

Laplace Transform

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Abstract

This entry formalizes the Laplace transform and concrete Laplace transforms for arithmetic functions, frequency shift, integration and (higher) differentiation in the time domain. It proves Lerch's lemma and uniqueness of the Laplace transform for continuous functions. In order to formalize the foundational assumptions, this entry contains a formalization of piecewise continuous functions and functions of exponential order.

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	<code>theory Laplace-Transform-Library</code>	
	<code>imports</code>	
	<code>HOL-Analysis.Analysis</code>	
	<code>begin</code>	

1 References

Much of this formalization is based on Schiff's textbook [3]. Parts of this formalization are inspired by the HOL-Light formalization ([4], [1], [2]), but stated more generally for piecewise continuous (instead of piecewise continuously differentiable) functions.

2 Library Additions

2.1 Derivatives

lemma *DERIV-compose-FDERIV*:— TODO: generalize and move from HOL-ODE

```
assumes DERIV  $f (g x) :> f'$ 
assumes ( $g$  has-derivative  $g'$ ) (at  $x$  within  $s$ )
shows (( $\lambda x. f (g x)$ ) has-derivative ( $\lambda x. g' x * f'$ )) (at  $x$  within  $s$ )
using assms has-derivative-compose[of  $g g' x s f (*) f'$ ]
by (auto simp: has-field-derivative-def ac-simps)
```

lemmas *has-derivative-sin*[*derivative-intros*] = *DERIV-sin*[*THEN DERIV-compose-FDERIV*]
and *has-derivative-cos*[*derivative-intros*] = *DERIV-cos*[*THEN DERIV-compose-FDERIV*]
and *has-derivative-exp*[*derivative-intros*] = *DERIV-exp*[*THEN DERIV-compose-FDERIV*]

2.2 Integrals

lemma *negligible-real-ivl*:

```
fixes  $a b :: \text{real}$ 
assumes  $a \geq b$ 
shows negligible { $a .. b$ }
proof –
  from assms have { $a .. b$ } = { $a$ }  $\vee$  { $a .. b$ } = {}
  by auto
  then show ?thesis
  by auto
qed
```

lemma *absolutely-integrable-on-combine*:

```
fixes  $f :: \text{real} \Rightarrow 'a :: \text{euclidean-space}$ 
assumes  $f$  absolutely-integrable-on { $a..c$ }
  and  $f$  absolutely-integrable-on { $c..b$ }
  and  $a \leq c$ 
  and  $c \leq b$ 
shows  $f$  absolutely-integrable-on { $a..b$ }
using assms
unfolding absolutely-integrable-on-def integrable-on-def
by (auto intro!: has-integral-combine)
```

lemma *dominated-convergence-at-top*:

```

fixes  $f :: \text{real} \Rightarrow 'n::\text{euclidean-space} \Rightarrow 'm::\text{euclidean-space}$ 
assumes  $f: \bigwedge k. (f\ k) \text{ integrable-on } s$  and  $h: h \text{ integrable-on } s$ 
  and  $le: \bigwedge k\ x. x \in s \implies \text{norm } (f\ k\ x) \leq h\ x$ 
  and  $conv: \forall x \in s. ((\lambda k. f\ k\ x) \longrightarrow g\ x) \text{ at-top}$ 
shows  $g \text{ integrable-on } s ((\lambda k. \text{integral } s\ (f\ k)) \longrightarrow \text{integral } s\ g) \text{ at-top}$ 
proof –
  have 3: set-integrable lebesgue s h
    unfolding absolutely-integrable-on-def
  proof
    show  $(\lambda x. \text{norm } (h\ x)) \text{ integrable-on } s$ 
    proof (intro integrable-spike-finite[OF - - h, where S={}] ballI)
      fix  $x$  assume  $x \in s - \{\}$  then show  $\text{norm } (h\ x) = h\ x$ 
        using order-trans[OF norm-ge-zero le[of x]] by auto
      qed auto
    qed fact
  have 2: set-borel-measurable lebesgue s (f k) for k
    using f[of k]
    using has-integral-implies-lebesgue-measurable[of f k]
    by (auto intro: simp: integrable-on-def set-borel-measurable-def)
  have  $conv'$ :  $\forall x \in s. ((\lambda k. f\ k\ x) \longrightarrow g\ x) \text{ sequentially}$ 
    using conv filterlim-filtermap filterlim-compose filterlim-real-sequentially by
blast
  from 2 have 1: set-borel-measurable lebesgue s g
    unfolding set-borel-measurable-def
    by (rule borel-measurable-LIMSEQ-metric) (use conv' in <auto split: split-indicator>)
  have 4: AE x in lebesgue. ((\lambda i. indicator s x *_R f i x) \longrightarrow indicator s x *_R g
x) at-top
     $\forall_F i \text{ in at-top. } AE\ x \text{ in lebesgue. } \text{norm } (\text{indicator } s\ x\ *_R\ f\ i\ x) \leq \text{indicator } s\ x$ 
 $*_R\ h\ x$ 
    using conv le by (auto intro!: always-eventually split: split-indicator)

  note 1 2 3 4
  note * = this[unfolded set-borel-measurable-def set-integrable-def]
  have  $g: g \text{ absolutely-integrable-on } s$ 
    unfolding set-integrable-def
    by (rule integrable-dominated-convergence-at-top[OF *])
  then show  $g \text{ integrable-on } s$ 
    by (auto simp: absolutely-integrable-on-def)
  have  $((\lambda k. (LINT\ x:s|lebesgue. f\ k\ x)) \longrightarrow (LINT\ x:s|lebesgue. g\ x)) \text{ at-top}$ 
    unfolding set-lebesgue-integral-def
    using *
    by (rule integral-dominated-convergence-at-top)
  then show  $((\lambda k. \text{integral } s\ (f\ k)) \longrightarrow \text{integral } s\ g) \text{ at-top}$ 
    using g absolutely-integrable-integrable-bound[OF le f h]
    by (subst (asm) (1 2) set-lebesgue-integral-eq-integral) auto
qed

lemma has-integral-dominated-convergence-at-top:
  fixes  $f :: \text{real} \Rightarrow 'n::\text{euclidean-space} \Rightarrow 'm::\text{euclidean-space}$ 

```

```

assumes  $\bigwedge k. (f\ k\ \text{has-integral } y\ k)\ s\ h\ \text{integrable-on } s$ 
   $\bigwedge k\ x. x \in s \implies \text{norm } (f\ k\ x) \leq h\ x\ \forall x \in s. ((\lambda k. f\ k\ x) \longrightarrow g\ x)\ \text{at-top}$ 
  and  $x: (y \longrightarrow x)\ \text{at-top}$ 
shows  $(g\ \text{has-integral } x)\ s$ 
proof –
  have  $\text{int-f}: \bigwedge k. (f\ k)\ \text{integrable-on } s$ 
    using  $\text{assms}$  by  $(\text{auto simp: integrable-on-def})$ 
  have  $(g\ \text{has-integral } (\text{integral } s\ g))\ s$ 
    by  $(\text{intro integrable-integral dominated-convergence-at-top}[OF\ \text{int-f}\ \text{assms}(2)])$ 
fact+
  moreover have  $\text{integral } s\ g = x$ 
proof  $(\text{rule tendsto-unique})$ 
  show  $((\lambda i. \text{integral } s\ (f\ i)) \longrightarrow x)\ \text{at-top}$ 
    using  $\text{integral-unique}[OF\ \text{assms}(1)]\ x$  by  $\text{simp}$ 
  show  $((\lambda i. \text{integral } s\ (f\ i)) \longrightarrow \text{integral } s\ g)\ \text{at-top}$ 
    by  $(\text{intro dominated-convergence-at-top}[OF\ \text{int-f}\ \text{assms}(2)])\ \text{fact+}$ 
qed  $\text{simp}$ 
ultimately show  $?thesis$ 
  by  $\text{simp}$ 
qed

```

```

lemma  $\text{integral-indicator-eq-restriction}$ :
  fixes  $f::'a::\text{euclidean-space} \Rightarrow 'b::\text{banach}$ 
  assumes  $f: f\ \text{integrable-on } R$ 
  and  $R \subseteq S$ 
  shows  $\text{integral } S\ (\lambda x. \text{indicator } R\ x\ *_R\ f\ x) = \text{integral } R\ f$ 
proof –
  let  $?f = \lambda x. \text{indicator } R\ x\ *_R\ f\ x$ 
  have  $?f\ \text{integrable-on } R$ 
    using  $f\ \text{negligible-empty}$ 
    by  $(\text{rule integrable-spike})\ \text{auto}$ 
  from  $\text{integrable-integral}[OF\ \text{this}]$ 
  have  $(?f\ \text{has-integral } \text{integral } R\ ?f)\ S$ 
    by  $(\text{rule has-integral-on-superset})\ (\text{use } \langle R \subseteq S \rangle\ \text{in } \langle \text{auto simp: indicator-def} \rangle)$ 
  also have  $\text{integral } R\ ?f = \text{integral } R\ f$ 
    using  $\text{negligible-empty}$ 
    by  $(\text{rule integral-spike})\ \text{auto}$ 
  finally show  $?thesis$ 
    by  $\text{blast}$ 
qed

```

```

lemma
   $\text{improper-integral-at-top}$ :
  fixes  $f::\text{real} \Rightarrow 'a::\text{euclidean-space}$ 
  assumes  $f\ \text{absolutely-integrable-on } \{a..\}$ 
  shows  $((\lambda x. \text{integral } \{a..x\}\ f) \longrightarrow \text{integral } \{a..\}\ f)\ \text{at-top}$ 
proof –
  let  $?f = \lambda(k::\text{real})\ (t::\text{real}). \text{indicator } \{a..k\}\ t\ *_R\ f\ t$ 
  have  $f: f\ \text{integrable-on } \{a..k\}\ \text{for } k$ 

```

```

    using set-lebesgue-integral-eq-integral(1)[OF assms]
    by (rule integrable-on-subinterval) simp
  from this negligible-empty have ?f k integrable-on {a..k} for k
    by (rule integrable-spike) auto
  from this have ?f k integrable-on {a..} for k
    by (rule integrable-on-superset) auto
  moreover
  have (λx. norm (f x)) integrable-on {a..}
    using assms by (simp add: absolutely-integrable-on-def)
  moreover
  note -
  moreover
  have ∀F k in at-top. k ≥ x for x::real
    by (simp add: eventually-ge-at-top)
  then have ∀ x∈{a..}. ((λk. ?f k x) → f x) at-top
    by (auto intro!: Lim-transform-eventually[OF tendsto-const] simp: indicator-def
    eventually-at-top-linorder)
  ultimately
  have ((λk. integral {a..} (?f k)) → integral {a..} f) at-top
    by (rule dominated-convergence-at-top) (auto simp: indicator-def)
  also have (λk. integral {a..} (?f k)) = (λk. integral {a..k} f)
    by (auto intro!: ext integral-indicator-eq-restriction f)
  finally show ?thesis .
qed

```

```

lemma norm-integrable-onI: (λx. norm (f x)) integrable-on S
  if f absolutely-integrable-on S
  for f::'a::euclidean-space⇒'b::euclidean-space
  using that by (auto simp: absolutely-integrable-on-def)

```

lemma

```

has-integral-improper-at-topI:
  fixes f::real ⇒ 'a::banach
  assumes I: ∀F k in at-top. (f has-integral I k) {a..k}
  assumes J: (I → J) at-top
  shows (f has-integral J) {a..}
  apply (subst has-integral')
proof (auto, goal-cases)
  case (1 e)
  from tendstoD[OF J <0 < e>]
  have ∀F x in at-top. dist (I x) J < e .
  moreover have ∀F x in at-top. (x::real) > 0 by simp
  moreover have ∀F x in at-top. (x::real) > - a — TODO: this seems to be
  strange?
  by simp
  moreover note I
  ultimately have ∀F x in at-top. x > 0 ∧ x > - a ∧ dist (I x) J < e ∧
    (f has-integral I x) {a..x} by eventually-elim auto
  then obtain k where k: ∀ b≥k. norm (I b - J) < e k > 0 k > - a

```

```

    and I:  $\bigwedge c. c \geq k \implies (f \text{ has-integral } I \ c) \ \{a..c\}$ 
  by (auto simp: eventually-at-top-linorder dist-norm)
show ?case
  apply (rule exI[where x=k])
  apply (auto simp:  $\langle 0 < k \rangle$ )
  subgoal premises prems for b c
  proof -
    have ball-eq:  $\text{ball } 0 \ k = \{-k <..< k\}$  by (auto simp: abs-real-def split: if-splits)
    from prems  $\langle 0 < k \rangle$  have  $c \geq 0 \ b \leq 0$ 
      by (auto simp: subset-iff)
    with prems  $\langle 0 < k \rangle$  have  $c \geq k$ 
      apply (auto simp: ball-eq)
      apply (auto simp: subset-iff)
      apply (drule spec[where x=(c + k)/2])
      apply (auto simp: algebra-split-simps not-less)
      using  $\langle 0 \leq c \rangle$  by linarith
    then have  $\text{norm } (I \ c - J) < e$  using k by auto
  moreover
  from prems  $\langle 0 < k \rangle \ \langle c \geq 0 \rangle \ \langle b \leq 0 \rangle \ \langle c \geq k \rangle \ \langle k > -a \rangle$  have  $a \geq b$ 
    apply (auto simp: ball-eq)
    apply (auto simp: subset-iff)
    by (meson  $\langle b \leq 0 \rangle$  less-eq-real-def minus-less-iff not-le order-trans)
  have  $((\lambda x. \text{if } x \in \text{cbox } a \ c \ \text{then } f \ x \ \text{else } 0) \text{ has-integral } I \ c) \ (\text{cbox } b \ c)$ 
    apply (subst has-integral-restrict-closed-subintervals-eq)
    using I[of c] prems  $\langle a \geq b \rangle \ \langle k \leq c \rangle$ 
    by (auto)
  from negligible-empty - this have  $((\lambda x. \text{if } a \leq x \ \text{then } f \ x \ \text{else } 0) \text{ has-integral}$ 
I c) (cbox b c)
    by (rule has-integral-spike) auto
  ultimately
  show ?thesis
    by (intro exI[where x=I c]) auto
qed
done
qed

```

lemma has-integral-improperE:

```

  fixes f::real  $\Rightarrow$  'a::euclidean-space
  assumes I: (f has-integral I) {a..}
  assumes ai: f absolutely-integrable-on {a..}
  obtains J where
     $\bigwedge k. (f \text{ has-integral } J \ k) \ \{a..k\}$ 
    (J  $\longrightarrow$  I) at-top

```

proof -

```

  define J where J k = integral {a .. k} f for k
  have (f has-integral J k) {a..k} for k
    unfolding J-def
    by (force intro: integrable-on-subinterval has-integral-integrable[OF I])
  moreover

```

```

have  $I\text{-def}[symmetric]$ :  $\text{integral } \{a..\} f = I$ 
  using  $I$  by auto
from  $\text{improper-integral-at-top}[OF ai]$ 
have  $(J \longrightarrow I)$  at-top
  unfolding  $J\text{-def } I\text{-def}$  .
ultimately show ?thesis ..
qed

```

2.3 Miscellaneous

```

lemma  $AE\text{-BallI}$ :  $AE x \in X$  in  $F. P x$  if  $\forall x \in X. P x$ 
  using that by (intro always-eventually) auto

```

```

lemma  $\text{bounded-le-Sup}$ :
  assumes  $\text{bounded } (f ' S)$ 
  shows  $\forall x \in S. \text{norm } (f x) \leq \text{Sup } (\text{norm } ' f ' S)$ 
  by (auto intro!: cSup-upper bounded-imp-bdd-above simp: bounded-norm-comp
assms)

```

end

3 Piecewise Continuous Functions

```

theory  $\text{Piecewise-Continuous}$ 
  imports
     $\text{Laplace-Transform-Library}$ 
begin

