CPSVerification

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Contents

theory *hs-prelims*
imports *Ordinary-Differential-Equations.Picard-Lindeloef-Qualitative*

begin

Chapter 1

Hybrid Systems Preliminaries

This chapter contains preliminary lemmas for verification of Hybrid Systems.

1.1 Miscellaneous

1.1.1 Functions

lemma *case-of-fst*[*simp*]: $(\lambda x.\ case\ x\ of\ (t, x) \Rightarrow f\ t) = (\lambda\ x.\ (f \circ fst)\ x)$
  by *auto*

lemma *case-of-snd*[*simp*]: $(\lambda x.\ case\ x\ of\ (t, x) \Rightarrow f\ x) = (\lambda\ x.\ (f \circ snd)\ x)$
  by *auto*

1.1.2 Limits

lemma *cSup-eq-linorder*:
  fixes $c::'a::conditionally\text{-}complete\text{-}linorder$
  assumes $X \neq \{\}$ **and** $\forall\, x \in X.\ x \leq c$
    and *bdd-above* X **and** $\forall\, y{<}c.\ \exists\, x{\in}X.\ y < x$
  shows $Sup\ X = c$
  apply(*rule order-antisym*)
  using *assms* **apply**(*simp add*: *cSup-least*)
  using *assms* **by**(*subst le-cSup-iff*)

lemma *cSup-eq*:
  fixes $c::'a::conditionally\text{-}complete\text{-}lattice$
  assumes $\forall\, x \in X.\ x \leq c$ **and** $\exists\, x \in X.\ c \leq x$
  shows $Sup\ X = c$
  apply(*rule order-antisym*)
   apply(*rule cSup-least*)
  using *assms* **apply**(*blast*, *blast*)
  using *assms*(*2*) **apply** *safe*

```
  apply(subgoal-tac x ≤ Sup X, simp)
  by (metis assms(1) cSup-eq-maximum eq-iff)

lemma bdd-above-ltimes:
  fixes c::'a::linordered-ring-strict
  assumes c ≥ 0 and bdd-above X
  shows bdd-above {c ∗ x |x. x ∈ X}
  using assms unfolding bdd-above-def apply clarsimp
  apply(rule-tac x=c ∗ M in exI, clarsimp)
  using mult-left-mono by blast

lemma finite-nat-minimal-witness:
  fixes P :: ('a::finite) ⇒ nat ⇒ bool
  assumes ∀ i. ∃ N::nat. ∀ n ≥ N. P i n
  shows ∃ N. ∀ i. ∀ n ≥ N. P i n
proof−
  let ?bound i = (LEAST N. ∀ n ≥ N. P i n)
  let ?N = Max {?bound i |i. i ∈ UNIV}
  {fix n::nat and i::'a
    obtain M where ∀ n ≥ M. P i n
      using assms by blast
    hence obs: ∀ m ≥ ?bound i. P i m
      using LeastI[of λN. ∀ n ≥ N. P i n] by blast
    assume n ≥ ?N
    have finite {?bound i |i. i ∈ UNIV}
      using finite-Atleast-Atmost-nat by fastforce
    hence ?N ≥ ?bound i
      using Max-ge by blast
    hence n ≥ ?bound i
      using ‹n ≥ ?N› by linarith
    hence P i n
      using obs by blast}
  thus ∃ N. ∀ i n. N ≤ n ⟶ P i n
    by blast
qed

lemma suminf-eq-sum:
  fixes f :: nat ⇒ ('a::real-normed-vector)
  assumes ⋀n. n > m ⟹ f n = 0
  shows (∑ n. f n) = (∑ n ≤ m. f n)
  using assms by (meson atMost-iff finite-atMost not-le suminf-finite)
```

1.1.3 Real numbers

```
lemma sqrt-le-itself: 1 ≤ x ⟹ sqrt x ≤ x
 by (metis basic-trans-rules(23) monoid-mult-class.power2-eq-square more-arith-simps(6)

    mult-left-mono real-sqrt-le-iff' zero-le-one)
```

lemma *sqrt-real-nat-le*:*sqrt* (*real n*) $\leq$ *real n*
by (*metis* (*full-types*) *abs-of-nat le-square of-nat-mono of-nat-mult real-sqrt-abs2 real-sqrt-le-iff*)

lemma *sq-le-cancel*:
shows (*a*::*real*) $\geq$ *0* $\Longrightarrow$ *b* $\geq$ *0* $\Longrightarrow$ *a*ˆ*2* $\leq$ *b* $*$ *a* $\Longrightarrow$ *a* $\leq$ *b*
and (*a*::*real*) $\geq$ *0* $\Longrightarrow$ *b* $\geq$ *0* $\Longrightarrow$ *a*ˆ*2* $\leq$ *a* $*$ *b* $\Longrightarrow$ *a* $\leq$ *b*
apply(*metis less-eq-real-def mult.commute mult-le-cancel-left semiring-normalization-rules*(*29*))
by(*metis less-eq-real-def mult-le-cancel-left semiring-normalization-rules*(*29*))

lemma *abs-le-eq*:
shows (*r*::*real*) $>$ *0* $\Longrightarrow$ ($|x|$ $<$ *r*) = ($-r$ $<$ *x* $\wedge$ *x* $<$ *r*)
and (*r*::*real*) $>$ *0* $\Longrightarrow$ ($|x|$ $\leq$ *r*) = ($-r$ $\leq$ *x* $\wedge$ *x* $\leq$ *r*)
by *linarith linarith*

lemma *real-ivl-eqs*:
assumes *0* $<$ *r*
shows *ball x r* = {*x*−*r*<−−< *x*+*r*} **and** {*x*−*r*<−−< *x*+*r*} = {*x*−*r*<..< *x*+*r*}
and *ball* (*r* / *2*) (*r* / *2*) = {*0*<−−<*r*} **and** {*0*<−−<*r*} = {*0*<..<*r*}
and *ball 0 r* = {−*r*<−−<*r*} **and** {−*r*<−−<*r*} = {−*r*<..<*r*}
and *cball x r* = {*x*−*r*−−*x*+*r*} **and** {*x*−*r*−−*x*+*r*} = {*x*−*r*..*x*+*r*}
and *cball* (*r* / *2*) (*r* / *2*) = {*0*−−*r*} **and** {*0*−−*r*} = {*0*..*r*}
and *cball 0 r* = {−*r*−−*r*} **and** {−*r*−−*r*} = {−*r*..*r*}
unfolding *open-segment-eq-real-ivl closed-segment-eq-real-ivl*
using *assms* **apply**(*auto simp*: *cball-def ball-def dist-norm*)
by(*simp-all add*: *field-simps*)

named-theorems *trig-simps simplification rules for trigonometric identities*

lemmas *trig-identities* = *sin-squared-eq*[*THEN sym*] *cos-squared-eq*[*symmetric*] *cos-diff*[*symmetric*] *cos-double*

declare *sin-minus* [*trig-simps*]
and *cos-minus* [*trig-simps*]
and *trig-identities*(*1*,*2*) [*trig-simps*]
and *sin-cos-squared-add* [*trig-simps*]
and *sin-cos-squared-add2* [*trig-simps*]
and *sin-cos-squared-add3* [*trig-simps*]
and *trig-identities*(*3*) [*trig-simps*]

lemma *sin-cos-squared-add4* [*trig-simps*]:
fixes *x* :: *'a*:: {*banach*,*real-normed-field*}
shows $x * (sin\ t)^2 + x * (cos\ t)^2 = x$
by (*metis mult.right-neutral semiring-normalization-rules*(*34*) *sin-cos-squared-add*)

lemma [*trig-simps*, *simp*]:
fixes *x* :: *'a*:: {*banach*,*real-normed-field*}
shows $(x * cos\ t - y * sin\ t)^2 + (x * sin\ t + y * cos\ t)^2 = x^2 + y^2$

proof−
have $(x * cos\ t - y * sin\ t)^2 = x^2 * (cos\ t)^2 + y^2 * (sin\ t)^2 - 2 * (x * cos\ t) * (y * sin\ t)$
by(*simp add*: *power2-diff power-mult-distrib*)
also have $(x * sin\ t + y * cos\ t)^2 = y^2 * (cos\ t)^2 + x^2 * (sin\ t)^2 + 2 * (x * cos\ t) * (y * sin\ t)$
by(*simp add*: *power2-sum power-mult-distrib*)
ultimately show $(x * cos\ t - y * sin\ t)^2 + (x * sin\ t + y * cos\ t)^2 = x^2 + y^2$

by (*simp add*: *Groups.mult-ac*(*2*) *Groups.mult-ac*(*3*) *right-diff-distrib sin-squared-eq*)

qed

lemma [*trig-simps*, *simp*]:
fixes *x* :: *'a*:: {*banach*,*real-normed-field*}
shows $(x * cos\ t + y * sin\ t)^2 + (y * cos\ t - x * sin\ t)^2 = x^2 + y^2$
using *trig-simps*(*10*)[*of y t x*] **by** (*simp add*: *add.commute*)

thm *trig-simps*

1.2 Analisys

1.2.1 Single variable derivatives

notation *has-derivative* ((*1*(*D* - ↦ (-))/ -) [*65*,*65*] *61*)
notation *has-vderiv-on* ((*1 D* - = (-)/ *on* -) [*65*,*65*] *61*)
notation *norm* ((*1*‖-‖) [*65*] *61*)

lemma *exp-scaleR-has-derivative-right*[*derivative-intros*]:
fixes *f*::*real* ⇒ *real*
assumes $D\ f \mapsto f'$ *at x within s* **and** $(\lambda h.\ f'\ h *_R (exp\ (f\ x *_R A) * A)) = g'$
shows $D\ (\lambda x.\ exp\ (f\ x *_R A)) \mapsto g'$ *at x within s*
proof −
from *assms* **have** *bounded-linear* f' **by** *auto*
with *real-bounded-linear* **obtain** *m* **where** f': $f' = (\lambda h.\ h * m)$ **by** *blast*
show *?thesis*
using *vector-diff-chain-within*[*OF - exp-scaleR-has-vector-derivative-right*, *of f m x s A*]
assms f' **by** (*auto simp*: *has-vector-derivative-def o-def*)
qed

named-theorems *poly-derivatives compilation of optimised miscellaneous derivative rules.*

declare *has-vderiv-on-const* [*poly-derivatives*]
and *has-vderiv-on-id* [*poly-derivatives*]
and *derivative-intros*(*191*) [*poly-derivatives*]
and *derivative-intros*(*192*) [*poly-derivatives*]

and *derivative-intros*(*194*) [*poly-derivatives*]

lemma *has-vderiv-on-compose-eq*:
assumes $D\ f = f'\ on\ g\ `\ T$
and $D\ g = g'\ on\ T$
and $h = (\lambda x.\ g'\ x *_R f'\ (g\ x))$
shows $D\ (\lambda t.\ f\ (g\ t)) = h\ on\ T$
apply(*subst ssubst*[*of h*], *simp*)
using *assms has-vderiv-on-compose* **by** *auto*

lemma *vderiv-on-compose-add* [*derivative-intros*]:
assumes $D\ x = x'\ on\ (\lambda\tau.\ \tau + t)\ `\ T$
shows $D\ (\lambda\tau.\ x\ (\tau + t)) = (\lambda\tau.\ x'\ (\tau + t))\ on\ T$
apply(*rule has-vderiv-on-compose-eq*[*OF assms*])
by(*auto intro*: *derivative-intros*)

lemma *has-vector-derivative-mult-const* [*derivative-intros*]:
$((*)\ a\ has\text{-}vector\text{-}derivative\ a)\ F$
by (*auto intro*: *derivative-eq-intros*)

lemma *has-derivative-mult-const* [*derivative-intros*]: $D\ (*)\ a \mapsto (\lambda x.\ x *_R a)\ F$
using *has-vector-derivative-mult-const* **unfolding** *has-vector-derivative-def* **by** *simp*

lemma *has-vderiv-on-mult-const*: $D\ (*)\ a = (\lambda x.\ a)\ on\ T$
using *has-vector-derivative-mult-const* **unfolding** *has-vderiv-on-def* **by** *auto*

lemma *has-vderiv-on-divide-cnst*: $a \neq 0 \Longrightarrow D\ (\lambda t.\ t/a) = (\lambda t.\ 1/a)\ on\ T$
unfolding *has-vderiv-on-def has-vector-derivative-def* **apply** *clarify*
apply(*rule-tac* $f'1{=}\lambda t.\ t$ **and** $g'1{=}\lambda\ x.\ 0$ **in** *derivative-eq-intros*(*18*))
by(*auto intro*: *derivative-eq-intros*)

lemma *has-vderiv-on-power*: $n \geq 1 \Longrightarrow D\ (\lambda t.\ t\ \hat{}\ n) = (\lambda t.\ n * (t\ \hat{}\ (n - 1)))$ $on\ T$
unfolding *has-vderiv-on-def has-vector-derivative-def* **apply** *clarify*
by(*rule-tac* $f'1{=}\lambda\ t.\ t$ **in** *derivative-eq-intros*(*15*)) *auto*

lemma *has-vderiv-on-exp*: $D\ (\lambda t.\ exp\ t) = (\lambda t.\ exp\ t)\ on\ T$
unfolding *has-vderiv-on-def has-vector-derivative-def* **by** (*auto intro*: *derivative-intros*)

lemma *has-vderiv-on-cos-comp*:
$D\ (f{::}real \Rightarrow real) = f'\ on\ T \Longrightarrow D\ (\lambda t.\ cos\ (f\ t)) = (\lambda t.\ -\ (f'\ t) * sin\ (f\ t))$ $on\ T$
apply(*rule has-vderiv-on-compose-eq*[*of* $\lambda t.\ cos\ t$])
unfolding *has-vderiv-on-def has-vector-derivative-def* **apply** *clarify*
by(*auto intro*!: *derivative-eq-intros simp*: *fun-eq-iff*)

lemma *has-vderiv-on-sin-comp*:
$D\ (f{::}real \Rightarrow real) = f'\ on\ T \Longrightarrow D\ (\lambda t.\ sin\ (f\ t)) = (\lambda t.\ (f'\ t) * cos\ (f\ t))\ on\ T$

apply(*rule has-vderiv-on-compose-eq*[*of* $\lambda t.$ *sin t*])
unfolding *has-vderiv-on-def has-vector-derivative-def* **apply** *clarify*
by(*auto intro*!: *derivative-eq-intros simp*: *fun-eq-iff*)

lemma *has-vderiv-on-exp-comp*:
D (f::*real* $\Rightarrow$ *real*) $= f'$ *on* $T \Longrightarrow D$ ($\lambda t.$ *exp* (f t)) $=$ ($\lambda t.$ (f' t) $*$ *exp* (f t)) *on* T
apply(*rule has-vderiv-on-compose-eq*[*of* $\lambda t.$ *exp t*])
by (*rule has-vderiv-on-exp*, *simp-all add*: *mult.commute*)

lemma [*poly-derivatives*]: D $f = f'$ *on* $T \Longrightarrow g = (\lambda t. - f'\ t) \Longrightarrow D$ ($\lambda t. - f\ t$) $= g$ *on* T
using *has-vderiv-on-uminus* **by** *auto*

lemma [*poly-derivatives*]:
assumes (a::*real*) $\neq 0$ **and** D $f = f'$ *on* T **and** $g = (\lambda t.\ (f'\ t)/a)$
shows D ($\lambda t.$ (f t)/a) $= g$ *on* T
apply(*rule has-vderiv-on-compose-eq*[*of* $\lambda t.$ t/a $\lambda t.$ $1/a$])
using *assms* **by**(*auto intro*: *has-vderiv-on-divide-cnst*)

lemma [*poly-derivatives*]:
fixes f::*real* $\Rightarrow$ *real*
assumes $n \geq 1$ **and** D $f = f'$ *on* T **and** $g = (\lambda t.\ n * (f'\ t) * (f\ t)\hat{}(n-1))$
shows D ($\lambda t.$ (f t)ˆn) $= g$ *on* T
apply(*rule has-vderiv-on-compose-eq*[*of* $\lambda t.$ tˆn])
using *assms*(*1*) **apply**(*rule has-vderiv-on-power*)
using *assms* **by** *auto*

lemma [*poly-derivatives*]:
assumes D (f::*real* $\Rightarrow$ *real*) $= f'$ *on* T **and** $g = (\lambda t. - (f'\ t) * \mathit{sin}\ (f\ t))$
shows D ($\lambda t.$ *cos* (f t)) $= g$ *on* T
using *assms* **and** *has-vderiv-on-cos-comp* **by** *auto*

lemma [*poly-derivatives*]:
assumes D (f::*real* $\Rightarrow$ *real*) $= f'$ *on* T **and** $g = (\lambda t.\ (f'\ t) * \mathit{cos}\ (f\ t))$
shows D ($\lambda t.$ *sin* (f t)) $= g$ *on* T
using *assms* **and** *has-vderiv-on-sin-comp* **by** *auto*

lemma [*poly-derivatives*]:
assumes D (f::*real* $\Rightarrow$ *real*) $= f'$ *on* T **and** $g = (\lambda t.\ (f'\ t) * \mathit{exp}\ (f\ t))$
shows D ($\lambda t.$ *exp* (f t)) $= g$ *on* T
using *assms* **and** *has-vderiv-on-exp-comp* **by** *auto*

lemma D $(\lambda t.\ a * t^2\ /\ 2 + v * t + x) = (\lambda t.\ a * t + v)$ *on* T
by(*auto intro*!: *poly-derivatives*)

lemma D $(\lambda t.\ v * t - a * t^2\ /\ 2 + x) = (\lambda x.\ v - a * x)$ *on* T
by(*auto intro*!: *poly-derivatives*)

lemma $c \neq 0 \Longrightarrow D\ (\lambda t.\ a5 * t\hat{}5 + a3 * (t\hat{}3\ /\ c) - a2 * exp\ (t\hat{}2) + a1 * cos\ t + a0) =$
$(\lambda t.\ 5 * a5 * t\hat{}4 + 3 * a3 * (t\hat{}2\ /\ c) - 2 * a2 * t * exp\ (t\hat{}2) - a1 * sin\ t)$ *on T*
by(*auto intro*!: *poly-derivatives*)

lemma $c \neq 0 \Longrightarrow D\ (\lambda t.\ - a3 * exp\ (t\hat{}3\ /\ c) + a1 * sin\ t + a2 * t\hat{}2) =$
$(\lambda t.\ a1 * cos\ t + 2 * a2 * t - 3 * a3 * t\hat{}2\ /\ c * exp\ (t\hat{}3\ /\ c))$ *on T*
apply(*intro poly-derivatives*)
using *poly-derivatives*(*1*,*2*) **by** *force+*

lemma $c \neq 0 \Longrightarrow D\ (\lambda t.\ exp\ (a * sin\ (cos\ (t\hat{}4)\ /\ c))) =$
$(\lambda t.\ - 4 * a * t\hat{}3 * sin\ (t\hat{}4)\ /\ c * cos\ (cos\ (t\hat{}4)\ /\ c) * exp\ (a * sin\ (cos\ (t\hat{}4)\ /\ c)))$ *on T*
apply(*intro poly-derivatives*)
using *poly-derivatives*(*1*,*2*) **by** *force+*

1.2.2 Filters

lemma *eventually-at-within-mono*:
assumes $t \in$ *interior T* **and** $T \subseteq S$
and *eventually P* (*at t within T*)
shows *eventually P* (*at t within S*)
by (*meson assms eventually-within-interior interior-mono subsetD*)

lemma *netlimit-at-within-mono*:
fixes *t*::*'a*::{*perfect-space*,*t2-space*}
assumes $t \in$ *interior T* **and** $T \subseteq S$
shows *netlimit* (*at t within S*) = *t*
using *assms*(*1*) *interior-mono*[*OF* ‹$T \subseteq S$›] *netlimit-within-interior* **by** *auto*

lemma *has-derivative-at-within-mono*:
assumes (*t*::*real*) $\in$ *interior T* **and** $T \subseteq S$
and $D\ f \mapsto f'$ *at t within T*
shows $D\ f \mapsto f'$ *at t within S*
using *assms*(*3*) **apply**(*unfold has-derivative-def tendsto-iff*, *safe*)
unfolding *netlimit-at-within-mono*[*OF assms*(*1*,*2*)] *netlimit-within-interior*[*OF assms*(*1*)]
by (*rule eventually-at-within-mono*[*OF assms*(*1*,*2*)]) *simp*

lemma *eventually-all-finite2*:
fixes *P* :: (*'a*::*finite*) $\Rightarrow$ *'b* $\Rightarrow$ *bool*
assumes *h*:$\forall$ *i*. *eventually* (*P i*) *F*
shows *eventually* ($\lambda x.\ \forall i.\ P\ i\ x$) *F*
proof(*unfold eventually-def*)
let *?F* = *Rep-filter F*
have *obs*: $\forall$ *i*. *?F* (*P i*)
using *h* **by** *auto*
have *?F* ($\lambda x.\ \forall i \in UNIV.\ P\ i\ x$)

apply(*rule finite-induct*)
by(*auto intro*: *eventually-conj simp*: *obs h*)
thus $?F\ (\lambda x.\ \forall i.\ P\ i\ x)$
by *simp*
qed

lemma *eventually-all-finite-mono*:
fixes $P :: ('a::finite) \Rightarrow 'b \Rightarrow bool$
assumes *h1*: $\forall i.\ eventually\ (P\ i)\ F$
and *h2*: $\forall x.\ (\forall i.\ (P\ i\ x)) \longrightarrow Q\ x$
shows *eventually* $Q\ F$
proof−
have $eventually\ (\lambda x.\ \forall i.\ P\ i\ x)\ F$
using *h1 eventually-all-finite2* **by** *blast*
thus *eventually* $Q\ F$
unfolding *eventually-def*
using *h2 eventually-mono* **by** *auto*
qed

1.2.3 Multivariable derivatives

lemma *frechet-vec-lambda*:
fixes $f::real \Rightarrow ('a::banach)\hat{}('m::finite)$ **and** $x::real$ **and** $T::real\ set$
defines $x_0 \equiv netlimit\ (at\ x\ within\ T)$ **and** $m \equiv real\ CARD('m)$
assumes $\forall i.\ ((\lambda y.\ (f\ y\ \$\ i - f\ x_0\ \$\ i - (y - x_0) *_R f'\ x\ \$\ i)\ /_R\ (\|y - x_0\|)) \longrightarrow 0)\ (at\ x\ within\ T)$
shows $((\lambda y.\ (f\ y - f\ x_0 - (y - x_0) *_R f'\ x)\ /_R\ (\|y - x_0\|)) \longrightarrow 0)\ (at\ x\ within\ T)$
proof(*simp add*: *tendsto-iff*, *clarify*)
fix $\varepsilon::real$ **assume** $0 < \varepsilon$
let $?\Delta = \lambda y.\ y - x_0$ **and** $?\Delta f = \lambda y.\ f\ y - f\ x_0$
let $?P = \lambda i\ e\ y.\ inverse\ |?\Delta\ y| * (\|f\ y\ \$\ i - f\ x_0\ \$\ i - ?\Delta\ y *_R f'\ x\ \$\ i\|) < e$
and $?Q = \lambda y.\ inverse\ |?\Delta\ y| * (\|?\Delta f\ y - ?\Delta\ y *_R f'\ x\|) < \varepsilon$
have $0 < \varepsilon\ /\ sqrt\ m$
using $\langle 0 < \varepsilon \rangle$ **by** (*auto simp*: *assms*)
hence $\forall i.\ eventually\ (\lambda y.\ ?P\ i\ (\varepsilon\ /\ sqrt\ m)\ y)\ (at\ x\ within\ T)$
using *assms* **unfolding** *tendsto-iff* **by** *simp*
thus $eventually\ ?Q\ (at\ x\ within\ T)$
proof(*rule eventually-all-finite-mono*, *simp add*: *norm-vec-def L2-set-def*, *clarify*)
fix $t::real$
let $?c = inverse\ |t - x_0|$ **and** $?u\ t = \lambda i.\ f\ t\ \$\ i - f\ x_0\ \$\ i - ?\Delta\ t *_R f'\ x\ \$\ i$
assume *hyp*:$\forall i.\ ?c * (\|?u\ t\ i\|) < \varepsilon\ /\ sqrt\ m$
hence $\forall i.\ (?c *_R (\|?u\ t\ i\|))^2 < (\varepsilon\ /\ sqrt\ m)^2$
by (*simp add*: *power-strict-mono*)
hence $\forall i.\ ?c^2 * ((\|?u\ t\ i\|))^2 < \varepsilon^2\ /\ m$
by (*simp add*: *power-mult-distrib power-divide assms*)
hence $\forall i.\ ?c^2 * ((\|?u\ t\ i\|))^2 < \varepsilon^2\ /\ m$
by (*auto simp*: *assms*)
also have $(\{\}::'m\ set) \neq UNIV \wedge finite\ (UNIV :: 'm\ set)$

by *simp*
ultimately have $(\sum i \in UNIV.\ ?c^2 * ((\|?u\ t\ i\|))^2) < (\sum (i::'m) \in UNIV.\ \varepsilon^2 / m)$
by (*metis* (*lifting*) *sum-strict-mono*)
moreover have $?c^2 * (\sum i \in UNIV.\ (\|?u\ t\ i\|)^2) = (\sum i \in UNIV.\ ?c^2 * (\|?u\ t\ i\|)^2)$
using *sum-distrib-left* **by** *blast*
ultimately have $?c^2 * (\sum i \in UNIV.\ (\|?u\ t\ i\|)^2) < \varepsilon^2$
by (*simp add*: *assms*)
hence $sqrt\ (?c^2 * (\sum i \in UNIV.\ (\|?u\ t\ i\|)^2)) < sqrt\ (\varepsilon^2)$
using *real-sqrt-less-iff* **by** *blast*
also have $... = \varepsilon$
using ‹$0 < \varepsilon$› **by** *auto*
moreover have $?c * sqrt\ (\sum i \in UNIV.\ (\|?u\ t\ i\|)^2) = sqrt\ (?c^2 * (\sum i \in UNIV.\ (\|?u\ t\ i\|)^2))$
by (*simp add*: *real-sqrt-mult*)
ultimately show $?c * sqrt\ (\sum i \in UNIV.\ (\|?u\ t\ i\|)^2) < \varepsilon$
by *simp*
qed
qed

lemma *frechet-vec-nth*:
fixes $f::real \Rightarrow ('a::real\text{-}normed\text{-}vector)\hat{}'m$ **and** $x::real$ **and** $T::real\ set$
defines $x_0 \equiv netlimit\ (at\ x\ within\ T)$
assumes $((\lambda y.\ (f\ y - f\ x_0 - (y - x_0) *_R f'\ x) /_R (\|y - x_0\|)) \longrightarrow 0)\ (at\ x\ within\ T)$
shows $((\lambda y.\ (f\ y\ \$\ i - f\ x_0\ \$\ i - (y - x_0) *_R f'\ x\ \$\ i) /_R (\|y - x_0\|)) \longrightarrow 0)\ (at\ x\ within\ T)$
proof(*unfold tendsto-iff dist-norm*, *clarify*)
let $?\Delta = \lambda y.\ y - x_0$ **and** $?\Delta f = \lambda y.\ f\ y - f\ x_0$
fix $\varepsilon::real$ **assume** $0 < \varepsilon$
let $?P = \lambda y.\ \|(?\Delta f\ y - ?\Delta\ y *_R f'\ x) /_R (\|?\Delta\ y\|) - 0\| < \varepsilon$
and $?Q = \lambda y.\ \|(f\ y\ \$\ i - f\ x_0\ \$\ i - ?\Delta\ y *_R f'\ x\ \$\ i) /_R (\|?\Delta\ y\|) - 0\| < \varepsilon$
have *eventually* $?P$ (*at x within T*)
using ‹$0 < \varepsilon$› *assms* **unfolding** *tendsto-iff* **by** *auto*
thus *eventually* $?Q$ (*at x within T*)
proof(*rule-tac P=?P* **in** *eventually-mono*, *simp-all*)
let $?u\ y\ i = f\ y\ \$\ i - f\ x_0\ \$\ i - ?\Delta\ y *_R f'\ x\ \$\ i$
fix y **assume** *hyp*:$inverse\ |?\Delta\ y| * (\|?\Delta f\ y - ?\Delta\ y *_R f'\ x\|) < \varepsilon$
have $\|(?\Delta f\ y - ?\Delta\ y *_R f'\ x)\ \$\ i\| \le \|?\Delta f\ y - ?\Delta\ y *_R f'\ x\|$
using *Finite-Cartesian-Product.norm-nth-le* **by** *blast*
also have $\|?u\ y\ i\| = \|(?\Delta f\ y - ?\Delta\ y *_R f'\ x)\ \$\ i\|$
by *simp*
ultimately have $\|?u\ y\ i\| \le \|?\Delta f\ y - ?\Delta\ y *_R f'\ x\|$
by *linarith*
hence $inverse\ |?\Delta\ y| * (\|?u\ y\ i\|) \le inverse\ |?\Delta\ y| * (\|?\Delta f\ y - ?\Delta\ y *_R f'\ x\|)$
by (*simp add*: *mult-left-mono*)
thus $inverse\ |?\Delta\ y| * (\|f\ y\ \$\ i - f\ x_0\ \$\ i - ?\Delta\ y *_R f'\ x\ \$\ i\|) < \varepsilon$

    using *hyp* **by** *linarith*
  qed
qed

lemma *has-derivative-vec-lambda*:
  fixes f::*real* $\Rightarrow$ ($'a$::*banach*) ^($'n$::*finite*)
  assumes $\forall\, i.\ D\ (\lambda t.\ f\ t\ \$\ i) \mapsto (\lambda\ h.\ h *_R f'\ x\ \$\ i)\ (at\ x\ within\ T)$
  shows $D\ f \mapsto (\lambda h.\ h *_R f'\ x)\ at\ x\ within\ T$
  apply(*unfold has-derivative-def*, *safe*)
   apply(*force simp*: *bounded-linear-def bounded-linear-axioms-def*)
  using *assms frechet-vec-lambda*[*of x T*] **unfolding** *has-derivative-def* **by** *auto*

lemma *has-derivative-vec-nth*:
  assumes $D\ f \mapsto (\lambda h.\ h *_R f'\ x)\ at\ x\ within\ T$
  shows $D\ (\lambda t.\ f\ t\ \$\ i) \mapsto (\lambda h.\ h *_R f'\ x\ \$\ i)\ at\ x\ within\ T$
  apply(*unfold has-derivative-def*, *safe*)
   apply(*force simp*: *bounded-linear-def bounded-linear-axioms-def*)
  using *frechet-vec-nth*[*of x T f*] *assms* **unfolding** *has-derivative-def* **by** *auto*

lemma *has-vderiv-on-vec-eq*[*simp*]:
  fixes x::*real* $\Rightarrow$ ($'a$::*banach*) ^($'n$::*finite*)
  shows $(D\ x = x'\ on\ T) = (\forall\, i.\ D\ (\lambda t.\ x\ t\ \$\ i) = (\lambda t.\ x'\ t\ \$\ i)\ on\ T)$
  unfolding *has-vderiv-on-def has-vector-derivative-def* **apply** *safe*
  using *has-derivative-vec-nth has-derivative-vec-lambda* **by** *blast+*

end
theory *hs-prelims-dyn-sys*
  imports *hs-prelims*

begin

1.3 Dynamical Systems

1.3.1 Initial value problems and orbits

notation *image* ($\mathcal{P}$)

lemma *image-le-pred*: $(\mathcal{P}\ f\ A \subseteq \{s.\ G\ s\}) = (\forall\, x{\in}A.\ G\ (f\ x))$
  unfolding *image-def* **by** *force*

definition *ivp-sols* :: (*real* $\Rightarrow$ $'a$ $\Rightarrow$ ($'a$::*real-normed-vector*)) $\Rightarrow$ *real set* $\Rightarrow$ $'a$ *set* $\Rightarrow$
  real $\Rightarrow$ $'a$ $\Rightarrow$ (*real* $\Rightarrow$ $'a$) *set* (*Sols*)
  where $Sols\ f\ T\ S\ t_0\ s = \{X\ |X.\ (D\ X = (\lambda t.\ f\ t\ (X\ t))\ on\ T) \wedge X\ t_0 = s \wedge X \in T \rightarrow S\}$

lemma *ivp-solsI*:
  assumes $D\ X = (\lambda t.\ f\ t\ (X\ t))\ on\ T\ X\ t_0 = s\ X \in T \rightarrow S$
  shows $X \in Sols\ f\ T\ S\ t_0\ s$

using *assms* **unfolding** *ivp-sols-def* **by** *blast*

lemma *ivp-solsD*:
assumes $X \in \mathit{Sols}\ f\ T\ S\ t_0\ s$
shows $D\ X = (\lambda t.\ f\ t\ (X\ t))\ \mathit{on}\ T$
and $X\ t_0 = s$ **and** $X \in T \to S$
using *assms* **unfolding** *ivp-sols-def* **by** *auto*

abbreviation $\mathit{down}\ T\ t \equiv \{\tau{\in}T.\ \tau{\le}\ t\}$

definition *g-orbit* :: $(('a{::}\mathit{ord}) \Rightarrow 'b) \Rightarrow ('b \Rightarrow \mathit{bool}) \Rightarrow 'a\ \mathit{set} \Rightarrow 'b\ \mathit{set}\ (\gamma)$
where $\gamma\ X\ G\ T = \bigcup\{\mathcal{P}\ X\ (\mathit{down}\ T\ t)\ |t.\ \mathcal{P}\ X\ (\mathit{down}\ T\ t) \subseteq \{s.\ G\ s\}\}$

lemma *g-orbit-eq*:
fixes $X{::}('a{::}\mathit{preorder}) \Rightarrow 'b$
shows $\gamma\ X\ G\ T = \{X\ t\ |t.\ t \in T \wedge (\forall \tau{\in}\mathit{down}\ T\ t.\ G\ (X\ \tau))\}$
unfolding *g-orbit-def* **apply** *safe*
using *le-left-mono* **by** *blast auto*

lemma $\gamma\ X\ (\lambda s.\ \mathit{True})\ T = \{X\ t\ |t.\ t \in T\}$ **for** $X{::}('a{::}\mathit{preorder}) \Rightarrow 'b$
unfolding *g-orbit-eq* **by** *simp*

definition *g-orbital* :: $('a \Rightarrow 'a) \Rightarrow ('a \Rightarrow \mathit{bool}) \Rightarrow \mathit{real\ set} \Rightarrow 'a\ \mathit{set} \Rightarrow \mathit{real} \Rightarrow$
$('a{::}\mathit{real\text{-}normed\text{-}vector}) \Rightarrow 'a\ \mathit{set}$
where $\mathit{g\text{-}orbital}\ f\ G\ T\ S\ t_0\ s = \bigcup\{\gamma\ X\ G\ T\ |X.\ X \in \mathit{ivp\text{-}sols}\ (\lambda t.\ f)\ T\ S\ t_0\ s\}$

lemma *g-orbital-eq*: $\mathit{g\text{-}orbital}\ f\ G\ T\ S\ t_0\ s =$
$\{X\ t\ |t\ X.\ t \in T \wedge \mathcal{P}\ X\ (\mathit{down}\ T\ t) \subseteq \{s.\ G\ s\} \wedge X \in \mathit{Sols}\ (\lambda t.\ f)\ T\ S\ t_0\ s\ \}$
unfolding *g-orbital-def ivp-sols-def g-orbit-eq image-le-pred* **by** *auto*

lemma $\mathit{g\text{-}orbital}\ f\ G\ T\ S\ t_0\ s =$
$\{X\ t\ |t\ X.\ t \in T \wedge (D\ X = (f \circ X)\ \mathit{on}\ T) \wedge X\ t_0 = s \wedge X \in T \to S \wedge (\mathcal{P}\ X$
$(\mathit{down}\ T\ t) \subseteq \{s.\ G\ s\})\}$
unfolding *g-orbital-eq ivp-sols-def* **by** *auto*

lemma $\mathit{g\text{-}orbital}\ f\ G\ T\ S\ t_0\ s = (\bigcup\ X{\in}\mathit{Sols}\ (\lambda t.\ f)\ T\ S\ t_0\ s.\ \gamma\ X\ G\ T)$
unfolding *g-orbital-def ivp-sols-def g-orbit-eq* **by** *auto*

lemma *g-orbitalI*:
assumes $X \in \mathit{Sols}\ (\lambda t.\ f)\ T\ S\ t_0\ s$
and $t \in T$ **and** $(\mathcal{P}\ X\ (\mathit{down}\ T\ t) \subseteq \{s.\ G\ s\})$
shows $X\ t \in \mathit{g\text{-}orbital}\ f\ G\ T\ S\ t_0\ s$
using *assms* **unfolding** *g-orbital-eq(1)* **by** *auto*

lemma *g-orbitalD*:
assumes $s' \in \mathit{g\text{-}orbital}\ f\ G\ T\ S\ t_0\ s$
obtains X **and** t **where** $X \in \mathit{Sols}\ (\lambda t.\ f)\ T\ S\ t_0\ s$
and $X\ t = s'$ **and** $t \in T$ **and** $(\mathcal{P}\ X\ (\mathit{down}\ T\ t) \subseteq \{s.\ G\ s\})$
using *assms* **unfolding** *g-orbital-def g-orbit-eq* **by** *auto*

no-notation *g-orbit* (γ)

1.3.2 Differential Invariants

definition *diff-invariant* :: ($'a \Rightarrow bool$) $\Rightarrow$ (($'a$::*real-normed-vector*) $\Rightarrow$ $'a$) $\Rightarrow$ *real set* $\Rightarrow$
$'a$ *set* $\Rightarrow$ *real* $\Rightarrow$ ($'a \Rightarrow bool$) $\Rightarrow$ *bool*
where *diff-invariant* $I\ f\ T\ S\ t_0\ G \equiv (\bigcup \circ (\mathcal{P}\ (g\text{-}orbital\ f\ G\ T\ S\ t_0)))\ \{s.\ I\ s\} \subseteq \{s.\ I\ s\}$

lemma *diff-invariant-eq*: *diff-invariant* $I\ f\ T\ S\ t_0\ G =$
$(\forall s.\ I\ s \longrightarrow (\forall X{\in}Sols\ (\lambda t.\ f)\ T\ S\ t_0\ s.\ (\forall t{\in}T.(\forall \tau{\in}(down\ T\ t).\ G\ (X\ \tau)) \longrightarrow I\ (X\ t))))$
unfolding *diff-invariant-def g-orbital-eq image-le-pred* **by** *auto*

lemma *diff-inv-eq-inv-set*:
diff-invariant $I\ f\ T\ S\ t_0\ G = (\forall s.\ I\ s \longrightarrow (g\text{-}orbital\ f\ G\ T\ S\ t_0\ s) \subseteq \{s.\ I\ s\})$
unfolding *diff-invariant-eq g-orbital-eq image-le-pred* **by** *auto*

named-theorems *diff-invariant-rules rules for obtainin differential invariants.*

lemma [*diff-invariant-rules*]:
assumes *Thyp*: *is-interval* T $t_0 \in T$
and $\forall X.\ (D\ X = (\lambda\tau.\ f\ (X\ \tau))\ on\ T) \longrightarrow (D\ (\lambda\tau.\ \mu\ (X\ \tau) - \nu\ (X\ \tau)) = ((*_R)\ 0)\ on\ T)$
shows *diff-invariant* $(\lambda s.\ \mu\ s = \nu\ s)\ f\ T\ S\ t_0\ G$
proof(*simp add*: *diff-invariant-eq ivp-sols-def*, *clarsimp*)
fix X τ **assume** *tHyp*:$\tau \in T$ **and** *x-ivp*:$D\ X = (\lambda\tau.\ f\ (X\ \tau))\ on\ T$ $\mu\ (X\ t_0) = \nu\ (X\ t_0)$
hence *obs1*: $\forall t{\in}T.\ D\ (\lambda\tau.\ \mu\ (X\ \tau) - \nu\ (X\ \tau)) \mapsto (\lambda\tau.\ \tau *_R 0)\ at\ t\ within\ T$
using *assms* **by** (*auto simp*: *has-vderiv-on-def has-vector-derivative-def*)
have *obs2*: $\{t_0{-}{-}\tau\} \subseteq T$
using *closed-segment-subset-interval tHyp Thyp* **by** *blast*
hence $D\ (\lambda\tau.\ \mu\ (X\ \tau) - \nu\ (X\ \tau)) = (\lambda\tau.\ \tau *_R 0)\ on\ \{t_0{-}{-}\tau\}$
using *obs1 x-ivp* **by** (*auto intro*!: *has-derivative-subset*[*OF - obs2*]
simp: *has-vderiv-on-def has-vector-derivative-def*)
then obtain t **where** $t \in \{t_0{-}{-}\tau\}$ **and** $\mu\ (X\ \tau) - \nu\ (X\ \tau) - (\mu\ (X\ t_0) - \nu\ (X\ t_0)) = (\tau - t_0) * t *_R 0$
using *mvt-very-simple-closed-segmentE* **by** *blast*
thus $\mu\ (X\ \tau) = \nu\ (X\ \tau)$
by (*simp add*: *x-ivp*(*2*))
qed

lemma [*diff-invariant-rules*]:
fixes μ::$'a$::*banach* $\Rightarrow$ *real*
assumes *Thyp*: *is-interval* T $t_0 \in T$
and $\forall X.\ (D\ X = (\lambda\tau.\ f\ (X\ \tau))\ on\ T) \longrightarrow (\forall \tau{\in}T.\ (\tau > t_0 \longrightarrow \mu'\ (X\ \tau) \geq \nu'\ (X\ \tau)) \wedge$

$(\tau < t_0 \longrightarrow \mu'\ (X\ \tau) \leq \nu'\ (X\ \tau))) \wedge (D\ (\lambda\tau.\ \mu\ (X\ \tau) - \nu\ (X\ \tau)) = (\lambda\tau.\ \mu'\ (X\ \tau) - \nu'\ (X\ \tau))$ *on* $T)$
shows *diff-invariant* $(\lambda s.\ \nu\ s \leq \mu\ s)\ f\ T\ S\ t_0\ G$
proof(*simp add*: *diff-invariant-eq ivp-sols-def*, *clarsimp*)
fix $X\ \tau$ **assume** $\tau \in T$ **and** *x-ivp*:$D\ X = (\lambda\tau.\ f\ (X\ \tau))$ *on* $T\ \nu\ (X\ t_0) \leq \mu\ (X\ t_0)$
{**assume** $\tau \neq t_0$
hence *primed*: $\bigwedge\tau.\ \tau \in T \Longrightarrow \tau > t_0 \Longrightarrow \mu'\ (X\ \tau) \geq \nu'\ (X\ \tau)$
$\bigwedge\tau.\ \tau \in T \Longrightarrow \tau < t_0 \Longrightarrow \mu'\ (X\ \tau) \leq \nu'\ (X\ \tau)$
using *x-ivp assms* **by** *auto*
have *obs1*: $\forall t \in T.\ D\ (\lambda\tau.\ \mu\ (X\ \tau) - \nu\ (X\ \tau)) \mapsto (\lambda\tau.\ \tau *_R (\mu'\ (X\ t) - \nu'\ (X\ t)))$ *at* t *within* T
using *assms x-ivp* **by** (*auto simp*: *has-vderiv-on-def has-vector-derivative-def*)
have *obs2*: $\{t_0 <--< \tau\} \subseteq T\ \{t_0 -- \tau\} \subseteq T$
using ‹$\tau \in T$› *Thyp* ‹$\tau \neq t_0$› **by** (*auto simp*: *convex-contains-open-segment is-interval-convex-1 closed-segment-subset-interval*)
hence $D\ (\lambda\tau.\ \mu\ (X\ \tau) - \nu\ (X\ \tau)) = (\lambda\tau.\ \mu'\ (X\ \tau) - \nu'\ (X\ \tau))$ *on* $\{t_0 -- \tau\}$
using *obs1 x-ivp* **by** (*auto intro*!: *has-derivative-subset*[*OF - obs2*(*2*)] *simp*: *has-vderiv-on-def has-vector-derivative-def*)
then obtain t **where** $t \in \{t_0 <--< \tau\}$ **and**
$(\mu\ (X\ \tau) - \nu\ (X\ \tau)) - (\mu\ (X\ t_0) - \nu\ (X\ t_0)) = (\lambda\tau.\ \tau * (\mu'\ (X\ t) - \nu'\ (X\ t)))\ (\tau - t_0)$
using *mvt-simple-closed-segmentE* ‹$\tau \neq t_0$› **by** *blast*
hence *mvt*: $\mu\ (X\ \tau) - \nu\ (X\ \tau) = (\tau - t_0) * (\mu'\ (X\ t) - \nu'\ (X\ t)) + (\mu\ (X\ t_0) - \nu\ (X\ t_0))$
by *force*
have $\tau > t_0 \Longrightarrow t > t_0\ \neg\ t_0 \leq \tau \Longrightarrow t < t_0\ t \in T$
using ‹$t \in \{t_0 <--< \tau\}$› *obs2* **unfolding** *open-segment-eq-real-ivl* **by** *auto*
moreover have $t > t_0 \Longrightarrow (\mu'\ (X\ t) - \nu'\ (X\ t)) \geq 0\ t < t_0 \Longrightarrow (\mu'\ (X\ t) - \nu'\ (X\ t)) \leq 0$
using *primed*(*1*,*2*)[*OF* ‹$t \in T$›] **by** *auto*
ultimately have $(\tau - t_0) * (\mu'\ (X\ t) - \nu'\ (X\ t)) \geq 0$
apply(*case-tac* $\tau \geq t_0$) **by** (*force*, *auto simp*: *split-mult-pos-le*)
hence $(\tau - t_0) * (\mu'\ (X\ t) - \nu'\ (X\ t)) + (\mu\ (X\ t_0) - \nu\ (X\ t_0)) \geq 0$
using *x-ivp*(*2*) **by** *auto*
hence $\nu\ (X\ \tau) \leq \mu\ (X\ \tau)$
using *mvt* **by** *simp*}
thus $\nu\ (X\ \tau) \leq \mu\ (X\ \tau)$
using *x-ivp* **by** *blast*
qed

lemma [*diff-invariant-rules*]:
fixes μ::'*a*::*banach* $\Rightarrow$ *real*
assumes *Thyp*: *is-interval* $T\ t_0 \in T$
and $\forall\ X.\ (D\ X = (\lambda\tau.\ f\ (X\ \tau))$ *on* $T) \longrightarrow (\forall\tau \in T.\ (\tau > t_0 \longrightarrow \mu'\ (X\ \tau) \geq \nu'\ (X\ \tau)) \wedge$
$(\tau < t_0 \longrightarrow \mu'\ (X\ \tau) \leq \nu'\ (X\ \tau))) \wedge (D\ (\lambda\tau.\ \mu\ (X\ \tau) - \nu\ (X\ \tau)) = (\lambda\tau.\ \mu'\ (X\ \tau) - \nu'\ (X\ \tau))$ *on* $T)$
shows *diff-invariant* $(\lambda s.\ \nu\ s < \mu\ s)\ f\ T\ S\ t_0\ G$

proof(*simp add*: *diff-invariant-eq ivp-sols-def*, *clarsimp*)
  fix X τ **assume** $\tau \in T$ **and** *x-ivp*:$D\ X = (\lambda\tau.\ f\ (X\ \tau))$ *on* T $\nu\ (X\ t_0) < \mu\ (X\ t_0)$
  {assume $\tau \neq t_0$
  hence *primed*: $\bigwedge\tau.\ \tau \in T \Longrightarrow \tau > t_0 \Longrightarrow \mu'\ (X\ \tau) \geq \nu'\ (X\ \tau)$
    $\bigwedge\tau.\ \tau \in T \Longrightarrow \tau < t_0 \Longrightarrow \mu'\ (X\ \tau) \leq \nu'\ (X\ \tau)$
    using *x-ivp assms* **by** *auto*
  have *obs1*: $\forall\, t{\in}T.\ D\ (\lambda\tau.\ \mu\ (X\ \tau) - \nu\ (X\ \tau)) \mapsto (\lambda\tau.\ \tau *_R (\mu'\ (X\ t) - \nu'\ (X\ t)))$ *at* t *within* T
    using *assms x-ivp* **by** (*auto simp*: *has-vderiv-on-def has-vector-derivative-def*)
  have *obs2*: $\{t_0{<}{-}{-}{<}\tau\} \subseteq T$ $\{t_0{-}{-}\tau\} \subseteq T$
    using ‹$\tau \in T$› *Thyp* ‹$\tau \neq t_0$› **by** (*auto simp*: *convex-contains-open-segment is-interval-convex-1 closed-segment-subset-interval*)
  hence $D\ (\lambda\tau.\ \mu\ (X\ \tau) - \nu\ (X\ \tau)) = (\lambda\tau.\ \mu'\ (X\ \tau) - \nu'\ (X\ \tau))$ *on* $\{t_0{-}{-}\tau\}$
    using *obs1 x-ivp* **by** (*auto intro*!: *has-derivative-subset*[*OF* - *obs2*(*2*)] *simp*: *has-vderiv-on-def has-vector-derivative-def*)
  then obtain t **where** $t \in \{t_0{<}{-}{-}{<}\tau\}$ **and**
    $(\mu\ (X\ \tau) - \nu\ (X\ \tau)) - (\mu\ (X\ t_0) - \nu\ (X\ t_0)) = (\lambda\tau.\ \tau * (\mu'\ (X\ t) - \nu'\ (X\ t)))\ (\tau - t_0)$
    using *mvt-simple-closed-segmentE* ‹$\tau \neq t_0$› **by** *blast*
  hence *mvt*: $\mu\ (X\ \tau) - \nu\ (X\ \tau) = (\tau - t_0) * (\mu'\ (X\ t) - \nu'\ (X\ t)) + (\mu\ (X\ t_0) - \nu\ (X\ t_0))$
    by *force*
  have $\tau > t_0 \Longrightarrow t > t_0$ $\neg\ t_0 \leq \tau \Longrightarrow t < t_0$ $t \in T$
    using ‹$t \in \{t_0{<}{-}{-}{<}\tau\}$› *obs2* **unfolding** *open-segment-eq-real-ivl* **by** *auto*
  moreover have $t > t_0 \Longrightarrow (\mu'\ (X\ t) - \nu'\ (X\ t)) \geq 0$ $t < t_0 \Longrightarrow (\mu'\ (X\ t) - \nu'\ (X\ t)) \leq 0$
    using *primed*(*1*,*2*)[*OF* ‹$t \in T$›] **by** *auto*
  ultimately have $(\tau - t_0) * (\mu'\ (X\ t) - \nu'\ (X\ t)) \geq 0$
    apply(*case-tac* $\tau \geq t_0$) **by** (*force*, *auto simp*: *split-mult-pos-le*)
  hence $(\tau - t_0) * (\mu'\ (X\ t) - \nu'\ (X\ t)) + (\mu\ (X\ t_0) - \nu\ (X\ t_0)) > 0$
    using *x-ivp*(*2*) **by** *auto*
  hence $\nu\ (X\ \tau) < \mu\ (X\ \tau)$
    using *mvt* **by** *simp***}**
  thus $\nu\ (X\ \tau) < \mu\ (X\ \tau)$
    using *x-ivp* **by** *blast*
qed

lemma [*diff-invariant-rules*]:
assumes *diff-invariant* I_1 f T S t_0 G
  and *diff-invariant* I_2 f T S t_0 G
shows *diff-invariant* $(\lambda s.\ I_1\ s \wedge I_2\ s)$ f T S t_0 G
  using *assms* **unfolding** *diff-invariant-def* **by** *auto*

lemma [*diff-invariant-rules*]:
assumes *diff-invariant* I_1 f T S t_0 G
  and *diff-invariant* I_2 f T S t_0 G
shows *diff-invariant* $(\lambda s.\ I_1\ s \vee I_2\ s)$ f T S t_0 G
  using *assms* **unfolding** *diff-invariant-def* **by** *auto*

1.3.3 Picard-Lindeloef

A locale with the assumptions of Picard-Lindeloef theorem. It extends *ll-on-open-it* by assuming that $t_0 \in T$.

locale *picard-lindeloef* =
  fixes f::*real* ⇒ ('*a*::{*heine-borel*,*banach*}) ⇒ '*a* **and** T::*real set* **and** S::'*a set*
and t_0::*real*
  assumes *open-domain*: *open* T *open* S
    and *interval-time*: *is-interval* T
    and *init-time*: $t_0 \in T$
    and *cont-vec-field*: $\forall\, s \in S.$ *continuous-on* T $(\lambda t.\ f\ t\ s)$
    and *lipschitz-vec-field*: *local-lipschitz* $T\ S\ f$
begin

sublocale *ll-on-open-it* $T\ f\ S\ t_0$
 by (*unfold-locales*) (*auto simp*: *cont-vec-field lipschitz-vec-field interval-time open-domain*)

lemmas *subintervalI* = *closed-segment-subset-domain*

lemma *csols-eq*: *csols* t_0 s = $\{(X,\ t).\ t \in T \wedge\ X \in$ *Sols* f $\{t_0{-}{-}t\}\ S\ t_0\ s\}$
  unfolding *ivp-sols-def csols-def solves-ode-def* **using** *subintervalI*[*OF init-time*]
by *auto*

abbreviation *ex-ivl* $s \equiv$ *existence-ivl* t_0 s

lemma *unique-solution*:
  assumes *xivp*: $D\ X = (\lambda t.\ f\ t\ (X\ t))$ *on* $\{t_0{-}{-}t\}$ $X\ t_0 = s$ $X \in \{t_0{-}{-}t\} \to S$
and $t \in T$
    and *yivp*: $D\ Y = (\lambda t.\ f\ t\ (Y\ t))$ *on* $\{t_0{-}{-}t\}$ $Y\ t_0 = s$ $Y \in \{t_0{-}{-}t\} \to S$ **and**
$s \in S$
  shows $X\ t = Y\ t$
proof−
  have $(X,\ t) \in$ *csols* t_0 s
    using *xivp* ‹$t \in T$› **unfolding** *csols-eq ivp-sols-def* **by** *auto*
  hence *ivl-fact*: $\{t_0{-}{-}t\} \subseteq$ *ex-ivl* s
    unfolding *existence-ivl-def* **by** *auto*
  have *obs*: $\bigwedge z\ T'.\ t_0 \in T' \wedge$ *is-interval* $T' \wedge T' \subseteq$ *ex-ivl* $s \wedge (z$ *solves-ode* $f)$ T'
$S \Longrightarrow$
  $z\ t_0 =$ *flow* $t_0\ s\ t_0 \Longrightarrow (\forall\, t{\in}T'.\ z\ t =$ *flow* $t_0\ s\ t)$
    using *flow-usolves-ode*[*OF init-time* ‹$s \in S$›] **unfolding** *usolves-ode-from-def*
by *blast*
  have $\forall\,\tau{\in}\{t_0{-}{-}t\}.\ X\ \tau =$ *flow* $t_0\ s\ \tau$
    using *obs*[*of* $\{t_0{-}{-}t\}$ X] *xivp ivl-fact flow-initial-time*[*OF init-time* ‹$s \in S$›]
    unfolding *solves-ode-def* **by** *simp*
  also have $\forall\,\tau{\in}\{t_0{-}{-}t\}.\ Y\ \tau =$ *flow* $t_0\ s\ \tau$
    using *obs*[*of* $\{t_0{-}{-}t\}$ Y] *yivp ivl-fact flow-initial-time*[*OF init-time* ‹$s \in S$›]
    unfolding *solves-ode-def* **by** *simp*
  ultimately show $X\ t = Y\ t$

by *auto*
qed

lemma *solution-eq-flow*:
assumes *xivp*: $D\ X = (\lambda t.\ f\ t\ (X\ t))$ *on ex-ivl s* $X\ t_0 = s$ $X \in$ *ex-ivl s* $\rightarrow S$
and $t \in$ *ex-ivl s* **and** $s \in S$
shows $X\ t =$ *flow* $t_0\ s\ t$
proof−
have *obs*: $\bigwedge z\ T'.\ t_0 \in T' \wedge$ *is-interval* $T' \wedge T' \subseteq$ *ex-ivl s* $\wedge$ (*z solves-ode f*) T' $S \Longrightarrow$
$z\ t_0 =$ *flow* $t_0\ s\ t_0 \Longrightarrow (\forall\, t{\in}T'.\ z\ t =$ *flow* $t_0\ s\ t)$
using *flow-usolves-ode*[*OF init-time* ‹$s \in S$›] **unfolding** *usolves-ode-from-def* **by** *blast*
have $\forall\,\tau{\in}$*ex-ivl s*. $X\ \tau =$ *flow* $t_0\ s\ \tau$
using *obs*[*of ex-ivl s X*] *existence-ivl-initial-time*[*OF init-time* ‹$s \in S$›]
xivp flow-initial-time[*OF init-time* ‹$s \in S$›] **unfolding** *solves-ode-def* **by** *simp*
thus $X\ t =$ *flow* $t_0\ s\ t$
by (*auto simp*: ‹$t \in$ *ex-ivl s*›)
qed

end

lemma *local-lipschitz-add*:
fixes *f1 f2* :: *real* $\Rightarrow$ *'a::banach* $\Rightarrow$ *'a*
assumes *local-lipschitz T S f1*
and *local-lipschitz T S f2*
shows *local-lipschitz T S* ($\lambda t\ s.$ *f1 t s* + *f2 t s*)
proof(*unfold local-lipschitz-def*, *clarsimp*)
fix *s* **and** *t* **assume** $s \in S$ **and** $t \in T$
obtain ε_1 *L1* **where** $\varepsilon_1 > 0$ **and** *L1*: $\bigwedge\tau.\ \tau{\in}$*cball t* $\varepsilon_1 \cap T \Longrightarrow$ *L1*−*lipschitz-on* (*cball s* $\varepsilon_1 \cap S$) (*f1* τ)
using *local-lipschitzE*[*OF assms*(*1*) ‹$t \in T$› ‹$s \in S$›] **by** *blast*
obtain ε_2 *L2* **where** $\varepsilon_2 > 0$ **and** *L2*: $\bigwedge\tau.\ \tau{\in}$*cball t* $\varepsilon_2 \cap T \Longrightarrow$ *L2*−*lipschitz-on* (*cball s* $\varepsilon_2 \cap S$) (*f2* τ)
using *local-lipschitzE*[*OF assms*(*2*) ‹$t \in T$› ‹$s \in S$›] **by** *blast*
have *ballH*: *cball s* (*min* $\varepsilon_1\ \varepsilon_2$) $\cap S \subseteq$ *cball s* $\varepsilon_1 \cap S$ *cball s* (*min* $\varepsilon_1\ \varepsilon_2$) $\cap S \subseteq$ *cball s* $\varepsilon_2 \cap S$
by *auto*
have *obs1*: $\forall\,\tau{\in}$*cball t* $\varepsilon_1 \cap T$. *L1*−*lipschitz-on* (*cball s* (*min* $\varepsilon_1\ \varepsilon_2$) $\cap S$) (*f1* τ)
using *lipschitz-on-subset*[*OF L1 ballH*(*1*)] **by** *blast*
also have *obs2*: $\forall\,\tau{\in}$*cball t* $\varepsilon_2 \cap T$. *L2*−*lipschitz-on* (*cball s* (*min* $\varepsilon_1\ \varepsilon_2$) $\cap S$) (*f2* τ)
using *lipschitz-on-subset*[*OF L2 ballH*(*2*)] **by** *blast*
ultimately have $\forall\,\tau{\in}$*cball t* (*min* $\varepsilon_1\ \varepsilon_2$) $\cap T$.
(*L1* + *L2*)−*lipschitz-on* (*cball s* (*min* $\varepsilon_1\ \varepsilon_2$) $\cap S$) ($\lambda s.$ *f1* τ *s* + *f2* τ *s*)
using *lipschitz-on-add* **by** *fastforce*
thus $\exists\, u{>}0.\ \exists\, L.\ \forall\, t{\in}$*cball t u* $\cap T$. *L*−*lipschitz-on* (*cball s u* $\cap S$) ($\lambda s.$ *f1 t s* + *f2 t s*)
apply(*rule-tac x*=*min* $\varepsilon_1\ \varepsilon_2$ **in** *exI*)

using ‹ε_1 > *0*› ‹ε_2 > *0*› **by** *force*
qed

lemma *picard-lindeloef-add*: *picard-lindeloef f1 T S* t_0 ⟹ *picard-lindeloef f2 T S* t_0 ⟹
picard-lindeloef (λ*t s*. *f1 t s* + *f2 t s*) *T S* t_0
unfolding *picard-lindeloef-def* **apply**(*clarsimp*, *rule conjI*)
using *continuous-on-add* **apply** *fastforce*
using *local-lipschitz-add* **by** *blast*

lemma *picard-lindeloef-constant*: *picard-lindeloef* (λ*t s*. *c*) *UNIV UNIV* t_0
apply(*unfold-locales*, *simp-all add*: *local-lipschitz-def lipschitz-on-def*, *clarsimp*)
by (*rule-tac x=1* **in** *exI*, *clarsimp*, *rule-tac x=1/2* **in** *exI*, *simp*)

1.3.4 Flows for ODEs

A locale designed for verification of hybrid systems. The user can select both, the interval of existence of her choice, and the computation rule of the flow via the variables T and φ.

