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ABSTRACT. One of the greatest achievements in analysis in the 1920s and 1930s was the theory of value distribution of meromorphic functions linked with the name of R. Nevanlinna. A vast literature, including Soviet contributions, is devoted to this subject.

Much less fully reflected in the literature is the multidimensional aspect of this theory, which involves the distribution of the inverse images of analytic sets under holomorphic mappings of complex manifolds. This side of the theory is rich in relations to algebraic and differential geometry, and is one of the most important branches of the modern geometric theory of functions of a complex variable. This book gives an introduction to the multidimensional theory of value distribution and presents the major results of this theory.

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Contents

SUPPLEMENT

A Brief Survey of Other Work

Here we wish to describe briefly some results in multidimensional value distribution theory which did not appear in the main text of the book. We begin with holomorphic curves. This is the part of the theory which is most closely connected to the one-dimensional theory and the part which is best developed.

The theory of entire curves $f\colon \mathbb{C} \to \mathbb{C}^n$ is the object of the work of V. P. Petrenko [1]–[7] and his students (Krutin′ [1], Krytov [1], Babets [1] et al.). One aspect of this work is that instead of the proximity function $m_f(D,r)$, which measures the deviation of f from the hyperplane D in the integral metric, the function

$$L_f(D,r) = \max_{|z|=r} \ln \frac{|f(z)||a|}{|(f(z),a)|}, \tag{1}$$

is introduced; it evaluates the deviation in a stronger uniform metric ($a \in \mathbb{C}^n$ is the vector defining D as a hyperplane in $\mathbb{P}^{n-1}$ in homogeneous coordinates). Instead of the defect in the sense of Nevanlinna or Valiron, the quantity

$$\beta_f(D) = \varliminf_{r\to\infty} \frac{L_f(D,r)}{T_f(r)}, \tag{2}$$

appears; it is called by Petrenko the *deviation of f from D*.

It is clear that the Nevanlinna defect $\delta_f(D) \le \beta_f(D)$, while for curves f of finite lower order it is proved that if the Valiron defect $\Delta_f(D) = 0$, then $\beta_f(D) = 0$ also. Thus the research on the deviation carried out by Petrenko and his students gives information also about the defects of holomorphic curves.

Holomorphic curves are related to *algebroid functions*—that is, multivalued analytic functions of one variable z which are defined by polynomial equations in w

$$A_0(z)w^n + \cdots + A_n(z) = 0 \tag{3}$$

with entire coefficients A_j. To every such function is associated the holomorphic curve $[A_0, \dots, A_n]\colon \mathbb{C} \to \mathbb{P}^n$. On the basis of this relation, Petrenko has established a number of properties of algebroid functions. He has also applied his results to the study of the asymptotic behavior of solutions of linear differential equations of nth order with entire coefficients and to the study of algebroid solutions of algebraic differential equations. One can become acquainted with this research in Petrenko's book [6] and his later paper [7].

In the work of E. I. Nochka a defect relation for holomorphic curves $f\colon \mathbb{C} \to \mathbb{P}^n$ is presented, which takes into account multiplicity and degeneracy. One says that f intersects a hyperplane $D = \{ [w] \in \mathbb{P}^n : a_0 w_0 + \cdots + a_n w_n = 0 \}$ with multiplicity ν if all the zeros of the functions $f_D = (f, a)$ have orders at least ν and if at least one zero is of order ν (if $f(\mathbb{C}) \subset D$ or $f(\mathbb{C}) \cap D = \emptyset$, then ν is considered to be ∞). The curve f is called *k-nondegenerate* if $f(\mathbb{C})$ is contained in some k-dimensional subspace of $\mathbb{P}^n$ but is not contained in any subspaces of lower dimension. Then this is true:

THEOREM. *Let a k-nondegenerate curve $f\colon \mathbb{C} \to \mathbb{P}^n$ be given and let the $D_j \subset \mathbb{P}^n$ be q hyperplanes in general position. If f intersects every D_j with multiplicity ν_j, then*

$$\sum_1^q \left(1 - \frac{k}{\nu_j}\right) \leq 2n - k + 1. \tag{4}$$

From this theorem Nochka deduced estimates of the degree of degeneracy of holomorphic curves, in particular for the case of complete degeneration: if in $\mathbb{P}^n$ there are given $q > 2n$ hyperplanes in general position and q numbers ν_j such that $\sum(1 - n/\nu_j) > n + 1$, then there does not exist a nonconstant meromorphic curve $f\colon \mathbb{C} \to \mathbb{P}^n$ intersecting each D_j with multiplicity at least ν_j. This same condition ensures the normality of a family of holomorphic curves in the disk $\{ |z| < 1 \}$; this is a generalization of a classical theorem of Schottky and Montel.

Already in the 1930s, H. Cartan conjectured that the sum of the Nevanlinna defects $\delta_f(D_j)$ of hyperplanes in general position for k-nondegenerate holomorphic curves $f\colon \mathbb{C} \to \mathbb{P}^n$ is estimated by the same quantity $2n - k + 1$ which is on the right side of (4).(1) Recently, Shen-Han Sung [1] announced that he had proved this conjecture. In Noguchi [2] and Ochiai [2], estimates of defects are given for holomorphic curves which are not in $\mathbb{P}^n$ but in some algebraic manifold.

For holomorphic mappings preserving dimension , the defect relation *counting multiplicity* was earlier obtained by Sakai [1]. Namely, if a nondegenerate holomorphic mapping $f\colon \mathbb{C}^n \to \mathbb{P}^n$ intersects hyperplanes D_j in general position with multiplicities at least ν_j ($j = 1, \ldots, q$) (for the definition see

(1)Certainly a k-nondegenerate curve in $\mathbb{P}^n$ can be viewed as a nondegenerate curve in $\mathbb{P}^k$. However, one cannot use the defect relation for nondegenerate curves and replace $2n - k + 1$ by $k + 1$, since the intersections $D_j \cap \mathbb{P}^k$ may not be in general position.

Chapter I), then

$$\sum_1^q \left(1 - \frac{1}{\nu_j}\right) \leq n+1. \tag{5}$$

For $n = 1$ this inequality is well known (see, for example, Hayman [1], §2.5.1); in particular, for $n = 1$ it follows from this that there can be no more than four branch values for which $\nu_j \geq 2$, and if there are precisely four then $\nu_j = 2$ for each of them (this case is achieved by the elliptic function $\wp$).

Sakai applies his theorem to the functional equation

$$F_\nu(z) = z_1^{\nu_1} + \cdots + z_{n+1}^{\nu_{n+1}} = 1, \tag{6}$$

where $\nu = (\nu_1, \ldots, \nu_{n+1})$ is a set of natural numbers. He proves that there is no nondegenerate holomorphic mapping from $\mathbb{C}^n$ to the hypersurface $A_\nu = \{ z \in \mathbb{C}^{n+1} : F_\nu(z) = 1 \}$ if $1/\nu_1 + \cdots + 1/\nu_{n+1} < 1$. In fact if there were such a map f, then $g = (f_1^{\nu_1}, \ldots, f_{n+1}^{\nu_{n+1}})$ would be a nondegenerate mapping from $\mathbb{C}^n$ to the hyperplane $H = \{ w_1 + \cdots + w_{n+1} = 1 \} \subset \mathbb{C}^{n+1}$, which is biholomorphically equivalent to $\mathbb{C}^n$. It clearly intersects the hyperplanes $H_j = \{ w \in H : w_j = 0 \}$ with multiplicities at least ν_j $(j = 1, \ldots, n+1)$ and in addition omits the hyperplane at infinity $H_\infty = \mathbb{P}^n \setminus \mathbb{C}^n$. Therefore, the sum on the left-hand side of (5) is equal to $n + 2 - (1/\nu_1 + \cdots + 1/\nu_{n+1})$, which by the assumptions on the ν_j is greater than $n + 1$. This contradicts (5) and proves the assertion.

