Chapter 5. — Dimension of the space of linear superpositions

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Chapter 5. — Dimension of the space of linear superpositions

In this chapter we present a calculation of the functional dimension of the space of functions representable by means of linear superpositions and prove that a representation of analytic functions by means superpositions of smooth functions can not be stable.

§ 1. (ε, δ)-*entropy and the "dimension" of function spaces*

Let G_n be a closed region of n-dimensional euclidean space, and $C(G_n)$ the space of all functions continuous in G_n. Two functions $f_1(x), f_2(x) \in C(G_n)$ are called (ε, δ)-distinguishable if there exists an n-dimensional closed sphere $S_\delta \subset G_n$ of radius δ such that

$$\min_{x \in S_\delta} |f_1(x) - f_2(x)| \geqslant \varepsilon .$$

Let $F \subset C(G_n)$ be a set of continuous functions. A subset $K \subset F$ is called (ε, δ)-distinguishable if any two of its elements are (ε, δ)-distinguishable. We denote by $N_{\varepsilon,\delta}(F)$ the maximum number of elements in an (ε, δ)-distinguishable subset of F.

Definition 5.1.1. The number $H_{\varepsilon,\delta}(F) = \log_2 N_{\varepsilon,\delta}(F)$, by analogy with the definition of ε-entropy, is called the (ε, δ)-entropy of F.

Let $f_0 \in F$. We denote by $F_{\lambda\varepsilon}(f_0)$ the set of functions $f \in F$ such that $|f(x) - f_0(x)| \leqslant \lambda\varepsilon$. It follows immediately from the definition that the expression $\overline{\lim_{\delta\to 0}}\ \overline{\lim_{\varepsilon\to 0}} - \dfrac{\log_2 H_{\varepsilon,\delta}(F_{\lambda\varepsilon}(f_0))}{\log_2 \delta}$ as a function of λ does not decrease as $\lambda \to \infty$.

Definition 5.1.2. The number

$$r(F, f_0) = \lim_{\lambda\to\infty} \overline{\lim_{\delta\to 0}}\ \overline{\lim_{\varepsilon\to 0}} - \frac{\log_2 H_{\varepsilon,\delta}(F_{\lambda\varepsilon}(f_0))}{\log_2 \delta}$$

is called the functional "dimension" of F at f_0. The number $r(F) = \sup\,(F, f_0)$ is called the functional "dimension" of F.

The functional "dimension" $r(F)$ of a set of functions $F \subset C(G_n)$ has the following properties.

5.1.1. Let $\Phi \subset F$ be a set of functions. Then $r(\Phi) \leqslant r(F)$. Moreover, if Φ is everywhere dense in F in the uniform metric, then $r(\Phi) = r(F)$.

Proof. The first part of the assertion follows immediately from the definition. For a proof of the second part it is sufficient to show that $r(\Phi, \varphi_0) \geqslant r(F, \varphi_0)$ for any element $\varphi_0 \in \Phi$. Suppose that the functions $f_1, \ldots, f_N$ from a $(2\varepsilon, \delta)$-distinguishable subset of $F_{\lambda\varepsilon}(\varphi_0)$. Since Φ is everywhere dense in F, there exist functions $\varphi_1, \ldots, \varphi_N \in \Phi$ such that $\max_{x \in G_n} |f_i(x) - \varphi_i(x)| \leqslant \min\left(\frac{\varepsilon}{2}, \lambda\varepsilon\right)$ $(i = 1, 2, \ldots, N)$. These functions form an (ε,δ)-distinguishable subset of $F_{2\lambda\varepsilon}(\varphi_0)$. Consequently $N_{\varepsilon,\delta}(\Phi_{2\lambda\varepsilon}(\varphi_0)) \geqslant N_{2\varepsilon,\delta}(F_{\lambda\varepsilon}(\varphi_0))$. Hence $r(\Phi, \varphi_0) \geqslant r(F, \varphi_0)$.

5.1.2. For any set $F \subset C(G_n)$ we have $r(F) \leqslant n$.

Proof. Suppose that $f_0 \in F$ and $f_1, f_2, \ldots, f_p$ is a maximal set (with respect to p) of pairwise (ε, δ)-distinguishable functions of $F_{\lambda\varepsilon}(f_0)$. Let $\sigma_1, \sigma_2, \ldots, \sigma_q$ be a maximal set (with respect to q) of spheres of radius $\delta/3$ in G_n, such that no two of them have common interior points. Then any pair of functions $f_i(x)$ and $f_j(x)$ of the given set satisfies on at least one of the spheres σ_l the inequality $\min_{x \in \sigma_l} |f_i(x) - f_j(x)| \geqslant \varepsilon$. For the functions $f_i(x)$ and $f_j(x)$ satisfy on some sphere $S_\delta \subset G_n$ the inequality $\min_{x \in S_\delta} |f_i(x) - f_j(x)| \geqslant \varepsilon$. Since q is maximal, it follows that one of the spheres $\sigma_l \subset S_\delta$. Consequently on this sphere the inequality we need is satisfied. We denote by a_l the centre of the sphere σ_l $(l = 1, 2, \ldots, q)$. Every set of functions $f_{i_1}, f_{i_2}, \ldots, f_{i_r}$ each pair of which has values differing by not less than ε at one and the same point consists of a number $r \leqslant 2\lambda + 1$ of functions. (All functions are taken from the set indicated above.) Since every pair of functions $f_i(x)$ and $f_j(x)$ has values differing by not less than ε at one of the points a_l at least, we have $p \leqslant 2\lambda + 1$. But since the spheres $\{\sigma_i\}$ do not intersect, $q \leqslant C/\delta^n$, where C is a constant depending only on n. Consequently,

$$r(F, f_0) \leqslant \lim_{\lambda \to \infty} \lim_{\delta \to 0} \lim_{\varepsilon \to 0} - \frac{\log_2 \log_2 (2\lambda + 1)^{\frac{C}{\delta^n}}}{\log_2 \delta} = n.$$

5.1.3. If F is everywhere dense (in the uniform metric) in the space $C(G_n)$, then $r(F) = n$. In particular $r(C(G_n)) = n$.

