

Liouville Numbers

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Abstract

In this work, we define the concept of Liouville numbers as well as the standard construction to obtain Liouville numbers and we prove their most important properties: irrationality and transcendence.

This is historically interesting since Liouville numbers constructed in the standard way where the first numbers that were proven to be transcendental. The proof is very elementary and requires only standard arithmetic and the Mean Value Theorem for polynomials and the boundedness of polynomials on compact intervals.

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1 Liouville Numbers

1.1 Preliminary lemmas

```
theory Liouville-Numbers-Misc
imports
  Complex-Main
  HOL-Computational-Algebra.Polynomial
begin
```

We will require these inequalities on factorials to show properties of the standard construction later.

lemma *fact-ineq*: $n \geq 1 \implies \text{fact } n + k \leq \text{fact } (n + k)$

proof (*induction k*)

case (*Suc k*)

from *Suc* **have** $\text{fact } n + \text{Suc } k \leq \text{fact } (n + k) + 1$ **by** *simp*

also from *Suc* **have** $\dots \leq \text{fact } (n + \text{Suc } k)$ **by** *simp*

finally show *?case* .

qed *simp-all*

lemma *Ints-sum*:

assumes $\bigwedge x. x \in A \implies f x \in \mathbf{Z}$

shows $\text{sum } f A \in \mathbf{Z}$

by (cases finite A, insert assms, induction A rule: finite-induct)
(auto intro!: Ints-add)

lemma *suminf-split-initial-segment'*:

summable (f :: nat \Rightarrow 'a::real-normed-vector) \implies

$\text{suminf } f = (\sum n. f (n + k + 1)) + \text{sum } f \{..k\}$

by (subst suminf-split-initial-segment[of - Suc k], assumption, subst lessThan-Suc-atMost)

simp-all

lemma *Rats-eq-int-div-int'*: $(\mathbf{Q} :: \text{real set}) = \{\text{of-int } p / \text{of-int } q \mid p \ q. \ q > 0\}$

proof safe

fix x :: real assume x $\in \mathbf{Q}$

then obtain p q where pq: x = of-int p / of-int q q $\neq 0$

by (subst (asm) Rats-eq-int-div-int) auto

show $\exists p \ q. x = \text{real-of-int } p / \text{real-of-int } q \wedge 0 < q$

proof (cases q > 0)

case False

show ?thesis by (rule exI[of - -p], rule exI[of - -q]) (insert False pq, auto)

qed (insert pq, force)

qed auto

lemma *Rats-cases'*:

assumes (x :: real) $\in \mathbf{Q}$

obtains p q where q > 0 x = of-int p / of-int q

using assms by (subst (asm) Rats-eq-int-div-int') auto

The following inequality gives a lower bound for the absolute value of an integer polynomial at a rational point that is not a root.

lemma *int-poly-rat-no-root-ge*:

fixes p :: real poly and a b :: int

assumes $\bigwedge n. \text{coeff } p \ n \in \mathbf{Z}$

assumes b > 0 poly p (a / b) $\neq 0$

defines n \equiv degree p

shows abs (poly p (a / b)) $\geq 1 / \text{of-int } b ^ n$

proof -

let ?S = $(\sum i \leq n. \text{coeff } p \ i * \text{of-int } a ^ i * (\text{of-int } b ^ (n - i)))$

from (b > 0) have eq: ?S = of-int b ^ n * poly p (a / b)

by (simp add: poly-altdef power-divide mult-ac n-def sum-distrib-left power-diff)

have ?S $\in \mathbf{Z}$ by (intro Ints-sum Ints-mult assms Ints-power) simp-all

moreover from assms have ?S $\neq 0$ by (subst eq) auto

ultimately have abs ?S ≥ 1 by (elim Ints-cases) simp

with eq (b > 0) show ?thesis by (simp add: field-simps abs-mult)

qed

end

theory *Liouville-Numbers*

imports

Complex-Main

HOL-Computational-Algebra.Polynomial

Liouville-Numbers-Misc

begin

A Liouville number is a real number that can be approximated well – but not perfectly – by a sequence of rational numbers. “Well“, in this context, means that the error of the n -th rational in the sequence is bounded by the n -th power of its denominator.