locale *local-flow* = *picard-lindeloef* (λ *t*. *f*) *T S 0*
for *f*::'*a*::{*heine-borel*,*banach*} ⇒ '*a* **and** *T S L* +
fixes φ :: *real* ⇒ '*a* ⇒ '*a*
assumes *ivp*:
⋀ *t s*. *t* ∈ *T* ⟹ *s* ∈ *S* ⟹ *D* (λ*t*. φ *t s*) = (λ*t*. *f* (φ *t s*)) *on* {*0*−−*t*}
⋀ *s*. *s* ∈ *S* ⟹ φ *0 s* = *s*
⋀ *t s*. *t* ∈ *T* ⟹ *s* ∈ *S* ⟹ (λ*t*. φ *t s*) ∈ {*0*−−*t*} → *S*
begin

lemma *in-ivp-sols-ivl*:
assumes *t* ∈ *T s* ∈ *S*
shows (λ*t*. φ *t s*) ∈ *Sols* (λ*t*. *f*) {*0*−−*t*} *S 0 s*
apply(*rule ivp-solsI*)
using *ivp assms* **by** *auto*

lemma *eq-solution-ivl*:
assumes *xivp*: *D X* = (λ*t*. *f* (*X t*)) *on* {*0*−−*t*} *X 0* = *s X* ∈ {*0*−−*t*} → *S*
and *indom*: *t* ∈ *T s* ∈ *S*
shows *X t* = φ *t s*
apply(*rule unique-solution*[*OF xivp* ‹*t* ∈ *T*›])
using ‹*s* ∈ *S*› *ivp indom* **by** *auto*

lemma *ex-ivl-eq*:
assumes *s* ∈ *S*
shows *ex-ivl s* = *T*
using *existence-ivl-subset*[*of s*] **apply** *safe*
unfolding *existence-ivl-def csols-eq*
using *in-ivp-sols-ivl*[*OF* - *assms*] **by** *blast*

lemma *has-derivative-on-open1*:

```
  assumes  t > 0 t ∈ T s ∈ S
  obtains B where t ∈ B and open B and B ⊆ T
    and D (λτ. φ τ s) ↦ (λτ. τ *R f (φ t s)) at t within B
proof−
  obtain r::real where rHyp: r > 0 ball t r ⊆ T
    using open-contains-ball-eq open-domain(1) ‹t ∈ T› by blast
  moreover have t + r/2 > 0
    using ‹r > 0› ‹t > 0› by auto
  moreover have {0−−t} ⊆ T
    using subintervalI[OF init-time ‹t ∈ T›] .
  ultimately have subs: {0<−−<t + r/2} ⊆ T
    unfolding abs-le-eq abs-le-eq real-ivl-eqs[OF ‹t > 0›] real-ivl-eqs[OF ‹t + r/2 > 0›]
    by clarify (case-tac t < x, simp-all add: cball-def ball-def dist-norm subset-eq field-simps)
  have t + r/2 ∈ T
    using rHyp unfolding real-ivl-eqs[OF rHyp(1)] by (simp add: subset-eq)
  hence {0−−t + r/2} ⊆ T
    using subintervalI[OF init-time] by blast
  hence (D (λt. φ t s) = (λt. f (φ t s)) on {0−−(t + r/2)})
    using ivp(1)[OF - ‹s ∈ S›] by auto
  hence vderiv: (D (λt. φ t s) = (λt. f (φ t s)) on {0<−−<t + r/2})
    apply(rule has-vderiv-on-subset)
    unfolding real-ivl-eqs[OF ‹t + r/2 > 0›] by auto
  have t ∈ {0<−−<t + r/2}
    unfolding real-ivl-eqs[OF ‹t + r/2 > 0›] using rHyp ‹t > 0› by simp
  moreover have D (λτ. φ τ s) ↦ (λτ. τ *R f (φ t s)) (at t within {0<−−<t + r/2})
    using vderiv calculation unfolding has-vderiv-on-def has-vector-derivative-def by blast
  moreover have open {0<−−<t + r/2}
    unfolding real-ivl-eqs[OF ‹t + r/2 > 0›] by simp
  ultimately show ?thesis
    using subs that by blast
qed

lemma has-derivative-on-open2:
  assumes t < 0 t ∈ T s ∈ S
  obtains B where t ∈ B and open B and B ⊆ T
    and D (λτ. φ τ s) ↦ (λτ. τ *R f (φ t s)) at t within B
proof−
  obtain r::real where rHyp: r > 0 ball t r ⊆ T
    using open-contains-ball-eq open-domain(1) ‹t ∈ T› by blast
  moreover have t − r/2 < 0
    using ‹r > 0› ‹t < 0› by auto
  moreover have {0−−t} ⊆ T
    using subintervalI[OF init-time ‹t ∈ T›] .
  ultimately have subs: {0<−−<t − r/2} ⊆ T
    unfolding open-segment-eq-real-ivl closed-segment-eq-real-ivl
```

real-ivl-eqs[*OF rHyp*(*1*)] **by**(*auto simp*: *subset-eq*)
have $t - r/2 \in T$
using *rHyp* **unfolding** *real-ivl-eqs* **by** (*simp add*: *subset-eq*)
hence $\{0{-}{-}t - r/2\} \subseteq T$
using *subintervalI*[*OF init-time*] **by** *blast*
hence $(D\ (\lambda t.\ \varphi\ t\ s) = (\lambda t.\ f\ (\varphi\ t\ s))\ on\ \{0{-}{-}(t - r/2)\})$
using *ivp*(*1*)[*OF* - ‹$s \in S$›] **by** *auto*
hence *vderiv*: $(D\ (\lambda t.\ \varphi\ t\ s) = (\lambda t.\ f\ (\varphi\ t\ s))\ on\ \{0{<}{-}{-}{<}t - r/2\})$
apply(*rule has-vderiv-on-subset*)
unfolding *open-segment-eq-real-ivl closed-segment-eq-real-ivl* **by** *auto*
have $t \in \{0{<}{-}{-}{<}t - r/2\}$
unfolding *open-segment-eq-real-ivl* **using** *rHyp* ‹$t < 0$› **by** *simp*
moreover have $D\ (\lambda\tau.\ \varphi\ \tau\ s) \mapsto (\lambda\tau.\ \tau *_R f\ (\varphi\ t\ s))\ (at\ t\ within\ \{0{<}{-}{-}{<}t - r/2\})$
using *vderiv calculation* **unfolding** *has-vderiv-on-def has-vector-derivative-def* **by** *blast*
moreover have *open* $\{0{<}{-}{-}{<}t - r/2\}$
unfolding *open-segment-eq-real-ivl* **by** *simp*
ultimately show *?thesis*
using *subs that* **by** *blast*
qed

lemma *has-derivative-on-open3*:
assumes $s \in S$
obtains B **where** $0 \in B$ **and** *open* B **and** $B \subseteq T$
and $D\ (\lambda\tau.\ \varphi\ \tau\ s) \mapsto (\lambda\tau.\ \tau *_R f\ (\varphi\ 0\ s))\ at\ 0\ within\ B$
proof−
obtain r::*real* **where** *rHyp*: $r > 0\ ball\ 0\ r \subseteq T$
using *open-contains-ball-eq open-domain*(*1*) *init-time* **by** *blast*
hence $r/2 \in T\ -r/2 \in T\ r/2 > 0$
unfolding *real-ivl-eqs* **by** *auto*
hence *subs*: $\{0{-}{-}r/2\} \subseteq T\ \{0{-}{-}(-r/2)\} \subseteq T$
using *subintervalI*[*OF init-time*] **by** *auto*
hence $(D\ (\lambda t.\ \varphi\ t\ s) = (\lambda t.\ f\ (\varphi\ t\ s))\ on\ \{0{-}{-}r/2\})$
$(D\ (\lambda t.\ \varphi\ t\ s) = (\lambda t.\ f\ (\varphi\ t\ s))\ on\ \{0{-}{-}(-r/2)\})$
using *ivp*(*1*)[*OF* - ‹$s \in S$›] **by** *auto*
also have $\{0{-}{-}r/2\} = \{0{-}{-}r/2\} \cup closure\ \{0{-}{-}r/2\} \cap closure\ \{0{-}{-}(-r/2)\}$
$\{0{-}{-}(-r/2)\} = \{0{-}{-}(-r/2)\} \cup closure\ \{0{-}{-}r/2\} \cap closure\ \{0{-}{-}(-r/2)\}$
unfolding *closed-segment-eq-real-ivl* ‹$r/2 > 0$› **by** *auto*
ultimately have *vderivs*:
$(D\ (\lambda t.\ \varphi\ t\ s) = (\lambda t.\ f\ (\varphi\ t\ s))\ on\ \{0{-}{-}r/2\} \cup closure\ \{0{-}{-}r/2\} \cap closure\ \{0{-}{-}(-r/2)\})$
$(D\ (\lambda t.\ \varphi\ t\ s) = (\lambda t.\ f\ (\varphi\ t\ s))\ on\ \{0{-}{-}(-r/2)\} \cup closure\ \{0{-}{-}r/2\} \cap closure\ \{0{-}{-}(-r/2)\})$
unfolding *closed-segment-eq-real-ivl* ‹$r/2 > 0$› **by** *auto*
have *obs*: $0 \in \{-r/2{<}{-}{-}{<}r/2\}$
unfolding *open-segment-eq-real-ivl* **using** ‹$r/2 > 0$› **by** *auto*
have *union*: $\{-r/2{-}{-}r/2\} = \{0{-}{-}r/2\} \cup \{0{-}{-}(-r/2)\}$
unfolding *closed-segment-eq-real-ivl* **by** *auto*

hence $(D\ (\lambda t.\ \varphi\ t\ s) = (\lambda t.\ f\ (\varphi\ t\ s))\ on\ \{-r/2--r/2\})$
using *has-vderiv-on-union*[*OF vderivs*] **by** *simp*
hence $(D\ (\lambda t.\ \varphi\ t\ s) = (\lambda t.\ f\ (\varphi\ t\ s))\ on\ \{-r/2<--<r/2\})$
using *has-vderiv-on-subset*[*OF - segment-open-subset-closed*[*of* $-r/2\ r/2$]] **by** *auto*
hence $D\ (\lambda\tau.\ \varphi\ \tau\ s) \mapsto (\lambda\tau.\ \tau *_R f\ (\varphi\ 0\ s))\ (at\ 0\ within\ \{-r/2<--<r/2\})$
unfolding *has-vderiv-on-def has-vector-derivative-def* **using** *obs* **by** *blast*
moreover have *open* $\{-r/2<--<r/2\}$
unfolding *open-segment-eq-real-ivl* **by** *simp*
moreover have $\{-r/2<--<r/2\} \subseteq T$
using *subs union segment-open-subset-closed* **by** *blast*
ultimately show *?thesis*
using *obs that* **by** *blast*
qed

lemma *has-derivative-on-open*:
assumes $t \in T\ s \in S$
obtains B **where** $t \in B$ **and** *open* B **and** $B \subseteq T$
and $D\ (\lambda\tau.\ \varphi\ \tau\ s) \mapsto (\lambda\tau.\ \tau *_R f\ (\varphi\ t\ s))\ at\ t\ within\ B$
apply(*subgoal-tac* $t < 0 \lor t = 0 \lor t > 0$)
using *has-derivative-on-open1*[*OF - assms*] *has-derivative-on-open2*[*OF - assms*]
has-derivative-on-open3[*OF* ‹$s \in S$›] **by** *blast force*

lemma *in-domain*:
assumes $s \in S$
shows $(\lambda t.\ \varphi\ t\ s) \in T \to S$
unfolding *ex-ivl-eq*[*symmetric*] *existence-ivl-def*
using *local.mem-existence-ivl-subset ivp*(*3*)[*OF - assms*] **by** *blast*

lemma *has-vderiv-on-domain*:
assumes $s \in S$
shows $D\ (\lambda t.\ \varphi\ t\ s) = (\lambda t.\ f\ (\varphi\ t\ s))\ on\ T$
proof(*unfold has-vderiv-on-def has-vector-derivative-def*, *clarsimp*)
fix t **assume** $t \in T$
then obtain B **where** $t \in B$ **and** *open* B **and** $B \subseteq T$
and *Dhyp*: $D\ (\lambda t.\ \varphi\ t\ s) \mapsto (\lambda\tau.\ \tau *_R f\ (\varphi\ t\ s))\ at\ t\ within\ B$
using *assms has-derivative-on-open*[*OF* ‹$t \in T$›] **by** *blast*
hence $t \in$ *interior* B
using *interior-eq* **by** *auto*
thus $D\ (\lambda t.\ \varphi\ t\ s) \mapsto (\lambda\tau.\ \tau *_R f\ (\varphi\ t\ s))\ at\ t\ within\ T$
using *has-derivative-at-within-mono*[*OF -* ‹$B \subseteq T$› *Dhyp*] **by** *blast*
qed

lemma *in-ivp-sols*:
assumes $s \in S$
shows $(\lambda t.\ \varphi\ t\ s) \in Sols\ (\lambda t.\ f)\ T\ S\ 0\ s$
using *has-vderiv-on-domain ivp*(*2*) *in-domain* **apply**(*rule ivp-solsI*)
using *assms* **by** *auto*

lemma *eq-solution*:
assumes $X \in Sols\ (\lambda t.\ f)\ T\ S\ 0\ s$ **and** $t \in T$ **and** $s \in S$
shows $X\ t = \varphi\ t\ s$
proof−
have $D\ X = (\lambda t.\ f\ (X\ t))$ *on* $(ex\text{-}ivl\ s)$ **and** $X\ 0 = s$ **and** $X \in (ex\text{-}ivl\ s) \to S$
using *ivp-solsD*[*OF assms*(*1*)] **unfolding** *ex-ivl-eq*[*OF* ‹$s \in S$›] **by** *auto*
note *solution-eq-flow*[*OF this*]
hence $X\ t = flow\ 0\ s\ t$
unfolding *ex-ivl-eq*[*OF* ‹$s \in S$›] **using** *assms* **by** *blast*
also have $\varphi\ t\ s = flow\ 0\ s\ t$
apply(*rule solution-eq-flow ivp*)
apply(*simp-all add*: *assms*(*2*,*3*) *ivp*(*2*)[*OF* ‹$s \in S$›])
unfolding *ex-ivl-eq*[*OF* ‹$s \in S$›] **by** (*auto simp*: *has-vderiv-on-domain assms in-domain*)
ultimately show $X\ t = \varphi\ t\ s$
by *simp*
qed

lemma *ivp-sols-collapse*:
assumes $T = UNIV$ **and** $s \in S$
shows $Sols\ (\lambda t.\ f)\ T\ S\ 0\ s = \{(\lambda t.\ \varphi\ t\ s)\}$
using *in-ivp-sols eq-solution assms* **by** *auto*

lemma *additive-in-ivp-sols*:
assumes $s \in S$ **and** $\mathcal{P}\ (\lambda\tau.\ \tau + t)\ T \subseteq T$
shows $(\lambda\tau.\ \varphi\ (\tau + t)\ s) \in Sols\ (\lambda t.\ f)\ T\ S\ 0\ (\varphi\ (0 + t)\ s)$
apply(*rule ivp-solsI*, *rule vderiv-on-compose-add*)
using *has-vderiv-on-domain has-vderiv-on-subset assms* **apply** *blast*
using *in-domain assms* **by** *auto*

lemma *is-monoid-action*:
assumes $s \in S$ **and** $T = UNIV$
shows $\varphi\ 0\ s = s$ **and** $\varphi\ (t_1 + t_2)\ s = \varphi\ t_1\ (\varphi\ t_2\ s)$
proof−
show $\varphi\ 0\ s = s$
using *ivp assms* **by** *simp*
have $\varphi\ (0 + t_2)\ s = \varphi\ t_2\ s$
by *simp*
also have $\varphi\ t_2\ s \in S$
using *in-domain assms* **by** *auto*
finally show $\varphi\ (t_1 + t_2)\ s = \varphi\ t_1\ (\varphi\ t_2\ s)$
using *eq-solution*[*OF additive-in-ivp-sols*] *assms* **by** *auto*
qed

definition *orbit* :: $'a \Rightarrow\ 'a\ set\ (\gamma^{\varphi})$
where $\gamma^{\varphi}\ s = g\text{-}orbital\ f\ (\lambda s.\ True)\ T\ S\ 0\ s$

lemma *orbit-eq*[*simp*]:
assumes $s \in S$

shows $\gamma^\varphi\ s = \{\varphi\ t\ s|\ t.\ t \in T\}$
using *eq-solution assms* **unfolding** *orbit-def g-orbital-eq ivp-sols-def*
by(*auto intro*!: *has-vderiv-on-domain ivp*(*2*) *in-domain*)

lemma *g-orbital-collapses*:
assumes $s \in S$
shows *g-orbital f G T S 0 s* $= \{\varphi\ t\ s|\ t.\ t \in T \wedge (\forall \tau \in down\ T\ t.\ G\ (\varphi\ \tau\ s))\}$
proof(*rule subset-antisym*, *simp-all only*: *subset-eq*)
let *?gorbit* $= \{\varphi\ t\ s\ |t.\ t \in T \wedge (\forall \tau \in down\ T\ t.\ G\ (\varphi\ \tau\ s))\}$
{fix s' **assume** $s' \in$ *g-orbital f G T S 0 s*
then obtain X **and** t **where** *x-ivp*:$X \in$ *Sols* $(\lambda t.\ f)\ T\ S\ 0\ s$
and $X\ t = s'$ **and** $t \in T$ **and** *guard*:$(\mathcal{P}\ X\ (down\ T\ t) \subseteq \{s.\ G\ s\})$
unfolding *g-orbital-def g-orbit-eq* **by** *auto*
have *obs*:$\forall \tau \in (down\ T\ t).\ X\ \tau = \varphi\ \tau\ s$
using *eq-solution*[*OF x-ivp - assms*] **by** *blast*
hence $\mathcal{P}\ (\lambda t.\ \varphi\ t\ s)\ (down\ T\ t) \subseteq \{s.\ G\ s\}$
using *guard* **by** *auto*
also have $\varphi\ t\ s = X\ t$
using *eq-solution*[*OF x-ivp* ‹$t \in T$› *assms*] **by** *simp*
ultimately have $s' \in$ *?gorbit*
using ‹$X\ t = s'$› ‹$t \in T$› **by** *auto***}**
thus $\forall s' \in$ *g-orbital f G T S 0 s*. $s' \in$ *?gorbit*
by *blast*
next
let *?gorbit* $= \{\varphi\ t\ s\ |t.\ t \in T \wedge (\forall \tau \in down\ T\ t.\ G\ (\varphi\ \tau\ s))\}$
{fix s' **assume** $s' \in$ *?gorbit*
then obtain t **where** $\mathcal{P}\ (\lambda t.\ \varphi\ t\ s)\ (down\ T\ t) \subseteq \{s.\ G\ s\}$ **and** $t \in T$ **and** φ
$t\ s = s'$
by *blast*
hence $s' \in$ *g-orbital f G T S 0 s*
using *assms* **by**(*auto intro*!: *g-orbitalI in-ivp-sols*)**}**
thus $\forall s' \in$*?gorbit*. $s' \in$ *g-orbital f G T S 0 s*
by *blast*
qed

end

lemma *line-is-local-flow*:
$0 \in T \Longrightarrow$ *is-interval* $T \Longrightarrow$ *open* $T \Longrightarrow$ *local-flow* $(\lambda\ s.\ c)\ T$ *UNIV* $(\lambda\ t\ s.\ s$
$+\ t *_R c)$
apply(*unfold-locales*, *simp-all add*: *local-lipschitz-def lipschitz-on-def*, *clarsimp*)
apply(*rule-tac x=1* **in** *exI*, *clarsimp*, *rule-tac x=1/2* **in** *exI*, *simp*)
apply(*rule-tac* $f'1=\lambda\ s.\ 0$ **and** $g'1=\lambda\ s.\ c$ **in** *derivative-intros*(*191*))
apply(*rule derivative-intros*, *simp*)+
by *simp-all*

end
theory *hs-prelims-matrices*
imports *hs-prelims-dyn-sys*

begin

Chapter 2

Linear Algebra for Hybrid Systems

Linear systems of ordinary differential equations (ODEs) are those whose vector fields are linear operators. That is, there is a matrix A such that the system $x'\ t = f\ (x\ t)$ can be rewritten as $x'\ t = A *v\ x\ t$. The end goal of this section is to prove that every linear system of ODEs has a unique solution, and to obtain a characterization of said solution. We start by formalising various properties of vector spaces.

2.1 Vector operations

abbreviation e $k \equiv$ *axis k 1*

abbreviation *entries* $(A::'a\,\hat{}\,'n\,\hat{}\,'m) \equiv \{A\ \$\ i\ \$\ j \mid i\ j.\ i \in UNIV \wedge j \in UNIV\}$

abbreviation *kronecker-delta* :: $'a \Rightarrow 'a \Rightarrow 'b \Rightarrow ('b::zero)$ $(\delta_K$ - - - $[55,\ 55,\ 55]$ $55)$
  where $\delta_K\ i\ j\ q \equiv (if\ i = j\ then\ q\ else\ 0)$

lemma *finite-sum-univ-singleton*: $(sum\ g\ UNIV) = sum\ g\ \{i\} + sum\ g\ (UNIV - \{i\})$ **for** *i::'a::finite*
  by (*metis add.commute finite-class.finite-UNIV sum.subset-diff top-greatest*)

lemma *kronecker-delta-simps*[*simp*]:
  fixes *q*::(*'a::semiring-0*) **and** *i::'n::finite*
  shows $(\sum j{\in}UNIV.\ f\ j * (\delta_K\ j\ i\ q)) = f\ i * q$
    and $(\sum j{\in}UNIV.\ f\ j * (\delta_K\ i\ j\ q)) = f\ i * q$
    and $(\sum j{\in}UNIV.\ (\delta_K\ i\ j\ q) * f\ j) = q * f\ i$
    and $(\sum j{\in}UNIV.\ (\delta_K\ j\ i\ q) * f\ j) = q * f\ i$
  by (*auto simp*: *finite-sum-univ-singleton*[*of - i*])

lemma *sum-axis*[*simp*]:

fixes q::('*a*::*semiring-0*)
shows ($\sum j{\in}UNIV.\ f\ j * axis\ i\ q\ \$\ j) = f\ i * q$
and ($\sum j{\in}UNIV.\ axis\ i\ q\ \$\ j * f\ j) = q * f\ i$
unfolding *axis-def* **by**(*auto simp*: *vec-eq-iff*)

lemma *sum-scalar-nth-axis*: $sum\ (\lambda i.\ (x\ \$\ i) *s\ \mathrm{e}\ i)\ UNIV = x$ **for** x :: ('*a*::*semiring-1*) ^'*n*
unfolding *vec-eq-iff axis-def* **by** *simp*

lemma *scalar-eq-scaleR*[*simp*]: $c *s\ x = c *_R x$ **for** c :: *real*
unfolding *vec-eq-iff* **by** *simp*

lemma *matrix-add-rdistrib*: $((B + C) ** A) = (B ** A) + (C ** A)$
by (*vector matrix-matrix-mult-def sum.distrib*[*symmetric*] *field-simps*)

lemma *vec-mult-inner*: $(A *v\ v) \cdot w = v \cdot (transpose\ A *v\ w)$ **for** A::*real* ^'*n*^'*n*
unfolding *matrix-vector-mult-def transpose-def inner-vec-def*
apply(*simp add*: *sum-distrib-right sum-distrib-left*)
apply(*subst sum.swap*)
apply(*subgoal-tac* $\forall\ i\ j.\ A\ \$\ i\ \$\ j * v\ \$\ j * w\ \$\ i = v\ \$\ j * (A\ \$\ i\ \$\ j * w\ \$\ i)$)
by *presburger* (*simp*)

lemma *uminus-axis-eq*[*simp*]: $-\ axis\ i\ k = axis\ i\ (-k)$ **for** k::'*a*::*ring*
unfolding *axis-def* **by**(*simp add*: *vec-eq-iff*)

lemma *norm-axis-eq*[*simp*]: $\|axis\ i\ k\| = \|k\|$
proof(*simp add*: *axis-def norm-vec-def L2-set-def*)
have $(\sum j{\in}UNIV.\ (\|(\delta_K\ j\ i\ k)\|)^2) = (\sum j{\in}\{i\}.\ (\|(\delta_K\ j\ i\ k)\|)^2) + (\sum j{\in}(UNIV{-}\{i\}).\ (\|(\delta_K\ j\ i\ k)\|)^2)$
using *finite-sum-univ-singleton* **by** *blast*
also have ... $= (\|k\|)^2$ **by** *simp*
finally show $sqrt\ (\sum j{\in}UNIV.\ (norm\ (if\ j = i\ then\ k\ else\ 0))^2) = norm\ k$ **by** *simp*
qed

lemma *matrix-axis-0*:
fixes A :: ('*a*::*idom*) ^'*n*^'*m*
assumes $k \neq 0$ **and** h:$\forall\ i.\ (A *v\ (axis\ i\ k)) = 0$
shows $A = 0$
proof−
{**fix** i::'*n*
have $0 = (\sum j{\in}UNIV.\ (axis\ i\ k)\ \$\ j *s\ column\ j\ A)$
using *h matrix-mult-sum*[*of A axis i k*] **by** *simp*
also have ... $= k *s\ column\ i\ A$
by(*simp add*: *axis-def vector-scalar-mult-def column-def vec-eq-iff mult.commute*)
finally have $k *s\ column\ i\ A = 0$
unfolding *axis-def* **by** *simp*
hence $column\ i\ A = 0$
using *vector-mul-eq-0* ‹$k \neq 0$› **by** *blast*}
thus $A = 0$

unfolding *column-def vec-eq-iff* **by** *simp*
qed

lemma *scaleR-norm-sgn-eq*: $(\|x\|) *_R\ sgn\ x = x$
by (*metis divideR-right norm-eq-zero scale-eq-0-iff sgn-div-norm*)

lemma *vector-scaleR-commute*: $A *v\ c *_R x = c *_R (A *v\ x)$ **for** x :: $('a::real\text{-}normed\text{-}algebra\text{-}1)\hat{\ }'n$
unfolding *scaleR-vec-def matrix-vector-mult-def* **by**(*auto simp*: *vec-eq-iff scaleR-right.sum*)

lemma *scaleR-vector-assoc*: $c *_R (A *v\ x) = (c *_R A) *v\ x$ **for** x :: $('a::real\text{-}normed\text{-}algebra\text{-}1)\hat{\ }'n$
unfolding *matrix-vector-mult-def* **by**(*auto simp*: *vec-eq-iff scaleR-right.sum*)

lemma *mult-norm-matrix-sgn-eq*:
fixes x :: $('a::real\text{-}normed\text{-}algebra\text{-}1)\hat{\ }'n$
shows $(\|A *v\ sgn\ x\|) * (\|x\|) = \|A *v\ x\|$
proof−
have $\|A *v\ x\| = \|A *v\ ((\|x\|) *_R\ sgn\ x)\|$
by(*simp add*: *scaleR-norm-sgn-eq*)
also have ... $= (\|A *v\ sgn\ x\|) * (\|x\|)$
by(*simp add*: *vector-scaleR-commute*)
finally show *?thesis* **..**
qed

2.2 Matrix norms

Here we develop the foundations for obtaining the Lipschitz constant for every linear system of ODEs $x'\ t = A *v\ x\ t$. For that we derive some properties of two matrix norms.

2.2.1 Matrix operator norm

abbreviation *op-norm* :: $('a::real\text{-}normed\text{-}algebra\text{-}1)\hat{\ }'n\hat{\ }'m \Rightarrow real$ $((1\|\text{-}\|_{op})$ [*65*] *61*)
where $\|A\|_{op} \equiv onorm\ (\lambda x.\ A *v\ x)$

lemma *norm-matrix-bound*:
fixes A::$('a::real\text{-}normed\text{-}algebra\text{-}1)\hat{\ }'n\hat{\ }'m$
shows $\|x\| = 1 \Longrightarrow \|A *v\ x\| \le \|(\chi\ i\ j.\ \|A\ \$\ i\ \$\ j\|) *v\ 1\|$
proof−
fix x::$('a, 'n)$ *vec* **assume** $\|x\| = 1$
hence *xi-le1*:$\bigwedge i.\ \|x\ \$\ i\| \le 1$
by (*metis Finite-Cartesian-Product.norm-nth-le*)
{**fix** j::$'m$
have $\|(\sum i{\in}UNIV.\ A\ \$\ j\ \$\ i * x\ \$\ i)\| \le (\sum i{\in}UNIV.\ \|A\ \$\ j\ \$\ i * x\ \$\ i\|)$
using *norm-sum* **by** *blast*
also have ... $\le (\sum i{\in}UNIV.\ (\|A\ \$\ j\ \$\ i\|) * (\|x\ \$\ i\|))$
by (*simp add*: *norm-mult-ineq sum-mono*)
also have ... $\le (\sum i{\in}UNIV.\ (\|A\ \$\ j\ \$\ i\|) * 1)$

using *xi-le1* **by** (*simp add*: *sum-mono mult-left-le*)
finally have $\|(\sum i{\in}UNIV.\ A\ \$\ j\ \$\ i * x\ \$\ i)\| \le (\sum i{\in}UNIV.\ (\|A\ \$\ j\ \$\ i\|) * 1)$ **by** *simp*}
hence $\bigwedge j.\ \|(A *v\ x)\ \$\ j\| \le ((\chi\ i1\ i2.\ \|A\ \$\ i1\ \$\ i2\|) *v\ 1)\ \$\ j$
unfolding *matrix-vector-mult-def* **by** *simp*
hence $(\sum j{\in}UNIV.\ (\|(A *v\ x)\ \$\ j\|)^2) \le (\sum j{\in}UNIV.\ (\|((\chi\ i1\ i2.\ \|A\ \$\ i1\ \$\ i2\|) *v\ 1)\ \$\ j\|)^2)$
by (*metis* (*mono-tags*, *lifting*) *norm-ge-zero power2-abs power-mono real-norm-def sum-mono*)
thus $\|A *v\ x\| \le \|(\chi\ i\ j.\ \|A\ \$\ i\ \$\ j\|) *v\ 1\|$
unfolding *norm-vec-def L2-set-def* **by** *simp*
qed

lemma *onorm-set-proptys*:
fixes A::('*a*::*real-normed-algebra-1*)^'*n*^'*m*
shows *bounded* (*range* $(\lambda x.\ (\|A *v\ x\|)\ /\ (\|x\|))$)
and *bdd-above* (*range* $(\lambda x.\ (\|A *v\ x\|)\ /\ (\|x\|))$)
and (*range* $(\lambda x.\ (\|A *v\ x\|)\ /\ (\|x\|))) \neq \{\}$
unfolding *bounded-def bdd-above-def image-def dist-real-def* **apply**(*rule-tac x=0* **in** *exI*)
apply(*rule-tac* $x=\|(\chi\ i\ j.\ \|A\ \$\ i\ \$\ j\|) *v\ 1\|$ **in** *exI*, *clarsimp*,
subst mult-norm-matrix-sgn-eq[*symmetric*], *clarsimp*,
rule-tac x=sgn - **in** *norm-matrix-bound*, *simp add*: *norm-sgn*)+
by *force*

lemma *op-norm-set-proptys*:
fixes A::('*a*::*real-normed-algebra-1*)^'*n*^'*m*
shows *bounded* $\{\|A *v\ x\| \mid x.\ \|x\| = 1\}$
and *bdd-above* $\{\|A *v\ x\| \mid x.\ \|x\| = 1\}$
and $\{\|A *v\ x\| \mid x.\ \|x\| = 1\} \neq \{\}$
unfolding *bounded-def bdd-above-def* **apply** *safe*
apply(*rule-tac x=0* **in** *exI*, *rule-tac* $x=\|(\chi\ i\ j.\ \|A\ \$\ i\ \$\ j\|) *v\ 1\|$ **in** *exI*)
apply(*force simp*: *norm-matrix-bound dist-real-def*)
apply(*rule-tac* $x=\|(\chi\ i\ j.\ \|A\ \$\ i\ \$\ j\|) *v\ 1\|$ **in** *exI*, *force simp*: *norm-matrix-bound*)
using *ex-norm-eq-1* **by** *blast*

lemma *op-norm-def*:
fixes A::('*a*::*real-normed-algebra-1*)^'*n*^'*m*
shows $\|A\|_{op} = Sup\ \{\|A *v\ x\| \mid x.\ \|x\| = 1\}$
apply(*rule antisym*[*OF onorm-le cSup-least*[*OF op-norm-set-proptys*(*3*)]])
apply(*case-tac x = 0*, *simp*)
apply(*subst mult-norm-matrix-sgn-eq*[*symmetric*], *simp*)
apply(*rule cSup-upper*[*OF - op-norm-set-proptys*(*2*)])
apply(*force simp*: *norm-sgn*)
unfolding *onorm-def* **apply**(*rule cSup-upper*[*OF - onorm-set-proptys*(*2*)])
by (*simp add*: *image-def*, *clarsimp*) (*metis div-by-1*)

lemma *norm-matrix-le-op-norm*: $\|x\| = 1 \Longrightarrow \|A *v\ x\| \le \|A\|_{op}$
apply(*unfold onorm-def*, *rule cSup-upper*[*OF - onorm-set-proptys*(*2*)])

unfolding *image-def* **by** (*clarsimp*, *rule-tac x=x* **in** *exI*) *simp*

lemma *op-norm-ge-0*: $0 \leq \|A\|_{op}$
using *ex-norm-eq-1 norm-ge-zero norm-matrix-le-op-norm basic-trans-rules*(*23*)
by *blast*

lemma *norm-sgn-le-op-norm*: $\|A *v\ sgn\ x\| \leq \|A\|_{op}$
by(*cases x=0*, *simp-all add*: *norm-sgn norm-matrix-le-op-norm op-norm-ge-0*)

lemma *norm-matrix-le-mult-op-norm*: $\|A *v\ x\| \leq (\|A\|_{op}) * (\|x\|)$
proof−
have $\|A *v\ x\| = (\|A *v\ sgn\ x\|) * (\|x\|)$
by(*simp add*: *mult-norm-matrix-sgn-eq*)
also have ... $\leq (\|A\|_{op}) * (\|x\|)$
using *norm-sgn-le-op-norm*[*of A*] **by** (*simp add*: *mult-mono′*)
finally show *?thesis* **by** *simp*
qed

lemma *blin-norm-matrix*: *bounded-linear* ((∗*v*) *A*) **for** *A*::(′*a*::*real-normed-algebra-1*) ^′*n* ^′*m*
by (*unfold-locales*) (*auto intro*: *norm-matrix-le-mult-op-norm simp*:
mult.commute matrix-vector-right-distrib vector-scaleR-commute)

lemma *op-norm-zero-iff*: $(\|A\|_{op} = 0) = (A = 0)$ **for** *A*::(′*a*::*real-normed-field*) ^′*n* ^′*m*
unfolding *onorm-eq-0*[*OF blin-norm-matrix*] **using** *matrix-axis-0*[*of 1 A*] **by** *fastforce*

lemma *op-norm-triangle*: $\|A + B\|_{op} \leq (\|A\|_{op}) + (\|B\|_{op})$
using *onorm-triangle*[*OF blin-norm-matrix*[*of A*] *blin-norm-matrix*[*of B*]]
matrix-vector-mult-add-rdistrib[*symmetric*, *of A - B*] **by** *simp*

lemma *op-norm-scaleR*: $\|c *_R A\|_{op} = |c| * (\|A\|_{op})$
unfolding *onorm-scaleR*[*OF blin-norm-matrix*, *symmetric*] *scaleR-vector-assoc*
..

lemma *op-norm-matrix-matrix-mult-le*:
fixes *A*::(′*a*::*real-normed-algebra-1*) ^′*n* ^′*m*
shows $\|A ** B\|_{op} \leq (\|A\|_{op}) * (\|B\|_{op})$
proof(*rule onorm-le*)
have $0 \leq (\|A\|_{op})$
by(*rule onorm-pos-le*[*OF blin-norm-matrix*])
fix *x* **have** $\|A ** B *v\ x\| = \|A *v\ (B *v\ x)\|$
by (*simp add*: *matrix-vector-mul-assoc*)
also have ... $\leq (\|A\|_{op}) * (\|B *v\ x\|)$
by (*simp add*: *norm-matrix-le-mult-op-norm*[*of - B *v x*])
also have ... $\leq (\|A\|_{op}) * ((\|B\|_{op}) * (\|x\|))$
using *norm-matrix-le-mult-op-norm*[*of B x*] ‹$0 \leq (\|A\|_{op})$› *mult-left-mono* **by** *blast*
finally show $\|A ** B *v\ x\| \leq (\|A\|_{op}) * (\|B\|_{op}) * (\|x\|)$
by *simp*

qed

lemma *norm-matrix-vec-mult-le-transpose*:
$\|x\| = 1 \Longrightarrow (\|A *v\ x\|) \leq sqrt\ (\|transpose\ A ** A\|_{op}) * (\|x\|)$ **for** A::*real*^'n^'n
proof−
  assume $\|x\| = 1$
  have $(\|A *v\ x\|)^2 = (A *v\ x) \cdot (A *v\ x)$
    using *dot-square-norm*[*of* $(A *v\ x)$] **by** *simp*
  also have ... $= x \cdot (transpose\ A *v\ (A *v\ x))$
    using *vec-mult-inner* **by** *blast*
  also have ... $\leq (\|x\|) * (\|transpose\ A *v\ (A *v\ x)\|)$
    using *norm-cauchy-schwarz* **by** *blast*
  also have ... $\leq (\|transpose\ A ** A\|_{op}) * (\|x\|)$^*2*
    apply(*subst matrix-vector-mul-assoc*)
    using *norm-matrix-le-mult-op-norm*[*of transpose* $A ** A\ x$]
    by (*simp add*: ‹$\|x\| = 1$›)
  finally have $((\|A *v\ x\|))$^*2* $\leq (\|transpose\ A ** A\|_{op}) * (\|x\|)$^*2*
    by *linarith*
  thus $(\|A *v\ x\|) \leq sqrt\ ((\|transpose\ A ** A\|_{op})) * (\|x\|)$
    by (*simp add*: ‹$\|x\| = 1$› *real-le-rsqrt*)
qed

lemma *op-norm-le-sum-column*: $\|A\|_{op} \leq (\sum i{\in}UNIV.\ \|column\ i\ A\|)$ **for** A::*real*^'n^'m

proof(*unfold op-norm-def*, *rule cSup-least*[*OF op-norm-set-proptys*(*3*)], *clarsimp*)
  fix x::*real*^'n **assume** *x-def*:$\|x\| = 1$
  hence *x-hyp*:$\bigwedge i.\ \|x\ \$\ i\| \leq 1$
    by (*simp add*: *norm-bound-component-le-cart*)
  have $(\|A *v\ x\|) = \|(\sum i{\in}UNIV.\ x\ \$\ i *s\ column\ i\ A)\|$
    by(*subst matrix-mult-sum*[*of A*], *simp*)
  also have ... $\leq (\sum i{\in}UNIV.\ \|x\ \$\ i *s\ column\ i\ A\|)$
    by (*simp add*: *sum-norm-le*)
  also have ... $= (\sum i{\in}UNIV.\ (\|x\ \$\ i\|) * (\|column\ i\ A\|))$
    by (*simp add*: *mult-norm-matrix-sgn-eq*)
  also have ... $\leq (\sum i{\in}UNIV.\ \|column\ i\ A\|)$
    using *x-hyp* **by** (*simp add*: *mult-left-le-one-le sum-mono*)
  finally show $\|A *v\ x\| \leq (\sum i{\in}UNIV.\ \|column\ i\ A\|)$ **.**
qed

lemma *op-norm-le-transpose*: $\|A\|_{op} \leq \|transpose\ A\|_{op}$ **for** A::*real*^'n^'n
proof−
  have *obs*:$\forall x.\ \|x\| = 1 \longrightarrow (\|A *v\ x\|) \leq sqrt\ ((\|transpose\ A ** A\|_{op})) * (\|x\|)$
    using *norm-matrix-vec-mult-le-transpose* **by** *blast*
  have $(\|A\|_{op}) \leq sqrt\ ((\|transpose\ A ** A\|_{op}))$
    using *obs* **apply**(*unfold op-norm-def*)
    by (*rule cSup-least*[*OF op-norm-set-proptys*(*3*)]) *clarsimp*
  hence $((\|A\|_{op}))^2 \leq (\|transpose\ A ** A\|_{op})$
    using *power-mono*[*of* $(\|A\|_{op})$ - *2*] *op-norm-ge-0* **by** *force*
  also have ... $\leq (\|transpose\ A\|_{op}) * (\|A\|_{op})$

using *op-norm-matrix-matrix-mult-le* **by** *blast*
finally have $((\|A\|_{op}))^2 \leq (\|transpose\ A\|_{op}) * (\|A\|_{op})$ **by** *linarith*
thus $(\|A\|_{op}) \leq (\|transpose\ A\|_{op})$
using *sq-le-cancel*[*of* $(\|A\|_{op})$] *op-norm-ge-0* **by** *blast*
qed

2.2.2 Matrix maximum norm

abbreviation *max-norm* $(A::real\hat{\ }'n\hat{\ }'m) \equiv Max\ (abs\ `\ (entries\ A))$

notation *max-norm* $((1\|\text{-}\|_{max})\ [65]\ 61)$

lemma *max-norm-def*: $\|A\|_{max} = Max\ \{|A\ \$\ i\ \$\ j| |i\ j.\ i{\in}UNIV \wedge j{\in}UNIV\}$
by(*simp add*: *image-def*, *rule arg-cong*[*of - - Max*], *blast*)

lemma *max-norm-set-proptys*: *finite* $\{|A\ \$\ i\ \$\ j|\ |i\ j.\ i \in UNIV \wedge j \in UNIV\}$ (**is** *finite ?X*)
proof−
have $\bigwedge i.$ *finite* $\{|A\ \$\ i\ \$\ j|\ |\ j.\ j \in UNIV\}$
using *finite-Atleast-Atmost-nat* **by** *fastforce*
hence *finite* $(\bigcup i{\in}UNIV.\ \{|A\ \$\ i\ \$\ j|\ |\ j.\ j \in UNIV\})$ (**is** *finite ?Y*)
using *finite-class.finite-UNIV* **by** *blast*
also have $?X \subseteq ?Y$ **by** *auto*
ultimately show *?thesis*
using *finite-subset* **by** *blast*
qed

lemma *max-norm-ge-0*: $0 \leq \|A\|_{max}$
proof−
have $\bigwedge i\ j.\ |A\ \$\ i\ \$\ j| \geq 0$ **by** *simp*
also have $\bigwedge i\ j.\ |A\ \$\ i\ \$\ j| \leq \|A\|_{max}$
unfolding *max-norm-def* **using** *max-norm-set-proptys Max-ge max-norm-def* **by** *blast*
finally show $0 \leq \|A\|_{max}$.
qed

lemma *op-norm-le-max-norm*:
fixes $A::real\hat{\ }('n::finite)\hat{\ }('m::finite)$
shows $\|A\|_{op} \leq real\ CARD('m) * real\ CARD('n) * (\|A\|_{max})$
apply(*rule onorm-le-matrix-component*)
unfolding *max-norm-def* **by**(*rule Max-ge*[*OF max-norm-set-proptys*]) *force*

2.3 Picard Lindeloef for linear systems

Now we prove our first objective. First we obtain the Lipschitz constant for linear systems of ODEs, and then we prove that IVPs arising from these satisfy the conditions for Picard-Lindeloef theorem (hence, they have a unique solution).

lemma *matrix-lipschitz-constant*:
fixes $A::real\hat{}'n\hat{}'n$
shows $dist\ (A *v\ x)\ (A *v\ y) \leq (real\ CARD('n))^2 * (\|A\|_{max}) * dist\ x\ y$
unfolding *dist-norm matrix-vector-mult-diff-distrib*[*symmetric*]
proof(*subst mult-norm-matrix-sgn-eq*[*symmetric*])
have $\|A\|_{op} \leq (\|A\|_{max}) * (real\ CARD('n) * real\ CARD('n))$
by (*metis* (*no-types*) *Groups.mult-ac*(*2*) *op-norm-le-max-norm*)
then have $(\|A\|_{op}) * (\|x - y\|) \leq (real\ CARD('n))^2 * (\|A\|_{max}) * (\|x - y\|)$
by (*metis* (*no-types*, *lifting*) *mult.commute mult-right-mono norm-ge-zero power2-eq-square*)
also have $(\|A *v\ sgn\ (x - y)\|) * (\|x - y\|) \leq (\|A\|_{op}) * (\|x - y\|)$
by (*simp add*: *norm-sgn-le-op-norm mult-mono'*)
ultimately show $(\|A *v\ sgn\ (x - y)\|) * (\|x - y\|) \leq (real\ CARD('n))^2 * (\|A\|_{max}) * (\|x - y\|)$
using *order-trans-rules*(*23*) **by** *blast*
qed

lemma *picard-lindeloef-linear-system*:
fixes $A::real\hat{}'n\hat{}'n$
defines $L \equiv (real\ CARD('n))^2 * (\|A\|_{max})$
shows *picard-lindeloef* (λ *t s*. *A* $*v$ *s*) *UNIV UNIV 0*
apply(*unfold-locales*, *simp-all add*: *local-lipschitz-def lipschitz-on-def*, *clarsimp*)
apply(*rule-tac x=1* **in** *exI*, *clarsimp*, *rule-tac x=L* **in** *exI*, *safe*)
using *max-norm-ge-0*[*of A*] **unfolding** *assms* **by** *force* (*rule matrix-lipschitz-constant*)

lemma *picard-lindeloef-affine-system*:
fixes $A::real\hat{}'n\hat{}'n$
shows *picard-lindeloef* (λ *t s*. *A* $*v$ *s* + *b*) *UNIV UNIV 0*
apply(*rule picard-lindeloef-add*[*OF picard-lindeloef-linear-system*])
using *picard-lindeloef-constant* **by** *auto*

2.4 Matrix Exponential

The general solution for linear systems of ODEs is an exponential function. Unfortunately, this operation is only available in Isabelle for the type class "banach". Hence, we define a type of squared matrices and prove that it is an instance of this class.

2.4.1 Squared matrices operations

typedef *'m sq-mtx* = *UNIV*::($real\hat{}'m\hat{}'m$) *set*
morphisms *to-vec sq-mtx-chi* **by** *simp*

declare *sq-mtx-chi-inverse* [*simp*]
and *to-vec-inverse* [*simp*]

setup-lifting *type-definition-sq-mtx*

lift-definition *sq-mtx-ith*::$'m$ *sq-mtx* $\Rightarrow$ $'m$ $\Rightarrow$ (*real*^$'m$) (**infixl** $$ *90*) **is** *vec-nth* .

lift-definition *sq-mtx-vec-prod*::$'m$ *sq-mtx* $\Rightarrow$ (*real*^$'m$) $\Rightarrow$ (*real*^$'m$) (**infixl** $*_V$ *90*)
is *matrix-vector-mult* .

lift-definition *sq-mtx-column*::$'m$ $\Rightarrow$ $'m$ *sq-mtx* $\Rightarrow$ (*real*^$'m$)
is λi X. *column* i (*to-vec* X) .

lift-definition *vec-sq-mtx-prod*::(*real*^$'m$) $\Rightarrow$ $'m$ *sq-mtx* $\Rightarrow$ (*real*^$'m$) **is** *vector-matrix-mult* .

lift-definition *sq-mtx-diag*::*real* $\Rightarrow$ ($'m$::*finite*) *sq-mtx* (diag) **is** *mat* .

lift-definition *sq-mtx-transpose*::($'m$::*finite*) *sq-mtx* $\Rightarrow$ $'m$ *sq-mtx* (-†) **is** *transpose* .

lift-definition *sq-mtx-row*::$'m$ $\Rightarrow$ ($'m$::*finite*) *sq-mtx* $\Rightarrow$ *real*^$'m$ (row) **is** *row* .

lift-definition *sq-mtx-col*::$'m$ $\Rightarrow$ ($'m$::*finite*) *sq-mtx* $\Rightarrow$ *real*^$'m$ (col) **is** *column* .

lift-definition *sq-mtx-rows*::($'m$::*finite*) *sq-mtx* $\Rightarrow$ (*real*^$'m$) *set* **is** *rows* .

lift-definition *sq-mtx-cols*::($'m$::*finite*) *sq-mtx* $\Rightarrow$ (*real*^$'m$) *set* **is** *columns* .

lemma *to-vec-eq-ith*[*simp*]: (*to-vec* A) \$ i = A $$ i
by *transfer simp*

lemma *sq-mtx-chi-ith*[*simp*]: (*sq-mtx-chi* A) $$ *i1* \$ *i2* = A \$ *i1* \$ *i2*
by *transfer simp*

lemma *sq-mtx-chi-vec-lambda-ith*[*simp*]: *sq-mtx-chi* (χ i j. x i j) $$ *i1* \$ *i2* = x *i1* *i2*
by(*simp add*: *sq-mtx-ith-def*)

lemma *sq-mtx-eq-iff*:
shows ($\bigwedge i$. A $$ i = B $$ i) $\Longrightarrow$ $A = B$
and ($\bigwedge i\ j$. A $$ i \$ j = B $$ i \$ j) $\Longrightarrow$ $A = B$
by(*transfer*, *simp add*: *vec-eq-iff*)+

lemma *sq-mtx-vec-prod-eq*: m $*_V$ x = (χ i. *sum* (λj. (($m$$$i$)\$$j$) $*$ (x\$$j$)) *UNIV*)
by(*transfer*, *simp add*: *matrix-vector-mult-def*)

lemma *sq-mtx-transpose-transpose*[*simp*]:$(A^\dagger)^\dagger = A$
by(*transfer*, *simp*)

lemma *transpose-mult-vec-canon-row*[*simp*]:($A^\dagger$) $*_V$ (e i) = row i A
by *transfer* (*simp add*: *row-def transpose-def axis-def matrix-vector-mult-def*)

lemma *row-ith*[*simp*]:row i A = A \$\$ i
by *transfer* (*simp add*: *row-def*)

lemma *mtx-vec-prod-canon*:$A *_V$ (e i) = col i A
by (*transfer*, *simp add*: *matrix-vector-mult-basis*)

2.4.2 Squared matrices form Banach space

instantiation *sq-mtx* :: (*finite*) *ring*
begin

lift-definition *plus-sq-mtx* :: *'a sq-mtx* ⇒ *'a sq-mtx* ⇒ *'a sq-mtx* **is** (+) **.**

lift-definition *zero-sq-mtx* :: *'a sq-mtx* **is** *0* **.**

lift-definition *uminus-sq-mtx* ::*'a sq-mtx* ⇒ *'a sq-mtx* **is** *uminus* **.**

lift-definition *minus-sq-mtx* :: *'a sq-mtx* ⇒ *'a sq-mtx* ⇒ *'a sq-mtx* **is** (−) **.**

lift-definition *times-sq-mtx* :: *'a sq-mtx* ⇒ *'a sq-mtx* ⇒ *'a sq-mtx* **is** (**) **.**

declare *plus-sq-mtx.rep-eq* [*simp*]
and *minus-sq-mtx.rep-eq* [*simp*]

instance apply *intro-classes*
by(*transfer*, *simp add*: *algebra-simps matrix-mul-assoc matrix-add-rdistrib matrix-add-ldistrib*)+

end

lemma *sq-mtx-plus-ith*[*simp*]:(A + B) \$\$ i = A \$\$ i + B \$\$ i
by(*unfold plus-sq-mtx-def*, *transfer*, *simp*)

lemma *sq-mtx-minus-ith*[*simp*]:(A − B) \$\$ i = A \$\$ i − B \$\$ i
by(*unfold minus-sq-mtx-def*, *transfer*, *simp*)

lemma *mtx-vec-prod-add-rdistr*:$(A + B) *_V x = A *_V x + B *_V x$
unfolding *plus-sq-mtx-def* **apply**(*transfer*)
by (*simp add*: *matrix-vector-mult-add-rdistrib*)

lemma *mtx-vec-prod-minus-rdistrib*:$(A - B) *_V x = A *_V x - B *_V x$
unfolding *minus-sq-mtx-def* **by**(*transfer*, *simp add*: *matrix-vector-mult-diff-rdistrib*)

lemma *mtx-vec-prod-minus-ldistrib*: $A *_V (c - d) = A *_V c - A *_V d$
by (*metis* (*no-types*, *lifting*) *add-diff-cancel diff-add-cancel*
matrix-vector-right-distrib sq-mtx-vec-prod.rep-eq)

lemma *sq-mtx-times-vec-assoc*: $(A * B) *_V x0 = A *_V (B *_V x0)$
by (*transfer*, *simp add*: *matrix-vector-mul-assoc*)

lemma *sq-mtx-vec-mult-sum-cols*:$A *_V\ x = sum\ (\lambda i.\ x\ \$\ i *_R \text{col}\ i\ A)\ UNIV$
by(*transfer*) (*simp add*: *matrix-mult-sum scalar-mult-eq-scaleR*)

instantiation *sq-mtx* :: (*finite*) *real-normed-vector*
begin

definition *norm-sq-mtx* :: $'a$ *sq-mtx* $\Rightarrow$ *real* **where** $\|A\| = \|to\text{-}vec\ A\|_{op}$

lift-definition *scaleR-sq-mtx*::*real* $\Rightarrow$ $'a$ *sq-mtx* $\Rightarrow$ $'a$ *sq-mtx* **is** *scaleR* **.**

definition *sgn-sq-mtx* :: $'a$ *sq-mtx* $\Rightarrow$ $'a$ *sq-mtx*
where *sgn-sq-mtx* $A = (inverse\ (\|A\|)) *_R A$

definition *dist-sq-mtx* :: $'a$ *sq-mtx* $\Rightarrow$ $'a$ *sq-mtx* $\Rightarrow$ *real*
where *dist-sq-mtx* $A\ B = \|A - B\|$

definition *uniformity-sq-mtx* :: ($'a$ *sq-mtx* $\times$ $'a$ *sq-mtx*) *filter*
where *uniformity-sq-mtx* = $(INF\ e{:}\{0{<}..\}.\ principal\ \{(x,\ y).\ dist\ x\ y < e\})$

definition *open-sq-mtx* :: $'a$ *sq-mtx set* $\Rightarrow$ *bool*
where *open-sq-mtx* $U = (\forall x{\in}U.\ \forall_F\ (x',\ y)\ in\ uniformity.\ x' = x \longrightarrow y \in U)$

instance apply *intro-classes*
unfolding *sgn-sq-mtx-def open-sq-mtx-def dist-sq-mtx-def uniformity-sq-mtx-def*
prefer *10* **apply**(*transfer*, *simp add*: *norm-sq-mtx-def op-norm-triangle*)
prefer *9* **apply**(*simp-all add*: *norm-sq-mtx-def zero-sq-mtx-def op-norm-zero-iff*)
by(*transfer*, *simp add*: *norm-sq-mtx-def op-norm-scaleR algebra-simps*)+

end

lemma *sq-mtx-scaleR-ith*[*simp*]: $(c *_R A)\ \$\$\ i = (c\ *_R (A\ \$\$\ i))$
by(*unfold scaleR-sq-mtx-def*, *transfer*, *simp*)

lemma *le-mtx-norm*: $m \in \{\|A *_V\ x\|\ |x.\ \|x\| = 1\} \Longrightarrow m \le \|A\|$
using *cSup-upper*[*of* - $\{\|(to\text{-}vec\ A) *v\ x\|\ |\ x.\ \|x\| = 1\}$]
by (*simp add*: *op-norm-set-proptys*(*2*) *op-norm-def norm-sq-mtx-def sq-mtx-vec-prod.rep-eq*)

lemma *norm-vec-mult-le*: $\|A *_V\ x\| \le (\|A\|) * (\|x\|)$
by (*simp add*: *norm-matrix-le-mult-op-norm norm-sq-mtx-def sq-mtx-vec-prod.rep-eq*)

lemma *sq-mtx-norm-le-sum-col*: $\|A\| \le (\sum i{\in}UNIV.\ \|\text{col}\ i\ A\|)$
using *op-norm-le-sum-column*[*of to-vec A*] **apply**(*simp add*: *norm-sq-mtx-def*)
by(*transfer*, *simp add*: *op-norm-le-sum-column*)

lemma *norm-le-transpose*: $\|A\| \le \|A^\dagger\|$
unfolding *norm-sq-mtx-def* **by** *transfer* (*rule op-norm-le-transpose*)

lemma *norm-eq-norm-transpose*[*simp*]: $\|A^\dagger\| = \|A\|$

using *norm-le-transpose*[*of* A] **and** *norm-le-transpose*[*of* $A^\dagger$] **by** *simp*

lemma *norm-column-le-norm*: $\|A$ \$\$ $i\| \leq \|A\|$
using *norm-vec-mult-le*[*of* $A^\dagger$ e i] **by** *simp*

instantiation *sq-mtx* :: (*finite*) *real-normed-algebra-1*
begin

lift-definition *one-sq-mtx* :: *'a sq-mtx* **is** *sq-mtx-chi* (*mat 1*) **.**

lemma *sq-mtx-one-idty*: $1 * A = A$ $A * 1 = A$ **for** A::*'a sq-mtx*
by(*transfer*, *transfer*, *unfold mat-def matrix-matrix-mult-def*, *simp add*: *vec-eq-iff*)+

lemma *sq-mtx-norm-1*: $\|(1{::}'a\ sq\text{-}mtx)\| = 1$
unfolding *one-sq-mtx-def norm-sq-mtx-def* **apply**(*simp add*: *op-norm-def*)
apply(*subst cSup-eq*[*of* - *1*])
using *ex-norm-eq-1* **by** *auto*

lemma *sq-mtx-norm-times*: $\|A * B\| \leq (\|A\|) * (\|B\|)$ **for** A::*'a sq-mtx*
unfolding *norm-sq-mtx-def times-sq-mtx-def* **by**(*simp add*: *op-norm-matrix-matrix-mult-le*)

instance apply *intro-classes*
apply(*simp-all add*: *sq-mtx-one-idty sq-mtx-norm-1 sq-mtx-norm-times*)
apply(*simp-all add*: *sq-mtx-chi-inject vec-eq-iff one-sq-mtx-def zero-sq-mtx-def mat-def*)
by(*transfer*, *simp add*: *scalar-matrix-assoc matrix-scalar-ac*)+

end

lemma *sq-mtx-one-vec*[*simp*]: $1 *_V s = s$
by (*auto simp*: *sq-mtx-vec-prod-def one-sq-mtx-def*
mat-def vec-eq-iff matrix-vector-mult-def)

lemma *Cauchy-cols*:
fixes X :: *nat* ⇒ (*'a::finite*) *sq-mtx*
assumes *Cauchy* X
shows *Cauchy* (λn. col i (X n))
proof(*unfold Cauchy-def dist-norm*, *clarsimp*)
fix ε::*real* **assume** $\varepsilon > 0$
from *this* **obtain** M **where** *M-def*:$\forall m \geq M.\ \forall n \geq M.\ \|X\ m - X\ n\| < \varepsilon$
using ‹*Cauchy X*› **unfolding** *Cauchy-def* **by**(*simp add*: *dist-sq-mtx-def*) *blast*
{**fix** m n **assume** $m \geq M$ **and** $n \geq M$
hence $\varepsilon > \|X\ m - X\ n\|$
using *M-def* **by** *blast*
moreover have $\|X\ m - X\ n\| \geq \|(X\ m - X\ n) *_V \text{e}\ i\|$
by(*rule le-mtx-norm*[*of* - $X\ m - X\ n$], *force*)
moreover have $\|(X\ m - X\ n) *_V \text{e}\ i\| = \|X\ m *_V \text{e}\ i - X\ n *_V \text{e}\ i\|$
by (*simp add*: *mtx-vec-prod-minus-rdistrib*)
moreover have ... $= \|\text{col}\ i\ (X\ m) - \text{col}\ i\ (X\ n)\|$

by (*simp add*: *mtx-vec-prod-minus-rdistrib mtx-vec-prod-canon*)
ultimately have $\|\text{col } i\ (X\ m) - \text{col } i\ (X\ n)\| < \varepsilon$
by *linarith*}
thus $\exists M.\ \forall m \geq M.\ \forall n \geq M.\ \|\text{col } i\ (X\ m) - \text{col } i\ (X\ n)\| < \varepsilon$
by *blast*
qed

lemma *col-convergent*:
assumes $\forall i.\ (\lambda n.\ \text{col } i\ (X\ n)) \longrightarrow L\ \$\ i$
shows *convergent X*
unfolding *convergent-def* **proof**(*rule-tac x=sq-mtx-chi* (*transpose L*) **in** *exI*)
let *?L* = *sq-mtx-chi* (*transpose L*)
show $X \longrightarrow ?L$
proof(*unfold LIMSEQ-def dist-norm*, *clarsimp*)
fix ε::*real* **assume** $\varepsilon > 0$
let *?a* = *CARD*(*'a*) **fix** ε::*real* **assume** $\varepsilon > 0$
hence $\varepsilon\ /\ ?a > 0$
by *simp*
from *this* **and** *assms* **have** $\forall i.\ \exists\ N.\ \forall n \geq N.\ \|\text{col } i\ (X\ n) - L\ \$\ i\| < \varepsilon/?a$
unfolding *LIMSEQ-def dist-norm convergent-def* **by** *blast*
then obtain *N* **where** $\forall i.\ \forall n \geq N.\ \|\text{col } i\ (X\ n) - L\ \$\ i\| < \varepsilon/?a$
using *finite-nat-minimal-witness*[*of* $\lambda\ i\ n.\ \|\text{col } i\ (X\ n) - L\ \$\ i\| < \varepsilon/?a$] **by**
blast
also have $\bigwedge i\ n.\ (\text{col } i\ (X\ n) - L\ \$\ i) = (\text{col } i\ (X\ n - ?L))$
unfolding *minus-sq-mtx-def* **by**(*transfer*, *simp add*: *transpose-def vec-eq-iff*
column-def)
ultimately have *N-def*:$\forall i.\ \forall n \geq N.\ \|\text{col } i\ (X\ n - ?L)\| < \varepsilon/?a$
by *auto*
have $\forall n \geq N.\ \|X\ n - ?L\| < \varepsilon$
proof(*rule allI*, *rule impI*)
fix *n*::*nat* **assume** $N \leq n$
hence $\forall\ i.\ \|\text{col } i\ (X\ n - ?L)\| < \varepsilon/?a$
using *N-def* **by** *blast*
hence $(\sum i \in UNIV.\ \|\text{col } i\ (X\ n - ?L)\|) < (\sum (i::'a) \in UNIV.\ \varepsilon/?a)$
using *sum-strict-mono*[*of* - $\lambda i.\ \|\text{col } i\ (X\ n - ?L)\|$] **by** *force*
moreover have $\|X\ n - ?L\| \leq (\sum i \in UNIV.\ \|\text{col } i\ (X\ n - ?L)\|)$
using *sq-mtx-norm-le-sum-col* **by** *blast*
moreover have $(\sum (i::'a) \in UNIV.\ \varepsilon/?a) = \varepsilon$
by *force*
ultimately show $\|X\ n - ?L\| < \varepsilon$
by *linarith*
qed
thus $\exists no.\ \forall n \geq no.\ \|X\ n - ?L\| < \varepsilon$
by *blast*
qed
qed

instance *sq-mtx* :: (*finite*) *banach*
proof(*standard*)

fix X::*nat* $\Rightarrow$ *'a sq-mtx*
assume *Cauchy X*
have $\bigwedge i$. *Cauchy* (λn. col i (X n))
using ‹*Cauchy X*› *Cauchy-cols* **by** *blast*
hence *obs*:$\forall i$. $\exists!$ L. (λn. col i (X n)) $\longrightarrow L$
using *Cauchy-convergent convergent-def LIMSEQ-unique* **by** *fastforce*
define L **where** $L = (\chi\ i.\ lim\ (\lambda n.\ \text{col}\ i\ (X\ n)))$
from *this* **and** *obs* **have** $\forall i$. (λn. col i (X n)) $\longrightarrow L$ \$ i
using *theI-unique*[*of* λL. (λn. col - (X n)) $\longrightarrow L$ L \$ -] **by** (*simp add*: *lim-def*)
thus *convergent X*
using *col-convergent* **by** *blast*
qed

2.5 Flow for squared matrix systems

Finally, we can use the *exp* operation to characterize the general solutions for linear systems of ODEs. We show that they all satisfy the *local-flow* locale.

lemma *mtx-vec-prod-has-derivative-mtx-vec-prod*:
assumes $\bigwedge$ i j. D (λt. (A t) \$\$ i \$ j) $\mapsto$ ($\lambda\tau$. $\tau *_R (A'\ t)$ \$\$ i \$ j) (*at t within s*)
and ($\lambda\tau$. $\tau *_R (A'\ t) *_V x$) $= g'$
shows D (λt. $A\ t *_V x$) $\mapsto g'$ *at t within s*
using *assms*(*2*) **unfolding** *sq-mtx-vec-mult-sum-cols* **apply** *safe*
apply(*rule-tac* $f'1=\lambda i\ \tau.\ \tau *_R$ (x \$ $i *_R$ col i (A' t)) **in** *derivative-eq-intros*(*9*))
apply(*simp-all add*: *scaleR-right.sum*)
apply(*rule-tac* $g'1=\lambda\tau.\ \tau *_R$ col i (A' t) **in** *derivative-eq-intros*(*4*), *simp-all add*: *mult.commute*)
using *assms* **unfolding** *sq-mtx-col-def column-def* **apply**(*transfer*, *simp*)
apply(*rule has-derivative-vec-lambda*)
by(*simp add*: *scaleR-vec-def*)

lemma *has-derivative-mtx-ith*:
assumes D A $\mapsto$ (λh. $h *_R A'\ x$) *at x within s*
shows D (λt. A t \$\$ i) $\mapsto$ (λh. $h *_R A'\ x$ \$\$ i) *at x within s*
unfolding *has-derivative-def tendsto-iff dist-norm* **apply** *safe*
apply(*force simp*: *bounded-linear-def bounded-linear-axioms-def*)
proof(*clarsimp*)
fix ε::*real* **assume** $0 < \varepsilon$
let $?x$ = *netlimit* (*at x within s*) **let** $?\Delta\ y = y - ?x$ **and** $?\Delta A\ y = A\ y - A\ ?x$
let $?P\ e = \lambda y.\ inverse\ |?\Delta\ y| * (\|?\Delta A\ y - ?\Delta\ y *_R A'\ x\|) < e$
let $?Q = \lambda y.\ inverse\ |?\Delta\ y| * (\|A\ y$ \$\$ $i - A\ ?x$ \$\$ $i - ?\Delta\ y *_R A'\ x$ \$\$ $i\|) < \varepsilon$
from *assms* **have** $\forall e>0$. *eventually* ($?P\ e$) (*at x within s*)
unfolding *has-derivative-def tendsto-iff* **by** *auto*
hence *eventually* ($?P\ \varepsilon$) (*at x within s*)
using ‹$0 < \varepsilon$› **by** *blast*

thus *eventually ?Q (at x within s)*
proof(*rule-tac P=?P ε* **in** *eventually-mono*, *simp-all*)
let *?u y i = A y $$ i − A ?x $$ i − ?Δ y* $*_R$ *A′ x $$ i*
fix *y* **assume** *hyp*: *inverse |?Δ y| ∗ (‖?ΔA y − ?Δ y* $*_R$ *A′ x‖) < ε*
have *‖?u y i‖ = ‖(?ΔA y − ?Δ y* $*_R$ *A′ x) $$ i‖*
by *simp*
also have ... ≤ *(‖?ΔA y − ?Δ y* $*_R$ *A′ x‖)*
using *norm-column-le-norm* **by** *blast*
ultimately have *‖?u y i‖ ≤ ‖?ΔA y − ?Δ y* $*_R$ *A′ x‖*
by *linarith*
hence *inverse |?Δ y| ∗ (‖?u y i‖) ≤ inverse |?Δ y| ∗ (‖?ΔA y − ?Δ y* $*_R$ *A′ x‖)*
by (*simp add*: *mult-left-mono*)
thus *inverse |?Δ y| ∗ (‖?u y i‖) < ε*
using *hyp* **by** *linarith*
qed
qed

lemma *exp-has-vderiv-on-linear*:
fixes *A*::((*′a*::*finite*) *sq-mtx*)
shows *D (λt. exp ((t − t0)* $*_R$ *A)* $*_V$ *x0) = (λt. A* $*_V$ *(exp ((t − t0)* $*_R$ *A)* $*_V$ *x0)) on T*
unfolding *has-vderiv-on-def has-vector-derivative-def* **apply** *clarsimp*
apply(*rule-tac A′=λt. A ∗ exp ((t − t0)* $*_R$ *A)* **in** *mtx-vec-prod-has-derivative-mtx-vec-prod*)
apply(*rule has-derivative-vec-nth*)
apply(*rule has-derivative-mtx-ith*)
apply(*rule-tac f′=id* **in** *exp-scaleR-has-derivative-right*)
apply(*rule-tac f′1=id* **and** *g′1=λx. 0* **in** *derivative-eq-intros*(*11*))
apply(*rule derivative-eq-intros*)
by(*simp-all add*: *fun-eq-iff exp-times-scaleR-commute sq-mtx-times-vec-assoc*)

lemma *picard-lindeloef-sq-mtx*:
fixes *A*::(*′n*::*finite*) *sq-mtx*
defines *L* ≡ (*real CARD*(*′n*))^2 ∗ (‖*to-vec A*‖$_{max}$)
shows *picard-lindeloef (λ t s. A* $*_V$ *s) UNIV UNIV* t_0
apply(*unfold-locales*, *simp-all add*: *local-lipschitz-def lipschitz-on-def*, *clarsimp*)
apply(*rule-tac x=1* **in** *exI*, *clarsimp*, *rule-tac x=L* **in** *exI*, *safe*)
using *max-norm-ge-0*[*of to-vec A*] **unfolding** *assms* **apply** *force*
by *transfer* (*rule matrix-lipschitz-constant*)

lemma *picard-lindeloef-sq-mtx-affine*:
fixes *A*::(*′n*::*finite*) *sq-mtx*
shows *picard-lindeloef (λ t s. A* $*_V$ *s + b) UNIV UNIV* t_0
apply(*rule picard-lindeloef-add*[*OF picard-lindeloef-sq-mtx*])
using *picard-lindeloef-constant* **by** *auto*

lemma *local-flow-exp*:
fixes *A*::(*′n*::*finite*) *sq-mtx*
shows *local-flow ((*$*_V$*) A) UNIV UNIV (λt s. exp (t* $*_R$ *A)* $*_V$ *s)*

unfolding *local-flow-def local-flow-axioms-def* **apply** *safe*
using *picard-lindeloef-sq-mtx* **apply** *blast*
using *exp-has-vderiv-on-linear*[*of 0*] **by** *auto*

end
theory *hs-vc-spartan*
imports *hs-prelims-dyn-sys*

begin

Chapter 3

Hybrid System Verification

type-synonym $'a\ pred = 'a \Rightarrow bool$

no-notation *Transitive-Closure.rtrancl* $((\text{-}^*)\ [1000]\ 999)$

notation *Union* (μ)
  and *g-orbital* $((1x\acute{}=\text{-}\ \&\ \text{-}\ on\ \text{-}\ \text{-}\ @\ \text{-}))$

abbreviation $skip \equiv (\lambda s.\ \{s\})$

3.1 Verification of regular programs

First we add lemmas for computation of weakest liberal preconditions (wlps).

definition $fbox :: ('a \Rightarrow 'b\ set) \Rightarrow 'b\ pred \Rightarrow 'a\ pred\ (|\text{-}]\ \text{-}\ [61,81]\ 82)$
  where $|F]\ P = (\lambda s.\ (\forall s'.\ s' \in F\ s \longrightarrow P\ s'))$

lemma *fbox-iso*: $P \leq Q \Longrightarrow |F]\ P \leq |F]\ Q$
  unfolding *fbox-def* **by** *auto*

lemma *fbox-invariants*:
  assumes $I \leq |F]\ I$ **and** $J \leq |F]\ J$
  shows $(\lambda s.\ I\ s \wedge J\ s) \leq |F]\ (\lambda s.\ I\ s \wedge J\ s)$
    and $(\lambda s.\ I\ s \vee J\ s) \leq |F]\ (\lambda s.\ I\ s \vee J\ s)$
  using *assms* **unfolding** *fbox-def* **by** *auto*

