Lambert Series

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May 14, 2024

Abstract

This entry provides a formalisation of *Lambert series*, i.e. series of the form $L(a_n, q) = \sum_{n=1}^{\infty} a_n q^n/(1-q^n)$ where a_n is a sequence of real or complex numbers. Proofs for all the basic properties are provided, such as

- the precise region in which $L(a_n, q)$ converges
- the functional equation $L(a_n, \frac{1}{q}) = -(\sum_{n=1}^{\infty} a_n) - L(a_n, q)$
- the power series expansion of $L(a_n, q)$ at $q = 0$
- the connection $L(a_n, q) = \sum_{k=1}^{\infty} f(q^k)$ for $f(z) = \sum_{n=1}^{\infty} a_n z^n$ that links a Lambert series to its "corresponding" power series
- connections to various number-theoretic functions, e.g. the divisor σ function via $\sum_{n=1}^{\infty} \sigma_\alpha(n) q^n = L(n^\alpha, q)$

The formalisation mainly follows the chapter on Lambert series in Konrad Knopp's classic textbook *Theory and Application of Infinite Series* [1] and includes all results presented therein.

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1 Missing Library Material

theory *Lambert_Series_Library*
imports
  "HOL-Complex_Analysis.Complex_Analysis"
  "HOL-Library.Landau_Symbols"
  "HOL-Real_Asymp.Real_Asymp"
begin

1.1 Miscellaneous

lemma *power_less_1_iff: "x ≥ 0 ⟹ (x :: real) ^ n < 1 ⟷ x < 1 ∧ n > 0"*
  ⟨*proof*⟩

lemma *fls_nth_sum: "fls_nth (∑x∈A. f x) n = (∑x∈A. fls_nth (f x) n)"*
  ⟨*proof*⟩

lemma *two_times_choose_two: "2 * (n choose 2) = n * (n - 1)"*
  ⟨*proof*⟩

lemma *Nats_not_empty [simp]: "ℕ ≠ {}"*
  ⟨*proof*⟩

1.2 Infinite sums

lemma *has_sum_iff: "(f has_sum S) A ⟷ f summable_on A ∧ infsum f A = S"*
  ⟨*proof*⟩

lemma *summable_on_reindex_bij_witness:*
  assumes *"⋀a. a ∈ S ⟹ i (j a) = a"*
  assumes *"⋀a. a ∈ S ⟹ j a ∈ T"*
  assumes *"⋀b. b ∈ T ⟹ j (i b) = b"*
  assumes *"⋀b. b ∈ T ⟹ i b ∈ S"*
  assumes *"⋀a. a ∈ S ⟹ h (j a) = g a"*
  shows *"g summable_on S ⟷ h summable_on T"*
  ⟨*proof*⟩

lemma *has_sum_diff:*
  fixes *f g :: "'a ⇒ 'b::{topological_ab_group_add}"*
  assumes *‹(f has_sum a) A›*
  assumes *‹(g has_sum b) A›*
  shows *‹((λx. f x - g x) has_sum (a - b)) A›*
  ⟨*proof*⟩

lemma *summable_on_diff:*
  fixes *f g :: "'a ⇒ 'b::{topological_ab_group_add}"*
  assumes *‹f summable_on A›*

```
  assumes <g summable_on A>
  shows <(λx. f x - g x) summable_on A>
  ⟨proof⟩

lemma infsum_diff:
  fixes f g :: "'a ⇒ 'b::{topological_ab_group_add, t2_space}"
  assumes <f summable_on A>
  assumes <g summable_on A>
  shows <infsum (λx. f x - g x) A = infsum f A - infsum g A>
⟨proof⟩

lemma summable_norm_add:
  assumes "summable (λn. norm (f n))" "summable (λn. norm (g n))"
  shows   "summable (λn. norm (f n + g n))"
⟨proof⟩

lemma summable_norm_diff:
  assumes "summable (λn. norm (f n))" "summable (λn. norm (g n))"
  shows   "summable (λn. norm (f n - g n))"
  ⟨proof⟩

lemma sums_imp_has_prod_exp:
  fixes f :: "_ ⇒'a::{real_normed_field,banach}"
  assumes "f sums F"
  shows   "(λn. exp (f n)) has_prod exp F"
⟨proof⟩

lemma telescope_summable_iff:
  fixes f :: "nat ⇒ 'a::{real_normed_vector}"
  shows "summable (λn. f (Suc n) - f n) ⟷ convergent f"
⟨proof⟩

lemma telescope_summable_iff':
  fixes f :: "nat ⇒ 'a::{real_normed_vector}"
  shows "summable (λn. f n - f (Suc n)) ⟷ convergent f"
  ⟨proof⟩

lemma norm_summable_mult_bounded:
  assumes "summable (λn. norm (f n))"
  assumes "g ∈ O(λ_. 1)"
  shows   "summable (λn. norm (f n * g n))"
⟨proof⟩

lemma summable_powser_comparison_test_bigo:
  fixes f g :: "nat ⇒ 'a :: {real_normed_field, banach}"
  assumes "summable f" "g ∈ O(λn. f n * c ^ n)" "norm c < 1"
  shows   "summable (λn. norm (g n))"
⟨proof⟩
```

lemma *geometric_sums_gen:*
  assumes "norm (x :: 'a :: real_normed_field) < 1"
  shows "(λn. x ^ (n + k)) sums (x ^ k / (1 - x))"
⟨*proof*⟩

lemma *has_sum_geometric:*
  fixes x :: "'a :: {real_normed_field, banach}"
  assumes "norm x < 1"
  shows "((λn. x ^ n) has_sum (x ^ m / (1 - x))) {m..}"
⟨*proof*⟩

lemma *n_powser_sums:*
  fixes q :: "'a :: {real_normed_field,banach}"
  assumes q: "norm q < 1"
  shows "(λn. of_nat n * q ^ n) sums (q / (1 - q) ^ 2)"
⟨*proof*⟩

