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Santa Barbara

Reflecting Solutions of High Order Elliptic
Differential Equations in Two Independent
Variables Across Analytic Arcs

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ABSTRACT

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by

Oleg Carleton

Consideration is given specifically to sixth order elliptic partial
differential equations in two independent real variables \( x, y \) such that
the coefficients of the highest order terms are real constants. It is
assumed that the differential operator has distinct characteristics
and that it can be factored as a product of second order operators of
the form

\[
\Delta_k + a_k(x_k, y_k) \frac{\partial}{\partial x_k} + b_k(x_k, y_k) \frac{\partial}{\partial y_k} + c_k(x_k, y_k)
\]

where \( x_k \) and \( y_k \) are real variables determined from the character-
istics, \( \Delta_k = \frac{\partial^2}{\partial x_k^2} + \frac{\partial^2}{\partial y_k^2} \) and the coefficients \( a_k, b_k, c_k \) are, in
general, complex-valued analytic functions of their arguments. This
class of equations includes those examined by Sloss. By analytically
continuing into the complex domain and using the complex character-
istic coordinates of the differential equation, it is shown that its solu-
tions, \( u \), may be reflected across analytic arcs on which \( u \) satisfies
certain analytic boundary conditions. Moreover, a method is given
whereby one can determine a region into which the solution is ex-
tensible. It is seen that this region of reflection is dependent on the
original domain of definition of the solution, the arc and the coefficients of the highest order terms of the equation and not on any "sufficiently small" quantities; i.e., the reflection is global in nature. The method employed may be applied to similar differential equations of order $2n$. Finally, included are some figures illustrating the region of reflection with respect to various arcs for two specific sixth order equations having no lower order terms.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>Chapter I. Representation of Second Order Equations</td>
<td></td>
</tr>
<tr>
<td>§ 1. Continuation into the complex domain</td>
<td>5</td>
</tr>
<tr>
<td>§ 2. The Riemann function</td>
<td>8</td>
</tr>
<tr>
<td>§ 3. A representation for solutions of Equation (1.1)</td>
<td>11</td>
</tr>
<tr>
<td>Chapter II. Reflection</td>
<td></td>
</tr>
<tr>
<td>§ 1. Geometric reflection across an analytic arc</td>
<td>30</td>
</tr>
<tr>
<td>§ 2. Statement of the problem and notation</td>
<td>35</td>
</tr>
<tr>
<td>§ 3. Equation (2.5) as a system</td>
<td>40</td>
</tr>
<tr>
<td>§ 4. Reflecting solutions of Equation (2.5)</td>
<td>42</td>
</tr>
<tr>
<td>§ 5. Concluding remarks and illustrations</td>
<td>70</td>
</tr>
<tr>
<td>Bibliography</td>
<td>79</td>
</tr>
<tr>
<td>Figure 1.1</td>
<td>14</td>
</tr>
<tr>
<td>------------</td>
<td>----</td>
</tr>
<tr>
<td>Figure 1.2</td>
<td>15</td>
</tr>
<tr>
<td>Figure 2.1</td>
<td>44</td>
</tr>
<tr>
<td>Figure 2.2</td>
<td>49</td>
</tr>
<tr>
<td>Figure 2.3</td>
<td>66</td>
</tr>
<tr>
<td>Figure 2.4</td>
<td>68</td>
</tr>
<tr>
<td>Figure 2.5</td>
<td>75</td>
</tr>
<tr>
<td>Figure 2.6</td>
<td>76</td>
</tr>
<tr>
<td>Figure 2.7</td>
<td>77</td>
</tr>
<tr>
<td>Figure 2.8</td>
<td>78</td>
</tr>
</tbody>
</table>
INTRODUCTION

In this paper, we wish to examine the reflection problem for a class of elliptic partial differential equations that generalizes the type of equations Sloss considered in [7]. Since the geometry of the problem is better illustrated by equations of order greater than four, while equations of order greater than six add nothing new to the understanding of the reflection process presented here, we shall limit our discussion to equations of order six. In particular, we shall consider a sixth order elliptic equation

\[ L[u] = \sum_{0 \leq i+j \leq 6} c_{ij} \frac{\partial^{i+j} u}{\partial x^i \partial y^j} = 0 \]

in two independent real variables \(x, y\) such that the coefficients of the highest order terms are real constants. We assume that this equation has distinct characteristics and that it can be factored as

\[ L[u] = \prod_{k=1}^{3} \left[ \Delta_k + a_k \frac{\partial}{\partial x_k} + b_k \frac{\partial}{\partial y_k} + c_k \right] u = 0. \]