Our approach will be the following:

- Liouville numbers cannot be rational.
- Any irrational algebraic number cannot be approximated in the Liouville sense
- Therefore, all Liouville numbers are transcendental.
- The standard construction fulfils all the properties of Liouville numbers.

1.2 Definition of Liouville numbers

The following definitions and proofs are largely adapted from those in the Wikipedia article on Liouville numbers. [1]

A Liouville number is a real number that can be approximated well – but not perfectly – by a sequence of rational numbers. The error of the n -th term $\frac{p_n}{q_n}$ is at most q_n^{-n} , where $p_n \in \mathbb{Z}$ and $q_n \in \mathbb{Z}_{\geq 2}$.

We will say that such a number can be approximated in the Liouville sense.

locale *liouville* =

fixes $x :: \text{real}$ **and** $p\ q :: \text{nat} \Rightarrow \text{int}$

assumes *approx-int-pos*: $\text{abs } (x - p\ n / q\ n) > 0$

and *denom-gt-1*: $q\ n > 1$

and *approx-int*: $\text{abs } (x - p\ n / q\ n) < 1 / \text{of-int } (q\ n) ^ n$

First, we show that any Liouville number is irrational.

lemma (*in liouville*) *irrational*: $x \notin \mathbb{Q}$

proof

assume $x \in \mathbb{Q}$

then obtain $c d :: \text{int}$ **where** $d: x = \text{of-int } c / \text{of-int } d \ d > 0$
by (*elim Rats-cases'*) *simp*
define n **where** $n = \text{Suc } (\text{nat } \lceil \log 2 \ d \rceil)$
note $q\text{-gt-1} = \text{denom-gt-1}[\text{of } n]$

have $\text{neq}: c * q \ n \neq d * p \ n$
proof
assume $c * q \ n = d * p \ n$
hence $\text{of-int } (c * q \ n) = \text{of-int } (d * p \ n)$ **by** (*simp only:*)
with $\text{approx-int-pos}[\text{of } n] \ d \ q\text{-gt-1}$ **show** *False* **by** (*auto simp: field-simps*)
qed
hence $\text{abs-pos}: 0 < \text{abs } (c * q \ n - d * p \ n)$ **by** *simp*

from $q\text{-gt-1} \ d$ **have** $\text{of-int } d = 2 \ \text{powr } \log 2 \ d$ **by** (*subst powr-log-cancel*) *simp-all*
also from d **have** $\log 2 \ (\text{of-int } d) \geq \log 2 \ 1$ **by** (*subst log-le-cancel-iff*) *simp-all*
hence $2 \ \text{powr } \log 2 \ d \leq 2 \ \text{powr } \text{of-nat } (\text{nat } \lceil \log 2 \ d \rceil)$
by (*intro powr-mono*) *simp-all*
also have $\dots = \text{of-int } (2 \ ^{\text{nat } \lceil \log 2 \ d \rceil})$
by (*subst powr-realpow*) *simp-all*
finally have $d \leq 2 \ ^{\text{nat } \lceil \log 2 \ (\text{of-int } d) \rceil}$
by (*subst (asm) of-int-le-iff*)
also have $\dots * q \ n \leq q \ n \ ^{\text{Suc } (\text{nat } \lceil \log 2 \ (\text{of-int } d) \rceil)}$
by (*subst power-Suc, subst mult.commute, intro mult-left-mono power-mono,*
insert q-gt-1) *simp-all*
also from $q\text{-gt-1}$ **have** $\dots = q \ n \ ^n$ **by** (*simp add: n-def*)
finally have $1 / \text{of-int } (q \ n \ ^n) \leq 1 / \text{real-of-int } (d * q \ n)$ **using** $q\text{-gt-1} \ d$
by (*intro divide-left-mono Rings.mult-pos-pos of-int-pos, subst of-int-le-iff*)
simp-all
also have $\dots \leq \text{of-int } (\text{abs } (c * q \ n - d * p \ n)) / \text{real-of-int } (d * q \ n)$ **using**
 $q\text{-gt-1} \ d \ \text{abs-pos}$
by (*intro divide-right-mono*) (*linarith, simp*)
also have $\dots = \text{abs } (x - \text{of-int } (p \ n) / \text{of-int } (q \ n))$ **using** $q\text{-gt-1} \ d(2)$
by (*simp-all add: divide-simps d(1) mult-ac*)
finally show *False* **using** $\text{approx-int}[\text{of } n]$ **by** *simp*
qed

