

LENNART CARLESON

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A REMARK ON DENJOY'S INEQUALITY AND HERMAN'S THEOREM

by LENNART CARLESON

1. In the preceding proof [1] by M. Herman of the Arnold conjecture, the Hurewicz (or the Chacon-Ornstein) ergodic theorem plays an important role and the proof is in this way non-constructive. The purpose of this note is to give a constructive argument which gives a remainder estimate in the basic Denjoy inequality. This argument also makes it possible to avoid the reduction to the case when

$$\int_0^1 |Df(x)| dx = V$$

is small, which was used by Herman.

Let us first recall the situation and some basic results from Herman's paper: $f(x)$ is an increasing continuous function on $-\infty < x < \infty$ such that $f(x+1) - f(x) = 1$, $0 < f(0) < 1$ and $f^i(x)$ are the iterates. Sometimes $f(x)$ will be considered on the torus $\mathbf{T}$ (modulo 1) and this will be clear from the context; α is the rotation number, i.e.:

$$|f^n(x) - x - n\alpha| < 1;$$

α is assumed irrational with continued fraction expansion $[a_1, a_2, \dots]$ and p_i/q_i are the convergents. There is a homomorphism h of $(0, 1) \pmod{1}$, $t = h(x)$, so that

$$h^{-1} \circ f \circ h(t) = t + \alpha.$$

Herman's theorem asserts that if $f(x)$ is smooth, then, for almost all α , it follows that $h(t)$ is also smooth.

There is a unique probability measure μ on $(0, 1)$ which is invariant under $f(x) \pmod{1}$ and:

$$\left| \sum_{i=0}^{q-1} \varphi(f^i(x_0)) - q \int_0^1 \varphi(f(x)) d\mu(x) \right| \leq \text{Var}(\varphi)$$

for all denominators $q = q_j$ in the convergents of α . This is Denjoy's inequality.

We shall prove the following theorem—without use of Herman's result but using his ideas:

For almost all α there are constants C and β so that

$$\left| \sum_{i=0}^{q_j-1} \varphi(f^i(x_0)) - q_j \int_0^1 \varphi(x) d\mu(x) \right| < C j^{-\beta}$$

for all φ on $\mathbf{T}$ with $|\varphi''(x)| \leq 1$. The same result holds if $\varphi'(x)$ only satisfies some Hölder condition.

Once this is proved it follows that

$$(1.1) \quad |\log Df^{q_j}| < Cj^{-\beta}$$

and for almost all α :

$$|\log Df^n| \leq C \sum_{j=1}^{c \log n} \frac{a_j}{j^\beta} = O((\log n)^{1-\beta'})$$

with $\beta' < \beta$. This is the crucial estimate needed for Herman's argument. (1.1) also implies the estimate $|f^q(x) - x - p| < q^{\delta-1}$, $\delta > 0$. See [1], Chapter VIII.

We shall use the letters C, c to denote different constants whose values are immaterial in the context.

2. Let q be one of the q_j and x_0 a fixed point. We define the measure on $(0, 1)$:

$$\nu_q = k \sum_{i=0}^{q-1} Df^i(x_0) \delta_{f^i(x_0)}$$

where k is chosen so that $\nu_q(0, 1) = 1$. Let I be an interval so that $f(I)$ does not contain x_0 or $f^q(x_0)$. Then it is easy to see that

$$\nu_q(f(I)) = f'(\xi) \nu_q(I) \quad \text{for some } \xi \in I.$$

If x_0 or $f^q(x_0) \in f(I)$, the situation is a little more complicated.

We first observe that:

$$(2.1) \quad |f^q(x_0) - x_0| < q^{-\lambda}, \quad \lambda > 0 \pmod{1}$$

(see [1], VIII, (2.1)) for almost all α since $\sqrt[q]{q_j} \rightarrow \text{const}$, almost everywhere. Assume that the length $|I|$ of I is greater than $q^{-\lambda/2}$, and that e.g. $x_0 \in f(I)$. Suppose also that e.g. I extends by $\frac{1}{2}|I|$ to the right of $f^{-1}(x_0)$. For every second q_i , $f^{q_i}(x_0) > x_0$ and by the inequality (2.1):

$$f^{q_i}(x_0) \in f(I) \quad \text{if } q_i > \sqrt{q}.$$

This is true for at least $c \log q$ different i 's, so that

$$\sum_{f^i(x_0) \in f(I)} Df^i(x_0) \geq c \log q$$

since $Df^{q_i}(x_0) \geq c > 0$, as was observed by Denjoy.