Proof. By 5.1.1 and 5.1.2 it is sufficient to show that $r\left(C\left(G_n\right)\right) \geqslant n$. We denote by $C_\varepsilon\left(G_n\right)$ the set of all $f(x) \in C\left(G_n\right)$ for which $\max_{x \in G_n} |f(x)| \leqslant \varepsilon$. Let $\theta > 0$ be a constant such that for any $\delta > 0$ we can find $H = [\theta/\delta^n]$ closed and pairwise non-intersecting spheres $\sigma_1, \sigma_2, \ldots, \sigma_H$ of radius δ in G_n. For any system of numbers $\{\alpha_i\}$ ($\alpha_i = \pm 1$, $i = 1, 2, \ldots, H$) we construct a function $f_{\{\alpha_i\}}(x) \in C_\varepsilon\left(G_n\right)$ such that $f_{\{\alpha_i\}}(x) = a_i \varepsilon$ for $x \in \sigma_i$ ($i = 1, 2, \ldots, H$). These functions are obviously pairwise (ε, δ)-distinguishable. The number of functions $f_{\{\alpha_i\}}(x)$ for all possible sets $\{\alpha_i\}$ is equal to 2^H. Consequently $H_{\varepsilon,\delta}\left(C_\varepsilon\left(G_n\right)\right) \geqslant H = [\theta/\delta^n]$. Hence $r\left(C(G)\right) \geqslant n$.

COROLLARY 5.1.1. *The space of all polynomials in* n *variables has functional "dimension"* n.

In the same way, the following properties are easily proved.

5.1.4. Let G_n^1 and G_n^2 be two non-intersecting closed regions in n- dimensional space, and $F\left(G_n^1 \cup G_n^2\right)$ a space of functions, defined and continuous on $G_n^1 \cup G_n^2$. Denote by $F\left(G_n^1\right)$ the space of all functions $\varphi(x)$, defined on the set G_n^1, for which there exists a function $\Phi(x) \in F\left(G_n^1 \cup G_n^2\right)$ such that $\varphi(x) \equiv \Phi(x)$ for $x \in G_n^1$. The space $F\left(G_n^2\right)$ is defined similarly. Then

$$r\left(F\left(G_n^1 \cup G_n^2\right)\right) = \max\left\{r\left(F\left(G_n^1\right)\right);\ r\left(F\left(G_n^2\right)\right)\right\}.$$

5.1.5. If F is a linear space, then $r(F) = r(F, f_0)$ for any function $f_0 \in F$. If F is a finite-dimensional linear space, then $r(F) = 0$.

5.1.6. Let F be a linear metric space with metric $\rho(\varphi, \psi)$ between a pair of functions $\varphi, \psi \in F$. We denote by $F(\rho_0)$ the set of all those functions $\varphi \in F$ for which $\rho(\varphi, 0) \leqslant \rho_0$. Then $r(F) = r\left(F(\rho_0)\right)$.

COROLLARY 5.1.2. *The set of all polynomials in* n *variables whose partial derivatives of order* p*, for any* $p = 1, 2, \ldots,$ *are bounded by a constant* $0 < K_p < \infty$ *has functional "dimension"* n.

5.1.7. Let F be a complete linear metric space and $F = \bigcup_{i=1}^{\infty} F_i$, where $\{F_i\}$ are sets of continuous functions. Then $r(F) = \max_i r(F_i)$.

We now write down the main result on the functional "dimension" of a set of linear superpositions.

5.1.8. Let $q_i = q_i(x_1, x_2, \ldots, x_n)$ be continuously differentiable functions of n variables, and $p_i = p_i(x_1, x_2, \ldots, x_n)$ continuous functions of n variables ($i = 1, 2, \ldots, N$). We denote by $F\left(G_n, \{p_i\}, \{q_i\}\right)$ the set of superpositions of the form $\sum_{i=1}^{N} p_i(x_1, x_2, \ldots, x_n) f_i(q_i(x_1, x_2, \ldots, x_n))$, where $(x_1, x_2, \ldots, x_n) \in G_n$, and $\{f_i(t)\}$ are arbitrary continuous functions of one variable. Then in any region D_n there exists a closed subregion $G_n \subset D_n$ such that

$$r(F(G_n, \{p_i\}, \{q_i\})) \leqslant 1.$$

For ease of presentation we limit the proof to the case $n = 2$ (§ 3). It is interesting to compare the result 5.1.8 with the following proposition.

5.1.9. Let $\alpha_i(x_1, x_2, \ldots, x_n) = \sum_{j=1}^{n} \alpha_{ij}(x_j) \quad (i = 1, 2, \ldots, 2n+1)$

be the continuous functions involved in Kolmogorov's formula (I). We denote by $\psi(G_n, \alpha_i)$ the space of all functions of the form $\psi(\alpha_i(x_1, x_2, \ldots, x_n))$, where $\psi(t)$ is an arbitrary continuous function of one variable and $(x_1, x_2, \ldots, x_n) \in G_n$. Then for any i and every region G_n, $r(\psi(G_n, \alpha_i)) = n$ (see 5.1.7).

Let $p_i(x_1, x_2, \ldots, x_n)$ be fixed continuous functions of n variables, $q_{1,i}(x_1, x_2, \ldots, x_n)$, $q_{2,i}(x_1, x_2, \ldots, x_n)$, ..., $q_{k,i}(x_1, x_2, \ldots, x_n)$ fixed continuously differentiable functions of n variables, and $f_i(t_1, t_2, \ldots, t_k)$ arbitrary continuous functions of k variables, $k < n$ $(i = 1, 2, \ldots, N)$. One would expect that the set of superpositions of the form (V) (see Chapter I) has functional "dimension" not greater than k. However, in this direction, only the following partial result has so far been proved.

5.1.10. Denote by $F(\lambda, G_n, \{p_i\}, \{q_{1,i}\}, \ldots, \{q_{k,i}\})$ the set of all those continuous functions $\varphi(x_1, x_2, \ldots, x_n)$ for which there exist continuous functions $\{f_i(t_1, t_2, \ldots, t_k)\}$ such that in G_n.

$$\varphi(x_1, x_2, \ldots, x_n)$$
$$= \sum_{i=1}^{N} p_i(x_1, x_2, \ldots, x_n) f_i(q_{1,i}(x_1, x_2, \ldots, x_n), \ldots, q_{k,i}(x_1, x_2, \ldots, x_n))$$

and

$$\max_i \sup_{(t_1, t_2, \ldots, t_k)} |f_i(t_1, t_2, \ldots, t_k)| \leqslant \lambda \sup_{(x_1, x_2, \ldots, x_n) \in G_n} |\varphi(x_1, x_2, \ldots, x_n)|$$

Then, for any $\lambda < \infty$, in any region D_n there exists a closed subregion $G_n \subset D_n$ such that

$$r(F(\lambda, G_n, \{p_i\}, \{q_{1,i}\}, \ldots, \{q_{k,i}\}), 0) \leqslant k.$$

From the last result and Banach's open mapping theorem there follows

COROLLARY 5.1.3. *For any continuous functions* p_i *and continuously differentiable functions* $q_{1,i}, q_{2,i}, \ldots, q_{k,i}$, $k < n$ $(i = 1, 2, \ldots, N)$ *and every region* G_n *there exists a continuous function that is not equal in* G_n *to any superposition of the form* (V).