Now, we compute wlps for specific programs.

lemma *fbox-eta*[*simp*]: $fbox\ skip\ P = P$
  unfolding *fbox-def* **by** *simp*

Next, we introduce assignments and their wlps.

definition $vec\text{-}upd :: 'a\hat{}'n \Rightarrow 'n \Rightarrow 'a \Rightarrow 'a\hat{}'n$
  where $vec\text{-}upd\ s\ i\ a = (\chi\ j.\ (((\$)\ s)(i := a))\ j)$

definition *assign* :: $'n \Rightarrow ('a\hat{~}'n \Rightarrow 'a) \Rightarrow 'a\hat{~}'n \Rightarrow ('a\hat{~}'n)$ *set* ((*2*- ::= -) [*70*, *65*] *61*)
 where $(x ::= e) = (\lambda s.\ \{\mathit{vec\text{-}upd}\ s\ x\ (e\ s)\})$

lemma *fbox-assign*[*simp*]: $|x ::= e]\ Q = (\lambda s.\ Q\ (\chi\ j.\ (((\$)\ s)(x := (e\ s)))\ j))$
 unfolding *vec-upd-def assign-def* **by** (*subst fbox-def*) *simp*

The wlp of a (kleisli) composition is just the composition of the wlps.

definition *kcomp* :: $('a \Rightarrow 'b\ set) \Rightarrow ('b \Rightarrow 'c\ set) \Rightarrow ('a\ \Rightarrow 'c\ set)$ (**infixl** ; *75*)
where
 $F\ ;\ G = \mu \circ \mathcal{P}\ G \circ F$

lemma *kcomp-eq*: $(f\ ;\ g)\ x = \bigcup\ \{g\ y\ |y.\ y \in f\ x\}$
 unfolding *kcomp-def image-def* **by** *auto*

lemma *fbox-kcomp*[*simp*]: $|G\ ;\ F]\ P = |G]\ |F]\ P$
 unfolding *fbox-def kcomp-def* **by** *auto*

lemma *fbox-kcomp-ge*:
 assumes $P \leq |G]\ R\ R \leq |F]\ Q$
 shows $P \leq |G\ ;\ F]\ Q$
 apply(*subst fbox-kcomp*)
 by (*rule order.trans*[*OF assms*(*1*)]) (*rule fbox-iso*[*OF assms*(*2*)])

We also have an implementation of the conditional operator and its wlp.

definition *ifthenelse* :: $'a\ pred \Rightarrow ('a \Rightarrow 'b\ set) \Rightarrow ('a \Rightarrow 'b\ set) \Rightarrow ('a \Rightarrow 'b\ set)$
 (*IF - THEN - ELSE -* [*64*,*64*,*64*] *63*) **where**
 IF P THEN X ELSE Y $\equiv (\lambda s.$ *if P s then X s else Y s*)

lemma *fbox-if-then-else*[*simp*]:
 $|IF\ T\ THEN\ X\ ELSE\ Y]\ Q = (\lambda s.\ (T\ s \longrightarrow (\ |X]\ Q)\ s) \land (\neg\ T\ s \longrightarrow (\ |Y]\ Q)\ s))$
 unfolding *fbox-def ifthenelse-def* **by** *auto*

lemma *fbox-if-then-else-ge*:
 assumes $(\lambda s.\ P\ s \land\ T\ s) \leq |X]\ Q$
  and $(\lambda s.\ P\ s \land \neg\ T\ s) \leq |Y]\ Q$
 shows $P \leq |IF\ T\ THEN\ X\ ELSE\ Y]\ Q$
 using *assms* **unfolding** *fbox-def ifthenelse-def* **by** *auto*

lemma *fbox-if-then-elseI*:
 assumes $T\ s \longrightarrow (\ |X]\ Q)\ s$
  and $\neg\ T\ s \longrightarrow (\ |Y]\ Q)\ s$
 shows $(\ |IF\ T\ THEN\ X\ ELSE\ Y]\ Q)\ s$
 using *assms* **unfolding** *fbox-def ifthenelse-def* **by** *auto*

The final wlp we add is that of the finite iteration.

definition *kpower* :: $('a \Rightarrow 'a\ set) \Rightarrow nat \Rightarrow ('a \Rightarrow 'a\ set)$
 where *kpower f n* $= (\lambda s.\ ((;)\ f\ \hat{~}\hat{~}\ n)\ skip\ s)$

lemma *kpower-base*:
  shows *kpower f 0 s* $= \{s\}$ **and** *kpower f* (*Suc 0*) *s* $=$ *f s*
  unfolding *kpower-def* **by**(*auto simp*: *kcomp-eq*)

lemma *kpower-simp*: *kpower f* (*Suc n*) *s* $=$ (*f* ; *kpower f n*) *s*
  unfolding *kcomp-eq* **apply**(*induct n*)
  unfolding *kpower-base* **apply**(*rule subset-antisym*, *clarsimp*, *force*, *clarsimp*)
  unfolding *kpower-def kcomp-eq* **by** *simp*

definition *kleene-star* :: $('a \Rightarrow 'a\ set) \Rightarrow ('a \Rightarrow 'a\ set)$ ((-*) [*1000*] *999*)
  where $(f^*)\ s = \bigcup\ \{kpower\ f\ n\ s\ |n.\ n \in UNIV\}$

lemma *kpower-inv*:
  fixes $F :: 'a \Rightarrow 'a\ set$
  assumes $\forall s.\ I\ s \longrightarrow (\forall s'.\ s' \in F\ s \longrightarrow I\ s')$
  shows $\forall s.\ I\ s \longrightarrow (\forall s'.\ s' \in (kpower\ F\ n\ s) \longrightarrow I\ s')$
  apply(*clarsimp*, *induct n*)
  unfolding *kpower-base* **apply** *simp*
  unfolding *kpower-simp* **apply**(*simp add*: *kcomp-eq*, *clarsimp*)
  apply(*subgoal-tac I y*, *simp*)
  using *assms* **by** *blast*

lemma *kstar-inv*: $I \le |F]\ I \Longrightarrow I \le |F^*]\ I$
  unfolding *kleene-star-def fbox-def* **apply** *clarsimp*
  apply(*unfold le-fun-def*, *subgoal-tac* $\forall x.\ I\ x \longrightarrow (\forall s'.\ s' \in F\ x \longrightarrow I\ s')$)
  apply(*thin-tac* $\forall x.\ I\ x \le (\forall s'.\ s' \in F\ x \longrightarrow I\ s')$)
  using *kpower-inv*[*of I F*] **by** *blast simp*

lemma *fbox-kstarI*:
  assumes $P \le I$ **and** $I \le Q$ **and** $I \le |F]\ I$
  shows $P \le |F^*]\ Q$
proof−
  have $I \le |F^*]\ I$
    using *assms*(*3*) *kstar-inv* **by** *blast*
  hence $P \le |F^*]\ I$
    using *assms*(*1*) **by** *auto*
  also have $|F^*]\ I \le |F^*]\ Q$
    by (*rule fbox-iso*[*OF assms*(*2*)])
  finally show *?thesis* **.**
qed

definition *loopi* :: $('a \Rightarrow 'a\ set) \Rightarrow 'a\ pred \Rightarrow ('a \Rightarrow 'a\ set)$ (*LOOP - INV -* [*64*,*64*] *63*)
  where *LOOP F INV I* $\equiv (F^*)$

lemma *fbox-loopI*: $P \le I \Longrightarrow I \le Q \Longrightarrow I \le |F]\ I \Longrightarrow P \le |LOOP\ F\ INV\ I]\ Q$
  unfolding *loopi-def* **using** *fbox-kstarI*[*of P*] **by** *simp*

3.2 Verification of hybrid programs

3.2.1 Verification by providing evolution

definition *g-evol* :: $(('a{::}ord) \Rightarrow 'b \Rightarrow 'b) \Rightarrow 'b\ pred \Rightarrow 'a\ set \Rightarrow ('b \Rightarrow 'b\ set)$ $(EVOL)$
where $EVOL\ \varphi\ G\ T = (\lambda s.\ g\text{-}orbit\ (\lambda t.\ \varphi\ t\ s)\ G\ T)$

lemma *fbox-g-evol*[*simp*]:
fixes φ :: $('a{::}preorder) \Rightarrow 'b \Rightarrow 'b$
shows $|EVOL\ \varphi\ G\ T]\ Q = (\lambda s.\ (\forall t{\in}T.\ (\forall \tau{\in}down\ T\ t.\ G\ (\varphi\ \tau\ s)) \longrightarrow Q\ (\varphi\ t\ s)))$
unfolding *g-evol-def g-orbit-eq fbox-def* **by** *auto*

3.2.2 Verification by providing solutions

lemma *fbox-g-orbital*: $|x' {=} f\ \&\ G\ on\ T\ S\ @\ t_0]\ Q =$
$(\lambda s.\ \forall X{\in}Sols\ (\lambda t.\ f)\ T\ S\ t_0\ s.\ \forall t{\in}T.\ (\forall \tau{\in}down\ T\ t.\ G\ (X\ \tau)) \longrightarrow Q\ (X\ t))$
unfolding *fbox-def g-orbital-eq* **by** (*auto simp*: *fun-eq-iff*)

context *local-flow*
begin

lemma *fbox-g-ode*: $|x' {=} f\ \&\ G\ on\ T\ S\ @\ 0]\ Q =$
$(\lambda s.\ s \in S \longrightarrow (\forall t{\in}T.\ (\forall \tau{\in}down\ T\ t.\ G\ (\varphi\ \tau\ s)) \longrightarrow Q\ (\varphi\ t\ s)))$ (**is** - = *?wlp*)
unfolding *fbox-g-orbital* **apply**(*rule ext*, *safe*, *clarsimp*)
apply(*erule-tac* $x{=}\lambda t.\ \varphi\ t\ s$ **in** *ballE*)
using *in-ivp-sols* **apply**(*force*, *force*, *force simp*: *init-time ivp-sols-def*)
apply(*subgoal-tac* $\forall \tau{\in}down\ T\ t.\ X\ \tau = \varphi\ \tau\ s$, *simp-all*, *clarsimp*)
apply(*subst eq-solution*, *simp-all add*: *ivp-sols-def*)
using *init-time* **by** *auto*

lemma *fbox-g-ode-ivl*: $t \geq 0 \Longrightarrow t \in T \Longrightarrow |x' {=} f\ \&\ G\ on\ \{0..t\}\ S\ @\ 0]\ Q =$
$(\lambda s.\ s \in S \longrightarrow (\forall t{\in}\{0..t\}.\ (\forall \tau{\in}\{0..t\}.\ G\ (\varphi\ \tau\ s)) \longrightarrow Q\ (\varphi\ t\ s)))$
unfolding *fbox-g-orbital* **apply**(*rule ext*, *clarsimp*, *safe*)
apply(*erule-tac* $x{=}\lambda t.\ \varphi\ t\ s$ **in** *ballE*, *force*)
using *in-ivp-sols-ivl* **apply**(*force simp*: *closed-segment-eq-real-ivl*)
using *in-ivp-sols-ivl* **apply**(*force simp*: *ivp-sols-def*)
apply(*subgoal-tac* $\forall t{\in}\{0..t\}.\ (\forall \tau{\in}\{0..t\}.\ X\ \tau = \varphi\ \tau\ s)$, *simp*, *clarsimp*)
apply(*subst eq-solution-ivl*, *simp-all add*: *ivp-sols-def*)
apply(*rule has-vderiv-on-subset*, *force*, *force simp*: *closed-segment-eq-real-ivl*)
apply(*force simp*: *closed-segment-eq-real-ivl*)
using *interval-time init-time* **apply** (*meson is-interval-1 order-trans*)
using *init-time* **by** *force*

lemma *fbox-orbit*: $|\gamma^\varphi]\ Q = (\lambda s.\ s \in S \longrightarrow (\forall\ t \in T.\ Q\ (\varphi\ t\ s)))$
unfolding *orbit-def fbox-g-ode* **by** *simp*

end

3.2.3 Verification with differential invariants

definition *g-ode-inv* :: $(('a::banach)\Rightarrow'a) \Rightarrow 'a\ pred \Rightarrow real\ set \Rightarrow 'a\ set \Rightarrow real \Rightarrow 'a\ pred \Rightarrow ('a \Rightarrow 'a\ set)$ ((1x´=- & - on - - @ - DINV -))
where $(x´= f\ \&\ G\ on\ T\ S\ @\ t_0\ DINV\ I) = (x´= f\ \&\ G\ on\ T\ S\ @\ t_0)$

lemma *fbox-g-orbital-guard*:
assumes $H = (\lambda s.\ G\ s \wedge Q\ s)$
shows $|x´=f\ \&\ G\ on\ T\ S\ @\ t_0]\ Q = |x´=f\ \&\ G\ on\ T\ S\ @\ t_0]\ H$
unfolding *fbox-g-orbital* **using** *assms* **by** *auto*

lemma *fbox-g-orbital-inv*:
assumes $P \leq I$ **and** $I \leq |x´=f\ \&\ G\ on\ T\ S\ @\ t_0]\ I$ **and** $I \leq Q$
shows $P \leq |x´=f\ \&\ G\ on\ T\ S\ @\ t_0]\ Q$
using *assms*(*1*) **apply**(*rule order.trans*)
using *assms*(*2*) **apply**(*rule order.trans*)
by (*rule fbox-iso*[*OF assms*(*3*)])

lemma *fbox-diff-inv*[*simp*]:
$(I \leq |x´=f\ \&\ G\ on\ T\ S\ @\ t_0]\ I) = diff\text{-}invariant\ I\ f\ T\ S\ t_0\ G$
by (*auto simp*: *diff-invariant-def ivp-sols-def fbox-def g-orbital-eq*)

lemma *fbox-g-odei*: $P \leq I \Longrightarrow I \leq |x´= f\ \&\ G\ on\ T\ S\ @\ t_0]\ I \Longrightarrow (\lambda s.\ I\ s \wedge G\ s) \leq Q \Longrightarrow$
$P \leq |x´= f\ \&\ G\ on\ T\ S\ @\ t_0\ DINV\ I]\ Q$
unfolding *g-ode-inv-def* **apply**(*rule-tac* $b=|x´= f\ \&\ G\ on\ T\ S\ @\ t_0]\ I$ **in** *order.trans*)
apply(*rule-tac I=I* **in** *fbox-g-orbital-inv*, *simp-all*)
apply(*subst fbox-g-orbital-guard*, *simp*)
by (*rule fbox-iso*, *force*)

abbreviation *g-global-orbit* :: $(('a::banach)\Rightarrow'a) \Rightarrow 'a\ pred \Rightarrow 'a \Rightarrow 'a\ set$
((1x´=- & -)) **where** $(x´=f\ \&\ G) \equiv (x´=f\ \&\ G\ on\ UNIV\ UNIV\ @\ 0)$

abbreviation *g-global-ode-inv* :: $(('a::banach)\Rightarrow'a) \Rightarrow 'a\ pred \Rightarrow 'a\ pred \Rightarrow 'a \Rightarrow 'a\ set$
((1x´=- & - DINV -)) **where** $(x´=f\ \&\ G\ DINV\ I) \equiv (x´=f\ \&\ G\ on\ UNIV\ UNIV\ @\ 0\ DINV\ I)$

end
theory *hs-vc-examples*
imports *hs-prelims-matrices hs-vc-spartan*

begin

3.2.4 Examples

Preliminary preparation for the examples.

— Finite set of program variables.

typedef *program-vars* = $\{''x'',''y''\}$
morphisms *to-str to-var*
apply(*rule-tac x*=$''x''$ **in** *exI*)
by *simp*

notation *to-var* ($\upharpoonright_V$)

lemma *number-of-program-vars*: *CARD*(*program-vars*) = *2*
using *type-definition.card type-definition-program-vars* **by** *fastforce*

instance *program-vars*::*finite*
apply(*standard*, *subst bij-betw-finite*[*of to-str UNIV* $\{''x'',''y''\}$])
apply(*rule bij-betwI'*)
apply (*simp add*: *to-str-inject*)
using *to-str* **apply** *blast*
apply (*metis to-var-inverse UNIV-I*)
by *simp*

lemma *program-vars-univ-eq*: (*UNIV*::*program-vars set*) = $\{\upharpoonright_V ''x'', \upharpoonright_V ''y''\}$
apply *auto* **by** (*metis to-str to-str-inverse insertE singletonD*)

lemma *program-vars-exhaust*: $x = \upharpoonright_V ''x'' \vee x = \upharpoonright_V ''y''$
using *program-vars-univ-eq* **by** *auto*

abbreviation *val-p* :: *real*ˆ*program-vars* ⇒ *string* ⇒ *real* (**infixl** $\downharpoonleft_V$ *90*)
where *store*$\downharpoonleft_V$*var* ≡ *store*\$$\upharpoonright_V$*var*

— Alternative to the finite set of program variables.

lemma *CARD*(*2*) = *CARD*(*program-vars*)
unfolding *number-of-program-vars* **by** *simp*

lemma [*simp*]: $i \neq (0::2) \longrightarrow i = 1$
using *exhaust-2* **by** *fastforce*

lemma *two-eq-zero*: $(2::2) = 0$
by *simp*

lemma *UNIV-2*: (*UNIV*::*2 set*) = $\{0,\ 1\}$
apply *safe* **using** *exhaust-2 two-eq-zero* **by** *auto*

lemma *UNIV-3*: (*UNIV*::*3 set*) = $\{0,\ 1,\ 2\}$
apply *safe* **using** *exhaust-3 three-eq-zero* **by** *auto*

lemma *sum-axis-UNIV-3*[*simp*]: ($\sum j \in$(*UNIV*::*3 set*). *axis i 1* \$ $j * f\ j$) = (*f*::*3* ⇒ *real*) *i*
unfolding *axis-def UNIV-3* **apply** *simp*
using *exhaust-3* **by** *force*

Circular Motion

— Verified with differential invariants.

abbreviation *circular-motion-vec-field* :: *real^program-vars* ⇒ *real^program-vars* (C)
where *circular-motion-vec-field* $s \equiv (\chi\ i.\ \mathit{if}\ i{=}\restriction_V ''x''\ \mathit{then}\ s\downharpoonright_V ''y''\ \mathit{else}\ -s\downharpoonright_V ''x'')$

lemma *circular-motion-invariants*:
$(\lambda s.\ r^2 = (s\downharpoonright_V ''x'')^2 + (s\downharpoonright_V ''y'')^2) \le |x\acute{}{=}C\ \&\ G]\ (\lambda s.\ r^2 = (s\downharpoonright_V ''x'')^2 + (s\downharpoonright_V ''y'')^2)$
by (*auto intro*!: *diff-invariant-rules poly-derivatives simp*: *to-var-inject*)

— Verified with the flow.

abbreviation *circular-motion-flow* :: *real* ⇒ *real^program-vars* ⇒ *real^program-vars* (φ_C)
where $\varphi_C\ t\ s \equiv (\chi\ i.\ \mathit{if}\ i{=}\restriction_V ''x''\ \mathit{then}\ s\downharpoonright_V ''x'' * \mathit{cos}\ t + s\downharpoonright_V ''y'' * \mathit{sin}\ t$
$\mathit{else} - s\downharpoonright_V ''x'' * \mathit{sin}\ t + s\downharpoonright_V ''y'' * \mathit{cos}\ t)$

lemma *local-flow-circ-motion*: *local-flow C UNIV UNIV* φ_C
apply(*unfold-locales*, *simp-all add*: *local-lipschitz-def lipschitz-on-def vec-eq-iff*, *clarsimp*)
apply(*rule-tac x=1* **in** *exI*, *clarsimp*, *rule-tac x=1* **in** *exI*)
apply(*simp add*: *dist-norm norm-vec-def L2-set-def program-vars-univ-eq to-var-inject power2-commute*)
apply(*clarsimp*, *case-tac* $i = \restriction_V ''x''$)
using *program-vars-exhaust* **by** (*force intro*!: *poly-derivatives simp*: *to-var-inject*)+

lemma *circular-motion*:
$(\lambda s.\ r^2 = (s\downharpoonright_V ''x'')^2 + (s\downharpoonright_V ''y'')^2) \le |x\acute{}{=}C\ \&\ G]\ (\lambda s.\ r^2 = (s\downharpoonright_V ''x'')^2 + (s\downharpoonright_V ''y'')^2)$
by (*force simp*: *local-flow.fbox-g-ode*[*OF local-flow-circ-motion*] *to-var-inject*)

— Verified by providing dynamics.

lemma *circular-motion-dyn*:
$(\lambda s.\ r^2 = (s\downharpoonright_V ''x'')^2 + (s\downharpoonright_V ''y'')^2) \le |EVOL\ \varphi_C\ G\ T]\ (\lambda s.\ r^2 = (s\downharpoonright_V ''x'')^2 + (s\downharpoonright_V ''y'')^2)$
by (*force simp*: *to-var-inject*)

no-notation *circular-motion-vec-field* (C)
and *circular-motion-flow* (φ_C)

— Verified as a linear system (using uniqueness).

abbreviation *circular-motion-sq-mtx* :: *2 sq-mtx* (C)
where $C \equiv$ *sq-mtx-chi* $(\chi\ i.\ \mathit{if}\ i{=}0\ \mathit{then} - \mathrm{e}\ 1\ \mathit{else}\ \mathrm{e}\ 0)$

abbreviation *circular-motion-mtx-flow* :: *real* ⇒ *real^2* ⇒ *real^2* (φ_C)

where φ_C *t s* ≡ (*χ i. if i = 0 then s$0 ∗ cos t − s$1 ∗ sin t else s$0 ∗ sin t + s$1 ∗ cos t*)

lemma *circular-motion-mtx-exp-eq*: *exp* (*t* $*_R$ *C*) $*_V$ *s* = φ_C *t s*
apply(*rule local-flow.eq-solution*[*OF local-flow-exp*, *symmetric*])
apply(*rule ivp-solsI*, *simp add*: *sq-mtx-vec-prod-def matrix-vector-mult-def*)
apply(*force intro*!: *poly-derivatives simp*: *matrix-vector-mult-def*)
using *exhaust-2 two-eq-zero* **by** (*force simp*: *vec-eq-iff*, *auto*)

lemma *circular-motion-sq-mtx*:
($\lambda s.\ r^2 = (s\$0)^2 + (s\$1)^2$) ≤ *fbox* (*x´*=($*_V$) *C* & *G*) ($\lambda s.\ r^2 = (s\$0)^2 + (s\$1)^2$)
unfolding *local-flow.fbox-g-ode*[*OF local-flow-exp*] *circular-motion-mtx-exp-eq* **by** *auto*

no-notation *circular-motion-sq-mtx* (*C*)
and *circular-motion-mtx-flow* (φ_C)

Bouncing Ball

— Verified with differential invariants.

named-theorems *bb-real-arith real arithmetic properties for the bouncing ball.*

lemma [*bb-real-arith*]:
assumes *0 > g* **and** *inv*: *2 ∗ g ∗ x − 2 ∗ g ∗ h = v ∗ v*
shows (*x*::*real*) ≤ *h*
proof−
have *v ∗ v = 2 ∗ g ∗ x − 2 ∗ g ∗ h ∧ 0 > g*
using *inv* **and** ‹*0 > g*› **by** *auto*
hence *obs*:*v ∗ v = 2 ∗ g ∗ (x − h) ∧ 0 > g ∧ v ∗ v ≥ 0*
using *left-diff-distrib mult.commute* **by** (*metis zero-le-square*)
hence (*v ∗ v*)/(*2 ∗ g*) = (*x − h*)
by *auto*
also from *obs* **have** (*v ∗ v*)/(*2 ∗ g*) ≤ *0*
using *divide-nonneg-neg* **by** *fastforce*
ultimately have *h − x ≥ 0*
by *linarith*
thus *?thesis* **by** *auto*
qed

abbreviation *cnst-acc-vec-field* :: *real* ⇒ *real^program-vars* ⇒ *real^program-vars* (*K*)
where *K a s* ≡ (*χ i. if i*=($\upharpoonright_V$''*x*'') *then s*$\downharpoonright_V$''*y*'' *else a*)

lemma *bouncing-ball-invariants*:
shows *g < 0* ⟹ *h ≥ 0* ⟹
(*λs. s*$\downharpoonright_V$''*x*'' = *h* ∧ *s*$\downharpoonright_V$''*y*'' = *0*) ≤ *fbox*
(*LOOP*
((*x´*=*K g* & (*λ s. s*$\downharpoonright_V$''*x*'' ≥ *0*) *DINV* (*λs. 2 ∗ g ∗ s*$\downharpoonright_V$''*x*'' − *2 ∗ g ∗ h* −

$(s\downharpoonright_V ''y'' * s\downharpoonright_V ''y'') = 0))$;
$(IF\ (\lambda s.\ s\downharpoonright_V ''x'' = 0)\ THEN\ (\upharpoonright_V ''y'' ::= (\lambda s.\ -\ s\downharpoonright_V ''y''))\ ELSE\ skip))$
$INV\ (\lambda s.\ \ s\downharpoonright_V ''x'' \geq 0 \wedge 2 * g * s\downharpoonright_V ''x'' - 2 * g * h - (s\downharpoonright_V ''y'' * s\downharpoonright_V ''y'') = 0))$
$(\lambda s.\ 0 \leq s\downharpoonright_V ''x'' \wedge s\downharpoonright_V ''x'' \leq h)$
apply(*rule fbox-loopI*, *simp-all*)
apply(*force*, *force simp*: *bb-real-arith*)
by (*rule fbox-g-odei*) (*auto intro*!: *poly-derivatives diff-invariant-rules simp*: *to-var-inject*)

— Verified with the flow.

lemma *picard-lindeloef-cnst-acc*:
fixes *g*::*real*
shows *picard-lindeloef* $(\lambda t.\ K\ g)$ *UNIV UNIV 0*
apply(*unfold-locales*, *simp-all add*: *local-lipschitz-def lipschitz-on-def*, *clarsimp*)
apply(*rule-tac x=1/2* **in** *exI*, *clarsimp*, *rule-tac x=1* **in** *exI*)
by(*simp add*: *dist-norm norm-vec-def L2-set-def program-vars-univ-eq to-var-inject*)

abbreviation *cnst-acc-flow* :: *real* ⇒ *real* ⇒ *real*ˆ*program-vars* ⇒ *real*ˆ*program-vars*
(φ_K)
where $\varphi_K\ a\ t\ s \equiv (\chi\ i.\ if\ i{=}(\upharpoonright_V\ ''x'')\ then\ a * t\ \hat{}\ 2/2 + s\ \$\ (\upharpoonright_V\ ''y'') * t + s\ \$\ (\upharpoonright_V\ ''x'')$
$else\ a * t + s\ \$\ (\upharpoonright_V\ ''y''))$

lemma *local-flow-cnst-acc*: *local-flow* $(K\ g)$ *UNIV UNIV* $(\varphi_K\ g)$
apply(*unfold-locales*, *simp-all add*: *local-lipschitz-def lipschitz-on-def*, *clarsimp*)
apply(*rule-tac x=1/2* **in** *exI*, *clarsimp*, *rule-tac x=1* **in** *exI*)
apply(*simp add*: *dist-norm norm-vec-def L2-set-def program-vars-univ-eq to-var-inject*)
apply(*clarsimp*, *case-tac* $i = \upharpoonright_V\ ''x''$)
using *program-vars-exhaust* **by**(*auto intro*!: *poly-derivatives simp*: *to-var-inject vec-eq-iff*)

lemma [*bb-real-arith*]:
assumes *invar*: $2 * g * x = 2 * g * h + v * v$
and *pos*: $g * \tau^2\ /\ 2 + v * \tau + (x{::}real) = 0$
shows $2 * g * h + (g * \tau + v) * (g * \tau + v) = 0$
proof−
from *pos* **have** $g * \tau^2\ + 2 * v * \tau + 2 * x = 0$ **by** *auto*
then have $g^2 * \tau^2\ + 2 * g * v * \tau + 2 * g * x = 0$
by (*metis* (*mono-tags*, *hide-lams*) *Groups.mult-ac*(*1*,*3*) *mult-zero-right monoid-mult-class.power2-eq-square semiring-class.distrib-left*)
hence $g^2 * \tau^2 + 2 * g * v * \tau + v^2 + 2 * g * h = 0$
using *invar* **by** (*simp add*: *monoid-mult-class.power2-eq-square*)
hence *obs*: $(g * \tau + v)^2 + 2 * g * h = 0$
apply(*subst power2-sum*) **by** (*metis* (*no-types*, *hide-lams*) *Groups.add-ac*(*2*, *3*)

Groups.mult-ac(*2*, *3*) *monoid-mult-class.power2-eq-square nat-distrib*(*2*))
thus $2 * g * h + (g * \tau + v) * (g * \tau + v) = 0$
by (*simp add*: *add.commute distrib-right power2-eq-square*)

qed

lemma [*bb-real-arith*]:
 assumes *invar*: $2 * g * x = 2 * g * h + v * v$
 shows $2 * g * (g * \tau^2 / 2 + v * \tau + (x::real)) =$
 $2 * g * h + (g * \tau + v) * (g * \tau + v)$ (**is** $?lhs = ?rhs$)
proof−
 have $?lhs = g^2 * \tau^2 + 2 * g * v * \tau + 2 * g * x$
 apply(*subst Rat.sign-simps*(*18*))+
 by(*auto simp*: *semiring-normalization-rules*(*29*))
 also have ... $= g^2 * \tau^2 + 2 * g * v * \tau + 2 * g * h + v * v$ (**is** ... = *?middle*)
 by(*subst invar*, *simp*)
 finally have *?lhs* = *?middle*.
 moreover
 {**have** $?rhs = g * g * (\tau * \tau) + 2 * g * v * \tau + 2 * g * h + v * v$
 by (*simp add*: *Groups.mult-ac*(*2*,*3*) *semiring-class.distrib-left*)
 also have ... = *?middle*
 by (*simp add*: *semiring-normalization-rules*(*29*))
 finally have *?rhs* = *?middle*.}
 ultimately show *?thesis* **by** *auto*
qed

lemma *bouncing-ball*: $g < 0 \Longrightarrow h \geq 0 \Longrightarrow$
 $(\lambda s.\ s\lfloor_V{}''x'' = h \wedge s\lfloor_V{}''y'' = 0) \leq fbox$
 (*LOOP*
 $((x' {=} K\ g\ \&\ (\lambda\ s.\ s\lfloor_V{}''x'' \geq 0))$;
 $(IF\ (\lambda s.\ s\lfloor_V{}''x'' = 0)\ THEN\ (\lceil_V{}''y'' ::= (\lambda s. - s\lfloor_V{}''y''))\ ELSE\ skip))$
 $INV\ (\lambda s.\ \ s\lfloor_V{}''x'' \geq 0 \wedge 2 * g * s\lfloor_V{}''x'' = 2 * g * h + (s\lfloor_V{}''y'' * s\lfloor_V{}''y'')))$
 $(\lambda s.\ 0 \leq s\lfloor_V{}''x'' \wedge s\lfloor_V{}''x'' \leq h)$
 apply(*rule fbox-loopI*, *simp-all add*: *local-flow.fbox-g-ode*[*OF local-flow-cnst-acc*])
 by (*auto simp*: *bb-real-arith to-var-inject*)

no-notation *cnst-acc-vec-field* (K)
 and *cnst-acc-flow* (φ_K)
 and *to-var* ($\lceil_V$)
 and *val-p* (**infixl** $\lfloor_V$ *90*)

— Verified as a linear system (computing exponential).

abbreviation *cnst-acc-sq-mtx* :: *3 sq-mtx* (K)
 where $K \equiv$ *sq-mtx-chi* (χ *i*::*3*. *if i*=*0 then* e *1 else if i*=*1 then* e *2 else 0*)

lemma *const-acc-mtx-pow2*: K^2 = *sq-mtx-chi* (χ *i*. *if i*=*0 then* e *2 else 0*)
 unfolding *power2-eq-square times-sq-mtx-def*
 by(*simp add*: *sq-mtx-chi-inject vec-eq-iff matrix-matrix-mult-def*)

lemma *const-acc-mtx-powN*: $n > 2 \Longrightarrow (\tau *_R K)\hat{\ }n = 0$
 apply(*induct n*, *simp*, *case-tac* $n \leq 2$)

apply(*simp only*: *le-less-Suc-eq power-Suc*, *simp*)
by(*auto simp*: *const-acc-mtx-pow2 sq-mtx-chi-inject vec-eq-iff times-sq-mtx-def zero-sq-mtx-def matrix-matrix-mult-def*)

lemma *exp-cnst-acc-sq-mtx*: $exp\ (\tau *_R K) = ((\tau *_R K)^2/_R\ 2) + (\tau *_R K) + 1$
unfolding *exp-def* **apply**(*subst suminf-eq-sum*[*of 2*])
using *const-acc-mtx-powN* **by** (*simp-all add*: *numeral-2-eq-2*)

lemma *exp-cnst-acc-sq-mtx-simps*:
$exp\ (\tau *_R K)\ \$\$\ 0\ \$\ 0 = 1$ $exp\ (\tau *_R K)\ \$\$\ 0\ \$\ 1 = \tau$ $exp\ (\tau *_R K)\ \$\$\ 0\ \$\ 2 = \tau\hat{}2/2$
$exp\ (\tau *_R K)\ \$\$\ 1\ \$\ 0 = 0$ $exp\ (\tau *_R K)\ \$\$\ 1\ \$\ 1 = 1$ $exp\ (\tau *_R K)\ \$\$\ 1\ \$\ 2 = \tau$
$exp\ (\tau *_R K)\ \$\$\ 2\ \$\ 0 = 0$ $exp\ (\tau *_R K)\ \$\$\ 2\ \$\ 1 = 0$ $exp\ (\tau *_R K)\ \$\$\ 2\ \$\ 2 = 1$
unfolding *exp-cnst-acc-sq-mtx scaleR-power const-acc-mtx-pow2*
by (*auto simp*: *plus-sq-mtx-def scaleR-sq-mtx-def one-sq-mtx-def mat-def scaleR-vec-def axis-def plus-vec-def*)

lemma *bouncing-ball-sq-mtx*:
$(\lambda s.\ 0 \leq s\$0 \wedge s\$0 = h \wedge s\$1 = 0 \wedge 0 > s\$2) \leq fbox$
$(LOOP\ ((x\acute{}=(*_V)\ K\ \&\ (\lambda\ s.\ s\$0 \geq 0))\ ;$
$(IF\ (\lambda\ s.\ s\$0 = 0)\ THEN\ (1 ::= (\lambda s.\ -\ s\$1))\ ELSE\ skip))$
$INV\ (\lambda s.\ 0{\leq}s\$0 \wedge 0{>}s\$2 \wedge 2 * s\$2 * s\$0 = 2 * s\$2 * h + (s\$1 * s\$1)))$
$(\lambda s.\ 0 \leq s\$0 \wedge s\$0 \leq h)$
apply(*rule fbox-loopI*[*of* - - $(\lambda s.\ 0{\leq}s\$0 \wedge 0{>}s\$2 \wedge 2 * s\$2 * s\$0 = 2 * s\$2 * h + (s\$1 * s\$1))$])
apply(*simp-all add*: *local-flow.fbox-g-ode*[*OF local-flow-exp*] *sq-mtx-vec-prod-eq*)
apply(*force*, *force simp*: *bb-real-arith*)
unfolding *UNIV-3* **apply**(*simp add*: *exp-cnst-acc-sq-mtx-simps*, *safe*)
using *bb-real-arith*(*2*)[*of* - - *h*] **apply** (*force simp*: *field-simps*)
subgoal for $s\ \tau$ **using** *bb-real-arith*(*3*)[*of s\$2*] **by**(*simp add*: *field-simps*)
done

no-notation *cnst-acc-sq-mtx* (*K*)

Thermostat

typedef *thermostat-vars* = {''t'',''T'',''on'',''TT''}
morphisms *to-str to-var*
apply(*rule-tac x*=''t'' **in** *exI*)
by *simp*

notation *to-var* ($\restriction_V$)

lemma *number-of-thermostat-vars*: *CARD*(*thermostat-vars*) = *4*
using *type-definition.card type-definition-thermostat-vars* **by** *fastforce*

instance *thermostat-vars*::*finite*

apply(*standard*)
apply(*subst bij-betw-finite*[*of to-str UNIV* {''t'',''T'',''on'',''TT''}])
apply(*rule bij-betwI'*)
apply (*simp add*: *to-str-inject*)
using *to-str* **apply** *blast*
apply (*metis to-var-inverse UNIV-I*)
by *simp*

lemma *thermostat-vars-univ-eq*:
(*UNIV*::*thermostat-vars set*) = {$\upharpoonleft_V$''t'',$\upharpoonleft_V$''T'',$\upharpoonleft_V$''on'',$\upharpoonleft_V$''TT''}
apply *auto* **by** (*metis to-str to-str-inverse insertE singletonD*)

lemma *thermostat-vars-exhaust*: x=$\upharpoonleft_V$''t'' $\vee$ x=$\upharpoonleft_V$''T'' $\vee$ x=$\upharpoonleft_V$''on'' $\vee$ x=$\upharpoonleft_V$''TT''
using *thermostat-vars-univ-eq* **by** *auto*

lemma *thermostat-vars-sum*:
fixes *f* :: *thermostat-vars* $\Rightarrow$ ('*a*::*banach*)
shows ($\sum$(*i*::*thermostat-vars*)$\in$*UNIV*. *f i*) =
f ($\upharpoonleft_V$''t'') + *f* ($\upharpoonleft_V$''T'') + *f* ($\upharpoonleft_V$''on'')+ *f* ($\upharpoonleft_V$''TT'')
unfolding *thermostat-vars-univ-eq* **by** (*simp add*: *to-var-inject*)

abbreviation *val-T* :: *real^thermostat-vars* $\Rightarrow$ *string* $\Rightarrow$ *real* (**infixl** $\downharpoonleft_V$ *90*)
where *store*$\downharpoonleft_V$*var* $\equiv$ *store*\$$\upharpoonleft_V$*var*

lemma *thermostat-vars-allI*:
P ($\upharpoonleft_V$''t'') $\Longrightarrow$ *P* ($\upharpoonleft_V$''T'') $\Longrightarrow$ *P* ($\upharpoonleft_V$''on'') $\Longrightarrow$ *P* ($\upharpoonleft_V$''TT'') $\Longrightarrow$ $\forall$ *i*. *P i*
using *thermostat-vars-exhaust* **by** *metis*

abbreviation *temp-vec-field* :: *real* $\Rightarrow$ *real* $\Rightarrow$ *real^thermostat-vars* $\Rightarrow$ *real^thermostat-vars*
(f_T)
where f_T *a L s* $\equiv$ (χ *i*. *if i*=$\upharpoonleft_V$''t'' *then 1 else* (*if i*=$\upharpoonleft_V$''T'' *then* $-$ *a* $*$ (*s*$\downharpoonleft_V$''T''
$-$ *L*) *else 0*))

abbreviation *temp-flow* :: *real* $\Rightarrow$ *real* $\Rightarrow$ *real* $\Rightarrow$ *real^thermostat-vars* $\Rightarrow$ *real^thermostat-vars*
(φ_T)
where φ_T *a L t s* $\equiv$ (χ *i*. *if i*=$\upharpoonleft_V$''T'' *then* $-$ *exp*($-$*a* $*$ *t*) $*$ (*L* $-$ *s*$\downharpoonleft_V$''T'') +
L else
(*if i*=$\upharpoonleft_V$''t'' *then t* + *s*$\downharpoonleft_V$''t'' *else*
(*if i*=$\upharpoonleft_V$''on'' *then s*$\downharpoonleft_V$''on'' *else s*$\downharpoonleft_V$''TT'')))

lemma *norm-diff-temp-dyn*: *0* < *a* $\Longrightarrow$ $\|f_T$ *a L* s_1 $-$ f_T *a L* $s_2\|$ = $|a|$ $*$ $|s_1\downharpoonleft_V$''T''
$-$ $s_2\downharpoonleft_V$''T''$|$
proof(*simp add*: *norm-vec-def L2-set-def thermostat-vars-sum to-var-inject*)
assume *a1*: *0* < *a*
have *f2*: $\bigwedge$*r ra*. |(*r*::*real*) + $-$ *ra*| = |*ra* + $-$ *r*|
by (*metis abs-minus-commute minus-real-def*)
have $\bigwedge$*r ra rb*. (*r*::*real*) $*$ *ra* + $-$ (*r* $*$ *rb*) = *r* $*$ (*ra* + $-$ *rb*)
by (*metis minus-real-def right-diff-distrib*)
hence |*a* $*$ ($s_1\downharpoonleft_V$''T'' + $-$ *L*) + $-$ (*a* $*$ ($s_2\downharpoonleft_V$''T'' + $-$ *L*))| = *a* $*$ |$s_1\downharpoonleft_V$''T'' +

$- s_2\downharpoonright_V {''T''}|$
  using *a1* **by** (*simp add*: *abs-mult*)
 thus $|a * (s_2\downharpoonright_V {''T''} - L) - a * (s_1\downharpoonright_V {''T''} - L)| = a * |s_1\downharpoonright_V {''T''} - s_2\downharpoonright_V {''T''}|$
  using *f2 minus-real-def* **by** *presburger*
qed

lemma *local-lipschitz-temp-dyn*:
 assumes $0 < (a{::}real)$
 shows *local-lipschitz UNIV UNIV* $(\lambda t{::}real.\ f_T\ a\ L)$
 apply(*unfold local-lipschitz-def lipschitz-on-def dist-norm*)
 apply(*clarsimp*, *rule-tac x=1* **in** *exI*, *clarsimp*, *rule-tac x=a* **in** *exI*)
 using *assms* **apply**(*simp add*: *norm-diff-temp-dyn*)
 apply(*simp add*: *norm-vec-def L2-set-def*)
 apply(*unfold thermostat-vars-univ-eq*, *simp add*: *to-var-inject*, *clarsimp*)
 unfolding *real-sqrt-abs*[*symmetric*] **by** (*rule real-le-lsqrt*) *auto*

lemma *local-flow-temp-up*: $a > 0 \Longrightarrow$ *local-flow* $(f_T\ a\ L)$ *UNIV UNIV* $(\varphi_T\ a\ L)$
 apply(*unfold-locales*, *simp-all*)
 using *local-lipschitz-temp-dyn* **apply** *blast*
  apply(*rule thermostat-vars-allI*, *simp-all add*: *to-var-inject*)
 using *thermostat-vars-exhaust* **by** (*auto intro*!: *poly-derivatives simp*: *vec-eq-iff to-var-inject*)

lemma *temp-dyn-down-real-arith*:
 assumes $a > 0$ **and** *Thyps*: $0 < Tmin\ Tmin \leq T\ T \leq Tmax$
  and *thyps*: $0 \leq (t{::}real)\ \forall\tau\in\{0..t\}.\ \tau \leq -\ (ln\ (Tmin\ /\ T)\ /\ a)$
 shows $Tmin \leq exp\ (-a * t) * T$ **and** $exp\ (-a * t) * T \leq Tmax$
proof−
 have $0 \leq t \wedge t \leq -\ (ln\ (Tmin\ /\ T)\ /\ a)$
  using *thyps* **by** *auto*
 hence $ln\ (Tmin\ /\ T) \leq -\ a * t \wedge -\ a * t \leq 0$
  using *assms*(*1*) *divide-le-cancel* **by** *fastforce*
 also have $Tmin\ /\ T > 0$
  using *Thyps* **by** *auto*
 ultimately have *obs*: $Tmin\ /\ T \leq exp\ (-a * t)\ exp\ (-a * t) \leq 1$
  using *exp-ln exp-le-one-iff* **by** (*metis exp-less-cancel-iff not-less*, *simp*)
 thus $Tmin \leq exp\ (-a * t) * T$
  using *Thyps* **by** (*simp add*: *pos-divide-le-eq*)
 show $exp\ (-a * t) * T \leq Tmax$
  using *Thyps mult-left-le-one-le*[*OF - exp-ge-zero obs*(*2*), *of T*]
   less-eq-real-def order-trans-rules(*23*) **by** *blast*
qed

lemma *temp-dyn-up-real-arith*:
 assumes $a > 0$ **and** *Thyps*: $Tmin \leq T\ T \leq Tmax\ Tmax < (L{::}real)$
  and *thyps*: $0 \leq t\ \forall\tau\in\{0..t\}.\ \tau \leq -\ (ln\ ((L - Tmax)\ /\ (L - T))\ /\ a)$
 shows $L - Tmax \leq exp\ (-(a * t)) * (L - T)$
  and $L - exp\ (-(a * t)) * (L - T) \leq Tmax$
  and $Tmin \leq L - exp\ (-(a * t)) * (L - T)$

proof−
  have $0 \leq t \wedge t \leq -(ln\ ((L - Tmax) / (L - T)) / a)$
    using *thyps* **by** *auto*
  hence $ln\ ((L - Tmax) / (L - T)) \leq - a * t \wedge - a * t \leq 0$
    using *assms(1) divide-le-cancel* **by** *fastforce*
  also have $(L - Tmax) / (L - T) > 0$
    using *Thyps* **by** *auto*
  ultimately have $(L - Tmax) / (L - T) \leq exp\ (-a * t) \wedge exp\ (-a * t) \leq 1$
    using *exp-ln exp-le-one-iff* **by** (*metis exp-less-cancel-iff not-less*)
  moreover have $L - T > 0$
    using *Thyps* **by** *auto*
  ultimately have *obs*: $(L - Tmax) \leq exp\ (-a * t) * (L - T) \wedge exp\ (-a * t) * (L - T) \leq (L - T)$
    by (*simp add*: *pos-divide-le-eq*)
  thus $(L - Tmax) \leq exp\ (-(a * t)) * (L - T)$
    by *auto*
  thus $L - exp\ (-(a * t)) * (L - T) \leq Tmax$
    by *auto*
  show $Tmin \leq L - exp\ (-(a * t)) * (L - T)$
    using *Thyps* **and** *obs* **by** *auto*
qed

lemmas *wlp-temp-dyn* = *local-flow.fbox-g-ode-ivl*[*OF local-flow-temp-up - UNIV-I*]

lemma *thermostat*:
  assumes $a > 0$ **and** $0 \leq t$ **and** $0 < Tmin$ **and** $Tmax < L$
  shows $(\lambda s.\ Tmin \leq s\downharpoonright_V{''T''} \wedge s\downharpoonright_V{''T''} \leq Tmax \wedge s\downharpoonright_V{''on''}{=}0) \leq fbox$
  $(LOOP\ (((\upharpoonleft_V{''t''}){::=}(\lambda s.0));((\upharpoonleft_V{''TT''}){::=}(\lambda s.\ s\downharpoonright_V{''T''}));$
  $(IF\ (\lambda s.\ s\downharpoonright_V{''on''}{=}0 \wedge s\downharpoonright_V{''TT''}{\leq}Tmin + 1)\ THEN\ (\upharpoonleft_V{''on''} ::= (\lambda s.1))\ ELSE$

  $(IF\ (\lambda s.\ s\downharpoonright_V{''on''}{=}1 \wedge s\downharpoonright_V{''TT''}{\geq}Tmax - 1)\ THEN\ (\upharpoonleft_V{''on''} ::= (\lambda s.0))\ ELSE\ skip));$
  $(IF\ (\lambda s.\ s\downharpoonright_V{''on''}{=}0)\ THEN\ (x'{=}(f_T\ a\ 0)\ \&\ (\lambda s.\ s\downharpoonright_V{''t''} \leq -(ln\ (Tmin/s\downharpoonright_V{''TT''}))/a)\ on\ \{0..t\}\ UNIV\ @\ 0)$
  $ELSE\ (x'{=}(f_T\ a\ L)\ \&\ (\lambda s.\ s\downharpoonright_V{''t''} \leq -(ln\ ((L{-}Tmax)/(L{-}s\downharpoonright_V{''TT''})))/a)\ on\ \{0..t\}\ UNIV\ @\ 0))\ )$
  $INV\ (\lambda s.\ Tmin \leq s\downharpoonright_V{''T''} \wedge s\downharpoonright_V{''T''}{\leq}Tmax \wedge (s\downharpoonright_V{''on''}{=}0 \vee s\downharpoonright_V{''on''}{=}1)))$
  $(\lambda s.\ Tmin \leq s\$\upharpoonleft_V{''T''} \wedge s\$\upharpoonleft_V{''T''} \leq Tmax)$
  apply(*rule fbox-loopI*, *simp-all add*: *wlp-temp-dyn*[*OF assms(1,2)*] *le-fun-def to-var-inject*, *safe*)
  using *temp-dyn-up-real-arith*[*OF assms(1) - - assms(4), of Tmin*]
    and *temp-dyn-down-real-arith*[*OF assms(1,3), of - Tmax*] **by** *auto*

no-notation *thermostat-vars.to-var* ($\upharpoonleft_V$)
    and *val-T* (**infixl** $\downharpoonright_V$ *90*)
    and *temp-vec-field* (f_T)
    and *temp-flow* (φ_T)

end

theory *cat2funcset*
imports ../*hs-prelims-dyn-sys Transformer-Semantics.Kleisli-Quantale*

begin

Chapter 4

Hybrid System Verification with predicate transformers

— We start by deleting some notation and introducing some new.

no-notation *bres* (**infixr** $\rightarrow$ *60*)
    and *dagger* ($-^{\dagger}$ [*101*] *100*)
    and *Relation.relcomp* (**infixl** ; *75*)
    and *eta* (η)
    and *kcomp* (**infixl** $\circ_K$ *75*)

type-synonym *'a pred = 'a* $\Rightarrow$ *bool*

notation *eta* (*skip*)
  and *kcomp* (**infixl** ; *75*)
  and *g-orbital* ((*1x*´=- & - *on* - - @ -))

4.1 Verification of regular programs

Properties of the forward box operator.

lemma $fb_{\mathcal{F}}\ F\ S = \{s.\ F\ s \subseteq S\}$
  unfolding *ffb-def map-dual-def klift-def kop-def dual-set-def*
  by(*auto simp*: *Compl-eq-Diff-UNIV fun-eq-iff f2r-def converse-def r2f-def*)

lemma *ffb-eq*: $fb_{\mathcal{F}}\ F\ S = \{s.\ \forall s'.\ s' \in F\ s \longrightarrow s' \in S\}$
  unfolding *ffb-def* **apply**(*simp add*: *kop-def klift-def map-dual-def*)
  unfolding *dual-set-def f2r-def r2f-def* **by** *auto*

lemma *ffb-iso*: $P \leq Q \Longrightarrow fb_{\mathcal{F}}\ F\ P \leq fb_{\mathcal{F}}\ F\ Q$
  unfolding *ffb-eq* **by** *auto*

lemma *ffb-invariants*:
  assumes $\{s.\ I\ s\} \leq fb_{\mathcal{F}}\ F\ \{s.\ I\ s\}$ **and** $\{s.\ J\ s\} \leq fb_{\mathcal{F}}\ F\ \{s.\ J\ s\}$
  shows $\{s.\ I\ s \wedge J\ s\} \leq fb_{\mathcal{F}}\ F\ \{s.\ I\ s \wedge J\ s\}$

and $\{s.\ I\ s \vee J\ s\} \leq fb_{\mathcal{F}}\ F\ \{s.\ I\ s \vee J\ s\}$
using *assms* **unfolding** *ffb-eq* **by** *auto*

The weakest liberal precondition (wlp) of the "skip" program is the identity.

lemma *ffb-skip*[*simp*]: $fb_{\mathcal{F}}\ skip\ S = S$
unfolding *ffb-def* **by**(*simp add*: *kop-def klift-def map-dual-def*)

Next, we introduce assignments and their wlps.

definition *vec-upd* :: $('a\hat{\ }'n) \Rightarrow 'n \Rightarrow 'a \Rightarrow 'a\hat{\ }'n$
where *vec-upd s i a* $= (\chi\ j.\ ((((\$)\ s)(i := a))\ j)$

definition *assign* :: $'n \Rightarrow ('a\hat{\ }'n \Rightarrow 'a) \Rightarrow ('a\hat{\ }'n) \Rightarrow ('a\hat{\ }'n)\ set$ ((*2*- ::= -) [*70*, *65*] *61*)
where $(x ::= e) = (\lambda s.\ \{vec\text{-}upd\ s\ x\ (e\ s)\})$

lemma *ffb-assign*[*simp*]: $fb_{\mathcal{F}}\ (x ::= e)\ Q = \{s.\ (\chi\ j.\ ((((\$)\ s)(x := (e\ s)))\ j) \in Q\}$
unfolding *vec-upd-def assign-def* **by** (*subst ffb-eq*) *simp*

The wlp of program composition is just the composition of the wlps.

lemma *ffb-kcomp*[*simp*]: $fb_{\mathcal{F}}\ (G\ ;\ F)\ P = fb_{\mathcal{F}}\ G\ (fb_{\mathcal{F}}\ F\ P)$
unfolding *ffb-def* **apply**(*simp add*: *kop-def klift-def map-dual-def*)
unfolding *dual-set-def f2r-def r2f-def* **by**(*auto simp*: *kcomp-def*)

lemma *ffb-kcomp-ge*:
assumes $P \leq fb_{\mathcal{F}}\ F\ R\ R \leq fb_{\mathcal{F}}\ G\ Q$
shows $P \leq fb_{\mathcal{F}}\ (F\ ;\ G)\ Q$
apply(*subst ffb-kcomp*)
by (*rule order.trans*[*OF assms*(*1*)]) (*rule ffb-iso*[*OF assms*(*2*)])

We also have an implementation of the conditional operator and its wlp.

definition *ifthenelse* :: $'a\ pred \Rightarrow ('a \Rightarrow 'b\ set) \Rightarrow ('a \Rightarrow 'b\ set) \Rightarrow ('a \Rightarrow 'b\ set)$
(*IF - THEN - ELSE -* [*64*,*64*,*64*] *63*) **where**
IF P THEN X ELSE Y $= (\lambda\ x.\ if\ P\ x\ then\ X\ x\ else\ Y\ x)$

lemma *ffb-if-then-else*[*simp*]:
$fb_{\mathcal{F}}$ (*IF T THEN X ELSE Y*) $Q = \{s.\ T\ s \longrightarrow s \in fb_{\mathcal{F}}\ X\ Q\} \cap \{s.\ \neg\ T\ s \longrightarrow s \in fb_{\mathcal{F}}\ Y\ Q\}$
unfolding *ffb-eq ifthenelse-def* **by** *auto*

lemma *ffb-if-then-elseI*:
assumes $P \cap \{s.\ T\ s\} \leq fb_{\mathcal{F}}\ X\ Q$
and $P \cap \{s.\ \neg\ T\ s\} \leq fb_{\mathcal{F}}\ Y\ Q$
shows $P \leq fb_{\mathcal{F}}$ (*IF T THEN X ELSE Y*) Q
using *assms* **apply**(*subst ffb-eq*)
apply(*subst* (*asm*) *ffb-eq*)+
unfolding *ifthenelse-def* **by** *auto*

We also deal with finite iteration.

lemma *kpower-inv*: $I \leq \{s.\ \forall y.\ y \in F\ s \longrightarrow y \in I\} \Longrightarrow I \leq \{s.\ \forall y.\ y \in (kpower\ F\ n\ s) \longrightarrow y \in I\}$
  apply(*induct n*, *simp*)
  apply *simp*
  by(*auto simp*: *kcomp-prop*)

lemma *kstar-inv*: $I \leq fb_{\mathcal{F}}\ F\ I \Longrightarrow I \subseteq fb_{\mathcal{F}}\ (kstar\ F)\ I$
  unfolding *kstar-def ffb-eq* **apply** *clarsimp*
  using *kpower-inv* **by** *blast*

lemma *ffb-kstarI*:
  assumes $P \leq I$ **and** $I \leq Q$ **and** $I \leq fb_{\mathcal{F}}\ F\ I$
  shows $P \leq fb_{\mathcal{F}}\ (kstar\ F)\ Q$
proof−
  have $I \subseteq fb_{\mathcal{F}}\ (kstar\ F)\ I$
    using *assms*(*3*) *kstar-inv* **by** *blast*
  hence $P \leq fb_{\mathcal{F}}\ (kstar\ F)\ I$
    using *assms*(*1*) **by** *auto*
  also have $fb_{\mathcal{F}}\ (kstar\ F)\ I \leq fb_{\mathcal{F}}\ (kstar\ F)\ Q$
    by (*rule ffb-iso*[*OF assms*(*2*)])
  finally show *?thesis* **.**
qed

definition *loopi* :: $('a \Rightarrow 'a\ set) \Rightarrow 'a\ pred \Rightarrow ('a \Rightarrow 'a\ set)$ ($LOOP$ - INV - [*64*,*64*] *63*)
  where $LOOP\ F\ INV\ I \equiv (kstar\ F)$

lemma *ffb-loopI*: $P \leq \{s.\ I\ s\} \Longrightarrow \{s.\ I\ s\} \leq Q \Longrightarrow \{s.\ I\ s\} \leq fb_{\mathcal{F}}\ F\ \{s.\ I\ s\} \Longrightarrow P \leq fb_{\mathcal{F}}\ (LOOP\ F\ INV\ I)\ Q$
  unfolding *loopi-def* **using** *ffb-kstarI*[*of P*] **by** *simp*

4.2 Verification of hybrid programs

4.2.1 Verification by providing evolution

definition *g-evol* :: $(('a{::}ord) \Rightarrow 'b \Rightarrow 'b) \Rightarrow 'b\ pred \Rightarrow 'a\ set \Rightarrow ('b \Rightarrow 'b\ set)$ ($EVOL$)
  where $EVOL\ \varphi\ G\ T = (\lambda s.\ g\text{-}orbit\ (\lambda t.\ \varphi\ t\ s)\ G\ T)$

lemma *fbox-g-evol*[*simp*]:
  fixes $\varphi :: ('a{::}preorder) \Rightarrow 'b \Rightarrow 'b$
  shows $fb_{\mathcal{F}}\ (EVOL\ \varphi\ G\ T)\ Q = \{s.\ (\forall t{\in}T.\ (\forall \tau{\in}down\ T\ t.\ G\ (\varphi\ \tau\ s)) \longrightarrow (\varphi\ t\ s) \in Q)\}$
  unfolding *g-evol-def g-orbit-eq ffb-eq* **by** *auto*

4.2.2 Verification by providing solutions

The wlp of evolution commands.

lemma *ffb-g-orbital*: $fb_{\mathcal{F}}\ (x{'}{=}\ f\ \&\ G\ on\ T\ S\ @\ t_0)\ Q =$

$\{s.\ \forall X{\in}Sols\ (\lambda t.\ f)\ T\ S\ t_0\ s.\ \forall t{\in}T.\ (\forall\tau{\in}down\ T\ t.\ G\ (X\ \tau)) \longrightarrow (X\ t) \in Q\}$
unfolding *ffb-eq g-orbital-eq subset-eq* **by** (*auto simp*: *fun-eq-iff image-le-pred*)

lemma *ffb-g-orbital-eq*: $fb_{\mathcal{F}}\ (x\acute{}= f\ \&\ G\ on\ T\ S\ @\ t_0)\ Q =$
$\{s.\ \forall X{\in}Sols\ (\lambda t.\ f)\ T\ S\ t_0\ s.\ \forall t{\in}T.\ (\mathcal{P}\ X\ (down\ T\ t) \subseteq \{s.\ G\ s\}) \longrightarrow \mathcal{P}\ X\ (down\ T\ t) \subseteq Q\}$
unfolding *ffb-g-orbital image-le-pred*
apply(*subgoal-tac* $\forall X\ t.\ (\mathcal{P}\ X\ (down\ T\ t) \subseteq Q) = (\forall\tau{\in}down\ T\ t.\ (X\ \tau) \in Q)$)
by (*auto simp*: *image-def*)

context *local-flow*
begin

lemma *ffb-g-ode*: $fb_{\mathcal{F}}\ (x\acute{}= f\ \&\ G\ on\ T\ S\ @\ 0)\ Q =$
$\{s.\ s \in S \longrightarrow (\forall t{\in}T.\ (\forall\tau{\in}down\ T\ t.\ G\ (\varphi\ \tau\ s)) \longrightarrow (\varphi\ t\ s) \in Q)\}$ (**is** - = *?wlp*)
unfolding *ffb-g-orbital* **apply**(*safe*, *clarsimp*)
apply(*erule-tac* $x{=}\lambda t.\ \varphi\ t\ x$ **in** *ballE*)
using *in-ivp-sols* **apply**(*force*, *force*, *force simp*: *init-time ivp-sols-def*)
apply(*subgoal-tac* $\forall\tau{\in}down\ T\ t.\ X\ \tau = \varphi\ \tau\ x$, *simp-all*, *clarsimp*)
apply(*subst eq-solution*, *simp-all add*: *ivp-sols-def*)
using *init-time* **by** *auto*

lemma *ffb-orbit*: $fb_{\mathcal{F}}\ \gamma^{\varphi}\ Q = \{s.\ s \in S \longrightarrow (\forall\ t \in T.\ \varphi\ t\ s \in Q)\}$
unfolding *orbit-def ffb-g-ode* **by** *simp*

end

4.2.3 Verification with differential invariants

definition *g-ode-inv* :: $(('a{::}banach){\Rightarrow}'a) \Rightarrow\ 'a\ pred \Rightarrow real\ set \Rightarrow\ 'a\ set \Rightarrow real \Rightarrow\ 'a\ pred \Rightarrow ('a \Rightarrow\ 'a\ set)$ ((*1x´=- & - on - - @ - DINV -*))
where $(x\acute{}= f\ \&\ G\ on\ T\ S\ @\ t_0\ DINV\ I) = (x\acute{}= f\ \&\ G\ on\ T\ S\ @\ t_0)$

lemma *ffb-g-orbital-guard*:
assumes $H = (\lambda s.\ G\ s \wedge Q\ s)$
shows $fb_{\mathcal{F}}\ (x\acute{}= f\ \&\ G\ on\ T\ S\ @\ t_0)\ \{s.\ Q\ s\} = fb_{\mathcal{F}}\ (x\acute{}= f\ \&\ G\ on\ T\ S\ @\ t_0)\ \{s.\ H\ s\}$
unfolding *ffb-g-orbital* **using** *assms* **by** *auto*

lemma *ffb-g-orbital-inv*:
assumes $P \leq I$ **and** $I \leq fb_{\mathcal{F}}\ (x\acute{}= f\ \&\ G\ on\ T\ S\ @\ t_0)\ I$ **and** $I \leq Q$
shows $P \leq fb_{\mathcal{F}}\ (x\acute{}= f\ \&\ G\ on\ T\ S\ @\ t_0)\ Q$
using *assms*(*1*) **apply**(*rule order.trans*)
using *assms*(*2*) **apply**(*rule order.trans*)
by (*rule ffb-iso*[*OF assms*(*3*)])

lemma *ffb-diff-inv*[*simp*]:
$(\{s.\ I\ s\} \leq fb_{\mathcal{F}}\ (x\acute{}= f\ \&\ G\ on\ T\ S\ @\ t_0)\ \{s.\ I\ s\}) = diff\text{-}invariant\ I\ f\ T\ S\ t_0\ G$

by (*auto simp*: *diff-invariant-def ivp-sols-def ffb-eq g-orbital-eq*)

lemma *diff-invariant* $I\,f\,T\,S\,t_0\ G = (((g\text{-}orbital\,f\,G\,T\,S\,t_0)^{\dagger})\ \{s.\ I\,s\} \subseteq \{s.\ I\,s\})$
unfolding *klift-def diff-invariant-def* **by** *simp*

lemma *bdf-diff-inv*:
diff-invariant $I\,f\,T\,S\,t_0\ G = (bd_{\mathcal{F}}\ (x\acute{}=f\ \&\ G\ on\ T\,S\ @\ t_0)\ \{s.\ I\,s\} \leq \{s.\ I\,s\})$
unfolding *ffb-fbd-galois-var* **by** (*auto simp*: *diff-invariant-def ivp-sols-def ffb-eq g-orbital-eq*)

lemma *diff-inv-guard-ignore*:
assumes $\{s.\ I\,s\} \leq fb_{\mathcal{F}}\ (x\acute{}=f\ \&\ (\lambda s.\ True)\ on\ T\,S\ @\ t_0)\ \{s.\ I\,s\}$
shows $\{s.\ I\,s\} \leq fb_{\mathcal{F}}\ (x\acute{}=f\ \&\ G\ on\ T\,S\ @\ t_0)\ \{s.\ I\,s\}$
using *assms* **unfolding** *ffb-diff-inv diff-invariant-eq image-le-pred* **by** *auto*

context *local-flow*
begin

lemma *ffb-diff-inv-eq*: *diff-invariant* $I\,f\,T\,S\ 0\ (\lambda s.\ True) =$
$(\{s.\ s \in S \longrightarrow I\,s\} = fb_{\mathcal{F}}\ (x\acute{}=f\ \&\ (\lambda s.\ True)\ on\ T\,S\ @\ 0)\ \{s.\ s \in S \longrightarrow I\ s\})$
unfolding *ffb-diff-inv*[*symmetric*] *ffb-g-orbital*
using *init-time* **apply**(*auto simp*: *subset-eq ivp-sols-def*)
apply(*subst ivp*(*2*)[*symmetric*], *simp*)
apply(*erule-tac* $x=\lambda t.\ \varphi\ t\ x$ **in** *allE*)
using *in-domain has-vderiv-on-domain ivp*(*2*) *init-time* **by** *force*

lemma *diff-inv-eq-inv-set*:
diff-invariant $I\,f\,T\,S\ 0\ (\lambda s.\ True) = (\forall s.\ I\,s \longrightarrow \gamma^{\varphi}\ s \subseteq \{s.\ I\,s\})$
unfolding *diff-inv-eq-inv-set orbit-def* **by** *simp*

end

lemma *ffb-g-odei*: $P \leq \{s.\ I\,s\} \Longrightarrow \{s.\ I\,s\} \leq fb_{\mathcal{F}}\ (x\acute{}=f\ \&\ G\ on\ T\,S\ @\ t_0)\ \{s.\ I\,s\} \Longrightarrow$
$\{s.\ I\,s \wedge G\,s\} \leq Q \Longrightarrow P \leq fb_{\mathcal{F}}\ (x\acute{}=f\ \&\ G\ on\ T\,S\ @\ t_0\ DINV\ I)\ Q$
unfolding *g-ode-inv-def* **apply**(*rule-tac* $b=fb_{\mathcal{F}}\ (x\acute{}=f\ \&\ G\ on\ T\,S\ @\ t_0)\ \{s.\ I\ s\}$ **in** *order.trans*)
apply(*rule-tac* $I=\{s.\ I\,s\}$ **in** *ffb-g-orbital-inv*, *simp-all*)
apply(*subst ffb-g-orbital-guard*, *simp*)
by (*rule ffb-iso*, *force*)