Here, \(x_k\) and \(y_k\) are real variables determined from the complex characteristics, \(\Delta_k = \frac{\partial^2}{\partial x_k^2} + \frac{\partial^2}{\partial y_k^2}\) and the coefficients \(a_k, b_k, c_k\) are complex-valued analytic functions of \(x_k\) and \(y_k\). We
propose to write (0, 2) as a system of three second order equations and to assign a general first order analytic boundary condition to each equation of the system. By analytically continuing into the complex domain and using the complex characteristic coordinates of (0, 1), we show that solutions, $u$, of Equation (0, 1) may be reflected across analytic arcs on which $u$ satisfies the above-mentioned boundary conditions and, moreover, that this reflection can be carried out in the large. That is to say, we present a method to determine a region into which the solutions can be reflected which depends only on the original domain of definition, the arc, the characteristic coordinates and, possibly, on the choice of certain simply-connected domains.

The problem of reflecting solutions of elliptic partial differential equations in two independent variables by analytic continuation into the complex domain was pioneered by H. Lewy. In a very nice paper, [5], he thoroughly treated the case of a linear second order elliptic equation with analytic coefficients. He showed that if $D$ is a simply-connected domain lying in the half-plane, say $y < 0$, having a segment $\kappa$ of the $x$-axis as part of its boundary and such that $D$ contains the portion $y < 0$ of a neighborhood of each point of $\kappa$, then $u$ can be analytically continued as a
solution into the entire mirror image, $\overline{D}$, of $D$ across $\kappa$. Garabedian [3] has examined the problem for second order analytic quasi-linear elliptic equations and indicated how his method may be applied to systems of such equations. In a recent paper, Kraft [4] modified Garabedian's techniques to treat first order elliptic quasi-linear systems in two independent variables. Since both Garabedian and Kraft dealt with nonlinear equations, their results concerning analytic continuation were strictly local and shed no light on the domain of reflection.

As concerns higher order equations and reflection in the large, Sloss [6] has continued solutions of the biharmonic equation across analytic arcs and Brown [1] has investigated the general fourth order elliptic equation with constant coefficients. However, Brown had to restrict himself to convex domains and he reflected only across segments of the $x$-axis. In [7], Sloss reflected solutions of elliptic equations of order $2n$ with constant coefficients and with no lower order terms across analytic arcs.

The method of Garabedian and Brown consists of transforming the original elliptic equation in two real variables into a hyperbolic equation in three real variables and then examining certain three dimensional Cauchy problems. This differs from the method of
Lewy and Sloss who utilize the complex characteristic coordinates of the elliptic equation to perform the extension. In this paper, we propose to adapt the techniques of Lewy and Sloss.

Before proceeding, we would like to introduce some notation.

Let $S$ be a set in the complex plane. We will consistently use the notation $\overline{S}$ to denote the set $\{ \overline{z} : z \in S \}$ where $z$ is a complex number and the bar denotes complex conjugation.

**Definition 0.1.** Let $D$ be a simply-connected domain in the $x, y$-plane having an arc $\kappa$ as part of its boundary. If every point $z_o = x_o + iy_o$ on $\kappa$ can be joined to every point $z = x + iy$ in $D$ by a rectifiable curve which, except for the end point $z_o$, lies entirely in $D$, then $D$ is said to be adjacent to $\kappa$.

Finally, unless stated otherwise, we shall deal exclusively with simply-connected domains whose boundaries are closed rectifiable Jordan curves.
CHAPTER I

§1. Continuation into the Complex Domain.

For the most part, we shall be dealing with differential operators of the form

\[ L = \Delta + a(x, y) \frac{\partial}{\partial x} + b(x, y) \frac{\partial}{\partial y} + c(x, y), \]

where \( \Delta = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \) is the Laplacian and \( a, b, c \) are, in general, complex-valued analytic functions of the real variables \( x, y \). For this reason, we devote the present chapter to a consideration of the equation

\[ L[u] = \Delta u + a(x, y) \frac{\partial u}{\partial x} + b(x, y) \frac{\partial u}{\partial y} + c(x, y) u = 0. \]

Our goal is to obtain a suitable representation for the solutions of this equation in terms of analytic functions of a complex variable. We shall use as a guide the presentation given by Vekua in [8], chapter 1.