```

3.1 at within filters

```

lemma  $\text{at-within-self-singleton}[simp]$ :  $\text{at } i$  within  $\{i\} = \text{bot}$ 
  by (auto intro!: antisym filter-leI simp: eventually-at-filter)

```

```

lemma  $\text{at-within-t1-space-avoid}$ :
   $(\text{at } x$  within  $X - \{i\}) = (\text{at } x$  within  $X)$  if  $x \neq i$  for  $x i :: 'a :: t1\text{-space}$ 

```

```

proof (safe intro!: antisym filter-leI)
  fix  $P$ 
  assume  $\text{eventually } P$   $(\text{at } x$  within  $X - \{i\})$ 
  moreover have  $\text{eventually } (\lambda x. x \neq i)$   $(\text{nhds } x)$ 
    by (rule t1-space-nhds) fact
  ultimately
  show  $\text{eventually } P$   $(\text{at } x$  within  $X)$ 
    unfolding  $\text{eventually-at-filter}$ 
    by  $\text{eventually-elim}$  auto
qed (simp add: eventually-mono order.order-iff-strict eventually-at-filter)

```

```

lemma  $\text{at-within-t1-space-avoid-finite}$ :
   $(\text{at } x$  within  $X - I) = (\text{at } x$  within  $X)$  if  $\text{finite } I$   $x \notin I$  for  $x :: 'a :: t1\text{-space}$ 
  using that

```

proof (*induction I*)
case (*insert i I*)
then show *?case*
 by *auto (metis Diff-insert at-within-t1-space-avoid)*
qed *simp*

lemma *at-within-interior*:
NO-MATCH (UNIV::'a set) (S::'a::topological-space set) $\implies x \in \text{interior } S \implies$
at x within S = at x
 by (*rule at-within-interior*)

3.2 intervals

lemma *Compl-Icc*: $- \{a .. b\} = \{..<a\} \cup \{b<..\}$ **for** $a b::'a::\text{linorder}$
 by *auto*

lemma *interior-Icc[*simp*]*: *interior* $\{a..b\} = \{a<..**<b\}**$
for $a b::'a::\{\text{linorder-topology, dense-order, no-bot, no-top}\}$
 — *TODO: is no-bot and no-top really required?*
 by (*auto simp add: Compl-Icc interior-closure*)

lemma *closure-finite[*simp*]*: *closure* $X = X$ **if** *finite* X **for** $X::'a::\text{t1-space set}$
using *that*
 by (*induction X (simp-all add: closure-insert)*)

definition *piecewise-continuous-on* :: $'a::\text{linorder-topology} \Rightarrow 'a \Rightarrow 'a \text{ set} \Rightarrow ('a \Rightarrow$
 $'b::\text{topological-space}) \Rightarrow \text{bool}$

where *piecewise-continuous-on* $a b I f \longleftrightarrow$
continuous-on $(\{a .. b\} - I) f \wedge \text{finite } I \wedge$
 $(\forall i \in I. (i \in \{a<..**<b\} \longrightarrow (\exists l. (f \longrightarrow l) (\text{at-left } i)))) \wedge**$
 $(i \in \{a..<b\} \longrightarrow (\exists u. (f \longrightarrow u) (\text{at-right } i))))$

lemma *piecewise-continuous-on-subset*:
piecewise-continuous-on $a b I f \implies \{c .. d\} \subseteq \{a .. b\} \implies \text{piecewise-continuous-on}$
 $c d I f$
 by (*force simp add: piecewise-continuous-on-def intro: continuous-on-subset*)

lemma *piecewise-continuous-onE*:
assumes *piecewise-continuous-on* $a b I f$
obtains $l u$
where *finite* I
and *continuous-on* $(\{a..b\} - I) f$
and $(\bigwedge i. i \in I \implies a < i \implies i \leq b \implies (f \longrightarrow l i) (\text{at-left } i))$
and $(\bigwedge i. i \in I \implies a \leq i \implies i < b \implies (f \longrightarrow u i) (\text{at-right } i))$
using *assms*
 by (*auto simp: piecewise-continuous-on-def Ball-def*) *metis*

lemma *piecewise-continuous-onI*:
assumes *finite* I *continuous-on* $(\{a..b\} - I) f$

and $(\bigwedge i. i \in I \implies a < i \implies i \leq b \implies (f \longrightarrow l i) \text{ (at-left } i))$
and $(\bigwedge i. i \in I \implies a \leq i \implies i < b \implies (f \longrightarrow u i) \text{ (at-right } i))$
shows *piecewise-continuous-on a b I f*
using *assms*
by *(force simp: piecewise-continuous-on-def)*

lemma *piecewise-continuous-onI'*:
fixes $a b::'a::\{\text{linorder-topology, dense-order, no-bot, no-top}\}$
assumes $\text{finite } I \bigwedge x. a < x \implies x < b \implies \text{isCont } f x$
and $a \notin I \implies \text{continuous (at-right } a) f$
and $b \notin I \implies \text{continuous (at-left } b) f$
and $(\bigwedge i. i \in I \implies a < i \implies i \leq b \implies (f \longrightarrow l i) \text{ (at-left } i))$
and $(\bigwedge i. i \in I \implies a \leq i \implies i < b \implies (f \longrightarrow u i) \text{ (at-right } i))$
shows *piecewise-continuous-on a b I f*
proof *(rule piecewise-continuous-onI)*
have $x \notin I \implies a \leq x \implies x \leq b \implies (f \longrightarrow f x) \text{ (at } x \text{ within } \{a..b\})$ **for** x
using *assms(2)[of x] assms(3,4)*
by *(cases a = x; cases b = x; cases x ∈ {a<..**b**)*
(auto simp: at-within-Icc-at-left at-within-Icc-at-right isCont-def
continuous-within filterlim-at-split at-within-interior)
then show *continuous-on ({a .. b} - I) f*
by *(auto simp: continuous-on-def ⟨finite I⟩ at-within-t1-space-avoid-finite)*
qed *fact+*

lemma *piecewise-continuous-onE'*:
fixes $a b::'a::\{\text{linorder-topology, dense-order, no-bot, no-top}\}$
assumes *piecewise-continuous-on a b I f*
obtains $l u$
where *finite I*
and $\bigwedge x. a < x \implies x < b \implies x \notin I \implies \text{isCont } f x$
and $(\bigwedge x. a < x \implies x \leq b \implies (f \longrightarrow l x) \text{ (at-left } x))$
and $(\bigwedge x. a \leq x \implies x < b \implies (f \longrightarrow u x) \text{ (at-right } x))$
and $\bigwedge x. a \leq x \implies x \leq b \implies x \notin I \implies f x = l x$
and $\bigwedge x. a \leq x \implies x \leq b \implies x \notin I \implies f x = u x$
proof –
from *piecewise-continuous-onE[OF assms]* **obtain** $l u$
where *finite I*
and *continuous: continuous-on ({a..b} - I) f*
and *left: ($\bigwedge i. i \in I \implies a < i \implies i \leq b \implies (f \longrightarrow l i) \text{ (at-left } i)$)*
and *right: ($\bigwedge i. i \in I \implies a \leq i \implies i < b \implies (f \longrightarrow u i) \text{ (at-right } i)$)*
by *metis*
define l' **where** $l' x = (\text{if } x \in I \text{ then } l x \text{ else } f x)$ **for** x
define u' **where** $u' x = (\text{if } x \in I \text{ then } u x \text{ else } f x)$ **for** x
note $\langle \text{finite } I \rangle$
moreover **from** *continuous*
have $a < x \implies x < b \implies x \notin I \implies \text{isCont } f x$ **for** x
by *(rule continuous-on-interior) (auto simp: interior-diff ⟨finite I⟩)*
moreover
from *continuous* **have** $a < x \implies x \leq b \implies x \notin I \implies (f \longrightarrow f x) \text{ (at-left } x)$

for x
by (*cases* $x = b$)
 (*auto simp: continuous-on-def at-within-t1-space-avoid-finite* \langle *finite* I \rangle
 at-within-Icc-at-left at-within-interior filterlim-at-split
 dest!: bspec[where $x=x$])
then have $a < x \implies x \leq b \implies (f \longrightarrow l' x)$ (*at-left* x) **for** x
 by (*auto simp: l'-def left*)
moreover
from *continuous* **have** $a \leq x \implies x < b \implies x \notin I \implies (f \longrightarrow f x)$ (*at-right*
 x) **for** x
 by (*cases* $x = a$)
 (*auto simp: continuous-on-def at-within-t1-space-avoid-finite* \langle *finite* I \rangle
 at-within-Icc-at-right at-within-interior filterlim-at-split
 dest!: bspec[where $x=x$])
then have $a \leq x \implies x < b \implies (f \longrightarrow u' x)$ (*at-right* x) **for** x
 by (*auto simp: u'-def right*)
moreover have $a \leq x \implies x \leq b \implies x \notin I \implies f x = l' x$ **for** x **by** (*auto simp:*
l'-def)
moreover have $a \leq x \implies x \leq b \implies x \notin I \implies f x = u' x$ **for** x **by** (*auto simp:*
u'-def)
 ultimately show *?thesis ..*
qed

lemma *tendsto-avoid-at-within*:
 ($f \longrightarrow l$) (*at* x *within* X)
if ($f \longrightarrow l$) (*at* x *within* $X - \{x\}$)
 using *that*
 by (*auto simp: eventually-at-filter dest!: topological-tendstoD intro!: topologi-*
cal-tendstoI)

lemma *tendsto-within-subset-eventuallyI*:
 ($f \longrightarrow fx$) (*at* x *within* X)
if $g: (g \longrightarrow gy)$ (*at* y *within* Y)
 and $ev: \forall_F x$ *in* (*at* y *within* Y). $fx = gx$
 and $xy: x = y$
 and $fxgy: fx = gy$
 and $XY: X - \{x\} \subseteq Y$
apply (*rule tendsto-avoid-at-within*)
apply (*rule tendsto-within-subset[where $S = Y$]*)
unfolding xy
 apply (*subst tendsto-cong[OF ev]*)
 apply (*rule g[folded fxgy]*)
apply (*rule XY[unfolded xy]*)
done

lemma *piecewise-continuous-on-insertE*:
 assumes *piecewise-continuous-on* a b (*insert* i I) f
 assumes $i \in \{a .. b\}$
 obtains g h **where**

piecewise-continuous-on a i I g
piecewise-continuous-on i b I h
 $\bigwedge x. a \leq x \implies x < i \implies g x = f x$
 $\bigwedge x. i < x \implies x \leq b \implies h x = f x$

proof –

from *piecewise-continuous-onE*[*OF assms(1)*] $\langle i \in \{a .. b\} \rangle$ **obtain** *l u* **where**
finite: finite I
and *cf: continuous-on* ($\{a..b\} - \text{insert } i I$) *f*
and *l:* ($\bigwedge i. i \in I \implies a < i \implies i \leq b \implies (f \longrightarrow l i) \text{ (at-left } i)$) $i > a \implies$
 $(f \longrightarrow l i) \text{ (at-left } i)$
and *u:* ($\bigwedge i. i \in I \implies a \leq i \implies i < b \implies (f \longrightarrow u i) \text{ (at-right } i)$) $i < b$
 $\implies (f \longrightarrow u i) \text{ (at-right } i)$
by *auto* (*metis* (*mono-tags*))

have *fl:* $(f(i := x) \longrightarrow l j) \text{ (at-left } j)$ **if** $j \in I$ $a < j \leq b$ **for** $j x$
using *l(1)*
apply (*rule tendsto-within-subset-eventuallyI*)
apply (*auto simp: eventually-at-filter that*)
apply (*cases j \neq i*)
subgoal premises *prems*
using *t1-space-nhds*[*OF prems*]
by *eventually-elim auto*
subgoal by *simp*
done

have *fr:* $(f(i := x) \longrightarrow u j) \text{ (at-right } j)$ **if** $j \in I$ $a \leq j < b$ **for** $j x$
using *u(1)*
apply (*rule tendsto-within-subset-eventuallyI*)
apply (*auto simp: eventually-at-filter that*)
apply (*cases j \neq i*)
subgoal premises *prems*
using *t1-space-nhds*[*OF prems*]
by *eventually-elim auto*
subgoal by *simp*
done

from *cf* **have** *tendsto:* $(f \longrightarrow f x) \text{ (at } x \text{ within } \{a..b\} - \text{insert } i I)$
if $x \in \{a .. b\} - \text{insert } i I$ **for** x **using** *that*
by (*auto simp: continuous-on-def*)
have *continuous-on* ($\{a..i\} - I$) $(f(i:=l i))$
apply (*cases a = i*)
subgoal by (*auto simp: continuous-on-def Diff-triv*)
unfolding *continuous-on-def*
apply *safe*
subgoal for x
apply (*cases x = i*)
subgoal
apply (*rule tendsto-within-subset-eventuallyI*)
apply (*rule l(2)*)
by (*auto simp: eventually-at-filter*)
subgoal

```

    apply (subst at-within-t1-space-avoid[symmetric], assumption)
    apply (rule tendsto-within-subset-eventuallyI[where y=x])
      apply (rule tendsto)
    using ⟨i ∈ {a .. b}⟩ by (auto simp: eventually-at-filter)
  done
done
then have piecewise-continuous-on a i I (f(i:=l i))
  using ⟨i ∈ {a .. b}⟩
  by (auto intro!: piecewise-continuous-onI finite fl fr)

moreover
have continuous-on ({i..b} - I) (f(i:=u i))
  apply (cases b = i)
  subgoal by (auto simp: continuous-on-def Diff-triv)
  unfolding continuous-on-def
  apply safe
  subgoal for x
    apply (cases x = i)
    subgoal
      apply (rule tendsto-within-subset-eventuallyI)
      apply (rule u(2))
      by (auto simp: eventually-at-filter)
    subgoal
      apply (subst at-within-t1-space-avoid[symmetric], assumption)
      apply (rule tendsto-within-subset-eventuallyI[where y=x])
      apply (rule tendsto)
      using ⟨i ∈ {a .. b}⟩ by (auto simp: eventually-at-filter)
    done
  done
done
then have piecewise-continuous-on i b I (f(i:=u i))
  using ⟨i ∈ {a .. b}⟩
  by (auto intro!: piecewise-continuous-onI finite fl fr)
moreover have (f(i:=l i)) x = f x if a ≤ x x < i for x
  using that by auto
moreover have (f(i:=u i)) x = f x if i < x x ≤ b for x
  using that by auto
ultimately show ?thesis ..
qed

lemma eventually-avoid-finite:
  ∀ F x in at y within Y. x ∉ I if finite I for y::'a::t1-space
  using that
proof (induction)
  case empty
  then show ?case by simp
next
  case (insert x F)
  then show ?case
    apply (auto intro!: eventually-conj)

