LINEAR DIFFERENCE EQUATIONS AND EXPONENTIAL POLYNOMIALS

BY
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Part I. Introduction. The principal result of this paper is Theorem 2, which is an existence and uniqueness theorem for analytic solutions of the difference equation

\[ \sum_{j=1}^{n} A_j \gamma(x + \omega_j) = \phi(x). \]

Important in the proof of Theorem 2, as well as of some interest in itself, is Theorem 1, which states the possibility of securing a particularly simple Mittag-Leffler expansion for the reciprocal of the exponential polynomial

\[ \sum_{j=1}^{n} A_j e^{\omega_j x}. \]

In Theorem 2, equation (1) is studied under the assumptions that \( \phi(x) \) is analytic in a sector \( S(\beta) \) such that \( \arg x < \beta \leq \frac{\pi}{2} \), and that \( \omega_1 = 0 \), while \( \omega_2, \ldots, \omega_n \) lie in \( S(\beta) \). It is assumed further that there is a non-negative number \( M \) such that \( \phi(x) \) is of type \( (M, \beta) \), by which is meant that \( \phi(x) \) is analytic both in \( S(\beta) \) and also at \( x = 0 \), and that for every pair of positive numbers \( \varepsilon, \delta \) there is a positive number \( C_0(\varepsilon, \delta) \) such that

\[ |\phi(x)| < C_0(\varepsilon, \delta) e^{\varepsilon |x|} \]

when \( |\arg x| < \beta - \delta \).

Under these conditions the totality of all those solutions of (1) which are of type \( (M, \beta) \) is shown to be a non-empty finite-parameter family of functions. For this family a representation is found in the form of a sum of contour integrals which are constructed from \( \phi(x) \) and from the principal parts of the meromorphic function \( \frac{1}{(\sum_{j=1}^{n} A_j e^{\omega_j x})} \). This representation is given by equations (41)-(45) below.

Equation (1) has been studied for real \( \omega_j \) and real \( x \) by Bochner [1][2] and by Raclis [10]. For complex values of \( \omega_j \) and \( x \) it has been studied by Halphén [6] in the case where \( \phi(x) \) is entire and of sufficiently small exponential type, by Pincherle [9] in the case where \( \phi(x) \) is entire and of arbitrary exponential type, and by Carmichael [3] and by Ghermanesco [5]

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(2) Numbers in brackets refer to the bibliography at the end of the paper.
in the case where \( \phi(x) \) is any entire function. In addition, Pincherle (loc. cit.) has considered the case where \( \phi(x) \) is analytic at infinity, and Ghermanesco (loc. cit.) has considered the case where \( \phi(x) \) is meromorphic. Local solutions of (1) have been found by Sheffer [11, 12].

In his classic work on the principal solution in the complex plane Nörlund [8, chap. IV] has studied two special cases of equation (1). These are the equations

\[
(4) \quad y(x + \omega) - y(x) = \omega \phi(x),
\]

and

\[
(5) \quad y(x + \omega) + y(x) = 2\phi(x).
\]

Nörlund considers these equations under the assumption that either \( \phi(x) \) is an entire function of sufficiently small exponential type, or else \( \phi(x) \) is analytic in a sector and satisfies a certain growth condition—this growth condition is roughly condition (3) of the present paper, together with a further restriction which consists in requiring that the \( M \) of condition (3) be sufficiently small. (In the present paper the number \( M \) is unrestricted.)

The basic method of attack which will be employed for Theorem 2 is the use of generalized power-series solutions for certain approximating \( q \)-difference equations. This method is a modification of a method introduced by the author [13, 14] in earlier papers.

**Part II. Notation.** The following notations will be used throughout this paper:

1. \( \omega_1, \ldots, \omega_n \) are given distinct complex numbers.
2. \( A_1, \ldots, A_n \) are given complex numbers, each different from zero.
3. \( f(z) \) is the exponential polynomial \( \sum_{n=1}^{\infty} A_n e^{\omega_n z} \).
4. \( F(z) = 1/(f(z)) \).
5. \( \mathcal{Z} = \{ \xi_1, \xi_2, \ldots \} \) is the set of (distinct) zeros of \( f(z) \).
6. \( j_\epsilon \) is the order of multiplicity of \( \xi_\epsilon \) as a zero of \( f(z) \).
7. \( P_\epsilon(z) \) or \( \sum_{\epsilon=1}^{\epsilon} B_\epsilon(z - \xi_\epsilon)^{-j_\epsilon} \) is the principal part of \( F(z) \) at \( z = \xi_\epsilon \).
8. For every positive number \( \delta \), \( \mathcal{Z}(\delta) \) is the set of all points whose distance from \( \mathcal{Z} \) is less than \( \delta \).
9. \( \mathcal{G}_1(\delta), \mathcal{G}_2(\delta), \ldots \) are the components of \( \mathcal{Z}(\delta) \).
10. \( \mathcal{F}_m(\delta) \) is the complete boundary, described in the positive sense, of \( \mathcal{G}_m(\delta) \) \( (m = 1, 2, \ldots) \).
11. \( \tilde{\omega}_j \) is the complex conjugate of \( \omega_j \).
12. \( \mathcal{P} \) is the closed convex of the points \( \tilde{\omega}_1, \ldots, \tilde{\omega}_n \). (That is, \( \mathcal{P} \) is the intersection of all closed half-planes containing \( \tilde{\omega}_1, \ldots, \tilde{\omega}_n \).)
13. \( \mathcal{E}_1, \mathcal{E}_2, \ldots, \mathcal{E}_r \) are the edges of \( \mathcal{P} \), considered as a closed polygon.
14. \( n_j \) is the number of points of the set \( \tilde{\omega}_1, \ldots, \tilde{\omega}_n \) lying on \( \mathcal{E}_j \), \( (j = 1, 2, \ldots, r) \).
(20) \( N \) is the maximum of the numbers \( n_j \) \((j = 1, 2, \ldots, r)\).
(21) \( l_i \) is the length of \( E_i \).
(22) \( l \) is the perimeter of \( P \).
(23) \( N_i \) is the half-line through the origin in the direction of the outer
    normal to \( E_j \) \((j = 1, 2, \ldots, r)\).
(24) \( \alpha_j \) is the inclination of \( N_i \), with \(-\pi < \alpha_j \leq \pi \) \((j = 1, 2, \ldots, r)\).
(25) \( S_0(\beta) \) is the union of \( S(\beta) \) (see introduction) with the set consisting
    of just one point, the origin.
(26) \( N(M, \beta) \) is defined, when \( M \) is non-negative, to be the set of all complex
    numbers \( x \) such that for every number \( \beta \) in the closed interval \((-\beta, \beta)\)
    the inequality \( \Re(x) \cos \beta + \Im(x) \sin \beta \leq M \) is valid\(\dagger\).
(27) \( b \) is a positive number greater than unity.
(28) \( S(b, \beta) \) is the set of points \( x \) such that either \( x = b \), or else for some \( \zeta \)
    in \( S(\beta) \) the equation \( x = b(1 - e^{-\zeta}) \) is valid.

Part III. Exponential polynomials.
A. The distribution of the zeros.

**Lemma 1.** (a) There exists a positive number \( L \) such that if \( 3C_i \) is the half-
    strip \((1) \) \( \{z; \Re[z \exp(-i\alpha_j)] \geq 0, \quad \Im[z \exp(-i\alpha_j)] < L\} \) \((j = 1, 2, \ldots, r)\),
    then all zeros of \( f(z) \) lie in the union of the \( 3C_i \). Moreover, for every pair of numbers
    \( R_1, R_2 \) with \( 0 \leq R_1 \leq R_2 \) the number \((b) \) \( N_j(R_1, R_2) \) of zeros \( z \) which lie in \( 3C_j \)
    and have \( \Re(z) \leq R_1 \) \((j = 1, 2, \ldots, r)\), then all zeros of \( f(z) \) lie in the union of the \( 3C_j \).
    Moreover, for every pair of numbers \( R_1, R_2 \) with \( 0 \leq R_1 \leq R_2 \) the number \((b) \) \( N_j(R_1, R_2) \) of zeros \( z \) which lie in \( 3C_j \)
    and have \( R_1 \leq \Re(z) \leq R_2 \) satisfies, when \( R_1 \) is sufficiently large, the
    relation
    \[
    (2\pi)^{-1} l_j(R_2 - R_1) - (n_j - 1) \leq N_j(R_1, R_2) \leq (2\pi)^{-1} l_j(R_2 - R_1) + (n_j - 1).
    \]
(b) If the origin belongs to \( P \), then \( f(z) \) is bounded away from zero if \( z \) is
    bounded away from the zeros of \( f(z) \). That is, for every positive \( \delta \) there is a posi-
    tive \( \lambda(\delta) \) such that \( |f(z)| \geq \lambda(\delta) \) whenever \( z \) is a point whose distance to the near-
    est zero of \( f(z) \) is at least \( \delta \).

**Proof.** This lemma follows readily from well known results and methods
due to C. E. Wilder, J. D. Tamarkin, and G. Pólya\(\dagger\).

**Corollary.** If \( \delta \) is sufficiently small, \( G_m(\delta) \) contains at most \( N - 1 \) distinct
    zeros of \( f(z) \) \((m = 1, 2, \ldots)\).

**Proof.** Let \( \delta < \pi/(2N) \). By equation (29) there is at most a finite set of values
    of \( m \) such that \( G_m(\delta) \) contains more than \( N - 1 \) zeros of \( f(z) \). A sufficient re-
    duction in the size of \( \delta \) will now bring the desired result.

\(\dagger\) \( \Re, \Im \) denote real and imaginary part, respectively.
\(\dagger\) Evidently \( 3C_i \) has \( N_i \) for axis of symmetry.
\(\dagger\) Here each zero is counted a number of times equal to its multiplicity.
\(\dagger\) The address of R. E. Langer \([7]\) contains an outline of these results and methods, and
    a bibliography of the theory.
B. The resolution into partial fractions of the reciprocal of an exponential polynomial.

Theorem 1. Let $\mathcal{P}$ contain the origin. Let $B$ be any point not in $\mathcal{Z}$. Then if $\delta$ is a sufficiently small positive number, all the following relations are valid:

\[(a) \quad F(z) = F(B) - \sum_{m=1}^{\infty} \frac{1}{2\pi i} \oint_{\gamma_m(\delta)} \frac{F(T)(z - B)}{(T - z)(T - B)} \, dT,\]

for every $z$ at positive distance from $\mathcal{Z}(\delta)$, and

\[(b) \quad F(z) = F(B) + \sum_{m=1}^{\infty} Q_m(z),\]

where

\[(30) \quad Q_m(z) = \sum_{\xi \in \gamma_m(\delta)} (P_\xi(z) - P_\xi(B)),\]

for every $z$ in the complement of $\mathcal{Z}$, and

- (c) There are at most $N-1$ distinct points $\xi_j$ in $\gamma_m(\delta)$ ($m=1, 2, \cdots$), and
- (d) The length of $\gamma_m(\delta)$ is not more than $2\pi(N-1)\delta$, and
- (e) There exists a positive number $\lambda(\delta)$ such that $|F(T)| < 1/\lambda(\delta)$ for all $T$ on $\gamma_m(\delta)$ ($m=1, 2, \cdots$), and
- (f) The series in (a) converges absolutely, and the corresponding series of absolute values converges uniformly, for $z$ in any bounded set at positive distance from $\mathcal{Z}(\delta)$, and the series in (b) converges absolutely, and the corresponding series of absolute values converges uniformly, for $z$ in any bounded set at positive distance from $\mathcal{Z}$.

