossing-derivatives*:
assumes *na*: $t0 < tg\ tg \leq t1\ v\ tg \geq w\ tg$
notes [*continuous-intros*] =
vderiv-on-continuous-on[*OF* v', *THEN continuous-on-subset*]
vderiv-on-continuous-on[*OF* w', *THEN continuous-on-subset*]
obtains *x0* **where**
$t0 < x0\ x0 \leq tg$
$v'\ x0 \geq w'\ x0$
$v\ x0 = w\ x0$
$\bigwedge t.\ t0 < t \Longrightarrow t < x0 \Longrightarrow v\ t < w\ t$
⟨*proof*⟩

lemma *defect-less*:
assumes *b*: $\bigwedge t.\ t0 < t \Longrightarrow t \leq t1 \Longrightarrow v'\ t - f\ t\ (v\ t) < w'\ t - f\ t\ (w\ t)$
notes [*continuous-intros*] =
vderiv-on-continuous-on[*OF* v', *THEN continuous-on-subset*]
vderiv-on-continuous-on[*OF* w', *THEN continuous-on-subset*]
shows $\forall\, t \in \{t0 <..\ t1\}.\ v\ t < w\ t$
⟨*proof*⟩

end

lemma *has-derivatives-less-lemma*:
fixes $v\ v'$ ::*real* $\Rightarrow$ *real*
assumes v': (v *has-vderiv-on* v') T
assumes y': (y *has-vderiv-on* y') T
assumes *lu*: $\bigwedge t.\ t \in T \Longrightarrow t > t0 \Longrightarrow v'\ t - f\ t\ (v\ t) < y'\ t - f\ t\ (y\ t)$
assumes *lower*: $v\ t0 \leq y\ t0$
assumes *eq-imp*: $v\ t0 = y\ t0 \Longrightarrow v'\ t0 < y'\ t0$
assumes *t*: $t0 < t\ t0 \in T\ t \in T$ *is-interval* T
shows $v\ t < y\ t$
⟨*proof*⟩

lemma *strict-lower-solution*:
fixes $v\ v'$ ::*real* $\Rightarrow$ *real*
assumes *sol*: (y *solves-ode* f) $T\ X$
assumes v': (v *has-vderiv-on* v') T
assumes *lower*: $\bigwedge t.\ t \in T \Longrightarrow t > t0 \Longrightarrow v'\ t < f\ t\ (v\ t)$
assumes *iv*: $v\ t0 \leq y\ t0\ v\ t0 = y\ t0 \Longrightarrow v'\ t0 < f\ t0\ (y\ t0)$

assumes *t*: $t0 < t$ $t0 \in T$ $t \in T$ *is-interval* T
shows $v\ t < y\ t$
⟨*proof*⟩

lemma *strict-upper-solution*:
fixes $w\ w'$::*real* ⇒ *real*
assumes *sol*: (y *solves-ode* f) T X
assumes w': (w *has-vderiv-on* w') T
and *upper*: $\bigwedge t.\ t \in T \Longrightarrow t > t0 \Longrightarrow f\ t\ (w\ t) < w'\ t$
and *iv*: $y\ t0 \leq w\ t0$ $y\ t0 = w\ t0 \Longrightarrow f\ t0\ (y\ t0) < w'\ t0$
assumes *t*: $t0 < t$ $t0 \in T$ $t \in T$ *is-interval* T
shows $y\ t < w\ t$
⟨*proof*⟩

lemma *uniform-limit-at-within-subset*:
assumes *uniform-limit* S x l (*at* t *within* T)
assumes $U \subseteq T$
shows *uniform-limit* S x l (*at* t *within* U)
⟨*proof*⟩

lemma *uniform-limit-le*:
fixes f::$'c \Rightarrow 'a \Rightarrow 'b$::{*metric-space*, *linorder-topology*}
assumes *I*: $I \neq bot$
assumes *u*: *uniform-limit* X f g I
assumes u': *uniform-limit* X f' g' I
assumes $\forall_F\ i$ *in* I. $\forall x \in X.\ f\ i\ x \leq f'\ i\ x$
assumes $x \in X$
shows $g\ x \leq g'\ x$
⟨*proof*⟩

lemma *uniform-limit-le-const*:
fixes f::$'c \Rightarrow 'a \Rightarrow 'b$::{*metric-space*, *linorder-topology*}
assumes *I*: $I \neq bot$
assumes *u*: *uniform-limit* X f g I
assumes $\forall_F\ i$ *in* I. $\forall x \in X.\ f\ i\ x \leq h\ x$
assumes $x \in X$
shows $g\ x \leq h\ x$
⟨*proof*⟩

lemma *uniform-limit-ge-const*:
fixes f::$'c \Rightarrow 'a \Rightarrow 'b$::{*metric-space*, *linorder-topology*}
assumes *I*: $I \neq bot$
assumes *u*: *uniform-limit* X f g I
assumes $\forall_F\ i$ *in* I. $\forall x \in X.\ h\ x \leq f\ i\ x$
assumes $x \in X$
shows $h\ x \leq g\ x$
⟨*proof*⟩

locale *ll-on-open-real* = *ll-on-open* T f X **for** T f **and** X::*real set*

begin

lemma *lower-solution*:
  fixes $v\ v'$ ::*real* $\Rightarrow$ *real*
  assumes *sol*: $(y$ *solves-ode* $f)\ S\ X$
  assumes v': $(v$ *has-vderiv-on* $v')\ S$
  assumes *lower*: $\bigwedge t.\ t \in S \Longrightarrow t > t0 \Longrightarrow v'\ t < f\ t\ (v\ t)$
  assumes *iv*: $v\ t0 \leq y\ t0$
  assumes *t*: $t0 \leq t\ t0 \in S\ t \in S$ *is-interval* $S\ S \subseteq T$
  shows $v\ t \leq y\ t$
⟨*proof*⟩

lemma *upper-solution*:
  fixes $v\ v'$ ::*real* $\Rightarrow$ *real*
  assumes *sol*: $(y$ *solves-ode* $f)\ S\ X$
  assumes v': $(v$ *has-vderiv-on* $v')\ S$
  assumes *upper*: $\bigwedge t.\ t \in S \Longrightarrow t > t0 \Longrightarrow f\ t\ (v\ t) < v'\ t$
  assumes *iv*: $y\ t0 \leq v\ t0$
  assumes *t*: $t0 \leq t\ t0 \in S\ t \in S$ *is-interval* $S\ S \subseteq T$
  shows $y\ t \leq v\ t$
⟨*proof*⟩

end

end
theory *Poincare-Map*
imports
  Flow
begin

abbreviation *plane* $n\ c \equiv \{x.\ x \cdot n = c\}$

lemma
  eventually-tendsto-compose-within:
  assumes *eventually* P (*at* l *within* S)
  assumes $P\ l$
  assumes $(f \longrightarrow l)$ (*at* x *within* T)
  assumes *eventually* $(\lambda x.\ f\ x \in S)$ (*at* x *within* T)
  shows *eventually* $(\lambda x.\ P\ (f\ x))$ (*at* x *within* T)
⟨*proof*⟩

lemma
  eventually-eventually-withinI:— aha...
  assumes $\forall_F\ x$ *in at* x *within* $A.\ P\ x\ P\ x$
  shows $\forall_F\ a$ *in at* x *within* $S.\ \forall_F\ x$ *in at* a *within* $A.\ P\ x$
  ⟨*proof*⟩

lemma *eventually-not-in-closed*:
  assumes *closed* P

assumes $f\ t \notin P\ t \in T$
assumes *continuous-on* $T\ f$
shows $\forall_F\ t$ *in at* t *within* $T.\ f\ t \notin P$
⟨*proof*⟩

context *ll-on-open-it* **begin**

lemma
existence-ivl-trans':
assumes $t + s \in$ *existence-ivl t0 x0*
$t \in$ *existence-ivl t0 x0*
shows $t + s \in$ *existence-ivl t* (*flow t0 x0 t*)
⟨*proof*⟩

end

context *auto-ll-on-open*— TODO: generalize to continuous systems
begin

definition *returns-to* ::'*a set* ⇒ '*a* ⇒ *bool*
where *returns-to P x* ⟷ ($\forall_F\ t$ *in at-right* 0. *flow0 x t* $\notin P$) ∧ (∃ $t>0$. $t \in$ *existence-ivl0 x* ∧ *flow0 x t* $\in P$)

definition *return-time* :: '*a set* ⇒ '*a* ⇒ *real*
where *return-time P x* =
(*if returns-to P x then* (*SOME t*.
$t > 0$ ∧
$t \in$ *existence-ivl0 x* ∧
flow0 x t $\in P$ ∧
(∀ $s \in \{0<..<t\}$. *flow0 x s* $\notin P$)) *else* 0)

lemma *returns-toI*:
assumes *t*: $t > 0$ $t \in$ *existence-ivl0 x flow0 x t* $\in P$
assumes *ev*: $\forall_F\ t$ *in at-right* 0. *flow0 x t* $\notin P$
assumes *closed P*
shows *returns-to P x*
⟨*proof*⟩

lemma *returns-to-outsideI*:
assumes *t*: $t \geq 0$ $t \in$ *existence-ivl0 x flow0 x t* $\in P$
assumes *ev*: $x \notin P$
assumes *closed P*
shows *returns-to P x*
⟨*proof*⟩

lemma *returns-toE*:
assumes *returns-to P x*
obtains *t0 t1* **where**
$0 < t0$

$t0 \le t1$
$t1 \in$ *existence-ivl0 x*
flow0 x t1 $\in P$
$\bigwedge t.\ 0 < t \Longrightarrow t < t0 \Longrightarrow$ *flow0 x t* $\notin P$
⟨*proof*⟩

lemma *return-time-some*:
assumes *returns-to P x*
shows *return-time P x* =
(*SOME t.* $t > 0 \wedge t \in$ *existence-ivl0 x* $\wedge$ *flow0 x t* $\in P \wedge (\forall s \in \{0<..<t\}.$ *flow0 x s* $\notin P$))
⟨*proof*⟩

lemma *return-time-ex1*:
assumes *returns-to P x*
assumes *closed P*
shows $\exists! t.\ t > 0 \wedge t \in$ *existence-ivl0 x* $\wedge$ *flow0 x t* $\in P \wedge (\forall s \in \{0<..<t\}.$ *flow0 x s* $\notin P$)
⟨*proof*⟩

lemma
return-time-pos-returns-to:
return-time P x $> 0 \Longrightarrow$ *returns-to P x*
⟨*proof*⟩

lemma
assumes *ret*: *returns-to P x*
assumes *closed P*
shows *return-time-pos*: *return-time P x* > 0
⟨*proof*⟩

lemma *returns-to-return-time-pos*:
assumes *closed P*
shows *returns-to P x* $\longleftrightarrow$ *return-time P x* > 0
⟨*proof*⟩