Let \( z = x + iy \) (\( x \) and \( y \) real) and \( U(z, \bar{z}) = u \left( \frac{z + \bar{z}}{2}, \frac{z - \bar{z}}{2i} \right) = u(x, y) \).

If we formally define the operations

\[ \frac{\partial}{\partial z} = \frac{1}{2} \left( \frac{\partial}{\partial x} - i \frac{\partial}{\partial y} \right), \quad \frac{\partial}{\partial \bar{z}} = \frac{1}{2} \left( \frac{\partial}{\partial x} + i \frac{\partial}{\partial y} \right) \]

then Equation (1.1) can be written as

\[ \frac{\partial^2 U}{\partial z \partial \bar{z}} + A(z, \bar{z}) \frac{\partial U}{\partial z} + B(z, \bar{z}) \frac{\partial U}{\partial \bar{z}} + C(z, \bar{z}) U = 0, \]

where
\[ A(z, \zeta) = \frac{1}{4} \left[ a \left( \frac{z + \zeta}{2} \right) \left( \frac{z - \zeta}{2i} \right) + ib \left( \frac{z + \zeta}{2} \right) \left( \frac{z - \zeta}{2i} \right) \right] , \]

\[ B(z, \zeta) = \frac{1}{4} \left[ a \left( \frac{z + \zeta}{2} \right) \left( \frac{z - \zeta}{2i} \right) - ib \left( \frac{z + \zeta}{2} \right) \left( \frac{z - \zeta}{2i} \right) \right] , \]

\[ C(z, \zeta) = \frac{1}{4} \left[ c \left( \frac{z + \zeta}{2} \right) \left( \frac{z - \zeta}{2i} \right) \right] . \]

(1.4)

It must be kept in mind that (1.3) is purely a symbolic form of the Equation (1.1). If it happens that \( U(z, \bar{z}) \) is an analytic function of \( z \) and \( \bar{z} \) then the operators \( \frac{\partial}{\partial z} \) and \( \frac{\partial}{\partial \bar{z}} \) defined in (1.2) become true derivatives with respect to \( z \) and \( \bar{z} \); that is,

\[ \frac{\partial}{\partial z} U(z, \bar{z}) = \frac{\partial}{\partial z} U(z, \zeta) \bigg|_{\zeta=z} , \]

\[ \frac{\partial}{\partial \bar{z}} U(z, \bar{z}) = \frac{\partial}{\partial \bar{z}} U(z, \zeta) \bigg|_{\zeta=\bar{z}} , \]

where \( \zeta \) is a complex variable independent of \( z \). This prompts us to consider the following equation:

\[ \mathcal{L}[U] = \frac{\partial^2 U}{\partial z \partial \bar{z}} + A(z, \zeta) \frac{\partial U}{\partial z} + B(z, \zeta) \frac{\partial U}{\partial \bar{z}} + C(z, \zeta) U = 0 . \]

(1.5)

**Definition 1.1.** Let \( \Omega \) be a simply-connected domain in the complex plane such that \( A(z, \zeta) \), \( B(z, \zeta) \) and \( C(z, \zeta) \) given in (1.4) are analytic functions of the two independent complex variables \( z, \zeta \) in the poly-cylindrical region \( (\Omega, \overline{\Omega}) = \{ (z, \zeta) : z \in \Omega, \zeta \in \overline{\Omega} \} \). Then \( \Omega \) is said to be a fundamental domain for Equation (1.1) or for Equation (1.5).
We remark that if the coefficients of Equation (1.1) are entire functions of their arguments, then $A$, $B$ and $C$ of Equation (1.5) will be entire functions of $z$ and $\zeta$ and in this case, any simply-connected domain in the complex plane may serve as a fundamental domain for (1.1).

Vekua shows that if $\Omega$ is a fundamental domain for Equation (1.1) and if $u(x, y)$ is given as a regular solution of (1.1) in $\Omega$ (i.e., $u$ has continuous first and second partial derivatives in $\Omega$), then $u$ is in fact analytic in $x$ and $y$, and the function $U(z, \zeta) = u\left(\frac{z + \zeta}{2}, \frac{z - \zeta}{2i}\right)$ is analytic for $(z, \zeta) \in (\Omega, \overline{\Omega})$ and satisfies Equation (1.5) in that region. On the other hand, if $U(z, \zeta)$ is given to be a solution of (1.5) in $(\Omega, \overline{\Omega})$ (and so necessarily an analytic function of $z$ and $\zeta$), then restriction to the real manifold $\zeta = \overline{z}$ gives $U(z, \overline{z}) = u(x, y)$ as an analytic function of the real variables $x$, $y$ which satisfies Equation (1.1) in $\Omega$.