Proof. (c) is an immediate consequence of the corollary to Lemma 1. (e) follows immediately from Lemma 1b. (d) follows immediately from (c). If $\delta$ is less than the distance from $B$ to $\mathcal{Z}$, then (b) is obviously implied by (a). It remains, then, to establish (a) and (f). We shall use Cauchy's method of resolving a meromorphic function into partial fractions.

Let $z$ be any point not in $\mathcal{Z}$.

Now (e) is valid for every $\delta$, and we assume $\delta$ sufficiently small so that (c) and (d) are true, and sufficiently small so that $z$ and $B$ are at positive distance from $\mathcal{Z}(\delta)$.

Let $R$ be a positive number, so large that $|z| < R$ and $|B| < R$ and $\delta < R$. Let $\mathcal{U}_R$ be the union of the circle $|z| < R$ with all the sets $\mathcal{G}_m(\delta)$ which have points in common with that circle. Let $\mathcal{K}_R$ be the complete boundary of $\mathcal{U}_R$ described in the positive sense.

Let $\mathcal{G}_1, \mathcal{G}_2, \cdots, \mathcal{G}_k$ be the components of $\mathcal{Z}(\delta)$ which are included in $\mathcal{U}_R$ but not wholly included in the circle $|z| < R$. Then there is a zero $\xi_j$ of $f(z)$ in $\mathcal{C}_j$ ($j=1, 2, \cdots, k$), which lies in the ring $R-\delta < |z| < R+\delta$.
We assume now that \( \delta \) is less than \( \pi l^{-1} \) (see Notations (20), (22)). Then it follows easily from (29), with \( R_2 = R + \delta \) and with \( R_1 = [(R - \delta^2) - L^2]^1/2 \) (\( L \) as in Lemma 1a), that if \( R \) is sufficiently large, the number of zeros in the ring \( R - \delta < |z| < R + \delta \) is less than \((2\pi)^{-l}2\pi(l)^{-1} + N_1 \) where \( N_1 = \sum_{l=1}^{N} (n_l - 1) \), and therefore \( k \leq N_1 \).

Since each \( \mathcal{C}_j \) is the union of at most \( N-1 \) circles of radius \( \delta \), the length of \( \mathcal{K}_R \) is at most \( 2\pi R + 2\pi(N-1)\delta N_1 \), which is less than \( 7R \) if \( R \) is large.

Hence

\[
\left| \frac{1}{2\pi i} \int_{\mathcal{K}_R} \frac{F(T)(z-B)}{(T-z)(T-B)} \, dT \right| \leq \frac{1}{2\pi} \frac{(7R)}{\lambda(\delta)} \frac{1}{(R - |z|)(R - |B|)}, \tag{31}
\]

which approaches zero as \( R \) becomes infinite.

But

\[
\frac{1}{2\pi i} \int_{\mathcal{K}_R} \frac{F(T)(z-B)}{(T-z)(T-B)} \, dT \tag{32}
= F(z) - F(B) + \sum_{\mathcal{U}_R} \frac{1}{2\pi i} \int_{\mathcal{U}_R} \frac{F(T)(z-B)}{(T-z)(T-B)} \, dT.
\]

Hence (a) is valid if the series in (a) converges. But (29) implies that \((T-z)^{-1}(T-B)^{-1} = O(m^{-2}) \) on \( \mathcal{U}_m(\delta) \), and this, together with (d) and (e), implies that the series in (a) converges, and implies statement (f).

REMARK. Theorem 1 may, in part, be summarized in the statement that if \( B \) is any point at which \( F(z) \) is finite, then the series \( \sum_{l=1}^{N-1} (P_l(z) - P_l(B)) \), provided the terms are properly bracketed, converges to \( F(z) - F(B) \). In the simple case of commensurate real exponents \( \omega_j \) it is plain that if the origin belongs to \( \mathcal{P} \), then no bracketing is needed. In the general case where the origin belongs to \( \mathcal{P} \) this bracketing is essential. Indeed, to secure convergence of the Mittag-Leffler expansion \( \sum_{l=1}^{N-1} (P_l(z) - P_l(B)) \), where \( P_l^*(z) \) is the sum of the first \( k_s \) terms in the Taylor’s series expansion of \( P_l(z) \) at \( z = B \), it is in general impossible to choose values for \( k_s \) which remain bounded as \( s \) becomes infinite. This, together with stronger statements on the nonconvergence of the unbracketed series \( \sum_{l=1}^{N-1} (P_l(z) - P_l(B)) \), has been shown by Borel [2] for the particular function \( F(z) = 1/(f(z)) \) with \( f(z) \) the exponential polynomial \( \sin \pi z \sin \alpha \pi z \), \( \alpha \) being a carefully chosen irrational real number.

Borel remarks upon the usefulness, in the particular case cited, of bracketing the principal parts. Whittaker [15] has made systematic use of such bracketing in the study of meromorphic functions of finite order. However, Whittaker uses a plan of bracketing different from the one used in the present
paper, and his results do not specialize in the case of the reciprocal of an exponential polynomial to Theorem 1 of the present paper.

Part IV. Further preliminary theorems.

**Lemma 2.** Let \( \omega_1 = 0 \) and let \( \omega_2, \cdots, \omega_n \) be distinct points of \( S(\beta) \). Let \( P \), \( \alpha_1, \cdots, \alpha_r \) be defined by (17) and (24). Then \( -\beta-\pi/2 < \alpha_s < (\beta+\pi/2) \) \((s=1, 2, \cdots, r)\).

**Proof.** This is geometrically apparent. We omit the analytic proof, which is easily supplied.

**Lemma 3.** If \( M_1 < M_2 \), and if \( z_1 \) is in \( N(M_1, \beta) \), while \( z_2 \) is in the complement of \( N(M_2, \beta) \), then \( |z_2 - z_1| > M_2 - M_1 \).

**Proof.** This is obvious.

**Lemma 4.** Let \( \omega_1 = 0 \), and let \( \omega_2, \cdots, \omega_n \) be distinct points of \( S(\beta) \). Then:

(a) If \( M \) is any non-negative number there are at most finitely many zeros of \( f(z) \) in \( N(M, \beta) \).

(b) If \( \xi_1, \cdots, \xi_p \) are the zeros of \( f(z) \) in \( N(M, \beta) \), then there is a real number \( M_1 \) greater than \( M \) such that \( \xi_1, \cdots, \xi_p \) are the only zeros of \( f(z) \) in \( N(M_1, \beta) \).

(c) If \( \xi_1, \cdots, \xi_p \) are the zeros of \( f(z) \) in \( N(M, \beta) \), and \( \xi_{p+1}, \xi_{p+2}, \cdots \) are the other zeros of \( f(z) \), then there is a positive distance from the set \( N(M, \beta) \) to the set \( \{\xi_{p+1}, \xi_{p+2}, \cdots\} \).

(d) Let \( \xi_1, \cdots, \xi_p \) be the zeros of \( f(z) \) in \( N(M_1, \beta) \). Let \( \xi_{p+1}, \xi_{p+2}, \cdots \) be numbered in any order of nondecreasing modulus. Let \( \delta_0 \) be a positive number sufficiently small so that if \( \delta < \delta_0 \), then the component of \( \mathcal{Z}(\delta) \) which contains \( \xi_s \) contains no other point of \( \mathcal{Z} \) \((s=1, 2, \cdots, p)\), and \( G_m(\delta) \) contains at most \( N-1 \) distinct points of \( \mathcal{Z} \) \((m=1, 2, \cdots)\). For every \( \delta \) less than \( \delta_0 \) let the components \( G_m(\delta) \) of \( \mathcal{Z}(\delta) \) be numbered in such a way that \( G_m(\delta) \) contains a \( \xi_j \) for which \( j \geq m \). (For example, let \( G_1(\delta) \) be chosen to contain \( \xi_1 \), and after \( G_s(\delta) \) \((s \leq k)\) have been chosen, let \( G_{k+1}(\delta) \) be chosen to contain the \( \xi_j \) of minimum subscript lying in the complement of \( G_1(\delta) + \cdots + G_k(\delta) \).

Then there is a positive number \( D \), and a finite set of real numbers \( \Gamma_1, \cdots, \Gamma_h \), lying in the open interval \((-\beta, \beta)\), such that for every sufficiently small positive \( \delta \) a sequence of numbers \( \gamma_{p+1}, \gamma_{p+2}, \cdots \) can be chosen, with every \( \gamma_m \) in the set \((\Gamma_1, \cdots, \Gamma_h)\), and with the inequality

\[
\Re(T) \cos \gamma_m - \Im(T) \sin \gamma_m > M_1 + Dm
\]

valid if \( T \) is on \( \mathcal{J}_m(\delta) \) and \( m > p \).

(e) If \( \xi_1, \cdots, \xi_p \) are the zeros of \( f(z) \) in \( N(M_1, \beta) \), then there is a positive number \( \beta_0 \) smaller than \( \beta \) such that \( \xi_1, \cdots, \xi_p \) are the zeros of \( f(z) \) in \( N(M_1, \beta_0) \).

**Proof.** (a) By Lemma 2 the outer normals to the sides of \( \mathcal{P} \) have their inclinations in the open interval \((-\beta+\pi/2, [\beta+\pi/2])\). Let \( \beta_0 \) be chosen smaller than \( \beta \) and such that the inclinations of the outer normals to \( \mathcal{P} \) lie in
the open interval \((- [\beta_2 + \pi/2], [\beta_2 + \pi/2])\). Then by Lemma 1 all but finitely many of the zeros of \(f(z)\) lie in \(S (\beta_2 + \pi/2)\). Since the intersection of \(S (\beta_2 + \pi/2)\) and \(\mathcal{N}(M, \beta)\) is clearly a bounded set, part (a) follows.

(b) By application of part (a) with \(M\) replaced by \(M_2\), we obtain the result that \(\mathcal{N}(M_2, \beta)\) will, for any \(M_2\), contain only finitely many zeros of \(f(z)\). Let \(M_2\) be any number greater than \(M\). Evidently the zeros of \(f(z)\) in \(\mathcal{N}(M_2, \beta)\) can be denoted by \(\xi_1, \xi_2, \cdots, \xi_t\), with \(t \geq p\). For every \(k\) with \(p < k \leq t\) we have a \(\beta_k\) in the closed interval \((- \beta, \beta)\) such that \(\Re(\xi_k) \cos \beta_k + \Im(\xi_k) \cdot \sin \beta_k > M\). Choosing \(M_1\) as any number which is less than the minimum of the numbers \(\Re(\xi_k) \cos \beta_k + \Im(\xi_k) \cdot \sin \beta_k (k = p + 1, \cdots, t)\), and which is greater than \(M\), we see that all the points \(\xi_{p+1}, \cdots, \xi_t\) are in the complement of \(\mathcal{N}(M_1, \beta)\). This establishes (b).

(c) This is an immediately consequence of (b) and Lemma 3.