lemma *return-time*:
assumes *ret*: *returns-to P x*
assumes *closed P*
shows *return-time P x* > 0
and *return-time-exivl*: *return-time P x* $\in$ *existence-ivl0 x*
and *return-time-returns*: *flow0 x* (*return-time P x*) $\in P$
and *return-time-least*: $\bigwedge s.\ 0 < s \Longrightarrow s <$ *return-time P x* $\Longrightarrow$ *flow0 x s* $\notin P$
⟨*proof*⟩

lemma *returns-to-earlierI*:
assumes *ret*: *returns-to P* (*flow0 x t*) *closed P*
assumes $t \ge 0$ $t \in$ *existence-ivl0 x*
assumes *ev*: $\forall_F$ *t in at-right 0*. *flow0 x t* $\notin P$

shows *returns-to P x*
⟨*proof*⟩

lemma *return-time-gt*:
assumes *ret*: *returns-to P x closed P*
assumes *flow-not*: $\bigwedge s.\ 0 < s \Longrightarrow s \leq t \Longrightarrow flow0\ x\ s \notin P$
shows $t <$ *return-time P x*
⟨*proof*⟩

lemma *return-time-le*:
assumes *ret*: *returns-to P x closed P*
assumes *flow-not*: $flow0\ x\ t \in P\ t > 0$
shows *return-time P x* $\leq t$
⟨*proof*⟩

lemma *returns-to-laterI*:
assumes *ret*: *returns-to P x closed P*
assumes *t*: $t > 0\ t \in$ *existence-ivl0 x*
assumes *flow-not*: $\bigwedge s.\ 0 < s \Longrightarrow s \leq t \Longrightarrow flow0\ x\ s \notin P$
shows *returns-to P* (*flow0 x t*)
⟨*proof*⟩

lemma *never-returns*:
assumes ¬*returns-to P x*
assumes *closed P* $t \geq 0\ t \in$ *existence-ivl0 x*
assumes *ev*: $\forall_F$ *t in at-right 0*. $flow0\ x\ t \notin P$
shows ¬*returns-to P* (*flow0 x t*)
⟨*proof*⟩

lemma *return-time-eqI*:
assumes *closed P*
and *t-pos*: $t > 0$
and *ex*: $t \in$ *existence-ivl0 x*
and *ret*: $flow0\ x\ t \in P$
and *least*: $\bigwedge s.\ 0 < s \Longrightarrow s < t \Longrightarrow flow0\ x\ s \notin P$
shows *return-time P x* $= t$
⟨*proof*⟩

lemma *return-time-step*:
assumes *returns-to P* (*flow0 x t*)
assumes *closed P*
assumes *flow-not*: $\bigwedge s.\ 0 < s \Longrightarrow s \leq t \Longrightarrow flow0\ x\ s \notin P$
assumes *t*: $t > 0\ t \in$ *existence-ivl0 x*
shows *return-time P* (*flow0 x t*) = *return-time P x* $- t$
⟨*proof*⟩

definition *poincare-map P x* = *flow0 x* (*return-time P x*)

lemma *poincare-map-step-flow*:

assumes *ret*: *returns-to P x closed P*
assumes *flow-not*: $\bigwedge s.\ 0 < s \Longrightarrow s \leq t \Longrightarrow \mathit{flow0}\ x\ s \notin P$
assumes *t*: $t > 0\ t \in \mathit{existence\text{-}ivl0}\ x$
shows *poincare-map P* (*flow0 x t*) = *poincare-map P x*
⟨*proof*⟩

lemma *poincare-map-returns*:
assumes *returns-to P x closed P*
shows *poincare-map P x* $\in$ *P*
⟨*proof*⟩

lemma *poincare-map-onto*:
assumes *closed P*
assumes $0 < t\ t \in \mathit{existence\text{-}ivl0}\ x\ \forall_F\ t\ \mathit{in}\ \mathit{at\text{-}right}\ 0.\ \mathit{flow0}\ x\ t \notin P$
assumes *flow0 x t* $\in$ *P*
shows *poincare-map P x* $\in$ *flow0 x* ' $\{0 <..\ t\} \cap P$
⟨*proof*⟩

end

lemma *isCont-blinfunD*:
fixes f'::$'a$::*metric-space* $\Rightarrow$ $'b$::*real-normed-vector* $\Rightarrow_L$ $'c$::*real-normed-vector*
assumes *isCont* f' *a* $0 < e$
shows $\exists\, d>0.\ \forall x.\ \mathit{dist}\ a\ x < d \longrightarrow \mathit{onorm}\ (\lambda v.\ \mathit{blinfun\text{-}apply}\ (f'\ x)\ v - \mathit{blinfun\text{-}apply}\ (f'\ a)\ v) < e$
⟨*proof*⟩

proposition *has-derivative-locally-injective-blinfun*:
fixes *f* :: $'n$::*euclidean-space* $\Rightarrow$ $'m$::*euclidean-space*
and f'::$'n \Rightarrow 'n \Rightarrow_L 'm$
and g'::$'m \Rightarrow_L 'n$
assumes $a \in s$
and *open s*
and g': $g'\ o_L\ (f'\ a) = 1_L$
and f': $\bigwedge x.\ x \in s \Longrightarrow (f\ \mathit{has\text{-}derivative}\ f'\ x)\ (\mathit{at}\ x)$
and *c*: *isCont* f' *a*
obtains *r* **where** $r > 0$ *ball a r* $\subseteq$ *s inj-on f* (*ball a r*)
⟨*proof*⟩

lift-definition *embed1-blinfun*::$'a$::*real-normed-vector* $\Rightarrow_L$ ($'a*'b$::*real-normed-vector*)
is $\lambda x.\ (x,\ 0)$
⟨*proof*⟩
lemma *blinfun-apply-embed1-blinfun*[*simp*]: *blinfun-apply embed1-blinfun x* = $(x,\ 0)$
⟨*proof*⟩

lift-definition *embed2-blinfun*::$'a$::*real-normed-vector* $\Rightarrow_L$ ($'b$::*real-normed-vector*$*'a$)
is $\lambda x.\ (0,\ x)$

⟨*proof*⟩
lemma *blinfun-apply-embed2-blinfun*[*simp*]: *blinfun-apply embed2-blinfun x* = (*0*, *x*)
⟨*proof*⟩

lemma *blinfun-inverseD*: $f\ o_L\ f' = 1_L \Longrightarrow f\ (f'\ x) = x$
⟨*proof*⟩

lemmas *continuous-on-open-vimageI* = *continuous-on-open-vimage*[*THEN iffD1*, *rule-format*]
lemmas *continuous-on-closed-vimageI* = *continuous-on-closed-vimage*[*THEN iffD1*, *rule-format*]

lemma *ball-times-subset*: *ball a* (*c*/*2*) × *ball b* (*c*/*2*) ⊆ *ball* (*a*, *b*) *c*
⟨*proof*⟩

lemma *linear-inverse-blinop-lemma*:
fixes *w*::′*a*::{*banach*, *perfect-space*} *blinop*
assumes *norm w* < *1*
shows
$summable\ (\lambda n.\ (-1)\hat{\ }n *_R w\hat{\ }n)$ (**is** *?C*)
$(\sum n.\ (-1)\hat{\ }n *_R w\hat{\ }n) * (1 + w) = 1$ (**is** *?I1*)
$(1 + w) * (\sum n.\ (-1)\hat{\ }n *_R w\hat{\ }n) = 1$ (**is** *?I2*)
$norm\ ((\sum n.\ (-1)\hat{\ }n *_R w\hat{\ }n) - 1 + w) \le (norm\ w)^2/(1 - norm\ (w))$ (**is** *?L*)
⟨*proof*⟩

lemma *linear-inverse-blinfun-lemma*:
fixes $w::'a \Rightarrow_L 'a::\{banach, perfect\text{-}space\}$
assumes *norm w* < *1*
obtains *I* **where**
$I\ o_L\ (1_L + w) = 1_L\ (1_L + w)\ o_L\ I = 1_L$
$norm\ (I - 1_L + w) \le (norm\ w)^2/(1 - norm\ (w))$
⟨*proof*⟩

definition $invertibles\text{-}blinfun = \{w.\ \exists\, wi.\ w\ o_L\ wi = 1_L \wedge wi\ o_L\ w = 1_L\}$

lemma *blinfun-inverse-open*:— 8.3.2 in Dieudonne, TODO: add continuity and derivative
shows *open* (*invertibles-blinfun*::
$('a::\{banach, perfect\text{-}space\} \Rightarrow_L 'b::banach)\ set$)
⟨*proof*⟩

lemma *blinfun-compose-assoc*[*ac-simps*]: $a\ o_L\ b\ o_L\ c = a\ o_L\ (b\ o_L\ c)$
⟨*proof*⟩

TODO: move *norm* (− *?x*) = *norm ?x* to class!

lemma (**in** *real-normed-vector*) *norm-minus-cancel* [*simp*]: *norm* (− *x*) = *norm x*
⟨*proof*⟩

TODO: move *norm* (*?a* − *?b*) = *norm* (*?b* − *?a*) to class!

lemma (**in** *real-normed-vector*) *norm-minus-commute*: *norm* $(a - b)$ = *norm* $(b - a)$
⟨*proof*⟩

instance *euclidean-space* ⊆ *banach*
⟨*proof*⟩

lemma *blinfun-apply-Pair-split*:
blinfun-apply g (a, b) = *blinfun-apply* g $(a, 0)$ + *blinfun-apply* g $(0, b)$
⟨*proof*⟩

lemma *blinfun-apply-Pair-add2*: *blinfun-apply* f $(0, a + b)$ = *blinfun-apply* f $(0, a)$ + *blinfun-apply* f $(0, b)$
⟨*proof*⟩

lemma *blinfun-apply-Pair-add1*: *blinfun-apply* f $(a + b, 0)$ = *blinfun-apply* f $(a, 0)$ + *blinfun-apply* f $(b, 0)$
⟨*proof*⟩

lemma *blinfun-apply-Pair-minus2*: *blinfun-apply* f $(0, a - b)$ = *blinfun-apply* f $(0, a)$ − *blinfun-apply* f $(0, b)$
⟨*proof*⟩

lemma *blinfun-apply-Pair-minus1*: *blinfun-apply* f $(a - b, 0)$ = *blinfun-apply* f $(a, 0)$ − *blinfun-apply* f $(b, 0)$
⟨*proof*⟩

lemma *implicit-function-theorem*:
fixes *f*::'*a*::*euclidean-space* ∗ '*b*::*euclidean-space* ⇒ '*c*::*euclidean-space*— TODO: generalize?!
assumes [*derivative-intros*]: ⋀*x*. *x* ∈ *S* ⟹ (*f* *has-derivative* *blinfun-apply* (*f'* *x*)) (*at* *x*)
assumes *S*: $(x, y) \in S$ *open* *S*
assumes $DIM('c) \le DIM('b)$
assumes *f'C*: *isCont* *f'* (x, y)
assumes $f\ (x, y) = 0$
assumes *T2*: $T\ o_L\ (f'\ (x, y)\ o_L$ *embed2-blinfun*$) = 1_L$
assumes *T1*: $(f'\ (x, y)\ o_L$ *embed2-blinfun*$)\ o_L\ T = 1_L$— TODO: reduce?!
obtains *u e r*
where $f\ (x, u\ x) = 0$ $u\ x = y$
⋀*s*. *s* ∈ *cball* *x* *e* ⟹ $f\ (s, u\ s) = 0$
continuous-on (*cball* *x* *e*) *u*
(λ*t*. (*t*, *u* *t*)) ‘ *cball* *x* *e* ⊆ *S*
$e > 0$
(*u* *has-derivative* − $T\ o_L\ f'\ (x, y)\ o_L$ *embed1-blinfun*) (*at* *x*)