1.3 Convergence radius

lemma *tendsto_imp_conv_radius_eq:*
  assumes "(λn. ereal (norm (f n) powr (1 / real n))) ⟶ c'" "c = inverse c'"
  shows "conv_radius f = c"
⟨*proof*⟩

lemma *conv_radius_powr_real:* "conv_radius (λn. real n powr a) = 1"
⟨*proof*⟩

lemma *conv_radius_one_over:* "conv_radius (λn. 1 / of_nat n :: 'a :: {real_normed_field, banach}) = 1"
⟨*proof*⟩

lemma *conv_radius_mono:*
  assumes "eventually (λn. norm (f n) ≥ norm (g n)) sequentially"
  shows "conv_radius f ≤ conv_radius g"
  ⟨*proof*⟩

lemma *conv_radius_const [simp]:*
  assumes "c ≠ 0"
  shows "conv_radius (λ_. c) = 1"
⟨*proof*⟩

lemma *conv_radius_bigo_polynomial:*
  assumes "f ∈ O(λn. of_nat n ^ k)"
  shows "conv_radius f ≥ 1"
⟨*proof*⟩

1.4 Limits

lemma *oscillation_imp_not_tendsto:*

```
  assumes "eventually (λn. f (g n) ∈ A) sequentially" "filterlim g F
sequentially"
  assumes "eventually (λn. f (h n) ∈ B) sequentially" "filterlim h F
sequentially"
  assumes "closed A" "closed B" "A ∩ B = {}"
  shows   "¬filterlim f (nhds c) F"
⟨proof⟩

lemma oscillation_imp_not_convergent:
  assumes "frequently (λn. f n ∈ A) sequentially"
  assumes "frequently (λn. f n ∈ B) sequentially"
  assumes "closed A" "closed B" "A ∩ B = {}"
  shows   "¬convergent f"
⟨proof⟩

lemma seq_bigo_1_iff:
  "g ∈ O(λ_::nat. 1) ⟷ bounded (range g)"
⟨proof⟩

lemma incseq_convergent':
  assumes "incseq (g :: nat ⇒ real)" "g ∈ O(λ_. 1)"
  shows   "convergent g"
⟨proof⟩

lemma decseq_convergent':
  assumes "decseq (g :: nat ⇒ real)" "g ∈ O(λ_. 1)"
  shows   "convergent g"
  ⟨proof⟩

lemma filterlim_of_int_iff:
  fixes c :: "'a :: real_normed_algebra_1"
  assumes "F ≠ bot"
  shows "filterlim (λx. of_int (f x)) (nhds c) F ⟷
          (∃c'. c = of_int c' ∧ eventually (λx. f x = c') F)"
⟨proof⟩

lemma filterlim_of_nat_iff:
  fixes c :: "'a :: real_normed_algebra_1"
  assumes "F ≠ bot"
  shows "filterlim (λx. of_nat (f x)) (nhds c) F ⟷
          (∃c'. c = of_nat c' ∧ eventually (λx. f x = c') F)"
⟨proof⟩

lemma uniform_limit_compose:
  assumes "uniform_limit B (λx y. f x y) (λy. f' y) F" "⋀y. y ∈ A ⟹
g y ∈ B"
  shows   "uniform_limit A (λx y. f x (g y)) (λy. f' (g y)) F"
⟨proof⟩
```

lemma *uniform_limit_const':*
  assumes *"filterlim f (nhds c) F"*
  shows *"uniform_limit A (λx y. f x) (λy. c) F"*
⟨*proof*⟩

lemma *uniform_limit_singleton_iff [simp]:*
  "uniform_limit {x} f g F ⟷ filterlim (λy. f y x) (nhds (g x)) F"
  ⟨*proof*⟩

end

2 Some Facts About Number-Theoretic Functions

theory *Number_Theoretic_Functions_Extras*
imports
  "Dirichlet_Series.Dirichlet_Series_Analysis"
  "Dirichlet_Series.Divisor_Count"
  Lambert_Series_Library
begin

lemma *(***in** *nat_power_field) nat_power_minus:*
  "a ≠ 0 ∨ n ≠ 0 ⟹ nat_power n (-a) = inverse (nat_power n a)"
  ⟨*proof*⟩

lemma *divisor_sigma_minus:*
  fixes *a :: "'a :: {nat_power_field, field_char_0}"*
  shows *"divisor_sigma (-a) n = divisor_sigma a n / nat_power n a"*
⟨*proof*⟩