(d) In view of Lemma 1, there exists a positive number \(K\), a function \(s(m)\) defined for \(m = 1, 2, \cdots\) and assuming values in the set \((1, \cdots, r)\), a sequence of non-negative numbers \(\rho_1, \rho_2, \cdots\), and a sequence of complex numbers \(\theta_1, \theta_2, \cdots\) satisfying \(|\theta_n| < K\) \((m = 1, 2, \cdots)\), such that

\[
\xi_m = \rho_m \exp (i\alpha_{s(m)}) + \theta_m.\tag{34}
\]

Now because of Lemma 2 there exists for every \(s\) in the set \((1, \cdots, r)\) a number \(\beta_s\), in the open interval \((- \beta, \beta)\), such that \(\cos (\alpha_s + \beta_s) > 0\). If \(s = s(m)\),

\[
\Re[\xi_m \exp (i\beta_s)] = \Re \{[\exp (i\beta_s)] \rho_m \exp (i\alpha_s) + \theta_m]\}
\]

\[
\geq \rho_m \cos (\alpha_s + \beta_s) - K.\tag{35}
\]

Let \(M_2\) be a positive number larger than \(M_1\), such that \(\xi_1, \cdots, \xi_p\) are the zeros of \(f(z)\) in \(\mathcal{N}(M_2, \beta)\). Evidently, from (35), there is a positive integer \(m_0\) such that \(\Re(\xi_m \exp (i\beta_s)) > M_2\) if \(m > m_0\), and \(s = s(m)\). We define \(g_m\) to be \(\beta_{s(m)}\), if \(m > m_0\). Then if \(m > m_0\) we have

\[
\Re(\xi_m) \cos g_m - \Im(\xi_m) \sin g_m > M_2.\tag{36}
\]

We consider next the integer \(m\) in the set \(p + 1, \cdots, m_0\). For each such \(m\) let \(g_m\) be a number in the open interval \((- \beta, \beta)\) such that (36) holds \((m = p + 1, \cdots, m_0)\). The existence of such \(g_m\) follows from the fact that the points \(\xi_{p+1}, \cdots, \xi_{m_0}\) are in the complement of \(\mathcal{N}(M_2, \beta)\).

Now it follows from Lemma 1 that there is a positive number \(D'\) such that \(\rho_m > D'm\) for all sufficiently large \(m\). Hence from (35) we conclude that there is a positive number \(D''\) such that

\[
\Re(\xi_m) \cos g_m - \Im(\xi_m) \sin g_m > D''m.\tag{37}
\]

for all sufficiently large \(m\). From (37) and (36) it follows that there is a positive \(D\) such that
(38) \[ \Re (\zeta_m) \cos g_m - \Im (\zeta_m) \sin g_m > M_2 + Dm \]

if \( m > p \).

Let \( \delta \) be a positive number not exceeding \( \delta_0 \) and such that \( 2(N-1)\delta \) is less than \( M_2 - M_1 \). Let \( \delta \) be a positive number less than \( \delta \). We define the sequence \( \gamma_{p+1}, \gamma_{p+2}, \ldots \) as follows: For each integer \( m \) greater than \( p \) we choose an integer \( j \) not less than \( m \) such that \( \zeta_j \) is a point of \( Z \) which lies in \( \mathcal{G}_m(\delta) \), and we define \( \gamma_m = g_j \). Then if \( T \) is on \( \mathcal{I}_m(\delta) \), \( |T - \zeta_j| \leq (2(N-1)\delta < M_2 - M_1 \). Hence \[ |[\Re (T) - \Re (\zeta_j)] \cos g_j - [\Im (T) - \Im (\zeta_j)] \sin g_j| < M_2 - M_1. \]

But \( \Re (T) \cos \gamma_m - \Im (T) \sin \gamma_m = \Re (\zeta_j) \cos g_j - \Im (\zeta_j) \sin g_j + [\Re (T) - \Re (\zeta_j)] \cdot \cos g_j - [\Im (T) - \Im (\zeta_j)] \sin g_j \geq M_2 + Dj - (M_2 - M_1) = M_1 + Dj \geq M_1 + Dm. \]

This proves (d), with \( \{\Gamma_1, \ldots, \Gamma_k\} = \{\beta_1, \ldots, \beta_j; \gamma_{p+1}, \ldots, \gamma_m\} \).

(e) Since \( N(M_1, \beta_0) \supseteq N(M_1, \beta) \), it suffices to prove that there is a positive \( \beta_0 \) less than \( \beta \) such that \( \gamma_j \) is in the complement of \( N(M_1, \beta_0) \), whenever \( j > p \).

Recalling that the set \( \{\gamma_{p+1}, \gamma_{p+2}, \ldots\} \) is a finite set, let \( \beta_0 = \max \{\gamma_m\} \)

Now it follows from (38), which holds for \( m = p + 1, p + 2, \ldots \), that \( \gamma_j \) (\( j = p + 1, p + 2, \ldots \)) is in the complement of \( N(M_1, \beta_0) \).

**Lemma 5.** Let \( \eta, X \) be any positive numbers. Then \( X \sin \eta < e^x - \cos \eta \).

**Proof.** This is obvious.

**Lemma 6.** Let \( 0 < \beta \leq \pi/2 \). Let \( z \in \mathbb{S}(\beta) \). Then \( 1 - e^{-z} \in \mathbb{S}(\beta) \).

**Proof.** Let \( \zeta = 1 - e^{-z} \). Let \( z = \rho (\cos \beta_1 + i \sin \beta_1) \), with \( 0 \leq \beta_1 < \beta \), and \( \rho > 0 \).

If \( \beta_1 = 0 \), \( \zeta > 0 \), and hence \( \zeta \in \mathbb{S}(\beta) \). If \( \beta_1 > 0 \), we define \( \eta \) by the equation

\[ \eta = \rho \sin \beta_1. \]

Then \( z = \eta \cot \beta_1 \pm i \eta \). Hence \( \zeta = (1 - e^{-\eta \cot \beta_1} \cos \eta) \pm i e^{-\eta \cot \beta_1} \sin \eta \).

Hence \( |3(\zeta)/\Re (\zeta)| \cot \beta_1 = (\cos \beta_1) \sin \eta (e^{\eta \cot \beta_1} - \cos \eta)^{-1} \) and by Lemma 5, with \( X = \cot \beta_1 \), the last number is less than unity, so that \( |3(\zeta)/\Re (\zeta)| < \tan \beta_1 \). This relation, together with the obvious relation \( \Re (\zeta) > 0 \), implies \( \zeta \in \mathbb{S}(\beta) \).

**Lemma 7.** (a) For every \( b, \mathbb{S}(b, \beta) \) is a bounded set.

(b) For every \( b, \mathbb{S}(b, \beta) \subseteq \mathbb{S}(\beta) \).

(c) If \( \mathcal{F} \) is a closed bounded subset of \( \mathbb{S}(\beta) \), then when \( b \) is sufficiently large \( \mathcal{F} \subseteq \mathbb{S}(b, \beta) \).

(d) \( \mathbb{S}(b, \beta) \) contains a neighborhood of \( b \).

(e) If \( x \in \mathbb{S}(b, \beta) \) and if \( z \in \mathbb{S}(b, \beta) \), then \( b + e^{-z}(x-b) \in \mathbb{S}(b, \beta) \).

**Proof.** (a) It is evident that if \( x \in \mathbb{S}(b, \beta) \), then \( |x| < 2b \).

(b) This follows immediately from Lemma 6.

(c) Let \( \mathcal{F} \) be any closed bounded subset of \( \mathbb{S}(\beta) \). Let \( X \) be a positive number such that \( |x| < X \) whenever \( x \in \mathcal{F} \). Let \( x \in \mathcal{F} \). Let \( b > 1 \), let \( g = 1 - b^{-1} \), and define \( z \) by the equation \( b(1-g^z) = x \). Then (?)

(?) For definiteness, throughout this paper, \( \log (1-b^{-1}) \) is understood to be that single-valued branch in the set \( \arg (1-b^{-1}) \neq \pi \) which is real when \( \arg (1-b^{-1}) = 0 \), and \( \log g \) is understood to be a negative number.
Thus, since \( d \frac{\log (1-xb^{-1}) - x \log q}{dq} = x(x-1)(1-q)(1-x+q^{-1}) q^{-1} = 0 \), we have

\[
(40) \quad z - x = \left( \int_1^q \frac{x(x-1)(1-t)}{(1-x+xt)t} \, dt \right) / \left( \int_1^q t^{-1} \, dt \right),
\]

whence, if \( b > X_1 > X \), then \( |z-x| < X(X+1)/(X_1-X) \). (For \( |(1-t)/(1-x+xt)| < (1/b)/(1-(X/b)) < 1/(X_1-X) \). Thus for every positive \( \epsilon \) there is a positive \( X_1 \) such that if \( x \) is in \( S \) and \( z \) is defined by (39), and if \( b > X_1 \), then \( |z-x| < \epsilon \). If \( \epsilon \) is less than the distance from \( S \) to the boundary of \( S(\beta) \), then \( z \) is in \( S(\beta) \). But \( b(1-q^e) = b(1-\exp [-z(-\log q)]) \), and if \( z \) is in \( S(\beta) \), so is \( z(-\log q) \). Hence \( x \in S(\beta, \beta) \), for all \( x \) in \( S \), if \( b > X_1 \).

(d) Let \( p = be^{-\pi \cosh \beta} \). Let \( G \) be the set \( \{ x; |x-b| < \rho \} \). Let \( x \in G \). If \( x = b \), then \( x \in S(\beta, \beta) \) by definition. If \( x \neq b \), let \( x = b - Re^{i\theta} \), with \( 0 < R < \rho \), and \( -\pi < \theta \leq \pi \). Then \( x = b(1-\epsilon^t) \), with \( z = \log (b/R) - i\theta \). Since \( R(x) > \log (b/R) - i\theta \), it follows that \( z \in S(\beta) \). Thus \( x \in S(\beta, \beta) \). Hence \( G \subseteq S(\beta, \beta) \).

(e) Let \( x = b(1-\epsilon^t) \), where \( \epsilon \in S(\beta) \). Then \( b + \epsilon^t(x-b) = b(1-\epsilon^t(i\theta)) \), but since \( z \) and \( \epsilon \) both are in \( S(\beta, \beta) \), so is \( z + \epsilon \).

**Lemma 8.** Let \( b > 1 \). Let \( q = 1-b^{-1} \). Then \( |b \log q + 1| < (2q)^{-1} \) and \( 1 < b \log q \) if \( q^{-1} > q^{-1} \).

The proof is obvious.

**Lemma 9.** Let \( x \) be any complex number. Let \( z \in S(\beta) \). Let \( b > 1 \). Let \( q = 1-b^{-1} \). Let \( \xi = b + (x-b) \exp (z \log q) \). Then

(a) \( |e^{\xi \log q - 1}| < |z|/(bg) \),
(b) \( |\xi| < |x| + q^{-1} |z| \),
(c) \( |\xi - (x+z)| < |z| (|x| + |z| + 1)/(bg^2) \).

**Proof.** (a) \( |\exp (z \log q - 1)| = |z \log q^b \exp (zs \log q) \, ds| \). Hence, since \( R(s \log q) \leq 0 \), it follows that \( |\exp (s \log q - 1)| \leq |s| |\log q| \leq |s|/(bg) \).

(b) \( \xi = x \exp (z \log q) + b \left[ 1 - \exp (z \log q) \right] \), and therefore, by (a), we have \( |\xi| \leq |x| + q^{-1} |z| \).

(c) \( \xi - (x+z) = (x-b) \left[ \exp (z \log q - 1) - z = z \right] + (b \log q - 1) dt = z \frac{(x-b) \log q}{dt} \exp \left( (z \log q - 1) dt \right) = \frac{(x-b) \log q}{dt} \exp (t \log q) \, dt \). Hence \( |\xi - (x+z)| \leq |z| (|x|/(bg^{-1} + (2q)^{-1} + q^{-1} |z|)/(bg^2) \).