Next, any irrational algebraic number cannot be approximated with rational numbers in the Liouville sense.

lemma *liouville-irrational-algebraic*:

fixes $x :: \text{real}$
assumes *irrationsl: $x \notin \mathbb{Q}$ and algebraic x*
obtains $c :: \text{real}$ **and** $n :: \text{nat}$
where $c > 0$ **and** $\bigwedge (p::\text{int}) (q::\text{int}). q > 0 \implies \text{abs } (x - p / q) > c / \text{of-int } q \ ^n$
proof —
from $\langle \text{algebraic } x \rangle$ **guess** p **by** (*elim algebraicE*) **note** $p = \text{this}$
define n **where** $n = \text{degree } p$

— The derivative of p is bounded within $\{x - 1..x + 1\}$.

let $?f = \lambda t. |poly (pderiv p) t|$
define M **where** $M = (SUP t:\{x-1..x+1\}. ?f t)$
define $roots$ **where** $roots = \{x. poly p x = 0\} - \{x\}$

define A -set **where** A -set = $\{1, 1/M\} \cup \{abs (x' - x) | x'. x' \in roots\}$
define A' **where** $A' = Min A$ -set
define A **where** $A = A' / 2$
— We define A to be a positive real number that is less than $1::'a$, $1 / M$ and any distance from x to another root of p .

— Properties of M , our upper bound for the derivative of p :
have $\exists s \in \{x-1..x+1\}. \forall y \in \{x-1..x+1\}. ?f s \geq ?f y$
by (*intro continuous-attains-sup*) (*auto intro!*: *continuous-intros*)
hence bdd : bdd -above ($?f ' \{x-1..x+1\}$) **by** *auto*

have M -pos: $M > 0$
proof —
from p **have** $pderiv p \neq 0$ **by** (*auto dest!*: *pderiv-iszero*)
hence $finite \{x. poly (pderiv p) x = 0\}$ **using** *poly-roots-finite* **by** *blast*
moreover **have** $\neg finite \{x-1..x+1\}$ **by** (*simp add: infinite-Icc*)
ultimately **have** $\neg finite (\{x-1..x+1\} - \{x. poly (pderiv p) x = 0\})$ **by** *simp*
hence $\{x-1..x+1\} - \{x. poly (pderiv p) x = 0\} \neq \{\}$ **by** (*intro notI*) *simp*
then obtain t **where** $t: t \in \{x-1..x+1\}$ **and** $poly (pderiv p) t \neq 0$ **by** *blast*
hence $0 < ?f t$ **by** *simp*
also from t **and** bdd **have** $\dots \leq M$ **unfolding** M -def **by** (*rule cSUP-upper*)
finally show $M > 0$.
qed

have M -sup: $?f t \leq M$ **if** $t \in \{x-1..x+1\}$ **for** t
proof —
from *that* **and** bdd **show** $?f t \leq M$
unfolding M -def **by** (*rule cSUP-upper*)
qed

— Properties of A :
from p *poly-roots-finite*[*of p*] **have** $finite A$ -set
unfolding A -set-def $roots$ -def **by** *simp*
have $x \notin roots$ **unfolding** $roots$ -def **by** *auto*
hence $A' > 0$ **using** *Min-gr-iff*[*OF* (*finite A-set*), *folded A'-def*, *of 0*]
by (*auto simp: A-set-def M-pos*)
hence A -pos: $A > 0$ **by** (*simp add: A-def*)

from ($A' > 0$) **have** $A < A'$ **by** (*simp add: A-def*)
moreover from *Min-le*[*OF* (*finite A-set*), *folded A'-def*]
have $A' \leq 1 \wedge A' \leq 1/M \wedge x'. x' \neq x \implies poly p x' = 0 \implies A' \leq abs (x' - x)$
unfolding A -set-def $roots$ -def **by** *auto*
ultimately have A -less: $A < 1 \wedge A < 1/M \wedge x'. x' \neq x \implies poly p x' = 0 \implies A < abs (x' - x)$

by *fastforce+*

— Finally: no rational number can approximate x “well enough”.