We observe that for $n = 1$ the result is precise: the functions $f_1(z) = \cos z$ and $f_2 = \sin z$ realize a nondegenerate holomorphic mapping from $\mathbb{C}$ to the surface $\{ z \in \mathbb{C}^2 : z_1^2 + z_2^2 = 1 \}$; here the sum of the $1/\nu_j$ equals 1. An analogous result for holomorphic curves was obtained earlier by Fujimoto [2]: if $1/\nu_1 + \cdots + 1/\nu_{n+1} < 1/n$, then given a mapping $f : \mathbb{C} \to A_\nu$, the image $f(\mathbb{C})$ lies in some submanifold of A_ν.

A number of works, mostly by Japanese mathematicians, are devoted to multidimensional generalizations of the well-known theorem of Edrei and Fuchs on meromorphic functions with maximal defect sum. There is a result of Mori for the case of curves which is particularly simple to formulate. Let a nondegenerate holomorphic curve $f : \mathbb{C} \to \mathbb{P}^n$ of finite order ρ be given and let there be $q > n$ hyperplanes $D_j \subset \mathbb{P}^n$ in general position, with $\operatorname{ord} N_f(D_j, r) < \rho$. Then if the sum of the defects

$$\sum_{j=1}^q \delta_f(D_j) = n+1 \tag{7}$$

i.e., is maximal, it follows that the order ρ is an integer. In Mori [2] there is a generalization of this result to holomorphic mappings of $\mathbb{C}^n$ to compact complex manifolds on which positive line bundles are given. In an earlier paper of Noguchi [1], an analogous result was obtained for holomorphic mappings into complex projective space.

Now we consider the *uniqueness problem* for holomorphic mappings. According to the classical result of R. Nevanlinna (see, for example, Hayman [1], Theorem 2.6), two nonconstant meromorphic functions f and g are the same function if for five distinct points $a_j \in \overline{\mathbb{C}}$ they have identical inverse images (not counting multiplicity). (In general it is not possible to replace the number 5 by 4, as is shown by the example of the functions $f(z) = e^z$ and $g(z) = e^{-z}$ and the points $0, \infty, \pm 1$.) A multidimensional variant of this theorem for mappings $\mathbb{C}^m \to \mathbb{P}^n$ was obtained by Fujimoto [2], [3]: If for two such mappings f and g the inverse images (counting multiplicity) of $q = 3n+2$ hyperplanes D_j in general position coincide, where at least one of the mappings is nondegenerate and neither of the images of $\mathbb{C}^m$ lies in a D_j, then $f \equiv g$. If we suppose in addition that f and g are algebraically independent, then we can take $q = 2n + 3$.

For mappings preserving dimension, a better result was proved by Drouilhet [1]. Let f and g be two nondegenerate holomorphic mappings from $\mathbb{C}^n$ to $\mathbb{P}^n$, and let a hypersurface $D \subset \mathbb{P}^n$ have self-intersections in general position and degree $q = n + 4$ (for instance, $n + 4$ hyperplanes in general position). If the inverse images $f^{-1}(D)$ and $g^{-1}(D)$ coincide as sets (without counting multiplicity) and if also $f|_{f^{-1}(D)} = g|_{g^{-1}(D)}$, then $f \equiv g$.

For meromorphic functions on $\mathbb{C}^m$, as for functions of one variable, it is sufficient that the preimages of five points $a_j \in \overline{\mathbb{C}}$ coincide (see Sadullaev and Degtyar′ [1]). It is known that for rational functions on $\mathbb{C}$ it is sufficient that the preimages of four points coincide (the sharpness of this number is affirmed by the example of the functions $(z^2 - z + 1)/z$ and $(z^2 - z + 1)/z^2$, where the preimages of $0, 1$ and ∞ are the same); for polynomials, two are enough. Nochka has extended this result to rational functions on algebraic manifolds.