**Lemma 10.** Let \( x, \xi \) be any two complex numbers, and let \( b \) be a positive number greater than \( 1 \), and greater than \( |\xi| + |x-\xi| \). Let \( q = 1-b^{-1} \). Let \( V = \log (x-b) - \log (\xi-b)/\log q \). Then:
Proof. (a) $V = (x - \xi)(\log q)^{-1}(\xi - b)^{-1} \int_0^1 [1 + (x - \xi)(\xi - b)^{-1}]^{-1} dt$. Since (by Lemma 8) $|\log g| > 5$, we obtain

$$V \leq b |x - \xi| (1 - |x - \xi| (b - |\xi|)^{-1} | \xi|)^{-1}$$

(b) Since $\log q = \log (1 - b^{-1}) = -\int_0^1 (b - t)^{-1} dt$, we have

$$V - (x - \xi) = (x - \xi)(\log q)^{-1} \int_0^1 \left\{ [(\xi - b) + (x - \xi)t]^{-1} + [b - t]^{-1} \right\} dt$$

from which (b) follows readily.

Lemma 11. Let $\zeta_1, \ldots, \zeta_p$ be any given complex numbers. Let $j_1, \ldots, j_p$ be given positive integers. Let $b$ be a real variable greater than 1. Let $c_{sj}(b)$ ($s = 1, \ldots, p; j = 0, 1, \ldots, j_s - 1$) be complex-valued functions of $b$. Let $q = 1 - b^{-1}$. Let $U = \log (1 - b^{-1}x)/(\log q)$. Let

$$H(x, b) = \sum_{s=1}^p \sum_{j=0}^{j_s-1} c_{sj}(b) U^{i|s|x^{|s|x}}.$$

Then if there is an open region $\mathcal{G}$ such that as $b$ becomes infinite $H(x, b)$ approaches a limit function $I(x)$ uniformly in $\mathcal{G}$, $I(x)$ must be of the form

$$I(x) = \sum_{s=1}^p \sum_{j=0}^{j_s-1} c_{sj} x^{j_s|x}$$

for some constants $c_{sj}$.

Proof. Assume that $\mathcal{G}$ is bounded. (The general case follows, by analytic continuation, from the bounded case.) Now $x = (1 - q^p)(1 - q)^{-1}$. As $b$ becomes infinite, $U$ approaches $x$ uniformly in $\mathcal{G}$. This follows at once from Lemma 10b, with $\xi = 0$. Let $D_x$, $D_U$ be symbols denoting operations of differentiation with respect to $x$, $U$ respectively. Let $\mathcal{C}$ be a circle which with its boundary is included in $\mathcal{G}$. Now $(D_U - \zeta_1)^{i_1} \cdots (D_U - \zeta_p)^{i_p} H(x, b) = 0$. Hence $(D_U - \zeta_1)^{i_1} \cdots (D_U - \zeta_p)^{i_p} I(x)$ is small throughout $\mathcal{C}$ if $b$ is large, since $H(x, b)$ approaches $I(x)$ uniformly in $\mathcal{G}$ as $b$ becomes infinite. Also $(D_U - \zeta_1)^{i_1} \cdots (D_U - \zeta_p)^{i_p} I(x) - (D_x - \zeta_1)^{i_1} \cdots (D_x - \zeta_p)^{i_p} I(x)$ is small throughout $\mathcal{C}$ if $b$ is large. (For $d^s U/dx^s$ is near $d^s x/dx^s$, for each $s$, uniformly in $\mathcal{C}$, if $b$ is large.) Hence $(D_x - \zeta_1)^{i_1} \cdots (D_x - \zeta_p)^{i_p} I(x)$, which is independent of $b$, must be zero throughout $\mathcal{C}$. Hence $I(x)$ has the asserted form.
LEMMA 12. If \( \phi(x) \) is any function of type \((M, \beta)\) (as defined in the introduction), then \( \phi'(x) \) is of type \((M, \beta)\).

Proof. This follows readily from the Cauchy integral formula.

Part V. Linear difference equations.

THEOREM 2. Given equation (1) with \( \omega_1 = 0 \) and with \( \omega_2, \ldots, \omega_n \) in \( S(\beta) \). Given that \( \phi(x) \) is of type \((M, \beta)\) (as defined in the introduction). Let \( B \) be any complex number such that \( f(B) \neq 0 \). Then there exists a solution \( y_0(x) \) of (1) which is of type \((M, \beta)\). Moreover, if \( \xi_1, \ldots, \xi_p \) are the distinct zeros\(^{(4)}\) of \( f(z) \) in \( \mathcal{N}(M, \beta) \) with respective orders \( j_1, \ldots, j_p \), then every solution \( y(x) \) of (1) which is of type \((M, \beta)\) is of the form

\[
y_0(x) + \sum_{s=1}^{p} \sum_{j=0}^{j_s-1} C_s x^j e^{\xi_s x}
\]

where the \( C_s \) are constants, and conversely every function of the form (41) is a solution of (1) of type \((M, \beta)\). Finally, there exist contours \( \mathcal{L}_{p+1}, \mathcal{L}_{p+2}, \ldots \), each being a half-line lying in \( S_0(\beta) \) with the origin for initial point, and the set of these half-lines being a finite set, such that if \( \delta \) is any sufficiently small positive number and if the contours \( \mathcal{J}_m(\delta) \) \((m = 1, 2, \ldots)\) are properly numbered, then

\[
y_0(x) = g \phi(x) + \sum_{s=1}^{p} G_s(x) - \sum_{m=p+1}^{\infty} Y_m(x),
\]

where

\[
g = F(B) - \sum_{s=1}^{p} P_s(B),
\]

and

\[
G_s(x) = \int_0^z (2\pi i)^{-1} \int_{\mathcal{J}_s(\delta)} e^{(s-1)T\phi(\xi)} F(T) dT d\xi,
\]

\((s = 1, 2, \ldots, p)\), and

\[
Y_m(x) = (2\pi i)^{-1} \int_{\mathcal{J}_m(\delta)} F(T)(T - B)^{-1} \cdot \int_{\mathcal{L}_m} e^{-ST}[\phi'(x + z) - B\phi(x + z)] dz dT,
\]

\((m = p+1, p+2, \ldots)\).

The construction of these contours \( \mathcal{L}_m \) depends upon \( M \), but is otherwise independent of \( \phi(x) \).

---

\(^{(4)}\) There are only finitely many such zeros, by Lemma 4a.
Proof. Let $\xi_{p+1}, \xi_{p+2}, \ldots$ be numbered in any order of nondecreasing modulus. Let $M_1$ be a positive number greater than $M$ and such that $\xi_{p+1}, \xi_{p+2}, \ldots$ are all in the complement of $\mathcal{N}(M_1, \beta)$. (The existence of such an $M_1$ follows from Lemma 4b.) Let $\delta$ be a positive number so small that:

(46) the distance from the set $(\xi_{p+1}, \xi_{p+2}, \ldots)$ to the set $\mathcal{N}(M_1, \beta)$ is greater than $2\delta$ (cf Lemma 4c),

(47) the minimum distance between distinct points of the set $\xi_1, \ldots, \xi_p$ is greater than $2\delta$,

(48) each component of $\mathbb{Z}(\delta)$ contains at most $N-1$ (distinct) zeros of $f(z)$,

(49) the distance from $B$ to $\mathbb{Z}$ is greater than $\delta$.

Because of (46), (47) the component of $\mathbb{Z}(\delta)$ containing $\xi_s$ ($s=1, 2, \ldots, p$) contains no other point of $\mathbb{Z}$. Let the components of $\mathbb{Z}(\delta)$ be numbered in any fashion such that $\mathbb{Z}(\delta)$ contains a $\xi_s$ for which $j \geq m$. (Cf. Lemma 4d.) Then evidently the component of $\mathbb{Z}(\delta)$ which contains $\xi_s$ is $\mathbb{Z}(\delta)$ ($s=1, 2, \ldots, p$).

Let $b$ be a positive number greater than 1. Let $q = 1 - b^{-1}$. Let $T_{1x}, T_{2x}, \ldots, T_{nx}$ be functions of $x$ defined as follows:

\begin{equation}
T_{jx} = q^{\omega_j}(x - b) + b \quad (j=1, 2, \ldots, n),
\end{equation}

where by $q^{\omega_j}$ is meant $e^{\omega_j \log q}$. We consider the functional equation

\begin{equation}
\sum_{j=1}^n A_j y(T_{jx}) = \phi(x),
\end{equation}

which, for large $b$, is in a formal sense an approximation to equation (1), since $q^{\omega_j}(x-b)+b$ is, for fixed $x$, near $x+\omega_j$ if $b$ is large. (Cf. Lemma 9c with $z=\omega_j$.)

One may verify without difficulty that if $f(z)$ has a zero of order $i_k$ at $z = k \log q$ ($k=0, 1, \ldots$)\(^{(10)}\), and if the Taylor's series expansion of $\phi(x)$ at $x = b$ is $\sum_{k=0}^\infty \phi_k (x - b)^k$, then the function $y(x, b)$ defined by

\begin{equation}
y(x, b) = \sum_{k=0}^\infty \frac{\phi_k (x - b)^k}{f^{(k)}(k \log q) \log q} \left( \log \left( 1 - b^{-1}x \right) \right)^k
\end{equation}

\begin{equation}
+ \sum_{s=1}^p \sum_{j=0}^{i_s-1} C_{s,j} \left( \log \left( 1 - b^{-1}x \right) \right)^j (1 - b^{-1}x)^{s/j} \log q,
\end{equation}

where the $C_{s,j}$ are arbitrary constants, is a solution of (51)(\(^{(10)}\)). Let $\sigma_s$ be defined as follows:

\begin{equation}
\sigma_s = \xi_s / (\log q) \quad (s = 1, \ldots, p).
\end{equation}

Let $\psi_s$ be defined as follows:

\(^{(10)}\) Only finitely many $\psi_s$ can be different from zero, since, by Lemma 4a, $f(z)$ has at most finitely many negative zeros.

\(^{(10)}\) Cf. the footnote to equation (39). By $(1 - b^{-1}z)^{s/j} \log q$ is meant $\exp \left[ \xi_s (\log q)^{-1} \cdot \log (1 - b^{-1}x) \right]$. 

(54) \( \psi_s = \phi_s \) if \( \sigma_s \) is a non-negative integer; \( \psi_s = 0 \) otherwise. Then

\[
y(x, b) = \sum_{k \in \{\sigma, \ldots, \sigma_p\}} \phi_k(x - b)^k F(k \log q)
\]

(55)

\[
y(x, b) = \sum_{i=1}^{p} \frac{\psi_s(x - b)^{\sigma_s}}{f^{(i)}(s)} \left( \frac{\log (1 - b^{-1}x)}{\log q} \right)^i + H(x, b)
\]

where (11)

(56)

\[
H(x, b) = \sum_{i=1}^{p} \sum_{j=0}^{i-1} C_{ij} \left( \frac{\log (1 - b^{-1}x)}{\log q} \right)^i (1 - b^{-1}x)^{\sigma_j}.
\]

Now if \( k \) is not in the set \( \{\sigma_1, \ldots, \sigma_p\} \) then

(57)

\[
F(k \log q) = F(B) + \sum_{m=1}^{p} Q_m(k \log q) + \sum_{m=p+1}^{\infty} Q_m(k \log q)
\]

by Theorem 1b. Hence, if \( k \) is not in the set \( \{\sigma_1, \ldots, \sigma_p\} \), then

\[
F(k \log q) = F(B) + \sum_{i=1}^{p} (P_i(k \log q) - P_i(B))
\]

(58)

\[
- \sum_{m=p+1}^{\infty} (2\pi i)^{-1} \int_{\gamma_m(s)} \frac{F(T)(k \log q - B)}{(T - k \log q)(T - B)} dT.
\]

Thus

(59)

\[
y(x, b) = g \phi(x) + \sum_{i=1}^{p} G_i(x, b) - \sum_{m=p+1}^{\infty} Y_m(x, b) + H(x, b)(15),
\]

where

(60)

\[
g = F(B) - \sum_{i=1}^{p} P_i(B),
\]

and

(61)

\[
G_i(x, b) = \sum_{k \in \{\sigma_1, \ldots, \sigma_p\}} \phi_k(x - b)^k P_i(k \log q)
\]

\[
+ \frac{\psi_s(x - b)^{\sigma_s}}{f^{(i)}(s)} \left( \frac{\log (1 - b^{-1}x)}{\log q} \right)^i.
\]

\((s=1, 2, \ldots, p), \) and

(15) In the sequel the symbol \( H(x, b) \) will be used generically to denote functions which are of the form (56) for some constants \( C_{ij} \), arbitrary or otherwise, in accordance with the text. (Each \( C_{ij} \) may vary with \( b \).)