Now:

$$\begin{aligned} \nu_q(f(I)) &= k \sum_{\substack{f^i(x_0) \in f(I) \\ i=0, \dots, q-1}} Df^i(x_0) = k f'(\xi) \sum_{\substack{f^i(x_0) \in I \\ i=-1, 0, \dots, q-2}} Df^i(x_0) \\ &= f'(\xi) \nu_q(I) + O(k f'(\xi)) \\ &= f'(\xi) \left(1 + O\left(\frac{1}{\log q}\right) \right) \nu_q(I) \end{aligned}$$

since $v_q(I) > ck \log q$. We obtain the following lemma:

Lemma 1. — *Let I be an interval of length $> q^{-\lambda/2}$. Then:*

$$v_q(f(I)) = f'(\xi) v_q(I), \quad \xi \in I, \quad \text{if } x_0, f^q(x_0) \notin f(I),$$

and
$$v_q(f(I)) = f'(\xi) \left(1 + O\left(\frac{1}{\log q}\right) \right) v_q(I), \quad \xi \in I,$$

in all cases, provided α is not in an exceptional set of measure zero.

3. Next we need some information on the mapping $x = h(t)$. Let ω be an interval on the t -axis and assume that

$$(3.1) \quad \frac{1}{q_{i-1}} > |\omega| \geq \frac{1}{q_i}, \quad a = \frac{q_{i+2}}{q_{i-1}}.$$

We bisect ω into two equal intervals ω_1 and ω_2 and we want to estimate $|h(\omega_1)|$ compared to $|h(\omega)|$. From (3.1) follows that

$$\bigcup_{v=1}^{2aq_i} f^v(h(\omega)) \supset (0, 1)$$

and every point is covered at most $4a^2$ times. A similar statement is true for ω_1 .

Namely, if $\alpha = \frac{p_{i+1}}{q_{i+1}} + \frac{\delta}{q_{i+1}^2}$, then $\frac{q_{i+1}}{q_{i+2}} < |\delta| < 1$, so that $2aq_i$ iterations of an interval of length q_{i+1}^{-1} gives a complete covering. Furthermore:

$$|f^v(h(\omega))| = \left(\prod_{\mu=0}^{v-1} f'(\xi_\mu) \right) |h(\omega)|, \quad \xi_\mu \in f^\mu(h(\omega)),$$

and similarly for ω_1 . Hence:

$$\begin{aligned} \frac{|f^v(h(\omega))|}{|f^v(h(\omega_1))|} &= \frac{|h(\omega)|}{|h(\omega_1)|} \cdot \prod_{\mu=0}^{v-1} \frac{f'(\xi_\mu)}{f'(\xi'_\mu)} \\ &\geq \frac{|h(\omega)|}{|h(\omega_1)|} e^{-ca^2} \end{aligned}$$

and
$$\begin{aligned} Ca^2 &\geq \sum_{v=1}^{4aq_i} |f^v(h(\omega))| \geq \frac{|h(\omega)|}{|h(\omega_1)|} \sum_{v=1}^{4aq_i} |f^v(h(\omega_1))| e^{-ca^2} \\ &\geq e^{-ca^2} \frac{|h(\omega)|}{|h(\omega_1)|}. \end{aligned}$$

This gives the following lemma:

Lemma 2. — *Let $\frac{1}{q_i} \leq |\omega| < \frac{1}{q_{i-1}}$ and bisect ω into ω_1 and ω_2 . Then, for almost all α :*

$$|h(\omega_1)| \geq \exp \left(\left(-c \frac{q_{i+2}}{q_{i-1}} \right)^2 \right) |h(\omega)|$$

and (see (2.1))

$$|h(\omega)| \leq |\omega|^\lambda C \frac{q_{i+2}}{q_{i-1}}.$$

4. We shall now describe the exceptional set of α .

Let δ be a small positive number and n a large integer. Denote by B_ℓ the interval:

$$B_\ell(n) : \delta \cdot \ell n \leq k < \delta(\ell + 1)n$$

$$\delta^{-1} \frac{1}{2} \frac{2^n}{n} \leq \ell < \delta^{-1} \frac{3}{4} \frac{2^n}{n}.$$

The intervals $B_\ell(n)$, $n = 1, 2, \dots$ and ℓ as above, are disjoint.

For every B_ℓ , define the number $b_{\ell,n}(\alpha)$:

$$b_{\ell,n}(\alpha) = \max_{k \in B_\ell} \frac{q_{k+1}}{q_k}.$$

For fixed (ℓ, n) , $b_{\ell,n}(\alpha) \leq C$ on a set of measure $\geq 2^{-n\delta}$. For fixed n , $b_{\ell,n}(\alpha) \leq C$ for $\geq 2^{3/4n}$ values of ℓ , if we exclude a set E_n of measure $\leq 2^{-n}$ and if $\delta < 1/4$. We now do this for all n and consider those α which do not belong to infinitely many E_n . We also exclude those sets of measure zero mentioned earlier.