$r > 0$
⋀*U v s*. $v\ x = y$ ⟹ (⋀*s*. *s* ∈ *U* ⟹ $f\ (s, v\ s) = 0$) ⟹ *U* ⊆ *cball* *x* *e* ⟹
continuous-on *U* *v* ⟹ *s* ∈ *U* ⟹ $(s, v\ s) \in$ *ball* (x, y) *r* ⟹ $u\ s = v\ s$

⟨*proof*⟩

lemma *implicit-function-theorem-unique*:
fixes f::$'a$::*euclidean-space* $*$ $'b$::*euclidean-space* $\Rightarrow$ $'c$::*euclidean-space*— TODO: generalize?!
assumes f'[*derivative-intros*]: $\bigwedge x.\ x \in S \Longrightarrow$ (*f has-derivative blinfun-apply* $(f'\ x))$ (*at x*)
assumes *S*: $(x,\ y) \in S$ *open S*
assumes *D*: $DIM('c) \leq DIM('b)$
assumes $f'C$: *continuous-on S* f'
assumes *z*: $f\ (x,\ y) = 0$
assumes *T2*: $T\ o_L\ (f'\ (x,\ y)\ o_L\ embed2\text{-}blinfun) = 1_L$
assumes *T1*: $(f'\ (x,\ y)\ o_L\ embed2\text{-}blinfun)\ o_L\ T = 1_L$— TODO: reduce?!
obtains *u e*
where $f\ (x,\ u\ x) = 0\ u\ x = y$
$\bigwedge s.\ s \in cball\ x\ e \Longrightarrow f\ (s,\ u\ s) = 0$
continuous-on (*cball x e*) *u*
$(\lambda t.\ (t,\ u\ t))$ ‘ *cball x e* $\subseteq S$
$e > 0$
(*u has-derivative* $(-\ T\ o_L\ f'\ (x,\ y)\ o_L\ embed1\text{-}blinfun)$) (*at x*)
$\bigwedge s.\ s \in cball\ x\ e \Longrightarrow f'\ (s,\ u\ s)\ o_L\ embed2\text{-}blinfun \in invertibles\text{-}blinfun$
$\bigwedge U\ v\ s.\ (\bigwedge s.\ s \in U \Longrightarrow f\ (s,\ v\ s) = 0) \Longrightarrow$
$u\ x = v\ x \Longrightarrow$
continuous-on $U\ v \Longrightarrow s \in U \Longrightarrow x \in U \Longrightarrow U \subseteq cball\ x\ e \Longrightarrow$ *connected* U $\Longrightarrow$ *open* $U \Longrightarrow u\ s = v\ s$
⟨*proof*⟩

lemma *uniform-limit-compose*:
assumes *ul*: *uniform-limit T f l F*
assumes *uc*: *uniformly-continuous-on S s*
assumes *ev*: $\forall_F$ *x in F*. *f x* ‘ $T \subseteq S$
assumes *subs*: *l* ‘ $T \subseteq S$
shows *uniform-limit T* $(\lambda i\ x.\ s\ (f\ i\ x))$ $(\lambda x.\ s\ (l\ x))$ *F*
⟨*proof*⟩

lemma
uniform-limit-in-open:
fixes *l*::$'a$::*topological-space*$\Rightarrow$$'b$::*heine-borel*
assumes *ul*: *uniform-limit T f l* (*at x*)
assumes *cont*: *continuous-on T l*
assumes *compact*: *compact T* **and** *T-ne*: $T \neq \{\}$
assumes *B*: *open B*
assumes *mem*: *l* ‘ $T \subseteq B$
shows $\forall_F$ *y in at x*. $\forall\, t \in T.\ f\ y\ t \in B$
⟨*proof*⟩

lemma
order-uniform-limitD1:
fixes *l*::$'a$::*topological-space*$\Rightarrow$*real*— TODO: generalize?!

assumes *ul*: *uniform-limit* T *f l* (*at x*)
assumes *cont*: *continuous-on* T *l*
assumes *compact*: *compact* T
assumes *less*: $\bigwedge t.\ t \in T \Longrightarrow l\ t < b$
shows $\forall_F$ *y in at x*. $\forall\, t \in T.\ f\ y\ t < b$
⟨*proof*⟩

lemma
order-uniform-limitD2:
fixes *l*::′*a*::*topological-space*⇒*real*— TODO: generalize?!
assumes *ul*: *uniform-limit* T *f l* (*at x*)
assumes *cont*: *continuous-on* T *l*
assumes *compact*: *compact* T
assumes *less*: $\bigwedge t.\ t \in T \Longrightarrow l\ t > b$
shows $\forall_F$ *y in at x*. $\forall\, t \in T.\ f\ y\ t > b$
⟨*proof*⟩

lemma *continuous-on-avoid-cases*:
fixes *l*::′*b*::*topological-space* ⇒ ′*a*::*linear-continuum-topology*— TODO: generalize!
assumes *cont*: *continuous-on* T *l* **and** *conn*: *connected* T
assumes *avoid*: $\bigwedge t.\ t \in T \Longrightarrow l\ t \neq b$
obtains $\bigwedge t.\ t \in T \Longrightarrow l\ t < b$ | $\bigwedge t.\ t \in T \Longrightarrow l\ t > b$
⟨*proof*⟩

lemma
order-uniform-limit-ne:
fixes *l*::′*a*::*topological-space*⇒*real*— TODO: generalize?!
assumes *ul*: *uniform-limit* T *f l* (*at x*)
assumes *cont*: *continuous-on* T *l*
assumes *compact*: *compact* T **and** *conn*: *connected* T
assumes *ne*: $\bigwedge t.\ t \in T \Longrightarrow l\ t \neq b$
shows $\forall_F$ *y in at x*. $\forall\, t \in T.\ f\ y\ t \neq b$
⟨*proof*⟩

lemma *open-cballE*:
assumes *open S x*∈*S*
obtains *e* **where** *e*>*0 cball x e* ⊆ *S*
⟨*proof*⟩

lemma *pos-half-less*: **fixes** *x*::*real* **shows** $x > 0 \Longrightarrow x\ /\ 2 < x$
⟨*proof*⟩

lemma *closed-levelset*: *closed* {*x*. *s x* = (*c*::′*a*::*t1-space*)} **if** *continuous-on UNIV s*
⟨*proof*⟩

lemma *closed-levelset-within*: *closed* {*x* ∈ *S*. *s x* = (*c*::′*a*::*t1-space*)} **if** *continuous-on S s closed S*
⟨*proof*⟩

context *c1-on-open-euclidean*
begin

lemma *open-existence-ivlE*:
  assumes $t \in$ *existence-ivl0 x t* ≥ 0
  obtains *e* **where** $e > 0$ *cball x e* $\times$ $\{0 .. t + e\}$ $\subseteq$ *Sigma X existence-ivl0*
⟨*proof*⟩

lemmas [*derivative-intros*] = *flow0-comp-has-derivative*

lemma *flow-isCont-state-space-comp*[*continuous-intros*]:
  t x $\in$ *existence-ivl0* (*s x*) $\Longrightarrow$ *isCont s x* $\Longrightarrow$ *isCont t x* $\Longrightarrow$ *isCont* (λx. *flow0* (*s x*) (*t x*)) *x*
  ⟨*proof*⟩

lemma *closed-plane*[*simp*]: *closed* $\{x.\ x \cdot i = c\}$
  ⟨*proof*⟩

lemma *flow-tendsto-compose*[*tendsto-intros*]:
  assumes ($x \longrightarrow xs$) *F* ($t \longrightarrow ts$) *F*
  assumes $ts \in$ *existence-ivl0 xs*
  shows ((λs. *flow0* (*x s*) (*t s*)) $\longrightarrow$ *flow0 xs ts*) *F*
⟨*proof*⟩

lemma *returns-to-implicit-function*:
  fixes *s*::*'a*::*euclidean-space* $\Rightarrow$ *real*
  assumes *rt*: *returns-to* $\{x \in S.\ s\ x = 0\}$ *x* (**is** *returns-to ?P x*)
  assumes *cS*: *closed S*
  assumes *Ds*: $\bigwedge x$. (*s has-derivative blinfun-apply* (*Ds x*)) (*at x*)
  assumes *DsC*: *isCont Ds* (*poincare-map ?P x*)
  assumes *nz*: *Ds* (*poincare-map ?P x*) (*f* (*poincare-map ?P x*)) $\neq 0$
  obtains *u e*
  where *s* (*flow0 x* (*u x*)) = 0
      u x = *return-time ?P x*
      ($\bigwedge y$. $y \in$ *cball x e* $\Longrightarrow$ *s* (*flow0 y* (*u y*)) = 0)
      continuous-on (*cball x e*) *u*
      (λt. (*t*, *u t*)) ‘ *cball x e* $\subseteq$ *Sigma X existence-ivl0*
      $0 < e$ (*u has-derivative* ($-$ *blinfun-scaleR-left*
            (*inverse* (*blinfun-apply* (*Ds* (*poincare-map ?P x*)) (*f* (*poincare-map ?P x*)))) o_L
              (*Ds* (*poincare-map ?P x*) o_L *flowderiv x* (*return-time ?P x*)) o_L *embed1-blinfun*)) (*at x*)
⟨*proof*⟩

lemma (**in** *auto-ll-on-open*) *f-tendsto*[*tendsto-intros*]:
  assumes *g1*: ($g1 \longrightarrow b1$) (*at s within S*) **and** $b1 \in X$
  shows ((λx. *f* (*g1 x*)) $\longrightarrow$ *f b1*) (*at s within S*)
  ⟨*proof*⟩