4.2.4 Derivation of the rules of dL

We derive domain specific rules of differential dynamic logic (dL). First we present a generalised version, then we show the rules as instances of the general ones.

lemma *diff-solve-axiom*:
fixes c::$'a$::{*heine-borel*, *banach*}

assumes $0 \in T$ **and** *is-interval* T *open* T
shows $fb_{\mathcal{F}}$ $(x\acute{}=(\lambda s.\ c)\ \&\ G\ on\ T\ UNIV\ @\ 0)\ Q =$
$\{s.\ \forall\, t{\in}T.\ (\mathcal{P}\ (\lambda\tau.\ s + \tau *_R c)\ (down\ T\ t) \subseteq \{s.\ G\ s\}) \longrightarrow (s + t *_R c) \in Q\}$
apply(*subst local-flow.ffb-g-ode*[*of* $\lambda s.\ c$ - - $(\lambda t\ s.\ s + t *_R c)$])
using *line-is-local-flow assms* **unfolding** *image-le-pred* **by** *auto*

lemma *diff-solve-rule*:
assumes *local-flow f T UNIV* φ
and $\forall\, s.\ s \in P \longrightarrow (\forall\ t{\in}T.\ (\mathcal{P}\ (\lambda t.\ \varphi\ t\ s)\ (down\ T\ t) \subseteq \{s.\ G\ s\}) \longrightarrow (\varphi\ t\ s) \in Q)$
shows $P \leq fb_{\mathcal{F}}\ (x\acute{}= f\ \&\ G\ on\ T\ UNIV\ @\ 0)\ Q$
using *assms* **by**(*subst local-flow.ffb-g-ode*) *auto*

lemma *diff-weak-axiom*: $fb_{\mathcal{F}}\ (x\acute{}= f\ \&\ G\ on\ T\ S\ @\ t_0)\ Q = fb_{\mathcal{F}}\ (x\acute{}= f\ \&\ G\ on\ T\ S\ @\ t_0)\ \{s.\ G\ s \longrightarrow s \in Q\}$
unfolding *ffb-g-orbital image-def* **by** *force*

lemma *diff-weak-rule*: $\{s.\ G\ s\} \leq Q \Longrightarrow P \leq fb_{\mathcal{F}}\ (x\acute{}= f\ \&\ G\ on\ T\ S\ @\ t_0)\ Q$
by(*auto intro*: *g-orbitalD simp*: *le-fun-def g-orbital-eq ffb-eq*)

lemma *ffb-eq-univD*: $fb_{\mathcal{F}}\ F\ P = UNIV \Longrightarrow (\forall\, y.\ y \in (F\ s) \longrightarrow y \in P)$
proof
fix y **assume** $fb_{\mathcal{F}}\ F\ P = UNIV$
hence $UNIV = \{s.\ \forall\, y.\ y \in (F\ s) \longrightarrow y \in P\}$
by(*subst ffb-eq*[*symmetric*], *simp*)
hence $\bigwedge x.\ \{x\} = \{s.\ s = x \wedge (\forall\, y.\ y \in (F\ s) \longrightarrow y \in P)\}$
by *auto*
then show *s2p* $(F\ s)\ y \longrightarrow y \in P$
by *auto*
qed

lemma *ffb-g-orbital-eq-univD*:
assumes $fb_{\mathcal{F}}\ (x\acute{}= f\ \&\ G\ on\ T\ S\ @\ t_0)\ \{s.\ C\ s\} = UNIV$
and $\forall\,\tau{\in}(down\ T\ t).\ x\ \tau \in (x\acute{}= f\ \&\ G\ on\ T\ S\ @\ t_0)\ s$
shows $\forall\,\tau{\in}(down\ T\ t).\ C\ (x\ \tau)$
proof
fix τ **assume** $\tau \in (down\ T\ t)$
hence $x\ \tau \in (x\acute{}= f\ \&\ G\ on\ T\ S\ @\ t_0)\ s$
using *assms*(*2*) **by** *blast*
also have $\forall\, y.\ y \in (x\acute{}= f\ \&\ G\ on\ T\ S\ @\ t_0)\ s \longrightarrow C\ y$
using *assms*(*1*) *ffb-eq-univD* **by** *fastforce*
ultimately show $C\ (x\ \tau)$ **by** *blast*
qed

lemma *diff-cut-axiom*:
assumes *Thyp*: *is-interval* T $t_0 \in T$
and $fb_{\mathcal{F}}\ (x\acute{}= f\ \&\ G\ on\ T\ S\ @\ t_0)\ \{s.\ C\ s\} = UNIV$
shows $fb_{\mathcal{F}}\ (x\acute{}= f\ \&\ G\ on\ T\ S\ @\ t_0)\ Q = fb_{\mathcal{F}}\ (x\acute{}= f\ \&\ (\lambda s.\ G\ s \wedge C\ s)\ on\ T\ S\ @\ t_0)\ Q$

proof(*rule-tac f=λ x. fb*$_\mathcal{F}$ *x Q* **in** *HOL.arg-cong*, *rule ext*, *rule subset-antisym*)
  fix *s*
  {fix *s′* **assume** $s' \in (x' = f \ \& \ G \ on \ T \ S \ @ \ t_0) \ s$
    then obtain *τ*::*real* **and** *X* **where** *x-ivp*: $X \in Sols \ (\lambda t. \ f) \ T \ S \ t_0 \ s$
      and $X \ \tau = s'$ **and** $\tau \in T$ **and** *guard-x*:$\mathcal{P} \ X \ (down \ T \ \tau) \subseteq \{s. \ G \ s\}$
      using *g-orbitalD*[*of s′ f G T S* t_0 *s*] **by** *blast*
    have $\forall t \in (down \ T \ \tau). \ \mathcal{P} \ X \ (down \ T \ t) \subseteq \{s. \ G \ s\}$
      using *guard-x* **by** (*force simp*: *image-def*)
    also have $\forall t \in (down \ T \ \tau). \ t \in T$
      using ‹$\tau \in T$› *Thyp closed-segment-subset-interval* **by** *auto*
    ultimately have $\forall t \in (down \ T \ \tau). \ X \ t \in (x' = f \ \& \ G \ on \ T \ S \ @ \ t_0) \ s$
      using *g-orbitalI*[*OF x-ivp*] **by** (*metis* (*mono-tags*, *lifting*))
    hence $\forall t \in (down \ T \ \tau). \ C \ (X \ t)$
      using *assms* **by** (*meson ffb-eq-univD mem-Collect-eq*)
    hence $s' \in (x' = f \ \& \ (\lambda s. \ G \ s \wedge C \ s) \ on \ T \ S \ @ \ t_0) \ s$
      using *g-orbitalI*[*OF x-ivp* ‹$\tau \in T$›] *guard-x* ‹$X \ \tau = s'$›
      unfolding *image-le-pred* **by** *fastforce***}**
  thus $(x' = f \ \& \ G \ on \ T \ S \ @ \ t_0) \ s \subseteq (x' = f \ \& \ (\lambda s. \ G \ s \wedge C \ s) \ on \ T \ S \ @ \ t_0) \ s$
    by *blast*
next show $\bigwedge s. \ (x' = f \ \& \ (\lambda s. \ G \ s \wedge C \ s) \ on \ T \ S \ @ \ t_0) \ s \subseteq (x' = f \ \& \ G \ on \ T \ S \ @ \ t_0) \ s$
    by (*auto simp*: *g-orbital-eq*)
qed

lemma *diff-cut-rule*:
  assumes *Thyp*: *is-interval* $T \ t_0 \in T$
    and *ffb-C*: $P \leq fb_\mathcal{F} \ (x' = f \ \& \ G \ on \ T \ S \ @ \ t_0) \ \{s. \ C \ s\}$
    and *ffb-Q*: $P \leq fb_\mathcal{F} \ (x' = f \ \& \ (\lambda s. \ G \ s \wedge C \ s) \ on \ T \ S \ @ \ t_0) \ Q$
  shows $P \leq fb_\mathcal{F} \ (x' = f \ \& \ G \ on \ T \ S \ @ \ t_0) \ Q$
proof(*subst ffb-eq*, *subst g-orbital-eq*, *clarsimp*)
  fix *t*::*real* **and** *X*::*real* ⇒ *′a* **and** *s* **assume** $s \in P$ **and** $t \in T$
    and *x-ivp*:$X \in Sols \ (\lambda t. \ f) \ T \ S \ t_0 \ s$
    and *guard-x*:$\mathcal{P} \ X \ (down \ T \ t) \subseteq \{s. \ G \ s\}$
  have $\forall r \in (down \ T \ t). \ X \ r \in (x' = f \ \& \ G \ on \ T \ S \ @ \ t_0) \ s$
    using *g-orbitalI*[*OF x-ivp*] *guard-x* **unfolding** *image-le-pred* **by** *auto*
  hence $\forall t \in (down \ T \ t). \ C \ (X \ t)$
    using *ffb-C* ‹$s \in P$› **by** (*subst* (*asm*) *ffb-eq*, *auto*)
  hence $X \ t \in (x' = f \ \& \ (\lambda s. \ G \ s \wedge C \ s) \ on \ T \ S \ @ \ t_0) \ s$
    using *guard-x* ‹$t \in T$› **by** (*auto intro*!: *g-orbitalI x-ivp*)
  thus $(X \ t) \in Q$
    using ‹$s \in P$› *ffb-Q* **by** (*subst* (*asm*) *ffb-eq*) *auto*
qed

The rules of dL

abbreviation *g-global-orbit* ::((*′a*::*banach*)⇒*′a*) ⇒ *′a pred* ⇒ *′a* ⇒ *′a set*
  ((*1x´=- & -*)) **where** (*x´=f & G*) ≡ (*x´=f & G on UNIV UNIV @ 0*)

abbreviation *g-global-ode-inv* ::((*′a*::*banach*)⇒*′a*) ⇒ *′a pred* ⇒ *′a pred* ⇒ *′a* ⇒ *′a set*

((1x´=- & - DINV -)) **where** $(x´=f\ \&\ G\ DINV\ I) \equiv (x´=f\ \&\ G\ on\ UNIV\ UNIV\ @\ 0\ DINV\ I)$

lemma *solve*:
assumes *local-flow f UNIV UNIV* φ
and $\forall s.\ s \in P \longrightarrow (\forall t.\ (\forall \tau \le t.\ G\ (\varphi\ \tau\ s)) \longrightarrow (\varphi\ t\ s) \in Q)$
shows $P \le fb_{\mathcal{F}}\ (x´= f\ \&\ G)\ Q$
apply(*rule diff-solve-rule*[*OF assms*(*1*)])
using *assms*(*2*) **unfolding** *image-le-pred* **by** *simp*

lemma *DS*:
fixes *c*::′*a*::{*heine-borel*, *banach*}
shows $fb_{\mathcal{F}}\ (x´=(\lambda s.\ c)\ \&\ G)\ Q = \{x.\ \forall t.\ (\forall \tau \le t.\ G\ (x + \tau *_R c)) \longrightarrow (x + t *_R c) \in Q\}$
by (*subst diff-solve-axiom*[*of UNIV*]) *auto*

lemma *DW*: $fb_{\mathcal{F}}\ (x´= f\ \&\ G)\ Q = fb_{\mathcal{F}}\ (x´= f\ \&\ G)\ \{s.\ G\ s \longrightarrow s \in Q\}$
by (*rule diff-weak-axiom*)

lemma *dW*: $\{s.\ G\ s\} \le Q \Longrightarrow P \le fb_{\mathcal{F}}\ (x´= f\ \&\ G)\ Q$
by (*rule diff-weak-rule*)

lemma *DC*:
assumes $fb_{\mathcal{F}}\ (x´= f\ \&\ G)\ \{s.\ C\ s\} = UNIV$
shows $fb_{\mathcal{F}}\ (x´= f\ \&\ G)\ Q = fb_{\mathcal{F}}\ (x´= f\ \&\ (\lambda s.\ G\ s \wedge C\ s))\ Q$
by (*rule diff-cut-axiom*) (*auto simp*: *assms*)

lemma *dC*:
assumes $P \le fb_{\mathcal{F}}\ (x´= f\ \&\ G)\ \{s.\ C\ s\}$
and $P \le fb_{\mathcal{F}}\ (x´= f\ \&\ (\lambda s.\ G\ s \wedge C\ s))\ Q$
shows $P \le fb_{\mathcal{F}}\ (x´= f\ \&\ G)\ Q$
apply(*rule diff-cut-rule*)
using *assms* **by** *auto*

lemma *dI*:
assumes $P \le \{s.\ I\ s\}$ **and** *diff-invariant I f UNIV UNIV 0 G* **and** $\{s.\ I\ s\} \le Q$
shows $P \le fb_{\mathcal{F}}\ (x´= f\ \&\ G)\ Q$
by (*rule ffb-g-orbital-inv*[*OF assms*(*1*) - *assms*(*3*)]) (*simp add*: *assms*(*2*))

end
theory *cat2funcset-examples*
imports ../*hs-prelims-matrices cat2funcset*

begin

4.2.5 Examples

Preliminary lemmas for the examples.

lemma [*simp*]: $i \ne (0::2) \longrightarrow i = 1$

using *exhaust-2* **by** *fastforce*

lemma *two-eq-zero*: $(2::2) = 0$
by *simp*

lemma *UNIV-2*: $(UNIV::2\ set) = \{0,\ 1\}$
apply *safe* **using** *exhaust-2 two-eq-zero* **by** *auto*

lemma *UNIV-3*: $(UNIV::3\ set) = \{0,\ 1,\ 2\}$
apply *safe* **using** *exhaust-3 three-eq-zero* **by** *auto*

lemma *sum-axis-UNIV-3*[*simp*]: $(\sum j\in(UNIV::3\ set).\ axis\ i\ 1\ \$\ j \cdot f\ j) = (f::3 \Rightarrow real)\ i$
unfolding *axis-def UNIV-3* **apply** *simp*
using *exhaust-3* **by** *force*

Pendulum

— Verified with differential invariants.

abbreviation *fpend* :: $real\hat{\ }2 \Rightarrow real\hat{\ }2\ (f)$
where $f\ s \equiv (\chi\ i.\ if\ i{=}0\ then\ s\$1\ else\ {-s\$0})$

lemma *pendulum-invariants*: $\{s.\ r^2 = (s\$0)^2 + (s\$1)^2\} \leq fb_{\mathcal{F}}\ (x\acute{}{=}\ f\ \&\ G)\ \{s.\ r^2 = (s\$0)^2 + (s\$1)^2\}$
by (*auto intro*!: *diff-invariant-rules poly-derivatives*)

— Verified with the flow.

abbreviation *pend-flow* :: $real \Rightarrow real\hat{\ }2 \Rightarrow real\hat{\ }2\ (\varphi)$
where $\varphi\ t\ s \equiv (\chi\ i.\ if\ i = 0\ then\ s\$0 \cdot cos\ t + s\$1 \cdot sin\ t\ else - s\$0 \cdot sin\ t + s\$1 \cdot cos\ t)$

lemma *local-flow-pend*: *local-flow f UNIV UNIV* φ
apply(*unfold-locales*, *simp-all add*: *local-lipschitz-def lipschitz-on-def vec-eq-iff*, *clarsimp*)
apply(*rule-tac x=1* **in** *exI*, *clarsimp*, *rule-tac x=1* **in** *exI*)
apply(*simp add*: *dist-norm norm-vec-def L2-set-def power2-commute UNIV-2*)
apply(*clarsimp*, *case-tac i = 0*, *simp*)
using *exhaust-2 two-eq-zero* **by** (*force intro*!: *poly-derivatives derivative-intros*)+

lemma *pendulum*: $\{s.\ r^2 = (s\$0)^2 + (s\$1)^2\} \leq fb_{\mathcal{F}}\ (x\acute{}{=}\ f\ \&\ G)\ \{s.\ r^2 = (s\$0)^2 + (s\$1)^2\}$
by (*force simp*: *local-flow.ffb-g-ode*[*OF local-flow-pend*])

— Verified by providing the dynamics

lemma *pendulum-dyn*: $\{s.\ r^2 = (s\$0)^2 + (s\$1)^2\} \leq fb_{\mathcal{F}}\ (EVOL\ \varphi\ G\ T)\ \{s.\ r^2 = (s\$0)^2 + (s\$1)^2\}$

by *force*

— Verified as a linear system (using uniqueness).

abbreviation *pend-sq-mtx* :: *2 sq-mtx* (A)
where $A \equiv$ *sq-mtx-chi* (χ *i*. *if i=0 then* e *1 else* − e *0*)

lemma *pend-sq-mtx-exp-eq-flow*: *exp* ($t *_R A$) $*_V$ $s = \varphi$ t s
apply(*rule local-flow.eq-solution*[*OF local-flow-exp*, *symmetric*])
apply(*rule ivp-solsI*, *clarsimp*)
unfolding *sq-mtx-vec-prod-def matrix-vector-mult-def* **apply** *simp*
apply(*force intro*!: *poly-derivatives simp*: *matrix-vector-mult-def*)
using *exhaust-2 two-eq-zero* **by** (*force simp*: *vec-eq-iff*, *auto*)

lemma *pendulum-sq-mtx*: $\{s.\ r^2 = (s\$0)^2 + (s\$1)^2\} \leq fb_{\mathcal{F}}$ ($x' = (*_V)$ A & G) $\{s.\ r^2 = (s\$0)^2 + (s\$1)^2\}$
unfolding *local-flow.ffb-g-ode*[*OF local-flow-exp*] *pend-sq-mtx-exp-eq-flow* **by** *auto*

no-notation *fpend* (f)
and *pend-sq-mtx* (A)
and *pend-flow* (φ)

Bouncing Ball

— Verified with differential invariants.

named-theorems *bb-real-arith real arithmetic properties for the bouncing ball*.

lemma [*bb-real-arith*]:
assumes $0 > g$ **and** *inv*: $2 \cdot g \cdot x - 2 \cdot g \cdot h = v \cdot v$
shows (x::*real*) $\leq h$
proof−
have $v \cdot v = 2 \cdot g \cdot x - 2 \cdot g \cdot h \wedge 0 > g$
using *inv* **and** $\langle 0 > g \rangle$ **by** *auto*
hence *obs*:$v \cdot v = 2 \cdot g \cdot (x - h) \wedge 0 > g \wedge v \cdot v \geq 0$
using *left-diff-distrib mult.commute* **by** (*metis zero-le-square*)
hence $(v \cdot v)/(2 \cdot g) = (x - h)$
by *auto*
also from *obs* **have** $(v \cdot v)/(2 \cdot g) \leq 0$
using *divide-nonneg-neg* **by** *fastforce*
ultimately have $h - x \geq 0$
by *linarith*
thus *?thesis* **by** *auto*
qed

abbreviation *fball* :: *real* ⇒ *real*ˆ*2* ⇒ *real*ˆ*2* (f)
where f g $s \equiv$ (χ *i*. *if i=0 then s\$1 else g*)

lemma *bouncing-ball-invariants*: $g < 0 \Longrightarrow h \geq 0 \Longrightarrow$

$\{s.\ s\$0 = h \wedge s\$1 = 0\} \leq fb_{\mathcal{F}}$
$(LOOP\ ($
$(x' {=} (f\ g)\ \&\ (\lambda\ s.\ s\$0 \geq 0)\ DINV\ (\lambda s.\ 2 \cdot g \cdot s\$0 - 2 \cdot g \cdot h - s\$1 \cdot s\$1 = 0))\ ;$
$(IF\ (\lambda\ s.\ s\$0 = 0)\ THEN\ (1 ::= (\lambda s. - s\$1))\ ELSE\ skip))$
$INV\ (\lambda s.\ 0 \leq s\$0\ \wedge 2 \cdot g \cdot s\$0 - 2 \cdot g \cdot h - s\$1 \cdot s\$1 = 0))$
$\{s.\ 0 \leq s\$0 \wedge s\$0 \leq h\}$
apply(*rule ffb-loopI*, *simp-all*)
apply(*force*, *force simp*: *bb-real-arith*)
apply(*rule ffb-g-odei*)
by (*auto intro*!: *diff-invariant-rules poly-derivatives simp*: *bb-real-arith*)

— Verified with the flow.

abbreviation *ball-flow* :: *real* ⇒ *real* ⇒ *real^2* ⇒ *real^2* (φ)
where $\varphi\ g\ t\ s \equiv (\chi\ i.\ if\ i{=}0\ then\ g \cdot t\ \hat{}\ 2/2 + s\$1 \cdot t + s\$0\ else\ g \cdot t + s\$1)$

lemma *local-flow-ball*: *local-flow* (*f g*) *UNIV UNIV* (φ *g*)
apply(*unfold-locales*, *simp-all add*: *local-lipschitz-def lipschitz-on-def*, *clarsimp*)
apply(*rule-tac x=1/2* **in** *exI*, *clarsimp*, *rule-tac x=1* **in** *exI*)
apply(*simp add*: *dist-norm norm-vec-def L2-set-def UNIV-2*)
apply(*clarsimp*, *case-tac i = 0*)
using *exhaust-2 two-eq-zero* **by** (*auto intro*!: *poly-derivatives simp*: *vec-eq-iff*) *force*

lemma [*bb-real-arith*]:
assumes *invar*: $2 * g * x = 2 * g * h + v * v$
and *pos*: $g * \tau^2\ /\ 2 + v * \tau + (x::real) = 0$
shows $2 * g * h + (g * \tau * (g * \tau + v) + v * (g * \tau + v)) = 0$
proof−
from *pos* **have** $g * \tau^2 + 2 * v * \tau + 2 * x = 0$ **by** *auto*
then have $g^2 * \tau^2 + 2 * g * v * \tau + 2 * g * x = 0$
by (*metis* (*mono-tags*, *hide-lams*) *Groups.mult-ac*(*1*,*3*) *mult-zero-right monoid-mult-class.power2-eq-square semiring-class.distrib-left*)
hence $g^2 * \tau^2 + 2 * g * v * \tau + v^2 + 2 * g * h = 0$
using *invar* **by** (*simp add*: *monoid-mult-class.power2-eq-square*)
hence *obs*: $(g * \tau + v)^2 + 2 * g * h = 0$
apply(*subst power2-sum*) **by** (*metis* (*no-types*, *hide-lams*) *Groups.add-ac*(*2*, *3*)
Groups.mult-ac(*2*, *3*) *monoid-mult-class.power2-eq-square nat-distrib*(*2*))
thus $2 * g * h + (g * \tau * (g * \tau + v) + v * (g * \tau + v)) = 0$
by (*simp add*: *add.commute distrib-right power2-eq-square*)
qed

lemma [*bb-real-arith*]:
assumes *invar*: $2 \cdot g \cdot x = 2 \cdot g \cdot h + v \cdot v$
shows $2 \cdot g \cdot (g \cdot \tau^2\ /\ 2 + v \cdot \tau + (x::real)) =$
$2 \cdot g \cdot h + (g \cdot \tau \cdot (g \cdot \tau + v) + v \cdot (g \cdot \tau + v))$ (**is** *?lhs = ?rhs*)
proof−

have *?lhs* $= g^2 \cdot \tau^2 + 2 \cdot g \cdot v \cdot \tau + 2 \cdot g \cdot x$
  apply(*subst Rat.sign-simps*(*18*))+
  by(*auto simp*: *semiring-normalization-rules*(*29*))
 also have ... $= g^2 \cdot \tau^2 + 2 \cdot g \cdot v \cdot \tau + 2 \cdot g \cdot h + v \cdot v$ (**is** ... = *?middle*)
  by(*subst invar*, *simp*)
 finally have *?lhs* = *?middle*.
moreover
{**have** *?rhs* $= g \cdot g \cdot (\tau \cdot \tau) + 2 \cdot g \cdot v \cdot \tau + 2 \cdot g \cdot h + v \cdot v$
 by (*simp add*: *Groups.mult-ac*(*2*,*3*) *semiring-class.distrib-left*)
also have ... = *?middle*
 by (*simp add*: *semiring-normalization-rules*(*29*))
finally have *?rhs* = *?middle*.}
ultimately show *?thesis* **by** *auto*
qed

lemma *bouncing-ball*: $g < 0 \Longrightarrow h \geq 0 \Longrightarrow$
 $\{s.\ s\$0 = h \wedge s\$1 = 0\} \leq fb_{\mathcal{F}}$
 (*LOOP* (
  $(x' {=} (f\ g)\ \&\ (\lambda\ s.\ s\$0 \geq 0))$;
  $(IF\ (\lambda\ s.\ s\$0 = 0)\ THEN\ (1 ::= (\lambda s.\ -\ s\$1))\ ELSE\ skip))$
 $INV\ (\lambda s.\ 0 \leq s\$0 \wedge 2 \cdot g \cdot s\$0 = 2 \cdot g \cdot h + s\$1 \cdot s\$1))$
 $\{s.\ 0 \leq s\$0 \wedge s\$0 \leq h\}$
by (*rule ffb-loopI*) (*auto simp*: *bb-real-arith local-flow.ffb-g-ode*[*OF local-flow-ball*])

— Verified by providing the dynamics

lemma *bouncing-ball-dyn*: $g < 0 \Longrightarrow h \geq 0 \Longrightarrow$
 $\{s.\ s\$0 = h \wedge s\$1 = 0\} \leq fb_{\mathcal{F}}$
 (*LOOP* (
  $(EVOL\ (\varphi\ g)\ (\lambda\ s.\ s\$0 \geq 0)\ T)$;
  $(IF\ (\lambda\ s.\ s\$0 = 0)\ THEN\ (1 ::= (\lambda s.\ -\ s\$1))\ ELSE\ skip))$
 $INV\ (\lambda s.\ 0 \leq s\$0 \wedge 2 \cdot g \cdot s\$0 = 2 \cdot g \cdot h + s\$1 \cdot s\$1))$
 $\{s.\ 0 \leq s\$0 \wedge s\$0 \leq h\}$
 by (*rule ffb-loopI*) (*auto simp*: *bb-real-arith*)

— Verified as a linear system (computing exponential).

abbreviation *ball-sq-mtx* :: *3 sq-mtx* (*A*)
 where *ball-sq-mtx* ≡ *sq-mtx-chi* (χ *i*. *if i=0 then* e *1 else if i=1 then* e *2 else 0*)

lemma *ball-sq-mtx-pow2*: A^2 = *sq-mtx-chi* (χ *i*. *if i=0 then* e *2 else 0*)
 unfolding *power2-eq-square times-sq-mtx-def*
 by(*simp add*: *sq-mtx-chi-inject vec-eq-iff matrix-matrix-mult-def*)

lemma *ball-sq-mtx-powN*: $n > 2 \Longrightarrow (\tau *_R A)\hat{}n = 0$
 apply(*induct n*, *simp*, *case-tac* $n \leq 2$)
  apply(*simp only*: *le-less-Suc-eq power-Suc*, *simp*)
 by(*auto simp*: *ball-sq-mtx-pow2 sq-mtx-chi-inject vec-eq-iff*
  times-sq-mtx-def zero-sq-mtx-def matrix-matrix-mult-def)

lemma *exp-ball-sq-mtx*: *exp* $(\tau *_R A) = ((\tau *_R A)^2/_R\ 2) + (\tau *_R A) + 1$
unfolding *exp-def* **apply**(*subst suminf-eq-sum*[*of 2*])
using *ball-sq-mtx-powN* **by** (*simp-all add*: *numeral-2-eq-2*)

lemma *exp-ball-sq-mtx-simps*:
exp $(\tau *_R A)$ $$ *0* $ *0* = *1* *exp* $(\tau *_R A)$ $$ *0* $ *1* = τ *exp* $(\tau *_R A)$ $$ *0* $ *2* = τˆ*2*/*2*
exp $(\tau *_R A)$ $$ *1* $ *0* = *0* *exp* $(\tau *_R A)$ $$ *1* $ *1* = *1* *exp* $(\tau *_R A)$ $$ *1* $ *2* = τ
exp $(\tau *_R A)$ $$ *2* $ *0* = *0* *exp* $(\tau *_R A)$ $$ *2* $ *1* = *0* *exp* $(\tau *_R A)$ $$ *2* $ *2* = *1*
unfolding *exp-ball-sq-mtx scaleR-power ball-sq-mtx-pow2*
by (*auto simp*: *plus-sq-mtx-def scaleR-sq-mtx-def one-sq-mtx-def mat-def scaleR-vec-def axis-def plus-vec-def*)

lemma *bouncing-ball-sq-mtx*:
{*s*. *0* ≤ *s*$*0* ∧ *s*$*0* = *h* ∧ *s*$*1* = *0* ∧ *0* > *s* $ *2*} ≤ $fb_{\mathcal{F}}$
(*LOOP* ((*x*´= $(*_V)$ *A* & (λ *s*. *s*$*0* ≥ *0*)) ;
(*IF* (λ *s*. *s*$*0* = *0*) *THEN* (*1* ::= (λ*s*. − *s*$*1*)) *ELSE skip*))
INV (λ*s*. *0*≤*s*$0 ∧ *0*>*s*$*2* ∧ *2* · *s*$*2* · *s*$*0* = *2* · *s*$*2* · *h* + (*s*$*1* · *s*$*1*)))
{*s*. *0* ≤ *s*$*0* ∧ *s*$*0* ≤ *h*}
apply(*rule ffb-loopI*, *simp-all add*: *local-flow.ffb-g-ode*[*OF local-flow-exp*] *sq-mtx-vec-prod-eq*)
apply(*clarsimp*, *force simp*: *bb-real-arith*)
unfolding *UNIV-3* **apply**(*simp add*: *exp-ball-sq-mtx-simps*, *safe*)
using *bb-real-arith*(*2*) **apply**(*force simp*: *add.commute mult.commute*)
using *bb-real-arith*(*3*) **by** (*force simp*: *add.commute mult.commute*)

no-notation *fpend* (*f*)
and *pend-flow* (φ)
and *ball-sq-mtx* (*A*)

end
theory *cat2rel*
imports
../*hs-prelims-dyn-sys*
../../*afpModified*/*VC-KAD*

begin

Chapter 5

Hybrid System Verification with relations

— We start by deleting some conflicting notation.

no-notation *Archimedean-Field.ceiling* ($\lceil$-$\rceil$)
  and *Archimedean-Field.floor-ceiling-class.floor* ($\lfloor$-$\rfloor$)
  and *Range-Semiring.antirange-semiring-class.ars-r* (r)
  and *Relation.Domain* ($r2s$)
  and *VC-KAD.gets* (- ::= - [*70*, *65*] *61*)
  and *cond-sugar* (*IF* - *THEN* - *ELSE* - *FI* [*64*,*64*,*64*] *63*)

notation *Id* (*skip*)
  and *cond-sugar* (*IF* - *THEN* - *ELSE* - [*64*,*64*,*64*] *63*)

5.1 Verification of regular programs

Properties of the forward box operator.

lemma *wp-rel*: $wp\ R\ \lceil P\rceil = \lceil\lambda\ x.\ \forall\ y.\ (x,y) \in R \longrightarrow P\ y\rceil$
proof−
  have $\lfloor wp\ R\ \lceil P\rceil\rfloor = \lfloor\lceil\lambda\ x.\ \forall\ y.\ (x,y) \in R \longrightarrow P\ y\rceil\rfloor$
    by (*simp add*: *wp-trafo pointfree-idE*)
  thus $wp\ R\ \lceil P\rceil = \lceil\lambda\ x.\ \forall\ y.\ (x,y) \in R \longrightarrow P\ y\rceil$
    by (*metis* (*no-types*, *lifting*) *wp-simp d-p2r pointfree-idE prp*)
qed

lemma *p2r-r2p-wp*: $\lceil\lfloor wp\ R\ P\rfloor\rceil = wp\ R\ P$
  apply(*subst d-p2r*[*symmetric*])
  using *wp-simp*[*symmetric*, *of R P*] **by** *blast*

lemma *p2r-r2p-simps*:
  $\lfloor\lceil P \sqcap Q\rceil\rfloor = (\lambda\ s.\ \lfloor\lceil P\rceil\rfloor\ s \wedge \lfloor\lceil Q\rceil\rfloor\ s)$
  $\lfloor\lceil P \sqcup Q\rceil\rfloor = (\lambda\ s.\ \lfloor\lceil P\rceil\rfloor\ s \vee \lfloor\lceil Q\rceil\rfloor\ s)$
  $\lfloor\lceil P\rceil\rfloor = P$

unfolding *p2r-def r2p-def* **by** (*auto simp*: *fun-eq-iff*)

Next, we introduce assignments and their *wp*.

definition *vec-upd* :: $('a\hat{\ }'b) \Rightarrow 'b \Rightarrow 'a \Rightarrow 'a\hat{\ }'b$
where $vec\text{-}upd\ s\ i\ a \equiv (\chi\ j.\ (((\$)\ s)(i := a))\ j)$

definition *assign* :: $'b \Rightarrow ('a\hat{\ }'b \Rightarrow 'a) \Rightarrow ('a\hat{\ }'b)\ rel\ ((2\text{-} ::= \text{-})\ [70,\ 65]\ 61)$
where $(x ::= e) \equiv \{(s,\ vec\text{-}upd\ s\ x\ (e\ s))|\ s.\ True\}$

lemma *wp-assign* [*simp*]: $wp\ (x ::= e)\ \lceil Q\rceil = \lceil\lambda s.\ Q\ (\chi\ j.\ (((\$)\ s)(x := (e\ s)))\ j)\rceil$
unfolding *wp-rel vec-upd-def assign-def* **by** (*auto simp*: *fun-upd-def*)

lemma *assignD*: $((s,s') \in (x ::= e)) = (s'\$\ x = e\ s \wedge (\forall\, y.\ y \neq x \longrightarrow s'\ \$\ y = s\ \$\ y))$
unfolding *vec-upd-def assign-def* **by** (*simp*, *subst vec-eq-iff*) *auto*

The *wp* of the composition was already obtained in KAD.Antidomain_Semiring: $|x \cdot y]\ z = \ |x]\ \ |y]\ z$.

There is also already an implementation of the conditional operator *if p then x else y fi* $= d\ p \cdot x + ad\ p \cdot y$ and its *wp*: $|$*if p then x else y fi*$]\ q = d\ p \cdot |x]\ q + ad\ p \cdot\ |y]\ q$.

We also deal with finite iteration.

context *antidomain-kleene-algebra*
begin

lemma *plus-inv*: $i \leq |x]\ i \Longrightarrow j \leq |x]\ j \Longrightarrow (i + j) \leq |x]\ (i + j)$
by (*metis ads-d-def dka.dsr5 fbox-simp fbox-subdist join.sup-mono order-trans*)

lemma *mult-inv*: $d\ i \leq |x]\ d\ i \Longrightarrow d\ j \leq |x]\ d\ j \Longrightarrow (d\ i \cdot d\ j) \leq |x]\ (d\ i \cdot d\ j)$
using *local.fbox-demodalisation3 local.fbox-frame local.fbox-simp* **by** *auto*

lemma *fbox-stari*:
assumes $d\ p \leq d\ i$ **and** $d\ i \leq |x]\ i$ **and** $d\ i \leq d\ q$
shows $d\ p \leq |x^\star]\ q$
by (*meson assms local.dual-order.trans fbox-iso fbox-star-induct-var*)

definition *loopi* :: $'a \Rightarrow 'a \Rightarrow 'a\ (loop\ \text{-}\ inv\ \text{-}\ \ [64,64]\ 63)$
where $loop\ x\ inv\ i = x^\star$

lemma *fbox-loopi*: $d\ p \leq d\ i \Longrightarrow d\ i \leq |x]\ i \Longrightarrow d\ i \leq d\ q \Longrightarrow d\ p \leq |loop\ x\ inv\ i]\ q$
unfolding *loopi-def* **using** *fbox-stari* **by** *blast*

end

abbreviation *loopi-sugar* :: $'a\ rel \Rightarrow 'a\ pred \Rightarrow 'a\ rel\ (LOOP\ \text{-}\ INV\ \text{-}\ \ [64,64]\ 63)$

where *LOOP R INV I* $\equiv$ *rel-antidomain-kleene-algebra.loopi R* $\lceil I \rceil$

lemma *wp-loopI*: $\lceil P\rceil \subseteq \lceil I\rceil \Longrightarrow \lceil I\rceil \subseteq \lceil Q\rceil \Longrightarrow \lceil I\rceil \subseteq wp\ R\ \lceil I\rceil \Longrightarrow \lceil P\rceil \subseteq wp$ (*LOOP R INV I*) $\lceil Q\rceil$
using *rel-antidomain-kleene-algebra.fbox-loopi*[*of* $\lceil P\rceil$] **by** *auto*

5.2 Verification of hybrid programs

5.2.1 Verification by providing evolution

definition *g-evol* :: $(('a::ord) \Rightarrow 'b \Rightarrow 'b) \Rightarrow 'b\ pred \Rightarrow 'a\ set \Rightarrow 'b\ rel$ (*EVOL*)
where *EVOL* φ *G T* = $\{(s,s')\ |s\ s'.\ s' \in$ *g-orbit* $(\lambda t.\ \varphi\ t\ s)\ G\ T\}$

lemma *wp-g-dyn*[*simp*]:
fixes φ :: $('a::preorder) \Rightarrow 'b \Rightarrow 'b$
shows *wp* (*EVOL* φ *G T*) $\lceil Q\rceil = \lceil \lambda s.\ \forall t{\in}T.\ (\forall \tau{\in}down\ T\ t.\ G\ (\varphi\ \tau\ s)) \longrightarrow Q\ (\varphi\ t\ s)\rceil$
unfolding *wp-rel g-evol-def g-orbit-eq* **by** *auto*

5.2.2 Verification by providing solutions

definition *g-ode* :: $(('a::banach) \Rightarrow 'a) \Rightarrow 'a\ pred \Rightarrow real\ set \Rightarrow 'a\ set \Rightarrow real \Rightarrow$ $'a\ rel$ ((1x´=- & - on - - @ -))
where $(x' = f\ \&\ G\ on\ T\ S\ @\ t_0) = \{(s,s')\ |s\ s'.\ s' \in g\text{-}orbital\ f\ G\ T\ S\ t_0\ s\}$

lemma *wp-g-orbital*: $wp\ (x' = f\ \&\ G\ on\ T\ S\ @\ t_0)\ \lceil Q\rceil =$
$\lceil \lambda\ s.\ \forall X{\in}Sols\ (\lambda t.\ f)\ T\ S\ t_0\ s.\ \forall t{\in}T.\ (\forall \tau{\in}down\ T\ t.\ G\ (X\ \tau)) \longrightarrow Q\ (X\ t)\rceil$
unfolding *g-orbital-eq wp-rel ivp-sols-def image-le-pred g-ode-def* **by** *auto*

context *local-flow*
begin

lemma *wp-g-ode*: $wp\ (x' = f\ \&\ G\ on\ T\ S\ @\ 0)\ \lceil Q\rceil =$
$\lceil \lambda\ s.\ s \in S \longrightarrow (\forall t{\in}T.\ (\forall \tau{\in}down\ T\ t.\ G\ (\varphi\ \tau\ s)) \longrightarrow Q\ (\varphi\ t\ s))\rceil$
unfolding *wp-g-orbital* **apply**(*clarsimp*, *safe*)
apply(*erule-tac* $x{=}\lambda t.\ \varphi\ t\ s$ **in** *ballE*)
using *in-ivp-sols* **apply**(*force*, *force*, *force simp*: *init-time ivp-sols-def*)
apply(*subgoal-tac* $\forall \tau{\in}down\ T\ t.\ X\ \tau = \varphi\ \tau\ s$, *simp-all*, *clarsimp*)
apply(*subst eq-solution*, *simp-all add*: *ivp-sols-def*)
using *init-time* **by** *auto*

lemma *wp-orbit*: $wp\ (\{(s,s')\ |\ s\ s'.\ s' \in \gamma^{\varphi}\ s\})\ \lceil Q\rceil = \lceil \lambda\ s.\ s \in S \longrightarrow (\forall\ t \in T.\ Q\ (\varphi\ t\ s))\rceil$
unfolding *orbit-def wp-g-ode g-ode-def*[*symmetric*] **by** *auto*

end

5.2.3 Verification with differential invariants

definition *g-ode-inv* :: (('a::banach)⇒'a) ⇒ 'a pred ⇒ real set ⇒ 'a set ⇒ real ⇒ 'a pred ⇒ 'a rel ((1x´=- & - on - - @ - DINV -))
 where (x´= f & G on T S @ t_0 DINV I) = (x´= f & G on T S @ t_0)

lemma *wp-g-orbital-guard*:
 assumes H = (λs. G s ∧ Q s)
 shows wp (x´= f & G on T S @ t_0) ⌈Q⌉ = wp (x´= f & G on T S @ t_0) ⌈H⌉
 unfolding *wp-g-orbital* **using** *assms* **by** *auto*

lemma *wp-g-orbital-inv*:
 assumes ⌈P⌉ ≤ ⌈I⌉ **and** ⌈I⌉ ≤ wp (x´= f & G on T S @ t_0) ⌈I⌉ **and** ⌈I⌉ ≤ ⌈Q⌉
 shows ⌈P⌉ ≤ wp (x´= f & G on T S @ t_0) ⌈Q⌉
 using *assms(1)* **apply**(*rule order.trans*)
 using *assms(2)* **apply**(*rule order.trans*)
 apply(*rule rel-antidomain-kleene-algebra.fbox-iso*)
 using *assms(3)* **by** *auto*

lemma *wp-diff-inv*[*simp*]: (⌈I⌉ ≤ wp (x´=f & G on T S @ t_0) ⌈I⌉) = *diff-invariant* I f T S t_0 G
 unfolding *diff-invariant-eq wp-g-orbital image-le-pred* **by**(*auto simp*: *p2r-def*)

lemma *wp-g-odei*: ⌈P⌉ ≤ ⌈I⌉ ⟹ ⌈I⌉ ≤ wp (x´= f & G on T S @ t_0) ⌈I⌉ ⟹ ⌈λs. I s ∧ G s⌉ ≤ ⌈Q⌉ ⟹
 ⌈P⌉ ≤ wp (x´= f & G on T S @ t_0 DINV I) ⌈Q⌉
 unfolding *g-ode-inv-def* **apply**(*rule-tac b=wp* (x´= f & G on T S @ t_0) ⌈I⌉ **in** *order.trans*)
  apply(*rule-tac I=I* **in** *wp-g-orbital-inv*, *simp-all*)
 apply(*subst wp-g-orbital-guard*, *simp*)
 by (*rule rel-antidomain-kleene-algebra.fbox-iso*, *simp*)

5.2.4 Derivation of the rules of dL

We derive domain specific rules of differential dynamic logic (dL). First we present a generalised version, then we show the rules as instances of the general ones.

lemma *diff-solve-axiom*:
 fixes c::'a::{*heine-borel*, *banach*}
 assumes 0 ∈ T **and** *is-interval* T *open* T
 shows wp (x´=(λs. c) & G on T UNIV @ 0) ⌈Q⌉ =
 ⌈λ s. ∀ t∈T. (𝒫 (λ t. s + t $*_R$ c) (down T t) ⊆ {s. G s}) ⟶ Q (s + t $*_R$ c)⌉
 apply(*subst local-flow.wp-g-ode*[**where** f=λs. c **and** φ=(λ t x. x + t $*_R$ c)])
 using *line-is-local-flow assms* **unfolding** *image-le-pred* **by** *auto*

lemma *diff-solve-rule*:
 assumes *local-flow* f T UNIV φ
  and ∀ s. P s ⟶ (∀ t∈T. (𝒫 (λt. φ t s) (down T t) ⊆ {s. G s}) ⟶ Q (φ t

```
s))
  shows ⌈P⌉ ≤ wp (x´= f & G on T UNIV @ 0) ⌈Q⌉
  using assms by(subst local-flow.wp-g-ode, auto)

lemma diff-weak-axiom: wp (x´= f & G on T S @ t0) ⌈Q⌉ = wp (x´= f & G on
T S @ t0) ⌈λ s. G s ⟶ Q s⌉
  unfolding wp-g-orbital image-def by force

lemma diff-weak-rule:
  assumes ⌈G⌉ ≤ ⌈Q⌉
  shows ⌈P⌉ ≤ wp (x´= f & G on T S @ t0) ⌈Q⌉
  using assms apply(subst wp-rel)
  by(auto simp: g-orbital-eq g-ode-def)

lemma wp-g-evol-IdD:
  assumes wp (x´= f & G on T S @ t0) ⌈C⌉ = Id
    and ∀τ∈(down T t). (s, x τ) ∈ (x´= f & G on T S @ t0)
  shows ∀τ∈(down T t). C (x τ)
proof
  fix τ assume τ ∈ (down T t)
  hence x τ ∈ g-orbital f G T S t0 s
    using assms(2) unfolding g-ode-def by blast
  also have ∀y. y ∈ (g-orbital f G T S t0 s) ⟶ C y
    using assms(1) unfolding wp-rel g-ode-def by(auto simp: p2r-def)
  ultimately show C (x τ)
    by blast
qed

lemma diff-cut-axiom:
  assumes Thyp: is-interval T t0 ∈ T
    and wp (x´= f & G on T S @ t0) ⌈C⌉ = Id
  shows wp (x´= f & G on T S @ t0) ⌈Q⌉ = wp (x´= f & (λs. G s ∧ C s) on
T S @ t0) ⌈Q⌉
proof(rule-tac f=λ x. wp x ⌈Q⌉ in HOL.arg-cong, rule subset-antisym)
  show (x´=f & G on T S @ t0) ⊆ (x´=f & λs. G s ∧ C s on T S @ t0)
  proof(clarsimp simp: g-ode-def)
    fix s and s' assume s' ∈ g-orbital f G T S t0 s
    then obtain τ::real and X where x-ivp: X ∈ Sols (λt. f) T S t0 s
      and X τ = s' and τ ∈ T and guard-x:(𝒫 X (down T τ) ⊆ {s. G s})
      using g-orbitalD[of s' f G T S t0 s] by blast
    have ∀t∈(down T τ). 𝒫 X (down T t) ⊆ {s. G s}
      using guard-x by (force simp: image-def)
    also have ∀t∈(down T τ). t ∈ T
      using ‹τ ∈ T› Thyp by auto
    ultimately have ∀t∈(down T τ). X t ∈ g-orbital f G T S t0 s
      using g-orbitalI[OF x-ivp] by (metis (mono-tags, lifting))
    hence ∀t∈(down T τ). C (X t)
      using wp-g-evol-IdD[OF assms(3)] unfolding g-ode-def by blast
    thus s' ∈ g-orbital f (λs. G s ∧ C s) T S t0 s
```

using *g-orbitalI*[*OF x-ivp* ‹$\tau \in T$›] *guard-x* ‹$X\ \tau = s$'›
unfolding *image-le-pred* **by** *fastforce*
qed
next show $(x' = f\ \&\ \lambda s.\ G\ s \wedge C\ s\ on\ T\ S\ @\ t_0) \subseteq (x' = f\ \&\ G\ on\ T\ S\ @\ t_0)$
by (*auto simp*: *g-orbital-eq g-ode-def*)
qed

lemma *diff-cut-rule*:
assumes *Thyp*: *is-interval* $T\ t_0 \in T$
and *wp-C*: $\lceil P \rceil \leq wp\ (x' = f\ \&\ G\ on\ T\ S\ @\ t_0)\ \lceil C \rceil$
and *wp-Q*: $\lceil P \rceil \subseteq wp\ (x' = f\ \&\ (\lambda s.\ G\ s \wedge C\ s)\ on\ T\ S\ @\ t_0)\ \lceil Q \rceil$
shows $\lceil P \rceil \subseteq wp\ (x' = f\ \&\ G\ on\ T\ S\ @\ t_0)\ \lceil Q \rceil$
proof(*subst wp-rel*, *simp add*: *g-orbital-eq p2r-def image-le-pred g-ode-def*, *clarsimp*)
fix t::*real* **and** X::*real* $\Rightarrow$ '*a* **and** s **assume** $P\ s$ **and** $t \in T$
and *x-ivp*:$X \in$ *Sols* $(\lambda t.\ f)\ T\ S\ t_0\ s$
and *guard-x*:$\forall x.\ x \in T \wedge x \leq t \longrightarrow G\ (X\ x)$
have $\forall t \in (down\ T\ t).\ X\ t \in$ *g-orbital* $f\ G\ T\ S\ t_0\ s$
using *g-orbitalI*[*OF x-ivp*] *guard-x* **unfolding** *image-le-pred* **by** *auto*
hence $\forall t \in (down\ T\ t).\ C\ (X\ t)$
using *wp-C* ‹$P\ s$› **by** (*subst* (*asm*) *wp-rel*, *auto simp*: *g-ode-def*)
hence $X\ t \in$ *g-orbital* $f\ (\lambda s.\ G\ s \wedge C\ s)\ T\ S\ t_0\ s$
using *guard-x* ‹$t \in T$› **by** (*auto intro*!: *g-orbitalI x-ivp*)
thus $Q\ (X\ t)$
using ‹$P\ s$› *wp-Q* **by** (*subst* (*asm*) *wp-rel*) (*auto simp*: *g-ode-def*)
qed

The rules of dL

abbreviation *g-global-ode* ::(('*a*::*banach*)$\Rightarrow$'*a*) $\Rightarrow$ '*a pred* $\Rightarrow$ '*a rel* ((*1x*´=- & -))
where $(x' = f\ \&\ G) \equiv (x' = f\ \&\ G\ on\ UNIV\ UNIV\ @\ 0)$

abbreviation *g-global-ode-inv* :: (('*a*::*banach*)$\Rightarrow$'*a*) $\Rightarrow$ '*a pred* $\Rightarrow$ '*a pred* $\Rightarrow$ '*a rel* ((*1x*´=- & - *DINV* -)) **where** $(x' = f\ \&\ G\ DINV\ I) \equiv (x' = f\ \&\ G\ on\ UNIV\ UNIV\ @\ 0\ DINV\ I)$

lemma *DS*:
fixes c::'*a*::{*heine-borel*, *banach*}
shows $wp\ (x' = (\lambda s.\ c)\ \&\ G)\ \lceil Q \rceil = \lceil \lambda x.\ \forall t.\ (\forall \tau \leq t.\ G\ (x + \tau *_R c)) \longrightarrow Q\ (x + t *_R c) \rceil$
by (*subst diff-solve-axiom*[*of UNIV*]) *auto*

lemma *solve*:
assumes *local-flow* f *UNIV UNIV* φ
and $\forall s.\ P\ s \longrightarrow (\forall t.\ (\forall \tau \leq t.\ G\ (\varphi\ \tau\ s)) \longrightarrow Q\ (\varphi\ t\ s))$
shows $\lceil P \rceil \leq wp\ (x' = f\ \&\ G)\ \lceil Q \rceil$
apply(*rule diff-solve-rule*[*OF assms*(*1*)])
using *assms*(*2*) **unfolding** *image-le-pred* **by** *simp*

lemma *DW*: $wp\ (x' = f\ \&\ G)\ \lceil Q \rceil = wp\ (x' = f\ \&\ G)\ \lceil \lambda s.\ G\ s \longrightarrow Q\ s \rceil$

by (*rule diff-weak-axiom*)

lemma *dW*: $\lceil G \rceil \leq \lceil Q \rceil \Longrightarrow \lceil P \rceil \leq wp\ (x' = f\ \&\ G)\ \lceil Q \rceil$
by (*rule diff-weak-rule*)

lemma *DC*:
assumes $wp\ (x' = f\ \&\ G)\ \lceil C \rceil = Id$
shows $wp\ (x' = f\ \&\ G)\ \lceil Q \rceil = wp\ (x' = f\ \&\ (\lambda s.\ G\ s \wedge C\ s))\ \lceil Q \rceil$
apply (*rule diff-cut-axiom*)
using *assms* **by** *auto*

lemma *dC*:
assumes $\lceil P \rceil \leq wp\ (x' = f\ \&\ G)\ \lceil C \rceil$
and $\lceil P \rceil \leq wp\ (x' = f\ \&\ (\lambda s.\ G\ s \wedge C\ s))\ \lceil Q \rceil$
shows $\lceil P \rceil \leq wp\ (x' = f\ \&\ G)\ \lceil Q \rceil$
apply(*rule diff-cut-rule*)
using *assms* **by** *auto*

lemma *dI*:
assumes $\lceil P \rceil \leq \lceil I \rceil$ **and** *diff-invariant I f UNIV UNIV 0 G* **and** $\lceil I \rceil \leq \lceil Q \rceil$
shows $\lceil P \rceil \leq wp\ (x' = f\ \&\ G)\ \lceil Q \rceil$
apply(*rule wp-g-orbital-inv*[*OF assms*(*1*) - *assms*(*3*)])
unfolding *wp-diff-inv* **using** *assms*(*2*) **.**

end
theory *cat2rel-examples*
imports ../*hs-prelims-matrices cat2rel*

begin

5.2.5 Examples

Preliminary preparation for the examples.

no-notation *Archimedean-Field.ceiling* ($\lceil - \rceil$)
and *Archimedean-Field.floor-ceiling-class.floor* ($\lfloor - \rfloor$)

lemma [*simp*]: $i \neq (0::2) \longrightarrow i = 1$
using *exhaust-2* **by** *fastforce*

lemma *two-eq-zero*: $(2::2) = 0$
by *simp*

lemma *UNIV-2*: $(UNIV::2\ set) = \{0,\ 1\}$
apply *safe* **using** *exhaust-2 two-eq-zero* **by** *auto*

lemma *UNIV-3*: $(UNIV::3\ set) = \{0,\ 1,\ 2\}$
apply *safe* **using** *exhaust-3 three-eq-zero* **by** *auto*

lemma *sum-axis-UNIV-3*[*simp*]: $(\sum j \in (UNIV::3\ set).\ axis\ i\ 1\ \$\ j \cdot f\ j) = (f::3$

$\Rightarrow$ *real*) *i*
unfolding *axis-def UNIV-3* **apply** *simp*
using *exhaust-3* **by** *force*

Pendulum

— Verified with differential invariants.

abbreviation *fpend* :: *real^2* $\Rightarrow$ *real^2* (*f*)
where $f\ s \equiv (\chi\ i.\ if\ i{=}0\ then\ s\$1\ else\ -s\ \$\ 0)$

lemma *pendulum-invariants*:
$\lceil \lambda s.\ r^2 = (s\ \$\ 0)^2 + (s\ \$\ 1)^2 \rceil \leq wp\ (x' = f\ \&\ G)\ \lceil \lambda s.\ r^2 = (s\ \$\ 0)^2 + (s\ \$\ 1)^2 \rceil$
by (*auto intro*!: *poly-derivatives diff-invariant-rules*)

— Verified with the flow.

abbreviation *pend-flow* :: *real* $\Rightarrow$ *real^2* $\Rightarrow$ *real^2* (φ)
where $\varphi\ t\ s \equiv (\chi\ i.\ if\ i = 0\ then\ s\ \$\ 0 \cdot cos\ t + s\ \$\ 1 \cdot sin\ t$
$else\ -\ s\ \$\ 0 \cdot sin\ t + s\ \$\ 1 \cdot cos\ t)$

lemma *local-flow-pend*: *local-flow f UNIV UNIV* φ
apply(*unfold-locales*, *simp-all add*: *local-lipschitz-def lipschitz-on-def vec-eq-iff*, *clarsimp*)
apply(*rule-tac x=1* **in** *exI*, *clarsimp*, *rule-tac x=1* **in** *exI*)
apply(*simp add*: *dist-norm norm-vec-def L2-set-def power2-commute UNIV-2*)
apply(*clarify*, *case-tac i* = *0*, *simp*)
using *exhaust-2 two-eq-zero* **by** (*force intro*!: *poly-derivatives*)+

lemma *pendulum*:
$\lceil \lambda s.\ r^2 = (s\ \$\ 0)^2 + (s\ \$\ 1)^2 \rceil \leq wp\ (x' = f\ \&\ G)\ \lceil \lambda s.\ r^2 = (s\ \$\ 0)^2 + (s\ \$\ 1)^2 \rceil$
by (*simp add*: *local-flow.wp-g-ode*[*OF local-flow-pend*])

— Verified by providing dynamics.

lemma *pendulum-dyn*:
$\lceil \lambda s.\ r^2 = (s\ \$\ 0)^2 + (s\ \$\ 1)^2 \rceil \leq wp\ (EVOL\ \varphi\ G\ T)\ \lceil \lambda s.\ r^2 = (s\ \$\ 0)^2 + (s\ \$\ 1)^2 \rceil$
by *simp*

— Verified as a linear system (using uniqueness).

abbreviation *pend-sq-mtx* :: *2 sq-mtx* (*A*)
where $A \equiv sq\text{-}mtx\text{-}chi\ (\chi\ i.\ if\ i{=}0\ then\ \mathrm{e}\ 1\ else\ -\ \mathrm{e}\ 0)$

lemma *pend-sq-mtx-exp-eq-flow*: $exp\ (t *_R A) *_V s = \varphi\ t\ s$
apply(*rule local-flow.eq-solution*[*OF local-flow-exp*, *symmetric*])

apply(*rule ivp-solsI*, *simp add*: *sq-mtx-vec-prod-def matrix-vector-mult-def*)
apply(*force intro*!: *poly-derivatives simp*: *matrix-vector-mult-def*)
using *exhaust-2 two-eq-zero* **by** (*force simp*: *vec-eq-iff*, *auto*)

lemma *pendulum-sq-mtx*:
$\lceil\lambda s.\ r^2 = (s\$0)^2 + (s\$1)^2\rceil \leq wp\ (x' = ((*_V)\ A)\ \&\ G)\ \lceil\lambda s.\ r^2 = (s\$0)^2 + (s\$1)^2\rceil$
unfolding *local-flow.wp-g-ode*[*OF local-flow-exp*] *pend-sq-mtx-exp-eq-flow* **by** *auto*

no-notation *fpend* (f)
and *pend-sq-mtx* (A)
and *pend-flow* (φ)

Bouncing Ball

— Verified with differential invariants.

named-theorems *bb-real-arith real arithmetic properties for the bouncing ball.*

lemma [*bb-real-arith*]:
assumes $0 > g$ **and** *inv*: $2 \cdot g \cdot x - 2 \cdot g \cdot h = v \cdot v$
shows $(x{::}real) \leq h$
proof−
have $v \cdot v = 2 \cdot g \cdot x - 2 \cdot g \cdot h \wedge 0 > g$
using *inv* **and** ‹$0 > g$› **by** *auto*
hence *obs*:$v \cdot v = 2 \cdot g \cdot (x - h) \wedge 0 > g \wedge v \cdot v \geq 0$
using *left-diff-distrib mult.commute* **by** (*metis zero-le-square*)
hence $(v \cdot v)/(2 \cdot g) = (x - h)$
by *auto*
also from *obs* **have** $(v \cdot v)/(2 \cdot g) \leq 0$
using *divide-nonneg-neg* **by** *fastforce*
ultimately have $h - x \geq 0$
by *linarith*
thus *?thesis* **by** *auto*
qed

abbreviation *fball* :: $real \Rightarrow real\hat{}2 \Rightarrow real\hat{}2$ (f)
where $f\ g\ s \equiv (\chi\ i.\ if\ i{=}(0)\ then\ s\ \$\ 1\ else\ g)$

lemma *bouncing-ball-invariants*:
fixes $h{::}real$
shows $g < 0 \Longrightarrow h \geq 0 \Longrightarrow \lceil\lambda s.\ s\ \$\ 0 = h \wedge s\ \$\ 1 = 0\rceil \leq$
wp
(*LOOP*
$((x' = f\ g\ \&\ (\lambda\ s.\ s\ \$\ 0 \geq 0)\ DINV\ (\lambda s.\ 2 \cdot g \cdot s\ \$\ 0 - 2 \cdot g \cdot h - s\ \$\ 1 \cdot s\ \$\ 1 = 0));$
$(IF\ (\lambda\ s.\ s\ \$\ 0 = 0)\ THEN\ (1 ::= (\lambda s.\ - s\ \$\ 1))\ ELSE\ skip))$
$INV\ (\lambda s.\ 0 \leq s\ \$\ 0 \wedge 2 \cdot g \cdot s\ \$\ 0 - 2 \cdot g \cdot h - s\ \$\ 1 \cdot s\ \$\ 1 = 0)$
) $\lceil\lambda s.\ 0 \leq s\ \$\ 0 \wedge s\ \$\ 0 \leq h\rceil$

apply(*rule wp-loopI*, *simp-all*)
apply(*force simp*: *bb-real-arith*)
apply(*rule wp-g-odei*)
by(*auto intro*!: *poly-derivatives diff-invariant-rules*)

— Verified with the flow.

abbreviation *ball-flow* :: *real* ⇒ *real* ⇒ *real*ˆ*2* ⇒ *real*ˆ*2* (φ)
where φ *g t s* ≡ (χ *i*. *if i=0 then g* · *t* ˆ *2*/*2* + *s* $ *1* · *t* + *s* $ *0 else g* · *t* + *s* $ *1*)

lemma *local-flow-ball*: *local-flow* (*f g*) *UNIV UNIV* (φ *g*)
apply(*unfold-locales*, *simp-all add*: *local-lipschitz-def lipschitz-on-def vec-eq-iff*, *clarsimp*)
apply(*rule-tac x*=*1*/*2* **in** *exI*, *clarsimp*, *rule-tac x*=*1* **in** *exI*)
apply(*simp add*: *dist-norm norm-vec-def L2-set-def UNIV-2*)
apply(*clarsimp*, *case-tac i* = *0*)
using *exhaust-2 two-eq-zero* **by** (*auto intro*!: *poly-derivatives*) *force*

lemma [*bb-real-arith*]:
assumes *invar*: *2* · *g* · *x* = *2* · *g* · *h* + *v* · *v*
and *pos*: $g \cdot \tau^2$ / *2* + *v* · τ + (*x*::*real*) = *0*
shows *2* · *g* · *h* + (− (*g* · τ) − *v*) · (− (*g* · τ) − *v*) = *0*
and *2* · *g* · *h* + (*g* · τ · (*g* · τ + *v*) + *v* · (*g* · τ + *v*)) = *0*
proof−
from *pos* **have** $g \cdot \tau^2$ + *2* · *v* · τ + *2* · *x* = *0* **by** *auto*
then have $g^2 \cdot \tau^2$ + *2* · *g* · *v* · τ + *2* · *g* · *x* = *0*
by (*metis* (*mono-tags*, *hide-lams*) *Groups.mult-ac*(*1*,*3*) *mult-zero-right monoid-mult-class.power2-eq-square semiring-class.distrib-left*)
hence $g^2 \cdot \tau^2$ + *2* · *g* · *v* · τ + v^2 + *2* · *g* · *h* = *0*
using *invar* **by** (*simp add*: *monoid-mult-class.power2-eq-square*)
hence *obs*: $(g \cdot \tau + v)^2$ + *2* · *g* · *h* = *0*
apply(*subst power2-sum*) **by** (*metis* (*no-types*, *hide-lams*) *Groups.add-ac*(*2*, *3*)

Groups.mult-ac(*2*, *3*) *monoid-mult-class.power2-eq-square nat-distrib*(*2*))
thus *2* · *g* · *h* + (*g* · τ · (*g* · τ + *v*) + *v* · (*g* · τ + *v*)) = *0*
by (*simp add*: *monoid-mult-class.power2-eq-square*)
have *2* · *g* · *h* + $(- ((g \cdot \tau) + v))^2$ = *0*
using *obs* **by** (*metis Groups.add-ac*(*2*) *power2-minus*)
thus *2* · *g* · *h* + (− (*g* · τ) − *v*) · (− (*g* · τ) − *v*) = *0*
by (*simp add*: *monoid-mult-class.power2-eq-square*)
qed

lemma [*bb-real-arith*]:
assumes *invar*: *2* · *g* · *x* = *2* · *g* · *h* + *v* · *v*
shows *2* · *g* · (*g* · τ^2 / *2* + *v* · τ + (*x*::*real*)) =
2 · *g* · *h* + (*g* · τ · (*g* · τ + *v*) + *v* · (*g* · τ + *v*)) (**is** *?lhs* = *?rhs*)
proof−
have *?lhs* = $g^2 \cdot \tau^2$ + *2* · *g* · *v* · τ + *2* · *g* · *x*

apply(*subst Rat.sign-simps*(*18*))+
by(*auto simp*: *semiring-normalization-rules*(*29*))
also have ... = $g^2 \cdot \tau^2 + 2 \cdot g \cdot v \cdot \tau + 2 \cdot g \cdot h + v \cdot v$ (**is** ... = *?middle*)
by(*subst invar*, *simp*)
finally have *?lhs* = *?middle*.
moreover
{**have** *?rhs* = $g \cdot g \cdot (\tau \cdot \tau) + 2 \cdot g \cdot v \cdot \tau + 2 \cdot g \cdot h + v \cdot v$
by (*simp add*: *Groups.mult-ac*(*2*,*3*) *semiring-class.distrib-left*)
also have ... = *?middle*
by (*simp add*: *semiring-normalization-rules*(*29*))
finally have *?rhs* = *?middle*.}
ultimately show *?thesis* **by** *auto*
qed

lemma *bouncing-ball*:
fixes *h*::*real*
assumes $g < 0$ **and** $h \geq 0$
shows $g < 0 \Longrightarrow h \geq 0 \Longrightarrow$
$\lceil\lambda s.\ s \$ 0 = h \wedge s \$ 1 = 0\rceil \leq wp$
(*LOOP*
((*x´*= *f g* & (λ *s*. $s \$ 0 \geq 0$));
(*IF* (λ *s*. $s \$ 0 = 0$) *THEN* (*1* ::= ($\lambda s.\ - s \$ 1$)) *ELSE skip*))
INV ($\lambda s.\ 0 \leq s \$ 0 \wedge 2 \cdot g \cdot s \$ 0 = 2 \cdot g \cdot h + s \$ 1 \cdot s \$ 1$))
$\lceil\lambda s.\ 0 \leq s \$ 0 \wedge s \$ 0 \leq h\rceil$
apply(*rule wp-loopI*, *simp-all add*: *local-flow.wp-g-ode*[*OF local-flow-ball*])
by (*auto simp*: *bb-real-arith*)

— Verified by providing dynamics.

lemma *bouncing-ball-dyn*:
fixes *h*::*real*
assumes $g < 0$ **and** $h \geq 0$
shows $g < 0 \Longrightarrow h \geq 0 \Longrightarrow$
$\lceil\lambda s.\ s \$ 0 = h \wedge s \$ 1 = 0\rceil \leq wp$
(*LOOP*
((*EVOL* (φ *g*) ($\lambda s.\ 0 \leq s \$ 0$) *T*);
(*IF* (λ *s*. $s \$ 0 = 0$) *THEN* (*1* ::= ($\lambda s.\ - s \$ 1$)) *ELSE skip*))
INV ($\lambda s.\ 0 \leq s \$ 0 \wedge 2 \cdot g \cdot s \$ 0 = 2 \cdot g \cdot h + s \$ 1 \cdot s \$ 1$))
$\lceil\lambda s.\ 0 \leq s \$ 0 \wedge s \$ 0 \leq h\rceil$
by (*rule wp-loopI*) (*auto simp*: *bb-real-arith*)

— Verified as a linear system (computing exponential).

abbreviation *ball-sq-mtx* :: *3 sq-mtx* (*A*)
where *ball-sq-mtx* ≡ *sq-mtx-chi* (χ *i*. *if i=0 then* e *1 else if i=1 then* e *2 else 0*)

lemma *ball-sq-mtx-pow2*: A^2 = *sq-mtx-chi* (χ *i*. *if i=0 then* e *2 else 0*)
unfolding *monoid-mult-class.power2-eq-square times-sq-mtx-def*
by (*simp add*: *sq-mtx-chi-inject vec-eq-iff matrix-matrix-mult-def*)

lemma *ball-sq-mtx-powN*: $n > 2 \Longrightarrow (\tau *_R A)\hat{}n = 0$
  apply(*induct n*, *simp*, *case-tac n* $\leq$ *2*)
   apply(*simp only*: *le-less-Suc-eq power-class.power.simps*(*2*), *simp*)
  by (*auto simp*: *ball-sq-mtx-pow2 sq-mtx-chi-inject vec-eq-iff*
      times-sq-mtx-def zero-sq-mtx-def matrix-matrix-mult-def)

lemma *exp-ball-sq-mtx*: $exp\ (\tau *_R A) = ((\tau *_R A)^2/_R\ 2) + (\tau *_R A) + 1$
  unfolding *exp-def* **apply**(*subst suminf-eq-sum*[*of 2*])
  using *ball-sq-mtx-powN* **by** (*simp-all add*: *numeral-2-eq-2*)

lemma *exp-ball-sq-mtx-simps*:
  $exp\ (\tau *_R A)\ \$\$\ 0\ \$\ 0 = 1$ $exp\ (\tau *_R A)\ \$\$\ 0\ \$\ 1 = \tau$ $exp\ (\tau *_R A)\ \$\$\ 0\ \$\ 2 = \tau\hat{}2/2$
  $exp\ (\tau *_R A)\ \$\$\ 1\ \$\ 0 = 0$ $exp\ (\tau *_R A)\ \$\$\ 1\ \$\ 1 = 1$ $exp\ (\tau *_R A)\ \$\$\ 1\ \$\ 2 = \tau$
  $exp\ (\tau *_R A)\ \$\$\ 2\ \$\ 0 = 0$ $exp\ (\tau *_R A)\ \$\$\ 2\ \$\ 1 = 0$ $exp\ (\tau *_R A)\ \$\$\ 2\ \$\ 2 = 1$
  unfolding *exp-ball-sq-mtx scaleR-power ball-sq-mtx-pow2*
  by (*auto simp*: *plus-sq-mtx-def scaleR-sq-mtx-def one-sq-mtx-def*
      mat-def scaleR-vec-def axis-def plus-vec-def)

lemma *bouncing-ball-sq-mtx*:
  $\lceil\lambda s.\ 0 \leq s\ \$\ 0 \wedge s\ \$\ 0 = h \wedge s\ \$\ 1 = 0 \wedge 0 > s\ \$\ 2\rceil \subseteq wp$
   (*LOOP*
     $((x\acute{}=(*_V)A\ \&\ (\lambda\ s.\ s\ \$\ 0 \geq 0));$
     $(IF\ (\lambda\ s.\ s\ \$\ 0 = 0)\ THEN\ (1 ::= (\lambda s.\ -\ s\ \$\ 1))\ ELSE\ skip))$
   $INV\ (\lambda s.\ 0 \leq s\$0 \wedge 0 > s\$2 \wedge 2 \cdot s\$2 \cdot s\$0 = 2 \cdot s\$2 \cdot h + (s\$1 \cdot s\$1)))$
  $\lceil\lambda s.\ 0 \leq s\ \$\ 0 \wedge s\ \$\ 0 \leq h\rceil$
  apply(*rule wp-loopI*, *simp-all add*: *local-flow.wp-g-ode*[*OF local-flow-exp*])
   apply(*force simp*: *bb-real-arith*)
  apply(*simp add*: *sq-mtx-vec-prod-eq*)
  unfolding *UNIV-3* **apply**(*simp add*: *exp-ball-sq-mtx-simps*, *safe*)
  using *bb-real-arith*(*3*) **apply**(*force simp*: *add.commute mult.commute*)
  using *bb-real-arith*(*4*) **by** (*force simp*: *add.commute mult.commute*)

no-notation *fpend* (*f*)
    and *pend-flow* (φ)
    and *ball-sq-mtx* (*A*)

end
theory *kat2rel*
  imports
  ../hs-prelims-dyn-sys
  ../../afpModified/VC-KAT

begin

Chapter 6

Hybrid System Verification with relations

— We start by deleting some conflicting notation.
no-notation *Archimedean-Field.ceiling* (⌈-⌉)
  and *Archimedean-Field.floor-ceiling-class.floor* (⌊-⌋)
  and *Relation.Domain* (*r2s*)
  and *VC-KAT.gets* (- ::= - [*70*, *65*] *61*)
  and *tau* (τ)
  and *if-then-else-sugar* (*IF - THEN - ELSE - FI* [*64*,*64*,*64*] *63*)

notation *Id* (*skip*)
  and *if-then-else-sugar* (*IF - THEN - ELSE -* [*64*,*64*,*64*] *63*)

6.1 Verification of regular programs

Below we explore the behavior of the forward box operator from the antidomain kleene algebra with the lifting ($\lceil - \rceil^*$) operator from predicates to relations $\lceil P \rceil = \{(s, s) \mid s.\ P\ s\}$ and its dropping counterpart *r2p* $R = (\lambda x.\ x \in \mathit{Domain}\ R)$.

thm *sH-H*

lemma *sH-weaken-pre*: *rel-kat.H* ⌈*P2*⌉ *R* ⌈*Q*⌉ ⟹ ⌈*P1*⌉ ⊆ ⌈*P2*⌉ ⟹ *rel-kat.H* ⌈*P1*⌉ *R* ⌈*Q*⌉
  unfolding *sH-H* **by** *auto*

Next, we introduce assignments and compute their Hoare triple.

definition *vec-upd* :: (*'a^'b*) ⇒ *'b* ⇒ *'a* ⇒ *'a^'b*
  where *vec-upd s i a* ≡ (χ *j*. ((($) *s*)(*i* := *a*)) *j*)

definition *assign* :: *'b* ⇒ (*'a^'b* ⇒ *'a*) ⇒ (*'a^'b*) *rel* ((*2*- ::= -) [*70*, *65*] *61*)
  where (*x* ::= *e*) ≡ {(*s*, *vec-upd s x* (*e s*))| *s*. *True*}

lemma *sH-assign-iff* [*simp*]: *rel-kat.H* $\lceil P \rceil$ $(x ::= e)$ $\lceil Q \rceil \longleftrightarrow (\forall s.\ P\ s \longrightarrow Q\ (\chi\ j.\ (((\$)\ s)(x := (e\ s)))\ j))$
  unfolding *sH-H vec-upd-def assign-def* **by** (*auto simp*: *fun-upd-def*)

Next, the Hoare rule of the composition:

lemma *sH-relcomp*: *rel-kat.H* $\lceil P \rceil$ X $\lceil R \rceil \Longrightarrow$ *rel-kat.H* $\lceil R \rceil$ Y $\lceil Q \rceil \Longrightarrow$ *rel-kat.H* $\lceil P \rceil$ $(X\ ;\ Y)$ $\lceil Q \rceil$
  using *rel-kat.H-seq-swap* **by** *force*

There is also already an implementation of the conditional operator *if* p *then* x *else* y *fi* $= t\ p \cdot x + !p \cdot y$ and its Hoare triple rule: $[\![$*PRE* $P \sqcap T\ X$ *POST* Q; *PRE* $P \sqcap -\ T\ Y$ *POST* $Q]\!] \Longrightarrow$ *PRE* P (*IF* T *THEN* X *ELSE* Y) *POST* Q.