In the paper of Sadullaev and Degtyar′ cited above it is also proved that for holomorphic mappings $f: \mathbb{C}^m \to \mathbb{P}^n$ the set of *proximity divisors* $\{ D \subset \mathbb{P}^n : \lim_{r\to\infty} m_f(D, r) = \infty \}$ has inner P-capacity 0. They have also obtained a generalization of the second main theorem to meromorphic functions on $\mathbb{C}^m$, where instead of the distribution of preimages of constants $a_j \in \overline{\mathbb{C}}$, they consider the distribution of sets $\{ z \in \mathbb{C}^m : f(z) = a_j(z) \}$, where the a_j are meromorphic functions growing slowly in comparison with f, i.e., $T_{a_j}(r) = o(T_f(r))$.

The theory of value distribution for holomorphic mappings described in the main part of this book can without particular difficulty be extended to *meromorphic mappings*. A mapping between complex manifolds A and M is said to be meromorphic if there exists an analytic subset $S \subset A$ of codimension at least 2 (the indeterminacy set of f) such that $f: A \backslash S \to M$ is a holomorphic mapping and the closure in $A \times M$ of the graph $\{ (z, f(z)) : z \in A \setminus S \}$ is an analytic subset of $A \times M$. The extension to meromorphic mappings of the results in Griffiths and King (with the same assumptions on the manifolds and divisors) can be found in Shiffman [3].

Further, in the main text we presented the second main theorem and the defect relation for mappings preserving dimension. This method extends easily to mappings $f: A \to M$ which lower dimension: here A is an m-dimensional affine manifold and M is an n-dimensional compact algebraic manifold with $m \geq n$. For such an extension it suffices to consider instead of M the manifold $M \times \mathbb{C}^{m-n}$ and extend f by the identity map with respect to the new coordinates, i.e., replace f by the mapping $\tilde{f} = (f, z_1 \circ \pi, \ldots, z_{m-n} \circ \pi)$, where $\pi: A \to \mathbb{C}^m$ is a proper projection. For the details of this, see Griffiths and King [1] or Shiffman [3].

The method which we have considered does not extend to mappings which *raise dimension.* We observe that already in the 50s Stoll [1] had proved a second main theorem and defect relation for holomorphic mappings $f: \mathbb{C}^m \to \mathbb{P}^n$ and inverse images of hyperplanes for any dimensions m and n. However, his proof is very complicated (the paper takes up 160 pages in *Acta Mathematica*). Recently Vitter [1] found a substantially simpler approach to this result. His method is based on the generalization to meromorphic functions of several variables of the *lemma on the logarithmic derivative*, using which R. Nevanlinna proved his classical second main theorem: let $f = [f_0, f_1]: \mathbb{C}^m \to \mathbb{P}^1$ be a meromorphic function; then for any $j = 1, \ldots, m$ and any $r \geq 0$, except for r in an at most countable union of intervals of finite total length,

$$\begin{aligned}\int_{S_r} \ln^+ \frac{|\partial f/\partial z_j|}{|f|} \cdot \sigma &= \int_{S_r} \ln^+ \frac{|f_0 \partial f_1/\partial z_j - f_1 \partial f_0/\partial z_j|}{|f_0 f_1|} \sigma \\ &\leq a_1 + a_2 \ln r + a_3 \ln T_f(r),\end{aligned} \tag{8}$$

where a_1, a_2 and a_3 are constants.

In the case of mappings which raise dimension, the rest of Vitter's proof follows a plan which generalizes an earlier proof of H. Cartan [1], who considered the case of meromorphic curves about ten years before Ahlfors. By this route Vitter obtains a second main theorem for nondegenerate meromorphic mappings $f: \mathbb{C}^m \to \mathbb{P}^n$ for arbitrary m and n: for any $q \geq n+1$ hyperplanes $D_j \subset \mathbb{P}^n$ in general position and any $r \geq 0$, except for those in an at most countable union of intervals of finite total length,

$$\sum_{j=1}^{q} N_f(D_j, r) \geq (q - n - 1) T_f(r) + N(S, r) - b_1 \ln r - b_2, \tag{9}$$

where S is the divisor of stationarity and b_1 and b_2 are constants (cf. (33) in §5). From this, for arbitrary dimensions, he proves in the standard manner the usual defect relation: the sum of the defects $\delta_f(D_j)$ of hyperplanes in general position does not exceed $n+1$.