```

apply (*cases* $y = x$)
subgoal by (*simp add: eventually-at-filter*)
subgoal by (*rule tendsto-imp-eventually-ne*) (*rule tendsto-ident-at*)
done
qed

lemma eventually-at-left-linorder:— TODO: generalize $?b < ?a \implies \forall_F x \text{ in } \text{at-left } ?a. x \in \{?b < .. < ?a\}$
 $a > (b :: 'a :: \text{linorder-topology}) \implies \text{eventually } (\lambda x. x \in \{b < .. < a\}) (\text{at-left } a)$
unfolding *eventually-at-left*
by *auto*

lemma eventually-at-right-linorder:— TODO: generalize $?a < ?b \implies \forall_F x \text{ in } \text{at-right } ?a. x \in \{?a < .. < ?b\}$
 $a > (b :: 'a :: \text{linorder-topology}) \implies \text{eventually } (\lambda x. x \in \{b < .. < a\}) (\text{at-right } b)$
unfolding *eventually-at-right*
by *auto*

lemma piecewise-continuous-on-congI:
piecewise-continuous-on $a \ b \ I \ g$
if *piecewise-continuous-on* $a \ b \ I \ f$
and *eq*: $\bigwedge x. x \in \{a .. b\} - I \implies g \ x = f \ x$
proof –
from *piecewise-continuous-onE*[*OF that(1)*]
obtain $l \ u$ **where** *finite: finite* I
and *:
continuous-on $(\{a .. b\} - I) \ f$
 $(\bigwedge i. i \in I \implies a < i \implies i \leq b \implies (f \longrightarrow l \ i) (\text{at-left } i))$
 $\bigwedge i. i \in I \implies a \leq i \implies i < b \implies (f \longrightarrow u \ i) (\text{at-right } i)$
by *blast*
note *finite*
moreover
from * **have** *continuous-on* $(\{a .. b\} - I) \ g$
using *that(2)*
by (*auto simp: eq cong: continuous-on-cong*) (*subst continuous-on-cong*[*OF refl eq*]; *assumption*)
moreover
have $\forall_F x \text{ in } \text{at-left } i. f \ x = g \ x$ **if** $a < i \ i \leq b$ **for** i
using *eventually-avoid-finite*[*OF* $\langle \text{finite } I \rangle$, *of* $i \ \{.. < i\}$]
eventually-at-left-linorder[*OF* $\langle a < i \rangle$]
by *eventually-elim* (*subst eq, use that in auto*)
then have $i \in I \implies a < i \implies i \leq b \implies (g \longrightarrow l \ i) (\text{at-left } i)$ **for** i
using *(2)
by (*rule Lim-transform-eventually*[*rotated*]) *auto*
moreover
have $\forall_F x \text{ in } \text{at-right } i. f \ x = g \ x$ **if** $a \leq i \ i < b$ **for** i
using *eventually-avoid-finite*[*OF* $\langle \text{finite } I \rangle$, *of* $i \ \{i < ..\}$]
eventually-at-right-linorder[*OF* $\langle i < b \rangle$]
by *eventually-elim* (*subst eq, use that in auto*)

then have $i \in I \implies a \leq i \implies i < b \implies (g \longrightarrow u \ i) \text{ (at-right } i)$ **for** i
using $*(\beta)$
by (rule *Lim-transform-eventually[rotated]*) *auto*
ultimately
show *?thesis*
by (rule *piecewise-continuous-onI*) *auto*
qed

lemma *piecewise-continuous-on-cong*[*cong*]:
piecewise-continuous-on $a \ b \ I \ f \iff \text{piecewise-continuous-on } c \ d \ J \ g$
if $a = c$
 $b = d$
 $I = J$
 $\bigwedge x. c \leq x \implies x \leq d \implies x \notin J \implies f \ x = g \ x$
using *that*
by (*auto intro: piecewise-continuous-on-congI*)

lemma *tendsto-at-left-continuous-on-avoidI*: $(f \longrightarrow g \ i) \text{ (at-left } i)$
if g : *continuous-on* $(\{a..i\} - I) \ g$
and gf : $\bigwedge x. a < x \implies x < i \implies g \ x = f \ x$
 $i \notin I$ *finite* $I \ a < i$
for $i::'a::\text{linorder-topology}$
proof (rule *Lim-transform-eventually*)
from *that* **have** $i \in \{a .. i\}$ **by** *auto*
from g **have** $(g \longrightarrow g \ i) \text{ (at } i \text{ within } \{a..i\} - I)$
using $\langle i \notin I \rangle \langle i \in \{a .. i\} \rangle$
by (*auto elim!: piecewise-continuous-onE simp: continuous-on-def*)
then show $(g \longrightarrow g \ i) \text{ (at-left } i)$
by (*metis that at-within-Icc-at-left at-within-t1-space-avoid-finite greaterThanLessThan-iff*)
show $\forall_F \ x \ \text{in } \text{at-left } i. \ g \ x = f \ x$
using *eventually-at-left-linorder*[*OF* $\langle a < i \rangle$]
by *eventually-elim* (*auto simp:* $\langle a < i \rangle \ gf$)
qed

lemma *tendsto-at-right-continuous-on-avoidI*: $(f \longrightarrow g \ i) \text{ (at-right } i)$
if g : *continuous-on* $(\{i..b\} - I) \ g$
and gf : $\bigwedge x. i < x \implies x < b \implies g \ x = f \ x$
 $i \notin I$ *finite* $I \ i < b$
for $i::'a::\text{linorder-topology}$
proof (rule *Lim-transform-eventually*)
from *that* **have** $i \in \{i .. b\}$ **by** *auto*
from g **have** $(g \longrightarrow g \ i) \text{ (at } i \text{ within } \{i..b\} - I)$
using $\langle i \notin I \rangle \langle i \in \{i .. b\} \rangle$
by (*auto elim!: piecewise-continuous-onE simp: continuous-on-def*)
then show $(g \longrightarrow g \ i) \text{ (at-right } i)$
by (*metis that at-within-Icc-at-right at-within-t1-space-avoid-finite greaterThanLessThan-iff*)
show $\forall_F \ x \ \text{in } \text{at-right } i. \ g \ x = f \ x$

using *eventually-at-right-linorder*[$OF \langle i < b \rangle$]
by *eventually-elim* (*auto simp*: $\langle i < b \rangle$ *gf*)
qed

lemma *piecewise-continuous-on-insert-leftI*:
piecewise-continuous-on $a \ b$ (*insert* $a \ I$) f **if** *piecewise-continuous-on* $a \ b \ I \ f$
apply (*cases* $a \in I$)
subgoal using *that* **by** (*auto dest*: *insert-absorb*)
subgoal
using *that*
apply (*rule* *piecewise-continuous-onE*)
subgoal for $l \ u$
apply (*rule* *piecewise-continuous-onI*[**where** $u=u(a:=f \ a)$])
apply (*auto intro*: *continuous-on-subset*)
apply (*rule* *tendsto-at-right-continuous-on-avoidI*, *assumption*)
apply *auto*
done
done
done

lemma *piecewise-continuous-on-insert-rightI*:
piecewise-continuous-on $a \ b$ (*insert* $b \ I$) f **if** *piecewise-continuous-on* $a \ b \ I \ f$
apply (*cases* $b \in I$)
subgoal using *that* **by** (*auto dest*: *insert-absorb*)
subgoal
using *that*
apply (*rule* *piecewise-continuous-onE*)
subgoal for $l \ u$
apply (*rule* *piecewise-continuous-onI*[**where** $l=l(b:=f \ b)$])
apply (*auto intro*: *continuous-on-subset*)
apply (*rule* *tendsto-at-left-continuous-on-avoidI*, *assumption*)
apply *auto*
done
done
done

theorem *piecewise-continuous-on-induct*[*consumes 1*, *case-names empty combine weaken*]:

assumes *pc*: *piecewise-continuous-on* $a \ b \ I \ f$
assumes 1: $\bigwedge a \ b \ f. \text{continuous-on } \{a .. b\} \ f \implies P \ a \ b \ \{\} \ f$
assumes 2: $\bigwedge a \ i \ b \ I \ f1 \ f2 \ f. a \leq i \implies i \leq b \implies i \notin I \implies P \ a \ i \ I \ f1 \implies P \ i \ b \ I \ f2 \implies$
piecewise-continuous-on $a \ i \ I \ f1 \implies$
piecewise-continuous-on $i \ b \ I \ f2 \implies$
 $(\bigwedge x. a \leq x \implies x < i \implies f1 \ x = f \ x) \implies$
 $(\bigwedge x. i < x \implies x \leq b \implies f2 \ x = f \ x) \implies$
 $(i > a \implies (f \longrightarrow f1 \ i) \text{ (at-left } i)) \implies$
 $(i < b \implies (f \longrightarrow f2 \ i) \text{ (at-right } i)) \implies$
 $P \ a \ b \ (\text{insert } i \ I) \ f$

```

assumes  $\exists: \bigwedge a b i I f. P a b I f \implies \text{finite } I \implies i \notin I \implies P a b (\text{insert } i I) f$ 
shows  $P a b I f$ 
proof -
  from pc have finite I
  by (auto simp: piecewise-continuous-on-def)
  then show ?thesis
  using pc
  proof (induction I arbitrary: a b f)
    case empty
    then show ?case
    by (auto simp: piecewise-continuous-on-def 1)
  next
  case (insert i I)
  show ?case
  proof (cases i \in \{a .. b\})
    case True
    from insert.premis[THEN piecewise-continuous-on-insertE, OF \langle i \in \{a .. b\} \rangle]
    obtain g h
      where g: piecewise-continuous-on a i I g
        and h: piecewise-continuous-on i b I h
        and gf: \bigwedge x. a \le x \implies x < i \implies g x = f x
        and hf: \bigwedge x. i < x \implies x \le b \implies h x = f x
      by metis
    from g have pcg: piecewise-continuous-on a i I (f(i:=g i))
      by (rule piecewise-continuous-on-congI) (auto simp: gf)
    from h have pch: piecewise-continuous-on i b I (f(i:=h i))
      by (rule piecewise-continuous-on-congI) (auto simp: hf)

    have fg: (f \longrightarrow g i) (at-left i) if a < i
      apply (rule tendsto-at-left-continuous-on-avoidI[where a=a and I=I])
      using g \langle i \notin I \rangle \langle a < i \rangle
      by (auto elim!: piecewise-continuous-onE simp: gf)
    have fh: (f \longrightarrow h i) (at-right i) if i < b
      apply (rule tendsto-at-right-continuous-on-avoidI[where b=b and I=I])
      using h \langle i \notin I \rangle \langle i < b \rangle
      by (auto elim!: piecewise-continuous-onE simp: hf)
    show ?thesis
    apply (rule 2)
    using True apply force
    using True apply force
      apply (rule insert)
      apply (rule insert.IH, rule pcg)
      apply (rule insert.IH, rule pch)
      apply fact
      apply fact
    using \exists
    by (auto simp: fg fh)
  next
  case False

```



```

with insert.prem
have piecewise-continuous-on a b I f
  by (auto simp: piecewise-continuous-on-def)
from insert.IH[OF this] show ?thesis
  by (rule 3) fact+
qed
qed
qed

```

```

lemma continuous-on-imp-piecewise-continuous-on:
  continuous-on {a .. b} f  $\implies$  piecewise-continuous-on a b {} f
  by (auto simp: piecewise-continuous-on-def)

```

```

lemma piecewise-continuous-on-imp-absolutely-integrable:
  fixes a b::real and f::real  $\Rightarrow$  'a::euclidean-space
  assumes piecewise-continuous-on a b I f
  shows f absolutely-integrable-on {a..b}
  using assms
proof (induction rule: piecewise-continuous-on-induct)
  case (empty a b f)
  show ?case
    by (auto intro!: absolutely-integrable-onI integrable-continuous-interval
        continuous-intros empty)
next
  case (combine a i b I f1 f2 f)
  from combine(10)
  have f absolutely-integrable-on {a..i}
    by (rule absolutely-integrable-spike[where S={i}]) (auto simp: combine)
  moreover
  from combine(11)
  have f absolutely-integrable-on {i..b}
    by (rule absolutely-integrable-spike[where S={i}]) (auto simp: combine)
  ultimately
  show ?case
    by (rule absolutely-integrable-on-combine) fact+
qed

```

```

lemma piecewise-continuous-on-integrable:
  fixes a b::real and f::real  $\Rightarrow$  'a::euclidean-space
  assumes piecewise-continuous-on a b I f
  shows f integrable-on {a..b}
  using piecewise-continuous-on-imp-absolutely-integrable[OF assms]
  unfolding absolutely-integrable-on-def by auto

```

```

lemma piecewise-continuous-on-comp:
  assumes p: piecewise-continuous-on a b I f
  assumes c:  $\bigwedge x. \text{isCont } (\lambda(x, y). g x y) x$ 
  shows piecewise-continuous-on a b I ( $\lambda x. g x (f x)$ )
proof -

```

from *piecewise-continuous-onE*[*OF p*]
obtain $l\ u$
where I : *finite I*
and cf : *continuous-on* ($\{a..b\} - I$) f
and l : ($\bigwedge i. i \in I \implies a < i \implies i \leq b \implies (f \longrightarrow l\ i)$) (*at-left i*)
and u : ($\bigwedge i. i \in I \implies a \leq i \implies i < b \implies (f \longrightarrow u\ i)$) (*at-right i*)
by *metis*
note \langle *finite I* \rangle
moreover
from c **have** cg : *continuous-on UNIV* ($\lambda(x, y). g\ x\ y$)
using c **by** (*auto simp: continuous-on-def isCont-def intro: tendsto-within-subset*)
then have *continuous-on* ($\{a..b\} - I$) ($\lambda x. g\ x\ (f\ x)$)
by (*intro continuous-on-compose2[OF cg, where f= $\lambda x. (x, f\ x)$, simplified]*)
(auto intro!: continuous-intros cf)
moreover
note $tendstcomp = tendsto-compose$ [*OF c[unfolded isCont-def], where f= $\lambda x. (x, f\ x)$, simplified, THEN tendsto-eq-rhs*]
have ($(\lambda x. g\ x\ (f\ x)) \longrightarrow g\ i\ (u\ i)$) (*at-right i*) **if** $i \in I\ a \leq i\ i < b$ **for** i
by (*rule tendstcomp*) (*auto intro!: tendsto-eq-intros u[OF $\langle i \in I \rangle$] that*)
moreover
have ($(\lambda x. g\ x\ (f\ x)) \longrightarrow g\ i\ (l\ i)$) (*at-left i*) **if** $i \in I\ a < i\ i \leq b$ **for** i
by (*rule tendstcomp*) (*auto intro!: tendsto-eq-intros l[OF $\langle i \in I \rangle$] that*)
ultimately show *?thesis*
by (*intro piecewise-continuous-onI*)
qed

lemma *bounded-piecewise-continuous-image*:
bounded ($f\ \langle\{a..b\}\rangle$)
if *piecewise-continuous-on* $a\ b\ I\ f$ **for** $a\ b::real$
using *that*
proof (*induction rule: piecewise-continuous-on-induct*)
case (*empty a b f*)
then show *?case* **by** (*auto intro!: compact-imp-bounded compact-continuous-image*)
next
case (*combine a i b I f1 f2 f*)
have ($f\ \langle\{a..b\}\rangle \subseteq (insert\ (f\ i)\ (f1\ \langle\{a..i\}\rangle \cup f2\ \langle\{i..b\}\rangle))$)
using *combine*
by (*auto simp: image-iff*) (*metis antisym-conv atLeastAtMost-iff le-cases not-less*)
also have *bounded ...*
using *combine* **by** *auto*
finally (*bounded-subset[rotated]*) **show** *?case* .
qed

lemma *tendsto-within-eventually*:
 $(f \longrightarrow l)$ (*at x within X*)
if
 $(f \longrightarrow l)$ (*at x within Y*)
 $\forall_F y$ *in at x within X. y $\in Y$*
using *- that(1)*

```

proof (rule tendsto-mono)
  show at x within X  $\leq$  at x within Y
  proof (rule filter-leI)
    fix P
    assume eventually P (at x within Y)
    with that(2) show eventually P (at x within X)
    unfolding eventually-at-filter
    by eventually-elim auto
  qed
qed

lemma at-within-eq-bot-lemma:
  at x within {b..c} = (if x < b  $\vee$  b > c then bot else at x within {b..c})
  for x b c::'a::linorder-topology
  by (auto intro!: not-in-closure-trivial-limitI)

lemma at-within-eq-bot-lemma2:
  at x within {a..b} = (if x > b  $\vee$  a > b then bot else at x within {a..b})
  for x a b::'a::linorder-topology
  by (auto intro!: not-in-closure-trivial-limitI)

lemma piecewise-continuous-on-combine:
  piecewise-continuous-on a c J f
  if piecewise-continuous-on a b J f piecewise-continuous-on b c J f
  using that
  apply (auto elim!: piecewise-continuous-onE)
  subgoal for l u l' u'
    apply (rule piecewise-continuous-onI[where
      l= $\lambda$ i. if i  $\leq$  b then l i else l' i and
      u= $\lambda$ i. if i < b then u i else u' i])
    subgoal by force
    subgoal
      apply (rule continuous-on-subset[where s=({a .. b}  $\cup$  {b .. c} - J)])
      apply (auto simp: continuous-on-def at-within-t1-space-avoid-finite)
      apply (rule Lim-Un)
      subgoal by auto
      subgoal by (subst at-within-eq-bot-lemma) auto
      apply (rule Lim-Un)
      subgoal by (subst at-within-eq-bot-lemma2) auto
      subgoal by auto
    done
  by auto
done

lemma piecewise-continuous-on-finite-superset:
  piecewise-continuous-on a b I f  $\implies$  I  $\subseteq$  J  $\implies$  finite J  $\implies$  piecewise-continuous-on
  a b J f
  for a b::'a::{linorder-topology, dense-order, no-bot, no-top}
  apply (auto simp add: piecewise-continuous-on-def)