Finally, we add a Hoare triple rule for a simple finite iteration.

context *kat*
begin

lemma *H-star-induct*: $H\ (t\ i)\ x\ i \Longrightarrow H\ (t\ i)\ (x^\star)\ i$
  unfolding *H-def* **by** (*simp add*: *local.star-sim2*)

lemma *H-stari*:
  assumes $t\ p \leq t\ i$ **and** $H\ (t\ i)\ x\ i$ **and** $t\ i \leq t\ q$
  shows $H\ (t\ p)\ (x^\star)\ q$
proof−
  have $H\ (t\ i)\ (x^\star)\ i$
    using *assms*(*2*) *H-star-induct* **by** *blast*
  hence $H\ (t\ p)\ (x^\star)\ i$
    apply(*simp add*: *H-def*)
    using *assms*(*1*) *local.phl-cons1* **by** *blast*
  thus *?thesis*
    unfolding *H-def* **using** *assms*(*3*) *local.phl-cons2* **by** *blast*
qed

definition *loopi* :: $'a \Rightarrow 'a \Rightarrow 'a$ (*loop* - *inv* - [*64*,*64*] *63*)
  where *loop* x *inv* $i = x^\star$

lemma *sH-loopi*: $t\ p \leq t\ i \Longrightarrow H\ (t\ i)\ x\ i \Longrightarrow t\ i \leq t\ q \Longrightarrow H\ (t\ p)$ (*loop* x *inv* i) q
  unfolding *loopi-def* **using** *H-stari* **by** *blast*

end

abbreviation *loopi-sugar* :: $'a$ *rel* $\Rightarrow$ $'a$ *pred* $\Rightarrow$ $'a$ *rel* (*LOOP* - *INV* - [*64*,*64*] *63*)
  where *LOOP R INV I* $\equiv$ *rel-kat.loopi R* $\lceil I \rceil$

lemma *sH-loopI*: $\lceil P \rceil \subseteq \lceil I \rceil \Longrightarrow \lceil I \rceil \subseteq \lceil Q \rceil \Longrightarrow$ *rel-kat.H* $\lceil I \rceil$ R $\lceil I \rceil \Longrightarrow$ *rel-kat.H* $\lceil P \rceil$ (*LOOP R INV I*) $\lceil Q \rceil$

using *rel-kat.sH-loopi*[*of* $\lceil P \rceil$ $\lceil I \rceil$ R $\lceil Q \rceil$] **by** *auto*

6.2 Verification of hybrid programs

6.2.1 Verification by providing evolution

definition *g-evol* :: $(('a::ord) \Rightarrow 'b \Rightarrow 'b) \Rightarrow 'b\ pred \Rightarrow 'a\ set \Rightarrow 'b\ rel$ $(EVOL)$
where $EVOL\ \varphi\ G\ T = \{(s,s')\ |s\ s'.\ s' \in$ *g-orbit* $(\lambda t.\ \varphi\ t\ s)\ G\ T\}$

lemma *sH-g-dyn*[*simp*]:
fixes $\varphi :: ('a::preorder) \Rightarrow 'b \Rightarrow 'b$
shows *rel-kat.H* $\lceil P \rceil$ $(EVOL\ \varphi\ G\ T)$ $\lceil Q \rceil = (\forall s.\ P\ s \longrightarrow (\forall t{\in}T.\ (\forall \tau{\in}down\ T\ t.\ G\ (\varphi\ \tau\ s)) \longrightarrow Q\ (\varphi\ t\ s)))$
unfolding *sH-H g-evol-def g-orbit-eq* **by** *auto*

6.2.2 Verification by providing solutions

definition *g-ode* :: $(('a::banach) \Rightarrow 'a) \Rightarrow 'a\ pred \Rightarrow real\ set \Rightarrow 'a\ set \Rightarrow real \Rightarrow 'a\ rel$ $((1x{\acute{}}{=}\text{-}\ \&\ \text{-}\ on\ \text{-}\ \text{-}\ @\ \text{-}))$
where $(x{\acute{}}{=}\ f\ \&\ G\ on\ T\ S\ @\ t_0) = \{(s,s')\ |s\ s'.\ s' \in$ *g-orbital* $f\ G\ T\ S\ t_0\ s\}$

lemma *sH-g-orbital*:
rel-kat.H $\lceil P \rceil$ $(x{\acute{}}{=}f\ \&\ G\ on\ T\ S\ @\ t_0)$ $\lceil Q \rceil =$
$(\forall s.\ P\ s \longrightarrow (\forall X{\in}ivp\text{-}sols\ (\lambda t.\ f)\ T\ S\ t_0\ s.\ \forall t{\in}T.\ (\forall \tau{\in}down\ T\ t.\ G\ (X\ \tau)) \longrightarrow Q\ (X\ t)))$
unfolding *g-orbital-eq g-ode-def image-le-pred sH-H* **by** *auto*

context *local-flow*
begin

lemma *sH-g-orbit*: *rel-kat.H* $\lceil P \rceil$ $(x{\acute{}}{=}f\ \&\ G\ on\ T\ S\ @\ 0)$ $\lceil Q \rceil =$
$(\forall s \in S.\ P\ s \longrightarrow (\forall t{\in}T.\ (\forall \tau{\in}down\ T\ t.\ G\ (\varphi\ \tau\ s)) \longrightarrow Q\ (\varphi\ t\ s)))$
unfolding *sH-g-orbital* **apply**(*clarsimp*, *safe*)
apply(*erule-tac x=s* **in** *allE*, *simp*, *erule-tac* $x{=}\lambda t.\ \varphi\ t\ s$ **in** *ballE*)
using *in-ivp-sols* **apply**(*force*, *force*)
apply(*erule-tac x=s* **in** *ballE*, *simp*)
apply(*subgoal-tac* $\forall \tau{\in}down\ T\ t.\ X\ \tau = \varphi\ \tau\ s$)
apply(*simp-all*, *clarsimp*)
apply(*subst eq-solution*, *simp-all add*: *ivp-sols-def*)
using *init-time* **by** *auto*

lemma *sH-orbit*:
rel-kat.H $\lceil P \rceil$ $(\{(s,s')\ |\ s\ s'.\ s' \in \gamma^{\varphi}\ s\})$ $\lceil Q \rceil = (\forall s \in S.\ P\ s \longrightarrow (\forall\ t \in T.\ Q\ (\varphi\ t\ s)))$
using *sH-g-orbit* **unfolding** *orbit-def g-ode-def* **by** *auto*

end

6.2.3 Verification with differential invariants

definition *g-ode-inv* :: $(('a::banach) \Rightarrow 'a) \Rightarrow 'a\ pred \Rightarrow real\ set \Rightarrow 'a\ set \Rightarrow real \Rightarrow 'a\ pred \Rightarrow 'a\ rel$ ((1x´=- & - on - - @ - DINV -))
where $(x' = f\ \&\ G\ on\ T\ S\ @\ t_0\ DINV\ I) = (x' = f\ \&\ G\ on\ T\ S\ @\ t_0)$

lemma *sH-g-orbital-guard*:
assumes $R = (\lambda s.\ G\ s \wedge Q\ s)$
shows $rel\text{-}kat.H\ \lceil P\rceil\ (x'=f\ \&\ G\ on\ T\ S\ @\ t_0)\ \lceil Q\rceil = rel\text{-}kat.H\ \lceil P\rceil\ (x'=f\ \&\ G\ on\ T\ S\ @\ t_0)\ \lceil R\rceil$
using *assms* **unfolding** *g-orbital-eq sH-H ivp-sols-def g-ode-def* **by** *auto*

lemma *sH-g-orbital-inv*:
assumes $\lceil P\rceil \le \lceil I\rceil$ **and** $rel\text{-}kat.H\ \lceil I\rceil\ (x'=f\ \&\ G\ on\ T\ S\ @\ t_0)\ \lceil I\rceil$ **and** $\lceil I\rceil \le \lceil Q\rceil$
shows $rel\text{-}kat.H\ \lceil P\rceil\ (x'=f\ \&\ G\ on\ T\ S\ @\ t_0)\ \lceil Q\rceil$
using *assms(1)* **apply**(*rule-tac* $p'=\lceil I\rceil$ **in** *rel-kat.H-cons-1*, *simp*)
using *assms(3)* **apply**(*rule-tac* $q'=\lceil I\rceil$ **in** *rel-kat.H-cons-2*, *simp*)
using *assms(2)* **by** *simp*

lemma *sH-diff-inv[simp]*: $rel\text{-}kat.H\ \lceil I\rceil\ (x'=f\ \&\ G\ on\ T\ S\ @\ t_0)\ \lceil I\rceil = diff\text{-}invariant\ I\ f\ T\ S\ t_0\ G$
unfolding *diff-invariant-eq sH-H g-orbital-eq image-le-pred g-ode-def* **by** *auto*

lemma *sH-g-odei*: $\lceil P\rceil \le \lceil I\rceil \Longrightarrow rel\text{-}kat.H\ \lceil I\rceil\ (x' = f\ \&\ G\ on\ T\ S\ @\ t_0)\ \lceil I\rceil \Longrightarrow \lceil \lambda s.\ I\ s \wedge G\ s\rceil \le \lceil Q\rceil \Longrightarrow$
$rel\text{-}kat.H\ \lceil P\rceil\ (x' = f\ \&\ G\ on\ T\ S\ @\ t_0\ DINV\ I)\ \lceil Q\rceil$
unfolding *g-ode-inv-def* **apply**(*rule-tac* $q'=\lceil \lambda s.\ I\ s \wedge G\ s\rceil$ **in** *rel-kat.H-cons-2*, *simp*)
apply(*subst sH-g-orbital-guard[symmetric]*, *force*)
by (*rule-tac* $I=I$ **in** *sH-g-orbital-inv*, *simp-all*)

6.2.4 Derivation of the rules of dL

We derive domain specific rules of differential dynamic logic (dL). In each subsubsection, we first derive the dL axioms (named below with two capital letters and "D" being the first one). This is done mainly to prove that there are minimal requirements in Isabelle to get the dL calculus.

lemma *diff-solve-axiom*:
fixes $c::'a::\{heine\text{-}borel,\ banach\}$
assumes $0 \in T$ **and** *is-interval T open T*
and $\forall s.\ P\ s \longrightarrow (\forall t{\in}T.\ (\mathcal{P}\ (\lambda\ t.\ s + t *_R c)\ (down\ T\ t) \subseteq \{s.\ G\ s\}) \longrightarrow Q\ (s + t *_R c))$
shows $rel\text{-}kat.H\ \lceil P\rceil\ (x'=(\lambda s.\ c)\ \&\ G\ on\ T\ UNIV\ @\ 0)\ \lceil Q\rceil$
apply(*subst local-flow.sH-g-orbit*[**where** $f=\lambda s.\ c$ **and** $\varphi=(\lambda\ t\ x.\ x + t *_R c)$])
using *line-is-local-flow assms* **unfolding** *image-le-pred* **by** *auto*

lemma *diff-solve-rule*:
assumes *local-flow* $f\ T\ UNIV\ \varphi$

and $\forall s.\ P\ s \longrightarrow (\forall\ t{\in}T.\ (\mathcal{P}\ (\lambda t.\ \varphi\ t\ s)\ (down\ T\ t) \subseteq \{s.\ G\ s\}) \longrightarrow Q\ (\varphi\ t\ s))$
shows *rel-kat.H* $\lceil P\rceil$ ($x{'}$=*f* & *G on T UNIV* @ *0*) $\lceil Q\rceil$
using *assms* **by**(*subst local-flow.sH-g-orbit*, *auto*)

lemma *diff-weak-rule*:
assumes $\lceil G\rceil \leq \lceil Q\rceil$
shows *rel-kat.H* $\lceil P\rceil$ ($x{'}$=*f* & *G on T S* @ t_0) $\lceil Q\rceil$
using *assms* **unfolding** *g-orbital-eq sH-H ivp-sols-def g-ode-def* **by** *auto*

lemma *diff-cut-rule*:
assumes *Thyp*: *is-interval T* $t_0 \in T$
and *wp-C*:*rel-kat.H* $\lceil P\rceil$ ($x{'}$=*f* & *G on T S* @ t_0) $\lceil C\rceil$
and *wp-Q*:*rel-kat.H* $\lceil P\rceil$ ($x{'}$=*f* & (λ *s. G s* $\wedge$ *C s*) *on T S* @ t_0) $\lceil Q\rceil$
shows *rel-kat.H* $\lceil P\rceil$ ($x{'}$=*f* & *G on T S* @ t_0) $\lceil Q\rceil$
proof(*subst sH-H*, *simp add*: *g-orbital-eq p2r-def image-le-pred g-ode-def*, *clarsimp*)
fix *t*::*real* **and** *X*::*real* $\Rightarrow$ *'a* **and** *s* **assume** *P s* **and** $t \in T$
and *x-ivp*:$X \in$ *ivp-sols* ($\lambda t.\ f$) *T S* t_0 *s*
and *guard-x*:$\forall x.\ x \in T \wedge x \leq t \longrightarrow G\ (X\ x)$
have $\forall\ t{\in}(down\ T\ t).\ X\ t \in$ *g-orbital f G T S* t_0 *s*
using *g-orbitalI*[*OF x-ivp*] *guard-x* **unfolding** *image-le-pred* **by** *auto*
hence $\forall\ t{\in}(down\ T\ t).\ C\ (X\ t)$
using *wp-C* ‹*P s*› **by** (*subst* (*asm*) *sH-H*, *auto simp*: *g-ode-def*)
hence $X\ t \in$ *g-orbital f* ($\lambda s.\ G\ s \wedge C\ s$) *T S* t_0 *s*
using *guard-x* ‹$t \in T$› **by** (*auto intro*!: *g-orbitalI x-ivp*)
thus *Q* (*X t*)
using ‹*P s*› *wp-Q* **by** (*subst* (*asm*) *sH-H*) (*auto simp*: *g-ode-def*)
qed

abbreviation *g-global-ode* ::(('*a*::*banach*)$\Rightarrow$'*a*) $\Rightarrow$ '*a pred* $\Rightarrow$ '*a rel* ((*1x*$'$=- & -))
where ($x{'}$= *f* & *G*) $\equiv$ ($x{'}$= *f* & *G on UNIV UNIV* @ *0*)

abbreviation *g-global-ode-inv* :: (('*a*::*banach*)$\Rightarrow$'*a*) $\Rightarrow$ '*a pred* $\Rightarrow$ '*a pred* $\Rightarrow$ '*a rel*
((*1x*$'$=- & - *DINV* -)) **where** ($x{'}$= *f* & *G DINV I*) $\equiv$ ($x{'}$= *f* & *G on UNIV UNIV* @ *0 DINV I*)

end
theory *kat2rel-examples*
imports ../*hs-prelims-matrices kat2rel*

begin

6.2.5 Examples

Preliminary preparation for the examples.

no-notation *Archimedean-Field.ceiling* ($\lceil$-$\rceil$)
and *Archimedean-Field.floor-ceiling-class.floor* ($\lfloor$-$\rfloor$)

lemma [*simp*]: $i \neq (0{::}2) \longrightarrow i = 1$
  using *exhaust-2* **by** *fastforce*

lemma *two-eq-zero*: $(2{::}2) = 0$
  by *simp*

lemma *UNIV-2*: $(UNIV{::}2\ set) = \{0,\ 1\}$
  apply *safe* **using** *exhaust-2 two-eq-zero* **by** *auto*

lemma *UNIV-3*: $(UNIV{::}3\ set) = \{0,\ 1,\ 2\}$
  apply *safe* **using** *exhaust-3 three-eq-zero* **by** *auto*

lemma *sum-axis-UNIV-3*[*simp*]: $(\sum j{\in}(UNIV{::}3\ set).\ axis\ i\ 1\ \$\ j \cdot f\ j) = (f{::}3 \Rightarrow real)\ i$
  unfolding *axis-def UNIV-3* **apply** *simp*
  using *exhaust-3* **by** *force*

Pendulum

— Verified with differential invariants.

abbreviation *fpend* :: $real\hat{\ }2 \Rightarrow real\hat{\ }2\ (f)$
  where $f\ s \equiv (\chi\ i.\ if\ i{=}0\ then\ s\$1\ else\ -s\ \$\ 0)$

lemma *pendulum-invariants*: *rel-kat.H*
  $\lceil\lambda s.\ r^2 = (s\ \$\ 0)^2 + (s\ \$\ 1)^2\rceil\ (x'{=}f\ \&\ G)\ \lceil\lambda s.\ r^2 = (s\ \$\ 0)^2 + (s\ \$\ 1)^2\rceil$
  by (*auto intro*!: *diff-invariant-rules poly-derivatives*)

— Verified with the flow.

abbreviation *pend-flow* :: $real \Rightarrow real\hat{\ }2 \Rightarrow real\hat{\ }2\ (\varphi)$
  where $\varphi\ \tau\ s \equiv (\chi\ i.\ if\ i = 0\ then\ s\ \$\ 0 \cdot cos\ \tau + s\ \$\ 1 \cdot sin\ \tau$
  $else - s\ \$\ 0 \cdot sin\ \tau + s\ \$\ 1 \cdot cos\ \tau)$

lemma *local-flow-pend*: *local-flow f UNIV UNIV* φ
  apply(*unfold-locales*, *simp-all add*: *local-lipschitz-def lipschitz-on-def vec-eq-iff*, *clarsimp*)
  apply(*rule-tac x=1* **in** *exI*, *clarsimp*, *rule-tac x=1* **in** *exI*)
  apply(*simp add*: *dist-norm norm-vec-def L2-set-def power2-commute UNIV-2*)
  apply(*clarify*, *case-tac* $i = 0$, *simp*)
  using *exhaust-2 two-eq-zero* **by** (*force intro*!: *poly-derivatives*)+

lemma *pendulum*: *rel-kat.H*
  $\lceil\lambda s.\ r^2 = (s\ \$\ 0)^2 + (s\ \$\ 1)^2\rceil\ (x'{=}f\ \&\ G)\ \lceil\lambda s.\ r^2 = (s\ \$\ 0)^2 + (s\ \$\ 1)^2\rceil$
  by (*simp only*: *local-flow.sH-g-orbit*[*OF local-flow-pend*], *simp*)

— Verified by providing dynamics.

lemma *pendulum-dyn*: *rel-kat.H*

$\lceil\lambda s.\ r^2 = (s\ \$\ 0)^2 + (s\ \$\ 1)^2\rceil$ $(EVOL\ \varphi\ G\ T)$ $\lceil\lambda s.\ r^2 = (s\ \$\ 0)^2 + (s\ \$\ 1)^2\rceil$
by *simp*

— Verified as a linear system (using uniqueness).

abbreviation *pend-sq-mtx* :: *2 sq-mtx* (*A*)
where $A \equiv$ *sq-mtx-chi* (χ *i. if i=0 then* e *1 else* − e *0*)

lemma *pend-sq-mtx-exp-eq-flow*: *exp* $(\tau *_R A) *_V s = \varphi\ \tau\ s$
apply(*rule local-flow.eq-solution*[*OF local-flow-exp*, *symmetric*])
apply(*rule ivp-solsI*, *clarsimp*)
unfolding *sq-mtx-vec-prod-def matrix-vector-mult-def* **apply** *simp*
apply(*force intro*!: *poly-derivatives simp*: *matrix-vector-mult-def*)
using *exhaust-2 two-eq-zero* **by** (*force simp*: *vec-eq-iff*, *auto*)

lemma *pendulum-sq-mtx*: *rel-kat.H*
$\lceil\lambda s.\ r^2 = (s\ \$\ 0)^2 + (s\ \$\ 1)^2\rceil$ $(x' = ((*_V)\ A)\ \&\ G)$ $\lceil\lambda s.\ r^2 = (s\ \$\ 0)^2 + (s\ \$$
$1)^2\rceil$
apply(*subst local-flow.sH-g-orbit*[*OF local-flow-exp*])
unfolding *pend-sq-mtx-exp-eq-flow* **by** *auto*

no-notation *fpend* (*f*)
and *pend-sq-mtx* (*A*)
and *pend-flow* (φ)

Bouncing Ball

— Verified with differential invariants.

named-theorems *bb-real-arith real arithmetic properties for the bouncing ball.*

lemma [*bb-real-arith*]:
assumes $0 > g$ **and** *inv*: $2 \cdot g \cdot x - 2 \cdot g \cdot h = v \cdot v$
shows $(x{::}real) \le h$
proof−
have $v \cdot v = 2 \cdot g \cdot x - 2 \cdot g \cdot h \wedge 0 > g$
using *inv* **and** $\langle 0 > g \rangle$ **by** *auto*
hence *obs*:$v \cdot v = 2 \cdot g \cdot (x - h) \wedge 0 > g \wedge v \cdot v \ge 0$
using *left-diff-distrib mult.commute* **by** (*metis zero-le-square*)
hence $(v \cdot v)/(2 \cdot g) = (x - h)$
by *auto*
also from *obs* **have** $(v \cdot v)/(2 \cdot g) \le 0$
using *divide-nonneg-neg* **by** *fastforce*
ultimately have $h - x \ge 0$
by *linarith*
thus *?thesis* **by** *auto*
qed

abbreviation *fball* :: *real* ⇒ *real^2* ⇒ *real^2* (*f*)

where *f g s* ≡ (*χ i. if i=0 then s $ 1 else g*)

lemma *fball-invariant*:
fixes *g h* :: *real*
defines *dinv*: $I \equiv (\lambda s.\ 2 \cdot g \cdot s \$ 0 - 2 \cdot g \cdot h - (s \$ 1 \cdot s \$ 1) = 0)$
shows *diff-invariant I* (*f g*) *UNIV UNIV 0 G*
unfolding *dinv* **apply**(*rule diff-invariant-rules*, *simp*, *simp*, *clarify*)
by(*auto intro*!: *poly-derivatives*)

lemma *bouncing-ball-invariants*:
fixes *h g*::*real*
defines *diff-inv*: $I \equiv (\lambda s{::}real\hat{\ }2.\ 2 \cdot g \cdot s \$ 0 - 2 \cdot g \cdot h - s \$ 1 \cdot s \$ 1 = 0)$
shows $g < 0 \Longrightarrow h \geq 0 \Longrightarrow$ *rel-kat.H*
$\lceil \lambda s.\ s \$ 0 = h \wedge s \$ 1 = 0 \rceil$
(*LOOP*
((*x´*= *f g* & $(\lambda\ s.\ s \$ 0 \geq 0)$ *DINV* $(\lambda s.\ 2 \cdot g \cdot s \$ 0 - 2 \cdot g \cdot h - s \$ 1 \cdot s \$ 1 = 0)$);
(*IF* $(\lambda\ s.\ s \$ 0 = 0)$ *THEN* (*1* ::= $(\lambda s.\ - s \$ 1)$) *ELSE skip*))
INV $(\lambda s.\ 0 \leq s \$ 0 \wedge 2 \cdot g \cdot s \$ 0 - 2 \cdot g \cdot h - s \$ 1 \cdot s \$ 1 = 0)$
) $\lceil \lambda s.\ 0 \leq s \$ 0 \wedge s \$ 0 \leq h \rceil$
apply(*rule sH-loopI*, *simp-all*, *force simp*: *bb-real-arith*)
apply(*rule sH-relcomp*[**where** $R{=}\lambda s.\ 0{\leq}s \$ 0 \wedge I\ s$])
apply(*rule sH-g-odei*, *simp-all add*: *diff-inv*)
apply(*force intro*!: *poly-derivatives diff-invariant-rules*)
by (*auto simp*: *bb-real-arith diff-inv sH-H*)

— Verified with the flow.

abbreviation *ball-flow* :: *real* ⇒ *real* ⇒ *real*ˆ*2* ⇒ *real*ˆ*2* (*φ*)
where $\varphi\ g\ \tau\ s \equiv (\chi\ i.\ if\ i{=}0\ then\ g \cdot \tau\ \hat{\ } 2/2 + s \$ 1 \cdot \tau + s \$ 0\ else\ g \cdot \tau + s \$ 1)$

lemma *local-flow-ball*: *local-flow* (*f g*) *UNIV UNIV* (*φ g*)
apply(*unfold-locales*, *simp-all add*: *local-lipschitz-def lipschitz-on-def vec-eq-iff*, *clarsimp*)
apply(*rule-tac x=1/2* **in** *exI*, *clarsimp*, *rule-tac x=1* **in** *exI*)
apply(*simp add*: *dist-norm norm-vec-def L2-set-def UNIV-2*)
apply(*clarsimp*, *case-tac i* = *0*)
using *exhaust-2 two-eq-zero* **by** (*auto intro*!: *poly-derivatives*) *force*

lemma [*bb-real-arith*]:
assumes *invar*: $2 \cdot g \cdot x = 2 \cdot g \cdot h + v \cdot v$
and *pos*: $g \cdot \tau^2 / 2 + v \cdot \tau + (x{::}real) = 0$
shows $2 \cdot g \cdot h + (- (g \cdot \tau) - v) \cdot (- (g \cdot \tau) - v) = 0$
and $2 \cdot g \cdot h + (g \cdot \tau \cdot (g \cdot \tau + v) + v \cdot (g \cdot \tau + v)) = 0$
proof−
from *pos* **have** $g \cdot \tau^2 + 2 \cdot v \cdot \tau + 2 \cdot x = 0$ **by** *auto*
then have $g^2 \cdot \tau^2 + 2 \cdot g \cdot v \cdot \tau + 2 \cdot g \cdot x = 0$
by (*metis* (*mono-tags*, *hide-lams*) *Groups.mult-ac*(*1*,*3*) *mult-zero-right*

monoid-mult-class.power2-eq-square semiring-class.distrib-left)
hence $g^2 \cdot \tau^2 + 2 \cdot g \cdot v \cdot \tau + v^2 + 2 \cdot g \cdot h = 0$
using *invar* **by** (*simp add*: *monoid-mult-class.power2-eq-square*)
hence *obs*: $(g \cdot \tau + v)^2 + 2 \cdot g \cdot h = 0$
apply(*subst power2-sum*) **by** (*metis* (*no-types*, *hide-lams*) *Groups.add-ac*(*2*, *3*)

Groups.mult-ac(*2*, *3*) *monoid-mult-class.power2-eq-square nat-distrib*(*2*))
thus $2 \cdot g \cdot h + (g \cdot \tau \cdot (g \cdot \tau + v) + v \cdot (g \cdot \tau + v)) = 0$
by (*simp add*: *monoid-mult-class.power2-eq-square*)
have $2 \cdot g \cdot h + (- ((g \cdot \tau) + v))^2 = 0$
using *obs* **by** (*metis Groups.add-ac*(*2*) *power2-minus*)
thus $2 \cdot g \cdot h + (- (g \cdot \tau) - v) \cdot (- (g \cdot \tau) - v) = 0$
by (*simp add*: *monoid-mult-class.power2-eq-square*)
qed

lemma [*bb-real-arith*]:
assumes *invar*: $2 \cdot g \cdot x = 2 \cdot g \cdot h + v \cdot v$
shows $2 \cdot g \cdot (g \cdot \tau^2 / 2 + v \cdot \tau + (x::real)) =$
$2 \cdot g \cdot h + (g \cdot \tau \cdot (g \cdot \tau + v) + v \cdot (g \cdot \tau + v))$ (**is** *?lhs* = *?rhs*)
proof−
have *?lhs* $= g^2 \cdot \tau^2 + 2 \cdot g \cdot v \cdot \tau + 2 \cdot g \cdot x$
apply(*subst Rat.sign-simps*(*18*))+
by(*auto simp*: *semiring-normalization-rules*(*29*))
also have ... $= g^2 \cdot \tau^2 + 2 \cdot g \cdot v \cdot \tau + 2 \cdot g \cdot h + v \cdot v$ (**is** ... = *?middle*)
by(*subst invar*, *simp*)
finally have *?lhs* = *?middle*.
moreover
{**have** *?rhs* $= g \cdot g \cdot (\tau \cdot \tau) + 2 \cdot g \cdot v \cdot \tau + 2 \cdot g \cdot h + v \cdot v$
by (*simp add*: *Groups.mult-ac*(*2*,*3*) *semiring-class.distrib-left*)
also have ... = *?middle*
by (*simp add*: *semiring-normalization-rules*(*29*))
finally have *?rhs* = *?middle*.}
ultimately show *?thesis* **by** *auto*
qed

lemma *bouncing-ball*: $g < 0 \Longrightarrow h \geq 0 \Longrightarrow$ *rel-kat.H*
$\lceil \lambda s.\ s \$ 0 = h \wedge s \$ 1 = 0 \rceil$
(*LOOP*
((*x´*= *f g* & (λ *s*. $s \$ 0 \geq 0$));
(*IF* (λ *s*. $s \$ 0 = 0$) *THEN* (*1* ::= ($\lambda s.\ - s \$ 1$)) *ELSE skip*))
INV ($\lambda s.\ 0 \leq s \$ 0 \wedge 2 \cdot g \cdot s \$ 0 = 2 \cdot g \cdot h + s \$ 1 \cdot s \$ 1$)
) $\lceil \lambda s.\ 0 \leq s \$ 0 \wedge s \$ 0 \leq h \rceil$
apply(*rule sH-loopI*, *simp-all*)
apply(*force simp*: *bb-real-arith*)
apply(*rule sH-relcomp*[**where** $R = \lambda s.\ 0 \leq s \$ 0 \wedge 2 \cdot g \cdot s \$ 0 = 2 \cdot g \cdot h + s$
$\$ 1 \cdot s \$ 1$])
apply(*subst local-flow.sH-g-orbit*[*OF local-flow-ball*], *clarsimp*)
apply(*force simp*: *bb-real-arith*, *simp*)
by(*auto simp*: *sH-H bb-real-arith*)

— Verified as a linear system (computing exponential).

abbreviation *ball-sq-mtx* :: *3 sq-mtx* (A)
where *ball-sq-mtx* ≡ *sq-mtx-chi* (χ *i. if i=0 then* e *1 else if i=1 then* e *2 else 0*)

lemma *ball-sq-mtx-pow2*: A^2 = *sq-mtx-chi* (χ *i. if i=0 then* e *2 else 0*)
unfolding *monoid-mult-class.power2-eq-square times-sq-mtx-def*
by (*simp add*: *sq-mtx-chi-inject vec-eq-iff matrix-matrix-mult-def*)

lemma *ball-sq-mtx-powN*: $m > 2 \Longrightarrow (\tau *_R A)\hat{\ }m = 0$
apply(*induct m*, *simp*, *case-tac* $m \leq 2$)
apply(*simp only*: *le-less-Suc-eq power-class.power.simps*(*2*), *simp*)
by (*auto simp*: *ball-sq-mtx-pow2 sq-mtx-chi-inject vec-eq-iff times-sq-mtx-def zero-sq-mtx-def matrix-matrix-mult-def*)

lemma *exp-ball-sq-mtx*: *exp* $(\tau *_R A) = ((\tau *_R A)^2/_R\ 2) + (\tau *_R A) + 1$
unfolding *exp-def* **apply**(*subst suminf-eq-sum*[*of 2*])
using *ball-sq-mtx-powN* **by** (*simp-all add*: *numeral-2-eq-2*)

lemma *exp-ball-sq-mtx-simps*:
exp $(\tau *_R A)$ \$\$ *0* \$ *0* = *1* *exp* $(\tau *_R A)$ \$\$ *0* \$ *1* = τ *exp* $(\tau *_R A)$ \$\$ *0* \$ *2* = $\tau\hat{\ }2/2$
exp $(\tau *_R A)$ \$\$ *1* \$ *0* = *0* *exp* $(\tau *_R A)$ \$\$ *1* \$ *1* = *1* *exp* $(\tau *_R A)$ \$\$ *1* \$ *2* = τ
exp $(\tau *_R A)$ \$\$ *2* \$ *0* = *0* *exp* $(\tau *_R A)$ \$\$ *2* \$ *1* = *0* *exp* $(\tau *_R A)$ \$\$ *2* \$ *2* = *1*
unfolding *exp-ball-sq-mtx scaleR-power ball-sq-mtx-pow2*
by (*auto simp*: *plus-sq-mtx-def scaleR-sq-mtx-def one-sq-mtx-def mat-def scaleR-vec-def axis-def plus-vec-def*)

lemma *bouncing-ball-K*: *rel-kat.H*
$\lceil\lambda s.\ 0 \leq s\ \$\ 0 \wedge s\ \$\ 0 = h \wedge s\ \$\ 1 = 0 \wedge 0 > s\ \$\ 2\rceil$
(*LOOP*
((x'=($*_V$) A & (λ *s. s* \$ *0* $\geq$ *0*));
(*IF* (λ *s. s* \$ *0* = *0*) *THEN* (*1* ::= ($\lambda s.\ -$ *s* \$ *1*)) *ELSE skip*))
INV ($\lambda s.\ 0 \leq s\$0 \wedge 0 > s\$2 \wedge\ 2 \cdot s\$2 \cdot s\$0 = 2 \cdot s\$2 \cdot h + (s\$1 \cdot s\$1)$))
$\lceil\lambda s.\ 0 \leq s\ \$\ 0 \wedge s\ \$\ 0 \leq h\rceil$
apply(*rule sH-loopI*, *simp-all*, *force simp*: *bb-real-arith*)
apply(*rule sH-relcomp*[**where** $R{=}\lambda s.\ 0 \leq s\$0 \wedge 0 > s\$2 \wedge\ 2 \cdot s\$2 \cdot s\$0 = 2 \cdot s\$2 \cdot h + (s\$1 \cdot s\$1)$])
apply(*subst local-flow.sH-g-orbit*[*OF local-flow-exp*], *simp-all add*: *sq-mtx-vec-prod-eq*)
unfolding *UNIV-3 image-le-pred*
apply(*simp add*: *exp-ball-sq-mtx-simps field-simps monoid-mult-class.power2-eq-square*)
by (*auto simp*: *bb-real-arith sH-H*)

no-notation *fpend* (f)
and *pend-flow* (φ)
and *ball-sq-mtx* (A)

end
theory *cat2ndfun*
imports *../hs-prelims-dyn-sys Transformer-Semantics.Kleisli-Quantale KAD.Modal-Kleene-Algebra*

begin

Chapter 7

Hybrid System Verification with non-deterministic functions

— We start by deleting some notation and introducing some new.

no-notation *Archimedean-Field.ceiling* ($\lceil$-$\rceil$)
  and *Archimedean-Field.floor-ceiling-class.floor* ($\lfloor$-$\rfloor$)
  and *Range-Semiring.antirange-semiring-class.ars-r* (r)
  and *Relation.relcomp* (**infixl** ; *75*)
  and *Isotone-Transformers.bqtran* ($\lfloor$-$\rfloor$)
  and *bres* (**infixr** $\rightarrow$ *60*)

type-synonym $'a$ *pred* $=$ $'a \Rightarrow$ *bool*

notation *Abs-nd-fun* ($\text{-}^{\bullet}$ [*101*] *100*)
  and *Rep-nd-fun* ($\text{-}_{\bullet}$ [*101*] *100*)
  and *fbox* (*wp*)

7.1 Nondeterministic Functions

Our semantics now corresponds to nondeterministic functions $'a$ *nd-fun*. Below we prove some auxiliary lemmas for them and show that they form an antidomain kleene algebra. The proof just extends the results on the Transformer_Semantics.Kleisli_Quantale theory.

declare *Abs-nd-fun-inverse* [*simp*]

lemma *nd-fun-ext*: $(\bigwedge x.\ (f_{\bullet})\ x = (g_{\bullet})\ x) \Longrightarrow f = g$
  apply(*subgoal-tac Rep-nd-fun f* $=$ *Rep-nd-fun g*)
  using *Rep-nd-fun-inject* **apply** *blast*
  by(*rule ext*, *simp*)

lemma *nd-fun-eq-iff*: $(\forall x.\ (f_\bullet)\ x = (g_\bullet)\ x) = (f = g)$
  by (*auto simp*: *nd-fun-ext*)

instantiation *nd-fun* :: (*type*) *antidomain-kleene-algebra*
begin

lift-definition *antidomain-op-nd-fun* :: $'a$ *nd-fun* $\Rightarrow$ $'a$ *nd-fun*
  is $\lambda f.\ (\lambda x.\ \mathit{if}\ ((f_\bullet)\ x = \{\})\ \mathit{then}\ \{x\}\ \mathit{else}\ \{\})^\bullet$**.**

lift-definition *zero-nd-fun* :: $'a$ *nd-fun*
  is $\zeta^\bullet$**.**

lift-definition *star-nd-fun* :: $'a$ *nd-fun* $\Rightarrow$ $'a$ *nd-fun*
  is $\lambda(f{::}'a\ \mathit{nd\text{-}fun}).\ \mathit{qstar}\ f$**.**

lift-definition *plus-nd-fun* :: $'a$ *nd-fun* $\Rightarrow$ $'a$ *nd-fun* $\Rightarrow$ $'a$ *nd-fun*
  is $\lambda f\ g.((f_\bullet) \sqcup (g_\bullet))^\bullet$**.**

named-theorems *nd-fun-aka antidomain kleene algebra properties for nondeterministic functions*.

lemma *nd-fun-assoc*[*nd-fun-aka*]: $(a{::}'a\ \mathit{nd\text{-}fun}) + b + c = a + (b + c)$
  by(*transfer*, *simp add*: *ksup-assoc*)

lemma *nd-fun-comm*[*nd-fun-aka*]: $(a{::}'a\ \mathit{nd\text{-}fun}) + b = b + a$
  by(*transfer*, *simp add*: *ksup-comm*)

lemma *nd-fun-distr*[*nd-fun-aka*]: $((x{::}'a\ \mathit{nd\text{-}fun}) + y) \cdot z = x \cdot z + y \cdot z$
  and *nd-fun-distl*[*nd-fun-aka*]: $x \cdot (y + z) = x \cdot y + x \cdot z$
  by(*transfer*, *simp add*: *kcomp-distr*, *transfer*, *simp add*: *kcomp-distl*)

lemma *nd-fun-zero-sum*[*nd-fun-aka*]: $0 + (x{::}'a\ \mathit{nd\text{-}fun}) = x$
  and *nd-fun-zero-dot*[*nd-fun-aka*]: $0 \cdot x = 0$
  by(*transfer*, *simp*, *transfer*, *auto*)

lemma *nd-fun-leq*[*nd-fun-aka*]: $((x{::}'a\ \mathit{nd\text{-}fun}) \leq y) = (x + y = y)$
  and *nd-fun-leq-add*[*nd-fun-aka*]: $z \cdot x \leq z \cdot (x + y)$
   apply(*transfer*)
  apply(*metis* (*no-types*, *lifting*) *less-eq-nd-fun.transfer sup.absorb-iff2 sup-nd-fun.transfer*)
  by(*transfer*, *simp add*: *kcomp-isol*)

lemma *nd-fun-ad-zero*[*nd-fun-aka*]: $ad\ (x{::}'a\ \mathit{nd\text{-}fun}) \cdot x = 0$
  and *nd-fun-ad*[*nd-fun-aka*]: $ad\ (x \cdot y) + ad\ (x \cdot ad\ (ad\ y)) = ad\ (x \cdot ad\ (ad\ y))$
  and *nd-fun-ad-one*[*nd-fun-aka*]: $ad\ (ad\ x) + ad\ x = 1$
   apply(*transfer*, *rule nd-fun-ext*, *simp add*: *kcomp-def*)
   apply(*transfer*, *rule nd-fun-ext*, *simp*, *simp add*: *kcomp-def*)
  by(*transfer*, *simp*, *rule nd-fun-ext*, *simp add*: *kcomp-def*)

lemma *nd-star-one*[*nd-fun-aka*]: $1 + (x{::}'a\ \mathit{nd\text{-}fun}) \cdot x^\star \leq x^\star$

and *nd-star-unfoldl*[*nd-fun-aka*]: $z + x \cdot y \leq y \Longrightarrow x^\star \cdot z \leq y$
and *nd-star-unfoldr*[*nd-fun-aka*]: $z + y \cdot x \leq y \Longrightarrow z \cdot x^\star \leq y$
apply(*transfer*, *metis Abs-nd-fun-inverse Rep-comp-hom UNIV-I fun-star-unfoldr*

le-sup-iff less-eq-nd-fun.abs-eq mem-Collect-eq one-nd-fun.abs-eq qstar-comm)
apply(*transfer*, *metis* (*no-types*, *lifting*) *Abs-comp-hom Rep-nd-fun-inverse fun-star-inductl less-eq-nd-fun.transfer sup-nd-fun.transfer*)
by(*transfer*, *metis qstar-inductr Rep-comp-hom Rep-nd-fun-inverse less-eq-nd-fun.abs-eq sup-nd-fun.transfer*)

instance
apply *intro-classes* **apply** *auto*
using *nd-fun-aka* **apply** *simp-all*
by(*transfer*; *auto*)+

end

Now that we know that nondeterministic functions form an Antidomain Kleene Algebra, we give a lifting operation from *'a pred* to *'a nd-fun*.

abbreviation *p2ndf* :: *'a pred* ⇒ *'a nd-fun* (($1\lceil\text{-}\rceil$))
where $\lceil Q\rceil \equiv (\lambda\, x{::}'a.\ \{s{::}'a.\ s = x \wedge Q\ s\})^\bullet$

lemma *le-p2ndf-iff*[*simp*]: $\lceil P\rceil \leq \lceil Q\rceil = (\forall s.\ P\ s \longrightarrow Q\ s)$
by(*transfer*, *auto simp*: *le-fun-def*)

lemma *eq-p2ndf-iff*[*simp*]: $(\lceil P\rceil = \lceil Q\rceil) = (P = Q)$
by(*subst eq-iff*, *auto simp*: *fun-eq-iff*)

lemma *p2ndf-le-eta*[*simp*]: $\lceil P\rceil \leq \eta^\bullet$
by(*transfer*, *simp add*: *le-fun-def*, *clarify*)

lemma *ads-d-p2ndf-simps*[*simp*]:
$d\ (\lceil P\rceil \cdot \lceil Q\rceil) = \lceil\lambda\ s.\ P\ s \wedge Q\ s\rceil$
$d\ (\lceil P\rceil + \lceil Q\rceil) = \lceil\lambda\ s.\ P\ s \vee Q\ s\rceil$
$d\ \lceil P\rceil = \lceil P\rceil$
apply(*simp-all add*: *ads-d-def times-nd-fun-def plus-nd-fun-def kcomp-def*)
apply(*simp-all add*: *antidomain-op-nd-fun-def*)
by (*rule nd-fun-ext*, *force*)+

lemma *p2ndf-times*[*simp*]: $\lceil P\rceil \cdot \lceil Q\rceil = \lceil\lambda s.\ P\ s \wedge Q\ s\rceil$
apply(*clarsimp simp*: *times-nd-fun-def nd-fun-eq-iff*[*symmetric*] *kcomp-def*)
by (*rule antisym*, *simp-all add*: *image-def subset-eq*)

lemma *p2ndf-plus*[*simp*]: $\lceil P\rceil + \lceil Q\rceil = \lceil\lambda s.\ P\ s \vee Q\ s\rceil$
apply(*clarsimp simp*: *plus-nd-fun-def nd-fun-eq-iff*[*symmetric*])
by (*rule antisym*, *auto simp*: *image-def subset-eq*)

lemma *ad-p2ndf*[*simp*]: $ad\ \lceil P\rceil = \lceil\lambda s.\ \neg\ P\ s\rceil$
unfolding *antidomain-op-nd-fun-def* **by**(*rule nd-fun-ext*, *auto*)

abbreviation *ndf2p* :: *'a nd-fun* ⇒ *'a* ⇒ *bool* ((*1*$\lfloor$-$\rfloor$))
  where $\lfloor f \rfloor \equiv (\lambda x.\ x \in \mathit{Domain}\ (\mathcal{R}\ (f_\bullet)))$

lemma *p2ndf-ndf2p-id*: $F \leq \eta^\bullet \Longrightarrow \lceil \lfloor F \rfloor \rceil = F$
  unfolding *f2r-def* **apply**(*rule nd-fun-ext*)
  apply(*subgoal-tac* $\forall x.\ (F_\bullet)\ x \subseteq \{x\}$, *simp*)
  by(*blast*, *simp add*: *le-fun-def less-eq-nd-fun.rep-eq*)

7.2 Verification of regular programs

Properties of the forward box operator.

lemma *wp-nd-fun*: $wp\ (F^\bullet)\ \lceil P \rceil = \lceil \lambda s.\ \forall s'.\ s' \in (F\ s) \longrightarrow P\ s' \rceil$
  apply(*simp add*: *fbox-def*, *transfer*, *simp*)
  by(*rule nd-fun-ext*, *auto simp*: *kcomp-def*)

lemma *wp-nd-fun2*: $wp\ F\ \lceil P \rceil = \lceil \lambda s.\ \forall s'.\ s' \in ((F_\bullet)\ s) \longrightarrow P\ s' \rceil$
  apply(*simp add*: *fbox-def antidomain-op-nd-fun-def*)
  by(*rule nd-fun-ext*, *auto simp*: *Rep-comp-hom kcomp-prop*)

lemma *p2ndf-ndf2p-wp*: $\lceil \lfloor wp\ R\ P \rfloor \rceil = wp\ R\ P$
  apply(*rule p2ndf-ndf2p-id*)
  by (*simp add*: *a-subid fbox-def one-nd-fun.transfer*)

lemma *ndf2p-wpD*: $\lfloor wp\ F\ \lceil Q \rceil \rfloor\ s = (\forall s'.\ s' \in (F_\bullet)\ s \longrightarrow Q\ s')$
  apply(*subgoal-tac* $F = (F_\bullet)^\bullet$)
  apply(*rule ssubst*[*of* $F\ (F_\bullet)^\bullet$], *simp*)
  apply(*subst wp-nd-fun*)
  by(*simp-all add*: *f2r-def*)

lemma *wp-invariants*:
  assumes $\lceil I \rceil \leq wp\ F\ \lceil I \rceil$ **and** $\lceil J \rceil \leq wp\ F\ \lceil J \rceil$
  shows $\lceil \lambda s.\ I\ s \wedge J\ s \rceil \leq wp\ F\ \lceil \lambda s.\ I\ s \wedge J\ s \rceil$
    and $\lceil \lambda s.\ I\ s \vee J\ s \rceil \leq wp\ F\ \lceil \lambda s.\ I\ s \vee J\ s \rceil$
  using *assms* **unfolding** *wp-nd-fun2* **by** *simp-all force*

We check that *wp* coincides with our other definition of the forward box operator $fb_{\mathcal{F}} = \partial_F \circ bd_{\mathcal{F}} \circ op_K$.

lemma *ffb-is-wp*: $fb_{\mathcal{F}}\ (F_\bullet)\ \{x.\ P\ x\} = \{s.\ \lfloor wp\ F\ \lceil P \rceil \rfloor\ s\}$
  unfolding *ffb-def* **unfolding** *map-dual-def klift-def kop-def fbox-def*
  unfolding *r2f-def f2r-def* **apply** *clarsimp*
  unfolding *antidomain-op-nd-fun-def* **unfolding** *dual-set-def*
  unfolding *times-nd-fun-def kcomp-def* **by** *force*

lemma *wp-is-ffb*: $wp\ F\ P = (\lambda x.\ \{x\} \cap fb_{\mathcal{F}}\ (F_\bullet)\ \{s.\ \lfloor P \rfloor\ s\})^\bullet$
  apply(*rule nd-fun-ext*, *simp*)
  unfolding *ffb-def* **unfolding** *map-dual-def klift-def kop-def fbox-def*
  unfolding *r2f-def f2r-def* **apply** *clarsimp*

unfolding *antidomain-op-nd-fun-def* **unfolding** *dual-set-def*
unfolding *times-nd-fun-def* **apply** *auto*
unfolding *kcomp-prop* **by** *auto*

The weakest liberal precondition (wlp) of the "skip" program is the identity.

abbreviation $skip \equiv \eta^{\bullet}$

lemma *wp-eta*[*simp*]: $wp\ skip\ \lceil P\rceil = \lceil P\rceil$
apply(*simp add*: *fbox-def*, *transfer*, *simp*)
by(*rule nd-fun-ext*, *auto simp*: *kcomp-def*)

Next, we introduce assignments and their *wp*.

definition *vec-upd* :: $('a\,\hat{}\,'b) \Rightarrow 'b \Rightarrow 'a \Rightarrow 'a\,\hat{}\,'b$
where $vec\text{-}upd\ s\ i\ a = (\chi\ j.\ ((((\$)\ s)(i := a))\ j)$

definition *assign* :: $'b \Rightarrow ('a\,\hat{}\,'b \Rightarrow 'a) \Rightarrow ('a\,\hat{}\,'b)\ nd\text{-}fun\ ((2\text{-}\ ::=\ \text{-})\ [70,\ 65]\ 61)$
where $(x ::= e) = (\lambda s.\ \{vec\text{-}upd\ s\ x\ (e\ s)\})^{\bullet}$

lemma *wp-assign*[*simp*]: $wp\ (x ::= e)\ \lceil Q\rceil = \lceil \lambda s.\ Q\ (\chi\ j.\ ((((\$)\ s)(x := (e\ s)))\ j)\rceil$
unfolding *wp-nd-fun2 nd-fun-eq-iff*[*symmetric*] *vec-upd-def assign-def* **by** *auto*

The *wp* of the composition was already obtained in KAD.Antidomain_Semiring: $wp\ (x \cdot y)\ z = wp\ x\ (wp\ y\ z)$.

abbreviation *seq-comp* :: $'a\ nd\text{-}fun \Rightarrow 'a\ nd\text{-}fun \Rightarrow 'a\ nd\text{-}fun$ (**infixl** ; *75*)
where $f\ ;\ g \equiv f \cdot g$

lemma *wlp-seq-comp*[*simp*]: $wp\ (F\ ;\ G)\ Q = wp\ F\ (wp\ G\ Q)$
by (*simp add*: *fbox-mult*)

We also have an implementation of the conditional operator and its *wp*.

definition (**in** *antidomain-kleene-algebra*) *cond* :: $'a \Rightarrow 'a \Rightarrow 'a \Rightarrow 'a$
(*if - then - else - fi* [*64*,*64*,*64*] *63*) **where** *if p then x else y fi* $= d\ p \cdot x + ad\ p \cdot y$

lemma *fbox-export1*: $ad\ p + |x]\ q = |d\ p \cdot x]\ q$
using *a-d-add-closure fbox-def fbox-mult*
by (*metis* (*mono-tags*, *lifting*) *a-de-morgan ads-d-def*)

lemma *fbox-cond-var*[*simp*]: $|if\ p\ then\ x\ else\ y\ fi]\ q = (ad\ p + |x]\ q) \cdot (d\ p + |y]\ q)$
using *cond-def a-closure′ ads-d-def ans-d-def fbox-add2 fbox-export1* **by** (*metis* (*no-types*, *lifting*))

abbreviation *cond-sugar* :: $'a\ pred \Rightarrow 'a\ nd\text{-}fun \Rightarrow 'a\ nd\text{-}fun \Rightarrow 'a\ nd\text{-}fun$
(*IF - THEN - ELSE -* [*64*,*64*,*64*] *63*) **where** $IF\ P\ THEN\ X\ ELSE\ Y \equiv cond\ \lceil P\rceil\ X\ Y$

lemma *wp-if-then-elseI*:

assumes $\lceil\lambda s.\ P\ s \wedge T\ s\rceil \leq wp\ X\ \lceil Q\rceil$
and $\lceil\lambda s.\ P\ s \wedge \neg\ T\ s\rceil \leq wp\ Y\ \lceil Q\rceil$
shows $\lceil P\rceil \leq wp\ (IF\ T\ THEN\ X\ ELSE\ Y)\ \lceil Q\rceil$
using *assms* **apply**(*subst wp-nd-fun2*)
apply(*subst* (*asm*) *wp-nd-fun2*)+
unfolding *cond-def* **apply**(*clarsimp*, *transfer*)
by(*auto simp*: *kcomp-prop*)

We also deal with finite iteration.

context *antidomain-kleene-algebra*
begin

lemma *plus-inv*: $i \leq |x]\ i \Longrightarrow j \leq |x]\ j \Longrightarrow (i + j) \leq |x]\ (i + j)$
by (*metis ads-d-def dka.dsr5 fbox-simp fbox-subdist join.sup-mono order-trans*)

lemma *fbox-frame*: $d\ p \cdot x \leq x \cdot d\ p \Longrightarrow d\ q \leq |x]\ t \Longrightarrow d\ p \cdot d\ q \leq |x]\ (d\ p \cdot d\ t)$
using *dual.mult-isol-var fbox-add1 fbox-demodalisation3 fbox-simp* **by** *auto*

lemma *mult-inv*: $d\ i \leq |x]\ d\ i \Longrightarrow d\ j \leq |x]\ d\ j \Longrightarrow (d\ i \cdot d\ j) \leq |x]\ (d\ i \cdot d\ j)$
using *local.fbox-demodalisation3 fbox-frame fbox-simp* **by** *auto*

lemma (**in** *antidomain-kleene-algebra*) *fbox-stari*:
assumes $d\ p \leq d\ i$ **and** $d\ i \leq |x]\ i$ **and** $d\ i \leq d\ q$
shows $d\ p \leq |x^\star]\ q$
by (*meson assms local.dual-order.trans fbox-iso fbox-star-induct-var*)

definition *loopi* :: $'a \Rightarrow 'a \Rightarrow 'a$ (*loop - inv -* [*64*,*64*] *63*)
where $loop\ x\ inv\ i = x^\star$

lemma *fbox-loopi*: $d\ p \leq d\ i \Longrightarrow d\ i \leq |x]\ i \Longrightarrow d\ i \leq d\ q \Longrightarrow d\ p \leq |loop\ x\ inv\ i]\ q$
unfolding *loopi-def* **using** *fbox-stari* **by** *blast*

end

lemma *ads-d-mono*: $x \leq y \Longrightarrow d\ x \leq d\ y$
by (*metis ads-d-def fbox-antitone-var fbox-dom*)

lemma *nd-fun-top-ads-d*:$(x{::}'a\ nd\text{-}fun) \leq 1 \Longrightarrow d\ x = x$
apply(*simp add*: *ads-d-def*, *transfer*, *simp*)
apply(*rule nd-fun-ext*, *simp*)
apply(*subst* (*asm*) *le-fun-def*)
by *auto*

lemma *wp-starI*:
assumes $P \leq I$ **and** $I \leq Q$ **and** $I \leq wp\ F\ I$
shows $P \leq wp\ (qstar\ (F{::}'a\ nd\text{-}fun))\ Q$
proof−

have $P \leq 1$
using *assms*(*1*,*3*) **by** (*metis a-subid basic-trans-rules*(*23*) *fbox-def*)
hence $d\ P = P$ **using** *nd-fun-top-ads-d* **by** *blast*
have $\bigwedge x\ y.\ d\ (wp\ x\ y) = wp\ x\ y$
by (*metis* (*mono-tags*, *lifting*) *a-d-add-closure ads-d-def as2 fbox-def fbox-simp*)
hence $d\ P \leq d\ I \wedge d\ I \leq wp\ F\ I \wedge d\ I \leq d\ Q$
using *assms* **by** (*metis* (*no-types*) *ads-d-mono assms*)
hence $d\ P \leq wp\ (F^\star)\ Q$
by(*simp add*: *fbox-stari*[*of* - *I*])
thus $P \leq wp\ (qstar\ F)\ Q$
using ‹$d\ P = P$› **by** (*transfer*, *simp*)
qed

abbreviation *loopi-sugar* :: $'a$ *nd-fun* $\Rightarrow$ $'a$ *pred* $\Rightarrow$ $'a$ *nd-fun* (*LOOP* - *INV* - [*64*,*64*] *63*)
where *LOOP R INV I* $\equiv$ *loopi R* $\lceil I \rceil$

lemma *wp-loopI*: $\lceil P\rceil \leq \lceil I\rceil \Longrightarrow \lceil I\rceil \leq \lceil Q\rceil \Longrightarrow \lceil I\rceil \leq wp\ R\ \lceil I\rceil \Longrightarrow \lceil P\rceil \leq wp$ (*LOOP R INV I*) $\lceil Q\rceil$
using *fbox-loopi*[*of* $\lceil P\rceil$] **by** *auto*

7.3 Verification of hybrid programs

7.3.1 Verification by providing evolution

definition *g-evol* :: (($'a$::*ord*) $\Rightarrow$ $'b \Rightarrow 'b$) $\Rightarrow$ $'b$ *pred* $\Rightarrow$ $'a$ *set* $\Rightarrow$ $'b$ *nd-fun* (*EVOL*)
where $EVOL\ \varphi\ G\ T = (\lambda s.\ g\text{-}orbit\ (\lambda t.\ \varphi\ t\ s)\ G\ T)^\bullet$

lemma *wp-g-dyn*[*simp*]:
fixes φ :: ($'a$::*preorder*) $\Rightarrow$ $'b \Rightarrow 'b$
shows $wp\ (EVOL\ \varphi\ G\ T)\ \lceil Q\rceil = \lceil \lambda s.\ \forall t{\in}T.\ (\forall \tau{\in}down\ T\ t.\ G\ (\varphi\ \tau\ s)) \longrightarrow Q\ (\varphi\ t\ s)\rceil$
unfolding *wp-nd-fun g-evol-def g-orbit-eq* **by** (*auto simp*: *fun-eq-iff*)