We observe also that Griffiths and King [1] give a generalization of the concept of the logarithmic derivative to holomorphic mappings. Let M be an n-dimensional complex manifold and let Ω be a meromorphic $(n, 0)$-form on it whose polar divisor D has self-intersections in general position. (In the case of

$M = \mathbb{P}^n$ with homogeneous coordinates $[W_0, \ldots, W_n]$ and affine coordinates $(w_1, \ldots, w_n)$, one can take

$$\Omega = \frac{1}{W_0 \cdots W_n} \sum_0^n (-1)^\nu W_\nu dW_0 \wedge \cdots \wedge dW_{\nu-1} \wedge dW_{\nu+1} \wedge \cdots \wedge dW_n$$
$$= \frac{dw_1 \wedge \cdots \wedge dw_n}{w_1 \cdots w_n}.)$$

For a holomorphic mapping $f: \mathbb{C}^n \to M$ the pullback $f^*(\Omega) = \lambda_f(z)\, dz_1 \wedge \cdots \wedge dz_n$ and the quantity

$$\nu_f(r) = \int_{S_r} \ln^+ |\lambda_f| \sigma \tag{10}$$

replaces the integral which appears in the lemma on the logarithmic derivative (for mappings $f: \mathbb{C} \to \mathbb{P}^1$ we clearly have $\lambda_f(z) = f'(z)/f(z)$). For this quantity, in Griffiths and King [1], p. 211, an estimate is obtained, which is however weaker than (9).

For the case of *curvilinear divisors*, the defect relation for mappings which raise dimension is still insufficiently worked out. One of the first results in this direction is due to Shiffman [4]. Let q distinct irreducible hypersurfaces D_j be given in $\mathbb{P}^n$ which are defined by homogeneous polynomials of degree p; suppose further that the D_j intersect in general position, in particular that no more than n of them pass through any given point. The Veronese mapping (see Shaferevich [1], Chapter I,§4), which is realized by monomials of degree p, imbeds $\mathbb{P}^n$ in the space $\mathbb{P}^N$, where $N = \binom{n+p}{p} - 1$, so that the images of the D_j lie on hyperplanes. Therefore, regarding the nondegenerate holomorphic mapping $f: \mathbb{C}^m \to \mathbb{P}^n$ as a mapping to $\mathbb{P}^N$, and using the defect relation for hyperplane divisors, we obtain the trivial estimate

$$\sum_{j=1}^q \delta_f(D_j) \leq \binom{n+p}{p}. \tag{11}$$

This estimate is clearly not optimal. The optimal estimate for the sum of the defects for a nonconstant holomorphic mapping $f: \mathbb{C}^m \to \mathbb{P}^n$ is clearly $2n$ (see the right-hand side of (4) for $k = 1$). However, in Shiffman [4] this is proved only for an extremely special class of mappings.

In conclusion, we briefly indicate some work where holomorphy is replaced by some metric-topological conditions. The first research in this direction was done by Ahlfors [1], who built up a theory of covering surfaces—a geometrical analog of Nevanlinna theory—which is true not only for conformal mappings but also for the more general quasiconformal mappings of Riemann surfaces. Schwartz [1], [2], extended some of the results of this theory to the case of multidimensional real manifolds.

I. M. Dektyarev [1]–[4] considered mappings from open orientable manifolds to compact Riemannian manifolds of the same dimension, where conditions close to quasiconformality were imposed on the mappings. In particular, he obtained sufficient conditions for quasi-surjectivity of such mappings; several of his results are related to complex manifolds and holomorphic mappings. Ronkin [2] considered manifolds with mixed structure—real-analytic fiber bundles over real-analytic manifolds whose fibers are complex lines. Such bundles are mapped real-analytically to compact complex manifolds, and the mappings are assumed to be holomorphic on each fiber. In this situation he obtains a generalization of the first main theorem in the form of Griffiths and proves a theorem about the set of defective divisors in the sense of Valiron (see subsection 3 of Chapter V).

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