Irrationality Criteria for Series by Erdős and Straus

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Abstract

We formalise certain irrationality criteria for infinite series of the form:

$$\sum_n \frac{b_n}{\prod_{i\leq n} a_i}$$

where b_n, a_i are integers. The result is due to P. Erdős and E.G. Straus [1], and in particular we formalise Theorem 2.1, Corollary 2.10 and Theorem 3.1. The latter is an application of Theorem 2.1 involving the prime numbers.

Contents

1 Miscellaneous **1**

2 Theorem 2.1 and Corollary 2.10 **2**

3 Some auxiliary results on the prime numbers. **3**

4 Theorem 3.1 **4**

5 Acknowledgements **4**

theory *Irrational-Series-Erdos-Straus* **imports**
  Prime-Number-Theorem.Prime-Number-Theorem
  Prime-Distribution-Elementary.PNT-Consequences
begin

1 Miscellaneous

lemma *suminf-comparison*:
  assumes *summable f* **and** *gf*: $\bigwedge n.$ *norm* $(g\ n) \leq f\ n$
  shows *suminf g* $\leq$ *suminf f*
⟨*proof*⟩

lemma *tendsto-of-int-diff-0*:
assumes $(\lambda n.\ f\ n - of\text{-}int(g\ n)) \longrightarrow (0::real)$ $\forall_F\ n\ in\ sequentially.\ f\ n > 0$
shows $\forall_F\ n\ in\ sequentially.\ 0 \le g\ n$
⟨*proof*⟩

lemma *eventually-mono-sequentially*:
assumes *eventually P sequentially*
assumes $\bigwedge x.\ P\ (x+k) \Longrightarrow Q\ (x+k)$
shows *eventually Q sequentially*
⟨*proof*⟩

lemma *frequently-eventually-at-top*:
fixes $P\ Q::'a::linorder \Rightarrow bool$
assumes *frequently P at-top eventually Q at-top*
shows *frequently* $(\lambda x.\ P\ x \wedge (\forall y \ge x.\ Q\ y)\ )$ *at-top*
⟨*proof*⟩

lemma *eventually-at-top-mono*:
fixes $P\ Q::'a::linorder \Rightarrow bool$
assumes *event-P*:*eventually P at-top*
assumes *PQ-imp*:$\bigwedge x.\ x \ge z \Longrightarrow \forall y \ge x.\ P\ y \Longrightarrow Q\ x$
shows *eventually Q at-top*
⟨*proof*⟩

lemma *frequently-at-top-elim*:
fixes $P\ Q::'a::linorder \Rightarrow bool$
assumes $\exists_F x\ in\ at\text{-}top.\ P\ x$
assumes $\bigwedge i.\ P\ i \Longrightarrow \exists j > i.\ Q\ j$
shows $\exists_F x\ in\ at\text{-}top.\ Q\ x$
⟨*proof*⟩

lemma *less-Liminf-iff*:
fixes $X :: - \Rightarrow - :: complete\text{-}linorder$
shows $Liminf\ F\ X < C \longleftrightarrow (\exists y < C.\ frequently\ (\lambda x.\ y \ge X\ x)\ F)$
⟨*proof*⟩

lemma *sequentially-even-odd-imp*:
assumes $\forall_F\ N\ in\ sequentially.\ P\ (2*N)$ $\forall_F\ N\ in\ sequentially.\ P\ (2*N+1)$
shows $\forall_F\ n\ in\ sequentially.\ P\ n$
⟨*proof*⟩

2 Theorem 2.1 and Corollary 2.10

context
fixes $a\ b\ ::nat \Rightarrow int$
assumes *a-pos*: $\forall\ n.\ a\ n > 0$ **and** *a-large*: $\forall_F\ n\ in\ sequentially.\ a\ n > 1$
and *ab-tendsto*: $(\lambda n.\ |b\ n|\ /\ (a\ (n-1) * a\ n)) \longrightarrow 0$
begin

private lemma *aux-series-summable*: *summable* $(\lambda n.\ b\ n\ /\ (\prod k{\le}n.\ a\ k))$
$\langle proof \rangle$ **fun** *get-c*::$(nat \Rightarrow int) \Rightarrow (nat \Rightarrow int) \Rightarrow int \Rightarrow nat \Rightarrow (nat \Rightarrow int)$ **where**
$get\text{-}c\ a'\ b'\ B\ N\ 0 = round\ (B * b'\ N\ /\ a'\ N)|$
$get\text{-}c\ a'\ b'\ B\ N\ (Suc\ n) = get\text{-}c\ a'\ b'\ B\ N\ n * a'\ (n{+}N) - B * b'\ (n{+}N)$