7.3.2 Verification by providing solutions

definition *g-ode* ::(($'a$::*banach*)$\Rightarrow$$'a$) $\Rightarrow$ $'a$ *pred* $\Rightarrow$ *real set* $\Rightarrow$ $'a$ *set* $\Rightarrow$ *real* $\Rightarrow$ $'a$ *nd-fun* ((*1x´*= - & - *on* - - @ -))
where $(x' = f\ \&\ G\ on\ T\ S\ @\ t_0) \equiv (\lambda\ s.\ g\text{-}orbital\ f\ G\ T\ S\ t_0\ s)^\bullet$

lemma *wp-g-orbital*: $wp\ (x' = f\ \&\ G\ on\ T\ S\ @\ t_0)\ \lceil Q\rceil =$
$\lceil \lambda\ s.\ \forall X{\in}ivp\text{-}sols\ (\lambda t.\ f)\ T\ S\ t_0\ s.\ \forall t{\in}T.\ (\forall \tau{\in}down\ T\ t.\ G\ (X\ \tau)) \longrightarrow Q\ (X\ t)\rceil$
unfolding *g-orbital-eq*(*1*) *wp-nd-fun g-ode-def* **by** (*auto simp*: *fun-eq-iff image-le-pred*)

context *local-flow*
begin

lemma *wp-g-ode*: $wp\ (x' = f\ \&\ G\ on\ T\ S\ @\ 0)\ \lceil Q\rceil =$

$\lceil \lambda\ s.\ s \in S \longrightarrow (\forall\, t{\in}T.\ (\forall\, \tau{\in} down\ T\ t.\ G\ (\varphi\ \tau\ s)) \longrightarrow Q\ (\varphi\ t\ s))\rceil$
unfolding *wp-g-orbital* **apply**(*clarsimp*, *simp add*: *fun-eq-iff*, *safe*)
apply(*erule-tac* $x{=}\lambda t.\ \varphi\ t\ x$ **in** *ballE*)
using *in-ivp-sols* **apply**(*force*, *force*, *force simp*: *init-time ivp-sols-def*)
apply(*subgoal-tac* $\forall\, \tau{\in} down\ T\ t.\ X\ \tau = \varphi\ \tau\ x$, *simp-all*, *clarsimp*)
apply(*subst eq-solution*, *simp-all add*: *ivp-sols-def*)
using *init-time* **by** *auto*

lemma *wp-orbit*: $wp\ (\gamma^{\varphi\bullet})\ \lceil Q\rceil = \lceil \lambda\ s.\ s \in S \longrightarrow (\forall\ t \in T.\ Q\ (\varphi\ t\ s))\rceil$
unfolding *orbit-def wp-g-ode g-ode-def*[*symmetric*] **by** *auto*

end

7.3.3 Verification with differential invariants

definition *g-ode-inv* :: $(('a{::}banach){\Rightarrow}'a) \Rightarrow 'a\ pred \Rightarrow real\ set \Rightarrow 'a\ set \Rightarrow real \Rightarrow 'a\ pred \Rightarrow 'a\ nd\text{-}fun$ $((1x{\acute{}}{=}\text{-}\ \&\ \text{-}\ on\ \text{-}\ \text{-}\ @\ \text{-}\ DINV\ \text{-}\ ))$
where $(x{\acute{}}{=}\ f\ \&\ G\ on\ T\ S\ @\ t_0\ DINV\ I) = (x{\acute{}}{=}\ f\ \&\ G\ on\ T\ S\ @\ t_0)$

lemma *wp-g-orbital-guard*:
assumes $H = (\lambda s.\ G\ s \wedge Q\ s)$
shows $wp\ (x{\acute{}}{=}\ f\ \&\ G\ on\ T\ S\ @\ t_0)\ \lceil Q\rceil = wp\ (x{\acute{}}{=}\ f\ \&\ G\ on\ T\ S\ @\ t_0)\ \lceil H\rceil$
unfolding *wp-g-orbital* **using** *assms* **by** *auto*

lemma *wp-g-orbital-inv*:
assumes $\lceil P\rceil \le \lceil I\rceil$ **and** $\lceil I\rceil \le wp\ (x{\acute{}}{=}\ f\ \&\ G\ on\ T\ S\ @\ t_0)\ \lceil I\rceil$ **and** $\lceil I\rceil \le \lceil Q\rceil$
shows $\lceil P\rceil \le wp\ (x{\acute{}}{=}\ f\ \&\ G\ on\ T\ S\ @\ t_0)\ \lceil Q\rceil$
using *assms*(*1*) **apply**(*rule order.trans*)
using *assms*(*2*) **apply**(*rule order.trans*)
apply(*rule fbox-iso*)
using *assms*(*3*) **by** *auto*

lemma *wp-diff-inv*[*simp*]: $(\lceil I\rceil \le wp\ (x{\acute{}}{=}\ f\ \&\ G\ on\ T\ S\ @\ t_0)\ \lceil I\rceil) = diff\text{-}invariant\ I\ f\ T\ S\ t_0\ G$
unfolding *diff-invariant-eq wp-g-orbital image-le-pred* **by**(*auto simp*: *fun-eq-iff*)

lemma *wp-g-odei*: $\lceil P\rceil \le \lceil I\rceil \Longrightarrow \lceil I\rceil \le wp\ (x{\acute{}}{=}\ f\ \&\ G\ on\ T\ S\ @\ t_0)\ \lceil I\rceil \Longrightarrow \lceil \lambda s.\ I\ s \wedge G\ s\rceil \le \lceil Q\rceil \Longrightarrow$
$\lceil P\rceil \le wp\ (x{\acute{}}{=}\ f\ \&\ G\ on\ T\ S\ @\ t_0\ DINV\ I)\ \lceil Q\rceil$
unfolding *g-ode-inv-def* **apply**(*rule-tac* $b{=}wp\ (x{\acute{}}{=}\ f\ \&\ G\ on\ T\ S\ @\ t_0)\ \lceil I\rceil$ **in** *order.trans*)
apply(*rule-tac* $I{=}I$ **in** *wp-g-orbital-inv*, *simp-all*)
apply(*subst wp-g-orbital-guard*, *simp*)
by (*rule fbox-iso*, *simp*)

7.3.4 Derivation of the rules of dL

We derive domain specific rules of differential dynamic logic (dL). First we present a generalised version, then we show the rules as instances of the general ones.

lemma *diff-solve-axiom*:
  fixes c::$'a$::{*heine-borel*, *banach*}
  assumes $0 \in T$ **and** *is-interval* T *open* T
  shows *wp* $(x' {=} (\lambda s.\ c)\ \&\ G$ *on* T *UNIV* $@\ 0)\ \lceil Q \rceil =$
  $\lceil \lambda\ s.\ \forall t{\in}T.\ (\mathcal{P}\ (\lambda\ t.\ s + t *_R c)\ (down\ T\ t) \subseteq \{s.\ G\ s\}) \longrightarrow Q\ (s + t *_R c) \rceil$
  apply(*subst local-flow.wp-g-ode*[**where** $f{=}\lambda s.\ c$ **and** $\varphi{=}(\lambda\ t\ s.\ s + t *_R c)$])
  using *line-is-local-flow*[*OF assms*] **unfolding** *image-le-pred* **by** *auto*

lemma *diff-solve-rule*:
  assumes *local-flow* $f\ T$ *UNIV* φ
    and $\forall s.\ P\ s \longrightarrow (\forall\ t{\in}T.\ (\mathcal{P}\ (\lambda t.\ \varphi\ t\ s)\ (down\ T\ t) \subseteq \{s.\ G\ s\}) \longrightarrow Q\ (\varphi\ t\ s))$
  shows $\lceil P \rceil \leq$ *wp* $(x' {=} f\ \&\ G$ *on* T *UNIV* $@\ 0)\ \lceil Q \rceil$
  using *assms* **by**(*subst local-flow.wp-g-ode*, *auto*)

lemma *diff-weak-axiom*:
  wp $(x' {=} f\ \&\ G$ *on* $T\ S\ @\ t_0)\ \lceil Q \rceil =$ *wp* $(x' {=} f\ \&\ G$ *on* $T\ S\ @\ t_0)\ \lceil \lambda\ s.\ G\ s \longrightarrow Q\ s \rceil$
  unfolding *wp-g-orbital image-def* **by** *force*

lemma *diff-weak-rule*: $\lceil G \rceil \leq \lceil Q \rceil \Longrightarrow \lceil P \rceil \leq$ *wp* $(x' {=} f\ \&\ G$ *on* $T\ S\ @\ t_0)\ \lceil Q \rceil$
  by (*subst wp-g-orbital*) (*auto simp*: *g-ode-def*)

lemma *wp-nd-fun-etaD*: *wp* $(F^\bullet)\ \lceil P \rceil = \eta^\bullet \Longrightarrow\ (\forall y.\ y \in (F\ x) \longrightarrow P\ y)$
proof
  fix y **assume** *wp* $(F^\bullet)\ \lceil P \rceil = (\eta^\bullet)$
  from *this* **have** $\eta^\bullet = \lceil \lambda s.\ \forall y.\ s2p\ (F\ s)\ y \longrightarrow P\ y \rceil$
    by(*subst wp-nd-fun*[*THEN sym*], *simp*)
  hence $\bigwedge x.\ \{x\} = \{s.\ s = x \wedge (\forall y.\ s2p\ (F\ s)\ y \longrightarrow P\ y)\}$
    apply(*subst* (*asm*) *Abs-nd-fun-inject*, *simp-all*)
    by(*drule-tac* $x{=}x$ **in** *fun-cong*, *simp*)
  then show $s2p\ (F\ x)\ y \longrightarrow P\ y$ **by** *auto*
qed

lemma *wp-g-orbit-IdD*:
  assumes *wp* $(x' {=} f\ \&\ G$ *on* $T\ S\ @\ t_0)\ \lceil C \rceil = \eta^\bullet$
    and $\forall \tau{\in}(down\ T\ t).\ x\ \tau \in$ *g-orbital* $f\ G\ T\ S\ t_0\ s$
  shows $\forall \tau{\in}(down\ T\ t).\ C\ (x\ \tau)$
proof
  fix τ **assume** $\tau \in (down\ T\ t)$
  hence $x\ \tau \in$ *g-orbital* $f\ G\ T\ S\ t_0\ s$
    using *assms*(*2*) **by** *blast*
  also have $\forall y.\ y \in$ (*g-orbital* $f\ G\ T\ S\ t_0\ s) \longrightarrow C\ y$
    using *assms*(*1*) **unfolding** *wp-nd-fun g-ode-def*

by (*subst* (*asm*) *nd-fun-eq-iff* [*symmetric*]) *auto*
ultimately show $C\ (x\ \tau)$
by *blast*
qed

lemma *diff-cut-axiom*:
assumes *Thyp*: *is-interval* T $t_0 \in T$
and *wp* ($x\'= f$ & G *on* T S @ t_0) $\lceil C \rceil = \eta^\bullet$
shows *wp* ($x\'= f$ & G *on* T S @ t_0) $\lceil Q \rceil$ = *wp* ($x\'= f$ & ($\lambda s.\ G\ s \wedge C\ s$) *on* T S @ t_0) $\lceil Q \rceil$
proof(*rule-tac* f=λ x. *wp* x $\lceil Q \rceil$ **in** *HOL.arg-cong*, *rule nd-fun-ext*, *rule subset-antisym*)
fix s **show** (($x\'= f$ & G *on* T S @ t_0)$_\bullet$) $s \subseteq$ (($x\'= f$ & ($\lambda s.\ G\ s \wedge C\ s$) *on* T S @ t_0)$_\bullet$) s
proof(*clarsimp simp*: *g-ode-def*)
fix s' **assume** $s' \in$ *g-orbital* f G T S t_0 s
then obtain τ::*real* **and** X **where** *x-ivp*: $X \in$ *ivp-sols* ($\lambda t.\ f$) T S t_0 s
and $X\ \tau = s'$ **and** $\tau \in T$ **and** *guard-x*:($\mathcal{P}$ X (*down* T τ) $\subseteq \{s.\ G\ s\}$)
using *g-orbitalD*[*of* s' f G T S t_0 s] **by** *blast*
have $\forall\, t{\in}$(*down* T τ). $\mathcal{P}$ X (*down* T t) $\subseteq \{s.\ G\ s\}$
using *guard-x* **by** (*force simp*: *image-def*)
also have $\forall\, t{\in}$(*down* T τ). $t \in T$
using ‹$\tau \in T$› *Thyp* **by** *auto*
ultimately have $\forall\, t{\in}$(*down* T τ). $X\ t \in$ *g-orbital* f G T S t_0 s
using *g-orbitalI*[*OF x-ivp*] **by** (*metis* (*mono-tags*, *lifting*))
hence $\forall\, t{\in}$(*down* T τ). $C\ (X\ t)$
using *wp-g-orbit-IdD*[*OF assms*(*3*)] **by** *blast*
thus $s' \in$ *g-orbital* f ($\lambda s.\ G\ s \wedge C\ s$) T S t_0 s
using *g-orbitalI*[*OF x-ivp* ‹$\tau \in T$›] *guard-x* ‹$X\ \tau = s'$›
unfolding *image-le-pred* **by** *fastforce*
qed
next
fix s **show** (($x\'= f$ & $\lambda s.\ G\ s \wedge C\ s$ *on* T S @ t_0)$_\bullet$) $s \subseteq$ (($x\'= f$ & G *on* T S @ t_0)$_\bullet$) s
by (*auto simp*: *g-orbital-eq g-ode-def*)
qed

lemma *diff-cut-rule*:
assumes *Thyp*: *is-interval* T $t_0 \in T$
and *wp-C*: $\lceil P \rceil \le$ *wp* ($x\'= f$ & G *on* T S @ t_0) $\lceil C \rceil$
and *wp-Q*: $\lceil P \rceil \le$ *wp* ($x\'= f$ & ($\lambda s.\ G\ s \wedge C\ s$) *on* T S @ t_0) $\lceil Q \rceil$
shows $\lceil P \rceil \le$ *wp* ($x\'= f$ & G *on* T S @ t_0) $\lceil Q \rceil$
proof(*simp add*: *wp-nd-fun g-orbital-eq image-le-pred g-ode-def*, *clarsimp*)
fix t::*real* **and** X::*real* $\Rightarrow$ $'a$ **and** s **assume** $P\ s$ **and** $t \in T$
and *x-ivp*:$X \in$ *ivp-sols* ($\lambda t.\ f$) T S t_0 s
and *guard-x*:$\forall\, x.\ x \in T \wedge x \le t \longrightarrow G\ (X\ x)$
have $\forall\, t{\in}$(*down* T t). $X\ t \in$ *g-orbital* f G T S t_0 s
using *g-orbitalI*[*OF x-ivp*] *guard-x* **unfolding** *image-le-pred* **by** *auto*
hence $\forall\, t{\in}$(*down* T t). $C\ (X\ t)$
using *wp-C* ‹$P\ s$› **by** (*subst* (*asm*) *wp-nd-fun2*, *auto simp*: *g-ode-def*)

hence $X\ t \in$ *g-orbital* $f\ (\lambda s.\ G\ s \wedge C\ s)\ T\ S\ t_0\ s$
using *guard-x* ‹$t \in T$› **by** (*auto intro*!: *g-orbitalI x-ivp*)
thus $Q\ (X\ t)$
using ‹$P\ s$› *wp-Q* **by** (*subst* (*asm*) *wp-nd-fun2*) (*auto simp*: *g-ode-def*)
qed

The rules of dL

abbreviation *g-global-ode* ::(('*a*::*banach*)⇒'*a*) ⇒ '*a pred* ⇒ '*a nd-fun* ((*1x´=- & -*))
where (*x´= f & G*) ≡ (*x´= f & G on UNIV UNIV @ 0*)

abbreviation *g-global-ode-inv* :: (('*a*::*banach*)⇒'*a*) ⇒ '*a pred* ⇒ '*a pred* ⇒ '*a nd-fun*
((*1x´=- & - DINV -*)) **where** (*x´= f & G DINV I*) ≡ (*x´= f & G on UNIV UNIV @ 0 DINV I*)

lemma *DS*:
fixes *c*::'*a*::{*heine-borel*, *banach*}
shows *wp* (*x´*=($\lambda s.\ c$) & *G*) ⌈*Q*⌉ = ⌈$\lambda x.\ \forall t.\ (\forall \tau \le t.\ G\ (x + \tau *_R c)) \longrightarrow Q\ (x + t *_R c)$⌉
by (*subst diff-solve-axiom*[*of UNIV*]) (*auto simp*: *fun-eq-iff*)

lemma *solve*:
assumes *local-flow f UNIV UNIV* φ
and $\forall s.\ P\ s \longrightarrow (\forall t.\ (\forall \tau \le t.\ G\ (\varphi\ \tau\ s)) \longrightarrow Q\ (\varphi\ t\ s))$
shows ⌈*P*⌉ ≤ *wp* (*x´= f & G*) ⌈*Q*⌉
apply(*rule diff-solve-rule*[*OF assms*(*1*)])
using *assms*(*2*) **unfolding** *image-le-pred* **by** *simp*

lemma *DW*: *wp* (*x´= f & G*) ⌈*Q*⌉ = *wp* (*x´= f & G*) ⌈$\lambda s.\ G\ s \longrightarrow Q\ s$⌉
by (*rule diff-weak-axiom*)

lemma *dW*: ⌈*G*⌉ ≤ ⌈*Q*⌉ ⟹ ⌈*P*⌉ ≤ *wp* (*x´= f & G*) ⌈*Q*⌉
by (*rule diff-weak-rule*)

lemma *DC*:
assumes *wp* (*x´= f & G*) ⌈*C*⌉ = $\eta^\bullet$
shows *wp* (*x´= f & G*) ⌈*Q*⌉ = *wp* (*x´= f &* ($\lambda s.\ G\ s \wedge C\ s$)) ⌈*Q*⌉
apply (*rule diff-cut-axiom*)
using *assms* **by** *auto*

lemma *dC*:
assumes ⌈*P*⌉ ≤ *wp* (*x´= f & G*) ⌈*C*⌉
and ⌈*P*⌉ ≤ *wp* (*x´= f &* ($\lambda s.\ G\ s \wedge C\ s$)) ⌈*Q*⌉
shows ⌈*P*⌉ ≤ *wp* (*x´= f & G*) ⌈*Q*⌉
apply(*rule diff-cut-rule*)
using *assms* **by** *auto*

lemma *dI*:

assumes $\lceil P\rceil \leq \lceil I\rceil$ **and** *diff-invariant I f UNIV UNIV 0 G* **and** $\lceil I\rceil \leq \lceil Q\rceil$
shows $\lceil P\rceil \leq wp\ (x' = f\ \&\ G)\ \lceil Q\rceil$
apply(*rule wp-g-orbital-inv*[*OF assms*(*1*) - *assms*(*3*)])
unfolding *wp-diff-inv* **using** *assms*(*2*) **.**

end
theory *cat2ndfun-examples*
imports ../*hs-prelims-matrices cat2ndfun*

begin

7.3.5 Examples

Preparation for the examples.

no-notation *Archimedean-Field.ceiling* ($\lceil$-$\rceil$)
and *Archimedean-Field.floor-ceiling-class.floor* ($\lfloor$-$\rfloor$)

lemma [*simp*]: $i \neq (0::2) \longrightarrow i = 1$
using *exhaust-2* **by** *fastforce*

lemma *two-eq-zero*: $(2::2) = 0$
by *simp*

lemma *UNIV-2*: $(UNIV::2\ set) = \{0,\ 1\}$
apply *safe* **using** *exhaust-2 two-eq-zero* **by** *auto*

lemma *UNIV-3*: $(UNIV::3\ set) = \{0,\ 1,\ 2\}$
apply *safe* **using** *exhaust-3 three-eq-zero* **by** *auto*

lemma *sum-axis-UNIV-3*[*simp*]: $(\sum j{\in}(UNIV::3\ set).\ axis\ i\ 1\ \$\ j \cdot f\ j) = (f::3 \Rightarrow real)\ i$
unfolding *axis-def UNIV-3* **apply** *simp*
using *exhaust-3* **by** *force*

Pendulum

— Verified with differential invariants.

abbreviation *fpend* :: $real\hat{~}2 \Rightarrow real\hat{~}2$ (f)
where $f\ s \equiv (\chi\ i.\ if\ i{=}0\ then\ s\$1\ else\ -s\ \$\ 0)$

lemma *pendulum-invariants*:
$\lceil\lambda s.\ r^2 = (s\ \$\ 0)^2 + (s\ \$\ 1)^2\rceil \leq wp\ (x' = f\ \&\ G)\ \lceil\lambda s.\ r^2 = (s\ \$\ 0)^2 + (s\ \$\ 1)^2\rceil$
by (*auto intro*!: *poly-derivatives diff-invariant-rules*)

— Verified with the flow.

abbreviation *pend-flow* :: $real \Rightarrow real\hat{~}2 \Rightarrow real\hat{~}2$ (φ)

where $\varphi\ t\ s \equiv (\chi\ i.\ \mathit{if}\ i = \mathit{0}\ \mathit{then}\ s\ \$\ \mathit{0} \cdot \mathit{cos}\ t + s\ \$\ \mathit{1} \cdot \mathit{sin}\ t$
$\mathit{else} - s\ \$\ \mathit{0} \cdot \mathit{sin}\ t + s\ \$\ \mathit{1} \cdot \mathit{cos}\ t)$

lemma *local-flow-pend*: *local-flow f UNIV UNIV* φ
apply(*unfold-locales*, *simp-all add*: *local-lipschitz-def lipschitz-on-def vec-eq-iff*, *clarsimp*)
apply(*rule-tac x=1* **in** *exI*, *clarsimp*, *rule-tac x=1* **in** *exI*)
apply(*simp add*: *dist-norm norm-vec-def L2-set-def power2-commute UNIV-2*)
apply(*clarify*, *case-tac* $i = \mathit{0}$, *simp*)
using *exhaust-2 two-eq-zero* **by** (*force intro*!: *poly-derivatives*)+

lemma *pendulum*:
$\lceil \lambda s.\ r^2 = (s\ \$\ \mathit{0})^2 + (s\ \$\ \mathit{1})^2 \rceil \leq wp\ (x' = f\ \&\ G)\ \lceil \lambda s.\ r^2 = (s\ \$\ \mathit{0})^2 + (s\ \$\ \mathit{1})^2 \rceil$
by (*simp add*: *local-flow.wp-g-ode*[*OF local-flow-pend*])

— Verified by providing dynamics.

lemma *pendulum-dyn*:
$\lceil \lambda s.\ r^2 = (s\ \$\ \mathit{0})^2 + (s\ \$\ \mathit{1})^2 \rceil \leq wp\ (EVOL\ \varphi\ G\ T)\ \lceil \lambda s.\ r^2 = (s\ \$\ \mathit{0})^2 + (s\ \$\ \mathit{1})^2 \rceil$
by *simp*

— Verified as a linear system (using uniqueness).

abbreviation *pend-sq-mtx* :: *2 sq-mtx* (*A*)
where $A \equiv$ *sq-mtx-chi* $(\chi\ i.\ \mathit{if}\ i{=}\mathit{0}\ \mathit{then}\ \mathrm{e}\ \mathit{1}\ \mathit{else} - \mathrm{e}\ \mathit{0})$

lemma *pend-sq-mtx-exp-eq-flow*: $exp\ (t *_R A) *_V s = \varphi\ t\ s$
apply(*rule local-flow.eq-solution*[*OF local-flow-exp*, *symmetric*])
apply(*rule ivp-solsI*, *simp add*: *sq-mtx-vec-prod-def matrix-vector-mult-def*)
apply(*force intro*!: *poly-derivatives simp*: *matrix-vector-mult-def*)
using *exhaust-2 two-eq-zero* **by** (*force simp*: *vec-eq-iff*, *auto*)

lemma *pendulum-sq-mtx*:
$\lceil \lambda s.\ r^2 = (s\$\mathit{0})^2 + (s\$\mathit{1})^2 \rceil \leq wp\ (x' = ((*_V)\ A)\ \&\ G)\ \lceil \lambda s.\ r^2 = (s\$\mathit{0})^2 + (s\$\mathit{1})^2 \rceil$
unfolding *local-flow.wp-g-ode*[*OF local-flow-exp*] *pend-sq-mtx-exp-eq-flow* **by** *auto*

no-notation *fpend* (*f*)
and *pend-sq-mtx* (*A*)
and *pend-flow* (φ)

Bouncing Ball

— Verified with differential invariants.

named-theorems *bb-real-arith real arithmetic properties for the bouncing ball.*

lemma [*bb-real-arith*]:
  assumes $0 > g$ **and** *inv*: $2 \cdot g \cdot x - 2 \cdot g \cdot h = v \cdot v$
  shows $(x::real) \leq h$
proof−
  have $v \cdot v = 2 \cdot g \cdot x - 2 \cdot g \cdot h \wedge 0 > g$
    using *inv* **and** $\langle 0 > g \rangle$ **by** *auto*
  hence *obs*:$v \cdot v = 2 \cdot g \cdot (x - h) \wedge 0 > g \wedge v \cdot v \geq 0$
    using *left-diff-distrib mult.commute* **by** (*metis zero-le-square*)
  hence $(v \cdot v)/(2 \cdot g) = (x - h)$
    by *auto*
  also from *obs* **have** $(v \cdot v)/(2 \cdot g) \leq 0$
    using *divide-nonneg-neg* **by** *fastforce*
  ultimately have $h - x \geq 0$
    by *linarith*
  thus *?thesis* **by** *auto*
qed

abbreviation *fball* :: *real* ⇒ *real*ˆ*2* ⇒ *real*ˆ*2* (*f*)
  where $f\ g\ s \equiv (\chi\ i.\ if\ i{=}(0)\ then\ s\ \$\ 1\ else\ g)$

lemma *bouncing-ball-invariants*:
  fixes *h*::*real*
  shows $g < 0 \Longrightarrow h \geq 0 \Longrightarrow \lceil \lambda s.\ s\ \$\ 0 = h \wedge s\ \$\ 1 = 0 \rceil \leq$
  wp
    (*LOOP*
      $((x' = f\ g\ \&\ (\lambda\ s.\ s\ \$\ 0 \geq 0)\ DINV\ (\lambda s.\ 2 \cdot g \cdot s\ \$\ 0 - 2 \cdot g \cdot h - s\ \$\ 1 \cdot$
$s\ \$\ 1 = 0));$
        $(IF\ (\lambda\ s.\ s\ \$\ 0 = 0)\ THEN\ (1 ::= (\lambda s.\ -\ s\ \$\ 1))\ ELSE\ skip))$
    $INV\ (\lambda s.\ 0 \leq s\ \$\ 0 \wedge 2 \cdot g \cdot s\ \$\ 0 - 2 \cdot g \cdot h - s\ \$\ 1 \cdot s\ \$\ 1 = 0)$
  $)\ \lceil \lambda s.\ 0 \leq s\ \$\ 0 \wedge s\ \$\ 0 \leq h \rceil$
  apply(*rule wp-loopI*, *simp-all*)
   apply(*force simp*: *bb-real-arith*)
  apply(*rule wp-g-odei*)
  by(*auto intro*!: *poly-derivatives diff-invariant-rules*)

— Verified with the flow.

abbreviation *ball-flow* :: *real* ⇒ *real* ⇒ *real*ˆ*2* ⇒ *real*ˆ*2* (φ)
  where $\varphi\ g\ t\ s \equiv (\chi\ i.\ if\ i{=}0\ then\ g \cdot t\ \hat{}\ 2/2 + s\ \$\ 1 \cdot t + s\ \$\ 0\ else\ g \cdot t + s$
$\$\ 1)$

lemma *local-flow-ball*: *local-flow* (*f g*) *UNIV UNIV* (φ *g*)
   apply(*unfold-locales*, *simp-all add*: *local-lipschitz-def lipschitz-on-def vec-eq-iff*,
clarsimp)
  apply(*rule-tac x=1/2* **in** *exI*, *clarsimp*, *rule-tac x=1* **in** *exI*)
  apply(*simp add*: *dist-norm norm-vec-def L2-set-def UNIV-2*)
   apply(*clarsimp*, *case-tac i = 0*)
  using *exhaust-2 two-eq-zero* **by** (*auto intro*!: *poly-derivatives*) *force*

lemma [*bb-real-arith*]:
assumes *invar*: $2 \cdot g \cdot x = 2 \cdot g \cdot h + v \cdot v$
and *pos*: $g \cdot \tau^2 \;/\; 2 + v \cdot \tau + (x{::}real) = 0$
shows $2 \cdot g \cdot h + (g \cdot \tau \cdot (g \cdot \tau + v) + v \cdot (g \cdot \tau + v)) = 0$
proof−
from *pos* **have** $g \cdot \tau^2 \; + 2 \cdot v \cdot \tau + 2 \cdot x = 0$ **by** *auto*
then have $g^2 \; \cdot \tau^2 \; + 2 \cdot g \cdot v \cdot \tau + 2 \cdot g \cdot x = 0$
by (*metis* (*mono-tags*, *hide-lams*) *Groups.mult-ac*(*1*,*3*) *mult-zero-right*
monoid-mult-class.power2-eq-square semiring-class.distrib-left)
hence $g^2 \cdot \tau^2 + 2 \cdot g \cdot v \cdot \tau + v^2 + 2 \cdot g \cdot h = 0$
using *invar* **by** (*simp add*: *monoid-mult-class.power2-eq-square*)
hence *obs*: $(g \cdot \tau + v)^2 + 2 \cdot g \cdot h = 0$
apply(*subst power2-sum*) **by** (*metis* (*no-types*, *hide-lams*) *Groups.add-ac*(*2*, *3*)

Groups.mult-ac(*2*, *3*) *monoid-mult-class.power2-eq-square nat-distrib*(*2*))
thus $2 \cdot g \cdot h + (g \cdot \tau \cdot (g \cdot \tau + v) + v \cdot (g \cdot \tau + v)) = 0$
by (*simp add*: *monoid-mult-class.power2-eq-square*)
have $2 \cdot g \cdot h + (-\; ((g \cdot \tau) + v))^2 = 0$
using *obs* **by** (*metis Groups.add-ac*(*2*) *power2-minus*)
qed

lemma [*bb-real-arith*]:
assumes *invar*: $2 \cdot g \cdot x = 2 \cdot g \cdot h + v \cdot v$
shows $2 \cdot g \cdot (g \cdot \tau^2 \;/\; 2 + v \cdot \tau + (x{::}real)) =$
$2 \cdot g \cdot h + (g \cdot \tau \cdot (g \cdot \tau + v) + v \cdot (g \cdot \tau + v))$ (**is** *?lhs* = *?rhs*)
proof−
have *?lhs* $= g^2 \cdot \tau^2 + 2 \cdot g \cdot v \cdot \tau + 2 \cdot g \cdot x$
apply(*subst Rat.sign-simps*(*18*))+
by(*auto simp*: *semiring-normalization-rules*(*29*))
also have ... $= g^2 \cdot \tau^2 + 2 \cdot g \cdot v \cdot \tau + 2 \cdot g \cdot h + v \cdot v$ (**is** ... = *?middle*)
by(*subst invar*, *simp*)
finally have *?lhs* = *?middle*.
moreover
{**have** *?rhs* $= g \cdot g \cdot (\tau \cdot \tau) + 2 \cdot g \cdot v \cdot \tau + 2 \cdot g \cdot h + v \cdot v$
by (*simp add*: *Groups.mult-ac*(*2*,*3*) *semiring-class.distrib-left*)
also have ... = *?middle*
by (*simp add*: *semiring-normalization-rules*(*29*))
finally have *?rhs* = *?middle*.}
ultimately show *?thesis* **by** *auto*
qed

lemma *bouncing-ball*:
fixes *h*::*real*
assumes $g < 0$ **and** $h \geq 0$
shows $g < 0 \Longrightarrow h \geq 0 \Longrightarrow$
$\lceil \lambda s.\; s \;\$\; 0 = h \wedge s \;\$\; 1 = 0 \rceil \leq wp$
(*LOOP*
$((x' = f\, g \;\&\; (\lambda\, s.\; s \;\$\; 0 \geq 0));$
(*IF* $(\lambda\, s.\; s \;\$\; 0 = 0)$ *THEN* $(1 ::= (\lambda s.\; -\; s \;\$\; 1))$ *ELSE skip*))

INV ($\lambda s.$ *0* $\leq$ *s* \$ *0* $\wedge$ *2* $\cdot$ *g* $\cdot$ *s* \$ *0* = *2* $\cdot$ *g* $\cdot$ *h* + *s* \$ *1* $\cdot$ *s* \$ *1*))
$\lceil\lambda s.$ *0* $\leq$ *s* \$ *0* $\wedge$ *s* \$ *0* $\leq$ *h*$\rceil$
apply(*rule wp-loopI*, *simp-all add*: *local-flow.wp-g-ode*[*OF local-flow-ball*])
by (*auto simp*: *bb-real-arith*)

— Verified as a linear system (computing exponential).

abbreviation *ball-sq-mtx* :: *3 sq-mtx* (*A*)
where *ball-sq-mtx* $\equiv$ *sq-mtx-chi* (χ *i*. *if i=0 then* e *1 else if i=1 then* e *2 else 0*)

lemma *ball-sq-mtx-pow2*: A^2 = *sq-mtx-chi* (χ *i*. *if i=0 then* e *2 else 0*)
unfolding *power2-eq-square times-sq-mtx-def*
by(*simp add*: *sq-mtx-chi-inject vec-eq-iff matrix-matrix-mult-def*)

lemma *ball-sq-mtx-powN*: *n* > *2* $\Longrightarrow$ ($\tau *_R A$) ˆ*n* = *0*
apply(*induct n*, *simp*, *case-tac n* $\leq$ *2*)
apply(*simp only*: *le-less-Suc-eq power-Suc*, *simp*)
by(*auto simp*: *ball-sq-mtx-pow2 sq-mtx-chi-inject vec-eq-iff*
times-sq-mtx-def zero-sq-mtx-def matrix-matrix-mult-def)

lemma *exp-ball-sq-mtx*: *exp* ($\tau *_R A$) = (($\tau *_R A)^2/_R$ *2*) + ($\tau *_R A$) + *1*
unfolding *exp-def* **apply**(*subst suminf-eq-sum*[*of 2*])
using *ball-sq-mtx-powN* **by** (*simp-all add*: *numeral-2-eq-2*)

lemma *exp-ball-sq-mtx-simps*:
exp ($\tau *_R A$) \$\$ *0* \$ *0* = *1* *exp* ($\tau *_R A$) \$\$ *0* \$ *1* = τ *exp* ($\tau *_R A$) \$\$ *0* \$ *2* = τˆ*2*/*2*
exp ($\tau *_R A$) \$\$ *1* \$ *0* = *0* *exp* ($\tau *_R A$) \$\$ *1* \$ *1* = *1* *exp* ($\tau *_R A$) \$\$ *1* \$ *2* = τ
exp ($\tau *_R A$) \$\$ *2* \$ *0* = *0* *exp* ($\tau *_R A$) \$\$ *2* \$ *1* = *0* *exp* ($\tau *_R A$) \$\$ *2* \$ *2* = *1*
unfolding *exp-ball-sq-mtx scaleR-power ball-sq-mtx-pow2*
by (*auto simp*: *plus-sq-mtx-def scaleR-sq-mtx-def one-sq-mtx-def*
mat-def scaleR-vec-def axis-def plus-vec-def)

lemma *bouncing-ball-sq-mtx*:
$\lceil\lambda s.$ *0* $\leq$ *s* \$ *0* $\wedge$ *s* \$ *0* = *h* $\wedge$ *s* \$ *1* = *0* $\wedge$ *0* > *s* \$ *2*$\rceil$ $\leq$ *wp*
(*LOOP*
((*x*´=($*_V$)*A* & (λ *s*. *s* \$ *0* $\geq$ *0*));
(*IF* (λ *s*. *s* \$ *0* = *0*) *THEN* (*1* ::= ($\lambda s.$ − *s* \$ *1*)) *ELSE skip*))
INV ($\lambda s.$ *0* $\leq$ *s*\$*0* $\wedge$ *0* > *s*\$*2* $\wedge$ *2* $\cdot$ *s*\$*2* $\cdot$ *s*\$*0* = *2* $\cdot$ *s*\$*2* $\cdot$ *h* + (*s*\$*1* $\cdot$ *s*\$*1*)))
$\lceil\lambda s.$ *0* $\leq$ *s* \$ *0* $\wedge$ *s* \$ *0* $\leq$ *h*$\rceil$
apply(*rule wp-loopI*, *simp-all add*: *local-flow.wp-g-ode*[*OF local-flow-exp*])
apply(*force simp*: *bb-real-arith*)
apply(*simp add*: *sq-mtx-vec-prod-eq*)
unfolding *UNIV-3* **apply**(*simp add*: *exp-ball-sq-mtx-simps*, *safe*)
using *bb-real-arith*(*2*) **apply**(*force simp*: *add.commute mult.commute*)
using *bb-real-arith*(*3*) **by** (*force simp*: *add.commute mult.commute*)

no-notation *fpend* (f)
  and *pend-flow* (φ)
  and *ball-sq-mtx* (A)

end

7.4 VC_diffKAD

theory *VC-diffKAD-auxiliarities*
imports
Main
../afpModified/VC-KAD
Ordinary-Differential-Equations.ODE-Analysis

begin

7.4.1 Stack Theories Preliminaries: VC_KAD and ODEs

To make our notation less code-like and more mathematical we declare:

no-notation *Archimedean-Field.ceiling* ($\lceil$-$\rceil$)
 and *Archimedean-Field.floor* ($\lfloor$-$\rfloor$)
 and *Set.image* (`)
 and *Range-Semiring.antirange-semiring-class.ars-r* (r)

notation *p2r* ($\lceil$-$\rceil$)
 and *r2p* ($\lfloor$-$\rfloor$)
 and *Set.image* (-(|-|))
 and *Product-Type.prod.fst* (π_1)
 and *Product-Type.prod.snd* (π_2)
 and *List.zip* (**infixl** $\otimes$ *63*)
 and *rel-ad* ($\Delta^c{}_1$)

This and more notation is explained by the following lemmata.

lemma shows $\lceil P\rceil = \{(s, s) \mid s.\ P\ s\}$
 and $\lfloor R\rfloor = (\lambda x.\ x \in r2s\ R)$
 and $r2s\ R = \{x \mid x.\ \exists\ y.\ (x,y) \in R\}$
 and $\pi_1\ (x,y) = x \wedge \pi_2\ (x,y) = y$
 and $\Delta^c{}_1\ R = \{(x, x) \mid x.\ \nexists y.\ (x, y) \in R\}$
 and $wp\ R\ Q = \Delta^c{}_1\ (R\ ;\ \Delta^c{}_1\ Q)$
 and $[x1,x2,x3,x4] \otimes [y1,y2] = [(x1,y1),(x2,y2)]$
 and $\{a..b\} = \{x.\ a \le x \wedge x \le b\}$
 and $\{a<..<b\} = \{x.\ a < x \wedge x < b\}$
 and $(x\ solves\text{-}ode\ f)\ \{0..t\}\ R = ((x\ has\text{-}vderiv\text{-}on\ (\lambda t.\ f\ t\ (x\ t)))\ \{0..t\} \wedge x \in \{0..t\} \to R)$
 and $f \in A \to B = (f \in \{f.\ \forall\ x.\ x \in A \longrightarrow (f\ x) \in B\})$
 and $(x\ has\text{-}vderiv\text{-}on\ x')\{0..t\} =$
  $(\forall r{\in}\{0..t\}.\ (x\ has\text{-}vector\text{-}derivative\ x'\ r)\ (at\ r\ within\ \{0..t\}))$
 and $(x\ has\text{-}vector\text{-}derivative\ x'\ r)\ (at\ r\ within\ \{0..t\}) =$

$(x$ *has-derivative* $(\lambda x.\ x *_R x'\ r))$ $(at\ r\ within\ \{0..t\})$
apply(*simp-all add*: *p2r-def r2p-def rel-ad-def rel-antidomain-kleene-algebra.fbox-def*

solves-ode-def has-vderiv-on-def)
apply(*blast*, *fastforce*, *fastforce*)
using *has-vector-derivative-def* **by** *auto*

Observe also, the following consequences and facts:

proposition $\pi_1 (\!| R |\!) = r2s\ R$
by (*simp add*: *fst-eq-Domain*)

proposition $\Delta^c{}_1\ R = Id - \{(s,\ s)\ |s.\ s \in (\pi_1 (\!| R |\!))\}$
by(*simp add*: *image-def rel-ad-def*, *fastforce*)

proposition $P \subseteq Q \Longrightarrow wp\ R\ P \subseteq wp\ R\ Q$
by(*simp add*: *rel-antidomain-kleene-algebra.dka.dom-iso rel-antidomain-kleene-algebra.fbox-iso*)

proposition *boxProgrPred-IsProp*: $wp\ R\ \lceil P \rceil \subseteq Id$
by(*simp add*: *rel-antidomain-kleene-algebra.a-subid′ rel-antidomain-kleene-algebra.addual.bbox-def*)

proposition *rdom-p2r-contents*:$(a,\ b) \in rdom\ \lceil P \rceil = ((a = b) \wedge P\ a)$
proof−
have $(a,\ b) \in rdom\ \lceil P \rceil = ((a = b) \wedge (a,\ a) \in rdom\ \lceil P \rceil)$ **using** *p2r-subid* **by** *fastforce*
also have ... $= ((a = b) \wedge (a,\ a) \in \lceil P \rceil)$ **by** *simp*
also have ... $= ((a = b) \wedge P\ a)$ **by** (*simp add*: *p2r-def*)
ultimately show *?thesis* **by** *simp*
qed

~~..Should not add these complement-rule's to simp..~~
proposition *rel-ad-rule1*: $(x,x) \notin \Delta^c{}_1\ \lceil P \rceil \Longrightarrow P\ x$
by(*auto simp*: *rel-ad-def p2r-subid p2r-def*)

proposition *rel-ad-rule2*: $(x,x) \in \Delta^c{}_1\ \lceil P \rceil \Longrightarrow \neg\ P\ x$
by(*metis ComplD VC-KAD.p2r-neg-hom rel-ad-rule1 empty-iff mem-Collect-eq p2s-neg-hom*

rel-antidomain-kleene-algebra.a-one rel-antidomain-kleene-algebra.am1 relcomp.relcompI)

proposition *rel-ad-rule3*: $R \subseteq Id \Longrightarrow (x,x) \notin R \Longrightarrow (x,x) \in \Delta^c{}_1\ R$
by(*metis IdI Un-iff d-p2r rel-antidomain-kleene-algebra.addual.ars3*
rel-antidomain-kleene-algebra.addual.ars-r-def rpr)

proposition *rel-ad-rule4*: $(x,x) \in R \Longrightarrow (x,x) \notin \Delta^c{}_1\ R$
by(*metis empty-iff rel-antidomain-kleene-algebra.addual.ars1 relcomp.relcompI*)

proposition *boxProgrPred-chrctrztn*:$(x,x) \in wp\ R\ \lceil P \rceil = (\forall\ y.\ (x,y) \in R \longrightarrow P\ y)$
by(*metis boxProgrPred-IsProp rel-ad-rule1 rel-ad-rule2 rel-ad-rule3*
rel-ad-rule4 d-p2r wp-simp wp-trafo)

lemma (**in** *antidomain-kleene-algebra*) *fbox-starI*:
assumes $d\ p \leq d\ i$ **and** $d\ i \leq |x]\ i$ **and** $d\ i \leq d\ q$
shows $d\ p \leq |x^\star]\ q$
proof−
from ‹$d\ i \leq |x]\ i$› **have** $d\ i \leq |x]\ (d\ i)$
  using *local.fbox-simp* **by** *auto*
hence $|1]\ p \leq |x^\star]\ i$ **using** ‹$d\ p \leq d\ i$› **by** (*metis* (*no-types*)
  local.dual-order.trans local.fbox-one local.fbox-simp local.fbox-star-induct-var)
thus *?thesis* **using** ‹$d\ i \leq d\ q$› **by** (*metis* (*full-types*)
  local.fbox-mult local.fbox-one local.fbox-seq-var local.fbox-simp)
qed

proposition *cons-eq-zipE*:
(x, y) # *tail* = *xList* ⊗ *yList* ⟹ ∃ *xTail yTail*. *x* # *xTail* = *xList* ∧ *y* # *yTail* = *yList*
by(*induction xList*, *simp-all*, *induction yList*, *simp-all*)

proposition *set-zip-left-rightD*:
$(x, y) \in$ *set* (*xList* ⊗ *yList*) ⟹ $x \in$ *set xList* ∧ $y \in$ *set yList*
apply(*rule conjI*)
apply(*rule-tac y=y* **and** *ys=yList* **in** *set-zip-leftD*, *simp*)
apply(*rule-tac x=x* **and** *xs=xList* **in** *set-zip-rightD*, *simp*)
done

declare *zip-map-fst-snd* [*simp*]

7.4.2 VC_diffKAD Preliminaries

In dL, the set of possible program variables is split in two, the set of variables V and their primed counterparts V'. To implement this, we use Isabelle's string-type and define a function that primes a given string. We then define the set of primed-strings based on it.

definition *vdiff* ::*string* ⇒ *string* (∂ - [*55*] *70*) **where**
(∂ *x*) = ″*d*[″@*x*@″]″

definition *varDiffs* :: *string set* **where**
varDiffs = {*y*. ∃ *x*. *y* = ∂ *x*}

proposition *vdiff-inj*:(∂ *x*) = (∂ *y*) ⟹ *x* = *y*
by(*simp add*: *vdiff-def*)

proposition *vdiff-noFixPoints*:*x* ≠ (∂ *x*)
by(*simp add*: *vdiff-def*)

lemma *varDiffsI*:*x* = (∂ *z*) ⟹ *x* ∈ *varDiffs*
by(*simp add*: *varDiffs-def vdiff-def*)

lemma *varDiffsE*:
assumes $x \in$ *varDiffs*
obtains y **where** $x = ''d[''@y@'']''$
using *assms* **unfolding** *varDiffs-def vdiff-def* **by** *auto*

proposition *vdiff-invarDiffs*:(∂ x) $\in$ *varDiffs*
by (*simp add*: *varDiffsI*)

(primed) dSolve preliminaries

This subsubsection is to define a function that takes a system of ODEs (expressed as a list $xfList$), a presumed solution $uInput = [u_1, \ldots, u_n]$, a state s and a time t, and outputs the induced flow $sol\, s[xfList \leftarrow uInput]\, t$.

abbreviation *varDiffs-to-zero* ::*real store* $\Rightarrow$ *real store* (*sol*) **where**
sol a $\equiv$ (*override-on a* (λ *x*. *0*) *varDiffs*)

proposition *varDiffs-to-zero-vdiff*[*simp*]: (*sol s*) (∂ *x*) = *0*
apply(*simp add*: *override-on-def varDiffs-def*)
by *auto*

proposition *varDiffs-to-zero-beginning*[*simp*]: *take 2 x* $\neq$ $''d[''$ $\Longrightarrow$ (*sol s*) *x* = *s*
x
apply(*simp add*: *varDiffs-def override-on-def vdiff-def*)
by *fastforce*

— Next, for each entry of the input-list, we update the state using said entry.

definition *vderiv-of f S* = (*SOME f'*. (*f has-vderiv-on f'*) *S*)

primrec *state-list-upd* :: ((*real* $\Rightarrow$ *real store* $\Rightarrow$ *real*) $\times$ *string* $\times$ (*real store* $\Rightarrow$
real)) *list* $\Rightarrow$
real $\Rightarrow$ *real store* $\Rightarrow$ *real store* **where**
state-list-upd [] *t s* = *s*|
state-list-upd (*uxf* # *tail*) *t s* = (*state-list-upd tail t s*)
((π_1 (π_2 *uxf*)) := (π_1 *uxf*) *t s*,
∂ (π_1 (π_2 *uxf*)) := (*if t* = *0 then* (π_2 (π_2 *uxf*)) *s*
else vderiv-of (λ *r*. (π_1 *uxf*) *r s*) {*0*<..< (*2* $*_R$ *t*)} *t*))

abbreviation *state-list-cross-upd* ::*real store* $\Rightarrow$ (*string* $\times$ (*real store* $\Rightarrow$ *real*)) *list*
$\Rightarrow$
(*real* $\Rightarrow$ *real store* $\Rightarrow$ *real*) *list* $\Rightarrow$ *real* $\Rightarrow$ (*char list* $\Rightarrow$ *real*) (-[-$\leftarrow$-] - [*64*,*64*,*64*]
63) **where**
s[*xfList*$\leftarrow$*uInput*] *t* $\equiv$ *state-list-upd* (*uInput* $\otimes$ *xfList*) *t s*

proposition *state-list-cross-upd-empty*[*simp*]: (*s*[[]$\leftarrow$*list*] *t*) = *s*
by(*induction list*, *simp-all*)

lemma *inductive-state-list-cross-upd-its-vars*:
assumes *distHyp*:*distinct* (*map* π_1 ((*y*, *g*) # *xftail*))

and *varHyp*:$\forall\, xf \in set((y,\ g)\ \#\ xftail).\ \pi_1\ xf \notin varDiffs$
and *indHyp*:$(u,\ x,\ f) \in set\ (utail \otimes xftail) \Longrightarrow (s[xftail \leftarrow utail]\ t)\ x = u\ t\ s$
and *disjHyp*:$(u,\ x,\ f) = (v,\ y,\ g) \vee (u,\ x,\ f) \in set\ (utail \otimes xftail)$
shows $(s[(y,\ g)\ \#\ xftail \leftarrow v\ \#\ utail]\ t)\ x = u\ t\ s$
using *disjHyp* **proof**
  assume $(u,\ x,\ f) = (v,\ y,\ g)$
  hence $(s[(y,\ g)\ \#\ xftail \leftarrow v\ \#\ utail]\ t)\ x = ((s[xftail \leftarrow utail]\ t)(x := u\ t\ s,$
  $\partial\ x := if\ t = 0\ then\ f\ s\ else\ vderiv\text{-}of\ (\lambda\ r.\ u\ r\ s)\ \{0 <..< (2 *_R t)\}\ t))\ x$ **by**
simp
  also have ... $= u\ t\ s$ **by** (*simp add*: *vdiff-def*)
  ultimately show *?thesis* **by** *simp*
next
  assume *yTailHyp*:$(u,\ x,\ f) \in set\ (utail \otimes xftail)$
  from *this* **and** *indHyp* **have** *3*:$(s[xftail \leftarrow utail]\ t)\ x = u\ t\ s$ **by** *fastforce*
  from *yTailHyp* **and** *distHyp* **have** *2*:$y \neq x$ **using** *set-zip-left-rightD* **by** *force*
  from *yTailHyp* **and** *varHyp* **have** *1*:$x \neq \partial\ y$
  using *set-zip-left-rightD vdiff-invarDiffs* **by** *fastforce*
  from *1* **and** *2* **have** $(s[(y,\ g)\ \#\ xftail \leftarrow v\ \#\ utail]\ t)\ x = (s[xftail \leftarrow utail]\ t)\ x$
by *simp*
  thus *?thesis* **using** *3* **by** *simp*
qed

theorem *state-list-cross-upd-its-vars*:
assumes *distinctHyp*:*distinct* $(map\ \pi_1\ xfList)$
and *lengthHyp*:$length\ xfList = length\ uInput$
and *varsHyp*:$\forall\ xf \in set\ xfList.\ \pi_1\ xf \notin varDiffs$
and *its-var*: $(u,x,f) \in set\ (uInput \otimes xfList)$
shows $(s[xfList \leftarrow uInput]\ t)\ x = u\ t\ s$
using *assms* **apply**(*induct xfList uInput arbitrary*: *x rule*: *list-induct2′*, *simp*,
simp, *simp*)
by(*clarify*, *rule inductive-state-list-cross-upd-its-vars*, *simp-all*)

lemma *override-on-upd*:$x \in X \Longrightarrow (override\text{-}on\ f\ g\ X)(x := z) = (override\text{-}on\ f$
$(g(x := z))\ X)$
by (*rule ext*, *simp add*: *override-on-def*)

lemma *inductive-state-list-cross-upd-its-dvars*:
assumes $\exists\, g.\ (s[xfTail \leftarrow uTail]\ 0) = override\text{-}on\ s\ g\ varDiffs$
and $\forall\, xf \in set\ (xf\ \#\ xfTail).\ \pi_1\ xf \notin varDiffs$
and $\forall\, uxf \in set\ (u\ \#\ uTail \otimes xf\ \#\ xfTail).\ \pi_1\ uxf\ 0\ s = s\ (\pi_1\ (\pi_2\ uxf))$
shows $\exists\, g.\ (s[xf\ \#\ xfTail \leftarrow u\ \#\ uTail]\ 0) = override\text{-}on\ s\ g\ varDiffs$
proof−
let $?gLHS = (s[(xf\ \#\ xfTail) \leftarrow (u\ \#\ uTail)]\ 0)$
have *observ*:$\partial\ (\pi_1\ xf) \in varDiffs$ **by** (*auto simp*: *varDiffs-def*)
from *assms*(*1*) **obtain** *g* **where** $(s[xfTail \leftarrow uTail]\ 0) = override\text{-}on\ s\ g\ varDiffs$
by *force*
then have $?gLHS = (override\text{-}on\ s\ g\ varDiffs)(\pi_1\ xf := u\ 0\ s,\ \partial\ (\pi_1\ xf) := \pi_2$
$xf\ s)$ **by** *simp*
also have $\ldots = (override\text{-}on\ s\ g\ varDiffs)(\partial\ (\pi_1\ xf) := \pi_2\ xf\ s)$

using *override-on-def varDiffs-def assms* **by** *auto*
also have ... = (*override-on s* (*g*(∂ (π_1 *xf*) := π_2 *xf s*)) *varDiffs*)
using *observ* **and** *override-on-upd* **by** *force*
ultimately show *?thesis* **by** *auto*
qed

theorem *state-list-cross-upd-its-dvars*:
assumes *lengthHyp*:*length xfList* = *length uInput*
and *varsHyp*:∀ *xf* ∈ *set xfList*. π_1 *xf* ∉ *varDiffs*
and *solHyp1*:∀ *uxf*∈*set* (*uInput* ⊗ *xfList*). (π_1 *uxf*) *0 s* = *s* (π_1 (π_2 *uxf*))
shows ∃ *g*. (*s*[*xfList*←*uInput*] *0*) = (*override-on s g varDiffs*)
using *assms* **proof**(*induct xfList uInput rule*: *list-induct2'*)
case *1*
  have (*s*[[]←[]] *0*) = *override-on s s varDiffs*
  unfolding *override-on-def* **by** *simp*
  thus *?case* **by** *metis*
next
  case (*2 xf xfTail*)
  have (*s*[(*xf* # *xfTail*)←[]] *0*) = *override-on s s varDiffs*
  unfolding *override-on-def* **by** *simp*
  thus *?case* **by** *metis*
next
  case (*3 u utail*)
  have (*s*[[]←*utail*] *0*) = *override-on s s varDiffs*
  unfolding *override-on-def* **by** *simp*
  thus *?case* **by** *force*
next
  case (*4 xf xfTail u uTail*)
  then have ∃ *g*. (*s*[*xfTail*←*uTail*] *0*) = *override-on s g varDiffs* **by** *simp*
  thus *?case* **using** *inductive-state-list-cross-upd-its-dvars 4.prems* **by** *blast*
qed

lemma *vderiv-unique-within-open-interval*:
assumes (*f has-vderiv-on f'*) {*0*<..< *t*} **and** *t*>*0*
    and (*f has-vderiv-on f''*){*0*<..< *t*} **and** *tauHyp*:τ ∈ {*0*<..< *t*}
shows *f'* τ = *f''* τ
using *assms* **apply**(*simp add*: *has-vderiv-on-def has-vector-derivative-def*)
using *frechet-derivative-unique-within-open-interval* **by** (*metis box-real*(*1*) *scaleR-one tauHyp*)

lemma *has-vderiv-on-cong-open-interval*:
assumes *gHyp*:∀ τ > *0*. *f* τ = *g* τ **and** *tHyp*: *t*>*0*
and *fHyp*:(*f has-vderiv-on f'*) {*0*<..<*t*}
shows (*g has-vderiv-on f'*) {*0*<..<*t*}
proof−
from *gHyp* **have** ⋀τ. τ ∈ {*0*<..< *t*} ⟹ *f* τ = *g* τ **using** *tHyp* **by** *force*
hence *eqDs*:(*f has-vderiv-on f'*) {*0*<..<*t*} = (*g has-vderiv-on f'*) {*0*<..<*t*}
apply(*rule-tac has-vderiv-on-cong*) **by** *auto*
thus (*g has-vderiv-on f'*) {*0*<..<*t*} **using** *eqDs fHyp* **by** *simp*

qed

lemma *closed-vderiv-on-cong-to-open-vderiv*:
assumes *gHyp*:$\forall\ \tau > 0.\ f\ \tau = g\ \tau$
and *fHyp*:$\forall\, t \geq 0.\ (f\ \textit{has-vderiv-on}\ f')\ \{0..t\}$
and *tHyp*: $t>0$ **and** *cHyp*: $c > 1$
shows $\textit{vderiv-of}\ g\ \{0<..<\ (c *_R\ t)\}\ t = f'\ t$
proof−
have *ctHyp*:$c \cdot t > 0$ **using** *tHyp* **and** *cHyp* **by** *auto*
from *fHyp* **have** $(f\ \textit{has-vderiv-on}\ f')\ \{0<..<c \cdot t\}$ **using** *has-vderiv-on-subset*
by (*metis greaterThanLessThan-subseteq-atLeastAtMost-iff less-eq-real-def*)
then have *derivHyp*:$(g\ \textit{has-vderiv-on}\ f')\ \{0<..<c \cdot t\}$
using *gHyp ctHyp* **and** *has-vderiv-on-cong-open-interval* **by** *blast*
hence *f'Hyp*:$\forall\ f''.\ (g\ \textit{has-vderiv-on}\ f'')\ \{0<..<c \cdot t\} \longrightarrow (\forall\ \tau \in \{0<..<\ c \cdot t\}.$
$f'\ \tau = f''\ \tau)$
using *vderiv-unique-within-open-interval ctHyp* **by** *blast*
also have $(g\ \textit{has-vderiv-on}\ (\textit{vderiv-of}\ g\ \{0<..<\ (c *_R\ t)\}))\ \{0<..<c \cdot t\}$
by(*simp add*: *vderiv-of-def*, *metis derivHyp someI-ex*)
ultimately show$\textit{vderiv-of}\ g\ \{0<..<c *_R\ t\}\ t = f'\ t$ **using** *tHyp cHyp* **by** *force*
qed

lemma *vderiv-of-to-sol-its-vars*:
assumes *distinctHyp*:$\textit{distinct}\ (\textit{map}\ \pi_1\ \textit{xfList})$
and *lengthHyp*:$\textit{length xfList} = \textit{length uInput}$
and *varsHyp*:$\forall\ xf \in \textit{set xfList}.\ \pi_1\ xf \notin \textit{varDiffs}$
and *solHyp2*:$\forall\, t \geq 0.\ ((\lambda\tau.\ (\textit{sol}\ s[\textit{xfList} \leftarrow \textit{uInput}]\ \tau)\ x)$
$\textit{has-vderiv-on}\ (\lambda\tau.\ f\ (\textit{sol}\ s[\textit{xfList} \leftarrow \textit{uInput}]\ \tau)))\ \{0..t\}$
and *tHyp*: $t>0$ **and** *uxfHyp*:$(u,\ x,\ f) \in \textit{set}\ (\textit{uInput} \otimes \textit{xfList})$
shows $\textit{vderiv-of}\ (\lambda\tau.\ u\ \tau\ (\textit{sol}\ s))\ \{0<..<\ (2 *_R\ t)\}\ t = f\ (\textit{sol}\ s[\textit{xfList} \leftarrow \textit{uInput}]$
$t)$
apply(*rule-tac* $f = (\lambda\tau.\ (\textit{sol}\ s[\textit{xfList} \leftarrow \textit{uInput}]\ \tau)\ x)$ **in** *closed-vderiv-on-cong-to-open-vderiv*)
subgoal using *assms* **and** *state-list-cross-upd-its-vars* **by** *metis*
by(*simp-all add*: *solHyp2 tHyp*)

lemma *inductive-to-sol-zero-its-dvars*:
assumes *eqFuncs*:$\forall\ s.\ \forall\, g.\ \forall\, xf \in \textit{set}\ ((x,\ f)\ \#\ \textit{xfs}).\ \pi_2\ xf\ (\textit{override-on}\ s\ g\ \textit{varDiffs})$
$= \pi_2\ xf\ s$
and *eqLengths*:$\textit{length}\ ((x,\ f)\ \#\ \textit{xfs}) = \textit{length}\ (u\ \#\ us)$
and *distinct*:$\textit{distinct}\ (\textit{map}\ \pi_1\ ((x,\ f)\ \#\ \textit{xfs}))$
and *vars*:$\forall\, xf \in \textit{set}\ ((x,\ f)\ \#\ \textit{xfs}).\ \pi_1\ xf \notin \textit{varDiffs}$
and *solHyp1*:$\forall\, uxf \in \textit{set}\ ((u\ \#\ us) \otimes ((x,\ f)\ \#\ \textit{xfs})).\ \pi_1\ uxf\ 0\ (\textit{sol}\ s) = \textit{sol}\ s\ (\pi_1$
$(\pi_2\ uxf))$
and *disjHyp*:$(y,\ g) = (x,\ f) \vee (y,\ g) \in \textit{set xfs}$
and *indHyp*:$(y,\ g) \in \textit{set xfs} \Longrightarrow (\textit{sol}\ s[\textit{xfs} \leftarrow us]\ 0)\ (\partial\ y) = g\ (\textit{sol}\ s[\textit{xfs} \leftarrow us]\ 0)$
shows $(\textit{sol}\ s[(x,\ f)\ \#\ \textit{xfs} \leftarrow u\ \#\ us]\ 0)\ (\partial\ y) = g\ (\textit{sol}\ s[(x,\ f)\ \#\ \textit{xfs} \leftarrow u\ \#\ us]\ 0)$
proof−
from *assms* **obtain** *h1* **where** *h1Def*:$(\textit{sol}\ s[((x,\ f)\ \#\ \textit{xfs}) \leftarrow (u\ \#\ us)]\ 0) =$
$(\textit{override-on}\ (\textit{sol}\ s)\ h1\ \textit{varDiffs})$ **using** *state-list-cross-upd-its-dvars* **by** *blast*
from *disjHyp* **show** $(\textit{sol}\ s[(x,\ f)\ \#\ \textit{xfs} \leftarrow u\ \#\ us]\ 0)\ (\partial\ y) = g\ (\textit{sol}\ s[(x,\ f)\ \#$

xfs←*u* # *us*] *0*)
proof
  assume *eqHeads*:$(y,\ g) = (x,\ f)$
  then have *g* (*sol s*[(*x*, *f*) # *xfs*←*u* # *us*] *0*) = *f* (*sol s*) **using** *h1Def eqFuncs* **by** *simp*
  also have ... = (*sol s*[(*x*, *f*) # *xfs*←*u* # *us*] *0*) (∂ *y*) **using** *eqHeads* **by** *auto*
  ultimately show *?thesis* **by** *linarith*
next
  assume *tailHyp*:(*y*, *g*) ∈ *set xfs*
  then have $y \neq x$ **using** *distinct set-zip-left-rightD* **by** *force*
  hence $\partial\ x \neq \partial\ y$ **by**(*simp add*: *vdiff-def*)
  have $x \neq \partial\ y$ **using** *vars vdiff-invarDiffs* **by** *auto*
  obtain *h2* **where** *h2Def*:(*sol s*[*xfs*←*us*] *0*) = *override-on* (*sol s*) *h2 varDiffs*
  using *state-list-cross-upd-its-dvars eqLengths distinct vars* **and** *solHyp1* **by** *force*
  have (*sol s*[(*x*, *f*) # *xfs*←*u* # *us*] *0*) (∂ *y*) = *g* (*sol s*[*xfs*←*us*] *0*)
  using *tailHyp indHyp* ‹$x \neq \partial\ y$› **and** ‹$\partial\ x \neq \partial\ y$› **by** *simp*
  also have ... = *g* (*override-on* (*sol s*) *h2 varDiffs*) **using** *h2Def* **by** *simp*
  also have ... = *g* (*sol s*) **using** *eqFuncs* **and** *tailHyp* **by** *force*
  also have ... = *g* (*sol s*[(*x*, *f*) # *xfs*←*u* # *us*] *0*)
  using *eqFuncs h1Def tailHyp* **and** *eq-snd-iff* **by** *fastforce*
  ultimately show *?thesis* **by** *simp*
  qed
qed

lemma *to-sol-zero-its-dvars*:
assumes *funcsHyp*:∀ *s*. ∀ *g*. ∀ *xf* ∈ *set xfList*. π_2 *xf* (*override-on s g varDiffs*) = π_2 *xf s*
and *distinctHyp*:*distinct* (*map* π_1 *xfList*)
and *lengthHyp*:*length xfList* = *length uInput*
and *varsHyp*:∀ *xf* ∈ *set xfList*. π_1 *xf* ∉ *varDiffs*
and *solHyp1*:∀ *uxf* ∈ *set* (*uInput* ⊗ *xfList*). (π_1 *uxf*) *0* (*sol s*) = (*sol s*) (π_1 (π_2 *uxf*))
and *ygHyp*:(*y*, *g*) ∈ *set xfList*
shows (*sol s*[*xfList*←*uInput*] *0*)(∂ *y*) = *g* (*sol s*[*xfList*←*uInput*] *0*)
using *assms* **apply**(*induct xfList uInput rule*: *list-induct2′*, *simp*, *simp*, *simp*, *clarify*)
by(*rule inductive-to-sol-zero-its-dvars*, *simp-all*)

lemma *inductive-to-sol-greater-than-zero-its-dvars*:
assumes *lengthHyp*:*length* ((*y*, *g*) # *xfs*) = *length* (*v* # *vs*)
and *distHyp*:*distinct* (*map* π_1 ((*y*, *g*) # *xfs*))
and *varHyp*: ∀ *xf*∈*set* ((*y*, *g*) # *xfs*). π_1 *xf* ∉ *varDiffs*
and *indHyp*:(*u*,*x*,*f*) ∈ *set* (*vs* ⊗ *xfs*) ⟹ (*s*[*xfs*←*vs*]*t*)(∂ *x*) = *vderiv-of* (λ*r*. *u r s*) {*0*<..<*2*$*_R$*t*} *t*
and *disjHyp*:(*v*, *y*, *g*) = (*u*, *x*, *f*) ∨ (*u*, *x*, *f*) ∈ *set* (*vs* ⊗ *xfs*) **and** *tHyp*:$t > 0$
shows (*s*[(*y*, *g*) # *xfs*←*v* # *vs*] *t*) (∂ *x*) = *vderiv-of* (λ*r*. *u r s*) {*0*<..<*2* $*_R$ *t*} *t*
proof−
let *?lhs* = ((*s*[*xfs*←*vs*] *t*)(*y* := *v t s*, ∂ *y* := *vderiv-of* (λ *r*. *v r s*) {*0*<..< (*2* · *t*)} *t*)) (∂ *x*)

let *?rhs* = *vderiv-of* ($\lambda r.$ *u r s*) {*0<..<* (*2* $\cdot$ *t*)} *t*
have (*s*[(*y*, *g*) # *xfs*$\leftarrow$*v* # *vs*] *t*) (∂ *x*) = *?lhs* **using** *tHyp* **by** *simp*
also have *vderiv-of* ($\lambda r.$ *u r s*) {*0<..<2* $*_R$ *t*} *t* =*?rhs* **by** *simp*
ultimately have *obs*:*?thesis* = (*?lhs* = *?rhs*) **by** *simp*
from *disjHyp* **have** *?lhs* = *?rhs*
proof
  assume *uxfEq*:(*v*, *y*, *g*) = (*u*, *x*, *f*)
  then have *?lhs* = *vderiv-of* (λ *r*. *u r s*) {*0<..<* (*2* $\cdot$ *t*)} *t* **by** *simp*
  also have *vderiv-of* (λ *r*. *u r s*) {*0<..<* (*2* $\cdot$ *t*)} *t* = *?rhs* **using** *uxfEq* **by** *simp*
  ultimately show *?lhs* = *?rhs* **by** *simp*
next
  assume *sygTail*:(*u*, *x*, *f*) $\in$ *set* (*vs* $\otimes$ *xfs*)
  from *this* **have** $y \neq x$ **using** *distHyp set-zip-left-rightD* **by** *force*
  hence $\partial\ x \neq \partial\ y$ **by**(*simp add*: *vdiff-def*)
  have $y \neq \partial\ x$ **using** *varHyp* **using** *vdiff-invarDiffs* **by** *auto*
  then have *?lhs* = (*s*[*xfs*$\leftarrow$*vs*] *t*) (∂ *x*) **using** ‹$y \neq \partial\ x$› **and** ‹$\partial\ x \neq \partial\ y$› **by** *simp*
  also have (*s*[*xfs*$\leftarrow$*vs*] *t*) (∂ *x*) = *?rhs* **using** *indHyp sygTail* **by** *simp*
  ultimately show *?lhs* = *?rhs* **by** *simp*
qed
from *this* **and** *obs* **show** *?thesis* **by** *simp*
qed

lemma *to-sol-greater-than-zero-its-dvars*:
assumes *distinctHyp*:*distinct* (*map* π_1 *xfList*)
and *lengthHyp*:*length xfList* = *length uInput*
and *varsHyp*:$\forall$ *xf* $\in$ *set xfList*. π_1 *xf* $\notin$ *varDiffs*
and *uxfHyp*:(*u*, *x*, *f*) $\in$ *set* (*uInput* $\otimes$ *xfList*) **and** *tHyp*:*t* > *0*
shows (*s*[*xfList*$\leftarrow$*uInput*] *t*) (∂ *x*) = *vderiv-of* (λ *r*. *u r s*) {*0<..<* (*2* $*_R$ *t*)} *t*
using *assms* **apply**(*induct xfList uInput rule*: *list-induct2'*, *simp*, *simp*, *simp*, *clarify*)
by(*rule-tac f=f* **in** *inductive-to-sol-greater-than-zero-its-dvars*, *auto*)

dInv preliminaries

Here, we introduce syntactic notation to talk about differential invariants.