```

```

  apply (rule continuous-on-subset, assumption, force)
subgoal for i
  apply (cases i ∈ I)
  apply (auto simp: continuous-on-def at-within-t1-space-avoid-finite)
  apply (drule bspec[where x=i])
  apply (auto simp: at-within-t1-space-avoid)
  apply (cases i = b)
  apply (auto simp: at-within-Icc-at-left )
  apply (subst (asm) at-within-interior[where x=i])
  by (auto simp: filterlim-at-split)
subgoal for i
  apply (cases i ∈ I)
  apply (auto simp: continuous-on-def at-within-t1-space-avoid-finite)
  apply (drule bspec[where x=i])
  apply (auto simp: at-within-t1-space-avoid)
  apply (cases i = a)
  apply (auto simp: at-within-Icc-at-right)
  apply (subst (asm) at-within-interior[where x=i])
  subgoal by (simp add: interior-Icc)
  by (auto simp: filterlim-at-split)
done

```

```

lemma piecewise-continuous-on-splitI:
  piecewise-continuous-on a c K f
  if
    piecewise-continuous-on a b I f
    piecewise-continuous-on b c J f
    I ⊆ K J ⊆ K finite K
  for a b::'a::{linorder-topology, dense-order, no-bot, no-top}
  apply (rule piecewise-continuous-on-combine[where b=b])
  subgoal
    by (rule piecewise-continuous-on-finite-superset, fact)
    (use that in ⟨auto elim!: piecewise-continuous-onE⟩)
  subgoal
    by (rule piecewise-continuous-on-finite-superset, fact)
    (use that in ⟨auto elim!: piecewise-continuous-onE⟩)
  done
end

```

4 Existence

```

theory Existence imports
  Piecewise-Continuous
begin

```

4.1 Definition

```

definition has-laplace :: (real ⇒ complex) ⇒ complex ⇒ complex ⇒ bool

```

(**infixr** *has'-laplace* 46)
where (*f has-laplace L*) $s \longleftrightarrow ((\lambda t. \exp (t *_R - s) * f t) \text{ has-integral } L) \{0..\}$

lemma *has-laplaceI*:
assumes $((\lambda t. \exp (t *_R - s) * f t) \text{ has-integral } L) \{0..\}$
shows (*f has-laplace L*) s
using *assms*
by (*auto simp: has-laplace-def*)

lemma *has-laplaceD*:
assumes (*f has-laplace L*) s
shows $((\lambda t. \exp (t *_R - s) * f t) \text{ has-integral } L) \{0..\}$
using *assms*
by (*auto simp: has-laplace-def*)

lemma *has-laplace-unique*:
 $L = M$ **if**
(*f has-laplace L*) s
(*f has-laplace M*) s
using *that*
by (*auto simp: has-laplace-def has-integral-unique*)

4.2 Condition for Existence: Exponential Order

definition *exponential-order* $M c f \longleftrightarrow 0 < M \wedge (\forall_F t \text{ in at-top. norm } (f t) \leq M * \exp (c * t))$

lemma *exponential-orderI*:
assumes $0 < M$ **and** *eo*: $\forall_F t \text{ in at-top. norm } (f t) \leq M * \exp (c * t)$
shows *exponential-order* $M c f$
by (*auto intro!: assms simp: exponential-order-def*)

lemma *exponential-orderD*:
assumes *exponential-order* $M c f$
shows $0 < M \wedge \forall_F t \text{ in at-top. norm } (f t) \leq M * \exp (c * t)$
using *assms* **by** (*auto simp: exponential-order-def*)

context
fixes $f::\text{real} \Rightarrow \text{complex}$
begin

definition *laplace-integrand::complex* $\Rightarrow \text{real} \Rightarrow \text{complex}$
where *laplace-integrand* $s t = \exp (t *_R - s) * f t$

lemma *laplace-integrand-absolutely-integrable-on-Icc*:
laplace-integrand s *absolutely-integrable-on* $\{a..b\}$
if $\exists x \in \{a..b\}$ *in lebesgue. cmod* $(f x) \leq B$ *f integrable-on* $\{a..b\}$
apply (*cases* $b \leq a$)
subgoal **by** (*auto intro!: absolutely-integrable-onI integrable-negligible[OF negli-*

```

gible-real-ivlI])
proof goal-cases
  case 1
  have compact (( $\lambda x$ . exp (- (x *R s))) ‘ {a .. b})
    by (rule compact-continuous-image) (auto intro!: continuous-intros)
  then obtain C where C: 0 ≤ C a ≤ x ⇒ x ≤ b ⇒ cmod (exp (- (x *R s)))
≤ C for x
  using 1
  apply (auto simp: bounded-iff dest!: compact-imp-bounded)
  by (metis atLeastAtMost-iff exp-ge-zero order-refl order-trans scaleR-complex.sel(1))

have m: ( $\lambda x$ . indicator {a..b} x *R f x) ∈ borel-measurable lebesgue
  apply (rule has-integral-implies-lebesgue-measurable)
  apply (rule integrable-integral)
  apply (rule that)
  done
have complex-set-integrable lebesgue {a..b} ( $\lambda x$ . exp (- (x *R s)) * (indicator {a
.. b} x *R f x))
  unfolding set-integrable-def
  apply (rule integrableI-bounded-set-indicator[where B=C * B])
  apply (simp; fail)
  apply (rule borel-measurable-times)
  apply measurable
  apply (simp add: measurable-completion)
  apply (simp add: measurable-completion)
  apply (rule m)
  apply (simp add: emeasure-lborel-Icc-eq)
  using that(1)
  apply eventually-elim
  apply (auto simp: norm-mult)
  apply (rule mult-mono)
  using C
  by auto
then show ?case
  unfolding set-integrable-def
  by (simp add: laplace-integrand-def[abs-def] indicator-inter-arith[symmetric])
qed

lemma laplace-integrand-integrable-on-Icc:
  laplace-integrand s integrable-on {a..b}
  if AE x∈{a..b} in lebesgue. cmod (f x) ≤ B f integrable-on {a..b}
  using laplace-integrand-absolutely-integrable-on-Icc[OF that]
  using set-lebesgue-integral-eq-integral(1) by blast

lemma eventually-laplace-integrand-le:
  ∀F t in at-top. cmod (laplace-integrand s t) ≤ M * exp (- (Re s - c) * t)
  if exponential-order M c f
  using exponential-orderD(2)[OF that]
proof (eventually-elim)

```

```

case (elim t)
show ?case
  unfolding laplace-integrand-def
  apply (rule norm-mult-ineq[THEN order-trans])
  apply (auto intro!: mult-left-mono[THEN order-trans, OF elim])
  apply (auto simp: exp-minus divide-simps algebra-simps exp-add[symmetric])
done
qed

lemma
  assumes eo: exponential-order M c f
  and cs: c < Re s
  shows laplace-integrand-integrable-on-Ici-iff:
    laplace-integrand s integrable-on {a..}  $\longleftrightarrow$ 
      ( $\forall k > a$ . laplace-integrand s integrable-on {a..k})
    (is ?th1)
  and laplace-integrand-absolutely-integrable-on-Ici-iff:
    laplace-integrand s absolutely-integrable-on {a..}  $\longleftrightarrow$ 
      ( $\forall k > a$ . laplace-integrand s absolutely-integrable-on {a..k})
    (is ?th2)
proof -
  have  $\forall_F t$  in at-top. a < (t::real)
  using eventually-gt-at-top by blast
  then have  $\forall_F t$  in at-top. t > a  $\wedge$  cmod (laplace-integrand s t)  $\leq$  M * exp (-
  (Re s - c) * t)
  using eventually-laplace-integrand-le[OF eo]
  by eventually-elim (auto)
  then obtain A where A: A > a and le: t  $\geq$  A  $\implies$  cmod (laplace-integrand s
  t)  $\leq$  M * exp (- (Re s - c) * t) for t
  unfolding eventually-at-top-linorder
  by blast

  let ?f =  $\lambda(k::real) (t::real)$ . indicat-real {A..k} t *R laplace-integrand s t

  from exponential-orderD[OF eo] have M  $\neq$  0 by simp
  have 2: ( $\lambda t$ . M * exp (- (Re s - c) * t)) integrable-on {A..}
  unfolding integrable-on-cmult-iff[OF  $\langle M \neq 0 \rangle$ ] norm-exp-eq-Re
  by (rule integrable-on-exp-minus-to-infinity) (simp add: cs)

  have 3: t  $\in$  {A..}  $\implies$  cmod (?f k t)  $\leq$  M * exp (- (Re s - c) * t)
  (is t  $\in \implies$  ?lhs t  $\leq$  ?rhs t)
  for t k
proof safe
  fix t assume A  $\leq$  t
  have ?lhs t  $\leq$  cmod (laplace-integrand s t)
  by (auto simp: indicator-def)
  also have ...  $\leq$  ?rhs t using  $\langle A \leq t \rangle$  le by (simp add: laplace-integrand-def)
  finally show ?lhs t  $\leq$  ?rhs t .
qed

```

```

have  $\downarrow$ :  $\forall t \in \{A..\}$ .  $((\lambda k. ?f k t) \longrightarrow \text{laplace-integrand } s t)$  at-top
proof safe
  fix  $t$  assume  $t: t \geq A$ 
  have  $\forall_F k$  in at-top.  $k \geq t$ 
    by (simp add: eventually-ge-at-top)
  then have  $\forall_F k$  in at-top.  $\text{laplace-integrand } s t = ?f k t$ 
    by (eventually-elim (use t in <auto simp: indicator-def>))
  then show  $((\lambda k. ?f k t) \longrightarrow \text{laplace-integrand } s t)$  at-top using tendsto-const
    by (rule Lim-transform-eventually[rotated])
qed

```

show *th1: ?th1*

```

proof safe
  assume  $\forall k > a$ . laplace-integrand s integrable-on {a..k}
  note  $li = \text{this}[\text{rule-format}]$ 
  have  $liA$ : laplace-integrand s integrable-on {A..k} for  $k$ 
  proof cases
    assume  $k \leq A$ 
    then have  $\{A..k\} = (\text{if } A = k \text{ then } \{k\} \text{ else } \{\})$  by auto
    then show ?thesis by (auto intro!: integrable-negligible)
  next
    assume  $n: \neg k \leq A$ 
    show ?thesis
      by (rule integrable-on-subinterval[OF li[of k]] (use A n in auto))
  qed
  have ?f k integrable-on {A..k} for  $k$ 
    using  $liA[\text{of } k]$  negligible-empty
    by (rule integrable-spike) auto
  then have  $1: ?f k$  integrable-on {A..} for  $k$ 
    by (rule integrable-on-superset) auto
  note  $1\ 2\ 3\ 4$ 
  note  $*$  = this[unfolded set-integrable-def]
  from  $li[\text{of } A]$  dominated-convergence-at-top(1)[OF *]
  show laplace-integrand s integrable-on {a..}
    by (rule integrable-Un') (use <a < A> in <auto simp: max-def li>)
qed (rule integrable-on-subinterval, assumption, auto)

```

show *?th2*

```

proof safe
  assume  $ai: \forall k > a$ . laplace-integrand s absolutely-integrable-on {a..k}
  then have laplace-integrand s absolutely-integrable-on {a..A}
    using  $A$  by auto
  moreover
  from  $ai$  have  $\forall k > a$ . laplace-integrand s integrable-on {a..k}
    using set-lebesgue-integral-eq-integral(1) by blast
  with  $th1$  have  $i$ : laplace-integrand s integrable-on {a..} by auto
  have  $1: ?f k$  integrable-on {A..} for  $k$ 
    apply (rule integrable-on-superset[where S={A..k}])

```



```

using - negligible-empty
  apply (rule integrable-spike[where  $f = \text{laplace-integrand } s$ ])
  apply (rule integrable-on-subinterval)
  apply (rule i)
  by (use  $\langle a < A \rangle$  in auto)
have laplace-integrand  $s$  absolutely-integrable-on  $\{A..\}$ 
  using - dominated-convergence-at-top(1)[OF 1 2 3 4] 2
  by (rule absolutely-integrable-integrable-bound) (use le in auto)
ultimately
have laplace-integrand  $s$  absolutely-integrable-on  $(\{a..A\} \cup \{A..\})$ 
  by (rule set-integrable-Un) auto
also have  $\{a..A\} \cup \{A..\} = \{a..\}$  using  $\langle a < A \rangle$  by auto
finally show local.laplace-integrand  $s$  absolutely-integrable-on  $\{a..\}$  .
qed (rule set-integrable-subset, assumption, auto)
qed

```

```

theorem laplace-exists-laplace-integrandI:
  assumes laplace-integrand  $s$  integrable-on  $\{0..\}$ 
  obtains  $F$  where ( $f$  has-laplace  $F$ )  $s$ 
proof -
  from assms
  have ( $f$  has-laplace integral  $\{0..\}$  (laplace-integrand  $s$ ))  $s$ 
  unfolding has-laplace-def laplace-integrand-def by blast
  thus ?thesis ..
qed

```

```

lemma
  assumes eo: exponential-order  $M$   $c$   $f$ 
  and pc:  $\bigwedge k. \text{AE } x \in \{0..k\} \text{ in lebesgue. } c \text{ mod } (f \ x) \leq B \ k \ \bigwedge k. f \text{ integrable-on } \{0..k\}$ 
  and  $s: \text{Re } s > c$ 
  shows laplace-integrand-integrable: laplace-integrand  $s$  integrable-on  $\{0..\}$  (is ?th1)
  and laplace-integrand-absolutely-integrable:
    laplace-integrand  $s$  absolutely-integrable-on  $\{0..\}$  (is ?th2)
  using eo laplace-integrand-absolutely-integrable-on-Icc[OF pc]  $s$ 
  by (auto simp: laplace-integrand-integrable-on-Ici-iff
    laplace-integrand-absolutely-integrable-on-Ici-iff
    set-lebesgue-integral-eq-integral)

```

```

lemma piecewise-continuous-on-AE-boundedE:
  assumes pc:  $\bigwedge k. \text{piecewise-continuous-on } a \ k \ (I \ k) \ f$ 
  obtains  $B$  where  $\bigwedge k. \text{AE } x \in \{a..k\} \text{ in lebesgue. } c \text{ mod } (f \ x) \leq B \ k$ 
  apply atomize-elim
  apply (rule choice)
  apply (rule allI)
  subgoal for  $k$ 
  using bounded-piecewise-continuous-image[OF pc[of  $k$ ]]
  by (force simp: bounded-iff)

