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SOME APPLICATIONS OF THE GAUSS-LUCAS THEOREM [1)]

par L. A. Rubel

The Gauss-Lucas Theorem, that the zeros of the derivative of a non-constant polynomial lie in the convex hull of the set of zeros of the polynomial, is a surprisingly powerful and versatile tool in classical analysis, despite its simplicity. To illustrate this point, we prove several results, using the Gauss-Lucas Theorem as our principal tool. To begin with, we present a short proof of the Gauss-Lucas Theorem. As applications, we first give a new lower bound on the largest modulus of the zeros of a polynomial, in terms of the coefficients of the polynomial. Next, we strengthen slightly a result of Edrei [2] on the zeros of the partial sums of a power series. Finally, we reformulate a method of Fejér, and use it to strengthen some classical results on lacunary polynomials and entire functions with lacunary power series.

The Gauss-Lucas Theorem. *The zeros of the derivative of a non-constant polynomial* P *lie in the convex hull of the set of zeros of* P.

Proof. It is enough to prove that any open half-plane that contains the zeros of P contains the zeros of P'/P. Without loss of generality, we may suppose that all the zeros of P lie in the open right half-plane. Writing.

$$P(z) = a \prod (z - z_n) ,$$

with $z_n = x_n + iy_n$, $x_n > 0$, we have

$$P'(z)/P(z) = \sum (z - z_n)^{-1} ,$$

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so that

$$Re\left(P'(z)/P(z)\right) = \sum (x - x_n) \mid z - z_n \mid^{-2} .$$

Hence, if $x < 0$, then $Re\,(P'(z)/P(z)) < 0$, and P'/P consequently has no zeros in the open left half-plane.

THEOREM. *If* $P(z) = a_0 + a_1 z + \dots + a_n z^n$, $a_n \neq 0$, then P *has a zero of modulus at least*

$$\max_{0 \leqq \nu \leqq n-1} \left\{ \binom{n}{\nu}^{-1} \left| \frac{a_{n-\nu}}{a_n} \right| \right\}^{1/\nu},$$

Proof. First, considering the ν-th derivative of P,

$$P^{(\nu)}(z) = \sum_{k=\nu}^{n} a_k \frac{k\,!}{(k-\nu)\,!} z^{k-\nu} ,$$

we see that the product of the zeros of $P^{(\nu)}$ is

$$\pm \frac{a_\nu}{a_n} \frac{\nu\,!\,(n-\nu)\,!}{n\,!} ,$$

so that $P^{(\nu)}$ must have a zero of modulus at least

$$\left| \frac{a_\nu}{a_n} \frac{\nu\,!\,(n-\nu)\,!}{n\,!} \right|^{1/(n-\nu)} ,$$

since there are $n - \nu$ roots. But by the Gauss-Lucas Theorem, the modulus of the largest root of P cannot be smaller than this, and the result is proved on interchanging ν and $n - \nu$.

COROLLARY. *If* $Q(z) = b_0 + b_1 z + \dots + b_n z^n$, $b_0 \neq 0$, then Q *has a zero of modulus at most*

$$\min_{0 \leqq \nu \leqq n-1} \left\{ \binom{n}{\nu} \left| \frac{b_0}{b_\nu} \right| \right\}^{1/\nu} .$$

Proof. Apply the preceding theorem to $P(z) = z^n Q(1/z)$.

The first part of the next result was proved, in a different way, by Edrei [2].

THEOREM. *Suppose that the formal power series, not a polynomial,*

$$f(z) = a_0 + a_1 z + a_2 z^2 + \dots, \qquad a_0 \neq 0,$$

has the property that for infinitely many n, there is a closed half-plane T_n that contains the origin and that contains all the zeros of the partial sum $S_n(z) = a_0 + a_1 z + \dots + a_n z^n$. Then no two consecutive coefficients of $f(z)$ may vanish. If one coefficient vanishes, then there is a line through the origin that contains all the zeros of all the partial sums.