§ 2. (ε, δ)-*entropy of the set of linear superpositions*

We denote by $S(\delta, z)$ the disc of radius δ with centre at z. Let $p(z) = p(x, y)$ and $q(z) = q(x, y)$ be functions defined in a closed region G of the x, y-plane and having the properties:

a) $p(x, y), \dfrac{\partial q(x, y)}{\partial x}, \dfrac{\partial q(x, y)}{\partial y}$ are continuous in G and have modulus of continuity $\omega(\delta)$,

b) the inequalities $0 < \gamma \leqslant |\operatorname{grad}[q(r)]| \leqslant \dfrac{1}{\gamma}$ and $|p(z)| \leqslant \dfrac{1}{\gamma}$, where γ is some constant, are satisfied everywhere in G.

LEMMA 5.2.1. *Let* $S(\delta, z) \subset G$ *and let* $\mu_q(t)$ *be the function equal to* $2\sqrt{\delta^2 - (t - q(z))^2 |\operatorname{grad}[q(z)]|^{-2}}$ *on*

$$q(z) - \delta|\operatorname{grad}[q(z)]| \leqslant t \leqslant q(z) + \delta|\operatorname{grad}[q(z)]|$$

and equal to zero elsewhere. Then

$$\int_{-\infty}^{\infty} |\mu_q(t) - h_1(e(q, t) \cap S(\delta, z))|\, dt \leqslant c_1(\gamma)\, \omega(\delta)\, \delta^2,$$

where $c_1(\gamma)$ *is a constant depending only on* γ.

Proof. Let $[a, b] \subset e(q, t) \cap S(\delta, z)$ be the segment of the level curve $e(q, t)$, endpoints a and b, lying on the boundary of $S(\delta, z)$; $[z, a]$ and $[z, b]$ the vectors with origin at z and endpoints at a and b, respectively;

$$\alpha_1 = \gamma(\overrightarrow{[z, a]}, \operatorname{grad}[q(z)]), \quad \alpha_2 = \gamma(\overrightarrow{[z, b]}, \operatorname{grad}[q(z)]).$$

We have

$$|t - q(z)| = |q(a) - q(z)| = \left| \int_{s \in [z, a]} \frac{\partial q}{\partial s}\, ds \right|$$

$$= \delta \cos \alpha_1 |\operatorname{grad}[q(z)]| (1 + 0(1)\, \omega(\delta))$$

Hence

$$\delta \sin \alpha_1 = \sqrt{\delta^2 - (t - q(z) + 0(\gamma)\,\delta\omega(\delta))^2 \,|\, \text{grad}\ [q(z)]\,|^{-2}}$$

and similarly

$$\delta \sin \alpha_2 = \sqrt{\delta^2 - (t - q(z) + 0(\gamma)\,\delta\omega(\delta))^2 \,|\, \text{grad}\ [q(z)]\,|^{-2}}$$

By b) the size of the angle swept out by the tangent vector to the level curve $e(q, t)$ on moving along $[a, b]$ does not exceed $C_2(\gamma)\,\omega(\delta)$. Therefore

$$h_1([a, b]) = \delta(\sin \alpha_1 + \sin \alpha_2)(1 + 0(\gamma)\,\omega(\delta))$$
$$= 2\sqrt{\delta^2 - (t - q(z) + 0(\gamma)\,\delta\omega(\delta))^2 \,|\, \text{grad}\ [q(z)]\,|^{-2}} + 0(\gamma)\,\delta\omega(\delta).$$

If $\alpha_1 \geqslant C_3(\gamma)\,\omega(\delta)$ (C_3 is a sufficiently large constant), then $[a, b] = e(q, t) \cap S(\delta, z)$. Consequently, for

$$|\,t - q(z)\,| \leqslant \theta = \delta \cos [C_3\,\omega(\delta)]\,|\,\text{grad}\,[q(z)]\,| \times (1 + 0(1)\,\omega(\delta))$$

we have $h_1(e(q, t) \cap S(\delta, z)) = h_1([a, b])$. Since for every t (by b))

$$h_1(e(q, t) \cap S(\delta, z)) \leqslant C_4(\gamma)\,\delta\,(1 + \omega(\delta)),$$

we have

$$\int_{-\infty}^{\infty} |\,h_1(e(q, t) \cap S(\delta, z)) - \mu_q(t)\,|\,dt =$$
$$= \int_{q(z)-\Theta}^{q(z)+\Theta} |\,h_1(e(q, t) \cap S(\delta, z)) - \mu_q(t)\,|\,dt + 0(\gamma)\,\delta^2\omega(\delta).$$

We now estimate

$$\int_{q(z)-\Theta}^{q(z)+\Theta} |\,h_1(e(q, t) \cap S(\delta, z)) - \mu_q(t)\,|\,dt =$$
$$= \int_{q(z)-\Theta}^{q(z)+\Theta} |\,h_1([a, b]) - \mu_q(t)\,|\,dt \leqslant$$
$$\leqslant 2 \int_{q(z)-\Theta}^{q(z)+\Theta} \Big(\sqrt{\delta^2 - (t - q(z) + 0(\gamma)\,\delta\omega(\delta))^2 \,|\, \text{grad}\ [q(z)]\,|^{-2}}$$
$$- \sqrt{\delta^2 - (t - q(z))^2 \,|\, \text{grad}\ [q(z)]\,|^{-2}}\Big)\,dt + 0(\gamma)\,\delta^2\omega(\delta)$$
$$= 0(\gamma)\,\delta^2\omega(\delta) \int_{-1}^{1} \frac{d\tau}{\sqrt{1 - \tau^2}} + 0(\gamma)\,\delta^2\omega(\delta) = 0(\gamma)\,\delta^2\omega(\delta).$$

Here we have the mean value theorem. This proves the lemma.