```

done

theorem *piecewise-continuous-on-has-laplace*:

assumes *eo*: exponential-order $M\ c\ f$

and *pc*: $\bigwedge k. \text{piecewise-continuous-on } 0\ k\ (I\ k)\ f$

and *s*: $\text{Re } s > c$

obtains F **where** (*f* has-laplace F) *s*

proof –

from *piecewise-continuous-on-AE-boundedE*[*OF pc*]

obtain B **where** *AE*: $\text{AE } x \in \{0..k\}$ in lebesgue. $\text{cmod } (f\ x) \leq B\ k$ **for** k **by** force

have *int*: *f* integrable-on $\{0..k\}$ **for** k

using *pc*

by (*rule piecewise-continuous-on-integrable*)

show *?thesis*

using *pc*

apply (*rule piecewise-continuous-on-AE-boundedE*)

apply (*rule laplace-exists-laplace-integrandI*)

apply (*rule laplace-integrand-integrable*)

apply (*rule eo*)

apply *assumption*

apply (*rule int*)

apply (*rule s*)

by (*rule that*)

qed

end

4.3 Concrete Laplace Transforms

lemma *exp-scaleR-has-vector-derivative-left*[*derivative-intros*]:

$((\lambda t. \text{exp } (t *_{\mathbb{R}} A)) \text{ has-vector-derivative } A * \text{exp } (t *_{\mathbb{R}} A))$ (*at t within S*)

by (*metis exp-scaleR-has-vector-derivative-right exp-times-scaleR-commute*)

lemma

fixes *a*::complex – TODO: generalize

assumes *a*: $0 < \text{Re } a$

shows *integrable-on-cexp-minus-to-infinity*: $(\lambda x. \text{exp } (x *_{\mathbb{R}} - a))$ integrable-on $\{c..\}$

and *integral-cexp-minus-to-infinity*: $\text{integral } \{c..\} (\lambda x. \text{exp } (x *_{\mathbb{R}} - a)) = \text{exp } (c *_{\mathbb{R}} - a) / a$

proof –

from *a* **have** $a \neq 0$ **by** *auto*

define *f* **where** $f = (\lambda k\ x. \text{if } x \in \{c..\text{real } k\} \text{ then } \text{exp } (x *_{\mathbb{R}} - a) \text{ else } 0)$

{

fix $k :: \text{nat}$ **assume** *k*: *of-nat* $k \geq c$

from $\langle a \neq 0 \rangle k$

have $((\lambda x. \text{exp } (x *_{\mathbb{R}} - a)) \text{ has-integral } (-\text{exp } (k *_{\mathbb{R}} - a) / a - (-\text{exp } (c *_{\mathbb{R}} - a) / a))$ $\{c..\text{real } k\}$

by (*intro fundamental-theorem-of-calculus*)

$(\text{auto intro!}: \text{derivative-eq-intros } \text{exp-scaleR-has-vector-derivative-left}$
 $\text{simp}: \text{divide-inverse-commute}$
 $\text{simp del}: \text{scaleR-minus-left } \text{scaleR-minus-right})$
hence $(f\ k \text{ has-integral } (\text{exp } (c *_{\mathbb{R}} - a)/a - \text{exp } (k *_{\mathbb{R}} - a)/a)) \{c..\}$ **unfolding**
f-def
by $(\text{subst has-integral-restrict}) \text{simp-all}$
} note $\text{has-integral-f} = \text{this}$

have $\text{integrable-fk}: f\ k \text{ integrable-on } \{c..\}$ **for** k
proof –
have $(\lambda x. \text{exp } (x *_{\mathbb{R}} - a)) \text{ integrable-on } \{c..\text{of-real } k\}$ **(is ?P)**
unfolding *f-def* **by** $(\text{auto intro!}: \text{continuous-intros } \text{integrable-continuous-real})$
then have $\text{int}: (f\ k) \text{ integrable-on } \{c..\text{of-real } k\}$
by $(\text{rule integrable-eq}) (\text{simp add}: \text{f-def})$
show *?thesis*
by $(\text{rule integrable-on-superset}[OF \text{int}]) (\text{auto simp}: \text{f-def})$

qed
have $\text{limseq}: \bigwedge x. x \in \{c..\} \implies (\lambda k. f\ k\ x) \longrightarrow \text{exp } (x *_{\mathbb{R}} - a)$
apply $(\text{auto intro!}: \text{Lim-transform-eventually}[OF \text{tendsto-const}] \text{simp}: \text{f-def})$
by $(\text{meson eventually-sequentiallyI } \text{nat-ceiling-le-eq})$
have $\text{bnd}: \bigwedge x. x \in \{c..\} \implies \text{cmod } (f\ k\ x) \leq \text{exp } (-\text{Re } a * x)$ **for** k
by $(\text{auto simp}: \text{f-def})$

have $[\text{simp}]: f\ k = (\lambda -. 0)$ **if** $\text{of-nat } k < c$ **for** k **using** *that* **by** $(\text{auto simp}: \text{fun-eq-iff } \text{f-def})$
have $\text{integral-f}: \text{integral } \{c..\} (f\ k) =$
 $(\text{if } \text{real } k \geq c \text{ then } \text{exp } (c *_{\mathbb{R}} - a)/a - \text{exp } (k *_{\mathbb{R}} - a)/a \text{ else } 0)$
for k **using** $\text{integral-unique}[OF \text{has-integral-f}[of k]]$ **by** *simp*

have $(\lambda k. \text{exp } (c *_{\mathbb{R}} - a)/a - \text{exp } (k *_{\mathbb{R}} - a)/a) \longrightarrow \text{exp } (c *_{\mathbb{R}} - a)/a - 0/a$
apply $(\text{intro } \text{tendsto-intros } \text{filterlim-compose}[OF \text{exp-at-bot}]$
 $\text{filterlim-tendsto-neg-mult-at-bot}[OF \text{tendsto-const}] \text{filterlim-real-sequentially})+$
apply $(\text{rule } \text{tendsto-norm-zero-cancel})$
by $(\text{auto intro!}: \text{assms } \langle a \neq 0 \rangle \text{filterlim-real-sequentially}$
 $\text{filterlim-compose}[OF \text{exp-at-bot}] \text{filterlim-compose}[OF \text{filterlim-uminus-at-bot-at-top}]$
 $\text{filterlim-at-top-mult-tendsto-pos}[OF \text{tendsto-const}])$

moreover
note $A = \text{dominated-convergence}[\text{where } g = \lambda x. \text{exp } (x *_{\mathbb{R}} - a),$
 $OF \text{integrable-fk } \text{integrable-on-exp-minus-to-infinity}[\text{where } a = \text{Re } a \text{ and } c = c,$
 $OF \langle 0 < \text{Re } a \rangle]$
 $\text{bnd } \text{limseq}]$
from $A(1)$ **show** $(\lambda x. \text{exp } (x *_{\mathbb{R}} - a)) \text{ integrable-on } \{c..\}$.
from $\text{eventually-gt-at-top}[of \text{nat } \lceil c \rceil]$ **have** $\text{eventually } (\lambda k. \text{of-nat } k > c)$ *sequentially*
by *eventually-elim linarith*
hence $\text{eventually } (\lambda k. \text{exp } (c *_{\mathbb{R}} - a)/a - \text{exp } (k *_{\mathbb{R}} - a)/a = \text{integral } \{c..\} (f\ k))$ *sequentially*
by *eventually-elim (simp add: integral-f)*
ultimately have $(\lambda k. \text{integral } \{c..\} (f\ k)) \longrightarrow \text{exp } (c *_{\mathbb{R}} - a)/a - 0/a$

by (rule *Lim-transform-eventually*)
 from *LIMSEQ-unique*[*OF A(2) this*]
 show *integral* {*c..*} $(\lambda x. \exp (x *_R - a)) = \exp (c *_R - a) / a$ by *simp*
 qed

lemma *has-integral-cexp-minus-to-infinity*:
 fixes *a::complex*— **TODO**: generalize
 assumes *a*: $0 < \operatorname{Re} a$
 shows $((\lambda x. \exp (x *_R - a)) \text{ has-integral } \exp (c *_R - a) / a)$ {*c..*}
 using *integral-cexp-minus-to-infinity*[*OF assms*]
 integrable-on-cexp-minus-to-infinity[*OF assms*]
 using *has-integral-integrable-integral* by *blast*

lemma *has-laplace-one*:
 $((\lambda s. 1) \text{ has-laplace inverse } s)$ *s* if $\operatorname{Re} s > 0$
proof (*safe intro!*: *has-laplaceI*)
 from *that* have $((\lambda t. \exp (t *_R - s)) \text{ has-integral inverse } s)$ {*0..*}
 by (rule *has-integral-cexp-minus-to-infinity*[*THEN has-integral-eq-rhs*])
 (*auto simp: inverse-eq-divide*)
 then show $((\lambda t. \exp (t *_R - s) * 1) \text{ has-integral inverse } s)$ {*0..*} by *simp*
 qed

lemma *has-laplace-add*:
 assumes *f*: (*f* *has-laplace* *F*) *S*
 assumes *g*: (*g* *has-laplace* *G*) *S*
 shows $((\lambda x. f x + g x) \text{ has-laplace } F + G)$ *S*
 apply (rule *has-laplaceI*)
 using *has-integral-add*[*OF has-laplaceD*[*OF f*] *has-laplaceD*[*OF g*]]
 by (*auto simp: algebra-simps*)

lemma *has-laplace-cmul*:
 assumes (*f* *has-laplace* *F*) *S*
 shows $((\lambda x. r *_R f x) \text{ has-laplace } r *_R F)$ *S*
 apply (rule *has-laplaceI*)
 using *has-laplaceD*[*OF assms*, *THEN has-integral-cmul*[**where** *c=r*]]
 by *auto*

lemma *has-laplace-uminus*:
 assumes (*f* *has-laplace* *F*) *S*
 shows $((\lambda x. - f x) \text{ has-laplace } - F)$ *S*
 using *has-laplace-cmul*[*OF assms*, *of -1*]
 by *auto*

lemma *has-laplace-minus*:
 assumes *f*: (*f* *has-laplace* *F*) *S*
 assumes *g*: (*g* *has-laplace* *G*) *S*
 shows $((\lambda x. f x - g x) \text{ has-laplace } F - G)$ *S*
 using *has-laplace-add*[*OF f* *has-laplace-uminus*[*OF g*]]
 by *simp*

lemma *has-laplace-spike*:
 (*f* *has-laplace* *L*) *s*
if *L*: (*g* *has-laplace* *L*) *s*
and *negligible* *T*
and $\bigwedge t. t \notin T \implies t \geq 0 \implies f\ t = g\ t$
by (*auto* *intro!*: *has-laplaceI* *has-integral-spike*[**where** *S*=*T*, *OF* - - *has-laplaceD*[*OF* *L*]]) *that*)

lemma *has-laplace-frequency-shift*:— First Translation Theorem in Schiff
 ($(\lambda t. \exp(t *_R b) * f\ t)$ *has-laplace* *L*) *s*
if (*f* *has-laplace* *L*) (*s* - *b*)
using *that*
by (*auto* *intro!*: *has-laplaceI* *dest!*: *has-laplaceD*
simp: *mult-exp-exp algebra-simps*)

theorem *has-laplace-derivative-time-domain*:

(*f'* *has-laplace* *s* * *L* - *f0*) *s*
if *L*: (*f* *has-laplace* *L*) *s*
and *f'*: $\bigwedge t. t > 0 \implies (f\ \text{has-vector-derivative}\ f'\ t)$ (*at* *t*)
and *f0*: (*f* \longrightarrow *f0*) (*at-right* 0)
and *eo*: *exponential-order* *M* *c* *f*
and *cs*: *c* < *Re* *s*

— Proof and statement follow "The Laplace Transform: Theory and Applications"

by Joel L. Schiff.

proof (*rule* *has-laplaceI*)
have *ce*: *continuous-on* *S* ($\lambda t. \exp(t *_R - s)$) **for** *S*
by (*auto* *intro!*: *continuous-intros*)
have *de*: ($(\lambda t. \exp(t *_R - s))$ *has-vector-derivative* ($- s * \exp(- (t *_R s))$))
(*at* *t*) **for** *t*
by (*auto* *simp*: *has-vector-derivative-def* *intro!*: *derivative-eq-intros* *ext*)
have ($(\lambda x. -s * (f\ x * \exp(- (x *_R s))))$ *has-integral* - *s* * *L*) {0..}
apply (*rule* *has-integral-mult-right*)
using *has-laplaceD*[*OF* *L*]
by (*auto* *simp*: *ac-simps*)

define *g* **where** *g* *x* = (*if* *x* ≤ 0 *then* *f0* *else* *f* *x*) **for** *x*

have *eog*: *exponential-order* *M* *c* *g*

proof —

from *exponential-orderD*[*OF* *eo*] **have** 0 < *M*
and *ev*: $\forall_F t$ *in* *at-top*. *cmod* (*f* *t*) ≤ *M* * *exp* (*c* * *t*) .
have $\forall_F t$: *real* *in* *at-top*. *t* > 0 **by** *simp*
with *ev* **have** $\forall_F t$ *in* *at-top*. *cmod* (*g* *t*) ≤ *M* * *exp* (*c* * *t*)
by *eventually-elim* (*auto* *simp*: *g-def*)
with <0 < *M*> **show** ?*thesis*
by (*rule* *exponential-orderI*)

qed

```

have Lg: (g has-laplace L) s
  using L
  by (rule has-laplace-spike[where T={0}]) (auto simp: g-def)
have g':  $\bigwedge t. 0 < t \implies (g \text{ has-vector-derivative } f' t) \text{ (at } t)$ 
  using f'
  by (rule has-vector-derivative-transform-within-open[where S={0<..}]) (auto
simp: g-def)
have cg: continuous-on {0..k} g for k
  apply (auto simp: g-def continuous-on-def)
  apply (rule filterlim-at-within-If)
  subgoal by (rule tendsto-intros)
  subgoal
    apply (rule tendsto-within-subset)
    apply (rule f0)
    by auto
  subgoal premises prems for x
  proof -
    from prems have 0 < x by auto
    from order-tendstoD[OF tendsto-ident-at this]
    have eventually ((<) 0) (at x within {0..k}) by auto
    then have  $\forall_F x \text{ in at } x \text{ within } \{0..k\}. f x = (\text{if } x \leq 0 \text{ then } f0 \text{ else } f x)$ 
      by eventually-elim auto
    moreover
    note [simp] = at-within-open[where S={0<..}]
    have continuous-on {0<..} f
      by (rule continuous-on-vector-derivative)
      (auto simp add: intro!: f')
    then have (f  $\longrightarrow$  f x) (at x within {0..k})
      using <0 < x>
      by (auto simp: continuous-on-def intro: Lim-at-imp-Lim-at-within)
    ultimately show ?thesis
      by (rule Lim-transform-eventually[rotated])
  qed
done
then have pcg: piecewise-continuous-on 0 k { } g for k
  by (auto simp: piecewise-continuous-on-def)
from piecewise-continuous-on-AE-boundedE[OF this]
obtain B where B: AE x $\in$ {0..k} in lebesgue. cmod (g x)  $\leq$  B k for k by auto
have 1: laplace-integrand g s absolutely-integrable-on {0..}
  apply (rule laplace-integrand-absolutely-integrable[OF eog])
  apply (rule B)
  apply (rule piecewise-continuous-on-integrable)
  apply (rule pcg)
  apply (rule cs)
done
then have csi: complex-set-integrable lebesgue {0..} ( $\lambda x. \exp (x *_R - s) * g x$ )
  by (auto simp: laplace-integrand-def[abs-def])
from has-laplaceD[OF Lg, THEN has-integral-improperE, OF csi]
obtain J where J:  $\bigwedge k. ((\lambda t. \exp (t *_R - s) * g t) \text{ has-integral } J k) \{0..k\}$ 