5. We shall now prove that ν_q converges weakly to Lebesgue measure and shall also obtain an estimate of the error. We first prove that for some suitable $\gamma > 0$ and $C < \infty$:

$$(5.1) \quad C^{-1} \leq \frac{\nu_q(h(\omega))}{|h(\omega)|} \leq C, \quad \text{if } |\omega| > q^{-\gamma}.$$

Take some q_i so that $\sqrt{q} < q_i < q$ and so that $\frac{q_{i+1}}{q_{i-1}} < C$. This is possible for almost all α . Then:

$$\alpha = \frac{p_i}{q_i} + \frac{\delta_i}{q_i^2}, \quad 1 > \delta_i > c > 0 \text{ (or } < -c).$$

It follows that if $\frac{1}{q_i} < |\omega| < \frac{2}{q_i}$, then $\bigcup_{v=1}^{eq_i} f^v(h(\omega)) \supset (0, 1)$ and every point is covered a bounded number of times. Since both $\nu_q(I)$ and $|I|$ are transformed by the rules in lemma 1 it follows that:

$$\frac{\nu_q(h(\omega))}{|h(\omega)|} \frac{1}{C} \leq \frac{\nu_q(f^i(h(\omega)))}{|f^i(h(\omega))|} \leq C \frac{\nu_q(h(\omega))}{|h(\omega)|}$$

and since both measures are additive, (5.1) follows.

We now wish to prove (5.1) with a constant C very close to 1. Let us define M_k by

$$\sup_{|\omega| \geq q_k^{-1}} \frac{\nu_q(h(\omega))}{|h(\omega)|} = M_k.$$

Suppose that $q = q_s$ and choose n so that

$$2^{n-1} < s \leq 2^n.$$

The number of blocks $B_{\ell,n}$ so that M_k increases in $B_{\ell,n}$ by more than a factor $(1 + 2^{-n/2})$ is less than $C \cdot 2^{n/2}$. Hence there exists ℓ so that (with $k = \delta \ell n + 2$)

$$(i) \quad b_{\ell,n}(\alpha) \leq C,$$

$$(ii) \quad M_{k+\delta n} \leq (1 + 2^{-n/2}) M_k.$$

Now pick an interval ω of length between q_k^{-1} and $2q_k^{-1}$, for which

$$(5.2) \quad \nu_q(h(\omega)) = M_k |h(\omega)|.$$

Divide ω into $e^{c\delta n}$ equal intervals ω' by successive bisections. We assert that for every ω' :

$$(5.3) \quad \nu_q(h(\omega')) \geq M_k |h(\omega')| (1 - e^{-c\delta n}).$$

To see this, recall that, by lemma 2,

$$|h(\omega')| \geq \exp(-c\delta n) |h(\omega)|.$$

Hence if (5.3) is false for one interval ω' , it follows by (ii) that

$$\nu_q(h(\omega)) \leq M_k ((1 + 2^{-n/2}) - e^{-c\delta n} \cdot e^{-c\delta n}) |h(\omega)| < M_k |h(\omega)|$$

if δ is small enough. This contradicts the choice (5.2).

Let ω^* be an arbitrary interval of length $|\omega^*|$ so that

$$\frac{1}{20} q_k^{-1} < |\omega^*| < \frac{1}{10} q_k^{-1}.$$

Then for some ω'' of the same length and $\omega'' \subset \omega$:

$$h(\omega^*) = f^m(h(\omega'')), \quad m < Cq_k.$$

Divide ω^* and ω'' into intervals of length $e^{-c\delta n} |\omega^*|$ and let ω_0^* and ω_0'' be two corresponding intervals. Then:

$$\nu_q(h(\omega_0^*)) = \prod_{v=1}^m f'(\xi_v) \nu_q(h(\omega_0'')) (1 + O(2^{-n}))$$

$$|h(\omega_0^*)| = \prod_{v=1}^m f'(\xi_v) |h(\omega_0'')|$$

so that:
$$\frac{\nu_q(h(\omega_0^*))}{|h(\omega_0^*)|} = \frac{\nu_q(h(\omega_0''))}{|h(\omega_0'')|} \cdot \exp\left(\sum_{v=0}^m |f^v(h(\omega_0''))|\right)$$

$$= M_k (1 + O(e^{-cn\delta})) (1 + O(e^{-cn\delta}))$$

because, by lemma 2, $|f^v(h(\omega_0^*))| \leq e^{-cn\delta} |f^v(h(\omega^*))|$, and $\sum_{v=0}^m |f^v(h(\omega^*))| \leq C$.