lemma *norm_moebius_mu:*
  "norm (moebius_mu n ::'a :: {real_normed_algebra_1, comm_ring_1}) = ind squarefree n"
  ⟨*proof*⟩

lemma *conv_radius_nat_power: "conv_radius (λn. nat_power n a :: 'a :: {nat_power_normed_field, banach}) = 1"*
⟨*proof*⟩

lemma *not_convergent_liouville_lambda:*
  "¬convergent (liouville_lambda :: nat ⇒ 'a :: {real_normed_algebra, comm_ring_1, semiring_char_0})"
⟨*proof*⟩

lemma *conv_radius_liouville_lambda:*
  "conv_radius (liouville_lambda :: nat ⇒ 'a :: {real_normed_field, banach}) = 1"
⟨*proof*⟩

lemma *not_convergent_mangoldt:* "¬convergent (mangoldt :: nat ⇒ 'a :: {real_normed_algebra_1})"
⟨*proof*⟩

lemma *conv_radius_mangoldt:*
  "conv_radius (mangoldt :: nat ⇒ 'a :: {real_normed_field, banach}) = 1"
⟨*proof*⟩

lemma *not_convergent_moebius_mu:* "¬convergent (moebius_mu :: nat ⇒ 'a :: real_normed_field)"
⟨*proof*⟩

lemma *conv_radius_moebius_mu:*
  "conv_radius (moebius_mu :: nat ⇒ 'a :: {real_normed_field, banach}) = 1"
⟨*proof*⟩

lemma *not_convergent_totient:*
  "¬convergent (λn. of_nat (totient n) :: 'a :: {real_normed_field, banach})"
⟨*proof*⟩

lemma *conv_radius_totient:*
  "conv_radius (λn. of_nat (totient n) :: 'a :: {real_normed_field, banach}) = 1"
⟨*proof*⟩

end

3 Some Abel-Style Summation Tests

theory *Summation_Tests_More*
  imports *"HOL-Analysis.Analysis" "HOL-Library.Landau_Symbols" Lambert_Series_Library*
begin

The following five summation tests are taking from Chapter 10 of Knopp's textbook [**?**]. He introduces a strong variant of Abel's summation test and then deduces from it four summation test named after Abel, Dirichlet, du Bois-Reymond, and Dedekind.

lemma *abel_partial_summation:*
  fixes *f g :: "nat ⇒ 'a :: comm_ring_1"*
  defines *"F ≡ (λn. ∑k≤n. f k)"*
  shows *"(∑r=n+1..n+k. f r * g r) =*
      *(∑r=n+1..n+k. F r * (g r - g (Suc r))) -*
      *F n * g (Suc n) + F (n + k) * g (n + k + 1)"*
  ⟨*proof*⟩

```
theorem abel_summation_test_strong:
  fixes f g :: "nat ⇒ 'a :: {real_normed_field, banach}"
  defines "F ≡ (λn. ∑k≤n. f k)"
  assumes "summable (λr. F r * (g r - g (Suc r)))"
  assumes "convergent (λr. F r * g (Suc r))"
  shows   "summable (λr. f r * g r)"
  ⟨proof⟩

corollary abel_summation_test:
  fixes f g :: "nat ⇒ real"
  assumes "summable f"
  assumes "incseq g" "g ∈ O(λ_. 1)"
  shows   "summable (λr. f r * g r)"
⟨proof⟩

corollary dirichlet_summation_test:
  fixes f g :: "nat ⇒ real"
  assumes "(λn. ∑r≤n. f r) ∈ O(λ_. 1)"
  assumes "decseq g" "g ∈ o(λ_. 1)"
  shows   "summable (λr. f r * g r)"
⟨proof⟩

corollary dubois_reymond_summation_test:
  fixes f g :: "nat ⇒ 'a :: {real_normed_field, banach}"
  assumes "summable f"
  assumes "summable (λr. norm (g r - g (Suc r)))"
  shows   "summable (λr. f r * g r)"
⟨proof⟩

corollary dedekind_summation_test:
  fixes f g :: "nat ⇒ 'a :: {real_normed_field, banach}"
  assumes "(λn. ∑k≤n. f k) ∈ O(λ_. 1)"
  assumes "summable (λr. norm (g r - g (Suc r)))"
  assumes "g ∈ o(λ_. 1)"
  shows   "summable (λr. f r * g r)"
⟨proof⟩

end
```

4 Lambert Series

```
theory Lambert_Series
  imports
  "HOL-Complex_Analysis.Complex_Analysis"
  "HOL-Real_Asymp.Real_Asymp"
  "Dirichlet_Series.Dirichlet_Series_Analysis"
  "Dirichlet_Series.Divisor_Count"
  Polylog.Polylog
  Lambert_Series_Library
```

```
  Number_Theoretic_Functions_Extras
  Summation_Tests_More
begin
```