(14) This \( H(x, b) \) may be different from that in (55). The change in \( H(x, b) \) will take care of certain changes which occur in the range of the subscripts \( k \), in the passage from (55) to (59)–(62).
(62) \[ Y_m(x, b) = (2\pi i)^{-1} \int_{\gamma_m(\delta)} \frac{F(T)}{T - B} \sum_{k=0}^{\infty} \left( k \log q - B \right)^k \phi_k(x - b) \, dT. \]

(The order of limiting operations may be changed, as done just above, because of the convergence of the series \( \sum_{k=0}^{\infty} \phi_k \), \( J_m(k, T) \), where \( J_m(k, T) = (2\pi)^{-1} \int_{\gamma_m(\delta)} |F(T)| \left| k \log q - B \right| T - B \left| T - k \log q \right| dT \).

In this connection we note that \( |F(F)| < 1/\lambda(\delta) \) on \( \gamma_m(\delta) \) (by Lemma 1b), that if the \( \gamma_m(\delta) \) are properly numbered then on \( \gamma_m(\delta) \) \( T - B = 0(\nu_1) \) and \( |T - k \log q| = 0(\nu_1) \), because of Lemma 1a, and that the length of \( \gamma_m(\delta) \) is bounded \((m = p + 1, p + 2, \ldots)\), because of (48).

We seek next to write \((T - k \log q)^{-1}\) in a more convenient form, using the equation

\[ (T - k \log q)^{-1} = \int_0^\infty e^{-\rho(T - k \log q)} \, d\rho, \]

which is valid if \( z \) is any complex number such that \( \Re(z(T - k \log q)) > 0 \).

We reduce the size of \( \delta \) if necessary, and choose numbers \( \gamma_{p+1}, \gamma_{p+2}, \ldots \) and \( D \) having the property stated in Lemma 4d.

Let \( z_m = \gamma_m(\delta) (m = p + 1, p + 2, \ldots) \). Then if \( T \) is on \( \gamma_m(\delta) \),

\[ \Re(z_m(T - k \log q)) = \Re(z_m T) - k \log q \Re(z_m) \geq \Re(z_m T) \]

\[ = \Re(T) \cos \gamma_m - \Im(T) \sin \gamma_m > M_1 + D_m. \]

In particular, \( \Re(z_m(T - k \log q)) > 0 \) for every non-negative \( k \).

Let \( T \) be on \( \gamma_m(\delta) \). Then, letting \( S \) be an abbreviation for \( T - k \log q \), we have

\[ S^{-1} = \int_0^\infty e^{-\rho z_m} z_m d\rho. \]

Hence

\[ Y_m(x, b) = \frac{1}{2\pi i} \int_{\gamma_m(\delta)} \frac{F(T)}{T - B} \left[ \sum_{k=0}^{\infty} \phi_k(x - b)^k \right] (k \log q - B) \int_0^\infty e^{-\rho z_m} z_m d\rho \, dT \]

\[ = \frac{1}{2\pi i} \int_{\gamma_m(\delta)} \frac{F(T)}{T - B} \left[ \int_0^\infty \sum_{k=0}^{\infty} e^{-\rho z_m} \phi_k(x - b)^k \right] (k \log q - B) z_m d\rho \, dT. \]

(The change of order of limiting operations is justified by the convergence of the integral)
(67) \[ \int_0^\infty \sum_{k=0}^\infty |e^{-\rho \iota m}\phi_k| |x - b|^k k \log q - B| d\rho. \]

See Appendix, Note A.) Hence

(68) \[ Y_m(x, b) = \frac{1}{2\pi i} \int_{\gamma_m(b)} \frac{F(T)}{T - B} \int_0^\infty e^{-\rho \iota m T} \Phi(\rho) \iota m d\rho dT \]

where

\[ \Phi(\rho) = \sum_{k=0}^\infty \phi_k(x - b)^k (k \log q - B) e^{\rho \iota m k \log q}. \]

Therefore

(69) \[ Y_m(x, b) = \frac{1}{2\pi i} \int_{\gamma_m(b)} \frac{F(T)}{T - B} \int_0^\infty e^{-\rho \iota m T} (\theta_m(\rho) \phi'(\xi) - B\phi'(\xi)) \iota m d\rho dT, \]

where

\[ \theta_m(\rho) = e^{\rho \iota m \log q(x - b)} \log q, \quad \text{and} \quad \xi = b + \theta_m(\rho)/\log q. \]

The integral with respect to \( \rho \) in (69), which from the preceding discussion is convergent provided \( x \) lies in a suitable neighborhood of \( b \), can now be seen to converge, if \( b \) is sufficiently large, for every \( x \) in \( S(b, \beta) \), uniformly in every closed bounded subset of \( S(b, \beta) \), and therefore (69) gives an analytic continuation throughout \( S(b, \beta) \) of the function \( Y_m(x, b) \) as defined in (62). (Cf. Appendix, Note B.)

Let \( T_m \) be a point on \( \gamma_m(b) \) at minimum distance from \( B \). Let \( W_m \) be a point on \( \gamma_m(b) \) for which \( \iota (z_{mT}) \) is minimum. Let \( \delta_i \) be a positive number less than \( \beta \), such that \( \delta_1, \ldots, \delta_i \) are in the open interval \( (-[\beta - \delta_1], \beta - \delta_i) \). (Cf. Lemma 4d.) Then if \( x \) is in \( S(b, \beta - \delta_i) \), it follows from Lemma 7e that \( \xi \in S(b, \beta - \delta_i) \). Hence

(70) \[ \| Y_m(x, b) \| < \frac{(N - 1)h(x)\delta}{\lambda(\delta)\| T_m - B \| \int_0^\infty e^{-\rho E_m d\rho}}, \]

where \( h(x) = \| x - b\| \log q C_1(\epsilon, \delta_1) + \| B \| C_0(\epsilon, \delta_1) \| e^{\epsilon \| z_m \|} \| E_m = \| z_m W_m \| - (M + \epsilon)q^{-1}. \) (The justification of this statement is indicated by the discussion in Appendix, Note B.) Hence

(71) \[ \| Y_m(x, b) \| < \frac{(N - 1)\delta h(x)}{\lambda(\delta)\| T_m - B \| E_m}. \]

Now

(72) \[ \| z_m W_m \| > M_1 > Dm \quad (m = p + 1, p + 2, \ldots). \]

This follows from the definition of \( z_m \). Hence if \( \epsilon \) is sufficiently small and \( b \) is
sufficiently large, \( E_m > Dm \). Also, there is a positive constant \( D_1 \) such that

\[
| T_m - B | > D_1 m.
\]

This follows from (72). Thus

\[
| Y_m(x, b) | < \frac{(N - 1) \delta h(x)}{\lambda(b) D D_1} m^{-2}.
\]

Hence \( \sum_{m=p+1}^{\infty} Y_m(x, b) \) converges in \( S(b, \beta) \), uniformly for \( x \) in \( S(b, \beta - \delta_1) \). Since (by Lemma 7d) \( S(b, \beta - \delta_1) \) includes a neighborhood of \( b \), \( \sum_{m=p+1}^{\infty} Y_m(x, b) \) converges in \( S(b, \beta) \) to a function which is an analytic continuation of \( \sum_{m=p+1}^{\infty} Y_m(x, b) \) as defined using (62).

We now consider the function \( G_\epsilon(x, b) \) defined in (61). Let \( x, x_0 \) be points of \( S_0(\beta) \), such that the line segment joining \( x \) to \( x_0 \) does not pass through \( b \). Let \( u = x - b \) and let \( u_0 = x_0 - b \). Then, if \( x \) and \( x_0 \) are inside the circle of convergence of the series for \( \phi(x) \) in powers of \( x - b \), we have \( ^{10} \)

\[
G_\epsilon(x, b) = G^\star(x, b) + H(x, b),
\]

where

\[
G^\star(x, b) = \int_{u_0}^{u} \frac{1}{2 \pi i} \int_{\gamma_\epsilon(t)} \Phi(t, T, x) dT dt
\]

\((s = 1, 2, \cdots, p)\), where

\[
\Phi(t, T, x) = \frac{(u/t)^{T/\log q}}{t \log q} F(T).
\]

This follows from a straightforward computation of \( G^\star(x, b) \) by the method of residues. (Cf. Appendix, Note C.)

Also, if \( x_1 \) and \( x_2 \) are any two complex numbers (independent of \( x \), lying in \( S_0(\beta) \), and such that the line segment joining them does not pass through \( b \), then

\[
\int_{u_1}^{u_2} \frac{1}{2 \pi i} \int_{\gamma_\epsilon(t)} \Phi(t, T, x) dT dt = H(x, b).
\]

(Cf. Appendix, Note D.) If \( x_2 \) is taken as zero, while \( x_1 \) is taken as \( x_0 \), then by addition of (75) and (77) we obtain

\[
G_\epsilon(x, b) = G^{\star\star}(x, b) + H(x, b),
\]

where

\[
G^{\star\star}(x, b) = \int_{-b}^{u} \frac{1}{2 \pi i} \int_{\gamma_\epsilon(t)} \Phi(t, T, x) dT dt,
\]

\((^{10}) \) See the footnote on equation (56).
or

\[(80) \quad G^{**}(x, b) = \int_0^z \frac{1}{2\pi i} \int_{\gamma_1(i)} e^{iT\phi(\xi)} F(T) dT d\xi \]

(where \( V = \log (x - b) - \log (\xi - b) \), for all \( x \) sufficiently near \( b \). Moreover, the right-hand member of (80) is defined and analytic throughout \((14) \mathbb{S}(\beta)\), and therefore (78) gives an analytic continuation throughout \((14) \mathbb{S}(\beta)\) of \( G_*(x, b) \) as defined by (61).

Let

\[(81) \quad y_0(x, b) = g\phi(x) + \sum_{s=1}^p G^{**}_s(x, b) - \sum_{m=p+1}^{\infty} Y_m(x, b), \]

where \( g \) is defined by (60), and \( Y_m(x, b) \) is defined by (69). Then \( y_0(x, b) + H(x, b) \) is an analytic continuation throughout \((14) \mathbb{S}(\beta)\) of \( y(x, b) \) as defined in (52).