lemma *flow-avoids-surface-eventually-at-right-pos*:
  assumes $s\ x > 0 \lor s\ x = 0 \land blinfun\text{-}apply\ (Ds\ x)\ (f\ x) > 0$
  assumes x: $x \in X$
  assumes Ds: $\bigwedge x.\ (s\ has\text{-}derivative\ Ds\ x)\ (at\ x)$
  assumes DsC: $\bigwedge x.\ isCont\ Ds\ x$
  shows $\forall_F\ t\ in\ at\text{-}right\ 0.\ s\ (flow0\ x\ t) > (0{::}real)$
⟨*proof*⟩

lemma *flow-avoids-surface-eventually-at-right-neg*:
  assumes $s\ x < 0 \lor s\ x = 0 \land blinfun\text{-}apply\ (Ds\ x)\ (f\ x) < 0$
  assumes x: $x \in X$
  assumes Ds: $\bigwedge x.\ (s\ has\text{-}derivative\ Ds\ x)\ (at\ x)$
  assumes DsC: $\bigwedge x.\ isCont\ Ds\ x$
  shows $\forall_F\ t\ in\ at\text{-}right\ 0.\ s\ (flow0\ x\ t) < (0{::}real)$
  ⟨*proof*⟩

lemma *flow-avoids-surface-eventually-at-right*:
  assumes $x \notin S \lor s\ x \neq 0 \lor blinfun\text{-}apply\ (Ds\ x)\ (f\ x) \neq 0$
  assumes x: $x \in X$ **and** cS: $closed\ S$
  assumes Ds: $\bigwedge x.\ (s\ has\text{-}derivative\ Ds\ x)\ (at\ x)$
  assumes DsC: $\bigwedge x.\ isCont\ Ds\ x$
  shows $\forall_F\ t\ in\ at\text{-}right\ 0.\ (flow0\ x\ t) \notin \{x \in S.\ s\ x = (0{::}real)\}$
⟨*proof*⟩

lemma *eventually-returns-to*:
  fixes $s{::}'a{::}euclidean\text{-}space \Rightarrow real$
  assumes rt: $returns\text{-}to\ \{x \in S.\ s\ x = 0\}\ x$ (**is** $returns\text{-}to\ ?P\ x$)
  assumes cS: $closed\ S$
  assumes Ds: $\bigwedge x.\ (s\ has\text{-}derivative\ blinfun\text{-}apply\ (Ds\ x))\ (at\ x)$
  assumes DsC: $\bigwedge x.\ isCont\ Ds\ x$
  assumes $eventually\text{-}inside$: $\forall_F\ x\ in\ at\ (poincare\text{-}map\ ?P\ x).\ s\ x = 0 \longrightarrow x \in S$
  assumes nz: $Ds\ (poincare\text{-}map\ ?P\ x)\ (f\ (poincare\text{-}map\ ?P\ x)) \neq 0$
  assumes $nz0$: $x \notin S \lor s\ x \neq 0 \lor Ds\ x\ (f\ x) \neq 0$
  shows $\forall_F\ x\ in\ at\ x.\ returns\text{-}to\ ?P\ x$
⟨*proof*⟩

lemma
  return-time-isCont-outside:
  fixes $s{::}'a{::}euclidean\text{-}space \Rightarrow real$
  assumes rt: $returns\text{-}to\ \{x \in S.\ s\ x = 0\}\ x$ (**is** $returns\text{-}to\ ?P\ x$)
  assumes cS: $closed\ S$
  assumes Ds: $\bigwedge x.\ (s\ has\text{-}derivative\ blinfun\text{-}apply\ (Ds\ x))\ (at\ x)$
  assumes DsC: $\bigwedge x.\ isCont\ Ds\ x$
  assumes $through$: $(Ds\ (poincare\text{-}map\ ?P\ x))\ (f\ (poincare\text{-}map\ ?P\ x)) \neq 0$
  assumes $eventually\text{-}inside$: $\forall_F\ x\ in\ at\ (poincare\text{-}map\ ?P\ x).\ s\ x = 0 \longrightarrow x \in S$
  assumes $outside$: $x \notin S \lor s\ x \neq 0$
  shows $isCont\ (return\text{-}time\ ?P)\ x$
  ⟨*proof*⟩

lemma *isCont-poincare-map*:
  assumes *isCont* (*return-time P*) *x*
    returns-to P x closed P
  shows *isCont* (*poincare-map P*) *x*
  ⟨*proof*⟩

lemma *poincare-map-tendsto*:
  assumes (*return-time P* $\longrightarrow$ *return-time P x*) (*at x within S*)
    returns-to P x closed P
  shows (*poincare-map P* $\longrightarrow$ *poincare-map P x*) (*at x within S*)
  ⟨*proof*⟩

lemma
  return-time-continuous-below:
  fixes $s::'a::euclidean\text{-}space \Rightarrow real$
  assumes *rt*: *returns-to* $\{x \in S.\ s\ x = 0\}$ *x* (**is** *returns-to ?P x*)
  assumes *Ds*: $\bigwedge x.$ (*s has-derivative blinfun-apply* (*Ds x*)) (*at x*)
  assumes *cS*: *closed S*
  assumes *eventually-inside*: $\forall_F$ *x in at* (*poincare-map ?P x*). $s\ x = 0 \longrightarrow x \in S$
  assumes *DsC*: $\bigwedge x.$ *isCont Ds x*
  assumes *through*: (*Ds* (*poincare-map ?P x*)) (*f* (*poincare-map ?P x*)) $\neq 0$
  assumes *inside*: $x \in S$ $s\ x = 0$ *Ds x* (*f x*) < 0
  shows *continuous* (*at x within* $\{x.\ s\ x \leq 0\}$) (*return-time ?P*)
  ⟨*proof*⟩

lemma
  return-time-continuous-below-plane:
  fixes $s::'a::euclidean\text{-}space \Rightarrow real$
  assumes *rt*: *returns-to* $\{x \in R.\ x \cdot n = c\}$ *x* (**is** *returns-to ?P x*)
  assumes *cR*: *closed R*
  assumes *through*: *f* (*poincare-map ?P x*) $\cdot\ n \neq 0$
  assumes *R*: $x \in R$
  assumes *inside*: $x \cdot n = c$ $f\ x \cdot n < 0$
  assumes *eventually-inside*: $\forall_F$ *x in at* (*poincare-map ?P x*). $x \cdot n = c \longrightarrow x \in$
R
  shows *continuous* (*at x within* $\{x.\ x \cdot n \leq c\}$) (*return-time ?P*)
  ⟨*proof*⟩

lemma
  poincare-map-in-interior-eventually-return-time-equal:
  assumes *RP*: $R \subseteq P$
  assumes *cP*: *closed P*
  assumes *cR*: *closed R*
  assumes *ret*: *returns-to P x*
  assumes *evret*: $\forall_F$ *x in at x within S. returns-to P x*
  assumes *evR*: $\forall_F$ *x in at x within S. poincare-map P x* $\in R$
  shows $\forall_F$ *x in at x within S. returns-to R x* $\wedge$ *return-time P x* $=$ *return-time R*
x
⟨*proof*⟩

lemma *poincare-map-in-planeI*:
  assumes *returns-to* (*plane n c*) *x0*
  shows *poincare-map* (*plane n c*) *x0* · *n* = *c*
  ⟨*proof*⟩

lemma *less-return-time-imp-exivl*:
  h ∈ *existence-ivl0 x′* **if** *h* ≤ *return-time P x′ returns-to P x′ closed P 0* ≤ *h*
⟨*proof*⟩

lemma *eventually-returns-to-continuousI*:
  assumes *returns-to P x*
  assumes *closed P*
  assumes *continuous* (*at x within S*) (*return-time P*)
  shows $\forall_F$ *x in at x within S*. *returns-to P x*
⟨*proof*⟩

lemma *return-time-implicit-functionE*:
  fixes *s*::′*a*::*euclidean-space* ⇒ *real*
  assumes *rt*: *returns-to* {*x* ∈ *S*. *s x* = *0*} *x* (**is** *returns-to ?P* -)
  assumes *cS*: *closed S*
  assumes *Ds*: ⋀*x*. (*s has-derivative blinfun-apply* (*Ds x*)) (*at x*)
  assumes *DsC*: ⋀*x*. *isCont Ds x*
  assumes *Ds-through*: (*Ds* (*poincare-map ?P x*)) (*f* (*poincare-map ?P x*)) ≠ *0*
  assumes *eventually-inside*: $\forall_F$ *x in at* (*poincare-map ?P x*). *s x* = *0* ⟶ *x* ∈ *S*
  assumes *outside*: *x* ∉ *S* ∨ *s x* ≠ *0*
  obtains *e′* **where**
    0 < *e′*
    ⋀*y*. *y* ∈ *ball x e′* ⟹ *returns-to ?P y*
    ⋀*y*. *y* ∈ *ball x e′* ⟹ *s* (*flow0 y* (*return-time ?P y*)) = *0*
    continuous-on (*ball x e′*) (*return-time ?P*)
    (⋀*y*. *y* ∈ *ball x e′* ⟹ *Ds* (*poincare-map ?P y*) o_L *flowderiv y* (*return-time ?P y*) o_L *embed2-blinfun* ∈ *invertibles-blinfun*)
    (⋀*U v sa*.
      (⋀*sa*. *sa* ∈ *U* ⟹ *s* (*flow0 sa* (*v sa*)) = *0*) ⟹
      return-time ?P x = *v x* ⟹
      continuous-on U v ⟹ *sa* ∈ *U* ⟹ *x* ∈ *U* ⟹ *U* ⊆ *ball x e′* ⟹ *connected U* ⟹ *open U* ⟹ *return-time ?P sa* = *v sa*)
    (*return-time ?P has-derivative*
        − *blinfun-scaleR-left* (*inverse* ((*Ds* (*poincare-map ?P x*)) (*f* (*poincare-map ?P x*)))) o_L
            (*Ds* (*poincare-map ?P x*) o_L *Dflow x* (*return-time ?P x*)))
          (*at x*)
⟨*proof*⟩

lemma *return-time-has-derivative*:
  fixes *s*::′*a*::*euclidean-space* ⇒ *real*
  assumes *rt*: *returns-to* {*x* ∈ *S*. *s x* = *0*} *x* (**is** *returns-to ?P* -)
  assumes *cS*: *closed S*

assumes *Ds*: $\bigwedge x$. (*s has-derivative blinfun-apply* (*Ds x*)) (*at x*)
assumes *DsC*: $\bigwedge x$. *isCont Ds x*
assumes *Ds-through*: (*Ds* (*poincare-map ?P x*)) (*f* (*poincare-map ?P x*)) $\neq$ *0*
assumes *eventually-inside*: $\forall_F$ *x in at* (*poincare-map* $\{x \in S.\ s\ x = 0\}$ *x*). $s\ x = 0 \longrightarrow x \in S$
assumes *outside*: $x \notin S \vee s\ x \neq 0$
shows (*return-time ?P has-derivative*
$-$ *blinfun-scaleR-left* (*inverse* ((*Ds* (*poincare-map ?P x*)) (*f* (*poincare-map ?P x*)))) o_L
(*Ds* (*poincare-map ?P x*) o_L *Dflow x* (*return-time ?P x*)))
(*at x*)
⟨*proof*⟩