4.1 Definition

Given any sequence $a(n)$ for $n \geq 1$, the corresponding *Lambert series* is defined as

$$L(a, q) = \sum_{n=1}^{\infty} a(n) \frac{q^n}{1 - q^n} .$$

```
definition lambert :: "(nat ⇒ 'a :: {real_normed_field, banach}) ⇒ 'a
⇒ 'a" where
  "lambert a q =
     (let f = (λn. a (Suc n) * q ^ (Suc n) / (1 - q ^ (Suc n))) in
      if  summable f then ∑n. f n else 0)"

lemma lambert_eqI:
  assumes "(λn. a (Suc n) * q ^ (Suc n) / (1 - q ^ (Suc n))) sums x"
  shows   "lambert a q = x"
  ⟨proof⟩

lemma lambert_cong [cong]:
  "(⋀n. n > 0 ⟹ a n = a' n) ⟹ q = q' ⟹ lambert a q = lambert a'
q'"
  ⟨proof⟩

lemma lambert_0 [simp]: "lambert a 0 = 0"
  ⟨proof⟩

lemma lambert_0' [simp]: "lambert (λ_. 0) q = 0"
  ⟨proof⟩

lemma lambert_cmult: "lambert (λn. c * a n) q = c * lambert a q"
⟨proof⟩

lemma lambert_cmult': "lambert (λn. a n * c) q = lambert a q * c"
  ⟨proof⟩

lemma lambert_uminus: "lambert (λn. -a n) q = -lambert a q"
  ⟨proof⟩
```

We will later see that if $\sum_{n=1}^{\infty} a(n)$ exists then the Lambert series converges everywhere except on the unit circle; otherwise it has the same convergence radius as a (and that radius then has to be <1).

```
definition lambert_conv_radius :: "(nat ⇒ 'a :: {banach, real_normed_field})
⇒ ereal"
  where "lambert_conv_radius a = (if summable a then ∞ else conv_radius
a)"
```

lemma *lambert_conv_radius_gt_1_iff: "lambert_conv_radius a > 1 ⟷ summable a"*
⟨*proof*⟩

4.2 Uniform convergence, continuity, holomorphicity

We will now show some (uniform) convergence results for $L(a, q)$, which will then give us the holomorphicity and continuity of $L(a, q)$. We will also show some absolute summability results.

```
context
  fixes a :: "nat ⇒ 'a :: {real_normed_field, banach}"
  fixes f :: "nat ⇒ 'a ⇒ 'a" and A :: "'a"
  defines "f ≡ λk q. a k * q ^ k / (1 - q ^ k)"
  defines "A ≡ (∑n. a (Suc n))"
begin
```

Let $a(n)$ have convergence radius r. In discs of radius $\min(1, r)$, the Lambert series for $a(n)$ converges uniformly. This is a simple application of Weierstraß's M test.

```
lemma uniform_limit_lambert1_aux:
  fixes r :: real
  assumes "0 < r" "r < min 1 (conv_radius a)"
  shows   "uniform_limit (ball 0 r) (λn q. (∑k<n. f (Suc k) q)) (λq.
∑k. f (Suc k) q) sequentially"
⟨proof⟩
```

```
lemma uniform_limit_lambert1:
  fixes r :: real
  assumes "0 < r" "r < min 1 (conv_radius a)"
  shows   "uniform_limit (ball 0 r) (λn q. (∑k<n. f (Suc k) q)) (lambert
a) sequentially"
⟨proof⟩
```

Since $a_n \frac{q^n}{1-q^n} = -a_n - a_n \frac{(\frac{1}{q})^n}{1-(\frac{1}{q})^n}$, we can substitute $q \mapsto \frac{1}{q}$ in the above uniform convergence result to deduce that uniform convergence also holds on any annulus $r \leq |q| \leq R$ with $1 < r < R$.

```
lemma uniform_limit_lambert2:
  fixes r R :: real
  assumes r: "1 < r" "r < R"
  assumes "summable a"
  defines "D ≡ cball 0 R - ball 0 r"
  shows   "uniform_limit D (λn q. (∑k<n. f (Suc k) q)) (λq. -A - lambert
a (1 / q)) sequentially"
⟨proof⟩
```

With some more book-keeping, we show that the series converges uniformly in all compact sets that do not touch the unit circle and, if $\sum_{n=1}^{\infty} a(n)$ does not exist, lie fully within the convergence radius of $a(n)$. This is mentioned in Knopp's Theorem 259.

```
theorem uniform_limit_lambert:
  assumes "compact X" "X ⊆ eball 0 (lambert_conv_radius a) - sphere 0
1"
  shows   "uniform_limit X (λn q. (∑k<n. f (Suc k) q)) (lambert a) sequentially"
⟨proof⟩

lemma sums_lambert:
  assumes "norm q < lambert_conv_radius a" "norm q ≠ 1"
  shows   "(λk. f (Suc k) q) sums lambert a q"
⟨proof⟩
```

A side effect of this: the functional equation

$$L(a, \tfrac{1}{q}) = -\big(\sum_{n=1}^{\infty} a(n)\big) - L(a, q)\ ,$$

which is valid for all q with $q \neq 0$ and $|q| \neq 1$ if $\sum_{n=1}^{\infty} a(n)$ exists.

```
theorem lambert_reciprocal:
  assumes "summable a" and "q ≠ 0" and "norm q ≠ 1"
  shows   "lambert a (1 / q) = -A - lambert a q"
⟨proof⟩

lemma summable_lambert:
  assumes "norm q < lambert_conv_radius a" "norm q ≠ 1"
  shows   "summable (λk. f k q)"
  ⟨proof⟩
```

We have shown that the Lambert series for $a(n)$ converges everywhere except on the unit circle if $\sum_{n=1}^{\infty} a(n)$ exists, and it converges within the convergence radius of R of $a(n)$ otherwise.