LEMMA 5.2.2. *Let* $p(z), q(z)$ *satisfy conditions a) and b);* $S(\delta, z) \subset G$; *let* $f(t)$ *be an arbitrary continuous function, uniformly bounded in modulus by the constant* m. *Then*

$$\iint\limits_{(u,v)\in S(\delta,z)} p(u,v) f\big(q(u,v)\big)\,du\,dv$$

$$= p(z)\,\big|\operatorname{grad}[q(z)]\big|^{-1}\int_{-\infty}^{\infty} f(t)\,\mu_q(t)\,dt + \lambda(z)\,m\delta^2\omega(\delta),$$

where $|\lambda(z)| \leqslant C_5(\gamma)$.

Proof. Using a) and b) and Lemma 5.2.1 we have

$$\int\limits_{S(\delta,z)} p(u,v) f\big(q(u,v)\big)\,du\,dv$$

$$= p(z) \iint\limits_{(u,v)\in S(\delta,z)} f\big(q(u,v)\big)\,du\,dv + 0(1)\,m\delta^2\omega(\delta)$$

$$= p(z)\int_{-\infty}^{\infty}\Big\{f(t)\int\limits_{s\in e(q,t)\cap S(\delta,z)} \big|\operatorname{grad}[q(s)]\big|^{-2} ds\Big\}\,dt + 0(1)\,m\delta^2\omega(\delta)$$

$$= p(z)\,\big|\operatorname{grad}[q(z)]\big|^{-1}\int_{-\infty}^{\infty}\Big\{f(t)\int\limits_{s\in e(q,t)\cap S(\delta,z)} ds\Big\}\,dt + 0(\gamma)\,m\delta^2\omega(\delta)$$

$$= p(z)\,\big|\operatorname{grad}[q(z)]\big|^{-2}\int_{-\infty}^{\infty} f(t)\,h_1\big(e(q,t)\cap S(\delta,z)\big)\,dt + 0(\gamma)\,m\delta^2\omega(\delta)$$

$$= p(z)\,\big|\operatorname{grad}[q(z)]\big|^{-1}\int_{-\infty}^{\infty} f(t)\,\mu_q(t)\,dt + 0(\gamma)\,m\delta^2\omega(\delta).$$

This proves the lemma.

LEMMA 5.2.3. *Suppose that a number* $\alpha > 0$ *and functions* $p(z)$, $q(z), f(t)$ *satisfying the conditions of Lemma 5.2.2. are given. If for every integer* k *such that*

$$\min_{z\in G} q(z) \leqslant t_k = k\delta\frac{\alpha}{m} \leqslant \max_{z\in G} q(z)$$

and any integer l *such that*

$$\min_{z\in G}\big|\operatorname{grad}[q(z)]\big| \leqslant t_l' = l\frac{\alpha}{m} \leqslant \max_{z\in G}\big|\operatorname{grad}[q(z)]\big|,$$

the inequality

$$\left|\int_{t_k - t_l'\delta}^{t_k + t_l'\delta} f(t)\sqrt{\delta^2 - \left(\frac{t - t_k}{t_l'}\right)^2}\,dt\right| \leqslant \alpha\delta^2$$

is satisfied, then for every disc $S(\delta, z) \subset G$

$$\left| \iint_{(u,v) \in S(\delta, z)} p(u,v) f(q(u,v))\, du dv \right| \leqslant c_6(\gamma)(\alpha\delta^2 + m\delta^2\omega(\delta)).$$

Proof. Suppose that a disc $S(\delta, z) \subset G$ is given. By the condition of the lemma there are integers k and l such that $|q(z) - t_k| \leqslant \delta\alpha/m$ and $\big| |\operatorname{grad}[q(z)]| - t_l' \big| \leqslant \alpha/m$. From Lemma 5.2.2 we obtain

$$\left| \int_{(u,v) \in S(\delta, z)} p(u,v) f(q(u,v))\, du dv \right| \leqslant \frac{|p(z)|}{|\operatorname{grad}[q(z)]|} \left| \int_{-\infty}^{\infty} f(t)\mu_q(t)\, dt \right|$$

$$+ c_5(\gamma) m\delta^2\omega(\delta) \leqslant \frac{2}{\gamma^2} \left| \int_{q(z) - \delta|\operatorname{grad}[q(z)]|}^{q(z) + \delta|\operatorname{grad}[q(z)]|} f(t) \sqrt{\delta^2 - \frac{(t - q(z))^2}{|\operatorname{grad}[q(z)]|^2}}\, dt \right.$$

$$\left. - \int_{t_k - t_l'\delta}^{t_k + t_l'\delta} f(t) \sqrt{\delta^2 - \left(\frac{t - t_k}{t_l'}\right)^2}\, dt \right| + \frac{2}{\gamma^2}\alpha\delta^2 + c_5(\gamma) m\delta^2\omega(\delta) \leqslant$$

(by the mean value theorem)

$$\leqslant \frac{2}{\gamma^2}\alpha\delta^2 + c_5(\gamma) m\delta^2\omega(\delta) + \frac{2}{\gamma^2}\left(\int_{-1}^{1} \frac{\delta m d\tau}{\sqrt{1 - \tau^2}} \right) \delta \frac{\alpha}{m}$$

$$+ \frac{2}{\gamma^2}\left(\int_{-1}^{1} \frac{\delta^2 m d\tau}{\sqrt{1 - \tau^2}} \right) \frac{\alpha}{m} \leqslant c_6(\gamma)(\alpha\delta^2 + m\delta^2\omega(\delta)).$$

This proves the lemma.

We denote by $F_m = F_m(D; p_1, p_2, \dots, p_N; q_1, q_2, \dots, q_N)$ the set of superpositions of the form

$$f(x,y) = \sum_{i=1}^{N} p_i(x,y) f_i(q_i(x,y)), \text{ where } \{p_i(x,y)\}$$

and $\{q_i(x,y)\}$ are fixed functions, defined in the closed region D of the x, y plane and satisfying conditions a) and b) with a constant γ not depending on i and $\{f_i(t)\}$ are arbitrary continuous functions, defined on $\{[a_i, b_i]\} = \{[\min_{z \in D} q_i(z); \max_{z \in D} q_i(z)]\}$ and uniformly bounded in modulus by the constant m.