lemma *return-time-plane-has-derivative-blinfun*:
assumes *rt*: *returns-to* $\{x \in S.\ x \cdot i = c\}$ *x* (**is** *returns-to ?P* -)
assumes *cS*: *closed S*
assumes *fnz*: *f* (*poincare-map ?P x*) $\cdot\ i \neq 0$
assumes *eventually-inside*: $\forall_F$ *x in at* (*poincare-map ?P x*). $x \cdot i = c \longrightarrow x \in S$
assumes *outside*: $x \notin S \vee x \cdot i \neq c$
shows (*return-time ?P has-derivative*
($-$ *blinfun-scaleR-left* (*inverse* ((*blinfun-inner-left i*) (*f* (*poincare-map ?P x*)))) o_L
(*blinfun-inner-left i* o_L *Dflow x* (*return-time ?P x*)))) (*at x*)
⟨*proof*⟩

lemma *return-time-plane-has-derivative*:
assumes *rt*: *returns-to* $\{x \in S.\ x \cdot i = c\}$ *x* (**is** *returns-to ?P* -)
assumes *cS*: *closed S*
assumes *fnz*: *f* (*poincare-map ?P x*) $\cdot\ i \neq 0$
assumes *eventually-inside*: $\forall_F$ *x in at* (*poincare-map ?P x*). $x \cdot i = c \longrightarrow x \in S$
assumes *outside*: $x \notin S \vee x \cdot i \neq c$
shows (*return-time ?P has-derivative*
(λh. $-$ (*Dflow x* (*return-time ?P x*)) $h \cdot i$ / (*f* (*poincare-map ?P x*) $\cdot\ i$))) (*at x*)
⟨*proof*⟩

definition *Dpoincare-map i c S x* =
(λh. (*Dflow x* (*return-time* $\{x \in S.\ x \cdot i = c\}$ *x*)) h $-$
((*Dflow x* (*return-time* $\{x \in S.\ x \cdot i = c\}$ *x*)) $h \cdot i$ /
(*f* (*poincare-map* $\{x \in S.\ x \cdot i = c\}$ *x*) $\cdot\ i$)) $*_R$ *f* (*poincare-map* $\{x \in S.\ x \cdot i = c\}$ *x*))

definition *Dpoincare-map' i c S x* =
Dflow x (*return-time* $\{x \in S.\ x \cdot i - c = 0\}$ *x*) $-$
(*blinfun-scaleR-left* (*f* (*poincare-map* $\{x \in S.\ x \cdot i = c\}$ *x*)) o_L
(*blinfun-scaleR-left* (*inverse* ((*f* (*poincare-map* $\{x \in S.\ x \cdot i = c\}$ *x*) $\cdot\ i$))) o_L
(*blinfun-inner-left i* o_L *Dflow x* (*return-time* $\{x \in S.\ x \cdot i - c = 0\}$ *x*))))

theorem *poincare-map-plane-has-derivative*:
assumes *rt*: *returns-to* $\{x \in S.\ x \cdot i = c\}$ *x* (**is** *returns-to ?P* -)

assumes *cS*: *closed S*
assumes *fnz*: *f* (*poincare-map ?P x*) $\cdot$ *i* $\neq$ *0*
assumes *eventually-inside*: $\forall_F$ *x in at* (*poincare-map ?P x*). *x* $\cdot$ *i* = *c* $\longrightarrow$ *x* $\in$ *S*
assumes *outside*: *x* $\notin$ *S* $\vee$ *x* $\cdot$ *i* $\neq$ *c*
notes [*derivative-intros*] = *return-time-plane-has-derivative*[*OF rt cS fnz eventually-inside outside*]
shows (*poincare-map ?P has-derivative Dpoincare-map′ i c S x*) (*at x*)
⟨*proof*⟩

end

end
theory *Reachability-Analysis*
imports
Flow
Poincare-Map
begin

lemma *not-mem-eq-mem-not*: *a* $\notin$ *A* $\longleftrightarrow$ *a* $\in$ $-$ *A*
⟨*proof*⟩

lemma *continuous-orderD*:
fixes *g*::′*b*::*t2-space* $\Rightarrow$ ′*c*::*order-topology*
assumes *continuous* (*at x within S*) *g*
shows *g x* > *c* $\Longrightarrow$ $\forall_F$ *y in at x within S*. *g y* > *c*
g x < *c* $\Longrightarrow$ $\forall_F$ *y in at x within S*. *g y* < *c*
⟨*proof*⟩

lemma *frontier-halfspace-component-ge*: *n* $\neq$ *0* $\Longrightarrow$ *frontier* {*x*. *c* $\leq$ *x* $\cdot$ *n*} = *plane n c*
⟨*proof*⟩

lemma *closed-Collect-le-within*:
fixes *f g* :: ′*a* :: *topological-space* $\Rightarrow$ ′*b*::*linorder-topology*
assumes *f*: *continuous-on UNIV f*
and *g*: *continuous-on UNIV g*
and *closed R*
shows *closed* {*x* $\in$ *R*. *f x* $\leq$ *g x*}
⟨*proof*⟩

6.1 explicit representation of hyperplanes / halfspaces

datatype ′*a sctn* = *Sctn* (*normal*: ′*a*) (*pstn*: *real*)

definition *le-halfspace sctn x* $\longleftrightarrow$ *x* $\cdot$ *normal sctn* $\leq$ *pstn sctn*

definition *lt-halfspace sctn x* $\longleftrightarrow$ *x* $\cdot$ *normal sctn* < *pstn sctn*

definition *ge-halfspace sctn x* $\longleftrightarrow$ *x* $\cdot$ *normal sctn* $\geq$ *pstn sctn*

definition *gt-halfspace sctn x* $\longleftrightarrow$ *x* $\cdot$ *normal sctn* $>$ *pstn sctn*

definition *plane-of sctn* $=$ $\{$*x. x* $\cdot$ *normal sctn* $=$ *pstn sctn*$\}$

definition *above-halfspace sctn* $=$ *Collect* (*ge-halfspace sctn*)

definition *below-halfspace sctn* $=$ *Collect* (*le-halfspace sctn*)

definition *sbelow-halfspace sctn* $=$ *Collect* (*lt-halfspace sctn*)

definition *sabove-halfspace sctn* $=$ *Collect* (*gt-halfspace sctn*)

6.2 explicit H representation of polytopes (mind *Polytopes.thy*)

definition *below-halfspaces*
where *below-halfspaces sctns* $=$ $\bigcap$(*below-halfspace* ‘ *sctns*)

definition *sbelow-halfspaces*
where *sbelow-halfspaces sctns* $=$ $\bigcap$(*sbelow-halfspace* ‘ *sctns*)

definition *above-halfspaces*
where *above-halfspaces sctns* $=$ $\bigcap$(*above-halfspace* ‘ *sctns*)

definition *sabove-halfspaces*
where *sabove-halfspaces sctns* $=$ $\bigcap$(*sabove-halfspace* ‘ *sctns*)

lemmas *halfspace-simps* $=$
above-halfspace-def
sabove-halfspace-def
below-halfspace-def
sbelow-halfspace-def
below-halfspaces-def
sbelow-halfspaces-def
above-halfspaces-def
sabove-halfspaces-def
ge-halfspace-def[*abs-def*]
gt-halfspace-def[*abs-def*]
le-halfspace-def[*abs-def*]
lt-halfspace-def[*abs-def*]

6.3 predicates for reachability analysis

context *c1-on-open-euclidean*
begin

definition *flowpipe* ::
$(('a::euclidean\text{-}space) \times ('a \Rightarrow_L 'a))$ *set* $\Rightarrow$ *real* $\Rightarrow$ *real* $\Rightarrow$
$('a \times ('a \Rightarrow_L 'a))$ *set* $\Rightarrow$ $('a \times ('a \Rightarrow_L 'a))$ *set* $\Rightarrow$ *bool*

where $\mathit{flowpipe}\ X0\ hl\ hu\ CX\ X1 \longleftrightarrow 0 \leq hl \wedge hl \leq hu \wedge \mathit{fst}\ \text{`}\ X0 \subseteq X \wedge \mathit{fst}\ \text{`}\ CX \subseteq X \wedge \mathit{fst}\ \text{`}\ X1 \subseteq X \wedge$
$(\forall (x0, d0) \in X0. \forall h \in \{hl .. hu\}.$
$h \in \mathit{existence\text{-}ivl0}\ x0 \wedge (\mathit{flow0}\ x0\ h, \mathit{Dflow}\ x0\ h\ o_L\ d0) \in X1 \wedge (\forall h' \in \{0 .. h\}. (\mathit{flow0}\ x0\ h', \mathit{Dflow}\ x0\ h'\ o_L\ d0) \in CX))$

lemma *flowpipeD*:
assumes $\mathit{flowpipe}\ X0\ hl\ hu\ CX\ X1$
shows *flowpipe-safeD*: $\mathit{fst}\ \text{`}\ X0 \cup \mathit{fst}\ \text{`}\ CX \cup \mathit{fst}\ \text{`}\ X1 \subseteq X$
and *flowpipe-nonneg*: $0 \leq hl\ hl \leq hu$
and *flowpipe-exivl*: $hl \leq h \Longrightarrow h \leq hu \Longrightarrow (x0, d0) \in X0 \Longrightarrow h \in \mathit{existence\text{-}ivl0}\ x0$
and *flowpipe-discrete*: $hl \leq h \Longrightarrow h \leq hu \Longrightarrow (x0, d0) \in X0 \Longrightarrow (\mathit{flow0}\ x0\ h, \mathit{Dflow}\ x0\ h\ o_L\ d0) \in X1$
and *flowpipe-cont*: $hl \leq h \Longrightarrow h \leq hu \Longrightarrow (x0, d0) \in X0 \Longrightarrow 0 \leq h' \Longrightarrow h' \leq h \Longrightarrow (\mathit{flow0}\ x0\ h', \mathit{Dflow}\ x0\ h'\ o_L\ d0) \in CX$
⟨*proof*⟩

lemma *flowpipe-source-subset*: $\mathit{flowpipe}\ X0\ hl\ hu\ CX\ X1 \Longrightarrow X0 \subseteq CX$
⟨*proof*⟩

definition $\mathit{flowsto}\ X0\ T\ CX\ X1 \longleftrightarrow$
$(\forall (x0, d0) \in X0. \exists h \in T. h \in \mathit{existence\text{-}ivl0}\ x0 \wedge (\mathit{flow0}\ x0\ h, \mathit{Dflow}\ x0\ h\ o_L\ d0) \in X1 \wedge (\forall h' \in \mathit{open\text{-}segment}\ 0\ h. (\mathit{flow0}\ x0\ h', \mathit{Dflow}\ x0\ h'\ o_L\ d0) \in CX))$