We will now show that within $\min(1, R)$, this convergence is absolute.

```
lemma norm_summable_lambert:
  assumes "norm q < min 1 (conv_radius a)"
  shows   "summable (λk. norm (f k q))"
⟨proof⟩
```

If additionally $\sum_{k=1}^{\infty} a(k)$ converges absolutely, the absolute convergence of the Lambert series also holds everywhere.

```
lemma norm_summable_lambert':
  assumes "summable (λk. norm (a k))" and "norm q ≠ 1"
  shows   "summable (λk. norm (f k q))"
⟨proof⟩

lemma abs_summable_on_lambert:
  assumes "norm q < min 1 (conv_radius a)"
```

```
  shows    "(λk. f k q) abs_summable_on {1..}"
⟨proof⟩

lemma abs_summable_on_lambert':
  assumes "summable (λk. norm (a k))" and "norm q ≠ 1"
  shows    "(λk. f k q) abs_summable_on {1..}"
⟨proof⟩

lemma summable_on_lambert:
  assumes "norm q < min 1 (conv_radius a)"
  shows    "(λk. f k q) summable_on {1..}"
  ⟨proof⟩

lemma has_sum_lambert:
  assumes "norm q < min 1 (conv_radius a)"
  shows    "((λk. f k q) has_sum lambert a q) {1..}"
⟨proof⟩
```

We can also show a more precise convergence result that essentially fully reduces the question of convegence of a Lambert series to that of its "corresponding" power series: $\sum_{k=1}^{\infty} a(k)\frac{q^k}{1-q^k}$ converges if and only if the "corresponding" power series $\sum_{k=1}^{\infty} a(k)q^k$ converges or if $\sum_{k=1}^{\infty} a(k)$ converges. This is Theorem 259 in Knopp's book. A key ingredient, aside from the results we have amassed so far, is the du-Bois Reymond summation test.

```
theorem summable_lambert_iff:
  assumes "norm q ≠ 1"
  shows    "summable (λk. f k q) ⟷ summable a ∨ summable (λk. a k *
q ^ k)"
⟨proof⟩

end


lemma holomorphic_lambert [holomorphic_intros]:
  assumes "X ⊆ eball 0 (lambert_conv_radius a) - sphere 0 1"
  shows    "lambert a holomorphic_on X"
⟨proof⟩

lemma holomorphic_lambert' [holomorphic_intros]:
  assumes "f holomorphic_on A" "⋀z. z ∈ A ⟹ f z ∈ eball 0 (lambert_conv_radius
a) - sphere 0 1"
  shows    "(λz. lambert a (f z)) holomorphic_on A"
  ⟨proof⟩

lemma analytic_lambert [analytic_intros]:
  fixes a :: "nat ⇒ complex"
  assumes "A ⊆ eball 0 (lambert_conv_radius a) - sphere 0 1"
  shows    "lambert a analytic_on A"
```

⟨proof⟩

lemma *analytic_lambert' [analytic_intros]:*
  assumes *"f analytic_on A" "⋀z. z ∈ A ⟹ f z ∈ eball 0 (lambert_conv_radius a) - sphere 0 1"*
  shows *"(λz. lambert a (f z)) analytic_on A"*
  ⟨proof⟩

lemma *continuous_on_lambert [continuous_intros]:*
  fixes *a :: "nat ⇒ 'a :: {real_normed_field, banach, heine_borel}"*
  assumes *"A ⊆ eball 0 (lambert_conv_radius a) - sphere 0 1"*
  shows *"continuous_on A (lambert a)"*
⟨proof⟩

lemma *continuous_on_lambert' [continuous_intros]:*
  fixes *a :: "nat ⇒ 'a :: {real_normed_field, banach, heine_borel}"*
  assumes *"continuous_on A f" "⋀z. z ∈ A ⟹ f z ∈ eball 0 (lambert_conv_radius a) - sphere 0 1"*
  shows *"continuous_on A (λz. lambert a (f z))"*
  ⟨proof⟩

lemma *tendsto_lambert [tendsto_intros]:*
  fixes *a :: "nat ⇒ 'a :: {real_normed_field, banach, heine_borel}"*
  assumes *"(f ⟶ c) F" "c ∈ eball 0 (lambert_conv_radius a) - sphere 0 1"*
  shows *"((λx. lambert a (f x)) ⟶ lambert a c) F"*
⟨proof⟩

If $\sum_{n=1}^{\infty} a(n)$ exists, the Lambert series of $a(n)$ tends to it for $q \to \infty$.

lemma *tendsto_lambert_at_infinity:*
  assumes *"summable (a :: nat ⇒ 'a :: {real_normed_field, banach, heine_borel})"*
  shows *"(lambert a ⟶ -(∑n. a (Suc n))) at_infinity"*
⟨proof⟩

4.3 Power series expansion

By exchanging the order of summation, we can prove the power series expansion of $L(a, q)$ as

$$L(a, q) = \sum_{n=1}^{\infty} (a * 1)(n) q^n$$

where $*$ denotes the Dirichlet product, i.e. $(a * 1)(n) = \sum_{d|n} a(d)$.
This gives particularly nice results when $a(n)$ is a number-theoretic function.