Proof. Suppose, by way of contradiction, that two consecutive coefficients of f do vanish. They are contained in a block of zero coefficients, flanked left and right by non-zero coefficients, say a_p and a_q, respectively. Choose $n \geqq q$, and differentiate S_n successively p times, to get $S_n^* = S_n{}^{(p)}$,

$$S_n^*(z) = a_p^* + a_q^* z^r + z^{r+1} R(z),$$

where $a_p^* \neq 0$, $a_q^* \neq 0$, $r = q - p$, R is a polynomial, and S_n^* has degree $n - p$. Now define S_n^{**} by $S_n^{**}(z) = z^{n-p} S_n^*(1/z)$, so that S_n^{**} is again a polynomial. Differentiate S_n^{**} successively m times, where $m = n - q$, to get a polynomial S_n^{***},

$$S_n^{***}(z) = a_q^{**} + a_p^{**} z^s,$$

where $a_q^{**} \neq 0$, $a_p^{**} \neq 0$, and $s = q - p \geqq 3$. Now if S_n has all its zeros in a closed half-plane T_n that contains the origin, then repeated applications of the Gauss-Lucas Theorem show that S_n^* also has all its zeros in T_n. Then S_n^{**} has all its zeros in the closed half-plane $T_n^* = \{1/z \colon z \in T_n\} \cup \{0\}$. Again repeatedly applying the Gauss-Lucas Theorem, we see that S_n^{***} has all its zeros in T_n^*. But the zeros of S_n^{***} are just s-th roots of $-a_q^{**}/a_p^{**}$, and since $s \geqq 3$, we have a contradiction.

In the sequel, the word « set » will denote subsets of the finite complex plane.

DEFINITION. *If P is a polynomial, then $Z(P)$ denotes the set of zeros of P.*

Definition. *If E is a finite set, then $K(E)$ denotes the convex hull of E, and $K^*(E)$ denotes $K(E) \cup \{0\}$.*

Definition. *If E is a set, then $1/E$ denotes the set*

$$1/E = \{1/z : z \in E, z \neq 0\}.$$

Definition: *If P is a polynomial,*

$$P(z) = a_0 + a_1 z + \dots + a_n z^n, \qquad n > 0,$$

then $P^{\#}$ denotes the polynomial

$$P^{\#}(z) = \frac{1}{n}\{a_0 + (a_0 + a_1 z) + \dots + (a_0 + a_1 z + \dots + a_{n-1} z^{n-1})\},$$

that is,

$$P^{\#}(z) = a_0 + \frac{n-1}{n} a_1 z + \frac{n-2}{n} a_2 z^2 + \dots + \frac{1}{n} a_{n-1} z^{n-1}.$$

In other words, $P^{\#}$ is just the arithmetic mean of the proper partial sums of P. The next result is latent in the paper of Fejér [3].

Theorem. *If $a_0 \neq 0$ and $a_n \neq 0$, then*

$$Z(P^{\#}) \subseteq \frac{1}{K\left(\frac{1}{Z(P)}\right)},$$

or equivalently,

$$K\left(\frac{1}{Z(P^{\#})}\right) \subseteq K\left(\frac{1}{Z(P)}\right).$$

Addendum. It will be clear from the proof that if $a_0 \neq 0$, then $Z(P^{\#}) \subseteq 1/K^*(1/Z(P))$. Further, $Z(P^{\#}) \subseteq \{0\} \cup 1/K(1/Z(P))$ if $a_n \neq 0$ and $P(z) \neq a_n z^n$. In any event, so long as $P(z) \neq a_n z^n$, $Z(P^{\#}) \subseteq \{0\} \cup 1/K^*(1/Z(P))$.

Proof. A straightforward computation shows that if

$$R(z) = z^n P\left(\frac{1}{z}\right) = a_n + a_{n-1} z + \ldots + a_0 z^n .$$

and

$$Q(z) = \frac{d}{dz} R(z) = a_{n-1} + 2a_{n-2} z + \ldots + n a_0 z^{n-1} ,$$

then

$$P^{\#}(z) = \frac{1}{n} z^{n-1} Q \frac{1}{z} = a_0 + \frac{n-1}{n} a_1 z + \ldots + \frac{1}{n} a_{n-1} z^{n-1} .$$