have $\forall (a::int) (b::int). b > 0 \longrightarrow |x - \text{of-int } a / \text{of-int } b| > A / \text{of-int } b ^ n$
proof (*intro allI impI, rule ccontr*)

fix $a\ b::int$

assume $b: b > 0$ **and** $\neg(A / \text{of-int } b ^ n < |x - \text{of-int } a / \text{of-int } b|)$

hence $ab: \text{abs } (x - \text{of-int } a / \text{of-int } b) \leq A / \text{of-int } b ^ n$ **by** *simp*

also from $A\text{-pos } b$ **have** $A / \text{of-int } b ^ n \leq A / 1$

by (*intro divide-left-mono*) *simp-all*

finally have $ab': \text{abs } (x - a / b) \leq A$ **by** *simp*

also have $\dots \leq 1$ **using** $A\text{-less}$ **by** *simp*

finally have $ab'': a / b \in \{x-1..x+1\}$ **by** *auto*

have $\text{no-root}: \text{poly } p (a / b) \neq 0$

proof

assume $\text{poly } p (a / b) = 0$

moreover from $\langle x \notin \mathbb{Q} \rangle$ **have** $x \neq a / b$ **by** *auto*

ultimately have $A < \text{abs } (a / b - x)$ **using** $A\text{-less}(3)$ **by** *simp*

with ab' **show** *False* **by** *simp*

qed

have $\exists x0 \in \{x-1..x+1\}. \text{poly } p (a / b) - \text{poly } p\ x = (a / b - x) * \text{poly } (pderiv\ p)\ x0$

using ab'' **by** (*intro poly-MVT'*) (*auto simp: min-def max-def*)

with p **obtain** $x0::real$ **where** $x0:$

$x0 \in \{x-1..x+1\}$ $\text{poly } p (a / b) = (a / b - x) * \text{poly } (pderiv\ p)\ x0$ **by** *auto*

from $x0(2)$ no-root **have** $\text{deriv-pos}: \text{poly } (pderiv\ p)\ x0 \neq 0$ **by** *auto*

from $b\ p\ \text{no-root}$ **have** $p\text{-ab}: \text{abs } (\text{poly } p (a / b)) \geq 1 / \text{of-int } b ^ n$

unfolding $n\text{-def}$ **by** (*intro int-poly-rat-no-root-ge*)

note ab

also from $A\text{-less } b$ **have** $A / \text{of-int } b ^ n < (1/M) / \text{of-int } b ^ n$

by (*intro divide-strict-right-mono*) *simp-all*

also have $\dots = (1 / b ^ n) / M$ **by** *simp*

also from $M\text{-pos } ab\ p\text{-ab}$ **have** $\dots \leq \text{abs } (\text{poly } p (a / b)) / M$

by (*intro divide-right-mono*) *simp-all*

also from $\text{deriv-pos } M\text{-pos } x0(1)$

have $\dots \leq \text{abs } (\text{poly } p (a / b)) / \text{abs } (\text{poly } (pderiv\ p)\ x0)$

by (*intro divide-left-mono M-sup*) *simp-all*

also have $|\text{poly } p (a / b)| = |a / b - x| * |\text{poly } (pderiv\ p)\ x0|$

by (*subst x0(2)*) (*simp add: abs-mult*)

with deriv-pos **have** $|\text{poly } p (a / b)| / |\text{poly } (pderiv\ p)\ x0| = |x - a / b|$

by (*subst nonzero-divide-eq-eq*) *simp-all*

finally show *False* **by** *simp*

qed

with A -pos **show** *?thesis* **using** *that*[of A n] **by** *blast*
qed

Since Liouville numbers are irrational, but can be approximated well by rational numbers in the Liouville sense, they must be transcendental.