no-notation *Antidomain-Semiring.antidomain-left-monoid-class.am-add-op* (**infixl** $\oplus$ *65*)
no-notation *Dioid.times-class.opp-mult* (**infixl** $\odot$ *70*)
no-notation *Lattices.inf-class.inf* (**infixl** $\sqcap$ *70*)
no-notation *Lattices.sup-class.sup* (**infixl** $\sqcup$ *65*)

datatype *trms* = *Const real* (t_C - [*54*] *70*) | *Var string* (t_V - [*54*] *70*) |
    Mns trms ($\ominus$ - [*54*] *65*) | *Sum trms trms* (**infixl** $\oplus$ *65*) |
    Mult trms trms (**infixl** $\odot$ *68*)

primrec *tval* ::*trms* $\Rightarrow$ (*real store* $\Rightarrow$ *real*) ((*1*$[\![$ - $]\!]_t$)) **where**
$[\![t_C\ r]\!]_t = (\lambda\ s.\ r)$|
$[\![t_V\ x]\!]_t = (\lambda\ s.\ s\ x)$|
$[\![\ominus\ \vartheta]\!]_t = (\lambda\ s.\ -\ ([\![\vartheta]\!]_t)\ s)$|

$[\![\vartheta \oplus \eta]\!]_t = (\lambda\ s.\ ([\![\vartheta]\!]_t)\ s + ([\![\eta]\!]_t)\ s)|$
$[\![\vartheta \odot \eta]\!]_t = (\lambda\ s.\ ([\![\vartheta]\!]_t)\ s \cdot ([\![\eta]\!]_t)\ s)$

datatype *props* = *Eq trms trms* (**infixr** $\doteq$ *60*) | *Less trms trms* (**infixr** $\prec$ *62*) |
Leq trms trms (**infixr** $\preceq$ *61*) | *And props props* (**infixl** $\sqcap$ *63*) |
Or props props (**infixl** $\sqcup$ *64*)

primrec *pval* ::*props* $\Rightarrow$ (*real store* $\Rightarrow$ *bool*) ((*1*$[\![$-$]\!]_P$)) **where**
$[\![\vartheta \doteq \eta]\!]_P = (\lambda\ s.\ ([\![\vartheta]\!]_t)\ s = ([\![\eta]\!]_t)\ s)|$
$[\![\vartheta \prec \eta]\!]_P = (\lambda\ s.\ ([\![\vartheta]\!]_t)\ s < ([\![\eta]\!]_t)\ s)|$
$[\![\vartheta \preceq \eta]\!]_P = (\lambda\ s.\ ([\![\vartheta]\!]_t)\ s \leq ([\![\eta]\!]_t)\ s)|$
$[\![\varphi \sqcap \psi]\!]_P = (\lambda\ s.\ ([\![\varphi]\!]_P)\ s \wedge ([\![\psi]\!]_P)\ s)|$
$[\![\varphi \sqcup \psi]\!]_P = (\lambda\ s.\ ([\![\varphi]\!]_P)\ s \vee ([\![\psi]\!]_P)\ s)$

primrec *tdiff* ::*trms* $\Rightarrow$ *trms* (∂_t - [*54*] *70*) **where**
$(\partial_t\ t_C\ r) = t_C\ 0|$
$(\partial_t\ t_V\ x) = t_V\ (\partial\ x)|$
$(\partial_t \ominus \vartheta) = \ominus\ (\partial_t\ \vartheta)|$
$(\partial_t\ (\vartheta \oplus \eta)) = (\partial_t\ \vartheta) \oplus (\partial_t\ \eta)|$
$(\partial_t\ (\vartheta \odot \eta)) = ((\partial_t\ \vartheta) \odot \eta) \oplus (\vartheta \odot (\partial_t\ \eta))$

primrec *pdiff* ::*props* $\Rightarrow$ *props* (∂_P - [*54*] *70*) **where**
$(\partial_P\ (\vartheta \doteq \eta)) = ((\partial_t\ \vartheta) \doteq (\partial_t\ \eta))|$
$(\partial_P\ (\vartheta \prec \eta)) = ((\partial_t\ \vartheta) \preceq (\partial_t\ \eta))|$
$(\partial_P\ (\vartheta \preceq \eta)) = ((\partial_t\ \vartheta) \preceq (\partial_t\ \eta))|$
$(\partial_P\ (\varphi \sqcap \psi)) = (\partial_P\ \varphi) \sqcap (\partial_P\ \psi)|$
$(\partial_P\ (\varphi \sqcup \psi)) = (\partial_P\ \varphi) \sqcap (\partial_P\ \psi)$

primrec *trmVars* :: *trms* $\Rightarrow$ *string set* **where**
trmVars $(t_C\ r) = \{\}|$
trmVars $(t_V\ x) = \{x\}|$
trmVars $(\ominus\ \vartheta)$ = *trmVars* $\vartheta|$
trmVars $(\vartheta \oplus \eta)$ = *trmVars* $\vartheta\ \cup$ *trmVars* $\eta|$
trmVars $(\vartheta \odot \eta)$ = *trmVars* $\vartheta\ \cup$ *trmVars* η

fun *substList* ::(*string* $\times$ *trms*) *list* $\Rightarrow$ *trms* $\Rightarrow$ *trms* (-$\langle$-$\rangle$ [*54*] *80*) **where**
xtList$\langle t_C\ r\rangle = t_C\ r|$
$[]\langle t_V\ x\rangle = t_V\ x|$
((*y*,ξ) # *xtTail*)$\langle$*Var x*$\rangle$ = (*if* $x = y$ *then* ξ *else* *xtTail*$\langle$*Var x*$\rangle$)|
xtList$\langle\ominus\ \vartheta\rangle = \ominus$ (*xtList*$\langle\vartheta\rangle$)|
xtList$\langle\vartheta \oplus \eta\rangle$ = (*xtList*$\langle\vartheta\rangle$) $\oplus$ (*xtList*$\langle\eta\rangle$)|
xtList$\langle\vartheta \odot \eta\rangle$ = (*xtList*$\langle\vartheta\rangle$) $\odot$ (*xtList*$\langle\eta\rangle$)

proposition *substList-on-compl-of-varDiffs*:
assumes *trmVars* $\eta \subseteq$ (*UNIV* $-$ *varDiffs*)
and *set* (*map* π_1 *xtList*) $\subseteq$ *varDiffs*
shows *xtList*$\langle\eta\rangle = \eta$
using *assms* **apply**(*induction* η, *simp-all add*: *varDiffs-def*)
by(*induction xtList*, *auto*)

lemma *substList-help1*:*set* (*map* π_1 ((*map* (*vdiff* $\circ$ π_1) *xfList*) $\otimes$ *uInput*)) $\subseteq$ *varDiffs*
apply(*induct xfList uInput rule*: *list-induct2′*, *simp-all add*: *varDiffs-def*)
by *auto*

lemma *substList-help2*:
assumes *trmVars* $\eta \subseteq$ (*UNIV* $-$ *varDiffs*)
shows ((*map* (*vdiff* $\circ$ π_1) *xfList*) $\otimes$ *uInput*)$\langle\eta\rangle = \eta$
using *assms substList-help1 substList-on-compl-of-varDiffs* **by** *blast*

lemma *substList-cross-vdiff-on-non-ocurring-var*:
assumes $x \notin$ *set list1*
shows ((*map vdiff list1*) $\otimes$ *list2*)$\langle t_V\ (\partial\ x)\rangle = t_V\ (\partial\ x)$
using *assms* **apply**(*induct list1 list2 rule*: *list-induct2′*, *simp*, *simp*, *clarsimp*)
by(*simp add*: *vdiff-def*)

primrec *propVars* :: *props* $\Rightarrow$ *string set* **where**
propVars $(\vartheta \doteq \eta)$ = *trmVars* ϑ $\cup$ *trmVars* η|
propVars $(\vartheta \prec \eta)$ = *trmVars* ϑ $\cup$ *trmVars* η|
propVars $(\vartheta \preceq \eta)$ = *trmVars* ϑ $\cup$ *trmVars* η|
propVars $(\varphi \sqcap \psi)$ = *propVars* φ $\cup$ *propVars* ψ|
propVars $(\varphi \sqcup \psi)$ = *propVars* φ $\cup$ *propVars* ψ

primrec *subspList* :: (*string* $\times$ *trms*) *list* $\Rightarrow$ *props* $\Rightarrow$ *props* (-↾-↾ [*54*] *80*) **where**
xtList↾$\vartheta \doteq \eta$↾ = ((*xtList*$\langle\vartheta\rangle$) $\doteq$ (*xtList*$\langle\eta\rangle$))|
xtList↾$\vartheta \prec \eta$↾ = ((*xtList*$\langle\vartheta\rangle$) $\prec$ (*xtList*$\langle\eta\rangle$))|
xtList↾$\vartheta \preceq \eta$↾ = ((*xtList*$\langle\vartheta\rangle$) $\preceq$ (*xtList*$\langle\eta\rangle$))|
xtList↾$\varphi \sqcap \psi$↾ = ((*xtList*↾φ↾) $\sqcap$ (*xtList*↾ψ↾))|
xtList↾$\varphi \sqcup \psi$↾ = ((*xtList*↾φ↾) $\sqcup$ (*xtList*↾ψ↾))

ODE Extras

For exemplification purposes, we compile some concrete derivatives used commonly in classical mechanics. A more general approach should be taken that generates this theorems as instantiations.

named-theorems *ubc-definitions definitions used in the locale unique-on-bounded-closed*

declare *unique-on-bounded-closed-def* [*ubc-definitions*]
  and *unique-on-bounded-closed-axioms-def* [*ubc-definitions*]
  and *unique-on-closed-def* [*ubc-definitions*]
  and *compact-interval-def* [*ubc-definitions*]
  and *compact-interval-axioms-def* [*ubc-definitions*]
  and *self-mapping-def* [*ubc-definitions*]
  and *self-mapping-axioms-def* [*ubc-definitions*]
  and *continuous-rhs-def* [*ubc-definitions*]
  and *closed-domain-def* [*ubc-definitions*]
  and *global-lipschitz-def* [*ubc-definitions*]
  and *interval-def* [*ubc-definitions*]

and *nonempty-set-def* [*ubc-definitions*]
and *lipschitz-on-def* [*ubc-definitions*]

named-theorems *poly-deriv temporal compilation of derivatives representing galilean transformations*
named-theorems *galilean-transform temporal compilation of vderivs representing galilean transformations*
named-theorems *galilean-transform-eq the equational version of galilean−transform*

lemma *vector-derivative-line-at-origin*:$((\cdot)\ a\ \textit{has-vector-derivative}\ a)\ (\textit{at}\ x\ \textit{within}\ T)$
by (*auto intro*: *derivative-eq-intros*)

lemma [*poly-deriv*]:$((\cdot)\ a\ \textit{has-derivative}\ (\lambda x.\ x *_R a))\ (\textit{at}\ x\ \textit{within}\ T)$
using *vector-derivative-line-at-origin* **unfolding** *has-vector-derivative-def* **by** *simp*

lemma *quadratic-monomial-derivative*:
$((\lambda t{::}\textit{real}.\ a \cdot t^2)\ \textit{has-derivative}\ (\lambda t.\ a \cdot (2 \cdot x \cdot t)))\ (\textit{at}\ x\ \textit{within}\ T)$
apply(*rule-tac* $g'1{=}\lambda\ t.\ 2 \cdot x \cdot t$ **in** *derivative-eq-intros*(*6*))
apply(*rule-tac* $f'1{=}\lambda\ t.\ t$ **in** *derivative-eq-intros*(*15*))
by (*auto intro*: *derivative-eq-intros*)

lemma *quadratic-monomial-derivative2*:
$((\lambda t{::}\textit{real}.\ a \cdot t^2\ /\ 2)\ \textit{has-derivative}\ (\lambda t.\ a \cdot x \cdot t))\ (\textit{at}\ x\ \textit{within}\ T)$
apply(*rule-tac* $f'1{=}\lambda t.\ a \cdot (2 \cdot x \cdot t)$ **and** $g'1{=}\lambda\ x.\ 0$ **in** *derivative-eq-intros*(*18*))
using *quadratic-monomial-derivative* **by** *auto*

lemma *quadratic-monomial-vderiv*[*poly-deriv*]:$((\lambda t.\ a \cdot t^2\ /\ 2)\ \textit{has-vderiv-on}\ (\cdot)\ a)\ T$
apply(*simp add*: *has-vderiv-on-def has-vector-derivative-def*, *clarify*)
using *quadratic-monomial-derivative2* **by** (*simp add*: *mult-commute-abs*)

lemma *galilean-position*[*galilean-transform*]:
$((\lambda t.\ a \cdot t^2\ /\ 2 + v \cdot t + x)\ \textit{has-vderiv-on}\ (\lambda t.\ a \cdot t + v))\ T$
apply(*rule-tac* $f'{=}\lambda\ x.\ a \cdot x + v$ **and** $g'1{=}\lambda\ x.\ 0$ **in** *derivative-intros*(*191*))
apply(*rule-tac* $f'1{=}\lambda\ x.\ a \cdot x$ **and** $g'1{=}\lambda\ x.\ v$ **in** *derivative-intros*(*191*))
using *poly-deriv*(*2*) **by**(*auto intro*: *derivative-intros*)

lemma [*poly-deriv*]:
$t \in T \Longrightarrow ((\lambda\tau.\ a \cdot \tau^2\ /\ 2 + v \cdot \tau + x)\ \textit{has-derivative}\ (\lambda x.\ x *_R (a \cdot t + v)))\ (\textit{at}\ t\ \textit{within}\ T)$
using *galilean-position* **unfolding** *has-vderiv-on-def has-vector-derivative-def* **by** *simp*

lemma [*galilean-transform-eq*]:
$t > 0 \Longrightarrow \textit{vderiv-of}\ (\lambda t.\ a \cdot t\hat{\ }2\ /\ 2 + v \cdot t + x)\ \{0{<}..{<}2 \cdot t\}\ t = a \cdot t + v$
proof−
let $?f = \textit{vderiv-of}\ (\lambda t.\ a \cdot t\hat{\ }2\ /\ 2 + v \cdot t + x)\ \{0{<}..{<}2 \cdot t\}$
assume $t > 0$ **hence** $t \in \{0{<}..{<}2 \cdot t\}$ **by** *auto*

have $\exists$ *f*. (($\lambda t.\ a \cdot t^2\ /\ 2 + v \cdot t + x$) *has-vderiv-on f*) {*0*<..<*2* · *t*}
using *galilean-position* **by** *blast*
hence (($\lambda t.\ a \cdot t\hat{}2\ /\ 2 + v \cdot t + x$) *has-vderiv-on ?f*) {*0*<..<*2* · *t*}
unfolding *vderiv-of-def* **by** (*metis* (*mono-tags*, *lifting*) *someI-ex*)
also have (($\lambda t.\ a \cdot t^2\ /\ 2 + v \cdot t + x$) *has-vderiv-on* ($\lambda t.\ a \cdot t + v$)) {*0*<..<*2* · *t*}
using *galilean-position* **by** *simp*
ultimately show (*vderiv-of* ($\lambda t.\ a \cdot t\hat{}2\ /\ 2 + v \cdot t + x$) {*0*<..<*2* · *t*}) $t = a \cdot t + v$
apply(*rule-tac f′=?f* **and** τ=*t* **and** *t*=*2*·*t* **in** *vderiv-unique-within-open-interval*)
using ‹*t* ∈ {*0*<..<*2* · *t*}› **by** *auto*
qed

lemma $t > 0 \Longrightarrow$ *vderiv-of* ($\lambda t.\ a \cdot t\hat{}2\ /\ 2 + v \cdot t + x$) {*0*<..<*2* · *t*} $t = a \cdot t + v$
unfolding *vderiv-of-def* **apply**(*subst some1-equality*[*of* - ($\lambda t.\ a \cdot t + v$)])
apply(*rule-tac a*=$\lambda t.\ a \cdot t + v$ **in** *ex1I*)
apply(*simp-all add*: *galilean-position*)
apply(*rule ext*, *rename-tac f* τ)
apply(*rule-tac f*=$\lambda t.\ a \cdot t^2\ /\ 2 + v \cdot t + x$ **and** *t*=*2* · *t* **and** *f′*=*f* **in** *vderiv-unique-within-open-interval*)
apply(*simp-all add*: *galilean-position*)
oops

lemma *galilean-velocity*[*galilean-transform*]:(($\lambda r.\ a \cdot r + v$) *has-vderiv-on* ($\lambda t.\ a$)) *T*
apply(*rule-tac f′1*=λ *x*. *a* **and** *g′1*=λ *x*. *0* **in** *derivative-intros*(*191*))
unfolding *has-vderiv-on-def* **by**(*auto intro*: *derivative-eq-intros*)

lemma [*galilean-transform-eq*]:
$t > 0 \Longrightarrow$ *vderiv-of* ($\lambda r.\ a \cdot r + v$) {*0*<..<*2* · *t*} $t = a$
proof−
let *?f* = *vderiv-of* ($\lambda r.\ a \cdot r + v$) {*0*<..<*2* · *t*}
assume $t > 0$ **hence** *t* ∈ {*0*<..<*2* · *t*} **by** *auto*
have $\exists$ *f*. (($\lambda r.\ a \cdot r + v$) *has-vderiv-on f*) {*0*<..<*2* · *t*}
using *galilean-velocity* **by** *blast*
hence (($\lambda r.\ a \cdot r + v$) *has-vderiv-on ?f*) {*0*<..<*2* · *t*}
unfolding *vderiv-of-def* **by** (*metis* (*mono-tags*, *lifting*) *someI-ex*)
also have (($\lambda r.\ a \cdot r + v$) *has-vderiv-on* ($\lambda t.\ a$)) {*0*<..<*2* · *t*}
using *galilean-velocity* **by** *simp*
ultimately show (*vderiv-of* ($\lambda r.\ a \cdot r + v$) {*0*<..<*2* · *t*}) $t = a$
apply(*rule-tac f′=?f* **and** τ=*t* **and** *t*=*2*·*t* **in** *vderiv-unique-within-open-interval*)
using ‹*t* ∈ {*0*<..<*2* · *t*}› **by** *auto*
qed

lemma [*galilean-transform*]:
(($\lambda t.\ v \cdot t - a \cdot t^2\ /\ 2 + x$) *has-vderiv-on* ($\lambda x.\ v - a \cdot x$)) {*0*..*t*}
apply(*subgoal-tac* (($\lambda t.\ - a \cdot t^2\ /\ 2 + v \cdot t\ +x$) *has-vderiv-on* ($\lambda x.\ - a \cdot x + v$)) {*0*..*t*}, *simp*)

by(*rule galilean-transform*)

lemma [*galilean-transform-eq*]:$t > 0 \Longrightarrow$ *vderiv-of* $(\lambda t.\ v \cdot t - a \cdot t\hat{}2\ /\ 2 + x)$ $\{0<..<2 \cdot t\}$ $t = v - a \cdot t$
apply(*subgoal-tac vderiv-of* $(\lambda t.\ - a \cdot t^2\ /\ 2 + v \cdot t + x)$ $\{0<..<2 \cdot t\}$ $t = - a \cdot t + v$, *simp*)
by(*rule galilean-transform-eq*)

lemma [*galilean-transform*]:
$((\lambda t.\ v - a \cdot t)$ *has-vderiv-on* $(\lambda x.\ - a))$ $\{0..t\}$
apply(*subgoal-tac* $((\lambda t.\ - a \cdot t + v)$ *has-vderiv-on* $(\lambda x.\ - a))$ $\{0..t\}$, *simp*)
by(*rule galilean-transform*)

lemma [*galilean-transform-eq*]:$t > 0 \Longrightarrow$ *vderiv-of* $(\lambda r.\ v - a \cdot r)$ $\{0<..<2 \cdot t\}$ $t = - a$
apply(*subgoal-tac vderiv-of* $(\lambda t.\ - a \cdot t + v)$ $\{0<..<2 \cdot t\}$ $t = - a$, *simp*)
by(*rule galilean-transform-eq*)

lemma [*simp*]:$(\lambda x.$ *case x of* $(t, x) \Rightarrow f\ t) = (\lambda\ x.\ (f \circ \pi_1)\ x)$
by *auto*

end
theory *VC-diffKAD*
imports *VC-diffKAD-auxiliarities*

begin

7.4.3 Phase Space Relational Semantics

definition *solvesStoreIVP* :: (*real* $\Rightarrow$ *real store*) $\Rightarrow$ (*string* $\times$ (*real store* $\Rightarrow$ *real*)) *list* $\Rightarrow$
real store $\Rightarrow$ *bool*
((- *solvesTheStoreIVP* - *withInitState* -) [*70*, *70*, *70*] *68*) **where**
solvesStoreIVP φ_S *xfList s* $\equiv$
— F sends vdiffs-in-list to derivs.
$(\forall\ t \geq 0.\ (\forall\ xf \in$ *set xfList*. $\varphi_S\ t\ (\partial\ (\pi_1\ xf)) = \pi_2\ xf\ (\varphi_S\ t)) \wedge$
— F preserves the rest of the variables and F sends derivs of constants to 0.
$(\forall\ y.\ (y \notin (\pi_1 (\!|$*set xfList*$|\!)) \cup$ *varDiffs* $\longrightarrow \varphi_S\ t\ y = s\ y) \wedge$
$(y \notin (\pi_1 (\!|$*set xfList*$|\!)) \longrightarrow \varphi_S\ t\ (\partial\ y) = 0)) \wedge$
— F solves the induced IVP.
$(\forall\ xf \in$ *set xfList*. $((\lambda\ t.\ \varphi_S\ t\ (\pi_1\ xf))$ *solves-ode* $(\lambda\ t.\lambda\ r.(\pi_2\ xf)\ (\varphi_S\ t)))\ \{0..t\}$ *UNIV* $\wedge$
$\varphi_S\ 0\ (\pi_1\ xf) = s(\pi_1\ xf)))$

lemma *solves-store-ivpI*:
assumes $\forall\ t \geq 0.\forall\ xf \in$ *set xfList*. $(\varphi_S\ t\ (\partial\ (\pi_1\ xf))) = (\pi_2\ xf)\ (\varphi_S\ t)$
and $\forall\ t \geq 0.\forall\ y.\ y \notin (\pi_1 (\!|$*set xfList*$|\!)) \cup$*varDiffs* $\longrightarrow \varphi_S\ t\ y = s\ y$
and $\forall\ t \geq 0.\forall\ y.\ y \notin (\pi_1 (\!|$*set xfList*$|\!)) \longrightarrow \varphi_S\ t\ (\partial\ y) = 0$
and $\forall\ t \geq 0.\ \forall\ xf \in$ *set xfList*. $((\lambda\ t.\ \varphi_S\ t\ (\pi_1\ xf))$ *solves-ode* $(\lambda\ t.\lambda\ r.(\pi_2\ xf)$

$(\varphi_S\ t)))\ \{0..t\}\ UNIV$
  and $\forall\ xf \in set\ xfList.\ \varphi_S\ 0\ (\pi_1\ xf) = s(\pi_1\ xf)$
shows φ_S *solvesTheStoreIVP xfList withInitState s*
apply(*simp add*: *solvesStoreIVP-def*, *safe*)
using *assms* **apply** *simp-all*
by(*force*,*force*,*force*)

named-theorems *solves-store-ivpE elimination rules for solvesStoreIVP*

lemma [*solves-store-ivpE*]:
assumes φ_S *solvesTheStoreIVP xfList withInitState s*
shows $\forall\ t \geq 0.\forall\ y.\ y \notin (\pi_1(\!|set\ xfList|\!)) \cup varDiffs \longrightarrow \varphi_S\ t\ y = s\ y$
  and $\forall\ t \geq 0.\forall\ y.\ y \notin (\pi_1(\!|set\ xfList|\!)) \longrightarrow \varphi_S\ t\ (\partial\ y) = 0$
  and $\forall\ t \geq 0.\forall\ xf \in set\ xfList.\ (\varphi_S\ t\ (\partial\ (\pi_1\ xf))) = (\pi_2\ xf)\ (\varphi_S\ t)$
  and $\forall\ t \geq 0.\ \forall\ xf \in set\ xfList.\ ((\lambda\ t.\ \varphi_S\ t\ (\pi_1\ xf))\ solves\text{-}ode\ (\lambda\ t.\lambda\ r.(\pi_2\ xf)$
$(\varphi_S\ t)))\ \{0..t\}\ UNIV$
  and $\forall\ xf \in set\ xfList.\ \varphi_S\ 0\ (\pi_1\ xf) = s(\pi_1\ xf)$
using *assms solvesStoreIVP-def* **by** *auto*

lemma [*solves-store-ivpE*]:
assumes φ_S *solvesTheStoreIVP xfList withInitState s*
shows $\forall\ y.\ y \notin varDiffs \longrightarrow \varphi_S\ 0\ y = s\ y$
proof(*clarify*, *rename-tac x*)
fix x **assume** $x \notin varDiffs$
from *assms* **and** *solves-store-ivpE*(*5*) **have** $x \in (\pi_1(\!|set\ xfList|\!)) \Longrightarrow \varphi_S\ 0\ x = s$
x **by** *fastforce*
also have $x \notin (\pi_1(\!|set\ xfList|\!)) \cup varDiffs \Longrightarrow \varphi_S\ 0\ x = s\ x$
using *assms* **and** *solves-store-ivpE*(*1*) **by** *simp*
ultimately show $\varphi_S\ 0\ x = s\ x$ **using** ‹$x \notin varDiffs$› **by** *auto*
qed

named-theorems *solves-store-ivpD computation rules for solvesStoreIVP*

lemma [*solves-store-ivpD*]:
assumes φ_S *solvesTheStoreIVP xfList withInitState s*
  and $t \geq 0$
  and $y \notin (\pi_1(\!|set\ xfList|\!)) \cup varDiffs$
shows $\varphi_S\ t\ y = s\ y$
using *assms solves-store-ivpE*(*1*) **by** *simp*

lemma [*solves-store-ivpD*]:
assumes φ_S *solvesTheStoreIVP xfList withInitState s*
  and $t \geq 0$
  and $y \notin (\pi_1(\!|set\ xfList|\!))$
shows $\varphi_S\ t\ (\partial\ y) = 0$
using *assms solves-store-ivpE*(*2*) **by** *simp*

lemma [*solves-store-ivpD*]:
assumes φ_S *solvesTheStoreIVP xfList withInitState s*

and $t \geq 0$
and $xf \in set\ xfList$
shows $(\varphi_S\ t\ (\partial\ (\pi_1\ xf))) = (\pi_2\ xf)\ (\varphi_S\ t)$
using *assms solves-store-ivpE(3)* **by** *simp*

lemma [*solves-store-ivpD*]:
assumes φ_S *solvesTheStoreIVP xfList withInitState s*
and $t \geq 0$
and $xf \in set\ xfList$
shows $((\lambda\ t.\ \varphi_S\ t\ (\pi_1\ xf))$ *solves-ode* $(\lambda\ t.\lambda\ r.(\pi_2\ xf)\ (\varphi_S\ t)))\ \{0..t\}\ UNIV$
using *assms solves-store-ivpE(4)* **by** *simp*

lemma [*solves-store-ivpD*]:
assumes φ_S *solvesTheStoreIVP xfList withInitState s*
and $(x,f) \in set\ xfList$
shows $\varphi_S\ 0\ x = s\ x$
using *assms solves-store-ivpE(5)* **by** *fastforce*

lemma [*solves-store-ivpD*]:
assumes φ_S *solvesTheStoreIVP xfList withInitState s*
and $y \notin varDiffs$
shows $\varphi_S\ 0\ y = s\ y$
using *assms solves-store-ivpE(6)* **by** *simp*

definition *guarDiffEqtn* :: $(string \times (real\ store \Rightarrow real))\ list \Rightarrow (real\ store\ pred)$
$\Rightarrow$
real store rel (*ODEsystem - with -* [*70*, *70*] *61*) **where**
ODEsystem xfList with $G = \{(s,\varphi_S\ t)\ |s\ t\ \varphi_S.\ t \geq 0 \wedge (\forall\ r \in \{0..t\}.\ G\ (\varphi_S\ r))$
$\wedge$ *solvesStoreIVP* φ_S *xfList s*$\}$

7.4.4 Derivation of Differential Dynamic Logic Rules

"Differential Weakening"

lemma *wlp-evol-guard*:$Id \subseteq wp$ (*ODEsystem xfList with G*) $\lceil G \rceil$
by(*simp add*: *rel-antidomain-kleene-algebra.fbox-def rel-ad-def guarDiffEqtn-def p2r-def*, *force*)

theorem *dWeakening*:
assumes *guardImpliesPost*: $\lceil G \rceil \subseteq \lceil Q \rceil$
shows *PRE P* (*ODEsystem xfList with G*) *POST Q*
using *assms* **and** *wlp-evol-guard* **by** (*metis* (*no-types*, *hide-lams*) *d-p2r order-trans p2r-subid rel-antidomain-kleene-algebra.fbox-iso*)

theorem *dW*: *wp* (*ODEsystem xfList with G*) $\lceil Q \rceil = wp$ (*ODEsystem xfList with G*) $\lceil \lambda s.\ G\ s \longrightarrow Q\ s \rceil$
unfolding *rel-antidomain-kleene-algebra.fbox-def rel-ad-def guarDiffEqtn-def*
by(*simp add*: *relcomp.simps p2r-def*, *fastforce*)

"Differential Cut"

lemma *all-interval-guarDiffEqtn*:
assumes *solvesStoreIVP* φ_S *xfList s* $\wedge$ ($\forall$ $r \in \{0..t\}$. G (φ_S r)) $\wedge$ $0 \leq t$
shows $\forall$ $r \in \{0..t\}$. (s, φ_S r) $\in$ (*ODEsystem xfList with G*)
unfolding *guarDiffEqtn-def* **using** *atLeastAtMost-iff* **apply** *clarsimp*
apply(*rule-tac x=r* **in** *exI*, *rule-tac x=*φ_S **in** *exI*) **using** *assms* **by** *simp*

lemma *condAfterEvol-remainsAlongEvol*:
assumes *boxDiffC*:(s, s) $\in$ *wp* (*ODEsystem xfList with G*) $\lceil C \rceil$
and *FisSol*:*solvesStoreIVP* φ_S *xfList s* $\wedge$ ($\forall$ $r \in \{0..t\}$. G (φ_S r)) $\wedge$ $0 \leq t$
shows $\forall$ $r \in \{0..t\}$. G (φ_S r) $\wedge$ C (φ_S r)
proof−
from *boxDiffC* **have** $\forall$ c. (s,c) $\in$ (*ODEsystem xfList with G*) $\longrightarrow$ C c
  by (*simp add*: *boxProgrPred-chrctrztn*)
also from *FisSol* **have** $\forall$ $r \in \{0..t\}$. (s, φ_S r) $\in$ (*ODEsystem xfList with G*)
  using *all-interval-guarDiffEqtn* **by** *blast*
ultimately show *?thesis*
  using *FisSol atLeastAtMost-iff guarDiffEqtn-def* **by** *fastforce*
qed

theorem *dCut*:
assumes *pBoxDiffCut*:(*PRE P* (*ODEsystem xfList with G*) *POST C*)
assumes *pBoxCutQ*:(*PRE P* (*ODEsystem xfList with* (λ s. G s $\wedge$ C s)) *POST Q*)
shows *PRE P* (*ODEsystem xfList with G*) *POST Q*
apply(*clarify*, *subgoal-tac* $a = b$) **defer**
proof(*metis d-p2r rdom-p2r-contents*, *simp*, *subst boxProgrPred-chrctrztn*, *clarify*)
fix b y **assume** (b, b) $\in$ $\lceil P \rceil$ **and** (b, y) $\in$ *ODEsystem xfList with G*
then obtain φ_S t **where** $*$:*solvesStoreIVP* φ_S *xfList b* $\wedge$ ($\forall$ $r \in \{0..t\}$. G (φ_S r)) $\wedge$ $0 \leq t$ $\wedge$ φ_S $t = y$
  using *guarDiffEqtn-def* **by** *auto*
hence $\forall$ $r \in \{0..t\}$. (b, φ_S r) $\in$ (*ODEsystem xfList with G*)
  using *all-interval-guarDiffEqtn* **by** *blast*
from *this* **and** *pBoxDiffCut* **have** $\forall$ $r \in \{0..t\}$. C (φ_S r)
  using *boxProgrPred-chrctrztn* ‹(b, b) $\in$ $\lceil P \rceil$› **by** (*metis* (*no-types*, *lifting*) *d-p2r subsetCE*)
then have $\forall$ $r \in \{0..t\}$. (b, φ_S r) $\in$ (*ODEsystem xfList with* (λ s. G s $\wedge$ C s))
  using $*$ *all-interval-guarDiffEqtn* **by** (*metis* (*mono-tags*, *lifting*))
from *this* **and** *pBoxCutQ* **have** $\forall$ $r \in \{0..t\}$. Q (φ_S r)
  using *boxProgrPred-chrctrztn* ‹(b, b) $\in$ $\lceil P \rceil$› **by** (*metis* (*no-types*, *lifting*) *d-p2r subsetCE*)
thus Q y **using** $*$ **by** *auto*
qed

theorem *dC*:
assumes *Id* $\subseteq$ *wp* (*ODEsystem xfList with G*) $\lceil C \rceil$
shows *wp* (*ODEsystem xfList with G*) $\lceil Q \rceil$ = *wp* (*ODEsystem xfList with* (λ s. G s $\wedge$ C s)) $\lceil Q \rceil$
proof(*rule-tac f=*λ x. *wp* x $\lceil Q \rceil$ **in** *HOL.arg-cong*, *safe*)
  fix a b **assume** (a, b) $\in$ *ODEsystem xfList with G*

then obtain φ_S *t* **where** $*$:*solvesStoreIVP* φ_S *xfList a* $\wedge$ ($\forall$ $r \in \{0..t\}$. *G* (φ_S *r*)) $\wedge$ $0 \leq t \wedge \varphi_S\ t = b$
using *guarDiffEqtn-def* **by** *auto*
hence *1*:$\forall$ $r \in \{0..t\}$. (*a*, φ_S *r*) $\in$ *ODEsystem xfList with G*
by (*meson all-interval-guarDiffEqtn*)
from *this* **have** $\forall$ $r \in \{0..t\}$. *C* (φ_S *r*) **using** *assms boxProgrPred-chrctrztn*
by (*metis IdI boxProgrPred-IsProp subset-antisym*)
thus (*a*, *b*) $\in$ *ODEsystem xfList with* (λs. *G s* $\wedge$ *C s*)
using $*$ *guarDiffEqtn-def* **by** *blast*
next
fix *a b* **assume** (*a*, *b*) $\in$ *ODEsystem xfList with* (λs. *G s* $\wedge$ *C s*)
then show (*a*, *b*) $\in$ *ODEsystem xfList with G*
unfolding *guarDiffEqtn-def* **by**(*clarsimp*, *rule-tac x=t* **in** *exI*, *rule-tac x=*φ_S **in** *exI*, *simp*)
qed

Solve Differential Equation

lemma *prelim-dSolve*:
assumes *solHyp*:(λt. *sol s*[*xfList*$\leftarrow$*uInput*] *t*) *solvesTheStoreIVP xfList withInitState s*
and *uniqHyp*:$\forall$ *X*. *solvesStoreIVP X xfList s* $\longrightarrow$ ($\forall$ $t \geq 0$. (*sol s*[*xfList*$\leftarrow$*uInput*] *t*) = *X t*)
and *diffAssgn*: $\forall t \geq 0$. *G* (*sol s*[*xfList*$\leftarrow$*uInput*] *t*) $\longrightarrow$ *Q* (*sol s*[*xfList*$\leftarrow$*uInput*] *t*)
shows $\forall$ *c*. (*s*,*c*) $\in$ (*ODEsystem xfList with G*) $\longrightarrow$ *Q c*
proof(*clarify*)
fix *c* **assume** (*s*,*c*) $\in$ (*ODEsystem xfList with G*)
from *this* **obtain** *t*::*real* **and** φ_S::*real* $\Rightarrow$ *real store*
where *FHyp*:$t \geq 0$ $\wedge$ φ_S *t* = *c* $\wedge$ *solvesStoreIVP* φ_S *xfList s* $\wedge$ ($\forall$ $r \in \{0..t\}$. *G* (φ_S *r*))
using *guarDiffEqtn-def* **by** *auto*
from *this* **and** *uniqHyp* **have** (*sol s*[*xfList*$\leftarrow$*uInput*] *t*) = φ_S *t* **by** *blast*
then have *cHyp*:*c* = (*sol s*[*xfList*$\leftarrow$*uInput*] *t*) **using** *FHyp* **by** *simp*
from *this* **have** *G* (*sol s*[*xfList*$\leftarrow$*uInput*] *t*) **using** *FHyp* **by** *force*
then show *Q c* **using** *diffAssgn FHyp cHyp* **by** *auto*
qed

theorem *dS*:
assumes *solHyp*:$\forall$ *s*. *solvesStoreIVP* (λt. *sol s*[*xfList*$\leftarrow$*uInput*] *t*) *xfList s*
and *uniqHyp*:$\forall$ *s X*. *solvesStoreIVP X xfList s* $\longrightarrow$ ($\forall$ $t \geq 0$. (*sol s*[*xfList*$\leftarrow$*uInput*] *t*) = *X t*)
shows *wp* (*ODEsystem xfList with G*) $\lceil Q \rceil$ =
$\lceil\lambda$ *s*. $\forall t \geq 0$. ($\forall r \in \{0..t\}$. *G* (*sol s*[*xfList*$\leftarrow$*uInput*] *r*)) $\longrightarrow$ *Q* (*sol s*[*xfList*$\leftarrow$*uInput*] *t*)$\rceil$
apply(*simp add*: *p2r-def*, *rule subset-antisym*)
unfolding *guarDiffEqtn-def rel-antidomain-kleene-algebra.fbox-def rel-ad-def*
using *solHyp* **apply**(*simp add*: *relcomp.simps*) **apply** *clarify*
apply(*rule-tac x=x* **in** *exI*, *clarsimp*)
apply(*erule-tac x=sol x*[*xfList*$\leftarrow$*uInput*] *t* **in** *allE*, *erule disjE*)

apply(*erule-tac x=x* **in** *allE*, *erule-tac x=t* **in** *allE*)
apply(*erule impE*, *simp*, *erule-tac x=λt. sol x[xfList←uInput] t* **in** *allE*)
apply(*simp-all*, *clarify*, *rule-tac x=s* **in** *exI*, *simp add*: *relcomp.simps*)
using *uniqHyp* **by** *fastforce*

theorem *dSolve*:
assumes *solHyp*:∀ *s*. *solvesStoreIVP* (λ*t*. *sol s*[*xfList*←*uInput*] *t*) *xfList s*
and *uniqHyp*:∀ *s*. ∀ *X*. *solvesStoreIVP X xfList s* ⟶ (∀ *t* ≥ *0*.(*sol s*[*xfList*←*uInput*] *t*) = *X t*)
and *diffAssgn*: ∀ *s*. *P s* ⟶ (∀ *t*≥*0*. *G* (*sol s*[*xfList*←*uInput*] *t*) ⟶ *Q* (*sol s*[*xfList*←*uInput*] *t*))
shows *PRE P* (*ODEsystem xfList with G*) *POST Q*
apply(*clarsimp*, *subgoal-tac a=b*)
apply(*clarify*, *subst boxProgrPred-chrctrztn*)
apply(*simp-all add*: *p2r-def*)
apply(*rule-tac uInput=uInput* **in** *prelim-dSolve*)
apply(*simp add*: *solHyp*, *simp add*: *uniqHyp*)
by (*metis* (*no-types*, *lifting*) *diffAssgn*)

— We proceed to refine the previous rule by finding the necessary restrictions on varFunList and uInput so that the solution to the store-IVP is guaranteed.

lemma *conds4vdiffs-prelim*:
assumes *funcsHyp*:∀ *s g*. ∀ *xf*∈*set xfList*. π_2 *xf* (*override-on s g varDiffs*) = π_2 *xf s*
and *distinctHyp*:*distinct* (*map* π_1 *xfList*)
and *varsHyp*:∀ *xf* ∈ *set xfList*. π_1 *xf* ∉ *varDiffs*
and *lengthHyp*:*length xfList* = *length uInput*
and *solHyp1*:∀ *uxf* ∈ *set* (*uInput* ⊗ *xfList*). (π_1 *uxf*) *0* (*sol s*) = (*sol s*) (π_1 (π_2 *uxf*))
and *solHyp2*:∀ *t*≥*0*. ((λτ. (*sol s*[*xfList*←*uInput*] τ) *x*)
has-vderiv-on (λτ. *f* (*sol s*[*xfList*←*uInput*] τ))) {*0*..*t*}
and *xfHyp*:(*x*, *f*) ∈ *set xfList* **and** *tHyp*:*t* ≥ *0*
shows (*sol s*[*xfList*←*uInput*] *t*) (∂ *x*) = *f* (*sol s*[*xfList*←*uInput*] *t*)
proof−
from *xfHyp* **obtain** *u* **where** *xfuHyp*: (*u*,*x*,*f*) ∈ *set* (*uInput* ⊗ *xfList*)
by (*metis in-set-impl-in-set-zip2 lengthHyp*)
show (*sol s*[*xfList*←*uInput*] *t*) (∂ *x*) =*f* (*sol s*[*xfList*←*uInput*] *t*)
  proof(*cases t=0*)
  case *True*
    have (*sol s*[*xfList*←*uInput*] *0*) (∂ *x*) = *f* (*sol s*[*xfList*←*uInput*] *0*)
    using *assms* **and** *to-sol-zero-its-dvars* **by** *blast*
    then show *?thesis* **using** *True* **by** *blast*
  next
    case *False*
    from *this* **have** *t* > *0* **using** *tHyp* **by** *simp*
    hence (*sol s*[*xfList*←*uInput*] *t*) (∂ *x*) = *vderiv-of* (λ *r*. *u r* (*sol s*)) {*0*<..< (*2* $*_R$ *t*)} *t*
    using *xfuHyp assms to-sol-greater-than-zero-its-dvars* **by** *blast*

also have *vderiv-of* $(\lambda r.\ u\ r\ (sol\ s))$ $\{0{<}..{<}\ (2 *_R t)\}$ $t = f\ (sol\ s[xfList{\leftarrow}uInput]$ $t)$
using *assms xfuHyp* $\langle t > 0\rangle$ **and** *vderiv-of-to-sol-its-vars* **by** *blast*
ultimately show *?thesis* **by** *simp*
qed
qed

lemma *conds4vdiffs*:
assumes *funcsHyp*:$\forall\ s\ g.\ \forall\ xf{\in}set\ xfList.\ \pi_2\ xf\ (override\text{-}on\ s\ g\ varDiffs) = \pi_2\ xf\ s$
and *distinctHyp*:$distinct\ (map\ \pi_1\ xfList)$
and *varsHyp*:$\forall\ xf \in set\ xfList.\ \pi_1\ xf \notin varDiffs$
and *lengthHyp*:$length\ xfList = length\ uInput$
and *solHyp1*:$\forall\ uxf \in set\ (uInput \otimes xfList).\ (\pi_1\ uxf)\ 0\ (sol\ s) = (sol\ s)\ (\pi_1\ (\pi_2\ uxf))$
and *solHyp2*:$\forall\ t{\geq}0.\ \forall\ xf \in set\ xfList.\ ((\lambda\tau.\ (sol\ s[xfList{\leftarrow}uInput]\ \tau)\ (\pi_1\ xf))$ $has\text{-}vderiv\text{-}on\ (\lambda\tau.\ (\pi_2\ xf)\ (sol\ s[xfList{\leftarrow}uInput]\ \tau)))\ \{0..t\}$
shows $\forall\ t \geq 0.\ \forall\ xf \in set\ xfList.\ (sol\ s[xfList{\leftarrow}uInput]\ t)\ (\partial\ (\pi_1\ xf)) = (\pi_2\ xf)$ $(sol\ s[xfList{\leftarrow}uInput]\ t)$
apply(*rule allI*, *rule impI*, *rule ballI*, *rule conds4vdiffs-prelim*)
using *assms* **by** *simp-all*

lemma *conds4Consts*:
assumes *varsHyp*:$\forall\ xf \in set\ xfList.\ \pi_1\ xf \notin varDiffs$
shows $\forall\ x.\ x \notin (\pi_1 (\!|set\ xfList|\!)) \longrightarrow (sol\ s[xfList{\leftarrow}uInput]\ t)\ (\partial\ x) = 0$
using *varsHyp* **apply**(*induct xfList uInput rule*: *list-induct2'*)
apply(*simp-all add*: *override-on-def varDiffs-def vdiff-def*)
by *clarsimp*

lemma *conds4InitState*:
assumes *distinctHyp*:$distinct\ (map\ \pi_1\ xfList)$
and *lengthHyp*:$length\ xfList = length\ uInput$
and *varsHyp*:$\forall\ xf \in set\ xfList.\ \pi_1\ xf \notin varDiffs$
and *solHyp1*:$\forall\ uxf{\in}set\ (uInput \otimes xfList).\ (\pi_1\ uxf)\ 0\ (sol\ s) = (sol\ s)\ (\pi_1\ (\pi_2\ uxf))$
and *xfHyp*:$(x, f) \in set\ xfList$
shows $(sol\ s[xfList{\leftarrow}uInput]\ 0)\ x = s\ x$
proof−
from *xfHyp* **obtain** u **where** *uxfHyp*:$(u, x, f) \in set\ (uInput \otimes xfList)$
by (*metis in-set-impl-in-set-zip2 lengthHyp*)
from *varsHyp* **have** *toZeroHyp*:$(sol\ s)\ x = s\ x$ **using** *override-on-def xfHyp* **by** *auto*
from *uxfHyp* **and** *solHyp1* **have** $u\ 0\ (sol\ s) = (sol\ s)\ x$ **by** *fastforce*
also have $(sol\ s[xfList{\leftarrow}uInput]\ 0)\ x = u\ 0\ (sol\ s)$
using *state-list-cross-upd-its-vars uxfHyp* **and** *assms* **by** *blast*
ultimately show $(sol\ s[xfList{\leftarrow}uInput]\ 0)\ x = s\ x$ **using** *toZeroHyp* **by** *simp*
qed

lemma *conds4RestOfStrings*:

assumes $x \notin (\pi_1 (\!|set\ xfList|\!)) \cup varDiffs$
shows $(sol\ s[xfList \leftarrow uInput]\ t)\ x = s\ x$
using *assms* **apply**(*induct xfList uInput rule*: *list-induct2′*)
by(*auto simp*: *varDiffs-def*)

lemma *conds4storeIVP-on-toSol*:
assumes *funcsHyp*:$\forall s\ g.\ \forall xf \in set\ xfList.\ \pi_2\ xf\ (override\text{-}on\ s\ g\ varDiffs) = \pi_2\ xf\ s$
and *distinctHyp*:$distinct\ (map\ \pi_1\ xfList)$
and *lengthHyp*:$length\ xfList = length\ uInput$
and *varsHyp*:$\forall\ xf \in set\ xfList.\ \pi_1\ xf \notin varDiffs$
and *solHyp1*:$\forall uxf \in set\ (uInput \otimes xfList).\ (\pi_1\ uxf)\ 0\ (sol\ s) = (sol\ s)\ (\pi_1\ (\pi_2\ uxf))$
and *solHyp2*:$\forall\ t \geq 0.\ \forall\ xf \in set\ xfList.$
$((\lambda t.\ (sol\ s[xfList \leftarrow uInput]\ t)\ (\pi_1\ xf))\ has\text{-}vderiv\text{-}on\ (\lambda t.\ \pi_2\ xf\ (sol\ s[xfList \leftarrow uInput]\ t)))\ \{0..t\}$
shows $solvesStoreIVP\ (\lambda\ t.\ (sol\ s[xfList \leftarrow uInput]\ t))\ xfList\ s$
apply(*rule solves-store-ivpI*)
subgoal using *conds4vdiffs assms* **by** *blast*
subgoal using *conds4RestOfStrings* **by** *blast*
subgoal using *conds4Consts varsHyp* **by** *blast*
subgoal apply(*rule allI*, *rule impI*, *rule ballI*, *rule solves-odeI*)
  using *solHyp2* **by** *simp-all*
subgoal using *conds4InitState* **and** *assms* **by** *force*
done

theorem *dSolve-toSolve*:
assumes *funcsHyp*:$\forall s\ g.\ \forall xf \in set\ xfList.\ \pi_2\ xf\ (override\text{-}on\ s\ g\ varDiffs) = \pi_2\ xf\ s$
and *distinctHyp*:$distinct\ (map\ \pi_1\ xfList)$
and *lengthHyp*:$length\ xfList = length\ uInput$
and *varsHyp*:$\forall\ xf \in set\ xfList.\ \pi_1\ xf \notin varDiffs$
and *solHyp1*:$\forall\ s.\forall uxf \in set\ (uInput \otimes xfList).\ (\pi_1\ uxf)\ 0\ (sol\ s) = (sol\ s)\ (\pi_1\ (\pi_2\ uxf))$
and *solHyp2*:$\forall\ s.\forall\ t \geq 0.\ \forall\ xf \in set\ xfList.$
$((\lambda t.\ (sol\ s[xfList \leftarrow uInput]\ t)\ (\pi_1\ xf))\ has\text{-}vderiv\text{-}on\ (\lambda t.\ \pi_2\ xf\ (sol\ s[xfList \leftarrow uInput]\ t)))\ \{0..t\}$
and *uniqHyp*:$\forall\ s.\forall\ X.\ solvesStoreIVP\ X\ xfList\ s \longrightarrow (\forall\ t \geq 0.\ (sol\ s[xfList \leftarrow uInput]\ t) = X\ t)$
and *postCondHyp*:$\forall s.\ P\ s \longrightarrow (\forall t \geq 0.\ Q\ (sol\ s[xfList \leftarrow uInput]\ t))$
shows *PRE P* (*ODEsystem xfList with G*) *POST Q*
apply(*rule-tac uInput=uInput* **in** *dSolve*)
subgoal using *assms* **and** *conds4storeIVP-on-toSol* **by** *simp*
subgoal by (*simp add*: *uniqHyp*)
using *postCondHyp postCondHyp* **by** *simp*

— As before, we keep refining the rule dSolve. This time we find the necessary restrictions to attain uniqueness.

lemma *conds4UniqSol*:
fixes f::*real store* $\Rightarrow$ *real*
assumes *tHyp*:$t \geq 0$
and *contHyp*:*continuous-on* ($\{0..t\} \times$ *UNIV*) ($\lambda(t, (r$::*real*)). f (φ_s t))
shows *unique-on-bounded-closed* 0 $\{0..t\}$ τ (λt r. f (φ_s t)) *UNIV* (*if* $t = 0$ *then* 1 *else* $1/(t+1)$)
apply(*simp add*: *ubc-definitions*, *rule conjI*)
subgoal using *contHyp continuous-rhs-def* **by** *fastforce*
subgoal using *assms continuous-rhs-def* **by** *fastforce*
done

lemma *solves-store-ivp-at-beginning-overrides*:
assumes *solvesStoreIVP* φ_s *xfList a*
shows φ_s 0 = *override-on a* (φ_s 0) *varDiffs*
apply(*rule ext*, *subgoal-tac* $x \notin$ *varDiffs* $\longrightarrow$ φ_s 0 x = a x)
subgoal by (*simp add*: *override-on-def*)
using *assms* **and** *solves-store-ivpD*(*6*) **by** *simp*

lemma *ubcStoreUniqueSol*:
assumes *tHyp*:$t \geq 0$
assumes *contHyp*:$\forall$ *xf* $\in$ *set xfList*. *continuous-on* ($\{0..t\} \times$ *UNIV*)
($\lambda(t, (r$::*real*)). (π_2 *xf*) (*sol s*[*xfList*$\leftarrow$*uInput*] t))
and *eqDerivs*:$\forall$ *xf* $\in$ *set xfList*. $\forall$ $\tau \in \{0..t\}$. (π_2 *xf*) (φ_s τ) = (π_2 *xf*) (*sol s*[*xfList*$\leftarrow$*uInput*] τ)
and *Fsolves*:*solvesStoreIVP* φ_s *xfList s*
and *solHyp*:*solvesStoreIVP* (λ τ. (*sol s*[*xfList*$\leftarrow$*uInput*] τ)) *xfList s*
shows (*sol s*[*xfList*$\leftarrow$*uInput*] t) = φ_s t
proof
  fix x::*string* **show** (*sol s*[*xfList*$\leftarrow$*uInput*] t) x = φ_s t x
  proof(*cases* $x \in$ (π_1(|*set xfList*|)) $\cup$ *varDiffs*)
  case *False*
    then have *notInVars*:$x \notin$ (π_1(|*set xfList*|)) $\cup$ *varDiffs* **by** *simp*
    from *solHyp* **have** (*sol s*[*xfList*$\leftarrow$*uInput*] t) x = s x
    using *tHyp notInVars solves-store-ivpD*(*1*) **by** *blast*
   also from *Fsolves* **have** φ_s t x = s x **using** *tHyp notInVars solves-store-ivpD*(*1*)
by *blast*
    ultimately show (*sol s*[*xfList*$\leftarrow$*uInput*] t) x = φ_s t x **by** *simp*
  next case *True*
    then have $x \in$ (π_1(|*set xfList*|)) $\vee$ $x \in$ *varDiffs* **by** *simp*
    from *this* **show** *?thesis*
    proof
      assume $x \in$ (π_1(|*set xfList*|))
      from *this* **obtain** f **where** *xfHyp*:(x, f) $\in$ *set xfList* **by** *fastforce*

      then have *expand1*:$\forall$ *xf* $\in$ *set xfList*.(($\lambda\tau$. φ_s τ (π_1 *xf*)) *solves-ode*
      ($\lambda\tau$ r. (π_2 *xf*) (φ_s τ))){$0..t$} *UNIV* $\wedge$ φ_s 0 (π_1 *xf*) = s (π_1 *xf*)
      using *Fsolves tHyp* **by** (*simp add*:*solvesStoreIVP-def*)
      hence *expand2*:$\forall$ *xf* $\in$ *set xfList*. $\forall$ $\tau \in \{0..t\}$. ((λr. φ_s r (π_1 *xf*))
       has-vector-derivative (λr. (π_2 *xf*) (*sol s*[*xfList*$\leftarrow$*uInput*] τ)) τ) (*at* τ *within*

$\{0..t\}$)
using *eqDerivs* **by** (*simp add*: *solves-ode-def has-vderiv-on-def*)

then have $\forall$ *xf* $\in$ *set xfList*. (($\lambda\tau$. φ_s τ (π_1 *xf*)) *solves-ode*
($\lambda\tau$ *r*. (π_2 *xf*) (*sol s*[*xfList*$\leftarrow$*uInput*] τ))){*0..t*} *UNIV* $\wedge$ φ_s *0* (π_1 *xf*) = *s*
(π_1 *xf*)
by (*simp add*: *has-vderiv-on-def solves-ode-def expand1 expand2*)
then have *1*:(($\lambda\tau$. φ_s τ *x*) *solves-ode* ($\lambda\tau$ *r*. *f* (*sol s*[*xfList*$\leftarrow$*uInput*] τ))){*0..t*}
UNIV $\wedge$
φ_s *0 x* = *s x* **using** *xfHyp* **by** *fastforce*

from *solHyp* **and** *xfHyp* **have** *2*:((λ τ. (*sol s*[*xfList*$\leftarrow$*uInput*] τ) *x*) *solves-ode*

($\lambda\tau$ *r*. *f* (*sol s*[*xfList*$\leftarrow$*uInput*] τ))) {*0..t*} *UNIV* $\wedge$ (*sol s*[*xfList*$\leftarrow$*uInput*] *0*)
x = *s x*
using *solvesStoreIVP-def tHyp* **by** *fastforce*

from *tHyp* **and** *contHyp* **have** $\forall$ *xf* $\in$ *set xfList*. *unique-on-bounded-closed 0*
{*0..t*} (*s* (π_1 *xf*))
($\lambda\tau$ *r*. (π_2 *xf*) (*sol s*[*xfList*$\leftarrow$*uInput*] τ)) *UNIV* (*if t* = *0 then 1 else 1*/(*t*+*1*))

apply(*clarify*) **apply**(*rule conds4UniqSol*) **by**(*auto*)
from *this* **have** *3*:*unique-on-bounded-closed 0* {*0..t*} (*s x*) ($\lambda\tau$ *r*. *f* (*sol*
s[*xfList*$\leftarrow$*uInput*] τ))
UNIV (*if t* = *0 then 1 else 1*/(*t*+*1*)) **using** *xfHyp* **by** *fastforce*
from *1 2* **and** *3* **show** (*sol s*[*xfList*$\leftarrow$*uInput*] *t*) *x* = φ_s *t x*
using *unique-on-bounded-closed.unique-solution* **using** *real-Icc-closed-segment*
tHyp **by** *blast*
next
assume *x* $\in$ *varDiffs*
then obtain *y* **where** *xDef*:*x* = ∂ *y* **by** (*auto simp*: *varDiffs-def*)
show (*sol s*[*xfList*$\leftarrow$*uInput*] *t*) *x* = φ_s *t x*
proof(*cases y* $\in$ *set* (*map* π_1 *xfList*))
case *True*
then obtain *f* **where** *xfHyp*:(*y*, *f*) $\in$ *set xfList* **by** *fastforce*
from *tHyp* **and** *Fsolves* **have** φ_s *t x* = *f* (φ_s *t*)
using *solves-store-ivpD*(*3*) *xfHyp xDef* **by** *force*
also have (*sol s*[*xfList*$\leftarrow$*uInput*] *t*) *x* = *f* (*sol s*[*xfList*$\leftarrow$*uInput*] *t*)
using *solves-store-ivpD*(*3*) *xfHyp xDef solHyp tHyp* **by** *force*
ultimately show *?thesis* **using** *eqDerivs xfHyp tHyp* **by** *auto*
next case *False*
then have φ_s *t x* = *0*
using *xDef solves-store-ivpD*(*2*) *Fsolves tHyp* **by** *simp*
also have (*sol s*[*xfList*$\leftarrow$*uInput*] *t*) *x* = *0*
using *False solHyp tHyp solves-store-ivpD*(*2*) *xDef* **by** *fastforce*
ultimately show *?thesis* **by** *simp*
qed
qed
qed

qed

theorem *dSolveUBC*:
assumes *contHyp*:$\forall$ *s*. $\forall$ *t*$\geq$*0*. $\forall$ *xf* $\in$ *set xfList*. *continuous-on* ($\{$*0..t*$\}$ $\times$ *UNIV*)

(λ(*t*, (*r*::*real*)). (π_2 *xf*) (*sol s*[*xfList*$\leftarrow$*uInput*] *t*))
and *solHyp*:$\forall$ *s*. *solvesStoreIVP* (λ *t*. (*sol s*[*xfList*$\leftarrow$*uInput*] *t*)) *xfList s*
and *uniqHyp*:$\forall$ *s*. $\forall$ φ_s. φ_s *solvesTheStoreIVP xfList withInitState s* $\longrightarrow$
($\forall$ *t* $\geq$ *0*. $\forall$ *xf* $\in$ *set xfList*. $\forall$ *r* $\in$ $\{$*0..t*$\}$. (π_2 *xf*) (φ_s *r*) = (π_2 *xf*) (*sol s*[*xfList*$\leftarrow$*uInput*]
r))
and *diffAssgn*: $\forall$ *s*. *P s* $\longrightarrow$ ($\forall$ *t*$\geq$*0*. *G* (*sol s*[*xfList*$\leftarrow$*uInput*] *t*) $\longrightarrow$ *Q* (*sol s*[*xfList*$\leftarrow$*uInput*]
t))
shows *PRE P* (*ODEsystem xfList with G*) *POST Q*
apply(*rule-tac uInput*=*uInput* **in** *dSolve*)
prefer *2* **subgoal proof**(*clarify*)
fix *s*::*real store* **and** φ_s::*real* $\Rightarrow$ *real store* **and** *t*::*real*
assume *isSol*:*solvesStoreIVP* φ_s *xfList s* **and** *sHyp*:*0* $\leq$ *t*
from *this* **and** *uniqHyp* **have** $\forall$ *xf* $\in$ *set xfList*. $\forall$ *t* $\in$ $\{$*0..t*$\}$.
(π_2 *xf*) (φ_s *t*) = (π_2 *xf*) (*sol s*[*xfList*$\leftarrow$*uInput*] *t*) **by** *auto*
also have $\forall$ *xf* $\in$ *set xfList*. *continuous-on* ($\{$*0..t*$\}$ $\times$ *UNIV*)
(λ(*t*, (*r*::*real*)). (π_2 *xf*) (*sol s*[*xfList*$\leftarrow$*uInput*] *t*)) **using** *contHyp sHyp* **by** *blast*
ultimately show (*sol s*[*xfList*$\leftarrow$*uInput*] *t*) = φ_s *t*
using *sHyp isSol ubcStoreUniqueSol solHyp* **by** *simp*
qed using *assms* **by** *simp-all*

theorem *dSolve-toSolveUBC*:
assumes *funcsHyp*:$\forall$ *s g*. $\forall$ *xf*$\in$*set xfList*. π_2 *xf* (*override-on s g varDiffs*) = π_2 *xf*
s
and *distinctHyp*:*distinct* (*map* π_1 *xfList*)
and *lengthHyp*:*length xfList* = *length uInput*
and *varsHyp*:$\forall$ *xf* $\in$ *set xfList*. π_1 *xf* $\notin$ *varDiffs*
and *solHyp1*:$\forall$ *s*. $\forall$ *uxf*$\in$*set* (*uInput* $\otimes$ *xfList*). π_1 *uxf 0* (*sol s*) = *sol s* (π_1 (π_2
uxf))
and *solHyp2*:$\forall$ *s*. $\forall$ *t*$\geq$*0*. $\forall$ *xf*$\in$*set xfList*. ((λ*t*. (*sol s*[*xfList*$\leftarrow$*uInput*] *t*) (π_1 *xf*))
has-vderiv-on
(λ*t*. π_2 *xf* (*sol s*[*xfList*$\leftarrow$*uInput*] *t*))) $\{$*0..t*$\}$
and *contHyp*:$\forall$ *s*. $\forall$ *t*$\geq$*0*. $\forall$ *xf* $\in$ *set xfList*. *continuous-on* ($\{$*0..t*$\}$ $\times$ *UNIV*)
(λ(*t*, (*r*::*real*)). (π_2 *xf*) (*sol s*[*xfList*$\leftarrow$*uInput*] *t*))
and *uniqHyp*:$\forall$ *s*. $\forall$ φ_s. φ_s *solvesTheStoreIVP xfList withInitState s* $\longrightarrow$
($\forall$ *t* $\geq$ *0*. $\forall$ *xf* $\in$ *set xfList*. $\forall$ *r* $\in$ $\{$*0..t*$\}$. (π_2 *xf*) (φ_s *r*) = (π_2 *xf*) (*sol s*[*xfList*$\leftarrow$*uInput*]
r))
and *postCondHyp*:$\forall$ *s*. *P s* $\longrightarrow$ ($\forall$ *t*$\geq$*0*. *Q* (*sol s*[*xfList*$\leftarrow$*uInput*] *t*))
shows *PRE P* (*ODEsystem xfList with G*) *POST Q*
apply(*rule-tac uInput*=*uInput* **in** *dSolveUBC*)
using *contHyp* **apply** *simp*
apply(*rule allI*, *rule-tac uInput*=*uInput* **in** *conds4storeIVP-on-toSol*)
using *assms* **by** *auto*