Thus, from the preceding discussion, it is evident that Equations (1.1) and (1.5) are in a certain sense equivalent, and that to investigate the solutions of (1.1) we may work with Equation (1.5) and then restrict the results to the real manifold $\zeta = \overline{z}$. We point out that (1.5) has the same form as a real hyperbolic equation. We shall take advantage of this fact to obtain a representation for the solutions of (1.1).
§2. The Riemann Function.

In a manner completely analogous to the real case, the adjoint equation relative to (1.5) is defined to be

\[ \mathcal{L}^*[V] = \frac{\partial^2 V}{\partial z \partial \zeta} - \frac{\partial (AV)}{\partial z} - \frac{\partial (BV)}{\partial \zeta} + CV = 0. \]

A straightforward calculation serves to establish the fundamental identity

\[ V\mathcal{L}[U] - U\mathcal{L}^*[V] = \frac{\partial}{\partial z} \left( V \frac{\partial U}{\partial \zeta} + AV \right) + \frac{\partial}{\partial \zeta} \left( -U \frac{\partial V}{\partial z} + BV \right), \]

which is valid for any two functions \( U(z, \zeta) \) and \( V(z, \zeta) \) analytic in a common region \((z, \zeta) \in (\Omega, \overline{\Omega})\).

**Definition 1.2.** Let \( \Omega \) be a fundamental domain for Equation (1.1). The Riemann Function, \( R(z, \zeta; t, \tau) \), for (1.1) (or, for Equation (1.5)) is an analytic function of four complex variables \( z, t \) in \( \Omega \), \( \zeta, \tau \) in \( \overline{\Omega} \) which satisfies

\[ \mathcal{L}^*[R] = \frac{\partial^2 R}{\partial z \partial \zeta} - \frac{\partial (AR)}{\partial z} - \frac{\partial (BR)}{\partial \zeta} + CR = 0 \]

with respect to the variables \( z \) and \( \zeta \), and the conditions

\[ R(t, \zeta; t, \tau) = \exp \left[ \int_{\tau}^{\zeta} A(t, \eta) \, d\eta \right], \]

(1.9) \[ R(z, \tau; t, \tau) = \exp \left[ \int_{t}^{z} B(\xi, \tau) \, d\xi \right], \]
where $t$ and $\tau$ are fixed parameters in $\Omega$ and $\overline{\Omega}$, respectively.

The existence and uniqueness of the Riemann function may be established by first writing (1.8) in the form

$$
(1.10) \quad \frac{\partial^2}{\partial z \partial \zeta} \left[ R(z, \zeta; t, \eta) - \int_{\tau}^{\zeta} A(z, \eta) R(z, \eta; t, \tau) d\eta 
\right.
- \int_{t}^{z} B(\xi, \zeta) R(\xi, \zeta; t, \tau) d\xi

+ \int_{t}^{z} d\xi \int_{\tau}^{\zeta} C(\xi, \eta) R(\xi, \eta; t, \tau) d\eta \right] = 0
$$

and then integrating with respect to $z$ and $\zeta$ to get

$$
(1.11) \quad R(z, \zeta; t, \tau) - \int_{\tau}^{\zeta} A(z, \eta) R(z, \eta; t, \tau) d\eta - \int_{t}^{z} B(\xi, \zeta) R(\xi, \zeta; t, \tau) d\xi

+ \int_{t}^{z} d\xi \int_{\tau}^{\zeta} C(\xi, \eta) R(\xi, \eta; t, \tau) d\eta = 1,
$$

since (1.9) implies that $R(t, \tau; t, \tau) = 1$. In view of the fact that conditions (1.9) are equivalent to the conditions

$$
\frac{\partial}{\partial \zeta} R(t, \zeta; t, \tau) - A(t, \zeta) R(t, \zeta; t, \tau) = 0,
$$

(1.12) \quad \frac{\partial}{\partial z} R(z, \tau; t, \tau) - B(z, \tau) R(z, \tau; t, \tau) = 0,

$$
R(t, \tau; t, \tau) = 1,
$$

it is not difficult to verify that any solution of Equation (1.11) satisfies
(1.8) and conditions (1.9) and so must be the Riemann function for (1.1). But, the integral equation (1.11) is of Volterra type which, as Vekua shows, has a unique analytic solution for $z, t$ in $\Omega$ and $\zeta, \tau$ in $\overline{\Omega}$. Thus, the existence and uniqueness of the Riemann function is guaranteed.