lemma (in *liouville*) *transcendental*: \neg *algebraic* x

proof

assume *algebraic* x

from *liouville-irrational-algebraic*[*OF irrational this*] **guess** c n . **note** $cn = \textit{this}$

define r **where** $r = \text{nat } \lceil \log 2 (1 / c) \rceil$

define m **where** $m = n + r$

from $cn(1)$ **have** $(1/c) = 2^{\text{powr } \log 2 (1/c)}$ **by** (*subst powr-log-cancel*) *simp-all*

also have $\log 2 (1/c) \leq \text{of-nat } (\text{nat } \lceil \log 2 (1/c) \rceil)$ **by** *linarith*

hence $2^{\text{powr } \log 2 (1/c)} \leq 2^{\text{powr } \dots}$ **by** (*intro powr-mono*) *simp-all*

also have $\dots = 2^{\wedge r}$ **unfolding** r -def **by** (*simp add: powr-realpow*)

finally have $1 / (2^{\wedge r}) \leq c$ **using** $cn(1)$ **by** (*simp add: field-simps*)

have $\text{abs } (x - p m / q m) < 1 / \text{of-int } (q m)^{\wedge m}$ **by** (*rule approx-int*)

also have $\dots = (1 / \text{of-int } (q m)^{\wedge r}) * (1 / \text{real-of-int } (q m)^{\wedge n})$

by (*simp add: m-def power-add*)

also from *denom-gt-1*[of m] **have** $1 / \text{real-of-int } (q m)^{\wedge r} \leq 1 / 2^{\wedge r}$

by (*intro divide-left-mono power-mono*) *simp-all*

also have $\dots \leq c$ **by fact**

finally have $\text{abs } (x - p m / q m) < c / \text{of-int } (q m)^{\wedge n}$

using *denom-gt-1*[of m] **by** $-$ (*simp-all add: divide-right-mono*)

with $cn(2)$ [of $q m p m$] *denom-gt-1*[of m] **show** *False* **by** *simp*

qed

1.3 Standard construction for Liouville numbers

We now define the standard construction for Liouville numbers.

definition *standard-liouville* :: $(\text{nat} \Rightarrow \text{int}) \Rightarrow \text{int} \Rightarrow \text{real}$ **where**

standard-liouville p $q = (\sum k. p k / \text{of-int } q^{\wedge \text{fact } (\text{Suc } k)})$

lemma *standard-liouville-summable*:

fixes p :: $\text{nat} \Rightarrow \text{int}$ **and** q :: int

assumes $q > 1$ *range* $p \subseteq \{0..<q\}$

shows *summable* $(\lambda k. p k / \text{of-int } q^{\wedge \text{fact } (\text{Suc } k)})$

proof (*rule summable-comparison-test'*)

from *assms*(1) **show** *summable* $(\lambda n. (1 / q)^{\wedge n})$

by (*intro summable-geometric*) *simp-all*

next

fix n :: nat

from *assms* **have** $p n \in \{0..<q\}$ **by** *blast*

with *assms*(1) **have** $\text{norm } (p n / \text{of-int } q^{\wedge \text{fact } (\text{Suc } n)}) \leq$

$q / \text{of-int } q^{\wedge (\text{fact } (\text{Suc } n))}$ **by** (*auto simp: field-simps*)

also from *assms*(1) **have** $\dots = 1 / \text{of-int } q^{\wedge (\text{fact } (\text{Suc } n) - 1)}$

by (subst power-diff) (auto simp del: fact-Suc)
 also have $Suc\ n \leq fact\ (Suc\ n)$ by (rule fact-ge-self)
 with $assms(1)$ have $1 / real-of-int\ q \wedge (fact\ (Suc\ n) - 1) \leq 1 / of-int\ q \wedge n$
 by (intro divide-left-mono power-increasing)
 (auto simp del: fact-Suc simp add: algebra-simps)
 finally show $norm\ (p\ n / of-int\ q \wedge fact\ (Suc\ n)) \leq (1 / q) \wedge n$
 by (simp add: power-divide)
 qed

lemma *standard-liouville-sums*:
 assumes $q > 1$ range $p \subseteq \{0..<q\}$
 shows $(\lambda k. p\ k / of-int\ q \wedge fact\ (Suc\ k))$ sums *standard-liouville* $p\ q$
 using *standard-liouville-summable*[OF $assms$] **unfolding** *standard-liouville-def*
 by (simp add: summable-sums)