It is readily verified (cf. Appendix, Note E) that

\[(82) \quad \text{as } b \text{ becomes infinite, } y_0(x, b) \text{ approaches, uniformly in every closed bounded subset of } \mathbb{S}(\beta), \text{ the function } y_0(x) \text{ as defined by } \]

\[(83) \quad y_0(x) = g\phi(x) + \sum_{s=1}^p G^{**}_s(x) - \sum_{m=p+1}^{\infty} Y_m(x), \]

where

\[(84) \quad G^{**}_s(x) = \int_0^z \frac{1}{2\pi i} \int_{\gamma_1(i)} e^{(s-1)T\phi(\xi)} F(T) dT d\xi \]

\((s = 1, 2, \ldots, p)\), and

\[(85) \quad Y_m(x) = \frac{1}{2\pi i} \int_{\gamma_1(i)} \frac{F(T)}{T - B} \int_0^\infty e^{-x^mT} \phi_m(x, \rho) \rho m d\rho dT, \]

where \( \phi_m(x, \rho) = \phi(x + z_m\rho) - B\phi(x + z_m\rho) \).

Now \( \sum A_j y_0(T \phi, b) \), which equals \( \phi(x) \), is near \( \sum A_j y_0(x + \omega_j) \), uniformly on every closed bounded subset of \( \mathbb{S}(\beta) \), if \( b \) is large, since \( T \phi \) is near \( \phi + \omega_j \) (by Lemma 9c), and \( y_0(x + \omega_j, b) \) is near \( y_0(x + \omega) \). Hence \( y_0(x) \) is a solution of (1). Evidently \( y_0(x) \) is analytic in \( \mathbb{S}(\beta) \). It is easy to see that (83), (84), (85) define a function \( y_0(x) \) which is analytic at the origin as well as in \( \mathbb{S}(\beta) \). Hence \( y_0(x) \) is analytic in \( \mathbb{S}_0(\beta) \).

The next step is to secure an estimate of \( G^{**}_*(x) \). Evidently

\[(86) \quad G^{**}_*(x) = \sum_{j=1}^i \frac{B_{ij}}{(j - 1)!} \int_0^z e^{(s-1)T\phi(x - \xi)} \xi^{j-1} \phi(\xi) d\xi. \]

\((14)\) More accurately, throughout \( \mathbb{S}(\beta) \) deprived of the half-line \( \{ x; x \geq b \} \).

\((16)\) More accurately, throughout \( \mathbb{S}(\beta) \) cut along the half-line \( \{ x; x \geq b \} \).
If $|x| = R$ and if $|\xi| = r$, and if arg $x = \gamma$, then

$$G^{**}(x) = \sum_{j=1}^{L} \frac{B_{s_{j}}}{(j-1)!} \int_{0}^{R} e_{s}(r) e^{i(\gamma)(R-r)^{j-1}} e^{r} dr$$

where

$$e_{s}(r) = e^{(R-r)\xi} \exp \left( i\gamma \right) (R-r)^{j-1} e^{r},$$

and therefore, if $\delta_{1} < \beta - |\gamma|$, we have

$$|G^{**}(x)| \leq \sum_{j=1}^{L} \frac{|B_{s_{j}}|}{(j-1)!} \int_{0}^{R} E_{s}(r) C_{0}(\epsilon, \delta_{1}) e^{(M+\epsilon)r} dr$$

where $E_{s}(r) = e^{(R-r)\xi} \exp \left( i\gamma \right) (R-r)^{j-1} e^{r}$. Since $\xi$ is in $N(M, \beta)$, we have

$$M \leq \Re \left[ i\xi \exp \left( i\gamma \right) \right].$$

Hence

$$|G^{**}(x)| \leq \sum_{j=1}^{L} \frac{|B_{s_{j}}|}{(j-1)!} e^{(M+\epsilon)R \xi} C_{0}(\epsilon, \delta_{1})$$

or

$$|G^{**}(x)| \leq \sum_{j=1}^{L} \frac{|B_{s_{j}}|}{(j-1)!} e^{(M+\epsilon)|x|} |x| C_{0}(\epsilon, \delta_{1}).$$

The next step is to secure an estimate of $Y_{m}(x)$. Let $\delta_{1}$ be sufficiently small so that $z_{m}$ is in $S(\beta - \delta_{1}) (m = 0, 1, 2, \ldots)$. (We recall that there are only finitely many distinct numbers $z_{m}$.) Then if $x$ is in $S(\beta - \delta_{1})$, $x + z_{m} \beta$ is in $S(\beta - \delta_{1})$, and consequently for every positive $\epsilon$

$$|\phi(x + z_{m})| < C_{0}(\epsilon, \delta_{1}) e^{(M+\epsilon)|x|+\rho},$$

and $|\phi'(x + z_{m})| < C_{1}(\epsilon, \delta_{1}) e^{(M+\epsilon)|x|+\rho}$ (where $C_{1}(\epsilon, \delta_{1})$ is the symbol introduced in equation (71)). Thus

$$|Y_{m}(x)| \leq \sum_{s=1}^{L} \frac{1}{D_{m}m^{2}} \int_{0}^{\infty} e^{-(M+\epsilon)(1+s+\rho)} K(x, \rho) d\rho$$

where

$$K(x, \rho) = [C_{1}(\epsilon, \delta_{1}) + B |C_{0}(\epsilon, \delta_{1})| e^{(M+\epsilon)(1+s+\rho)}],$$

and therefore, if $\epsilon$ is sufficiently small so that $M+\epsilon < M$, we have

$$|Y_{m}(x)| \leq \sum_{s=1}^{L} \frac{1}{D_{m}m^{2}} [C_{1}(\epsilon, \delta_{1}) + B |C_{0}(\epsilon, \delta_{1})|].$$

Hence
It follows from (90) and (93) that \( y_0(x) \) is of type \((M, \beta)\).

Let \( H(x) \) be generic notation for a function of the form

\[
H(x) = \sum_{s=1}^{p} \sum_{j=0}^{i_j-1} C_{sj}x^j e^{isx}.
\]

It is easily verified that \( H(x) \) is always of type \((M, \beta)\), and is always a solution of the equation \( \sum A_j y(x + \omega_j) = 0 \). Hence every function of the form

\[
y_0(x) + H(x)
\]

is a solution of (1) of type \((M, \beta)\).

It remains to prove the converse, namely that every solution of (1) of type \((M, \beta)\) is of the form (95).

Let \( Y(x) \) be any solution of (1) of type \((M, \beta)\). Let

\[
\eta(x) = Y(x) - y_0(x).
\]

We shall show that \( \eta(x) = H(x) \).

Evidently \( \eta(x) \) is of type \((M, \beta)\). Let \( d_0(e, \delta_1), d_1(e, \delta_1), d_2(e, \delta_1) \) be such that

\[
|\eta(x)| \leq d_0(e, \delta_1)e^{\delta(x) + \delta_1} \text{ in } S(\beta - \delta_1), \quad |\eta'(x)| \leq d_1(e, \delta_1)e^{\delta(x) + \delta_1} \text{ in } S(\beta - \delta_1),
\]

and \( |\eta''(x)| \leq d_2(e, \delta_1)e^{\delta(x) + \delta_1} \text{ in } S(\beta - \delta_1) \). (We are using Lemma 12.)

Obviously \( \eta(x) \) is analytic in \( S(\beta) \). Hence \( \eta(x, \beta) \) is analytic at \( x = \beta \). Thus, if

\[
\eta(x) = \sum_{k=0}^{\infty} \eta_k(x - \beta)k
\]
and

\[(100) \quad \psi(x, b) = \sum_{k=0}^{\infty} \Psi_k(x - b)^k,\]

then (by comparison of like powers of \(x - b\) in (97)), we have

\[(101) \quad \eta_k f(k \log q) = \Psi_k.\]

Hence

\[(102) \quad \eta_k = \Psi_k F(k \log q) \quad \text{if} \quad f(k \log q) \neq 0, \quad \text{and} \quad \Psi_k = 0 \quad \text{if} \quad f(k \log q) = 0.\]

Consequently

\[(103) \quad \eta(x) = \sum_{\Psi_k \neq 0} \Psi_k F(k \log q)(x - b)^k + H(x, b).\]

Also,

\[(104) \quad \text{There is a positive } \beta_0 \text{less than } \beta, \text{ such that } \xi_1, \ldots, \xi_p \text{ are the zeros of } f(z) \text{ in } \mathcal{N}(M, \beta_0), \text{ such that the numbers } \omega_1, \ldots, \omega_n, \omega_{p+1}, \omega_{p+2}, \ldots \text{ are in } \mathcal{S}(\beta_0), \text{ and such that } \psi(x, b) \text{ is of type } (M, \beta_0). \text{ Moreover, if } \beta_1 \text{ is any number such that } \beta_0 < \beta_1 < \beta, \text{ then there is a positive number } b_1 \text{ such that } T_{\beta_1} x \in \mathcal{S}(\beta_1) (j = 1, 2, \ldots, n), \text{ when } x \in \mathcal{S}(\beta_0) \text{ and } b > b_1. \text{ (Cf. Appendix, Note F.)}\]

Using (58) we write

\[(105) \quad \eta(x) = g\psi(x, b) + \sum_{s=1}^{p} E_s(x, b) - \sum_{m=p+1}^{\infty} R_m(x, b) + H(x, b),\]

where \(g\) is defined by (60), and

\[(106) \quad E_s(x, b) = \sum_{\Psi_k \neq 0} \Psi_k P_s(k \log q)(x - b)^k\]

\((s = 1, 2, \ldots, p), \text{ and}\)

\[(107) \quad R_m(x, b) = \frac{1}{2\pi i} \int_{\gamma_m(i)} \frac{F(T)}{T - B} \Omega(x, b, T) dT\]

with

\[\Omega(x, b, T) = \sum_{k=0}^{\infty} \left( \frac{k \log q - B}{T - k \log q} \right) \Psi_k(x - b)^k.\]

Then in \(\mathcal{S}(\beta, \beta_0)\) we have, as in the treatment of \(Y_m(x, b)\),

\[(108) \quad R_m(x, b) = \frac{1}{2\pi i} \int_{\gamma_m(i)} \frac{F(T)}{T - B} \int_{0}^{\infty} e^{-\rho \log W(\rho, x, b) \zeta_m d\rho} T dT\]

where
W(ρ, x, b) = e^{ρx^2} \log q'(x - b) \log q'/(x - b) - Eψ(x, b)

with \( \xi = b + e^{ρx^2} \log q'(x - b) \) and with \( ψ'(ξ, b) \) the derivative of \( ψ(ξ, b) \) with respect to \( ξ \). And in \( S(β_0) \) we have, as in the treatment of \( G_α(x), \)

(109) \[ E_α(x, b) = E_α^{**}(x, b) + H(x, b) \]

where

(110) \[ E_α^{**}(x, b) = \int \frac{1}{2πi} \int \left( \frac{1}{\xi - b} \log q' \right) dTdξ, \]

with \( V = \left[ \log (x - b) - \log (ξ - b) \right]/(\log q). \) (It will be noted that (106) is an exact analogue of (61), since, by (97), \( Ψ_b = 0 \) whenever \( k = α_σ \).) Now

(111) \[ |ψ(x, b)| ≤ \sum_{j=1}^n |A_j| |T_jx - (x + ω_j)| G_j, \]

if \( x ∈ S(β_0) \), where

(112) \( G_j \) is the maximum of \( |η'(t)| \) for \( t \) on the line segment \( (T_jx, x + ω_j) \).

But \( |T_jx| ≤ |x| + q^{−1} |ω_j| \), and \( |x + ω_j| ≤ |x| + |ω_j| \). Hence \( |t| ≤ |x| + q^{−1} |ω_j| \).