```

```

    and [tendsto-intros]: (J  $\longrightarrow$  L) at-top
    by auto
    have (( $\lambda x. -s * (\exp (x *_{\mathbb{R}} - s) * g x)$ ) has-integral  $-s * J k$ ) {0..k} for k
    by (rule has-integral-mult-right) (rule J)
    then have *: (( $\lambda x. g x * (-s * \exp (- (x *_{\mathbb{R}} s)))$ ) has-integral  $-s * J k$ ) {0..k}
  for k
    by (auto simp: algebra-simps)
    have  $\forall_F k :: \text{real in at-top. } k \geq 0$ 
    using eventually-ge-at-top by blast
    then have evI:  $\forall_F k \text{ in at-top. } ((\lambda t. \exp (t *_{\mathbb{R}} - s) * f' t)$  has-integral
       $g k * \exp (k *_{\mathbb{R}} - s) + s * J k - g 0)$  {0..k}
    proof eventually-elim
      case (elim k)
      show ?case
        apply (subst mult.commute)
        apply (rule integration-by-parts-interior[OF bounded-bilinear-mult], fact)
        apply (rule cg) apply (rule ce) apply (rule g') apply force apply (rule de)
        apply (rule has-integral-eq-rhs)
        apply (rule *)
        by (auto simp: )
    qed
  have t1: (( $\lambda x. g x * \exp (x *_{\mathbb{R}} - s)$ )  $\longrightarrow 0$ ) at-top
    apply (subst mult.commute)
    unfolding laplace-integrand-def[symmetric]
    apply (rule Lim-null-comparison)
    apply (rule eventually-laplace-integrand-le[OF eog])
    apply (rule tendsto-mult-right-zero)
    apply (rule filterlim-compose[OF exp-at-bot])
    apply (rule filterlim-tendsto-neg-mult-at-bot)
    apply (rule tendsto-intros)
    using cs apply simp
    apply (rule filterlim-ident)
    done
  show (( $\lambda t. \exp (t *_{\mathbb{R}} - s) * f' t$ ) has-integral  $s * L - f0$ ) {0..}
    apply (rule has-integral-improper-at-topI[OF evI])
    subgoal
      apply (rule tendsto-eq-intros)
      apply (rule tendsto-intros)
      apply (rule t1)
      apply (rule tendsto-intros)
      apply (rule tendsto-intros)
      apply (rule tendsto-intros)
      apply (rule tendsto-intros)
      apply (rule tendsto-intros)
      by (simp add: g-def)
    done
  qed

```

lemma *exp-times-has-integral*:

(($\lambda t. \exp (c * t)$) has-integral (if $c = 0$ then t else $\exp (c * t) / c$) - (if $c = 0$

```

then t0 else exp (c * t0) / c) {t0 .. t}
  if t0 ≤ t
  for c t::real
  apply (cases c = 0)
  subgoal
    using that
    apply auto
    apply (rule has-integral-eq-rhs)
    apply (rule has-integral-const-real)
    by auto
  subgoal
    apply (rule fundamental-theorem-of-calculus)
    using that
    by (auto simp: has-vector-derivative-def intro!: derivative-eq-intros)
done

```

```

lemma integral-exp-times:
  integral {t0 .. t} (λt. exp (c * t)) = (if c = 0 then t - t0 else exp (c * t) / c -
  exp (c * t0) / c)
  if t0 ≤ t
  for c t::real
  using exp-times-has-integral[OF that, of c] that
  by (auto split: if-splits)

```

```

lemma filtermap-times-pos-at-top: filtermap ((* e) at-top = at-top
  if e > 0
  for e::real
  apply (rule filtermap-fun-inverse[of (*) (inverse e)])
  apply (rule filterlim-tendsto-pos-mult-at-top)
  apply (rule tendsto-intros)
  subgoal using that by simp
  apply (rule filterlim-ident)
  apply (rule filterlim-tendsto-pos-mult-at-top)
  apply (rule tendsto-intros)
  subgoal using that by simp
  apply (rule filterlim-ident)
  using that by auto

```

```

lemma exponential-order-additiveI:
  assumes 0 < M and eo: ∀ F t in at-top. norm (f t) ≤ K + M * exp (c * t) and
  c ≥ 0
  obtains M' where exponential-order M' c f
proof -
  consider c = 0 | c > 0 using ⟨c ≥ 0⟩ by arith
  then show ?thesis
  proof cases
    assume c = 0
    have exponential-order (max K 0 + M) c f
    using eo

```



```

    apply (auto intro!: exponential-orderI add-nonneg-pos ⟨0 < M⟩ simp: ⟨c =
0⟩)
  apply (auto simp: max-def)
  using eventually-elim2 by force
  then show ?thesis ..
next
  assume c > 0
  have ∀F t in at-top. norm (f t) ≤ K + M * exp (c * t)
  by fact
  moreover
  have ∀F t in (filtermap exp (filtermap ((* c) at-top)). K < t
  by (simp add: filtermap-times-pos-at-top ⟨c > 0⟩ filtermap-exp-at-top)
  then have ∀F t in at-top. K < exp (c * t)
  by (simp add: eventually-filtermap)
  ultimately
  have ∀F t in at-top. norm (f t) ≤ (1 + M) * exp (c * t)
  by eventually-elim (auto simp: algebra-simps)
  with add-nonneg-pos[OF zero-le-one ⟨0 < M⟩]
  have exponential-order (1 + M) c f
  by (rule exponential-orderI)
  then show ?thesis ..
qed
qed

```

lemma exponential-order-integral:

```

  fixes f::real ⇒ 'a::banach
  assumes I: ∧t. t ≥ a ⇒ (f has-integral I t) {a .. t}
  and eo: exponential-order M c f
  and c > 0
  obtains M' where exponential-order M' c I
proof -
  from exponential-orderD[OF eo] have 0 < M
  and bound: ∀F t in at-top. norm (f t) ≤ M * exp (c * t)
  by auto
  have ∀F t in at-top. t > a
  by simp
  from bound this
  have ∀F t in at-top. norm (f t) ≤ M * exp (c * t) ∧ t > a
  by eventually-elim auto
  then obtain t0 where t0: ∧t. t ≥ t0 ⇒ norm (f t) ≤ M * exp (c * t) t0 > a
  by (auto simp: eventually-at-top-linorder)
  have ∀F t in at-top. t > t0 by simp
  then have ∀F t in at-top. norm (I t) ≤ norm (integral {a..t0} f) + M * exp (c
* t0) / c + (M / c) * exp (c * t)
  proof eventually-elim
  case (elim t) then have that: t ≥ t0 by simp
  from t0 have a ≤ t0 by simp
  have f integrable-on {a .. t0} f integrable-on {t0 .. t}
  subgoal by (rule has-integral-integrable[OF I[OF ⟨a ≤ t0⟩]])

```

```

subgoal
apply (rule integrable-on-subinterval[OF has-integral-integrable[OF I[where
t=t]]])
  using ⟨t0 > a⟩ that by auto
done
have  $I t = \text{integral } \{a .. t0\} f + \text{integral } \{t0 .. t\} f$ 
by (smt I ⟨a ≤ t0⟩ ⟨f integrable-on {t0..t}⟩ has-integral-combine has-integral-integrable-integral
that)
also have  $\text{norm } \dots \leq \text{norm } (\text{integral } \{a .. t0\} f) + \text{norm } (\text{integral } \{t0 .. t\} f)$ 
by norm
also
have  $\text{norm } (\text{integral } \{t0 .. t\} f) \leq \text{integral } \{t0 .. t\} (\lambda t. M * \exp (c * t))$ 
apply (rule integral-norm-bound-integral)
apply fact
by (auto intro!: integrable-continuous-interval continuous-intros t0)
also have  $\dots = M * \text{integral } \{t0 .. t\} (\lambda t. \exp (c * t))$ 
by simp
also have  $\text{integral } \{t0 .. t\} (\lambda t. \exp (c * t)) = \exp (c * t) / c - \exp (c * t0)$ 
/ c
using ⟨c > 0⟩ ⟨t0 ≤ t⟩
by (subst integral-exp-times) auto
finally show ?case
using ⟨c > 0⟩
by (auto simp: algebra-simps)
qed
from exponential-order-additiveI[OF divide-pos-pos[OF ⟨0 < M⟩ ⟨0 < c⟩] this
less-imp-le[OF ⟨0 < c⟩]]
obtain M' where exponential-order M' c I .
then show ?thesis ..
qed

```

```

lemma integral-has-vector-derivative-piecewise-continuous:
fixes f :: real ⇒ 'a::euclidean-space — TODO: generalize?
assumes piecewise-continuous-on a b D f
shows  $\bigwedge x. x \in \{a .. b\} - D \implies$ 
 $((\lambda u. \text{integral } \{a..u\} f) \text{ has-vector-derivative } f(x))$  (at x within {a..b} - D)
using assms
proof (induction a b D f rule: piecewise-continuous-on-induct)
case (empty a b f)
then show ?case
by (auto intro: integral-has-vector-derivative)
next
case (combine a i b I f1 f2 f)
then consider  $x < i \mid i < x$  by auto arith

then show ?case
proof cases — TODO: this is very explicit...
case 1
have evless:  $\forall_F xa \text{ in } \text{nhds } x. xa < i$ 

```

```

apply (rule order-tendstoD[OF - ⟨x < i⟩])
by (simp add: filterlim-ident)
have eq: at x within {a..b} - insert i I = at x within {a .. i} - I
unfolding filter-eq-iff
proof safe
  fix P
  assume eventually P (at x within {a..i} - I)
  with evless show eventually P (at x within {a..b} - insert i I)
    unfolding eventually-at-filter
    by eventually-elim auto
next
  fix P
  assume eventually P (at x within {a..b} - insert i I)
  with evless show eventually P (at x within {a..i} - I)
    unfolding eventually-at-filter
    apply eventually-elim
    using 1 combine
    by auto
qed
have f x = f1 x using combine 1 by auto
have i-eq: integral {a..y} f = integral {a..y} f1 if y < i for y
  using negligible-empty
  apply (rule integral-spike)
  using combine 1 that
  by auto
from evless have ev-eq:  $\forall_F x$  in nhds x.  $x \in \{a..i\} - I \longrightarrow \text{integral } \{a..x\} f$ 
= integral {a..x} f1
  by eventually-elim (auto simp: i-eq)
show ?thesis unfolding eq ⟨f x = f1 x⟩
  apply (subst has-vector-derivative-cong-ev[OF ev-eq])
  using combine.IH[of x]
  using combine.hyps combine.prem 1
  by (auto simp: i-eq)
next
case 2
have evless:  $\forall_F xa$  in nhds x.  $xa > i$ 
  apply (rule order-tendstoD[OF - ⟨x > i⟩])
  by (simp add: filterlim-ident)
have eq: at x within {a..b} - insert i I = at x within {i .. b} - I
unfolding filter-eq-iff
proof safe
  fix P
  assume eventually P (at x within {i..b} - I)
  with evless show eventually P (at x within {a..b} - insert i I)
    unfolding eventually-at-filter
    by eventually-elim auto
next
  fix P
  assume eventually P (at x within {a..b} - insert i I)

```

```

with evless show eventually P (at x within {i..b} - I)
  unfolding eventually-at-filter
  apply eventually-elim
  using 2 combine
  by auto
qed
have f x = f2 x using combine 2 by auto
have i-eq: integral {a..y} f = integral {a..i} f + integral {i..y} f2 if i < y y
≤ b for y
proof -
  have integral {a..y} f = integral {a..i} f + integral {i..y} f
  apply (cases i = y)
  subgoal by auto
  subgoal
    apply (rule Henstock-Kurzweil-Integration.integral-combine[symmetric])
    using combine that apply auto
    apply (rule integrable-Un'[where A={a .. i} and B={i..y}])
    subgoal
      by (rule integrable-spike[where S={i} and f=f1])
      (auto intro: piecewise-continuous-on-integrable)
    subgoal
      apply (rule integrable-on-subinterval[where S={i..b}])
      by (rule integrable-spike[where S={i} and f=f2])
      (auto intro: piecewise-continuous-on-integrable)
    subgoal by (auto simp: max-def min-def)
    subgoal by auto
  done
done
also have integral {i..y} f = integral {i..y} f2
  apply (rule integral-spike[where S={i}])
  using combine 2 that
  by auto
finally show ?thesis .
qed
from evless have ev-eq:  $\forall_F y$  in nhds x.  $y \in \{i..b\} - I \longrightarrow \text{integral } \{a..y\} f$ 
= integral {a..i} f + integral {i..y} f2
  by eventually-elim (auto simp: i-eq)
show ?thesis unfolding eq
  apply (subst has-vector-derivative-cong-ev[OF ev-eq])
  using combine.IH[of x] combine.prem1 combine.hyps 2
  by (auto simp: i-eq intro!: derivative-eq-intros)
qed
qed (auto intro: has-vector-derivative-within-subset)

```

lemma *has-derivative-at-split*:

$(f \text{ has-derivative } f') \text{ (at } x) \iff (f \text{ has-derivative } f') \text{ (at-left } x) \wedge (f \text{ has-derivative } f') \text{ (at-right } x)$

for $x::'a::\{\text{linorder-topology, real-normed-vector}\}$

by (auto simp: has-derivative-at-within filterlim-at-split)

```

lemma has-vector-derivative-at-split:
  (f has-vector-derivative f') (at x)  $\longleftrightarrow$ 
  (f has-vector-derivative f') (at-left x)  $\wedge$ 
  (f has-vector-derivative f') (at-right x)
  using has-derivative-at-split[of f  $\lambda h. h *_{\mathbb{R}} f' x$ ]
  by (simp add: has-vector-derivative-def)

lemmas differentiableI-vector[intro]

lemma differentiable-at-splitD:
  f differentiable at-left x
  f differentiable at-right x
  if f differentiable (at x)
  for x::real
  using that[unfolded vector-derivative-works has-vector-derivative-at-split]
  by auto

lemma integral-differentiable:
  fixes f :: real  $\Rightarrow$  'a::banach
  assumes continuous-on {a..b} f
  and x  $\in$  {a..b}
  shows ( $\lambda u. \text{integral } \{a..u\} f$ ) differentiable at x within {a..b}
  using integral-has-vector-derivative[OF assms]
  by blast

theorem integral-has-vector-derivative-piecewise-continuous':
  fixes f :: real  $\Rightarrow$  'a::euclidean-space — TODO: generalize?
  assumes piecewise-continuous-on a b D f a < b
  shows
    ( $\forall x. a < x \longrightarrow x < b \longrightarrow x \notin D \longrightarrow (\lambda u. \text{integral } \{a..u\} f)$  differentiable at
x)  $\wedge$ 
    ( $\forall x. a \leq x \longrightarrow x < b \longrightarrow (\lambda t. \text{integral } \{a..t\} f)$  differentiable at-right x)  $\wedge$ 
    ( $\forall x. a < x \longrightarrow x \leq b \longrightarrow (\lambda t. \text{integral } \{a..t\} f)$  differentiable at-left x)
  using assms
proof (induction a b D f rule: piecewise-continuous-on-induct)
  case (empty a b f)
  have a < x  $\implies$  x < b  $\implies$  ( $\lambda u. \text{integral } \{a..u\} f$ ) differentiable (at x) for x
  using integral-differentiable[OF empty(1), of x]
  by (auto simp: at-within-interior)
  then show ?case
  using integral-differentiable[OF empty(1), of a]
  integral-differentiable[OF empty(1), of b]
   $\langle a < b \rangle$ 
  by (auto simp: at-within-Icc-at-right at-within-Icc-at-left le-less
intro: differentiable-at-withinI)
next
  case (combine a i b I f1 f2 f)
  from  $\langle \text{piecewise-continuous-on } a i I f1 \rangle$  have finite I