Now we prove that the standard construction indeed yields Liouville numbers.

lemma *standard-liouville-is-liouville*:
 assumes $q > 1$ range $p \subseteq \{0..<q\}$ frequently $(\lambda n. p\ n \neq 0)$ sequentially
 defines $b \equiv \lambda n. q \wedge fact\ (Suc\ n)$
 defines $a \equiv \lambda n. (\sum k \leq n. p\ k * q \wedge (fact\ (Suc\ n) - fact\ (Suc\ k)))$
 shows *liouville* (*standard-liouville* $p\ q$) $a\ b$

proof

fix $n :: nat$
 from $assms(1)$ have $1 < q \wedge 1$ by *simp*
 also from $assms(1)$ have $\dots \leq b\ n$ **unfolding** *b-def*
 by (intro power-increasing) (simp-all del: fact-Suc)
 finally show $b\ n > 1$.

note $summable = standard-liouville-summable[OF\ assms(1,2)]$
let $?S = \sum k. p\ (k + n + 1) / of-int\ q \wedge (fact\ (Suc\ (k + n + 1)))$
let $?C = (q - 1) / of-int\ q \wedge (fact\ (n+2))$

have $a\ n / b\ n = (\sum k \leq n. p\ k * (of-int\ q \wedge (fact\ (n+1) - fact\ (k+1))) / of-int\ q \wedge (fact\ (n+1)))$

by (simp add: a-def b-def sum-divide-distrib of-int-sum)

also have $\dots = (\sum k \leq n. p\ k / of-int\ q \wedge (fact\ (Suc\ k)))$

by (intro sum.cong refl, subst inverse-divide [symmetric], subst power-diff [symmetric])

(insert $assms(1)$, simp-all add: divide-simps fact-mono-nat del: fact-Suc)

also have $standard-liouville\ p\ q - \dots = ?S$ **unfolding** *standard-liouville-def*

by (subst diff-eq-eq) (intro suminf-split-initial-segment' summable)

finally have $abs\ (standard-liouville\ p\ q - a\ n / b\ n) = abs\ ?S$ by (simp only:)

moreover from $assms$ have $?S \geq 0$

by (intro suminf-nonneg allI divide-nonneg-pos summable-ignore-initial-segment summable) force+

ultimately have $eq: abs\ (standard-liouville\ p\ q - a\ n / b\ n) = ?S$ by *simp*