theorem *has_sum_lambert_powser:*
  assumes *"norm q < min 1 (conv_radius a)"*
  assumes *"dirichlet_prod a (λ_. 1) = b"*
  shows *"((λn. b n * q ^ n) has_sum lambert a q) {1..}"*
⟨proof⟩

lemma *sums_lambert_powser:*
  assumes *"norm q < min 1 (conv_radius a)"*
  assumes *"dirichlet_prod a (λ_. 1) = b"*
  shows *"(λn. b n * q ^ n) sums lambert a q"*
⟨*proof*⟩

lemma *conv_radius_dirichlet_prod_1_ge:*
  fixes *a b :: "nat ⇒ 'a :: {real_normed_field, banach}"*
  defines *"b ≡ dirichlet_prod a (λ_. 1)"*
  shows *"conv_radius b ≥ min 1 (conv_radius a)"*
⟨*proof*⟩

lemma *sums_lambert_powser':*
  assumes *"norm q < min 1 (conv_radius a)"*
  assumes *"fds b = fds a * fds_zeta" "b 0 = 0"*
  shows *"(λn. b n * q ^ n) sums lambert a q"*
  ⟨*proof*⟩

4.3.1 Divisor σ function

For any q with $|q| < 1$ and any $\alpha \in \mathbb{C}$, we have

$$\sum_{n=1}^{\infty} \sigma_\alpha(n) q^n = \sum_{n=1}^{\infty} n^\alpha \frac{q^n}{1 - q^n}$$

where $\sigma_\alpha(n)$ is the divisor σ function, i.e. $sigma_\alpha(n) = \sum_{d|n} d^\alpha$.

lemma *divisor_sigma_powser_conv_lambert:*
  fixes *α q :: "'a :: {nat_power_normed_field, banach}"*
  assumes *q: "norm q < 1"*
  shows *"(λn. divisor_sigma α n * q ^ n) sums lambert (λn. nat_power n α) q"*
⟨*proof*⟩

lemma *divisor_count_powser_conv_lambert:*
  fixes *q :: "'a :: {nat_power_normed_field, banach}"*
  assumes *q: "norm q < 1"*
  shows *"(λn. of_nat (divisor_count n) * q ^ n) sums lambert (λ_. 1) q"*
  ⟨*proof*⟩

4.3.2 Möbius μ function

For any q with $|q| < 1$, we have

$$\sum_{n=1}^{\infty} \mu(n) \frac{q^n}{1 - q^n} = q$$

where $\mu(n)$ is Möbus' μ function, which is 0 if n is not squarefree (i.e. contains the same prime factor more than once) and otherwise equal to $(-1)^k$, where k is the number of prime factors of n.

```
lemma lambert_moebius_mu:
  fixes q :: "'a :: {real_normed_field, banach}"
  assumes q: "norm q < 1"
  shows   "lambert moebius_mu q = q"
⟨proof⟩
```

```
lemma lambert_conv_radius_moebius_mu:
  "lambert_conv_radius (moebius_mu :: nat ⇒ 'a :: {real_normed_field,
banach}) = 1"
⟨proof⟩
```

4.3.3 Euler's totient function φ

For any q with $|q| < 1$, we have

$$\frac{q}{(1-q)^2} = \sum_{n=1}^{\infty} nq^n = \sum_{n=1}^{\infty} \varphi(n) \frac{q^n}{1-q^n}$$

where $\varphi(n)$ is Euler's totient function, i.e. the number of positive integers not greater than n that are coprime to n.

```
lemma lambert_totient:
  fixes q :: "'a :: {real_normed_field, banach}"
  assumes q: "norm q < 1"
  shows   "lambert (λn. of_nat (totient n) :: 'a) q = q / (1 - q) ^ 2"
⟨proof⟩
```

```
lemma lambert_conv_radius_totient:
  "lambert_conv_radius (λn. of_nat (totient n) :: 'a :: {real_normed_field,
banach}) = 1"
⟨proof⟩
```

4.3.4 Mangoldt's Λ function

For any q with $|q| < 1$, we have

$$\sum_{n=1}^{\infty} \ln n \; q^n = \sum_{n=1}^{\infty} \Lambda(n) \frac{q^n}{1-q^n}$$

where $\Lambda(n)$ is Mangoldt's function, which is defined to be equal to $\log n$ if n is prime and 0 otherwise.

```
lemma lambert_mangoldt:
  fixes q :: "'a :: {real_normed_field, banach}"
  assumes q: "norm q < 1"
```

```
  shows   "(λn. of_real (ln (Suc n)) * q ^ (Suc n)) sums lambert mangoldt
q"
⟨proof⟩
```

```
lemma lambert_conv_radius_mangoldt:
  "lambert_conv_radius (mangoldt :: nat ⇒ 'a :: {real_normed_field, banach})
= 1"
⟨proof⟩
```