```

by (auto elim!: piecewise-continuous-onE)

from combine(4) **have** piecewise-continuous-on a i (insert i I) f1
 by (rule piecewise-continuous-on-insert-rightI)
then have piecewise-continuous-on a i (insert i I) f
 by (rule piecewise-continuous-on-congI) (auto simp: combine)
moreover
from combine(5) **have** piecewise-continuous-on i b (insert i I) f2
 by (rule piecewise-continuous-on-insert-leftI)
then have piecewise-continuous-on i b (insert i I) f
 by (rule piecewise-continuous-on-congI) (auto simp: combine)
ultimately have piecewise-continuous-on a b (insert i I) f
 by (rule piecewise-continuous-on-combine)
then have f-int: f integrable-on {a .. b}
 by (rule piecewise-continuous-on-integrable)

from combine.IH
have f1: $x > a \implies x < i \implies x \notin I \implies (\lambda u. \text{integral } \{a..u\} f1)$ differentiable (at x)
 $x \geq a \implies x < i \implies (\lambda t. \text{integral } \{a..t\} f1)$ differentiable (at-right x)
 $x > a \implies x \leq i \implies (\lambda t. \text{integral } \{a..t\} f1)$ differentiable (at-left x)
and f2: $x > i \implies x < b \implies x \notin I \implies (\lambda u. \text{integral } \{i..u\} f2)$ differentiable (at x)
 $x \geq i \implies x < b \implies (\lambda t. \text{integral } \{i..t\} f2)$ differentiable (at-right x)
 $x > i \implies x \leq b \implies (\lambda t. \text{integral } \{i..t\} f2)$ differentiable (at-left x)
for x
by auto

have $(\lambda u. \text{integral } \{a..u\} f)$ differentiable at x **if** $a < x < b$ $x \neq i$ $x \notin I$ **for** x
proof –
from that **consider** $x < i \mid i < x$ **by** arith
then show ?thesis
proof cases
case 1
have at: at x within {a<..*i*} – I = at x
using that 1
by (intro at-within-open) (auto intro!: open-Diff finite-imp-closed ⟨finite I⟩)
then have $(\lambda u. \text{integral } \{a..u\} f1)$ differentiable at x within {a<..*i*} – I
using that 1 f1 **by** auto
then have $(\lambda u. \text{integral } \{a..u\} f)$ differentiable at x within {a<..*i*} – I
apply (rule differentiable-transform-within[OF - zero-less-one])
using that combine.hyps 1 **by** (auto intro!: integral-cong)
then show ?thesis **by** (simp add: at)

next
case 2
have at: at x within {i<..*b*} – I = at x
using that 2
by (intro at-within-open) (auto intro!: open-Diff finite-imp-closed ⟨finite I⟩)
then have $(\lambda u. \text{integral } \{a..i\} f + \text{integral } \{i..u\} f2)$ differentiable at x within

```

{i <..<b} - I
  using that 2 f2 by auto
  then have ( $\lambda u.$  integral {a..i} f + integral {i..u} f) differentiable at x within
{i <..<b} - I
    apply (rule differentiable-transform-within[OF - zero-less-one])
    using that combine.hyps 2 by (auto intro!: integral-spike[where S={i,x}])
  then have ( $\lambda u.$  integral {a..u} f) differentiable at x within {i <..<b} - I
    apply (rule differentiable-transform-within[OF - zero-less-one])
    subgoal using that 2 by auto
    apply (auto simp: )
    apply (subst Henstock-Kurzweil-Integration.integral-combine)
    using that 2  $\langle a \leq i \rangle$ 
    apply auto
    by (auto intro: integrable-on-subinterval f-int)
  then show ?thesis by (simp add: at)
qed
qed
moreover
have ( $\lambda t.$  integral {a..t} f) differentiable at-right x if  $a \leq x < b$  for x
proof -
  from that consider  $x < i \mid i \leq x$  by arith
  then show ?thesis
proof cases
  case 1
  have at: at x within {x..i} = at-right x
    using  $\langle x < i \rangle$  by (rule at-within-Icc-at-right)
  then have ( $\lambda u.$  integral {a..u} f1) differentiable at x within {x..i}
    using that 1 f1 by auto
  then have ( $\lambda u.$  integral {a..u} f) differentiable at x within {x..i}
    apply (rule differentiable-transform-within[OF - zero-less-one])
    using that combine.hyps 1 by (auto intro!: integral-spike[where S={i,x}])
  then show ?thesis by (simp add: at)
next
  case 2
  have at: at x within {x..b} = at-right x
    using  $\langle x < b \rangle$  by (rule at-within-Icc-at-right)
  then have ( $\lambda u.$  integral {a..i} f + integral {i..u} f2) differentiable at x within
{x..b}
    using that 2 f2 by auto
  then have ( $\lambda u.$  integral {a..i} f + integral {i..u} f) differentiable at x within
{x..b}
    apply (rule differentiable-transform-within[OF - zero-less-one])
    using that combine.hyps 2 by (auto intro!: integral-spike[where S={i,x}])
  then have ( $\lambda u.$  integral {a..u} f) differentiable at x within {x..b}
    apply (rule differentiable-transform-within[OF - zero-less-one])
    subgoal using that 2 by auto
    apply (auto simp: )
    apply (subst Henstock-Kurzweil-Integration.integral-combine)
    using that 2  $\langle a \leq i \rangle$ 

```

```

    apply auto
    by (auto intro: integrable-on-subinterval f-int)
  then show ?thesis by (simp add: at)
qed
qed
moreover
have (λt. integral {a..t} f) differentiable at-left x if a < x x ≤ b for x
proof -
  from that consider x ≤ i | i < x by arith
  then show ?thesis
  proof cases
    case 1
    have at: at x within {a..x} = at-left x
      using ⟨a < x⟩ by (rule at-within-Icc-at-left)
    then have (λu. integral {a..u} f1) differentiable at x within {a..x}
      using that 1 f1 by auto
    then have (λu. integral {a..u} f) differentiable at x within {a..x}
      apply (rule differentiable-transform-within[OF - zero-less-one])
      using that combine.hyps 1 by (auto intro!: integral-spike[where S={i,x}])
    then show ?thesis by (simp add: at)
  next
    case 2
    have at: at x within {i..x} = at-left x
      using ⟨i < x⟩ by (rule at-within-Icc-at-left)
    then have (λu. integral {a..i} f + integral {i..u} f2) differentiable at x within
    {i..x}
      using that 2 f2 by auto
    then have (λu. integral {a..i} f + integral {i..u} f) differentiable at x within
    {i..x}
      apply (rule differentiable-transform-within[OF - zero-less-one])
      using that combine.hyps 2 by (auto intro!: integral-spike[where S={i,x}])
    then have (λu. integral {a..u} f) differentiable at x within {i..x}
      apply (rule differentiable-transform-within[OF - zero-less-one])
      subgoal using that 2 by auto
      apply (auto simp: )
      apply (subst Henstock-Kurzweil-Integration.integral-combine)
      using that 2 ⟨a ≤ i⟩
      apply auto
      by (auto intro: integrable-on-subinterval f-int)
    then show ?thesis by (simp add: at)
  qed
qed
ultimately
show ?case
  by auto
next
case (weaken a b i I f)
from weaken.IH[OF ⟨a < b⟩]
obtain l u where IH:

```



```

 $\bigwedge x. a < x \implies x < b \implies x \notin I \implies (\lambda u. \text{integral } \{a..u\} f) \text{ differentiable } (\text{at } x)$ 
 $\bigwedge x. a \leq x \implies x < b \implies (\lambda t. \text{integral } \{a..t\} f) \text{ differentiable } (\text{at-right } x)$ 
 $\bigwedge x. a < x \implies x \leq b \implies (\lambda t. \text{integral } \{a..t\} f) \text{ differentiable } (\text{at-left } x)$ 
  by metis
  then show ?case by auto
qed

```

```

lemma closure  $(-S) \cap \text{closure } S = \text{frontier } S$ 
  by (auto simp add: frontier-def closure-complement)

```

```

theorem integral-time-domain-has-laplace:
  (( $\lambda t. \text{integral } \{0 .. t\} f$ ) has-laplace  $L / s$ ) s
  if pc:  $\bigwedge k. \text{piecewise-continuous-on } 0 k D f$ 
  and eo: exponential-order  $M c f$ 
  and L: ( $f$  has-laplace  $L$ ) s
  and s:  $\text{Re } s > c$ 
  and c:  $c > 0$ 
  and TODO:  $D = \{\}$  — TODO: generalize to actual piecewise-continuous-on
  for  $f::\text{real} \Rightarrow \text{complex}$ 

```

proof –

```

  define I where  $I = (\lambda t. \text{integral } \{0 .. t\} f)$ 
  have I': ( $I$  has-vector-derivative  $f t$ ) (at  $t$  within  $\{0..x\} - D$ )
    if  $t \in \{0 .. x\} - D$ 
    for  $x t$ 
    unfolding I-def
    by (rule integral-has-vector-derivative-piecewise-continuous; fact)
  have fi:  $f$  integrable-on  $\{0..t\}$  for  $t$ 
    by (rule piecewise-continuous-on-integrable) fact
  have Ic: continuous-on  $\{0 .. t\} I$  for  $t$ 
    unfolding I-def using fi
    by (rule indefinite-integral-continuous-1)
  have Ipc: piecewise-continuous-on  $0 t \{\}$   $I$  for  $t$ 
    by (rule piecewise-continuous-onI) (auto intro!: Ic)
  have I: ( $f$  has-integral  $I t$ )  $\{0 .. t\}$  for  $t$ 
    unfolding I-def
    using fi
    by (rule integrable-integral)
  from exponential-order-integral[OF I eo  $\langle 0 < c \rangle$ ] obtain  $M'$ 
    where Ieo: exponential-order  $M' c I$  .
  have Ili: laplace-integrand  $I s$  integrable-on  $\{0.. \}$ 
    using Ipc
    apply (rule piecewise-continuous-on-AE-boundedE)
    apply (rule laplace-integrand-integrable)
    apply (rule Ieo)
    apply assumption
    apply (rule integrable-continuous-interval)
    apply (rule Ic)
    apply (rule s)
  done

```

then obtain LI **where** $LI: (I \text{ has-laplace } LI) s$
by (*rule laplace-exists-laplace-integrandI*)

from *piecewise-continuous-onE*[*OF pc*] **have** $\langle \text{finite } D \rangle$ **by** *auto*
have $I'2: (I \text{ has-vector-derivative } f \ t) \ (at \ t) \ \text{if } t > 0 \ t \notin D \ \text{for } t$
apply (*subst at-within-open*[*symmetric, where* $S = \{0 < .. < t + 1\} - D$])
subgoal using *that* **by** *auto*
subgoal by (*auto intro!:open-Diff finite-imp-closed* $\langle \text{finite } D \rangle$)
subgoal using I' [**where** $x = t + 1$]
apply (*rule has-vector-derivative-within-subset*)
using *that*
by *auto*
done

have $I \text{-tndsto}: (I \longrightarrow 0) \ (at\text{-right } 0)$
apply (*rule tendsto-eq-rhs*)
apply (*rule continuous-on-Icc-at-rightD*)
apply (*rule Ic*)
apply (*rule zero-less-one*)
by (*auto simp: I-def*)
have $(f \text{ has-laplace } s * LI - 0) \ s$
by (*rule has-laplace-derivative-time-domain*[*OF LI I'2 I-tndsto Ieo s*])
(auto simp: TODO)
from *has-laplace-unique*[*OF this L*] **have** $LI = L / s$
using $s \ c$ **by** *auto*
with LI **show** $(I \text{ has-laplace } L / s) \ s$ **by** *simp*
qed

4.4 higher derivatives

definition $nderiv \ i \ f \ X = ((\lambda f. (\lambda x. \text{vector-derivative } f \ (at \ x \ \text{within } X))) \ \sim^i) \ f$

definition $ndiff \ n \ f \ X \longleftrightarrow (\forall i < n. \forall x \in X. \text{nderiv } i \ f \ X \text{ differentiable at } x \ \text{within } X)$

lemma *nderiv-zero*[*simp*]: $nderiv \ 0 \ f \ X = f$
by (*auto simp: nderiv-def*)

lemma *nderiv-Suc*[*simp*]:
 $nderiv \ (Suc \ i) \ f \ X = \text{vector-derivative } (nderiv \ i \ f \ X) \ (at \ x \ \text{within } X)$
by (*auto simp: nderiv-def*)

lemma *ndiff-zero*[*simp*]: $ndiff \ 0 \ f \ X$
by (*auto simp: ndiff-def*)

lemma *ndiff-Sucs*[*simp*]:
 $ndiff \ (Suc \ i) \ f \ X \longleftrightarrow$
 $(ndiff \ i \ f \ X) \wedge$
 $(\forall x \in X. \text{nderiv } i \ f \ X \text{ differentiable } (at \ x \ \text{within } X))$
apply (*auto simp: ndiff-def*)

using *less-antisym* by *blast*

theorem *has-laplace-vector-derivative*:

((λt . *vector-derivative* f (at t)) *has-laplace* $s * L - f0$) s
if L : (*f has-laplace* L) s
and f' : ($\bigwedge t$. $t > 0 \implies f$ *differentiable* (at t))
and $f0$: ($f \longrightarrow f0$) (*at-right* 0)
and eo : *exponential-order* $M c f$
and cs : $c < \text{Re } s$

proof –

have f' : ($\bigwedge t$. $0 < t \implies (f$ *has-vector-derivative* *vector-derivative* f (at t)) (at t))
using f'
by (*subst vector-derivative-works*[*symmetric*])
show *?thesis*
by (*rule has-laplace-derivative-time-domain*[*OF L f' f0 eo cs*])

qed

lemma *has-laplace-nderiv*:

(*nderiv* $n f \{0<..\}$ *has-laplace* $s \hat{\ }^n * L - (\sum i < n$. $s \hat{\ }^{(n - \text{Suc } i)} * f0 i$)) s
if L : (*f has-laplace* L) s
and f' : *ndiff* $n f \{0<..\}$
and $f0$: ($\bigwedge i$. $i < n \implies ($ *nderiv* $i f \{0<..\} \longrightarrow f0 i$) (*at-right* 0)
and eo : ($\bigwedge i$. $i < n \implies$ *exponential-order* $M c ($ *nderiv* $i f \{0<..\}$))
and cs : $c < \text{Re } s$

using $f' f0 eo$

proof (*induction* n)

case 0

then show *?case*
by (*auto simp: L*)

next

case (*Suc* n)

have awo : *at t within* $\{0<..\} = \text{at } t \text{ if } t > 0 \text{ for } t::\text{real}$
using *that*

by (*subst at-within-open*) *auto*

have ((λa . *vector-derivative* (*nderiv* $n f \{0<..\}$) (at a)) *has-laplace* $s * (s \hat{\ }^n * L - (\sum i < n$. $s \hat{\ }^{(n - \text{Suc } i)} * f0 i) - f0 n$) s
(is (- *has-laplace* *?L*) -)

apply (*rule has-laplace-vector-derivative*)

apply (*rule Suc.IH*)

subgoal using *Suc.prem*s **by** *auto*

subgoal using *Suc.prem*s **by** *auto*

subgoal using *Suc.prem*s **by** *auto*

subgoal using *Suc.prem*s **by** (*auto simp: awo*)

subgoal using *Suc.prem*s **by** *auto*

apply (*rule Suc.prem*s; *force*)

apply (*rule cs*)

done

also have *?L* = $s \hat{\ }^{\text{Suc } n} * L - (\sum i < \text{Suc } n$. $s \hat{\ }^{(\text{Suc } n - \text{Suc } i)} * f0 i$)
by (*auto simp: algebra-simps sum-distrib-left diff-Suc Suc-diff-le*)

```

      split: nat.splits
      intro!: sum.cong)
  finally show ?case
  by (rule has-laplace-spike[where T={0}]) (auto simp: awo)
qed

end

```

5 Lerch Lemma

```

theory Lerch-Lemma
  imports
    HOL-Analysis.Analysis
begin

```

The main tool to prove uniqueness of the Laplace transform.