"Differential Invariant."

lemma *solvesStoreIVP-couldBeModified*:
fixes *F*::*real* ⇒ *real store*
assumes *vars*:∀ *t*≥*0*. ∀ *xf*∈*set xfList*. ((λ*t*. *F t* (π_1 *xf*)) *solves-ode* (λ*t r*. π_2 *xf* (*F t*))) {*0*..*t*} *UNIV*
and *dvars*:∀ *t* ≥ *0*. ∀ *xf*∈*set xfList*. (*F t* (∂ (π_1 *xf*))) = (π_2 *xf*) (*F t*)
shows ∀ *t* ≥ *0*. ∀ *r*∈{*0*..*t*}. ∀ *xf* ∈ *set xfList*.
((λ *t*. *F t* (π_1 *xf*)) *has-vector-derivative F r* (∂ (π_1 *xf*))) (*at r within* {*0*..*t*})
proof(*clarify*, *rename-tac t r x f*)
fix *x f* **and** *t r*::*real*
assume *tHyp*:*0* ≤ *t* **and** *xfHyp*:(*x*, *f*) ∈ *set xfList* **and** *rHyp*:*r* ∈ {*0*..*t*}
from *this* **and** *vars* **have** ((λ*t*. *F t x*) *solves-ode* (λ*t r*. *f* (*F t*))) {*0*..*t*} *UNIV*
using *tHyp* **by** *fastforce*
hence ∗:∀ *r*∈{*0*..*t*}. ((λ *t*. *F t x*) *has-vector-derivative* (λ *t*. *f* (*F t*)) *r*) (*at r within* {*0*..*t*})
by (*simp add*: *solves-ode-def has-vderiv-on-def tHyp*)
have ∀ *t* ≥ *0*. ∀ *r*∈{*0*..*t*}. ∀ *xf* ∈ *set xfList*. (*F r* (∂ (π_1 *xf*))) = (π_2 *xf*) (*F r*)
using *assms* **by** *auto*
from *this rHyp* **and** *xfHyp* **have** (*F r* (∂ *x*)) = *f* (*F r*) **by** *force*
then show ((λ*t*. *F t* (π_1 (*x*, *f*))) *has-vector-derivative F r* (∂ (π_1 (*x*, *f*)))) (*at r within* {*0*..*t*})
using ∗ *rHyp* **by** *auto*
qed

lemma *derivationLemma-baseCase*:
fixes *F*::*real* ⇒ *real store*
assumes *solves*:*solvesStoreIVP F xfList a*
shows ∀ *x* ∈ (*UNIV* − *varDiffs*). ∀ *t* ≥ *0*. ∀ *r*∈{*0*..*t*}.
((λ *t*. *F t x*) *has-vector-derivative F r* (∂ *x*)) (*at r within* {*0*..*t*})
proof
fix *x*
assume *x* ∈ *UNIV* − *varDiffs*
then have *notVarDiff*:∀ *z*. *x* ≠ ∂ *z* **using** *varDiffs-def* **by** *fastforce*
show ∀ *t*≥*0*. ∀ *r*∈{*0*..*t*}. ((λ*t*. *F t x*) *has-vector-derivative F r* (∂ *x*)) (*at r within* {*0*..*t*})
proof(*cases x* ∈ *set* (*map* π_1 *xfList*))
case *True*
from *this* **and** *solves* **have** ∀ *t* ≥ *0*. ∀ *r*∈{*0*..*t*}. ∀ *xf* ∈ *set xfList*.
((λ *t*. *F t* (π_1 *xf*)) *has-vector-derivative F r* (∂ (π_1 *xf*))) (*at r within* {*0*..*t*})
apply(*rule-tac solvesStoreIVP-couldBeModified*) **using** *solves solves-store-ivpD* **by** *auto*
from *this* **show** *?thesis* **using** *True* **by** *auto*
next
case *False*
from *this notVarDiff* **and** *solves* **have** *const*:∀ *t* ≥ *0*. *F t x* = *a x*
using *solves-store-ivpD*(*1*) **by** (*simp add*: *varDiffs-def*)
have *constD*:∀ *t* ≥ *0*. ∀ *r*∈{*0*..*t*}. ((λ *r*. *a x*) *has-vector-derivative 0*) (*at r within* {*0*..*t*})
by (*auto intro*: *derivative-eq-intros*)

```
    {fix t r::real
     assume t≥0 and r ∈ {0..t}
     hence ((λ s. a x) has-vector-derivative 0) (at r within {0..t}) by (simp add:
constD)
     moreover have ⋀s. s ∈ {0..t} ⟹ (λ r. F r x) s = (λ r. a x) s
     using const by (simp add: ‹0 ≤ t›)
     ultimately have ((λ s. F s x) has-vector-derivative 0) (at r within {0..t})
     using has-vector-derivative-transform by (metis ‹r ∈ {0..t}›)}
    hence isZero:∀ t≥0.∀ r∈{0..t}.((λ t. F t x)has-vector-derivative 0)(at r within
{0..t})by blast
    from False solves and notVarDiff have ∀ t ≥ 0. F t (∂ x) = 0
    using solves-store-ivpD(2) by simp
    then show ?thesis using isZero by simp
  qed
qed

lemma derivationLemma:
assumes solvesStoreIVP F xfList a
and tHyp:t ≥ 0
and termVarsHyp:∀ x ∈ trmVars η. x ∈ (UNIV − varDiffs)
shows ∀ r∈{0..t}. ((λ s. ⟦η⟧t (F s))has-vector-derivative ⟦∂t η⟧t (F r)) (at r within
{0..t})
using termVarsHyp proof(induction η)
  case (Const r)
  then show ?case by simp
next
  case (Var y)
  then have yHyp:y ∈ UNIV − varDiffs by auto
  from this tHyp and assms(1) show ?case
  using derivationLemma-baseCase by auto
next
  case (Mns η)
  then show ?case
  apply(clarsimp)
  by(rule derivative-intros, simp)
next
  case (Sum η1 η2)
  then show ?case
  apply(clarsimp)
  by(rule derivative-intros, simp-all)
next
  case (Mult η1 η2)
  then show ?case
  apply(clarsimp)
  apply(subgoal-tac ((λs. ⟦η1⟧t (F s) *R ⟦η2⟧t (F s)) has-vector-derivative
   ⟦∂t η1⟧t (F r) · ⟦η2⟧t (F r) + ⟦η1⟧t (F r) · ⟦∂t η2⟧t (F r)) (at r within
{0..t}),simp)
 apply(rule-tac f'1=⟦∂t η1⟧t (F r) and g'1=⟦∂t η2⟧t (F r) in derivative-eq-intros(25))
  by (simp-all add: has-field-derivative-iff-has-vector-derivative)
```

qed

lemma *diff-subst-prprty-4terms*:
assumes *solves*:$\forall$ *xf* $\in$ *set xfList*. $F\ t\ (\partial\ (\pi_1\ xf)) = \pi_2\ xf\ (F\ t)$
and *tHyp*:$(t{::}real) \geq 0$
and *listsHyp*:$map\ \pi_2\ xfList = map\ tval\ uInput$
and *termVarsHyp*:$trmVars\ \eta \subseteq (UNIV - varDiffs)$
shows $[\![\partial_t\ \eta]\!]_t\ (F\ t) = [\![((map\ (vdiff \circ \pi_1)\ xfList) \otimes uInput)\langle\partial_t\ \eta\rangle]\!]_t\ (F\ t)$
using *termVarsHyp* **apply**(*induction* η) **apply**(*simp-all add*: *substList-help2*)
using *listsHyp* **and** *solves* **apply**(*induct xfList uInput rule*: *list-induct2'*, *simp*,
simp, *simp*)
proof(*clarify*, *rename-tac y g xfTail* ϑ *trmTail x*)
fix $x\ y{::}string$ **and** $\vartheta{::}trms$ **and** g **and** $xfTail{::}((string \times (real\ store \Rightarrow real))\ list)$
and *trmTail*
assume *IH*:$\bigwedge x.\ x \notin varDiffs \Longrightarrow map\ \pi_2\ xfTail = map\ tval\ trmTail \Longrightarrow$
$\forall xf{\in}set\ xfTail.\ F\ t\ (\partial\ (\pi_1\ xf)) = \pi_2\ xf\ (F\ t) \Longrightarrow$
$F\ t\ (\partial\ x) = [\![(map\ (vdiff \circ \pi_1)\ xfTail \otimes trmTail)\langle t_V\ (\partial\ x)\rangle]\!]_t\ (F\ t)$
and *1*:$x \notin varDiffs$ **and** *2*:$map\ \pi_2\ ((y,\ g)\ \#\ xfTail) = map\ tval\ (\vartheta\ \#\ trmTail)$
and *3*:$\forall xf{\in}set\ ((y,\ g)\ \#\ xfTail).\ F\ t\ (\partial\ (\pi_1\ xf)) = \pi_2\ xf\ (F\ t)$
hence $*$:$[\![(map\ (vdiff \circ \pi_1)\ xfTail \otimes trmTail)\langle Var\ (\partial\ x)\rangle]\!]_t\ (F\ t) = F\ t\ (\partial\ x)$
using *tHyp* **by** *auto*
show $F\ t\ (\partial\ x) = [\![((map\ (vdiff \circ \pi_1)\ ((y,\ g)\ \#\ xfTail)) \otimes (\vartheta\ \#\ trmTail))\ \langle t_V$
$(\partial\ x)\rangle]\!]_t\ (F\ t)$
  proof(*cases* $x \in set\ (map\ \pi_1\ ((y,\ g)\ \#\ xfTail))$)
    case *True*
    then have $x = y \vee (x \neq y \wedge x \in set\ (map\ \pi_1\ xfTail))$ **by** *auto*
    moreover
    {assume $x = y$
      from *this* **have** $((map\ (vdiff \circ \pi_1)\ ((y,\ g)\ \#\ xfTail)) \otimes (\vartheta\ \#\ trmTail))\langle t_V$
$(\partial\ x)\rangle = \vartheta$ **by** *simp*
      also from *3 tHyp* **have** $F\ t\ (\partial\ y) = g\ (F\ t)$ **by** *simp*
      moreover from *2* **have** $[\![\vartheta]\!]_t\ (F\ t) = g\ (F\ t)$ **by** *simp*
      ultimately have *?thesis* **by** (*simp add*: ‹$x = y$›)**}**
    moreover
    {assume $x \neq y \wedge x \in set\ (map\ \pi_1\ xfTail)$
      then have $\partial\ x \neq \partial\ y$ **using** *vdiff-inj* **by** *auto*
      from *this* **have** $((map\ (vdiff \circ \pi_1)\ ((y,\ g)\ \#\ xfTail)) \otimes (\vartheta\ \#\ trmTail))\ \langle t_V$
$(\partial\ x)\rangle =$
      $((map\ (vdiff \circ \pi_1)\ xfTail) \otimes trmTail)\ \langle t_V\ (\partial\ x)\rangle$ **by** *simp*
      hence *?thesis* **using** $*$ **by** *simp***}**
    ultimately show *?thesis* **by** *blast*
  next
    case *False*
    then have $((map\ (vdiff \circ \pi_1)\ ((y,\ g)\ \#\ xfTail)) \otimes (\vartheta\ \#\ trmTail))\ \langle t_V\ (\partial\ x)\rangle$
$= t_V\ (\partial\ x)$
   using *substList-cross-vdiff-on-non-ocurring-var* **by**(*metis*(*no-types*, *lifting*) *List.map.compositionality*)
    thus *?thesis* **by** *simp*
  qed
qed

lemma *eqInVars-impl-eqInTrms*:
assumes *termVarsHyp*:*trmVars* $\eta \subseteq (UNIV - varDiffs)$
and *initHyp*:$\forall x.\ x \notin varDiffs \longrightarrow b\ x = a\ x$
shows $[\![\eta]\!]_t\ a = [\![\eta]\!]_t\ b$
using *assms* **by**(*induction* η, *simp-all*)

lemma *non-empty-funList-implies-non-empty-trmList*:
shows $\forall\ list.(x,f) \in set\ list \wedge map\ \pi_2\ list = map\ tval\ tList \longrightarrow (\exists\ \vartheta.[\![\vartheta]\!]_t = f \wedge \vartheta \in set\ tList)$
by(*induction tList*, *auto*)

lemma *dInvForTrms-prelim*:
assumes *substHyp*:
$\forall\ st.\ G\ st \longrightarrow (\forall str.\ str \notin (\pi_1 (\!|set\ xfList|\!)) \longrightarrow st\ (\partial\ str) = 0) \longrightarrow$
$[\![((map\ (vdiff \circ \pi_1)\ xfList) \otimes uInput)\ \langle \partial_t\ \eta \rangle]\!]_t\ st = 0$
and *termVarsHyp*:*trmVars* $\eta \subseteq (UNIV - varDiffs)$
and *listsHyp*:$map\ \pi_2\ xfList = map\ tval\ uInput$
shows $[\![\eta]\!]_t\ a = 0 \longrightarrow (\forall\ c.\ (a,c) \in (ODEsystem\ xfList\ with\ G) \longrightarrow [\![\eta]\!]_t\ c = 0)$
proof(*clarify*)
fix *c* **assume** *aHyp*:$[\![\eta]\!]_t\ a = 0$ **and** *cHyp*:$(a,\ c) \in ODEsystem\ xfList\ with\ G$
from *this* **obtain** t::*real* **and** F::*real* $\Rightarrow$ *real store*
where *tcHyp*:$t \geq 0 \wedge F\ t = c \wedge solvesStoreIVP\ F\ xfList\ a \wedge (\forall r \in \{0..t\}.\ G\ (F\ r))$

using *guarDiffEqtn-def* **by** *auto*
then have $\forall x.\ x \notin varDiffs \longrightarrow F\ 0\ x = a\ x$ **using** *solves-store-ivpD*(*6*) **by** *blast*
from *this* **have** $[\![\eta]\!]_t\ a = [\![\eta]\!]_t\ (F\ 0)$ **using** *termVarsHyp eqInVars-impl-eqInTrms* **by** *blast*
hence *obs1*:$[\![\eta]\!]_t\ (F\ 0) = 0$ **using** *aHyp* **by** *simp*
from *tcHyp* **have** *obs2*:$\forall r \in \{0..t\}.\ ((\lambda s.\ [\![\eta]\!]_t\ (F\ s))$ *has-vector-derivative* $[\![\partial_t\ \eta]\!]_t\ (F\ r))$ (*at r within* $\{0..t\}$) **using** *derivationLemma termVarsHyp* **by** *blast*
have $\forall r \in \{0..t\}.\ \forall\ xf \in set\ xfList.\ F\ r\ (\partial\ (\pi_1\ xf)) = \pi_2\ xf\ (F\ r)$
using *tcHyp solves-store-ivpD*(*3*) **by** *fastforce*
hence $\forall r \in \{0..t\}.\ [\![\partial_t\ \eta]\!]_t\ (F\ r) = [\![((map\ (vdiff \circ \pi_1)\ xfList) \otimes uInput)\ \langle \partial_t\ \eta \rangle]\!]_t\ (F\ r)$
using *tcHyp diff-subst-prprty-4terms termVarsHyp listsHyp* **by** *fastforce*
also from *substHyp* **have** $\forall r \in \{0..t\}.\ [\![((map\ (vdiff \circ \pi_1)\ xfList) \otimes uInput)\langle \partial_t\ \eta \rangle]\!]_t\ (F\ r) = 0$
using *solves-store-ivpD*(*2*) *tcHyp* **by** *fastforce*
ultimately have $\forall r \in \{0..t\}.\ ((\lambda s.\ [\![\eta]\!]_t\ (F\ s))$ *has-vector-derivative 0*) (*at r within* $\{0..t\}$)
using *obs2* **by** *auto*
from *this* **and** *tcHyp* **have** $\forall s \in \{0..t\}.\ ((\lambda x.\ [\![\eta]\!]_t\ (F\ x))$ *has-derivative* $(\lambda x.\ x *_R 0))$
(*at s within* $\{0..t\}$) **by** (*metis has-vector-derivative-def*)
hence $[\![\eta]\!]_t\ (F\ t) - [\![\eta]\!]_t\ (F\ 0) = (\lambda x.\ x *_R 0)\ (t - 0)$
using *mvt-very-simple* **and** *tcHyp* **by** *fastforce*
then show $[\![\eta]\!]_t\ c = 0$ **using** *obs1 tcHyp* **by** *auto*
qed

theorem *dInvForTrms*:
assumes $\forall$ *st*. *G st* $\longrightarrow$ ($\forall$ *str*. *str* $\notin$ (π_1(|*set xfList*|)) $\longrightarrow$ *st* (∂ *str*) = *0*) $\longrightarrow$
$[\![((map\ (vdiff \circ \pi_1)\ xfList) \otimes uInput)\ \langle\partial_t\ \eta\rangle]\!]_t\ st = 0$
and *termVarsHyp*:*trmVars* $\eta \subseteq$ (*UNIV* − *varDiffs*)
and *listsHyp*:*map* π_2 *xfList* = *map tval uInput*
and *eta-f*:*f* = $[\![\eta]\!]_t$
shows *PRE* (λ *s*. *f s* = *0*) (*ODEsystem xfList with G*) *POST* (λ *s*. *f s* = *0*)
using *eta-f* **proof**(*clarsimp*)
fix *a b*
assume (*a*, *b*) $\in \lceil\lambda s.\ [\![\eta]\!]_t\ s = 0\rceil$ **and** $f = [\![\eta]\!]_t$
from *this* **have** *aHyp*:$a = b \wedge [\![\eta]\!]_t\ a = 0$ **by** (*metis* (*full-types*) *d-p2r rdom-p2r-contents*)
have $[\![\eta]\!]_t\ a = 0 \longrightarrow (\forall\ c.\ (a,c) \in$ (*ODEsystem xfList with G*) $\longrightarrow [\![\eta]\!]_t\ c = 0)$
using *assms dInvForTrms-prelim* **by** *metis*
from *this* **and** *aHyp* **have** $\forall$ *c*. (*a*,*c*) $\in$ (*ODEsystem xfList with G*) $\longrightarrow [\![\eta]\!]_t\ c =$
0 **by** *blast*
thus (*a*, *b*) $\in$ *wp* (*ODEsystem xfList with G*) $\lceil\lambda s.\ [\![\eta]\!]_t\ s = 0\rceil$
using *aHyp* **by** (*simp add*: *boxProgrPred-chrctrztn*)
qed

lemma *diff-subst-prprty-4props*:
assumes *solves*:$\forall$ *xf* $\in$ *set xfList*. *F t* (∂ (π_1 *xf*)) = π_2 *xf* (*F t*)
and *tHyp*:*t* $\geq$ *0*
and *listsHyp*:*map* π_2 *xfList* = *map tval uInput*
and *propVarsHyp*:*propVars* $\varphi \subseteq$ (*UNIV* − *varDiffs*)
shows $[\![\partial_P\ \varphi]\!]_P\ (F\ t) = [\![((map\ (vdiff \circ \pi_1)\ xfList) \otimes uInput)\upharpoonright\partial_P\ \varphi\upharpoonright]\!]_P\ (F\ t)$
using *propVarsHyp* **apply**(*induction* φ, *simp-all*)
using *assms diff-subst-prprty-4terms* **apply** *fastforce*
using *assms diff-subst-prprty-4terms* **apply** *fastforce*
using *assms diff-subst-prprty-4terms* **by** *fastforce*

lemma *dInvForProps-prelim*:
assumes *substHyp*:
$\forall$ *st*. *G st* $\longrightarrow$ ($\forall$ *str*. *str* $\notin$ (π_1(|*set xfList*|)) $\longrightarrow$ *st* (∂ *str*) = *0*) $\longrightarrow$
$[\![((map\ (vdiff \circ \pi_1)\ xfList) \otimes uInput)\ \langle\partial_t\ \eta\rangle]\!]_t\ st \geq 0$
and *termVarsHyp*:*trmVars* $\eta \subseteq$ (*UNIV* − *varDiffs*)
and *listsHyp*:*map* π_2 *xfList* = *map tval uInput*
shows $[\![\eta]\!]_t\ a > 0 \longrightarrow (\forall\ c.\ (a,c) \in$ (*ODEsystem xfList with G*) $\longrightarrow [\![\eta]\!]_t\ c > 0)$
and $[\![\eta]\!]_t\ a \geq 0 \longrightarrow (\forall\ c.\ (a,c) \in$ (*ODEsystem xfList with G*) $\longrightarrow [\![\eta]\!]_t\ c \geq 0)$
proof(*clarify*)
fix *c* **assume** *aHyp*:$[\![\eta]\!]_t\ a > 0$ **and** *cHyp*:(*a*, *c*) $\in$ *ODEsystem xfList with G*
from *this* **obtain** *t*::*real* **and** *F*::*real* $\Rightarrow$ *real store*
where *tcHyp*:$t \geq 0 \wedge F\ t = c \wedge$ *solvesStoreIVP F xfList a* $\wedge$ ($\forall$ *r*$\in${*0*..*t*}. *G* (*F r*))

using *guarDiffEqtn-def* **by** *auto*
then have $\forall$ *x*. *x* $\notin$ *varDiffs* $\longrightarrow$ *F 0 x* = *a x* **using** *solves-store-ivpD*(*6*) **by** *blast*
from *this* **have** $[\![\eta]\!]_t\ a = [\![\eta]\!]_t\ (F\ 0)$ **using** *termVarsHyp eqInVars-impl-eqInTrms*
by *blast*
hence *obs1*:$[\![\eta]\!]_t\ (F\ 0) > 0$ **using** *aHyp tcHyp* **by** *simp*

from *tcHyp* **have** *obs2*:$\forall r\in\{0..t\}$. $((\lambda s.\ [\![\eta]\!]_t\ (F\ s))$ *has-vector-derivative*
$[\![\partial_t\ \eta]\!]_t\ (F\ r))$ (*at r within* $\{0..t\}$) **using** *derivationLemma termVarsHyp* **by** *blast*
have $(\forall t\geq 0.\ \forall\ xf \in set\ xfList.\ F\ t\ (\partial\ (\pi_1\ xf)) = \pi_2\ xf\ (F\ t))$
using *tcHyp solves-store-ivpD*(*3*) **by** *blast*
hence $\forall r\in\{0..t\}.\ [\![\partial_t\ \eta]\!]_t\ (F\ r) = [\![((map\ (vdiff \circ \pi_1)\ xfList) \otimes uInput)\ \langle\partial_t\ \eta\rangle]\!]_t$
$(F\ r)$
using *diff-subst-prprty-4terms termVarsHyp tcHyp listsHyp* **by** *fastforce*
also from *substHyp* **have** $\forall r\in\{0..t\}.\ [\![((map\ (vdiff \circ \pi_1)\ xfList) \otimes uInput)\ \langle\partial_t$
$\eta\rangle]\!]_t\ (F\ r) \geq 0$
using *solves-store-ivpD*(*2*) *tcHyp* **by** (*metis atLeastAtMost-iff*)
ultimately have $*$:$\forall r\in\{0..t\}.\ [\![\partial_t\ \eta]\!]_t\ (F\ r) \geq 0$ **by** (*simp*)
from *obs2* **and** *tcHyp* **have** $\forall r\in\{0..t\}.\ ((\lambda s.\ [\![\eta]\!]_t\ (F\ s))$ *has-derivative*
$(\lambda x.\ x *_R ([\![\partial_t\ \eta]\!]_t\ (F\ r))))$ (*at r within* $\{0..t\}$) **by** (*simp add*: *has-vector-derivative-def*)

hence $\exists r\in\{0..t\}.\ [\![\eta]\!]_t\ (F\ t) - [\![\eta]\!]_t\ (F\ 0) = t \cdot ([\![(\partial_t\ \eta)]\!]_t)\ (F\ r)$
using *mvt-very-simple* **and** *tcHyp* **by** *fastforce*
then obtain *r* **where** $[\![\partial_t\ \eta]\!]_t\ (F\ r) \geq 0 \wedge 0 \leq r \wedge r \leq t \wedge [\![\partial_t\ \eta]\!]_t\ (F\ t) \geq 0$
$\wedge\ [\![\eta]\!]_t\ (F\ t) - [\![\eta]\!]_t\ (F\ 0) = t \cdot ([\![\partial_t\ \eta]\!]_t\ (F\ r))$
using $*$ *tcHyp* **by** (*meson atLeastAtMost-iff order-refl*)
thus $[\![\eta]\!]_t\ c > 0$
using *obs1 tcHyp* **by** (*metis cancel-comm-monoid-add-class.diff-cancel diff-ge-0-iff-ge*

diff-strict-mono linorder-neqE-linordered-idom linordered-field-class.sign-simps(*45*)
not-le)
next
show $0 \leq [\![\eta]\!]_t\ a \longrightarrow (\forall c.\ (a,\ c) \in ODEsystem\ xfList\ with\ G\ \longrightarrow 0 \leq [\![\eta]\!]_t\ c)$
proof(*clarify*)
fix *c* **assume** *aHyp*:$[\![\eta]\!]_t\ a \geq 0$ **and** *cHyp*:$(a,\ c) \in ODEsystem\ xfList\ with\ G$
from *this* **obtain** *t*::*real* **and** *F*::*real* $\Rightarrow$ *real store*
where *tcHyp*:$t\geq 0 \wedge F\ t = c \wedge solvesStoreIVP\ F\ xfList\ a \wedge (\forall r\in\{0..t\}.\ G\ (F\ r))$

using *guarDiffEqtn-def* **by** *auto*
then have $\forall x.\ x \notin varDiffs \longrightarrow F\ 0\ x = a\ x$ **using** *solves-store-ivpD*(*6*) **by** *blast*
from *this* **have** $[\![\eta]\!]_t\ a = [\![\eta]\!]_t\ (F\ 0)$ **using** *termVarsHyp eqInVars-impl-eqInTrms*
by *blast*
hence *obs1*:$[\![\eta]\!]_t\ (F\ 0) \geq 0$ **using** *aHyp tcHyp* **by** *simp*
from *tcHyp* **have** *obs2*:$\forall r\in\{0..t\}.\ ((\lambda s.\ [\![\eta]\!]_t\ (F\ s))$ *has-vector-derivative*
$[\![\partial_t\ \eta]\!]_t\ (F\ r))$ (*at r within* $\{0..t\}$) **using** *derivationLemma termVarsHyp* **by** *blast*
have $(\forall t\geq 0.\ \forall\ xf \in set\ xfList.\ F\ t\ (\partial\ (\pi_1\ xf)) = \pi_2\ xf\ (F\ t))$
using *tcHyp solves-store-ivpD*(*3*) **by** *blast*
from *this* **and** *tcHyp* **have** $\forall r\in\{0..t\}.\ [\![\partial_t\ \eta]\!]_t\ (F\ r) =$
$[\![((map\ (vdiff \circ \pi_1)\ xfList) \otimes uInput)\ \langle\partial_t\ \eta\rangle]\!]_t\ (F\ r)$
using *diff-subst-prprty-4terms termVarsHyp listsHyp* **by** *fastforce*
also from *substHyp* **have** $\forall r\in\{0..t\}.\ [\![((map\ (vdiff \circ \pi_1)\ xfList) \otimes uInput)\ \langle\partial_t$
$\eta\rangle]\!]_t\ (F\ r) \geq 0$
using *solves-store-ivpD*(*2*) *tcHyp* **by** (*metis atLeastAtMost-iff*)
ultimately have $*$:$\forall r\in\{0..t\}.\ [\![\partial_t\ \eta]\!]_t\ (F\ r) \geq 0$ **by** (*simp*)
from *obs2* **and** *tcHyp* **have** $\forall r\in\{0..t\}.\ ((\lambda s.\ [\![\eta]\!]_t\ (F\ s))$ *has-derivative*
$(\lambda x.\ x *_R ([\![\partial_t\ \eta]\!]_t\ (F\ r))))$ (*at r within* $\{0..t\}$) **by** (*simp add*: *has-vector-derivative-def*)

hence $\exists\, r{\in}\{0..t\}.\ [\![\eta]\!]_t\ (F\ t) - [\![\eta]\!]_t\ (F\ 0) = t \cdot ([\![\partial_t\ \eta]\!]_t\ (F\ r))$
using *mvt-very-simple* **and** *tcHyp* **by** *fastforce*
then obtain r **where** $[\![\partial_t\ \eta]\!]_t\ (F\ r) \geq 0 \wedge 0 \leq r \wedge r \leq t \wedge [\![\partial_t\ \eta]\!]_t\ (F\ t) \geq 0$
$\wedge\ [\![\eta]\!]_t\ (F\ t) - [\![\eta]\!]_t\ (F\ 0) = t \cdot ([\![\partial_t\ \eta]\!]_t\ (F\ r))$
using $*$ *tcHyp* **by** (*meson atLeastAtMost-iff order-refl*)
thus $[\![\eta]\!]_t\ c \geq 0$
using *obs1 tcHyp* **by** (*metis cancel-comm-monoid-add-class.diff-cancel diff-ge-0-iff-ge*

diff-strict-mono linorder-neqE-linordered-idom linordered-field-class.sign-simps(*45*)
not-le)
qed
qed

lemma *less-pval-to-tval*:
assumes $[\![((map\ (vdiff \circ \pi_1)\ xfList) \otimes uInput)\upharpoonright\partial_P\ (\vartheta \prec \eta)\upharpoonright]\!]_P\ st$
shows $[\![((map\ (vdiff{\circ}\pi_1)\ xfList) \otimes uInput)\langle\partial_t\ (\eta \oplus (\ominus\ \vartheta))\rangle]\!]_t\ st \geq 0$
using *assms* **by**(*auto*)

lemma *leq-pval-to-tval*:
assumes $[\![((map\ (vdiff \circ \pi_1)\ xfList) \otimes uInput)\upharpoonright\partial_P\ (\vartheta \preceq \eta)\upharpoonright]\!]_P\ st$
shows $[\![((map\ (vdiff{\circ}\pi_1)\ xfList) \otimes uInput)\langle\partial_t\ (\eta \oplus (\ominus\ \vartheta))\rangle]\!]_t\ st \geq 0$
using *assms* **by**(*auto*)

lemma *dInv-prelim*:
assumes *substHyp*:$\forall\ st.\ G\ st \longrightarrow\ (\forall\, str.\ str \notin (\pi_1 (\!|set\ xfList|\!)) \longrightarrow st\ (\partial\ str) =$
$0) \longrightarrow$
$[\![((map\ (vdiff \circ \pi_1)\ xfList) \otimes uInput)\upharpoonright\partial_P\ \varphi\upharpoonright]\!]_P\ st$
and *propVarsHyp*:$propVars\ \varphi \subseteq (UNIV - varDiffs)$
and *listsHyp*:$map\ \pi_2\ xfList = map\ tval\ uInput$
shows $[\![\varphi]\!]_P\ a \longrightarrow (\forall\ c.\ (a,c) \in (ODEsystem\ xfList\ with\ G) \longrightarrow [\![\varphi]\!]_P\ c)$
proof(*clarify*)
fix c **assume** *aHyp*:$[\![\varphi]\!]_P\ a$ **and** *cHyp*:$(a,\ c) \in ODEsystem\ xfList\ with\ G$
from *this* **obtain** t::*real* **and** F::*real* $\Rightarrow$ *real store*
where *tcHyp*:$t{\geq}0 \wedge F\ t = c \wedge solvesStoreIVP\ F\ xfList\ a$ **using** *guarDiffEqtn-def*
by *auto*
from *aHyp propVarsHyp* **and** *substHyp* **show** $[\![\varphi]\!]_P\ c$
proof(*induction* φ)
case (*Eq* $\vartheta\ \eta$)
hence *hyp*:$\forall\, st.\ G\ st \longrightarrow\ (\forall\, str.\ str \notin (\pi_1 (\!|set\ xfList|\!)) \longrightarrow st\ (\partial\ str) = 0) \longrightarrow$
$[\![((map\ (vdiff \circ \pi_1)\ xfList) \otimes uInput)\upharpoonright\partial_P\ (\vartheta \doteq \eta)\upharpoonright]\!]_P\ st$ **by** *blast*
then have $\forall\, st.\ G\ st \longrightarrow (\forall\, str.\ str \notin (\pi_1 (\!|set\ xfList|\!)) \longrightarrow st\ (\partial\ str) = 0) \longrightarrow$
$[\![((map\ (vdiff \circ \pi_1)\ xfList) \otimes uInput)\langle\partial_t\ (\vartheta \oplus (\ominus\ \eta))\rangle]\!]_t\ st = 0$ **by** *simp*
also have $trmVars\ (\vartheta \oplus (\ominus\ \eta)) \subseteq UNIV - varDiffs$ **using** *Eq.prems*(*2*) **by** *simp*
moreover have $[\![\vartheta \oplus (\ominus\ \eta)]\!]_t\ a = 0$ **using** *Eq.prems*(*1*) **by** *simp*
ultimately have $(\forall\, c.\ (a,\ c) \in ODEsystem\ xfList\ with\ G\ \longrightarrow [\![\vartheta \oplus (\ominus\ \eta)]\!]_t\ c =$
$0)$
using *dInvForTrms-prelim listsHyp* **by** *blast*
hence $[\![\vartheta \oplus (\ominus\ \eta)]\!]_t\ (F\ t) = 0$ **using** *tcHyp cHyp* **by** *simp*

from *this* **have** $[\![\vartheta]\!]_t\ (F\ t) = [\![\eta]\!]_t\ (F\ t)$ **by** *simp*
also have $([\![\vartheta \doteq \eta]\!]_P)\ c = ([\![\vartheta]\!]_t\ (F\ t) = [\![\eta]\!]_t\ (F\ t))$ **using** *tcHyp* **by** *simp*
ultimately show *?case* **by** *simp*
next
case $(\mathit{Less}\ \vartheta\ \eta)$
hence $\forall\, st.\ G\ st \longrightarrow (\forall\, str.\ str \notin (\pi_1 (\!|set\ xfList|\!)) \longrightarrow st\ (\partial\ str) = 0) \longrightarrow$
$0 \leq ([\![(map\ (vdiff \circ \pi_1)\ xfList \otimes uInput)\langle\partial_t\ (\eta \oplus (\ominus\ \vartheta))\rangle]\!]_t)\ st$
using *less-pval-to-tval* **by** *metis*
also from $\mathit{Less.prems}(2)$**have** $\mathit{trmVars}\ (\eta \oplus (\ominus\ \vartheta)) \subseteq \mathit{UNIV} - \mathit{varDiffs}$ **by** *simp*
moreover have $[\![\eta \oplus (\ominus\ \vartheta)]\!]_t\ a > 0$ **using** $\mathit{Less.prems}(1)$ **by** *simp*
ultimately have $(\forall\, c.\ (a,\ c) \in \mathit{ODEsystem\ xfList\ with\ G} \longrightarrow [\![\eta \oplus (\ominus\ \vartheta)]\!]_t\ c >$
$0)$
using $\mathit{dInvForProps\text{-}prelim}(1)$ *listsHyp* **by** *blast*
hence $[\![\eta \oplus (\ominus\ \vartheta)]\!]_t\ (F\ t) > 0$ **using** *tcHyp cHyp* **by** *simp*
from *this* **have** $[\![\eta]\!]_t\ (F\ t) > [\![\vartheta]\!]_t\ (F\ t)$ **by** *simp*
also have $[\![\vartheta \prec \eta]\!]_P\ c = ([\![\vartheta]\!]_t\ (F\ t) < [\![\eta]\!]_t\ (F\ t))$ **using** *tcHyp* **by** *simp*
ultimately show *?case* **by** *simp*
next
case $(\mathit{Leq}\ \vartheta\ \eta)$
hence $\forall\, st.\ G\ st \longrightarrow (\forall\, str.\ str \notin (\pi_1 (\!|set\ xfList|\!)) \longrightarrow st\ (\partial\ str) = 0) \longrightarrow$
$0 \leq ([\![(map\ (vdiff \circ \pi_1)\ xfList \otimes uInput)\langle\partial_t\ (\eta \oplus (\ominus\ \vartheta))\rangle]\!]_t)\ st$ **using** *leq-pval-to-tval*
by *metis*
also from $\mathit{Leq.prems}(2)$**have** $\mathit{trmVars}\ (\eta \oplus (\ominus\ \vartheta)) \subseteq \mathit{UNIV} - \mathit{varDiffs}$ **by** *simp*
moreover have $[\![\eta \oplus (\ominus\ \vartheta)]\!]_t\ a \geq 0$ **using** $\mathit{Leq.prems}(1)$ **by** *simp*
ultimately have $(\forall\, c.\ (a,\ c) \in \mathit{ODEsystem\ xfList\ with\ G} \longrightarrow [\![\eta \oplus (\ominus\ \vartheta)]\!]_t\ c \geq$
$0)$
using $\mathit{dInvForProps\text{-}prelim}(2)$ *listsHyp* **by** *blast*
hence $[\![\eta \oplus (\ominus\ \vartheta)]\!]_t\ (F\ t) \geq 0$ **using** *tcHyp cHyp* **by** *simp*
from *this* **have** $([\![\eta]\!]_t\ (F\ t) \geq [\![\vartheta]\!]_t\ (F\ t))$ **by** *simp*
also have $[\![\vartheta \preceq \eta]\!]_P\ c = ([\![\vartheta]\!]_t\ (F\ t) \leq [\![\eta]\!]_t\ (F\ t))$ **using** *tcHyp* **by** *simp*
ultimately show *?case* **by** *simp*
next
case $(\mathit{And}\ \varphi 1\ \varphi 2)$
then show *?case* **by**(*simp*)
next
case $(\mathit{Or}\ \varphi 1\ \varphi 2)$
from *this* **show** *?case* **by** *auto*
qed
qed

theorem *dInv*:
assumes $\forall\ st.\ G\ st \longrightarrow (\forall\, str.\ str \notin (\pi_1 (\!|set\ xfList|\!)) \longrightarrow st\ (\partial\ str) = 0) \longrightarrow$
$[\![((map\ (vdiff \circ \pi_1)\ xfList) \otimes uInput)\upharpoonleft\partial_P\ \varphi\upharpoonright]\!]_P\ st$
and $\mathit{termVarsHyp}{:}\mathit{propVars}\ \varphi \subseteq (\mathit{UNIV} - \mathit{varDiffs})$
and $\mathit{listsHyp}{:}map\ \pi_2\ xfList = map\ tval\ uInput$
and $\mathit{phi\text{-}p}{:}P = [\![\varphi]\!]_P$
shows $\mathit{PRE}\ P\ (\mathit{ODEsystem\ xfList\ with\ G})\ \mathit{POST}\ P$
proof(*clarsimp*)
fix *a b*

assume $(a,\ b) \in \lceil P \rceil$
from *this* **have** $aHyp{:}a = b \wedge P\ a$ **by** (*metis* (*full-types*) *d-p2r rdom-p2r-contents*)
have $P\ a \longrightarrow (\forall\ \ c.\ (a,c) \in (ODEsystem\ xfList\ with\ G) \longrightarrow P\ c)$
using *assms dInv-prelim* **by** *metis*
from *this* **and** *aHyp* **have** $\forall\ \ c.\ (a,c) \in (ODEsystem\ xfList\ with\ G) \longrightarrow P\ c$ **by** *blast*
thus $(a,\ b) \in wp\ (ODEsystem\ xfList\ with\ G\ )\ \lceil P \rceil$
using *aHyp* **by** (*simp add*: *boxProgrPred-chrctrztn*)
qed

theorem *dInvFinal*:
assumes $\forall\ \ st.\ G\ st \longrightarrow (\forall str.\ str \notin (\pi_1 (\!| set\ xfList |\!)) \longrightarrow st\ (\partial\ str) = 0) \longrightarrow [\![((map\ (vdiff \circ \pi_1)\ xfList) \otimes uInput) \upharpoonleft \partial_P\ \varphi \upharpoonright]\!]_P\ st$
and $termVarsHyp{:}propVars\ \varphi \subseteq (UNIV - varDiffs)$
and $listsHyp{:}map\ \pi_2\ xfList = map\ tval\ uInput$
and $impls{:}\lceil P \rceil \subseteq \lceil F \rceil \wedge \lceil F \rceil \subseteq \lceil Q \rceil$
and $phi\text{-}f{:}F = [\![\varphi]\!]_P$
shows *PRE P* (*ODEsystem xfList with G*) *POST Q*
apply(*rule-tac* $C{=}[\![\varphi]\!]_P$ **in** *dCut*)
apply(*subgoal-tac* $\lceil F \rceil \subseteq wp\ (ODEsystem\ xfList\ with\ G)\ \lceil F \rceil$, *simp*)
using *impls* **and** *phi-f* **apply** *blast*
apply(*subgoal-tac PRE F* (*ODEsystem xfList with G*) *POST F*, *simp*)
apply(*rule-tac* $\varphi{=}\varphi$ **and** *uInput=uInput* **in** *dInv*)
prefer *5* **apply**(*subgoal-tac PRE P* (*ODEsystem xfList with* $(\lambda s.\ G\ s \wedge F\ s)$) *POST Q*, *simp add*: *phi-f*)
apply(*rule dWeakening*)
using *impls* **apply** *simp*
using *assms* **by** *simp-all*

end
theory *VC-diffKAD-examples*
imports *VC-diffKAD*

begin

7.4.5 Rules Testing

In this section we test the recently developed rules with simple dynamical systems.

— Example of hybrid program verified with the rule dSolve and a single differential equation: $x' = v$.
lemma *motion-with-constant-velocity*:
$PRE\ (\lambda\ s.\ s\ ''y'' < s\ ''x''\ \wedge s\ ''v'' > 0)$
$(ODEsystem\ [(''x'',(\lambda\ s.\ s\ ''v''))]\ with\ (\lambda\ s.\ True))$
$POST\ (\lambda\ s.\ (s\ ''y'' < s\ ''x''))$
apply(*rule-tac* $uInput{=}[\lambda\ t\ s.\ s\ ''v'' \cdot t + s\ ''x'']$ **in** *dSolve-toSolveUBC*)
prefer *9* **subgoal by**(*simp add*: *wp-trafo vdiff-def add-strict-increasing2*)
apply(*simp-all add*: *vdiff-def varDiffs-def*)
prefer *2* **apply**(*simp add*: *solvesStoreIVP-def vdiff-def varDiffs-def*)

apply(*clarify*, *rule-tac* $f'1=\lambda\ x.\ s\ ''v''$ **and** $g'1=\lambda\ x.\ 0$ **in** *derivative-intros*(*191*))
apply(*rule-tac* $f'1=\lambda\ x.0$ **and** $g'1=\lambda\ x.1$ **in** *derivative-intros*(*194*))
by(*auto intro*: *derivative-intros*)

Same hybrid program verified with dSolve and the system of ODEs: $x' = v, v' = a$. The uniqueness part of the proof requires a preliminary lemma.

lemma *flow-vel-is-galilean-vel*:
assumes *solHyp*:φ_s *solvesTheStoreIVP* $[(x,\ \lambda s.\ s\ v),\ (v,\ \lambda s.\ s\ a)]$ *withInitState s*
and *tHyp*:$r \leq t$ **and** *rHyp*:$0 \leq r$ **and** *distinct*:$x \neq v \wedge v \neq a \wedge x \neq a \wedge a \notin$ *varDiffs*
shows $\varphi_s\ r\ v = s\ a \cdot r + s\ v$
proof−
from *assms* **have** *1*:$((\lambda t.\ \varphi_s\ t\ v)$ *solves-ode* $(\lambda t\ r.\ \varphi_s\ t\ a))\ \{0..t\}$ *UNIV* $\wedge\ \varphi_s\ 0\ v = s\ v$
by (*simp add*: *solvesStoreIVP-def*)
from *assms* **have** *obs*:$\forall\ r \in \{0..t\}.\ \varphi_s\ r\ a = s\ a$
by(*auto simp*: *solvesStoreIVP-def varDiffs-def*)
have *2*:$((\lambda t.\ s\ a \cdot t + s\ v)$ *solves-ode* $(\lambda t\ r.\ \varphi_s\ t\ a))\ \{0..t\}$ *UNIV*
unfolding *solves-ode-def* **apply**(*subgoal-tac* $((\lambda x.\ s\ a \cdot x + s\ v)$ *has-vderiv-on* $(\lambda x.\ s\ a))\ \{0..t\})$
using *obs* **apply** (*simp add*: *has-vderiv-on-def*) **by**(*rule galilean-transform*)
have *3*:*unique-on-bounded-closed* $0\ \{0..t\}\ (s\ v)\ (\lambda t\ r.\ \varphi_s\ t\ a)$ *UNIV* (*if* $t = 0$ *then* 1 *else* $1/(t+1)$)
apply(*simp add*: *ubc-definitions del*: *comp-apply*, *rule conjI*)
using *rHyp tHyp obs* **apply**(*simp-all del*: *comp-apply*)
apply(*clarify*, *rule continuous-intros*) **prefer** *3* **apply** *safe*
apply(*rule continuous-intros*)
apply(*auto intro*: *continuous-intros*)
by (*metis continuous-on-const continuous-on-eq*)
thus $\varphi_s\ r\ v = s\ a \cdot r + s\ v$
apply(*rule-tac unique-on-bounded-closed.unique-solution*[*of* $0\ \{0..t\}\ s\ v$ $(\lambda t\ r.\ \varphi_s\ t\ a)$ *UNIV* (*if* $t = 0$ *then* 1 *else* $1\ /\ (t + 1)$) $(\lambda t.\ \varphi_s\ t\ v)$])
using *rHyp tHyp 1 2* **and** *3* **by** *auto*
qed

lemma *motion-with-constant-acceleration*:
PRE $(\lambda\ s.\ s\ ''y'' < s\ ''x''\ \wedge s\ ''v'' \geq 0 \wedge s\ ''a'' > 0)$
(*ODEsystem* $[(''x'',(\lambda\ s.\ s\ ''v'')),(''v'',(\lambda\ s.\ s\ ''a''))]$ *with* $(\lambda\ s.\ True)$)
POST $(\lambda\ s.\ (s\ ''y'' < s\ ''x''))$
apply(*rule-tac uInput*=$[\lambda\ t\ s.\ s\ ''a'' \cdot t\ \hat{}\ 2/2 + s\ ''v'' \cdot t + s\ ''x'',$
$\lambda\ t\ s.\ s\ ''a'' \cdot t + s\ ''v'']$ **in** *dSolve-toSolveUBC*)
prefer *9* **subgoal** **by**(*simp add*: *wp-trafo vdiff-def add-strict-increasing2*)
prefer *6* **subgoal**
apply(*simp add*: *vdiff-def*, *clarify*, *rule conjI*)
by(*rule galilean-transform*)+
prefer *6* **subgoal**
apply(*simp add*: *vdiff-def*, *safe*)
by(*rule continuous-intros*)+
prefer *6* **subgoal**

apply(*simp add*: *vdiff-def*, *safe*)
subgoal for *s* φ_s *t r* **apply**(*rule flow-vel-is-galilean-vel*[*of* φ_s *''x''* - - - - *t*])
by(*simp-all add*: *varDiffs-def vdiff-def*)
apply(*simp add*: *solvesStoreIVP-def vdiff-def varDiffs-def*) **done**
by(*auto simp*: *varDiffs-def vdiff-def*)

Example of a hybrid system with two modes verified with the equality dS. We also need to provide a previous (similar) lemma.

lemma *flow-vel-is-galilean-vel2*:
assumes *solHyp*:φ_s *solvesTheStoreIVP* [(*x*, $\lambda s.\ s\ v$), (*v*, $\lambda s. - s\ a$)] *withInitState s*
and *tHyp*:$r \leq t$ **and** *rHyp*:$0 \leq r$ **and** *distinct*:$x \neq v \wedge v \neq a \wedge x \neq a \wedge a \notin$ *varDiffs*
shows $\varphi_s\ r\ v = s\ v - s\ a \cdot r$
proof−
from *assms* **have** *1*:(($\lambda t.\ \varphi_s\ t\ v$) *solves-ode* ($\lambda t\ r. - \varphi_s\ t\ a$)) {*0..t*} *UNIV* $\wedge\ \varphi_s$ *0* $v = s\ v$
by (*simp add*: *solvesStoreIVP-def*)
from *assms* **have** *obs*:$\forall\ r \in$ {*0..t*}. $\varphi_s\ r\ a = s\ a$
by(*auto simp*: *solvesStoreIVP-def varDiffs-def*)
have *2*:(($\lambda t. - s\ a \cdot t + s\ v$) *solves-ode* ($\lambda t\ r. - \varphi_s\ t\ a$)) {*0..t*} *UNIV*
unfolding *solves-ode-def* **apply**(*subgoal-tac* (($\lambda x. - s\ a \cdot x + s\ v$) *has-vderiv-on* ($\lambda x. - s\ a$)) {*0..t*})
using *obs* **apply** (*simp add*: *has-vderiv-on-def*) **by**(*rule galilean-transform*)
have *3*:*unique-on-bounded-closed 0* {*0..t*} (*s v*) ($\lambda t\ r. - \varphi_s\ t\ a$) *UNIV* (*if t* = *0 then 1 else 1*/(*t*+*1*))
apply(*simp add*: *ubc-definitions del*: *comp-apply*, *rule conjI*)
using *rHyp tHyp obs* **apply**(*simp-all del*: *comp-apply*)
apply(*clarify*, *rule continuous-intros*) **prefer** *3* **apply** *safe*
apply(*rule continuous-intros*)+
apply(*auto intro*: *continuous-intros*)
by (*metis continuous-on-const continuous-on-eq*)
thus $\varphi_s\ r\ v = s\ v - s\ a \cdot r$
apply(*rule-tac unique-on-bounded-closed.unique-solution*[*of 0* {*0..t*} *s v*
($\lambda t\ r. - \varphi_s\ t\ a$) *UNIV* (*if t* = *0 then 1 else 1* / (*t* + *1*)) ($\lambda t.\ \varphi_s\ t\ v$)])
using *rHyp tHyp 1 2* **and** *3* **by** *auto*
qed

lemma *single-hop-ball*:
PRE (λ *s*. $0 \leq s$ *''x''* $\wedge$ *s ''x''* = *H* $\wedge$ *s ''v''* = *0* $\wedge$ *s ''g''* > *0* $\wedge$ *1* $\geq$ *c* $\wedge$ *c* $\geq$ *0*)
(((*ODEsystem* [(*''x''*, λ *s. s ''v''*),(*''v''*,λ *s.* − *s ''g''*)] *with* (λ *s. 0* $\leq$ *s ''x''*)));
(*IF* (λ *s. s ''x''* = *0*) *THEN* (*''v''* ::= (λ *s.* − *c* $\cdot$ *s ''v''*)) *ELSE* (*''v''* ::= (λ *s. s ''v''*)) *FI*))
POST (λ *s. 0* $\leq$ *s ''x''* $\wedge$ *s ''x''* $\leq$ *H*)
apply(*simp*, *subst dS*[*of* [λ *t s.* − *s ''g''* $\cdot$ *t* ˆ *2*/*2* + *s ''v''* $\cdot$ *t* + *s ''x''*, λ *t s.* − *s ''g''* $\cdot$ *t* + *s ''v''*]])
— Given solution is actually a solution.
apply(*simp add*: *vdiff-def varDiffs-def solvesStoreIVP-def solves-ode-def has-vderiv-on-singleton*,

safe)
    apply(*rule galilean-transform-eq*, *simp*)+
    apply(*rule galilean-transform*)+
    — Uniqueness of the flow.
    apply(*rule ubcStoreUniqueSol*, *simp*)
    apply(*simp add*: *vdiff-def del*: *comp-apply*)
    apply(*auto intro*: *continuous-intros del*: *comp-apply*)[*1*]
    apply(*rule continuous-intros*)+
    apply(*simp add*: *vdiff-def*, *safe*)
    apply(*clarsimp*) **subgoal for** $s\ X\ t\ \tau$
    apply(*rule flow-vel-is-galilean-vel2*[*of X ''x''*])
    by(*simp-all add*: *varDiffs-def vdiff-def*)
    apply(*simp add*: *vdiff-def varDiffs-def solvesStoreIVP-def*)
    apply(*simp add*: *vdiff-def varDiffs-def solvesStoreIVP-def solves-ode-def*
      has-vderiv-on-singleton galilean-transform-eq galilean-transform)
    — Relation Between the guard and the postcondition.
    by(*auto simp*: *vdiff-def p2r-def*)

— Example of hybrid program verified with differential weakening.
lemma *system-where-the-guard-implies-the-postcondition*:
    PRE (λ *s*. *s ''x''* = *0*)
    (*ODEsystem* [(*''x''*,(λ *s*. *s ''x''* + *1*))] *with* (λ *s*. *s ''x''* $\geq$ *0*))
    POST (λ *s*. *s ''x''* $\geq$ *0*)
using *dWeakening* **by** *blast*

lemma *system-where-the-guard-implies-the-postcondition2*:
    PRE (λ *s*. *s ''x''* = *0*)
    (*ODEsystem* [(*''x''*,(λ *s*. *s ''x''* + *1*))] *with* (λ *s*. *s ''x''* $\geq$ *0*))
    POST (λ *s*. *s ''x''* $\geq$ *0*)
apply(*clarify*, *simp add*: *p2r-def*)
apply(*simp add*: *rel-ad-def rel-antidomain-kleene-algebra.addual.ars-r-def*)
apply(*simp add*: *rel-antidomain-kleene-algebra.fbox-def*)
apply(*simp add*: *relcomp-def rel-ad-def guarDiffEqtn-def solvesStoreIVP-def*)
by *auto*

— Example of system proved with a differential invariant.
lemma *circular-motion*:
    PRE (λ *s*. (*s ''x''*) · (*s ''x''*) + (*s ''y''*) · (*s ''y''*) − (*s ''r''*) · (*s ''r''*) = *0*)
    (*ODEsystem* [(*''x''*,(λ *s*. *s ''y''*)),(*''y''*,(λ *s*. − *s ''x''*))] *with G*)
    POST (λ *s*. (*s ''x''*) · (*s ''x''*) + (*s ''y''*) · (*s ''y''*) − (*s ''r''*) · (*s ''r''*) = *0*)
apply(*rule-tac* η=(t_V *''x''*)⊙(t_V *''x''*) ⊕ (t_V *''y''*)⊙(t_V *''y''*) ⊕ (⊖(t_V *''r''*)⊙(t_V
''r''))
  and *uInput*=[t_V *''y''*, ⊖ (t_V *''x''*)] **in** *dInvForTrms*)
apply(*simp-all add*: *vdiff-def varDiffs-def*)
apply(*clarsimp*, *erule-tac x*=*''r''* **in** *allE*)
by *simp*

— Example of systems proved with differential invariants, cuts and weakenings.
declare *d-p2r* [*simp del*]

lemma *motion-with-constant-velocity-and-invariants*:
$PRE\ (\lambda\ s.\ s\ ''x'' > s\ ''y'' \wedge s\ ''v'' > 0)$
$(ODEsystem\ [(''x'', \lambda\ s.\ s\ ''v'')]\ with\ (\lambda\ s.\ True))$
$POST\ (\lambda\ s.\ s\ ''x''> \ s\ ''y'')$
apply(*rule-tac* $C = \lambda\ s.\ \ s\ ''v'' > 0$ **in** *dCut*)
apply(*rule-tac* $\varphi = (t_C\ 0) \prec (t_V\ ''v'')$ **and** *uInput*$=[t_V\ ''v'']$**in** *dInvFinal*)
apply(*simp-all add*: *vdiff-def varDiffs-def*, *clarify*, *erule-tac* $x=''v''$ **in** *allE*, *simp*)
apply(*rule-tac* $C = \lambda\ s.\ \ s\ ''x'' > s\ ''y''$ **in** *dCut*)
apply(*rule-tac* $\varphi{=}(t_V\ ''y'') \prec (t_V\ ''x'')$ **and** *uInput*$=[t_V\ ''v'']$ **and**
$F{=}\lambda\ s.\ \ s\ ''x'' > s\ ''y''$ **in** *dInvFinal*)
apply(*simp-all add*: *vdiff-def varDiffs-def*, *clarify*, *erule-tac* $x=''y''$ **in** *allE*, *simp*)
using *dWeakening* **by** *simp*

lemma *motion-with-constant-acceleration-and-invariants*:
$PRE\ (\lambda\ s.\ s\ ''y'' < s\ ''x''\ \wedge s\ ''v'' \geq 0 \wedge s\ ''a'' > 0)$
$(ODEsystem\ [(''x'',(\lambda\ s.\ s\ ''v'')),(''v'',(\lambda\ s.\ s\ ''a''))]\ with\ (\lambda\ s.\ True))$
$POST\ (\lambda\ s.\ (s\ ''y'' < s\ ''x''))$
apply(*rule-tac* $C = \lambda\ s.\ \ s\ ''a'' > 0$ **in** *dCut*)
apply(*rule-tac* $\varphi = (t_C\ 0) \prec (t_V\ ''a'')$ **and** *uInput*$=[t_V\ ''v'', t_V\ ''a'']$**in** *dInvFinal*)
apply(*simp-all add*: *vdiff-def varDiffs-def*, *clarify*, *erule-tac* $x=''a''$ **in** *allE*, *simp*)
apply(*rule-tac* $C = \lambda\ s.\ \ s\ ''v'' \geq 0$ **in** *dCut*)
apply(*rule-tac* $\varphi = (t_C\ 0) \preceq (t_V\ ''v'')$ **and** *uInput*$=[t_V\ ''v'', t_V\ ''a'']$ **in** *dInvFinal*)
apply(*simp-all add*: *vdiff-def varDiffs-def*)
apply(*rule-tac* $C = \lambda\ s.\ \ s\ ''x'' > \ s\ ''y''$ **in** *dCut*)
apply(*rule-tac* $\varphi = (t_V\ ''y'') \prec (t_V\ ''x'')$ **and** *uInput*$=[t_V\ ''v'', t_V\ ''a'']$**in** *dInvFinal*)
apply(*simp-all add*: *varDiffs-def vdiff-def*, *clarify*, *erule-tac* $x=''y''$ **in** *allE*, *simp*)
using *dWeakening* **by** *simp*

— We revisit the two modes example from before, and prove it with invariants.
lemma *single-hop-ball-and-invariants*:
$PRE\ (\lambda\ s.\ 0 \leq s\ ''x'' \wedge s\ ''x'' = H \wedge s\ ''v'' = 0 \wedge s\ ''g'' > 0 \wedge 1 \geq c \wedge c \geq 0)$
$(((ODEsystem\ [(''x'', \lambda\ s.\ s\ ''v''),(''v'',\lambda\ s.\ -\ s\ ''g'')]\ with\ (\lambda\ s.\ 0 \leq s\ ''x'')));$
$(IF\ (\lambda\ s.\ s\ ''x'' = 0)\ THEN\ (''v'' ::= (\lambda\ s.\ -\ c \cdot s\ ''v''))\ ELSE\ (''v'' ::= (\lambda\ s.\ s\ ''v''))\ FI))$
$POST\ (\lambda\ s.\ 0 \leq s\ ''x'' \wedge s\ ''x'' \leq H)$
apply(*simp add*: *d-p2r*, *subgoal-tac rdom* $\lceil \lambda s.\ 0 \leq s\ ''x'' \wedge s\ ''x'' = H \wedge s\ ''v'' = 0 \wedge 0 < s\ ''g'' \wedge c \leq 1 \wedge 0 \leq c\rceil$
$\subseteq wp\ (ODEsystem\ [(''x'', \lambda s.\ s\ ''v''), (''v'', \lambda s.\ -\ s\ ''g'')]\ with\ (\lambda s.\ 0 \leq s\ ''x''))$
$\lceil inf\ (sup\ (-\ (\lambda s.\ s\ ''x'' = 0))\ (\lambda s.\ 0 \leq s\ ''x'' \wedge s\ ''x'' \leq H))\ (sup\ (\lambda s.\ s\ ''x'' = 0)\ (\lambda s.\ 0 \leq s\ ''x'' \wedge s\ ''x'' \leq H))\rceil$)
apply(*simp add*: *d-p2r*, *rule-tac* $C = \lambda\ s.\ \ s\ ''g'' > 0$ **in** *dCut*)
apply(*rule-tac* $\varphi = (t_C\ 0) \prec (t_V\ ''g'')$ **and** *uInput*$=[t_V\ ''v'', \ominus\ t_V\ ''g'']$**in** *dInvFinal*)
apply(*simp-all add*: *vdiff-def varDiffs-def*, *clarify*, *erule-tac* $x=''g''$ **in** *allE*, *simp*)

apply(*rule-tac* $C = \lambda\ s.\ \ s\ ''v'' \leq 0$ **in** *dCut*)
apply(*rule-tac* $\varphi = (t_V\ \ ''v'') \preceq (t_C\ \ 0)$ **and** *uInput*=$[t_V\ \ ''v'', \ominus\ t_V\ \ ''g'']$ **in** *dInvFinal*)
apply(*simp-all add*: *vdiff-def varDiffs-def*)
apply(*rule-tac* $C = \lambda\ s.\ \ s\ ''x'' \leq\ \ H$ **in** *dCut*)
apply(*rule-tac* $\varphi = (t_V\ \ ''x'') \preceq (t_C\ \ H)$ **and** *uInput*=$[t_V\ \ ''v'', \ominus\ t_V\ \ ''g'']$**in** *dInvFinal*)
apply(*simp-all add*: *varDiffs-def vdiff-def*)
using *dWeakening* **by** *simp*

— Finally, we add a well known example in the hybrid systems community, the bouncing ball.
lemma *bouncing-ball-invariant*:$0 \leq x \Longrightarrow 0 < g \Longrightarrow 2 \cdot g \cdot x = 2 \cdot g \cdot H - v \cdot v \Longrightarrow (x{::}real) \leq H$
proof−
assume $0 \leq x$ **and** $0 < g$ **and** $2 \cdot g \cdot x = 2 \cdot g \cdot H - v \cdot v$
then have $v \cdot v = 2 \cdot g \cdot H - 2 \cdot g \cdot x \wedge 0 < g$ **by** *auto*
hence $*{:}v \cdot v = 2 \cdot g \cdot (H - x) \wedge 0 < g \wedge v \cdot v \geq 0$
using *left-diff-distrib mult.commute* **by** (*metis zero-le-square*)
from *this* **have** $(v \cdot v)/(2 \cdot g) = (H - x)$ **by** *auto*
also from $*$ **have** $(v \cdot v)/(2 \cdot g) \geq 0$
by (*meson divide-nonneg-pos linordered-field-class.sign-simps*(*44*) *zero-less-numeral*)

ultimately have $H - x \geq 0$ **by** *linarith*
thus *?thesis* **by** *auto*
qed

lemma *bouncing-ball*:
PRE $(\lambda\ s.\ 0 \leq s\ ''x'' \wedge s\ ''x'' = H \wedge s\ ''v'' = 0 \wedge s\ ''g'' > 0)$
$((ODEsystem\ [(''x'', \lambda\ s.\ s\ ''v''),(''v'',\lambda\ s.\ -\ s\ ''g'')]\ with\ (\lambda\ s.\ 0 \leq s\ ''x''));$
$(IF\ (\lambda\ s.\ s\ ''x'' = 0)\ THEN\ (''v'' ::= (\lambda\ s.\ -\ s\ ''v''))\ ELSE\ (Id)\ FI))^*$
POST $(\lambda\ s.\ 0 \leq s\ ''x'' \wedge s\ ''x'' \leq H)$
apply(*rule rel-antidomain-kleene-algebra.fbox-starI*[*of* - $\lceil\lambda s.\ 0 \leq s\ ''x'' \wedge 0 < s\ ''g'' \wedge$
$2 \cdot s\ ''g'' \cdot s\ ''x'' = 2 \cdot s\ ''g'' \cdot H - (s\ ''v'' \cdot s\ ''v'')\rceil$]])
apply(*simp*, *simp add*: *d-p2r*)
apply(*subgoal-tac*
rdom $\lceil\lambda s.\ 0 \leq s\ ''x'' \wedge 0 < s\ ''g'' \wedge 2 \cdot s\ ''g'' \cdot s\ ''x'' = 2 \cdot s\ ''g'' \cdot H - s\ ''v'' \cdot s\ ''v''\rceil$
$\subseteq wp\ (ODEsystem\ [(''x'', \lambda s.\ s\ ''v''), (''v'', \lambda s.\ -\ s\ ''g'')]\ with\ (\lambda s.\ 0 \leq s\ ''x''))$
$\lceil inf\ \ (sup\ (-\ (\lambda s.\ s\ ''x'' = 0))\ (\lambda s.\ 0 \leq s\ ''x'' \wedge 0 < s\ ''g'' \wedge 2 \cdot s\ ''g'' \cdot s\ ''x'' =$
$2 \cdot s\ ''g'' \cdot H - s\ ''v'' \cdot s\ ''v''))$
$(sup\ (\lambda s.\ s\ ''x'' = 0)\ (\lambda s.\ 0 \leq s\ ''x'' \wedge 0 < s\ ''g'' \wedge 2 \cdot s\ ''g'' \cdot s\ ''x'' =$
$2 \cdot s\ ''g'' \cdot H - s\ ''v'' \cdot s\ ''v''))\rceil$)
apply(*simp add*: *d-p2r*)
apply(*rule-tac* $C = \lambda\ s.\ \ s\ ''g'' > 0$ **in** *dCut*)
apply(*rule-tac* $\varphi = ((t_C\ \ 0) \prec (t_V\ \ ''g''))$ **and** *uInput*=$[t_V\ \ ''v'', \ominus\ t_V\ \ ''g'']$**in**

dInvFinal)
apply(*simp-all add*: *vdiff-def varDiffs-def*, *clarify*, *erule-tac* $x=''g''$ **in** *allE*, *simp*)
apply(*rule-tac* $C = \lambda\ s.\ 2 \cdot s\ ''g'' \cdot s\ ''x'' = 2 \cdot s\ ''g'' \cdot H - s\ ''v'' \cdot s\ ''v''$ **in** *dCut*)
apply(*rule-tac* $\varphi = (t_C\ 2) \odot (t_V\ ''g'') \odot (t_C\ H) \oplus (\ominus\ ((t_V\ ''v'') \odot (t_V\ ''v'')))$
$\doteq (t_C\ 2) \odot (t_V\ ''g'') \odot (t_V\ ''x'')$ **and** *uInput*=$[t_V\ ''v'', \ominus\ t_V\ ''g'']$**in** *dInvFinal*)
apply(*simp-all add*: *vdiff-def varDiffs-def*, *clarify*, *erule-tac* $x=''g''$ **in** *allE*, *simp*)
apply(*rule dWeakening*, *clarsimp*)
using *bouncing-ball-invariant* **by** *auto*

declare *d-p2r* [*simp*]

end