4.3.5 Liouville's λ function

For any q with $|q| < 1$, we have

$$\sum_{n=1}^{\infty} q^{n^2} = \sum_{n=1}^{\infty} \lambda(n) \frac{q^n}{1-q^n}$$

where $\lambda(n)$ is Liouville's function, which is defined as the number of prime factors of n (taking multiplicity into account).

```
lemma lambert_liouville_lambda:
  fixes q :: "'a :: {real_normed_field, banach}"
  assumes q: "norm q < 1"
  shows   "(λn. ind is_square n * q ^ n) sums lambert liouville_lambda
q"
  ⟨proof⟩
```

```
lemma lambert_liouville_lambda':
  fixes q :: "'a :: {real_normed_field, banach}"
  assumes q: "norm q < 1"
  shows   "(λn. q ^ ((n+1) ^ 2)) sums lambert liouville_lambda q"
⟨proof⟩
```

```
lemma lambert_conv_radius_liouville_lambda:
  "lambert_conv_radius (liouville_lambda :: nat ⇒ 'a :: {real_normed_field,
banach}) = 1"
⟨proof⟩
```

4.4 Expressing a Lambert series in terms of a power series

Let $a(n)$ be a sequence of numbers. Then we can express the value of the Lambert series as an infinite sum in terms of the "normal" power series $f(q) = \sum_{k=1}^{\infty} a(k) q^k$:

$$L(a,q) = \sum_{n=1}^{\infty} f(q^n)$$

The proof is quite obvious, by expanding $f(q^n)$ into its power series and then switching the order of summation.

This gives us a number of interesting relationships, including a connection between $L(n^a, q)$ and the polylogarithm function Li_{-a}.

theorem *lambert_conv_powser_has_sum:*
  assumes *q: "norm q < min 1 (conv_radius a)"* **and** *[simp]: "a 0 = 0"*
  defines *"f ≡ (λq. ∑n. a n * q ^ n)"*
  shows *"((λn. f (q ^ n)) has_sum lambert a q) {1..}"*
⟨*proof*⟩

lemma *lambert_conv_powser_has_sum':*
  assumes *"norm q < r"* **and** *"r ≤ 1"*
  assumes *"⋀q. norm q < r ⟹ (λn. a (Suc n) * q ^ Suc n) sums f q"*
  shows *"((λn. f (q ^ n)) has_sum lambert a q) {1..}"*
⟨*proof*⟩

lemma *lambert_conv_powser_sums:*
  assumes *q: "norm q < min 1 (conv_radius a)"* **and** *[simp]: "a 0 = 0"*
  defines *"f ≡ (λq. ∑n. a n * q ^ n)"*
  shows *"(λn. f (q ^ Suc n)) sums lambert a q"*
⟨*proof*⟩

lemma *lambert_conv_powser_sums':*
  assumes *"norm q < r"* **and** *"r ≤ 1"*
  assumes *"⋀q. norm q < r ⟹ (λn. a (Suc n) * q ^ Suc n) sums f q"*
  shows *"(λn. f (q ^ Suc n)) sums lambert a q"*
⟨*proof*⟩

lemma *lambert_mult_exp_conv_powser_has_sum:*
  assumes *"norm q < r"* **and** *"r ≤ 1"* **and** *c: "norm c ≤ 1"*
  assumes *"⋀q. norm q < r ⟹ (λn. a (Suc n) * q ^ Suc n) sums f q"*
  shows *"((λn. f (c * q ^ n)) has_sum lambert (λn. c ^ n * a n) q) {1..}"*
⟨*proof*⟩

lemma *lambert_mult_exp_conv_powser_sums:*
  assumes *"norm q < r"* **and** *"r ≤ 1"* **and** *c: "norm c ≤ 1"*
  assumes *"⋀q. norm q < r ⟹ (λn. a (Suc n) * q ^ Suc n) sums f q"*
  shows *"((λn. f (c * q ^ Suc n)) sums lambert (λn. c ^ n * a n) q)"*
⟨*proof*⟩

lemma *lambert_power_int_has_sum_polylog_gen:*
  fixes *q :: complex*
  assumes *q: "norm q < 1"* **and** *c: "norm c ≤ 1"*
  shows *"((λn. polylog (-a) (c * q ^ n)) has_sum lambert (λn. c ^ n * of_nat n powi a) q) {1..}"*
  ⟨*proof*⟩

lemma *has_sum_lambert_recip_complex_gen:*
  fixes *q :: complex*
  assumes *q: "norm q < 1"* **and** *c: "norm c ≤ 1"*

```
  shows   "((λk. -ln (1 - c * q ^ k)) has_sum lambert (λn. c ^ n / of_nat
n) q) {1..}"
⟨proof⟩

lemma has_sum_lambert_recip_complex:
  fixes q :: complex
  assumes q: "norm q < 1"
  shows   "((λk. -ln (1 - q ^ k)) has_sum lambert (λn. 1 / of_nat n)
q) {1..}"
  ⟨proof⟩

lemma has_sum_lambert_recip_complex':
  fixes q :: complex
  assumes q: "norm q < 1"
  shows   "((λk. -ln (1 + q ^ k)) has_sum lambert (λn. (-1) ^ n / of_nat
n) q) {1..}"
  ⟨proof⟩

lemma has_sum_lambert_poly_complex:
  fixes q :: complex and a :: nat
  assumes q: "norm q < 1" and a: "a > 0"
  defines "E ≡ poly (eulerian_poly a)"
  shows   "((λn. E (q ^ n) * q ^ n / (1 - q ^ n) ^ (a + 1)) has_sum
             lambert (λn. complex_of_nat n ^ a) q) {1..}"
⟨proof⟩

lemma lambert_minus1_power_has_sum:
  assumes q: "norm q < 1"
  shows   "((λn. q ^ n / (1 + q ^ n)) has_sum lambert (λn. (-1) ^ Suc
n) q) {1..}"
  ⟨proof⟩

lemma lambert_exp_has_sum:
  fixes q :: "'a :: {real_normed_field, banach}"
  assumes q: "norm q < 1" and a: "norm a ≤ 1"
  shows   "((λn. a * q ^ n / (1 - a * q ^ n)) has_sum lambert (λn. a
^ n) q) {1..}"
⟨proof⟩
```