lemma *lerch-lemma-real*:

```

  fixes h::real  $\Rightarrow$  real
  assumes h-cont[continuous-intros]: continuous-on {0 .. 1} h
  assumes int-0:  $\bigwedge n. ((\lambda u. u \wedge^n * h u) \text{ has-integral } 0) \{0 .. 1\}$ 
  assumes u:  $0 \leq u \wedge u \leq 1$ 
  shows h u = 0

```

proof –

```

  from Stone-Weierstrass-uniform-limit[OF compact-Icc h-cont]
  obtain g where g: uniform-limit {0..1} g h sequentially polynomial-function (g
n) for n
  by blast
  then have rpf-g: real-polynomial-function (g n) for n
  by (simp add: real-polynomial-function-eq)

```

```

let ?P =  $\lambda n x. h x * g n x$ 

```

```

have continuous-on-g[continuous-intros]: continuous-on s (g n) for s n

```

```

  by (rule continuous-on-polynomial-function) fact

```

```

have P-cont: continuous-on {0 .. 1} (?P n) for n

```

```

  by (auto intro!: continuous-intros)

```

```

have uniform-limit {0 .. 1} ( $\lambda n x. h x * g n x$ ) ( $\lambda x. h x * h x$ ) sequentially

```

```

  by (auto intro!: uniform-limit-intros g assms compact-imp-bounded compact-continuous-image)

```

```

from uniform-limit-integral[OF this P-cont]

```

```

obtain I J where

```

```

  I: ( $\bigwedge n. (?P n \text{ has-integral } I n) \{0..1\}$ )

```

```

  and J: ( $(\lambda x. h x * h x) \text{ has-integral } J) \{0..1\}$ 

```

```

  and IJ:  $I \longrightarrow J$ 

```

```

  by auto

```

```

have (?P n has-integral 0) {0..1} for n

```

proof –

```

  from real-polynomial-function-imp-sum[OF rpf-g]

```

```

  obtain gn ga where g n = ( $\lambda x. \sum_{i \leq gn. ga i * x \wedge^i}$ ) by metis

```

```

then have ?P n x = (∑ i ≤ gn. x ^ i * h x * ga i) for x
  by (auto simp: sum-distrib-left algebra-simps)
moreover have ((λx. ... x) has-integral 0) {0 .. 1}
  by (auto intro!: has-integral-sum[THEN has-integral-eq-rhs] has-integral-mult-left
  assms)
ultimately show ?thesis by simp
qed
with I have I n = 0 for n
  using has-integral-unique by blast
with IJ J have ((λx. h x * h x) has-integral 0) (cbox 0 1)
  by (metis (full-types) LIMSEQ-le-const LIMSEQ-le-const2 cbox-real(2) dual-order.antisym
  order-refl)
with - - have h u * h u = 0
  by (rule has-integral-0-cbox-imp-0) (auto intro!: continuous-intros u)
then show h u = 0
  by simp
qed

```

lemma *lerch-lemma*:

```

fixes h::real ⇒ 'a::euclidean-space
assumes [continuous-intros]: continuous-on {0 .. 1} h
assumes int-0: ∧n. ((λu. u ^ n *R h u) has-integral 0) {0 .. 1}
assumes u: 0 ≤ u u ≤ 1
shows h u = 0
proof (rule euclidean-eqI)
fix b::'a assume b ∈ Basis
have continuous-on {0 .. 1} (λx. h x · b)
  by (auto intro!: continuous-intros)
moreover
from ⟨b ∈ Basis⟩ have ((λu. u ^ n * (h u · b)) has-integral 0) {0 .. 1} for n
  using int-0[of n] has-integral-componentwise-iff[of λu. u ^ n *R h u 0 {0 ..
  1}]
  by auto
moreover note u
ultimately show h u · b = 0 · b
  unfolding inner-zero-left
  by (rule lerch-lemma-real)
qed

```

end

6 Uniqueness of Laplace Transform

theory *Uniqueness*

imports

Existence

Lerch-Lemma

begin

We show uniqueness of the Laplace transform for continuous functions.

lemma *laplace-transform-zero*:— should also work for piecewise continuous

assumes *cont-f*: *continuous-on* $\{0..b\}$ *f*
assumes *eo*: *exponential-order* M *a* *f*
assumes *laplace*: $\bigwedge s. \text{Re } s > a \implies (f \text{ has-laplace } 0) s$
assumes $t \geq 0$
shows $f t = 0$

proof —

define *I* **where** $I \equiv \lambda s k. \text{integral } \{0..k\} (\text{laplace-integrand } f s)$
have *bounded-image*: *bounded* $(f \cdot \{0..b\})$ **for** *b*
by (*auto intro!*: *compact-imp-bounded compact-continuous-image cont-f intro*:
continuous-on-subset)
obtain *B* **where** $B: \forall x \in \{0..b\}. \text{cmod } (f x) \leq B$ **for** *b*
apply *atomize-elim*
apply (*rule choice*)
using *bounded-image[unfolded bounded-iff]*
by *auto*
have *fi*: *f integrable-on* $\{0..b\}$ **for** *b*
by (*auto intro!*: *integrable-continuous-interval intro*: *continuous-on-subset cont-f*)
have *aint*: *complex-set-integrable lebesgue* $\{0..b\}$ (*laplace-integrand f s*) **for** *b s*
by (*rule laplace-integrand-absolutely-integrable-on-Icc[OF*
AE-BallI[OF bounded-le-Sup[OF bounded-image]] fi])
have *int*: $((\lambda t. \text{exp } (t *_{\mathbb{R}} - s) * f t) \text{ has-integral } I s b)$ $\{0 .. b\}$ **for** *s b*
using *aint[of b s]*
unfolding *laplace-integrand-def[symmetric] I-def absolutely-integrable-on-def*
by *blast*
have *I-integral*: $\text{Re } s > a \implies (I s \longrightarrow \text{integral } \{0..b\} (\text{laplace-integrand } f s))$
at-top **for** *s*
unfolding *I-def*
by (*metis aint eo improper-integral-at-top laplace-integrand-absolutely-integrable-on-Ici-iff*)
have *imp*: $(I s \longrightarrow 0)$ *at-top* **if** *s*: $\text{Re } s > a$ **for** *s*
using *I-integral[of s] laplace[unfolded has-laplace-def, rule-format, OF s]*
unfolding *has-laplace-def I-def laplace-integrand-def*
by (*simp add: integral-unique*)

define *s0* **where** $s0 = a + 1$
then have $s0 > a$ **by** *auto*
have $\forall_F x \text{ in } \text{at-right } (0::\text{real}). 0 < x \wedge x < 1$
by (*auto intro!*: *eventually-at-rightI*)
moreover
from *exponential-orderD(2)[OF eo]*
have $\forall_F t \text{ in } \text{at-right } 0. \text{cmod } (f (- \ln t)) \leq M * \text{exp } (a * (- \ln t))$
unfolding *at-top-mirror filtermap-ln-at-right[symmetric] eventually-filtermap* .
ultimately have $\forall_F x \text{ in } \text{at-right } 0. \text{cmod } ((x \text{ powr } s0) * f (- \ln x)) \leq M * x$
powr $(s0 - a)$
(is $\forall_F x \text{ in } -. ?l x \leq ?r x)$
proof *eventually-elim*
case *x*: (*elim x*)
then have $\text{cmod } ((x \text{ powr } s0) * f (- \ln x)) \leq x \text{ powr } s0 * (M * \text{exp } (a * (-$

```

ln x)))
  by (intro norm-mult-ineq[THEN order-trans]) (auto intro!: x(2)[THEN order-trans])
  also have ... = M * x powr (s0 - a)
  by (simp add: exp-minus ln-inverse divide-simps powr-def mult-exp-exp algebra-simps)
  finally show ?case .
qed
then have ((λx. x powr s0 * f (- ln x)) → 0) (at-right 0)
  by (rule Lim-null-comparison)
  (auto intro!: tendsto-eq-intros ⟨a < s0⟩ eventually-at-rightI zero-less-one)
moreover have ∀F x in at x. ln x ≤ 0 if 0 < x < 1 for x::real
  using order-tendstoD(1)[OF tendsto-ident-at ⟨0 < x⟩, of UNIV]
  order-tendstoD(2)[OF tendsto-ident-at ⟨x < 1⟩, of UNIV]
  by eventually-elim simp
ultimately have [continuous-intros]:
  continuous-on {0..1} (λx. x powr s0 * f (- ln x))
  by (intro continuous-on-IccI;
      force intro!: continuous-on-tendsto-compose[OF cont-f] tendsto-eq-intros
      eventually-at-leftI
      zero-less-one)
{
  fix n::nat
  let ?i = (λu. u ^ n *R (u powr s0 * f (- ln u)))
  let ?I = λn b. integral {exp (- b).. 1} ?i
  have ∀F (b::real) in at-top. b > 0
    by (simp add: eventually-gt-at-top)
  then have ∀F b in at-top. I (s0 + Suc n) b = ?I n b
  proof eventually-elim
    case (elim b)
    have eq: exp (t *R - complex-of-real (s0 + real (Suc n))) * f t =
      complex-of-real (exp (- (real n * t)) * exp (- t) * exp (- (s0 * t))) * f t
    for t
    by (auto simp: Euler mult-exp-exp algebra-simps simp del: of-real-mult)
    from int[of s0 + Suc n b]
    have int': ((λt. exp (- (n * t)) * exp (-t) * exp (- (s0 * t)) * f t)
      has-integral I (s0 + Suc n) b) {0..b}
      (is (?fe has-integral -) -)
    unfolding eq .
    have ((λx. - exp (- x) *R exp (- x) ^ n *R (exp (- x) powr s0 * f (- ln
      (exp (- x)))))
      has-integral
      integral {exp (- 0)..exp (- b)} ?i - integral {exp (- b)..exp (- 0)} ?i)
    {0..b}
    by (rule has-integral-substitution-general[of {} 0 b λt. exp(-t) 0 1 ?i λx.
      -exp(-x)])
      (auto intro!: less-imp-le[OF ⟨b > 0⟩] continuous-intros integrable-continuous-real
      derivative-eq-intros)
    then have (?fe has-integral ?I n b) {0..b}

```

```

    using ⟨b > 0⟩
    by (auto simp: algebra-simps mult-exp-exp exp-of-nat-mult[symmetric]
scaleR-conv-of-real
    exp-add powr-def of-real-exp has-integral-neg-iff)
  with int' show ?case
    by (rule has-integral-unique)
qed
moreover have (I (s0 + Suc n) ⟶ 0) at-top
  by (rule imp) (use ⟨s0 > a⟩ in auto)
ultimately have (?I n ⟶ 0) at-top
  by (rule Lim-transform-eventually[rotated])
then have 1: ((λx. integral {exp (ln x)..1} ?i) ⟶ 0) (at-right 0)
  unfolding at-top-mirror filtermap-ln-at-right[symmetric] filtermap-filtermap
filterlim-filtermap
  by simp
have ∀F x in at-right 0. x > 0
  by (simp add: eventually-at-filter)
then have ∀F x in at-right 0. integral {exp (ln x)..1} ?i = integral {x .. 1} ?i
  by eventually-elim (auto simp:)
from Lim-transform-eventually[OF 1 this]
have ((λx. integral {x..1} ?i) ⟶ 0) (at-right 0)
  by simp
moreover
have ?i integrable-on {0..1}
  by (force intro: continuous-intros integrable-continuous-real)
from continuous-on-Icc-at-rightD[OF indefinite-integral-continuous-1'[OF this]
zero-less-one]
have ((λx. integral {x..1} ?i) ⟶ integral {0 .. 1} ?i) (at-right 0)
  by simp
ultimately have integral {0 .. 1} ?i = 0
  by (rule tendsto-unique[symmetric, rotated]) simp
then have (?i has-integral 0) {0 .. 1}
  using integrable-integral ⟨?i integrable-on {0..1}⟩
  by (metis (full-types))
} from lerch-lemma[OF - this, of exp (- t)]
show f t = 0 using ⟨t ≥ 0⟩
  by (auto intro!: continuous-intros)
qed

```

lemma *exponential-order-eventually-eq: exponential-order* M a f

if *exponential-order* M a g $\wedge t. t \geq k \implies f t = g t$

proof –

have $\forall_F t$ in at-top. $f t = g t$

using *that*

unfolding *eventually-at-top-linorder*

by *blast*

with *exponential-orderD(2)[OF that(1)]*

have $(\forall_F t$ in at-top. $\text{norm } (f t) \leq M * \text{exp } (a * t)$)

by *eventually-elim auto*

with *exponential-orderD(1)[OF that(1)]*
show *?thesis*
by (*rule exponential-orderI*)
qed

lemma *exponential-order-mono:*
assumes *eo: exponential-order M a f*
assumes $a \leq b \ M \leq N$
shows *exponential-order N b f*
proof (*rule exponential-orderI*)
from *exponential-orderD[OF eo] assms(3)*
show $0 < N$ **by** *simp*
have $\forall_F t \text{ in } \text{at-top. } (t::\text{real}) > 0$
by (*simp add: eventually-gt-at-top*)
then have $\forall_F t \text{ in } \text{at-top. } M * \exp(a * t) \leq N * \exp(b * t)$
by *eventually-elim*
(use $\langle 0 < N \rangle$ in $\langle \text{force intro: mult-mono assms} \rangle$)
with *exponential-orderD(2)[OF eo]*
show $\forall_F t \text{ in } \text{at-top. } \text{norm}(f t) \leq N * \exp(b * t)$
by (*eventually-elim simp*)
qed

lemma *exponential-order-uminus-iff:*
exponential-order M a $(\lambda x. - f x) = \text{exponential-order M a f}$
by (*auto simp: exponential-order-def*)

lemma *exponential-order-add:*
assumes *exponential-order M a f exponential-order M a g*
shows *exponential-order $(2 * M) a (\lambda x. f x + g x)$*
using *assms*
apply (*auto simp: exponential-order-def*)
subgoal premises *prems*
using *prems(1,3)*
apply (*eventually-elim*)
apply (*rule norm-triangle-le*)
by *linarith*
done

theorem *laplace-transform-unique:*
assumes $f: \bigwedge s. \text{Re } s > a \implies (f \text{ has-laplace } F) s$
assumes $g: \bigwedge s. \text{Re } s > b \implies (g \text{ has-laplace } F) s$
assumes [*continuous-intros*]: *continuous-on $\{0..\}$ f*
assumes [*continuous-intros*]: *continuous-on $\{0..\}$ g*
assumes *eof: exponential-order M a f*
assumes *eog: exponential-order N b g*
assumes $t \geq 0$
shows $f t = g t$
proof –
define c **where** $c = \max a b$

```

define  $L$  where  $L = \max M N$ 
from  $eof$  have  $eof$ : exponential-order  $L c f$ 
  by (rule exponential-order-mono) (auto simp: L-def c-def)
from  $eog$  have  $eog$ : exponential-order  $L c (\lambda x. - g x)$ 
  unfolding exponential-order-uminus-iff
  by (rule exponential-order-mono) (auto simp: L-def c-def)
from exponential-order-add[OF  $eof eog$ ]
have  $eom$ : exponential-order  $(2 * L) c (\lambda x. f x - g x)$ 
  by simp
have  $l0$ :  $((\lambda x. f x - g x) \text{ has-laplace } 0) s$  if  $\text{Re } s > c$  for  $s$ 
  using has-laplace-minus[OF  $f g, of s$ ] that by (simp add: c-def max-def split:
if-splits)
  have  $f t - g t = 0$ 
  by (rule laplace-transform-zero[OF -  $eom l0 \langle t \geq 0 \rangle$ ])
    (auto intro!: continuous-intros)
  then show ?thesis by simp
qed

end
theory Laplace-Transform
  imports
    Existence
    Uniqueness
begin

end

```

References

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