THEOREM 5.2.1. *There exist constants A and B such that if $\varepsilon > Am\omega(\delta)$ then for the (ε, δ)-entropy of the set of functions F_m, $H_{\varepsilon,\delta}(F_m) \leqslant \frac{B}{\delta}\left(\frac{m}{\varepsilon}\right)^2$, where A and B depend only on γ, N and D.*

Proof. We put

$$R(f(z), \delta) = \max_{S(\delta,z)\subset D} \left| \frac{1}{\pi\delta^2} \iint_{(u,v)\in S(\delta,z)} f(u,v)\, du dv \right| .$$

We denote by $\mathscr{H}_{\varepsilon,\delta}(F_m)$ the ε-entropy of the space F_m, taking as the distance between the functions $f_1(z), f_2(z) \in F_m$ the number $R(f_1(z) - f_2(z), \delta)$. The inequality $H_{2\varepsilon,\delta}(F_m) \leqslant \mathscr{H}_{\varepsilon,\delta}(F_m)$ holds owing to the fact that if two functions $f_1(z)$ and $f_2(z)$ are (ε, δ)-distinguishable, then they are ε-distinguishable also in the sense of the metric $R(f_1(z) - f_2(z), \delta)$. We now estimate the value of $\mathscr{H}_{\varepsilon,\delta}(F_m)$. Let k and l be integers such that

$$\min_{z\in D} q_i(z) \leqslant t_k = k\delta\frac{\alpha}{m} \leqslant \max_{z\in D} q_i(z)$$

and

$$\min_{z\in D} |\operatorname{grad}[q_i(z)]| \leqslant t_l' = l\frac{\alpha}{m} \leqslant \max_{z\in D} |\operatorname{grad}[q_i(z)]| .$$

To compute the function

$$f_\delta(z) = \frac{1}{\pi\delta^2} \iint_{(u,v)\in S(\delta,z)} f(u,v)\, du dv ,$$

where $f(x, y) \in F_m$, $S(\delta, z) \subset D$ to within ε, it is sufficient by Lemma 5.2.3 to give the values of

$$v_i(t_k, t_l') = \frac{1}{\pi\delta^2} \int_{t_k - t_l'\delta}^{t_k + t_l'\delta} f_i(t) \sqrt{\delta^2 - \left(\frac{t - t_k}{t_l'}\right)^2}\, dt$$

to within $\alpha = \pi\varepsilon / (2NC_B(\gamma))$ and to assume that δ is small enough so that

$$\varepsilon > \frac{2NC_B(\gamma)\, m\omega(\delta)}{\pi} = A(\gamma, N)\, m\omega(\delta) .$$

Since $|v_i(t_k, t_l')| \leqslant C_1 m$, to write the numbers $v_i(t_k, t_l')$ $(i, k, l$ fixed) $\log_2(C_1 m/\alpha)$ binary digits are sufficient. Since

$$| v_i(t_{k+1}, t_l') - v_i(t_k, t_l') | \leqslant c_8 \frac{1}{\delta^2} \left(\int_{-1}^{1} \frac{\delta m d\tau}{\sqrt{1-\tau^2}} \right) \delta \frac{\alpha}{m} = c_9(\gamma)\alpha$$

(here we again use the mean value theorem), to store the numbers $v_i(t_{k+1}, t_l') - v_i(t_k, t_l')$ to within α, $\log_2 C_9$ binary digits are sufficient. Therefore to write the numbers $v_i(t_k, t_l')$ (i, l fixed; k any admissible number) $C_{10}(\gamma)\left[\log_2 \frac{m}{\alpha} + (b_i - a_i)\frac{m}{\delta\alpha}\right] = \mathscr{H}_{i,l}$ binary digits are sufficient. Consequently the total number of digits sufficient to store all the numbers $v_i(t_k, t_l')$ to within α, that is, to store the functions $f_\delta(z)$ to within ε, is

$$\mathscr{H} = \sum_{i,l} \mathscr{H}_{i,l} \leqslant N c_{10}(\gamma)\left[\log_2 \frac{m}{\alpha} + (b_i - a_i)\frac{m}{\delta\alpha}\right]\frac{1}{\gamma}\frac{m}{\alpha} \leqslant \frac{B(\gamma, N, D)}{\delta}\left(\frac{m}{\varepsilon}\right)^2.$$

This proves the theorem.

§ 3. *Functional "dimension" of the space of linear superpositions*

Suppose that continuous functions $p_i(x, y)$ and continuously differentiable functions $q_i(x, y)$ ($i = 1, 2, \ldots, N$) are fixed. Let G be a closed region of the x, y plane. We denote by $F = F(G, \{p_i\}, \{q_i\})$ the set of superpositions of the form $f(x, y) = \sum_{i=1}^{N} p_i(x, y) f_i(q_i(x, y))$, where $(x, y) \in G$ and $\{f_i(t)\}$ are arbitrary continuous functions of one variable. We are interested in the functional dimension of the set F.

THEOREM 5.3.1. *In every region D of the x, y plane there exists a closed subregion $G \subset D$ such that*

$$r(F(G, \{p_i\}, \{q_i\})) \leqslant 1 .$$

Proof. By Theorem 4.5.1, in D there exists a closed subregion $G^* \subset D$ such that the set of superpositions $F(G^*, \{p_i\}, \{q_i\})$ is closed (in the uniform metric) in $C(G^*)$, and the functions $\{q_i(x, y)\}$ satisfy the condition: for any i, either grad $[q_i(x, y)] \neq 0$ on G^* or $q_i(x, y) \equiv$ const on G^*. We show that $r(F(G^*, \{p_i\}, \{q_i\})) \leqslant 1$. By Banach's open mapping theorem, there exists a constant K such that for any superposition $\sum_{i=1}^{N} p_i(x, y) f_i(q_i(x, y)) = f(x, y) \in F(G^*, \{p_i\}, \{q_i\})$ there are continuous functions $\{f_i^*(t)\}$, defined on the sets $\{q_i(G^*)\}$ and satisfying the conditions

8) $$f(x, y) = \sum_{i=1}^{N} p_i(x, y) f_i^*(q_i(x, y)) \text{ for all } (x, y) \in G^*;$$

9) $$\max_i \max_{t \in q_i(G^*)} |f_i^*(t)| \geqslant K \max_{(x,y) \in G^*} |f(x, y)|.$$