Also, if \( x ∈ S(β_0), x + ω_j ∈ S(β_0) \) and \( T_jx ∈ S(β_0) \). Hence \( t ∈ S(β_0) \). Therefore if \( δ_1 = β - β_1 \), we have

(113) \[ |η'(t)| ≤ d_1(ε, δ_1)e^{(M+ε)|t|}. \]

Hence

(114) \[ G_j ≤ d_1(ε, δ_1)e^{(M+ε)|ω_j|e^{(M+ε)|x|}}. \]

Now by Lemma 9c, with \( z = ω_j \), we have

(115) \[ |T_jx - (x + ω_j)| ≤ |ω_j| (|x| + |ω_j| + 1)b^{−1}q^2. \]

Hence, by (111), (114) and (115) we have, when \( x ∈ S(β_0), \) and \( b > b_1 + 1, \)

(116) \[ |ψ(x, b)| ≤ b^{−1}d^{**}(ε)e^{(M+ε)|x|}, \]

where \( d^{**}(ε) \) is independent of \( x \) and \( b \).

Let \( β_2 \) be a positive number less than \( β_0 \) such that \( ξ_1, \ldots, ξ_p \) are the zeros of \( f(z) \) in \( N(M, β_2) \) and such that the numbers \( ω_z, \ldots, ω_s, ω_{s+1}, \ldots, \), are in \( S(β_2). \) Then by the Cauchy integral formula, and (116), we have, using the analyticity of \( ψ \) at \( x = 0, |ψ'(x, b)| ≤ b^{−1}d^{**}(ε)e^{(M+ε)|x|} \) in \( S(β_2), \) where \( d^{**}(ε) \) is independent of \( x \) and \( b. \) Hence

(117) \[ |R_m(x, b)| ≤ b^{−1} \left( \frac{N - 1 - δ}{λ(δ)D_1D} \right) \left[ (1 + b^{−1}|x|)d^{**}(ε) + |B| d^{*}(ε) \right] \]

\[ \frac{e^{(M+ε)|x|}}{m^2}, \]
whence

\[ (118) \quad \left| \sum_{m=p+1}^{\infty} R_m(x, b) \right| \leq b^{-1} J(x), \]

where \( J(x) \) is a positive-valued function of \( x \) which is independent of \( b \) and which is bounded on every bounded subset of \( \mathcal{S}(\beta_2) \).

The next step is to estimate \( E_\ast^\ast(x, b) \). We have

\[ (119) \quad |e^{\gamma T}| \leq e^{|\mathcal{T}| |\mathcal{V}|}. \]

But \(|V| \leq I(x, b) = b |x| (b - 2 |x|)^{-1}\) by Lemma 10a and \(|T| \leq |\xi_\ast| + \delta \leq G_0\), if \( T \in \mathcal{F}_s(\delta) \) \((s = 1, 2, \cdots, p)\), with \( G_0 \) a positive number. Therefore

\[ (120) \quad |E_\ast^\ast(x)| \leq \frac{\lambda(\delta)(1 - b^{-1} |x|) \delta^{-1} I_\ast(x)}{G_0^{(s)}(\delta) e^{(M+2) |x| |b|^{-1}}}. \]

where \( I_\ast(x) \) is a positive-valued function of \( x \) which is independent of \( b \) and which is bounded on every fixed bounded subset of \( \mathcal{S}(\beta_2) \) if \( b \) is sufficiently large. Let

\[ (121) \quad \eta_0(x, b) = \psi(x, b) + \sum_{s=1}^{p} E_\ast^\ast(x, b) - \sum_{m=p+1}^{\infty} R_m(x, b). \]

By virtue of inequalities (118), (120), and (116) it is evident that as \( b \) becomes infinite \( \eta_0(x, b) \) tends uniformly in every bounded subset of \( \mathcal{S}(\beta_2) \) to a limit function which is identically zero.

Now from (105), (109) and (121) we have

\[ (122) \quad \eta(x) = \eta_0(x, b) + H(x, b), \]

and since \( \eta(x) \) is independent of \( b \), it follows that \( H(x, b) \) tends to the limit \( \eta(x) \) as \( b \) becomes infinite, the limit being approached uniformly in every bounded subset of \( \mathcal{S}(\beta_2) \). But this implies that \( \eta(x) \) is of the form \( H(x) \). (See Lemma 11.) This concludes the uniqueness proof.

Let \( \mathcal{L}_m \) \((m = p+1, p+2, \cdots)\) be the contour \( z = \rho s_m (0 \leq \rho) \) described in the sense of increasing \( \rho \). Then equations (42)–(45) are valid.

This completes the proof of Theorem 2.

Remarks. (i) The methods used in the proof of Theorem 2 can be thought of as a generalization of the method of principal solutions ("in direction 0") which was introduced by the author [14]. The generalization consists in that the exponents \( \xi_s / \log q \) appearing in \( H(x, b) \) are not required to be real and non-negative. There are other deviations of the methods of this paper from the methods of the earlier paper: among them the use of powers of the functions \( \log (1 - b^{-1} x) / \log q \) in the solutions of (51), and the failure to introduce parameters in (51). These other deviations, however, are matters of convenience only, and could have been avoided.
(ii) From (45) it is evident that \(Y_m(x)\) can be written in the form

\[
\int_{\mathcal{L}_m} \left[ \phi'(x + z) - B\phi(x + z) \right] H_m(z) dz,
\]

where

\[
H_m(z) = (2\pi i)^{-1} \int_{\gamma_T(z)} F(T)(T - B)^{-1} e^{-zT} dT.
\]

If we let \(Z_1, \ldots, Z_Q\) be the distinct numbers in the set \(\{z_{p+1}, z_{p+2}, \ldots\}\), and define \(I_t(z) = \sum_{z_{m}=z_t} H_m(z)\) (this series will converge for \(z\) on \(\mathcal{L}_m\), if \(z \neq 0\)), \(t = 1, 2, \ldots, Q\), and define \(C_t\) as the contour \(\mathcal{L}_m\) for \(z_m = z_t\), and define \(K_t(z) = (2\pi i)^{-1} \int_{\gamma_T(0)} F(T) dT\), then we shall have

\[
\gamma_0(x) = g\phi(x) + \sum_{t=1}^p \int_0^x K_t(x - \xi) \phi(\xi) d\xi
\]

\[
+ \sum_{t=1}^Q \int_{C_t} \left[ \phi'(x + z) - B\phi(x + z) \right] I_t(z) dz.
\]

In this form the representation of \(\gamma_0(x)\) bears a close analogy to Nörlund's representation of his principal solution of equation (4), [8, p. 70, equation (9)].

(iii) It is evident from the proof of Theorem 2 that the existence problem for equation (1) might have been approached from the standpoint of the symbolic calculus, in this fashion: One writes (1) in the form \(f(D)y = \phi\), whence, formally, \(y = F(D)\phi\), and then, again formally, from Theorem 1a, \(F(D) = F(B) - \sum_{m=1}^{\infty} (2\pi i)^{-1} \int_{\gamma_T(m)} F(T)(T - B)^{-1}(D - B)(T - D)^{-1} dT\), leading to

\[
y = F(B)\phi(x) - \sum_{m=1}^{\infty} Y_m^*(x),
\]

where

\[
Y_m^*(x) = (2\pi i)^{-1} \int_{\gamma_T(m)} F(T)(T - B)^{-1} h(x, T) dT,
\]

and where \(h(x, T) = (D - B)(T - D)^{-1}\phi(x)\), that is, where \(h(x, T)\) is a solution of the differential equation \(Th(x, T) - h'(x, T) = \phi'(x) - B\phi(x)\). Evidently \(Y_m(x)\), as defined by (85), is a particular case of \(Y_m^*(x)\) \((m = p+1, p+2, \ldots)\).

The approximating \(q\)-difference method appearing in this paper provides analytic calculations with \(q\), paralleling these formal calculations with the symbolic operator \(D\). From this point of view the approximating \(q\)-difference method plays a role analogous to that played by the Laplace transform in the treatment of differential or difference equations(16).

(16) Cf., for example, Doetsch [4, chap. 18, §3].
Part VI. Appendix.

Note A (referring to the integral (67)).

We observe that \(|\exp (-\rho \sigma_m (T - k \log q))| \leq \exp (-\rho \Re (\sigma_m T)) \leq \exp (-\rho M_1)|, while the power series \(\sum_{k=0}^{\infty} \phi_k |x - b|^k \log q - B|\), which is independent of \(\rho\), is convergent when \(|x - b| < b \sin \beta\) (by virtue of the analyticity of \(\phi(x)\) in \(\Sigma (\beta)\)).

Note B (referring to the paragraph following equation (70)).

We observe that since \(x\) is in \(\Sigma (b, \beta)\), and since \(-\rho \sigma_m \log q\) is in \(\Sigma (\beta)\), it follows from Lemma 7e that \(\xi\) is in \(\Sigma (b, \beta)\), and thus (by Lemma 7b) \(\xi\) is in \(\Sigma (\beta)\). Hence \(\phi(\xi)\) and \(\phi'(\xi)\) are defined, and (by Lemma 12), for suitably small positive \(\delta_1\) corresponding to any fixed closed bounded subset of \(\Sigma (b, \beta)\), 
\[ |\phi(\xi)| < C_0(\epsilon, \delta_1) \exp \left( (M + \epsilon)|\xi| \right), \] 
and 
\[ |\phi'(\xi)| < C_1(\epsilon, \delta_1) \exp \left( (M + \epsilon)|\xi| \right). \]

Then, since 
\[ |\xi| < |x| + q^{-1}p \] 
(by Lemma 9b), we have 
\[ |\phi(\xi)| < C_0(\epsilon, \delta_1) \exp \left( (M + \epsilon)(|x| + q^{-1}p) \right) \] 
and 
\[ |\phi'(\xi)| < C_1(\epsilon, \delta_1) \exp \left( (M + \epsilon)(|x| + q^{-1}p) \right). \]
Since 
\[ \exp (-\rho \sigma_m T) \leq \exp (-\rho M_1), \] 
it suffices that \(\epsilon\) be sufficiently small and \(b\) sufficiently large so that \((M + \epsilon)q^{-1} < M_1\) in order to insure convergence of the integral with respect to \(\rho\), in (69), for every \(x\) in \(\Sigma (b, \beta)\), uniformly in every closed bounded subset of \(\Sigma (b, \beta)\).

Note C (referring to equations (75) and (76) and the following sentence).

Evidently
\[
G^*(x, b) = \int_{u_0}^{u_0} 2(\pi i)^{-1} \int G(t, T, x) P_2(T) dT dt,
\]
where
\[
\Gamma(t, T, x) = e^{W T} \phi(t + b) (t \log q)^{-1},
\]
with \(W = (\log u - \log t) \log q\). Hence
\[
G^*(x, b) = \int_{u_0}^{u_0} \phi(t + b) (t \log q)^{-1} R(x, t) dt,
\]
where \(R(x, t)\) is the residue at \(\xi\) of \(e^{W T} P_2(T)\).