also have $?S \leq (\sum k. ?C * (1 / q) \wedge k)$

proof (*intro suminf-le allI summable-ignore-initial-segment summable*)
from *assms* **show** $\sum k. ?C * (1 / q) ^ k$
by (*intro summable-mult summable-geometric*) *simp-all*
next
fix $k :: nat$
from *assms* **have** $p (k + n + 1) \leq q - 1$ **by** *force*
with $\langle q > 1 \rangle$ **have** $p (k + n + 1) / \text{of-int } q ^ \text{fact } (Suc (k + n + 1)) \leq$
 $(q - 1) / \text{of-int } q ^ (\text{fact } (Suc (k + n + 1)))$
by (*intro divide-right-mono*) (*simp-all del: fact-Suc*)
also from $\langle q > 1 \rangle$ **have** $\dots \leq (q - 1) / \text{of-int } q ^ (\text{fact } (n + 2) + k)$
using *fact-ineq*[*of n+2 k*]
by (*intro divide-left-mono power-increasing*) (*simp-all add: add-ac*)
also have $\dots = ?C * (1 / q) ^ k$
by (*simp add: field-simps power-add del: fact-Suc*)
finally show $p (k + n + 1) / \text{of-int } q ^ \text{fact } (Suc (k + n + 1)) \leq \dots$
qed
also from *assms* **have** $\dots = ?C * (\sum k. (1 / q) ^ k)$
by (*intro suminf-mult summable-geometric*) *simp-all*
also from *assms* **have** $(\sum k. (1 / q) ^ k) = 1 / (1 - 1 / q)$
by (*intro suminf-geometric*) *simp-all*
also from *assms*(1) **have** $?C * \dots = \text{of-int } q ^ 1 / \text{of-int } q ^ \text{fact } (n + 2)$
by (*simp add: field-simps*)
also from *assms*(1) **have** $\dots \leq \text{of-int } q ^ \text{fact } (n + 1) / \text{of-int } q ^ \text{fact } (n + 2)$
by (*intro divide-right-mono power-increasing*) (*simp-all add: field-simps del: fact-Suc*)
also from *assms*(1) **have** $\dots = 1 / (\text{of-int } q ^ (\text{fact } (n + 2) - \text{fact } (n + 1)))$
by (*subst power-diff*) *simp-all*
also have $\text{fact } (n + 2) - \text{fact } (n + 1) = (n + 1) * \text{fact } (n + 1)$ **by** (*simp add: algebra-simps*)
also from *assms*(1) **have** $1 / (\text{of-int } q ^ \dots) < 1 / (\text{real-of-int } q ^ (\text{fact } (n + 1) * n))$
by (*intro divide-strict-left-mono power-increasing mult-right-mono*) *simp-all*
also have $\dots = 1 / \text{of-int } (b n) ^ n$
by (*simp add: power-mult b-def power-divide del: fact-Suc*)
finally show $|\text{standard-liouville } p q - a n / b n| < 1 / \text{of-int } (b n) ^ n$

from *assms*(3) **obtain** k **where** $k: k \geq n + 1 \wedge p k \neq 0$
by (*auto simp: frequently-def eventually-at-top-linorder*)
define k' **where** $k' = k - n - 1$
from *assms* k **have** $p k \geq 0$ **by** *force*
with k *assms* **have** $k': p (k' + n + 1) > 0$ **unfolding** k' -*def* **by** *force*
with *assms*(1,2) **have** $?S > 0$
by (*intro suminf-pos2*[*of - k*] *summable-ignore-initial-segment summable*)
(*force intro!: divide-pos-pos divide-nonneg-pos*)
with *eq* **show** $|\text{standard-liouville } p q - a n / b n| > 0$ **by** (*simp only:*)
qed

We can now show our main result: any standard Liouville number is transcendental.

theorem *transcendental-standard-liouville*:
assumes $q > 1$ range $p \subseteq \{0..<q\}$ frequently $(\lambda k. p k \neq 0)$ sequentially
shows \neg algebraic (standard-liouville $p q$)
proof –
from *assms* **interpret**
liouville standard-liouville p q
 $\lambda n. (\sum k \leq n. p k * q ^ \wedge (fact (Suc n) - fact (Suc k)))$
 $\lambda n. q ^ \wedge fact (Suc n)$
by (rule standard-liouville-is-liouville)
from *transcendental* **show** ?thesis .
qed

In particular: The the standard construction for constant sequences, such as the “classic” Liouville constant $\sum_{n=1}^{\infty} 10^{-n!} = 0.11000100\dots$, are transcendental.

This shows that Liouville numbers exists and therefore gives a concrete and elementary proof that transcendental numbers exist.

corollary *transcendental-standard-standard-liouville*:
 $a \in \{0 < .. < b\} \implies \neg$ algebraic (standard-liouville $(\lambda-. int a) (int b)$)
by (intro transcendental-standard-liouville) auto

corollary *transcendental-liouville-constant*:
 \neg algebraic (standard-liouville $(\lambda-. 1) 10$)
by (intro transcendental-standard-liouville) auto

end

References

- [1] Wikipedia. Liouville number — Wikipedia, the free encyclopedia. https://en.wikipedia.org/w/index.php?title=Liouville_number&oldid=696910651, 2015. [Online; accessed 22-July-2004].