4.5 Connection to Euler's function

In this section, we show a connection between Lambert series and Euler's function:

$$\varphi(q) = \prod_{k=1}^{\infty}(1 - q^k)$$

(not to be confused with Euler's totient function, commonly denoted with $\varphi(n)$)

For this, we apply the results from the previous section to $a(n) = \frac{1}{n}$ to obtain:

$$\sum_{k=1}^{\infty} \ln(1 - q^k) = -L\big(\tfrac{1}{n}, q\big)$$

lemma *sums_lambert_recip_complex:*
  fixes *q :: complex*
  assumes *q: "norm q < 1"*
  shows *"((λk. -ln (1 - q ^ Suc k)) sums lambert (λn. 1 / of_nat n) q)"*
  ⟨*proof*⟩

lemma *sums_lambert_recip_complex':*
  fixes *q :: complex*
  assumes *q: "norm q < 1"*
  shows *"((λk. -ln (1 + q ^ Suc k)) sums lambert (λn. (-1)^n / of_nat n) q)"*
  ⟨*proof*⟩

By exponentiating this, we get:

$$\varphi(q) \stackrel{\text{def}}{=} \prod_{n=1}^{\infty} \big(1 - q^n\big) = \exp\left(-\sum_{n=1}^{\infty} \frac{1}{n} \frac{q^n}{1 - q^n}\right)$$

In other words, the Lambert sum $\sum \frac{1}{n} \frac{q^n}{1-q^n}$ is a logarithm of Euler's function $\varphi(q)$.

Note that this does not show that this is *the* logarithm of $\varphi(q)$, but merely that it is *one* of the branches of the multi-valued logarithm of $\varphi(q)$. Nevertheless, we will – just like is typically in textbooks – ignore this in our informal explanations and write $\ln \varphi(q)$.

theorem *euler_phi_conv_lambert:*
  fixes *q :: complex*
  assumes *q: "norm q < 1"*
  shows *"(λn. 1 - q ^ Suc n) has_prod exp (-lambert (λn. 1 / of_nat n) q)"*
⟨*proof*⟩

With our general results on Lambert series, we also know that $\ln \varphi(q)$ has the power series expansion

$$\ln \varphi(q) = -\sum_{n=1}^{\infty} \sigma_{-1}(n) q^n = -\sum_{n=1}^{\infty} \frac{\sigma_1(n)}{n} q^n \ .$$

lemma *ln_euler_phi_powser:*
  fixes *q :: complex*
  assumes *q: "norm q < 1"*

```
  shows "(λn. divisor_sigma (-1) n * q ^ n) sums lambert (λn. 1 / of_nat
n) q"
  ⟨proof⟩

lemma ln_euler_phi_powser':
  fixes q :: complex
  assumes q: "norm q < 1"
  shows "(λn. divisor_sum n / n * q ^ n) sums lambert (λn. 1 / of_nat
n) q"
  ⟨proof⟩
```

We also show the following variant of the above, also mentioned by Knopp:

```
theorem euler_phi_variant_conv_lambert:
  fixes q :: complex
  assumes q: "norm q < 1"
  shows "(λn. 1 + q ^ Suc n) has_prod exp (-lambert (λn. (-1) ^ n / of_nat
n) q)"
⟨proof⟩
```

4.6 Application: Fibonacci numbers

Lastly, we show a connection between the Fibonacci numbers and Lambert series, namely that:

$$\sum_{n=1}^{\infty} \frac{1}{F_n} = \sqrt{5}\left[L\big(1, \tfrac{1}{2}(3-\sqrt{5})\big) - L\big(1, \tfrac{1}{2}(7-3\sqrt{5})\big)\right]$$

```
lemma fib_closed_form_alt:
  defines "φ ≡ (1 + sqrt 5) / 2"
  shows   "real (fib n) = (φ ^ n - (-1 / φ) ^ n) / sqrt 5"
⟨proof⟩

theorem sum_inv_even_fib_conv_lambert:
  defines "L ≡ lambert (λ_. 1)"
  shows   "((λn. 1 / real (fib (2*n))) has_sum
             (sqrt 5 * (L ((3 - sqrt 5) / 2) - L ((7 - 3 * sqrt 5) / 2))))
{1..}"
⟨proof⟩

end
```

References

[1] K. Knopp. *Theorie und Anwendung der Unendlichen Reihen*. Grundlehren der mathematischen Wissenschaften. Springer Berlin Heidelberg, 2013.