Now
\[
R(x, t) = e^{W T} \frac{1}{2\pi i} \int_{G(x)} \left[ \left( \sum_{m=0}^{\infty} \frac{(T - \xi)^m W^m}{m!} \right) \left( \sum_{j=1}^{\infty} B_{s_2}(T - \xi)^{-j} \right) \right] dT
\]
\[= e^{W T} \sum_{j=1}^{\infty} \frac{B_{s_2} W^{j-1}}{(j - 1)!}.\]

Hence
\[
G^*(x, b) = \int_{0}^{W} \sum_{k=0}^{\infty} \phi_{b k} \exp (\xi e^{-k \log q}) \sum_{j=1}^{\infty} \frac{B_{s_2} W^{j-1}}{(j - 1)!} dW.
\]
where \( W_0 = (\log u - \log u_0) / (\log g) \). Hence

\[
G^*_a(x, b) = \sum_{k \in \mathbb{R}_a} \phi_k u^k \sum_{j=1}^{l} \frac{B_{s,j}}{(j-1)!} \left[ I(s, j, k) + (j-1)! (k \log q - \xi^*_a)^{-j} \right] + \sum_{j=1}^{l} (B_{s,j} W_0^j) / (j!)
\]

where

\[
I(s, j, k) = - e^{\sum_{j=1}^{l} \phi_k u^k \log q} \sum_{m=0}^{j-1} \frac{W_0^{j-1-m}(j-1)!}{(k \log q - \xi^*_a)^{m+1} (j-1-m)!}.
\]

Thus

\[
G^*_a(x, b) = \sum_{k \in \mathbb{R}_a} \phi_k u^k P_s (k \log q) + \sum_{j=1}^{l} \frac{B_{s,j} \left( \log (1 - b^{-1}x) \right)^{j} \log q}{j!} + H(x, b)
\]

where

\[
H(x, b) = G_a(x, b) + H(x, b).
\]

**Note D** (referring to equation (77)).

By the argument of Note C, the left-hand member of (77) equals

\[
\int_{u_1}^{u_2} \phi(t + b) (t \log q)^{-1} \log u \cdot \sum_{k=1}^{l} B_{s,k} \log u - \log t \cdot L_j dt,
\]

where \( L_j = ((j-1)!)^{-1} (\log q)^{j-1} \). Hence the left-hand member of (77) equals

\[
\sum_{m=0}^{j-1} (\log u)^m C_m = H(x, b)
\]

where

\[
C_m = \int_{u_1}^{u_2} \phi(t + b) t^{(1+\xi^*_a)} \sum_{j=1}^{l} D_{s,j} (\log t)^{j-1} dt
\]

with \( D_{s,j} = B_{s,j} (\log q)^{-1} ((j-1-m)!)^{-1} (m!)^{-1} \).

**Note E** (referring to statement (82)).

Let \( \mathcal{S} \) be any closed bounded subset of \( \mathcal{S}(\beta) \). Let \( P \) be the maximum of \( |x| \) in \( \mathcal{S} \), and let \( b \) be greater than \( 3P \). Let \( \delta_1 \) be positive and sufficiently small so that \( \mathcal{S} \subset \mathcal{S}(\beta - \delta_1) \). Let \( x \) be any point of \( \mathcal{S} \).

We note that

\[
(G_{**}^a(x, b) - G_{**}^a(x)) = \int_{0}^{\pi} (2\pi)^{-1} \int_{\mathcal{F}(\xi)} J(x, \xi, T, b) \phi(\xi) F(T) dT d\xi
\]

where
\[ J(x, \xi, T, b) = (\xi - b)^{-1}(\log q)^{-1} e^{VT} - e^{(x-\xi)T}, \]
with \( V \) having the same significance as it had in Lemma 10.

Evidently
\[ J(x, \xi, T, b) = (\xi - b)^{-1}(\log q)^{-1} (e^{VT} - e^{(x-\xi)T}) \]
\[ + ((\xi - b)^{-1}(\log q)^{-1} - 1)e^{(x-\xi)T}. \]

But
\[ e^{VT} - e^{(x-\xi)T} = T \int_{x-\xi}^{V} e^{ar} \, dr. \]

Hence \[ |e^{VT} - e^{(x-\xi)T}| \leq |T| \left| V - (x-\xi) \right| \exp \left( R \left| T \right| \right) \]
where \( R = \max \left( \left| V \right|, \left| x-\xi \right| \right). \)

By Lemma 10a, \( |V| < P2b(b-2P)^{-1} \). By Lemma 10b, \( |V - (x-\xi)| < 2(P+1)^2q^{-1}(b-2P)^{-1}. \)

Hence \[ |e^{VT} - e^{(x-\xi)T}| \leq b^{-1}K(\bar{\sigma}) \]
where \( K(\bar{\sigma}) \) is a positive number depending upon \( \bar{\sigma} \) but independent of \( b \) and \( T \), the inequality holding for all \( T \) on \( \mathcal{F}_t(\delta) (s=1, 2, \ldots, p). \)

Also, \( \left| (\xi - b)^{-1}(\log q)^{-1} \right| \leq b(b-P)^{-1} \) (by Lemma 8), and \( \left| (\xi - b)^{-1}(\log q)^{-1} - 1 \right| = \left| (\xi - b)^{-1}(\log q)^{-1} \right| \left( (1 + b \log q) \log q \right) - |x-\xi| \log q \leq b(b-P)^{-1} \left[ (2gb)^{-1} + P(gb)^{-1} \right] \) (by Lemma 8). Thus \( |J(x, \xi, T, b)| \leq K_1(\bar{\sigma})b^{-1}, \)
where \( K_1(\bar{\sigma}) \) is a positive number depending upon \( \bar{\sigma} \) but independent of \( b \) and \( T \), the inequality holding for all \( T \) on \( \mathcal{F}_t(\delta) (s=1, 2, \ldots, p). \)

Since \( \phi(\xi) \) and \( F(T) \), in (E.1), are bounded by a bound independent of \( b \), we conclude that \( G^{**}(x, b) \) approaches \( G^{**}(x) \) as \( b \) becomes infinite, uniformly in \( \bar{\sigma}. \)

Now
\[ Y_m(x, b) - Y_m(x) \]
\[ = (2\pi i)^{-1} \int_{\mathcal{F}_m(\delta)} F(T)(T - B)^{-1} \int_0^\infty \exp (-\rho z_m T) d_m(x, \rho, T, b) \zeta_m d\rho dT \]
where
\[ d_m(x, \rho, T, b) = U_m \phi'(\xi_m) - B\phi(\xi_m) - [\phi'(x + z_m \rho) - B\phi(x + z_m \rho)], \]
with \( \xi_m = b + (x-b) \exp (\rho z_m \log q) \) and with \( U_m = (x-b) \log q \exp (\rho z_m \log q). \)

Evidently
\[ d_m(x, \rho, T, b) = (U_m - 1)\phi'(\xi_m) + [\phi'(\xi_m) - \phi'(x + z_m \rho)] \]
\[ - B[\phi(\xi_m) - \phi(x + z_m \rho)]. \]

Let \( \delta_1 \) be sufficiently small so that every \( z_m \) is in \( S(\beta - \delta_1). \) (We recall that there are only finitely many distinct \( z_m. \) ) Let \( b \) be sufficiently large so that \( \bar{\sigma} \) is in \( S(b, \beta - \delta_1). \) (Cf. Lemma 7c.) Then since \( x \) is in \( S(b, \beta - \delta_1), \) so is \( \xi_m \) (by Lemma
and therefore both \( x + z_m \rho \) and \( \xi_m \) are in \( S(\beta - \delta_i) \). (Cf. Lemma 7b.) Now \( U_m - 1 = x \log g \exp (p_m \log g) - (b \log g + 1) \log g \exp (p_m \log g) - 1 \). Hence by Lemmas 8 and 9a we have \(| U_m - 1 | \leq b - g^{-1} | x | + (2g b)^{-1} (b^2)^{-1} \rho \leq (b^2)^{-1} (| x | + \rho + 1) \). Also \( \phi'(\xi_m) \leq C_1(\epsilon, \delta_i) \exp \left[ (M + \epsilon) | \xi_m | \right] \), and since (by Lemma 9b) \(| \xi_m | \leq | x | + g^{-1} \rho \), we have \(| \phi'(\xi_m) \leq C_1(\epsilon, \delta_i) \exp \left[ (M + \epsilon) g^{-1} \cdot (| x | + \rho) \right] \). Now \( \phi'(\xi_m) - \phi'(x + z_m \rho) = \int_{x + z_m \rho}^{\xi_m} \phi''(t) dt \), and since \( t \), on the line segment \( x + z_m \rho, \xi_m \), is not more than \(| x | + g^{-1} \rho \), we conclude that \(| \phi'(\xi_m) - \phi'(x + z_m \rho) | \leq \phi'_{\xi_m} \leq | x | + (2g)^{-1} \rho \). By Lemma 9c we have \(| \phi'(\xi_m) - \phi'(x + z_m \rho) | \leq (6g^2)^{-1} \rho \). Hence \(| \phi'(\xi_m) - \phi'(x + z_m \rho) | \leq K_2(\rho)(\rho + 1)^{b - 1} \exp [p(\rho + 1)^{g - 1}] \), where \( K_2(\rho) \) is a positive number independent of \( \rho \) and \( \rho \), the inequality holding for every \( \rho \) and for every non-negative \( \rho \). Similarly \(| \phi'(\xi_m) - \phi'(x + z_m \rho) | \leq K_3(\rho)(\rho + 1)^{b - 1} \exp [p(\rho + 1)^{g - 1}] \), where \( K_3(\rho) \) has properties similar to those of \( K_2(\rho) \). Thus \(| \phi'_{\xi_m} \leq | x | + (2g)^{-1} \rho \). By Lemma 9d we have \(| \phi'_{\xi_m} \leq K_4(\rho)(\rho + 1)^{b - 1} \exp [p(\rho + 1)^{g - 1}] \), where \( K_4(\rho) \) has properties similar to those of \( K_3(\rho) \). This from it follows that if \( \epsilon \) is sufficiently small and \( b \) is sufficiently large, \(| \phi'_{\xi_m} \leq K_5(\rho)(\rho + 1)^{b - 1} \exp [p(\rho + 1)^{g - 1}] \), where \( K_5(\rho) \) is a positive number independent of \( \rho \). Hence, if \( T_m \) is a point of \( \mathcal{Y}(\delta) \) minimizing \(| T - B | \), and \( W_m \) is a point of \( \mathcal{Y}(\delta) \) minimizing \( \text{Re}(\xi_m W) \), then \(| Y_m(x, b) - Y_m(x) \) \leq \( | N - 1 | \delta | L(\delta) |^{-1} T_m - B | \cdot b^{-1} K_5(\rho)(\rho + 1)^{b - 1} \exp [p(\rho + 1)^{g - 1}] \). Also, \(| F_{XY} | \leq | x | + b \cdot | x | + | \omega_i | / g \) (by Lemma 9a). Let \( \epsilon \) be any positive number. Let \( \delta_i = \beta - \beta_i \). If \( b > b_0 \) and if \( x \) is in \( S(\delta_i) \), \( g^{\omega_i} x \) is in \( S(\beta_i) \). Hence \( T_{\omega_i} x \) is in \( S(\beta_i) \) \( (j = 1, 2, \ldots, n) \). Also, \( | T_{\omega_i} x | \leq | x | + b \cdot | x | + | \omega_i | / g \) (by Lemma 9a). Let \( \epsilon \) be any positive number. Let \( \delta_i = \beta - \beta_i \). If \( b > b_0 \) and if \( x \) is in \( S(\delta_i) \), then \(| \eta(T_{\omega_i} x) | \leq d_0(\epsilon, \delta_i) \exp [ | T_{\omega_i} x | (M + \epsilon) ] \leq d_0(\epsilon, \delta_i) \exp [ | x | (M + \epsilon) ] \exp (| (M + \epsilon)(\omega_i | / g) \). Obviously \( \eta(T_{\omega_i} x) \) is analytic if \( x = 0 \). Hence \( \eta(T_{\omega_i} x) \) is of type \((M, \beta_i)\). Hence \( \psi(x, b) \) is of type \((M, \beta_0)\).
Bibliography


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