We cover $(0, 1)$ by disjoint intervals ω^* and obtain:

$$1 = \sum_{\omega^*} \nu_q(h(\omega^*)) = M_k \sum_{\omega^*} |\omega^*| (1 + O(e^{-cn\delta}))$$

so that: $M_k = 1 + O(e^{-cn\delta}).$

Hence, if $|\omega| > q_k^{-1}$, it follows that

$$v_q(h(\omega)) \leq |h(\omega)| (1 + O((\log q)^{-\beta}))$$

and the reverse inequality is proved similarly.

If we observe that $|h(\omega)| \leq (\log q)^{-K}$ for all K if $|\omega| < q^{-c}$, we can conclude that

$$(5.4) \quad \int_0^1 \varphi(x) dv_q(x) = \int_0^1 \varphi dx + O((\log q)^{-\beta}) \quad \text{if } \varphi \in C^1.$$

It remains to prove the same remainder estimate in Denjoy's inequality.

We denote by ω_j the interval $\left(\frac{r}{q}, \frac{r+1}{q}\right)$ containing $h^{-1}(x_0) + j\alpha$ and denote by ω_{j_0} the subinterval $\left(\frac{r+\eta}{q}, \frac{r+1-\eta}{q}\right)$ of ω_j where $\eta = q_k/q$ and q_k is the integer defined above. We first observe that

$$\left| \varphi(f^j(x_0)) - q \int_{h(\omega_j)} \varphi(x) d\mu(x) \right| < C |h(\omega_j)|.$$

Divide $(0, q-1)$ into blocks $C_1, \dots, C_m$ of length q_k . Since q_k does not divide q we have to skip a set Γ of less than q_k numbers. This set Γ is chosen so that

$$\sum_{\Gamma} |h(\omega_j)| < \frac{q_k^2}{q} < q^{-c}.$$

To estimate $\sum_{C_v} (\varphi(f^j(x_0)) - q \int_{h(\omega_j)} \varphi(x) d\mu(x))$ we write $h(\omega_j) = h(\omega_{j_0}) \cup h(\omega_j \setminus \omega_{j_0})$. Then:

$$(5.5) \quad \sum_v \left(\sum_{C_v} \left| \varphi(f^j(x_0)) - 2\eta - q \int_{h(\omega_j \setminus \omega_{j_0})} \varphi(x) d\mu(x) \right| \right) < C\eta.$$

If $C_v = (\lambda, \lambda + q_k)$ we set $y_0 = f^\lambda(x_0)$. For $y \in h(\omega_{\lambda_0})$ we have $j = \lambda + s$,

$$\varphi(f^s(y_0)) - \varphi(f^s(y)) = \varphi'(z_s) \int_y^{y_0} Df^s(\xi) d\xi$$

and $f^s(y) \in h(\omega_j)$ and z_s is some number in $h(\omega_j)$. Hence:

$$\begin{aligned} & \sum_{C_v} \left(\varphi(f^j(x_0)) (1 - 2\eta) - q \int_{h(\omega_{j_0})} \varphi(x) d\mu(x) \right) \\ &= (1 - 2\eta) \sum_{s=0}^{q_k-1} \int_{h(\omega_{\lambda_0})} \varphi'(z_s) d\mu(y) \int_y^{y_0} Df^s(\xi) d\xi + \text{error} \\ &= (1 - 2\eta) \sum_{s=0}^{q_k-1} \int_{h(\omega_{\lambda_0})} d\mu(y) \int_y^{y_0} Df^s(\xi) \varphi'(f^s(\xi)) d\xi \\ &+ O(\text{Max}_{\lambda} |h(\omega_{\lambda_0})|) + \text{error}. \end{aligned}$$

We have used $|\varphi''(x)| \leq 1$. The error occurs because the intervals $h(\omega_{j_0})$ are not exactly maps of $h(\omega_{\lambda_0})$. The error is estimated as in (5.5). For the final sum we use (5.4) for $q = q_k$ and find the bound:

$$\sum_{s=0}^{q_k-1} \int_{h(\omega_{\lambda_0})} d\mu(y) \int_y^{y_0} Df^s(\xi) d\xi. O((\log q)^{-\beta}) = O\left(\frac{q_k}{q} (\log q)^{-\beta}\right).$$

This proves the remainder estimate.

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Lennart Carleson
Institut Mittag-Leffler, Avravagen 17
18262-Djursholm (Sweden)

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