Denote by $F_{\lambda\varepsilon} = F_{\lambda\varepsilon}(G^*, \{p_i\}, \{q_i\})$ the set of superpositions $f(x,y) \in F(G^*, \{p_i\}, \{q_i\})$ such that $\max_{(x,y) \in G^*} |f(x, y)| \leqslant \lambda\varepsilon$. By Theorem 5.2.1 and (8), (9), there exist constants A and B such that if $\omega(\delta) \leqslant (\lambda AK)^{-1}$ then $H_{\varepsilon,\delta}(F_{\lambda\varepsilon}) \leqslant B(\lambda K)^2/\delta$. Hence the functional dimension

$$r(F_i(G^*, \{p_i\}, \{q_i\})) \leqslant \lim_{\lambda \to \infty} \lim_{\delta \to 0} \lim_{\varepsilon \to 0} \frac{\log_2 \log_2 \frac{B(\lambda K)^2}{\delta}}{\log_2 \delta} = 1$$

This proves the theorem.

From Theorem 5.3.1 and the properties of functional dimension (§ 1) we have the following result, which is a stronger form of Theorem 4.6.1.

COROLLARY 5.3.1. *For any continuous functions* $\{p_i(x, y)\}$ *and continuously differentiable functions* $\{q_i(x, y)\}$ *and every region* D *the set of linear superpositions* $F(D, \{p_i\}, \{q_i\})$ *is nowhere dense in any space of functions that has in every region* $G \subset D$ *functional "dimension" greater than* 1.

Remark 5.3.1. All the results about linear superpositions of the form $\sum_{i=1}^{N} p_i(x, y) f_i(q_i(x, y))$ remain valid if we assume that $\{f_i(t)\}$ are arbitrary bounded measurable functions.

§ 4. *Variation of superpositions of smooth functions*

Let G_n be a closed region of the space of the variables $x_1, x_2, ..., x_n$ $(n \geqslant 2)$. A function $F(x) = F(x_1, x_2, ..., x_n)$ is called a superposition of order s generated by the functions of k $(k > 1)$ variables

$$f_{\beta_1, \beta_2 \ldots, \beta_\alpha}(t_1, t_2, ..., t_k) \ (\alpha = 0, 1, 2, ..., s; \ \beta_i = 1, 2, ..., k)$$

if it is defined in G by relations

$$\left\{\begin{array}{l} F = f(q_1, q_2, \ldots, q_k), \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ q_{\beta_1,\beta_2,\ldots,\beta_\alpha} = f_{\beta_1,\ldots,\beta_\alpha}(q_{\beta_1,\ldots,\beta_\alpha,1} q_{\beta_1,\ldots,\beta_\alpha,2}, \ldots, q_{\beta_1,\ldots,\beta_\alpha,k}), \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ q_{\beta_1,\beta_2,\ldots,\beta_{s+1}} = x_{\gamma(\beta_1,\beta_2,\ldots,\beta_{s+1})}, \end{array}\right. \quad \text{(VI)}$$

where $\gamma(\beta_1, \beta_2, \ldots, \beta_{s+1})$ is a function of the indices $\beta_1, \beta_2, \ldots, \beta_{s+1}$ and takes one of the values $1, 2, \ldots, n$. As before, we assume that the functions $\{\varphi_{\beta_1,\beta_2,\ldots,\beta_\alpha}(t_1, t_2, \ldots, t_k)\}$ are defined for all values of the arguments.

A superposition of any order, generated by functions of one variable, is again a function of one variable. Therefore in this case ($k = 1$) we consider superpositions of functions of one variable and the operation of addition, that is, superpositions definable in the following way.

A function $F(x) = F(x_1, x_2, \ldots, x_n)$ ($n > 1$) is called a superposition of order s of the functions $f_{\beta_1,\ldots,\beta_\alpha}(t)$ ($\alpha = 0, 1, 2, \ldots, s$; $\beta_i = 1, 2$) if the following relations are satisfied:

$$\left.\begin{array}{l} F = f(q_1 + q_2), \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ q_{\beta_1,\beta_2,\ldots,\beta_\alpha} = f_{\beta_1,\beta_2,\ldots,\beta_\alpha}(q_{\beta_1,\beta_2,\ldots,\beta_\alpha,1} + q_{\beta_1,\beta_2,\ldots,\beta_\alpha,2}) \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ q_{\beta_1,\beta_2,\ldots,\beta_{s+1}} = x_{\gamma(\beta_1,\beta_2,\ldots,\beta_{s+1})}, \end{array}\right\} \quad \text{(VII)}$$

where $\gamma(\beta_1, \beta_2, \ldots, \beta_{s+1})$ takes one of the values $1, 2, \ldots, n$.

Note that we can represent as superpositions of the form (VII), for example, all rational functions of $x_1, x_2, \ldots, x_n$ since we can write any arithmetic operation by such superpositions, for example, $u \cdot v = e^{\ln u + \ln v} = f(f_1(u) + f_2(v))$.

Let $F(x_1, x_2, \ldots, x_n)$ be a superposition of order s of the continuously differentiable functions $\{f_{\beta_1,\beta_2,\ldots,\beta_\alpha}(t_1, t_2, \ldots, t_k)\}$ and $\tilde{F}(x_1, x_2, \ldots, x_n)$ the superposition of the same form of the continuously differentiable functions $\{\tilde{f}_{\beta_1,\beta_2,\ldots,\beta_\alpha}(t_1, t_2, \ldots, t_k)\}$. We put

$$\varphi_{\beta_1,\beta_2,\ldots,\beta_\alpha} = \tilde{f}_{\beta_1,\ldots,\beta_\alpha} - f_{\beta_1,\ldots,\beta_\alpha} \quad (\alpha = 0, 1, 2, \ldots, s;\ \beta_i = 1, 2, \ldots, k)$$

$$\mu = \max_{\alpha, \beta_1, \ldots, \beta_\alpha} \sum_{i=1}^{k} \sup_t \left| \frac{\partial f_{\beta_1,\ldots,\beta_\alpha}(t_1, \ldots, t_k)}{\partial t_i} \right|,$$

$$\varepsilon = \max_{\alpha, \beta_1, \ldots, \beta_\alpha} \sup_t \left| \varphi_{\beta_1,\ldots,\beta_\alpha}(t_1, t_2, \ldots, t_k) \right|$$

LEMMA 5.4.1. *The inequality*

$$\sup_{x \in G} \left| \tilde{F}(x_1, x_2, \ldots, x_n) - F(x_1, x_2, \ldots, x_n) \right| \leqslant A(\mu, s)\, \varepsilon .$$

holds, where the constant $A(\mu, s)$ *depends only on* μ *and* s.