lemma *flowsto-to-empty-iff* [*simp*]: $\mathit{flowsto}\ a\ t\ b\ \{\} \longleftrightarrow a = \{\}$
⟨*proof*⟩

lemma *flowsto-from-empty-iff* [*simp*]: $\mathit{flowsto}\ \{\}\ t\ b\ c$
⟨*proof*⟩

lemma *flowsto-empty-time-iff* [*simp*]: $\mathit{flowsto}\ a\ \{\}\ b\ c \longleftrightarrow a = \{\}$
⟨*proof*⟩

lemma *flowstoE*:
assumes $\mathit{flowsto}\ X0\ T\ CX\ X1\ (x0, d0) \in X0$
obtains h **where** $h \in T\ h \in \mathit{existence\text{-}ivl0}\ x0\ (\mathit{flow0}\ x0\ h, \mathit{Dflow}\ x0\ h\ o_L\ d0) \in X1$
$\bigwedge h'. h' \in \mathit{open\text{-}segment}\ 0\ h \Longrightarrow (\mathit{flow0}\ x0\ h', \mathit{Dflow}\ x0\ h'\ o_L\ d0) \in CX$
⟨*proof*⟩

lemma *flowsto-safeD*: $\mathit{flowsto}\ X0\ T\ CX\ X1 \Longrightarrow \mathit{fst}\ \text{`}\ X0 \subseteq X$
⟨*proof*⟩

lemma *flowsto-union*:
assumes *1*: $\mathit{flowsto}\ X0\ T\ CX\ Y$ **and** *2*: $\mathit{flowsto}\ Z\ S\ CZ\ W$
shows $\mathit{flowsto}\ (X0 \cup Z)\ (T \cup S)\ (CX \cup CZ)\ (Y \cup W)$
⟨*proof*⟩

lemma *flowsto-subset*:
  assumes *flowsto X0 T CX Y*
  assumes $Z \subseteq X0$ $T \subseteq S$ $CX \subseteq CZ$ $Y \subseteq W$
  shows *flowsto Z S CZ W*
  ⟨*proof*⟩

lemmas *flowsto-unionI* = *flowsto-subset*[*OF flowsto-union*]

lemma *flowsto-unionE*:
  assumes *flowsto X0 T CX* $(Y \cup Z)$
  obtains *X1 X2* **where** $X0 = X1 \cup X2$ *flowsto X1 T CX Y flowsto X2 T CX Z*
⟨*proof*⟩

lemma *flowsto-trans*:
  assumes *A*: *flowsto A S B C* **and** *C*: *flowsto C T D E*
  shows *flowsto A* $\{s + t \mid s\ t.\ s \in S \wedge t \in T\}$ $(B \cup D \cup C)$ *E*
  ⟨*proof*⟩

lemma *flowsto-step*:
  assumes *A*: *flowsto A S B C*
  assumes *D*: *flowsto D T E F*
  shows *flowsto A* $(S \cup \{s + t \mid s\ t.\ s \in S \wedge t \in T\})$ $(B \cup E \cup C \cap D)$ $(C - D$
$\cup$ $F)$
⟨*proof*⟩

lemma
  flowsto-stepI:
    flowsto X0 U B C $\Longrightarrow$
    flowsto D T E F $\Longrightarrow$
    $Z \subseteq X0 \Longrightarrow$
    $(\bigwedge s.\ s \in U \Longrightarrow s \in S) \Longrightarrow$
    $(\bigwedge s\ t.\ s \in U \Longrightarrow t \in T \Longrightarrow s + t \in S) \Longrightarrow$
    $B \cup E \cup D \cap C \subseteq CZ \Longrightarrow C - D \cup F \subseteq W \Longrightarrow$ *flowsto Z S CZ W*
  ⟨*proof*⟩

lemma *flowsto-imp-flowsto*:
  flowpipe Y h h CY Z $\Longrightarrow$ *flowsto Y* $\{h\}$ (CY) *Z*
  ⟨*proof*⟩

lemma *connected-below-halfspace*:
  assumes $x \in$ *below-halfspace sctn*
  assumes $x \in S$ *connected S*
  assumes $S \cap$ *plane-of sctn* $= \{\}$
  shows $S \subseteq$ *below-halfspace sctn*
⟨*proof*⟩

lemma
  inter-Collect-eq-empty:
  assumes $\bigwedge x.\ x \in X0 \Longrightarrow \neg\ g\ x$ **shows** $X0 \cap$ *Collect g* $= \{\}$

⟨*proof*⟩

6.4 Poincare Map

lemma *closed-plane-of*[*simp*]: *closed* (*plane-of sctn*)
⟨*proof*⟩

definition *poincare-mapsto P X0 S CX Y* ⟷ (∀ (*x*, *d*) ∈ *X0*.
returns-to P x ∧ *fst* ' *X0* ⊆ *S* ∧
(*return-time P differentiable at x within S*) ∧
(∃ *D*. (*poincare-map P has-derivative blinfun-apply D*) (*at x within S*) ∧
(*poincare-map P x*, *D* o_L *d*) ∈ *Y*) ∧
(∀ *t*∈{*0*<..<*return-time P x*}. *flow0 x t* ∈ *CX*))

lemma *poincare-mapsto-empty*[*simp*]:
poincare-mapsto P {} *S CX Y*
⟨*proof*⟩

lemma *flowsto-eventually-mem-cont*:
assumes *flowsto X0 T CX Y* (*x*, *d*) ∈ *X0 T* ⊆ {*0*<..}
shows $\forall_F$ *t in at-right 0*. (*flow0 x t*, *Dflow x t* o_L *d*) ∈ *CX*
⟨*proof*⟩

lemma *frontier-aux-lemma*:
fixes *R* :: '*n*::*euclidean-space set*
assumes *closed R R* ⊆ {*x*. *x* · *n* = *c*} **and** [*simp*]: *n* ≠ *0*
shows *frontier* {*x* ∈ *R*. *c* ≤ *x* · *n*} = {*x* ∈ *R*. *c* = *x* · *n*}
⟨*proof*⟩

lemma *blinfun-minus-comp-distrib*: (*a* − *b*) o_L *c* = (*a* o_L *c*) − (*b* o_L *c*)
⟨*proof*⟩

lemma *flowpipe-split-at-above-halfspace*:
assumes *flowpipe X0 hl t CX Y fst* ' *X0* ∩ {*x*. *x* · *n* ≥ *c*} = {} **and** [*simp*]: *n* ≠ *0*
assumes *cR*: *closed R* **and** *Rs*: *R* ⊆ *plane n c*
assumes *PDP*: ⋀*x d*. (*x*, *d*) ∈ *CX* ⟹ *x* · *n* = *c* ⟹ (*x*,
d − (*blinfun-scaleR-left* (*f* (*x*)) o_L (*blinfun-scaleR-left* (*inverse* (*f x* · *n*)) o_L (*blinfun-inner-left n* o_L *d*)))) ∈ *PDP*
assumes *PDP-nz*: ⋀*x d*. (*x*, *d*) ∈ *PDP* ⟹ *f x* · *n* ≠ *0*
assumes *PDP-inR*: ⋀*x d*. (*x*, *d*) ∈ *PDP* ⟹ *x* ∈ *R*
assumes *PDP-in*: ⋀*x d*. (*x*, *d*) ∈ *PDP* ⟹ $\forall_F$ *x in at x within plane n c*. *x* ∈ *R*
obtains *X1 X2* **where** *X0* = *X1* ∪ *X2*
flowsto X1 {*0*<..*t*} (*CX* ∩ {*x*. *x* · *n* < *c*} × *UNIV*) (*CX* ∩ {*x* ∈ *R*. *x* · *n* = *c*} × *UNIV*)
flowsto X2 {*hl* .. *t*} (*CX* ∩ {*x*. *x* · *n* < *c*} × *UNIV*) (*Y* ∩ ({*x*. *x* · *n* < *c*} × *UNIV*))
poincare-mapsto {*x* ∈ *R*. *x* · *n* = *c*} *X1 UNIV* (*fst* ' *CX* ∩ {*x*. *x* · *n* < *c*}) *PDP*

⟨*proof*⟩

lemma *poincare-map-has-derivative-step*:
assumes *Deriv*: (*poincare-map P has-derivative blinfun-apply D*) (*at* (*flow0 x0 h*))
assumes *ret*: *returns-to P x0*
assumes *cont*: *continuous* (*at x0 within S*) (*return-time P*)
assumes *less*: $0 \leq h$ $h <$ *return-time P x0*
assumes *cP*: *closed P* **and** *x0*: $x0 \in S$
shows (($\lambda x.$ *poincare-map P x*) *has-derivative* ($D\ o_L$ *Dflow x0 h*)) (*at x0 within S*)
⟨*proof*⟩

lemma *poincare-mapsto-trans*:
assumes *poincare-mapsto p1 X0 S CX P1*
assumes *poincare-mapsto p2 P1 UNIV CY P2*
assumes $CX \cup CY \cup$ *fst* ‘ $P1 \subseteq CZ$
assumes $p2 \cap (CX \cup$ *fst* ‘ $P1) = \{\}$
assumes [*intro*, *simp*]: *closed p1*
assumes [*intro*, *simp*]: *closed p2*
assumes *cont*: $\bigwedge x\ d.\ (x, d) \in X0 \Longrightarrow$ *continuous* (*at x within S*) (*return-time p2*)
shows *poincare-mapsto p2 X0 S CZ P2*
⟨*proof*⟩

lemma *flowsto-poincare-trans*:— TODO: the proof is close to ⟦*poincare-mapsto ?p1.0 ?X0.0 ?S ?CX ?P1.0*; *poincare-mapsto ?p2.0 ?P1.0 UNIV ?CY ?P2.0*; $?CX \cup ?CY \cup$ *fst* ‘ $?P1.0 \subseteq ?CZ$; $?p2.0 \cap (?CX \cup$ *fst* ‘ $?P1.0) = \{\}$; *closed ?p1.0*; *closed ?p2.0*; $\bigwedge x\ d.\ (x, d) \in ?X0.0 \Longrightarrow$ *continuous* (*at x within ?S*) (*return-time ?p2.0*)⟧ $\Longrightarrow$ *poincare-mapsto ?p2.0 ?X0.0 ?S ?CZ ?P2.0*
assumes *f*: *flowsto X0 T CX P1*
assumes *poincare-mapsto p2 P1 UNIV CY P2*
assumes *nn*: $\bigwedge t.\ t \in T \Longrightarrow t \geq 0$
assumes *fst* ‘ $CX \cup CY \cup$ *fst* ‘ $P1 \subseteq CZ$
assumes $p2 \cap$ (*fst* ‘ $CX \cup$ *fst* ‘ $P1) = \{\}$
assumes [*intro*, *simp*]: *closed p2*
assumes *cont*: $\bigwedge x\ d.\ (x, d) \in X0 \Longrightarrow$ *continuous* (*at x within S*) (*return-time p2*)
assumes *subset*: *fst* ‘ $X0 \subseteq S$
shows *poincare-mapsto p2 X0 S CZ P2*
⟨*proof*⟩