lemma *ab-rationality-imp*:
assumes *ab-rational*:$(\sum n.\ (b\ n\ /\ (\prod i \le n.\ a\ i))) \in \mathbb{Q}$
shows $\exists\ (B{::}int){>}0.\ \exists\ c{::}nat{\Rightarrow}\ int.$
$(\forall_F\ n\ in\ sequentially.\ B{*}b\ n = c\ n * a\ n - c(n{+}1) \wedge |c(n{+}1)|{<}a\ n/2)$
$\wedge\ (\lambda n.\ c\ (Suc\ n)\ /\ a\ n) \longrightarrow 0$
$\langle proof \rangle$ **lemma** *imp-ab-rational*:
assumes $\exists\ (B{::}int){>}0.\ \exists\ c{::}nat{\Rightarrow}\ int.$
$(\forall_F\ n\ in\ sequentially.\ B{*}b\ n = c\ n * a\ n - c(n{+}1) \wedge |c(n{+}1)|{<}a$
$n/2)$
shows $(\sum n.\ (b\ n\ /\ (\prod i \le n.\ a\ i))) \in \mathbb{Q}$
$\langle proof \rangle$

theorem *theorem-2-1-Erdos-Straus* :
$(\sum n.\ (b\ n\ /\ (\prod i \le n.\ a\ i))) \in \mathbb{Q} \longleftrightarrow (\exists\ (B{::}int){>}0.\ \exists\ c{::}nat{\Rightarrow}\ int.$
$(\forall_F\ n\ in\ sequentially.\ B{*}b\ n = c\ n * a\ n - c(n{+}1) \wedge |c(n{+}1)|{<}a\ n/2))$
$\langle proof \rangle$

The following is a Corollary to Theorem 2.1.

corollary *corollary-2-10-Erdos-Straus*:
assumes *ab-event*:$\forall_F\ n\ in\ sequentially.\ b\ n > 0 \wedge a\ (n{+}1) \ge a\ n$
and *ba-lim-leq*:$lim\ (\lambda n.\ (b(n{+}1) - b\ n\ )/a\ n) \le 0$
and *ba-lim-exist*:$convergent\ (\lambda n.\ (b(n{+}1) - b\ n\ )/a\ n)$
and $liminf\ (\lambda n.\ a\ n\ /\ b\ n) = 0$
shows $(\sum n.\ (b\ n\ /\ (\prod i \le n.\ a\ i))) \notin \mathbb{Q}$
$\langle proof \rangle$

end

3 Some auxiliary results on the prime numbers.

lemma *nth-prime-nonzero*[*simp*]:$nth\text{-}prime\ n \neq 0$
$\langle proof \rangle$

lemma *nth-prime-gt-zero*[*simp*]:$nth\text{-}prime\ n > 0$
$\langle proof \rangle$

lemma *ratio-of-consecutive-primes*:
$(\lambda n.\ nth\text{-}prime\ (n{+}1)/nth\text{-}prime\ n) \longrightarrow 1$
$\langle proof \rangle$

lemma *nth-prime-double-sqrt-less*:
assumes $\varepsilon > 0$
shows $\forall_F\ n\ in\ sequentially.\ (nth\text{-}prime\ (2{*}n) - nth\text{-}prime\ n)$
$/\ sqrt\ (nth\text{-}prime\ n) < n\ powr\ (1/2{+}\varepsilon)$

⟨*proof*⟩

4 Theorem 3.1

Theorem 3.1 is an application of Theorem 2.1 with the sequences considered involving the prime numbers.

theorem *theorem-3-10-Erdos-Straus*:
fixes *a*::*nat* ⇒ *int*
assumes *a-pos*:∀ *n*. *a n* >*0* **and** *mono a*
and *nth-1*:(λ*n*. *nth-prime n* / (*a n*)^*2*) ⟶ *0*
and *nth-2*:*liminf* (λ*n*. *a n* / *nth-prime n*) = *0*
shows (∑ *n*. (*nth-prime n* / (∏ *i* ≤ *n*. *a i*))) ∉ ℚ
⟨*proof*⟩

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References

[1] P. Erdős and E. Straus. On the irrationality of certain series. *Pacific journal of mathematics*, 55(1):85–92, 1974.