Proof. We proceed by induction on s. For definiteness suppose that $k < 1$. Having verified the statement of the lemma for $s = 1$ and having made an appropriate inductive assumption for superpositions of order $s - 1$, we have

$$\sup_{x \in G} \left| \tilde{F}(x_1, x_2, \ldots, x_n) - F(x_1, x_2, \ldots, x_n) \right|$$

$$\leqslant \left| f(\tilde{q}_1, \ldots, \tilde{q}_k) - f(q_1, \ldots, q_k) \right| + \left| \varphi(\tilde{q}_1, \tilde{q}_2, \ldots, \tilde{q}_k) \right|$$

$$\leqslant \mu \max_{\beta_1} \sup_{x \in G} \left| \tilde{q}_{\beta_1} - q_{\beta_1} \right| + \varepsilon \leqslant \mu \cdot A(\mu, s-1)\, \varepsilon + \varepsilon = A(\mu, s)\, \varepsilon .$$

(the last by the indictive assumption). This proves the lemma.

Further, let $\omega(\delta)$ be the common modulus of continuity of all the functions $\left\{ \frac{\partial f_{\beta_1, \ldots, \beta_\alpha}(t_1, \ldots, t_k)}{\partial t_i} \right\}$ and, in addition, put

$$\varepsilon' = \max_{\alpha, \beta_1, \ldots, \beta_\alpha} \sum_{i=1}^{k} \sup_{t} \left| \frac{\partial \varphi_{\beta_1, \ldots, \beta_\alpha}(t_1, \ldots, t_k)}{\partial t_i} \right|$$

LEMMA 5.4.2. *We have (for case* $k > 1$*)*

$$\tilde{F}(x_1, \ldots, x_n) - F(x_1, \ldots, x_n) = \sum_{\alpha, \beta_1, \ldots, \beta_\alpha} p_{\beta_1, \ldots, \beta_\alpha}(x_1, x_2, \ldots, x_n)$$

$$\times \varphi_{\beta_1, \ldots \beta_\alpha,}\left(q_{\beta_1, \ldots, \beta_\alpha, 1}(x_1, \ldots, x_n), \ldots, q_{\beta_1, \ldots, \beta_\alpha, k}(x_1, \ldots, x_n)\right)$$

$$+ R(x_1, x_2, \ldots, x_n) ,$$

where

$$\left| R(x_1, x_2, \ldots, x_n) \right| \leqslant B(\mu, s, k)\left[\varepsilon' + \omega\left(A(\mu, s)\, \varepsilon\right)\right] \varepsilon ,$$

$$p_{\beta_1, \ldots, \beta_\alpha}(x_1, x_2, \ldots, x_n) = \prod_{i=0}^{\alpha - 1} \frac{\partial f_{\beta_1, \ldots, \beta_i}}{\partial q_{\beta_1, \ldots, \beta_{i+1}}}$$

(for $\alpha = 0$ $p(x_1, x_2, \ldots, x_n) \equiv 1$),

$B(\mu, s, k)$ *is a constant depending only on* μ, s, k. *For* $k = 1$ *the corresponding equation is slightly different (see Chapter I, (III)) :*

$$\tilde{F}(x_1, \ldots, x_n) - F(x_1, \ldots, x_n)$$
$$= \sum_{\alpha, \beta_1, \ldots, \beta_\alpha} p_{\beta_1, \ldots, \beta_\alpha}(x_1, x_2, \ldots, x_n)\, \varphi_{\beta_1, \ldots, \beta_\alpha}(q_{\beta_1, \ldots, \beta_\alpha, 1}(x_1, \ldots, x_n)$$
$$+ q_{\beta_1, \ldots, \beta_\alpha, 2}(x_1, \ldots, x_n)) + R(x_1, \ldots, x_n)\,.$$

Proof. As in the preceding lemma we proceed by induction on s. Again for definiteness we limit ourselves to the case $k > 1$. For $s = 1$ the assertion of the lemma is easily verified. We assume that it is true for superpositions of order $s - 1$. By Lemma 5.4.1, for superpositions of order s we have

$$\tilde{F}(x_1, \ldots, x_n) - F(x_1, \ldots, x_n) = f(\tilde{q}_1, \tilde{q}_2, \ldots, \tilde{q}_k) - f(q_1, q_2, \ldots, q_k)$$
$$+ \varphi(\tilde{q}_1, \tilde{q}_2, \ldots, \tilde{q}_k) = \varphi(q_1, q_2, \ldots, q_k) + \sum_{\beta_1 = 1}^{k} \frac{\partial f}{\partial q_{\beta_1}} (\tilde{q}_{\beta_1} - q_{\beta_1})$$
$$+ A(\mu, s)\, \varepsilon' \cdot \varepsilon + k \cdot A(\mu, s)\, \omega\big(A(\mu, s)\, \varepsilon\big)\, \varepsilon\,.$$

Since $\tilde{q}_{\beta_1}$ and q_{β_1} $(\beta_1 = 1, 2, \ldots, k)$ are superpositions of order $s - 1$, by the inductive hypothesis we have

$$\tilde{q}_{\beta_1} - q_{\beta_1} = \sum_{\substack{\alpha > 0 \\ \beta_2, \beta_3, \ldots, \beta_\alpha}} \hat{p}_{\beta_1, \ldots, \beta_\alpha}(x_1, x_2, \ldots, x_n)$$
$$\times \varphi_{\beta_1, \ldots \beta_\alpha,}(q_{\beta_1, \ldots, \beta_\alpha, 1}(x_1, x_2, \ldots, x_n), \ldots, q_{\beta_1, \ldots, \beta_\alpha, k}(x_1, x_2, \ldots, x_n))$$
$$+ \acute{R}(x_1, x_2, \ldots, x_n)\,,$$

where

$$\big|\hat{R}(x_1, x_2, \ldots, x_n)\big| \leqslant B(\mu, s-1, k)\big[\varepsilon' + \omega\big(A(\mu, s-1)\, \varepsilon\big)\big]\, \varepsilon\,,$$
$$\hat{p}_{\beta_1, \ldots, \beta_\alpha}(x_1, \ldots, x_n) = \prod_{i=1}^{\alpha - 1} \frac{\partial f_{\beta_1, \beta_2, \ldots, \beta_i}}{\partial q_{\beta_1, \ldots, \beta_{i+1}}}$$

(for $\alpha = 1$, $\hat{p}_{\beta_1}(x_1, \ldots, x_n) \equiv 1$).
When we now substative the expressions for the differences $\tilde{q}_{\beta_1} - q_{\beta_1}$ in the formula for $\tilde{F} - F$ above, we obtain the required representation of the difference of two superpositions $\tilde{F} - F$. This proves the lemma.