Hence

$$Z(P^{\#}) \subseteq \frac{1}{Z(Q)} \quad \textit{if} \quad a_0 \neq 0 ,$$

while

$$Z(P^{\#}) \subseteq \{0\} \cup \frac{1}{Z(Q)} \quad \textit{if} \quad a_0 = 0 .$$

Since $R \neq$ const., we may apply the Gauss-Lucas Theorem to get

$$Z(Q) \subseteq K(Z(R)) .$$

Now

$$Z(R) \subseteq \frac{1}{Z(P)} \quad \textit{if} \quad a_n \neq 0$$

while

$$Z(R) \subseteq \{0\} \cup \frac{1}{Z(P)} \quad \textit{if} \quad a_n = 0 .$$

Combining these results, the theorem is proved.

Corollary. *If a disc with center at the origin is free of zeros of P, then it is free of zeros of $P^{\#}$.*

Corollary. *If $a_0 a_n \neq 0$ and if $P^{\#}$ has at least three zeros whose reciprocals are non-collinear, then so does P.*

The first corollary is the basis of the proofs of the next results. These results are quite classical, except that the first is somewhat elaborated.

THEOREM. *Suppose that*

$$P(z) = a_0 + a_1 z^{k_1} + a_2 z^{k_2} + \dots + a_n z^{k_n}$$

where $0 < k_1 < k_2 < \dots < k_n$, *and* $a_j \neq 0$ *for* $j = 0,1 \dots, n$.

Let

$$A = \frac{a_0}{a_1} \frac{k_2}{k_2 - k_1} \frac{k_3}{k_3 - k_1} \cdots \frac{k_n}{k_n - k_1} .$$

Then P has at least one zero in the disc

$$|z| \leqq |A|^{-1/k_1} .$$

If $k_1 \geqq 3$, *then P must have at least two distinct zeros in this disc, and at least three distinct zeros whose reciprocals lie on or outside the regular polygon whose vertices are the* k_1*-th roots of* $-1/A$.

Proof. Apply the operation $\#$ repeatedly, taking into account the degrees of the resulting polynomials, to get the polynomial

$$P^*(z) = a_0 + \frac{k_2 - k_1}{k_2} \frac{k_3 - k_1}{k_3} \cdots \frac{k_n - k_1}{k_n} a_1 z^{k_1} .$$

Applying the first corollary, we obtain the first part of the theorem, since the zeros of P^* are the roots of $z^{k_1} = -A$. The other parts follow from simple geometric considerations and the fact that

$$K\left(\frac{1}{Z(P^*)}\right) \subseteq K\left(\frac{1}{Z(P)}\right) .$$

THEOREM. *Suppose that f is a transcendental entire function with power series expansion*

$$f(z) = \sum_{k=0}^{\infty} a_k z^{n_k} , \quad a_k \neq 0 \quad for \quad k = 0, 1, 2, \dots ,$$

and suppose that

$$\sum_{n_k > 0} \frac{1}{n_k} < \infty .$$

Then the range of f contains each complex number.

Proof. It is enough to prove that f has a zero, and we may clearly suppose that $n_0 = 0$. From the proceding result, we see that the n_k-th partial sum of the power series for f has a zero in the disc

$$|z| \leq \left\{ \frac{|a_0|}{|a_1|} \frac{1}{\left(1 - \frac{n_1}{n_2}\right)\left(1 - \frac{n_1}{n_3}\right) \cdots \left(1 - \frac{n_1}{n_k}\right)} \right\}^{1/n_k} .$$

But since $\sum 1/n_k < \infty$, the product $\prod_2^\infty (1-(n_1/n_k))$ converges, so that there is a fixed disc with center at the origin that contains a zero of the n_k-th partial sum for $k = 2, 3, 4, \ldots$. It follows that f has a zero in this disc, and the result is proved.

It should be pointed out that Biernacki [1] proved, under the same hypotheses, and using a stronger form of the Gauss-Lucas Theorem, that f takes each complex value infinitely often. It is likely that our method can give a slight improvement of the preceding result, but not to the full strength of Biernacki's result. A recent result of G. and M. Weiss [5] gives a partial analogue for functions regular in the unit disc.

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