6.5 conditions for continuous return time

definition *section s Ds S* $\longleftrightarrow$
($\forall x.$ (*s has-derivative blinfun-apply* (*Ds x*)) (*at x*)) $\wedge$
($\forall x.$ *isCont Ds x*) $\wedge$
($\forall x \in S.\ s\ x = (0{::}real) \longrightarrow Ds\ x\ (f\ x) \neq 0$) $\wedge$
closed S $\wedge$ $S \subseteq X$

lemma *sectionD*:
  assumes *section s Ds S*
  shows (*s has-derivative blinfun-apply* (*Ds x*)) (*at x*)
    isCont Ds x
    $x \in S \Longrightarrow s\ x = 0 \Longrightarrow Ds\ x\ (f\ x) \neq 0$
    closed S $S \subseteq X$
  ⟨*proof*⟩

definition *transversal p* $\longleftrightarrow$ ($\forall x \in p.\ \forall_F\ t$ *in at-right 0. flow0 x t* $\notin p$)

lemma *transversalD*: *transversal p* $\Longrightarrow x \in p \Longrightarrow \forall_F\ t$ *in at-right 0. flow0 x t* $\notin$ *p*
  ⟨*proof*⟩

lemma *transversal-section*:
  fixes *c*::*real*
  assumes *section s Ds S*
  shows *transversal* $\{x \in S.\ s\ x = 0\}$
  ⟨*proof*⟩

lemma *section-closed*[*intro*, *simp*]: *section s Ds S* $\Longrightarrow$ *closed* $\{x \in S.\ s\ x = 0\}$
  ⟨*proof*⟩

lemma *return-time-continuous-belowI*:
  assumes *ft*: *flowsto X0 T CX X1*
  assumes *pos*: $\bigwedge t.\ t \in T \Longrightarrow t > 0$
  assumes *X0*: *fst* ‘ *X0* $\subseteq \{x \in S.\ s\ x = 0\}$
  assumes *CX*: *fst* ‘ *CX* $\cap \{x \in S.\ s\ x = 0\} = \{\}$
  assumes *X1*: *fst* ‘ *X1* $\subseteq \{x \in S.\ s\ x = 0\}$
  assumes *sec*: *section s Ds S*
  assumes *nz*: $\bigwedge x.\ x \in S \Longrightarrow s\ x = 0 \Longrightarrow Ds\ x\ (f\ x) \neq 0$
  assumes *Dneg*: ($\lambda x.$ (*Ds x*) (*f x*)) ‘ *fst* ‘ *X0* $\subseteq \{..<0\}$
  assumes *rel-int*: $\bigwedge x.\ x \in$ *fst* ‘ *X1* $\Longrightarrow \forall_F\ x$ *in at x.* $s\ x = 0 \longrightarrow x \in S$
  assumes $(x, d) \in X0$
  shows *continuous* (*at x within* $\{x.\ s\ x \leq 0\}$) (*return-time* $\{x \in S.\ s\ x = 0\}$)
⟨*proof*⟩

end

end
theory *Flow-Congs*
  imports *Reachability-Analysis*
begin

lemma *lipschitz-on-congI*:
  assumes L'*−lipschitz-on* $s'\ g'$
  assumes $s' = s$

assumes $L' \leq L$
assumes $\bigwedge x\ y.\ x \in s \Longrightarrow g'\ x = g\ x$
shows L*−lipschitz-on s g*
⟨*proof*⟩

lemma *local-lipschitz-congI*:
assumes *local-lipschitz* $s'\ t'\ g'$
assumes $s' = s$
assumes $t' = t$
assumes $\bigwedge x\ y.\ x \in s \Longrightarrow y \in t \Longrightarrow g'\ x\ y = g\ x\ y$
shows *local-lipschitz s t g*
⟨*proof*⟩

context *ll-on-open-it*— TODO: do this more generically for *ll-on-open-it*
begin

context fixes *S Y g* **assumes** *cong*: $X = Y\ T = S\ \bigwedge x\ t.\ x \in Y \Longrightarrow t \in S \Longrightarrow f\ t\ x = g\ t\ x$
begin

lemma *ll-on-open-congI*: *ll-on-open S g Y*
⟨*proof*⟩

lemma *existence-ivl-subsetI*:
assumes *t*: $t \in$ *existence-ivl t0 x0*
shows $t \in$ *ll-on-open.existence-ivl S g Y t0 x0*
⟨*proof*⟩

lemma *existence-ivl-cong*:
shows *existence-ivl t0 x0* = *ll-on-open.existence-ivl S g Y t0 x0*
⟨*proof*⟩

lemma *flow-cong*:
assumes $t \in$ *existence-ivl t0 x0*
shows *flow t0 x0 t* = *ll-on-open.flow S g Y t0 x0 t*
⟨*proof*⟩

end

end

context *auto-ll-on-open* **begin**

context fixes *Y g* **assumes** *cong*: $X = Y\ \bigwedge x\ t.\ x \in Y \Longrightarrow f\ x = g\ x$
begin

lemma *auto-ll-on-open-congI*: *auto-ll-on-open g Y*
⟨*proof*⟩

lemma *existence-ivl0-cong*:
  shows *existence-ivl0 x0* = *auto-ll-on-open.existence-ivl0 g Y x0*
⟨*proof*⟩

lemma *flow0-cong*:
  assumes $t \in$ *existence-ivl0 x0*
  shows *flow0 x0 t* = *auto-ll-on-open.flow0 g Y x0 t*
⟨*proof*⟩

end

end

context *c1-on-open-euclidean* **begin**

context fixes *Y g* **assumes** *cong*: $X = Y$ $\bigwedge x\ t.\ x \in Y \Longrightarrow f\ x = g\ x$
begin

lemma *f′-cong*: (*g has-derivative blinfun-apply* $(f'\ x)$) (*at* x) **if** $x \in Y$
⟨*proof*⟩

lemma *c1-on-open-euclidean-congI*: *c1-on-open-euclidean g f′ Y*
⟨*proof*⟩

lemma *vareq-cong*: *vareq x0 t* = *c1-on-open-euclidean.vareq g f′ Y x0 t*
  if $t \in$ *existence-ivl0 x0*
⟨*proof*⟩

lemma *Dflow-cong*:
  assumes $t \in$ *existence-ivl0 x0*
  shows *Dflow x0 t* = *c1-on-open-euclidean.Dflow g f′ Y x0 t*
⟨*proof*⟩

lemma *flowsto-congI1*:
  assumes *flowsto A B C D*
  shows *c1-on-open-euclidean.flowsto g f′ Y A B C D*
⟨*proof*⟩

lemma *flowsto-congI2*:
  assumes *c1-on-open-euclidean.flowsto g f′ Y A B C D*
  shows *flowsto A B C D*
⟨*proof*⟩

lemma *flowsto-congI*: *flowsto A B C D* = *c1-on-open-euclidean.flowsto g f′ Y A B C D*
  ⟨*proof*⟩

lemma

returns-to-congI1:
assumes *returns-to A x*
shows *auto-ll-on-open.returns-to g Y A x*
⟨*proof*⟩

lemma
returns-to-congI2:
assumes *auto-ll-on-open.returns-to g Y x A*
shows *returns-to x A*
⟨*proof*⟩

lemma *returns-to-cong*: *auto-ll-on-open.returns-to g Y A x* = *returns-to A x*
⟨*proof*⟩

lemma
return-time-cong:
shows *return-time A x* = *auto-ll-on-open.return-time g Y A x*
⟨*proof*⟩

lemma *poincare-mapsto-congI1*:
assumes *poincare-mapsto A B C D E closed A*
shows *c1-on-open-euclidean.poincare-mapsto g Y A B C D E*
⟨*proof*⟩

lemma *poincare-mapsto-congI2*:
assumes *c1-on-open-euclidean.poincare-mapsto g Y A B C D E closed A*
shows *poincare-mapsto A B C D E*
⟨*proof*⟩

lemma *poincare-mapsto-cong*: *closed A* $\Longrightarrow$
poincare-mapsto A B C D E = *c1-on-open-euclidean.poincare-mapsto g Y A B C D E*
⟨*proof*⟩

end

end

end
theory *Cones*
imports
HOL−Analysis.Analysis
Triangle.Triangle
../ODE-Auxiliarities
begin

lemma *arcsin-eq-zero-iff*[*simp*]: $-1 \le x \Longrightarrow x \le 1 \Longrightarrow arcsin\ x = 0 \longleftrightarrow x = 0$
⟨*proof*⟩

definition *conemem* :: $'a$::*real-vector* $\Rightarrow$ $'a$ $\Rightarrow$ *real* $\Rightarrow$ $'a$ **where** *conemem u v t* = *cos t* $*_R$ *u* + *sin t* $*_R$ *v*
definition *conesegment u v* = *conemem u v* ` {*0*.. *pi* / *2*}

lemma
bounded-linear-image-conemem:
assumes *bounded-linear F*
shows *F* (*conemem u v t*) = *conemem* (*F u*) (*F v*) *t*
⟨*proof*⟩

lemma
bounded-linear-image-conesegment:
assumes *bounded-linear F*
shows *F* ` *conesegment u v* = *conesegment* (*F u*) (*F v*)
⟨*proof*⟩

lemma *discriminant*: $a * x^2 + b * x + c = (0::real) \Longrightarrow 0 \leq b^2 - 4 * a * c$
⟨*proof*⟩

lemma *quadratic-eq-factoring*:
assumes *D*: $D = b^2 - 4 * a * c$
assumes *nn*: $0 \leq D$
assumes *x1*: $x_1 = (-b + sqrt\ D) / (2 * a)$
assumes *x2*: $x_2 = (-b - sqrt\ D) / (2 * a)$
assumes *a*: $a \neq 0$
shows $a * x^2 + b * x + c = a * (x - x_1) * (x - x_2)$
⟨*proof*⟩

lemma *quadratic-eq-zeroes-iff*:
assumes *D*: $D = b^2 - 4 * a * c$
assumes *x1*: $x_1 = (-b + sqrt\ D) / (2 * a)$
assumes *x2*: $x_2 = (-b - sqrt\ D) / (2 * a)$
assumes *a*: $a \neq 0$
shows $a * x^2 + b * x + c = 0 \longleftrightarrow (D \geq 0 \wedge (x = x_1 \vee x = x_2))$ (**is** *?z* $\longleftrightarrow$ -)
⟨*proof*⟩

lemma *quadratic-ex-zero-iff*:
$(\exists x.\ a * x^2 + b * x + c = 0) \longleftrightarrow (a \neq 0 \wedge b^2 - 4 * a * c \geq 0 \vee a = 0 \wedge (b = 0 \longrightarrow c = 0))$
for *a b c*::*real*
⟨*proof*⟩

lemma *Cauchy-Schwarz-eq-iff*:
shows $(inner\ x\ y)^2 = inner\ x\ x * inner\ y\ y \longleftrightarrow ((\exists k.\ x = k *_R y) \vee y = 0)$
⟨*proof*⟩

lemma *Cauchy-Schwarz-strict-ineq*:

$(inner\ x\ y)^2 < inner\ x\ x * inner\ y\ y$ **if** $y \neq 0$ $\bigwedge k.\ x \neq k *_R y$
⟨proof⟩

lemma *Cauchy-Schwarz-eq2-iff*:
$|inner\ x\ y| = norm\ x * norm\ y \longleftrightarrow ((\exists k.\ x = k *_R y) \vee y = 0)$
⟨proof⟩

lemma *Cauchy-Schwarz-strict-ineq2*:
$|inner\ x\ y| < norm\ x * norm\ y$ **if** $y \neq 0$ $\bigwedge k.\ x \neq k *_R y$
⟨proof⟩

lemma *gt-minus-one-absI*: $abs\ k < 1 \Longrightarrow -1 < k$ **for** k::*real*
⟨proof⟩
lemma *gt-one-absI*: $abs\ k < 1 \Longrightarrow k < 1$ **for** k::*real*
⟨proof⟩

lemma *abs-impossible*:
$|y1| < x1 \Longrightarrow |y2| < x2 \Longrightarrow x1 * x2 + y1 * y2 \neq 0$ **for** *x1 x2*::*real*
⟨proof⟩

lemma *vangle-eq-arctan-minus*:— TODO: generalize?!
assumes *ij*: $i \in Basis$ $j \in Basis$ **and** *ij-neq*: $i \neq j$
assumes *xy1*: $|y1| < x1$
assumes *xy2*: $|y2| < x2$
assumes *less*: $y2 / x2 > y1 / x1$
shows $vangle\ (x1 *_R i + y1 *_R j)\ (x2 *_R i + y2 *_R j) = arctan\ (y2 / x2) - arctan\ (y1 / x1)$
(**is** *vangle ?u ?v = -*)
⟨proof⟩

lemma *vangle-le-pi2*: $0 \leq u \cdot v \Longrightarrow vangle\ u\ v \leq pi/2$
⟨proof⟩

lemma *inner-eq-vangle*: $u \cdot v = cos\ (vangle\ u\ v) * (norm\ u * norm\ v)$
⟨proof⟩

lemma *vangle-scaleR-self*:
$vangle\ (k *_R v)\ v = (if\ k = 0 \vee v = 0\ then\ pi / 2\ else\ if\ k > 0\ then\ 0\ else\ pi)$
$vangle\ v\ (k *_R v) = (if\ k = 0 \vee v = 0\ then\ pi / 2\ else\ if\ k > 0\ then\ 0\ else\ pi)$
⟨proof⟩

lemma *vangle-scaleR*:
$vangle\ (k *_R v)\ w = vangle\ v\ w$ $vangle\ w\ (k *_R v) = vangle\ w\ v$ **if** $k > 0$
⟨proof⟩

lemma *cos-vangle-eq-zero-iff-vangle*:
$cos\ (vangle\ u\ v) = 0 \longleftrightarrow (u = 0 \vee v = 0 \vee u \cdot v = 0)$
⟨proof⟩

lemma *ortho-imp-angle-pi-half*: $u \cdot v = 0 \Longrightarrow vangle\ u\ v = pi\ /\ 2$
⟨*proof*⟩

lemma *arccos-eq-zero-iff*: $arccos\ x = 0 \longleftrightarrow x = 1$ **if** $-1 \le x\ x \le 1$
⟨*proof*⟩

lemma *vangle-eq-zeroD*: $vangle\ u\ v = 0 \Longrightarrow (\exists\, k.\ v = k *_R u)$
⟨*proof*⟩

lemma *less-one-multI*:— TODO: also in AA!
fixes $e\ x::real$
shows $e \le 1 \Longrightarrow 0 < x \Longrightarrow x < 1 \Longrightarrow e * x < 1$
⟨*proof*⟩

lemma *conemem-expansion-estimate*:
fixes $u\ v\ u'\ v'::'a::euclidean\text{-}space$
assumes $t \in \{0\ ..\ pi\ /\ 2\}$
assumes *angle-pos*: $0 < vangle\ u\ v\ vangle\ u\ v < pi\ /\ 2$
assumes *angle-le*: $(vangle\ u'\ v') \le (vangle\ u\ v)$
assumes $norm\ u = 1\ norm\ v = 1$
shows $norm\ (conemem\ u'\ v'\ t) \ge min\ (norm\ u')\ (norm\ v') * norm\ (conemem\ u\ v\ t)$
⟨*proof*⟩

lemma *conemem-commute*: $conemem\ a\ b\ t = conemem\ b\ a\ (pi\ /\ 2 - t)$ **if** $0 \le t\ t \le pi\ /\ 2$
⟨*proof*⟩

lemma *conesegment-commute*: $conesegment\ a\ b = conesegment\ b\ a$
⟨*proof*⟩

definition $conefield\ u\ v = cone\ hull\ (conesegment\ u\ v)$

lemma *conefield-alt-def*: $conefield\ u\ v = cone\ hull\ \{u{-}{-}v\}$
⟨*proof*⟩

lemma
bounded-linear-image-cone-hull:
assumes *bounded-linear F*
shows $F\ `\ (cone\ hull\ T) = cone\ hull\ (F\ `\ T)$
⟨*proof*⟩

lemma
bounded-linear-image-conefield:
assumes *bounded-linear F*
shows $F\ `\ conefield\ u\ v = conefield\ (F\ u)\ (F\ v)$
⟨*proof*⟩

lemma *conefield-commute*: *conefield x y* = *conefield y x*
⟨*proof*⟩

lemma *convex-conefield*: *convex* (*conefield x y*)
⟨*proof*⟩

lemma *conefield-scaleRI*: $v \in$ *conefield* $(r *_R x)$ *y* **if** $v \in$ *conefield x y* $r > 0$
⟨*proof*⟩

lemma *conefield-scaleRD*: $v \in$ *conefield x y* **if** $v \in$ *conefield* $(r *_R x)$ *y* $r > 0$
⟨*proof*⟩

lemma *conefield-scaleR*: *conefield* $(r *_R x)$ y = *conefield x y* **if** $r > 0$
⟨*proof*⟩

lemma *conefield-expansion-estimate*:
fixes *u v*::*'a*::*euclidean-space* **and** *F*::*'a* ⇒ *'a*
assumes $t \in \{0 .. pi / 2\}$
assumes *angle-pos*: $0 <$ *vangle u v vangle u v* $< pi / 2$
assumes *angle-le*: *vangle* (*F u*) (*F v*) ≤ *vangle u v*
assumes *bounded-linear F*
assumes $x \in$ *conefield u v*
shows *norm* (*F x*) ≥ *min* (*norm* (*F u*)/*norm u*) (*norm* (*F v*)/*norm v*) ∗ *norm x*
⟨*proof*⟩

lemma *conefield-rightI*:
assumes *ij*: $i \in$ *Basis* $j \in$ *Basis* **and** *ij-neq*: $i \neq j$
assumes $y \in \{y1 .. y2\}$
shows $(i + y *_R j) \in$ *conefield* $(i + y1 *_R j)$ $(i + y2 *_R j)$
⟨*proof*⟩

lemma *conefield-right-vangleI*:
assumes *ij*: $i \in$ *Basis* $j \in$ *Basis* **and** *ij-neq*: $i \neq j$
assumes $y \in \{y1 .. y2\}$ $y1 < y2$
shows $(i + y *_R j) \in$ *conefield* $(i + y1 *_R j)$ $(i + y2 *_R j)$
⟨*proof*⟩

lemma *cone-conefield*[*intro*, *simp*]: *cone* (*conefield x y*)
⟨*proof*⟩

lemma *conefield-mk-rightI*:
assumes *ij*: $i \in$ *Basis* $j \in$ *Basis* **and** *ij-neq*: $i \neq j$
assumes $(i + (y / x) *_R j) \in$ *conefield* $(i + (y1 / x1) *_R j)$ $(i + (y2 / x2) *_R j)$
assumes $x > 0$ $x1 > 0$ $x2 > 0$
shows $(x *_R i + y *_R j) \in$ *conefield* $(x1 *_R i + y1 *_R j)$ $(x2 *_R i + y2 *_R j)$
⟨*proof*⟩

lemma *conefield-prod3I*:
assumes $x > 0$ $x1 > 0$ $x2 > 0$
assumes $y1$ / $x1 \le y$ / x y / $x \le y2$ / $x2$
shows $(x, y, 0) \in (conefield\ (x1, y1, 0)\ (x2, y2, 0)::(real*real*real)\ set)$
⟨*proof*⟩

end

7 Linear ODE

theory *Linear-ODE*
imports
../IVP/Flow
Bounded-Linear-Operator
Multivariate-Taylor
begin

lemma
exp-scaleR-has-derivative-right[*derivative-intros*]:
fixes $f::real \Rightarrow real$
assumes $(f\ has\text{-}derivative\ f')\ (at\ x\ within\ s)$
shows $((\lambda x.\ exp\ (f\ x *_R A))\ has\text{-}derivative\ (\lambda h.\ f'\ h *_R (exp\ (f\ x *_R A) * A)))$ $(at\ x\ within\ s)$
⟨*proof*⟩

context
fixes $A::'a::\{banach,perfect\text{-}space\}\ blinop$
begin

definition $linode\text{-}solution\ t0\ x0 = (\lambda t.\ exp\ ((t - t0) *_R A)\ x0)$

lemma *linode-solution-solves-ode*:
$(linode\text{-}solution\ t0\ x0\ solves\text{-}ode\ (\lambda\text{-}.\ A))\ UNIV\ UNIV\ linode\text{-}solution\ t0\ x0\ t0 = x0$
⟨*proof*⟩

lemma $(linode\text{-}solution\ t0\ x0\ usolves\text{-}ode\ (\lambda\text{-}.\ A)\ from\ t0)\ UNIV\ UNIV$
⟨*proof*⟩

end

end
theory *ODE-Analysis*
imports
Library/MVT-Ex
IVP/Flow
IVP/Upper-Lower-Solution
IVP/Reachability-Analysis
IVP/Flow-Congs

IVP/Cones
Library/Linear-ODE
begin

end

References

[1] W. Walter. *Ordinary Differential Equations*. Springer, 1 edition, 1998.