§ 5. *Instability of the representation of functions as superpositions of smooth functions*

Let A be a set of functions of n variables and B a set of functions of k variables ($k<n$). Suppose that a function $F(x_1, \ldots, x_n) \in A$ is in a region G_n of the space $x_1, x_2, \ldots, x_n$ an s-fold superposition, generated by a system of functions $\{f_{\beta_1,\ldots,\beta_\alpha}(t_1, \ldots, t_k)\}$ of B.

We say that this superposition is (A, B)-stable in G_n if every function $\tilde{F}(x_1, \ldots, x_n) \in A$ can be represented in G_n as the s-fold superposition of the same form of functions $\{\tilde{f}_{\beta_1,\ldots,\beta_\alpha}(t_1, t_2, \ldots, t_k)\}$ of B such that

$$\max_{\alpha;\,\beta_1,\ldots,\beta_\alpha} \sup_t \left|\tilde{f}_{\beta_1,\ldots,\beta_\alpha}(t_1, \ldots, t_k) - f_{\beta_1,\ldots,\beta_\alpha}(t_1, \ldots, t_k)\right|$$
$$\leqslant \lambda \sup_{x \in G_n} \left|\tilde{F}(x_1, \ldots, x_n) - F(x_1, \ldots, x_n)\right|,$$

where λ is a constant not depending either on $\tilde{F}$ or on the $\{\tilde{f}_{\beta_1,\ldots,\beta_\alpha}\}$.

We denote by $C^{(1)}_{\omega(\delta)}$ the space of all continuously differentiable functions of k variables whose partial derivatives have modulus of continuity $\omega(\delta)$ ($\omega(\delta) \to 0$ as $\delta \to 0$).

THEOREM 5.5.1. *Suppose that each function $F(x_1, \ldots, x_n) \in A$ is in some region D_n of the space $x_1, \ldots, x_n$ a superposition of order s of functions of k variables $\{f_{\beta_1,\ldots,\beta_\alpha}(t_1, \ldots, t_k)\}$ belonging to $C^{(1)}_{\omega(\delta)}$ ($k<n$). If for any subregion $G_n \subset D_n$ the functional "dimension" of A at $F(x_1, \ldots, x_n) \in A$ is greater than k, then the function $F(x_1, \ldots, x_n)$ cannot be an $(A, C^{(1)}_{\omega(\delta)})$-stable superposition in any such region $G \subset D_n$.*

Proof. Assume the contrary, that is, in a region $G_n \subset D_n$ the function $F(x_1, \ldots, x_n) \in A$ is an $(A, C^{(1)}_{\omega(\delta)})$-stable s-fold superposition of functions $\{f_{\beta_1,\ldots,\beta_\alpha}(t_1, \ldots, t_k)\}$ of $C^{(1)}_{\omega(\delta)}$. Then any function $\tilde{F}(x_1, \ldots, x_n) \in A$ can be represented as the superposition of the same form of functions $\{\tilde{f}_{\beta_1,\ldots,\beta_\alpha}(t_1, \ldots, t_k)\}$ of $C^{(1)}_{\omega(\delta)}$ such that

$$\max_{\alpha;\,\beta_1,\ldots,\beta_\alpha} \sup_t \left|\varphi_{\beta_1,\ldots,\beta_\alpha}(t_1, \ldots, t_k)\right| \leqslant \lambda \sup_{x \in G_n} \left|\tilde{F} - F\right|,$$

where $\varphi_{\beta_1,\ldots,\beta_\alpha} = \tilde{f}_{\beta_1,\ldots,\beta_\alpha} - f_{\beta_1,\ldots,\beta_\alpha}$. By Lemma 5.4.2 we have (for definiteness, $k > 1$)

$$\tilde{F} - F = \sum_{\alpha;\, \beta_1, \ldots, \beta_\alpha} p_{\beta_1,\ldots,\beta_\alpha}(x_1, \ldots, x_n)$$

$$\times\ \varphi_{\beta_1,\ldots,\beta_\alpha}(q_{\beta_1,\ldots,\beta_\alpha,1}(x_1, \ldots, x_n), \ldots, q_{\beta_1,\ldots,\beta_\alpha,k}(x_1, \ldots, x_n)) + R(x_1, \ldots, x_n),$$

where $| R(x_1, \ldots, x_n) | \leqslant \gamma(\varepsilon)\, \varepsilon$, $\gamma(\varepsilon) \to 0$ as $\varepsilon \to 0$, and

$$\varepsilon = \max_{\alpha;\, \beta_1, \ldots, \beta_\alpha} \sup_t | \varphi_{\beta_1,\ldots,\beta_\alpha}(t_1, \ldots, t_k) |$$

$$\leqslant \lambda \sup_{x \in G_n} | \tilde{F}(x_1, \ldots, x_n) - F(x_1, \ldots, x_n) |.$$

That $\gamma(\varepsilon) \to 0$ as $\varepsilon \to 0$ follows from the fact that as $\varepsilon \to 0$ the quantity

$$\varepsilon' = \max_{\alpha;\, \beta_1, \ldots, \beta_\alpha} \sum_{i=1}^{k} \sup \left| \frac{\partial \varphi_{\beta_1,\ldots,\beta_\alpha}(t_1, \ldots, t_k)}{\partial t_i} \right| \to 0,$$

provided only that the modulus of continuity of the partial derivatives of the functions $\{ \varphi_{\beta_1,\ldots,\beta_\alpha}(t_1, \ldots, t_k) \}$ is fixed. By 5.1.10 it follows that $r(A, F) \leqslant k$ in some subregion $G_n \subset D_n$. So we have obtained a contradiction to the assumption that $r(A, F) > k$ in any subregion $G_n \subset D_n$ and this proves the theorem.

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