Just as in the real case, it can be shown that as a function of its last two arguments, $t$ and $\tau$, the Riemann function for (1.5) satisfies Equation (1.5) and the conditions

\begin{align*}
\frac{\partial}{\partial \tau} R(z, \zeta; z, \tau) + A(z, \tau) R(z, \zeta; z, \tau) &= 0 , \\
\frac{\partial}{\partial t} R(z, \zeta; t, \zeta) + B(t, \zeta) R(z, \zeta; t, \zeta) &= 0 , \\
R(z, \zeta; z, \zeta) &= 1 ;
\end{align*}

i.e., with respect to the variables $t$ and $\tau$, the function $R(z, \zeta; t, \tau)$ is the Riemann function for the adjoint equation (1.6).

In case the coefficients $a, b, c$ of Equation (1.1) are all real valued, the Riemann function, $R(z, \zeta; t, \tau)$, for (1.5) has the additional important property that it assumes real values when $\zeta = \overline{z}$ and $\tau = \overline{t}$ (see [8], § 12).
§ 3. A Representation for Solutions of Equation (1.1).

In order to obtain a representation for the solutions of Equation (1.1) that will lend itself to reflection across analytic arcs $\kappa$, it is necessary to examine what happens to the solutions of Equation (1.5) as $z$ and $\zeta$ are allowed to approach $\kappa$ and $\bar{\kappa}$, respectively. Towards this end, we adapt the techniques of Lewy, [5], to establish the following lemma.

Lemma 1.1. Let $D$ be a simply-connected domain adjacent to an arc $\kappa$ such that $D \cup \kappa$ is contained in a fundamental domain for Equation (1.1). Let $u(x, y)$ be given as a regular solution of (1.1) in $D$ and let $U(z, \zeta) = u\left(\frac{z + \zeta}{2}, \frac{z - \zeta}{2i}\right)$. If $u(x, y)$ and its first partial derivatives are continuous in $D \cup \kappa$, then for any pair of fixed points $z_0 \in D \cup \kappa$, $\zeta_0 \in D \cup \kappa$, the functions $U(z, \zeta_0)$ and $U(z_0, \zeta)$ (and therefore $U(z_0, \zeta_0)$) are analytic for $z \in D$ and $\zeta \in \bar{D}$, respectively. Furthermore, $\frac{\partial U(z, \zeta_0)}{\partial z}$ (and therefore $U(z, \zeta_0)$) is continuous on $D \cup \kappa$ while $\frac{\partial U(z_0, \zeta)}{\partial \zeta}$ (and therefore $U(z_0, \zeta)$) is continuous on $\overline{D \cup \kappa}$.

Proof: Replace $V$ in Equation (1.7) by the Riemann function $R(z, \zeta; t, \tau)$. Keeping in mind that $U(z, \zeta)$ satisfies (1.5) in $(D, \bar{D})$, identity (1.7) becomes
\[ \frac{\partial}{\partial z} \left( R \frac{\partial U}{\partial \zeta} + ARU \right) + \frac{\partial}{\partial \zeta} \left( -U \frac{\partial R}{\partial z} + BRU \right) = 0. \]

Using the fact that \( R \frac{\partial U}{\partial \zeta} = \frac{\partial (RU)}{\partial \zeta} - U \frac{\partial R}{\partial \zeta} \), we rewrite this relation as

\[ (1.14) \quad - \frac{\partial^2}{\partial z \partial \zeta} \left[ R(z, \zeta; t, \tau) U(z, \zeta) \right] + \frac{\partial}{\partial z} \left[ U \left( \frac{\partial R}{\partial \zeta} - AR \right) \right] + \frac{\partial}{\partial \zeta} \left[ U \left( \frac{\partial R}{\partial z} - BR \right) \right] = 0. \]

Now interchange the pairs \((z, \zeta)\) and \((t, \tau)\) in \((1.14)\) and set

\[ P(t, \tau; z, \zeta) = \frac{\partial}{\partial t} \left[ R(t, \tau; z, \zeta) U(t, \tau) \right] - U \left( \frac{\partial R}{\partial t} - BR \right), \]
\[ Q(t, \tau; z, \zeta) = U(t, \tau) \left( \frac{\partial R}{\partial \tau} - AR \right) \]

to obtain

\[ (1.15) \quad \frac{\partial}{\partial t} Q(t, \tau; z, \zeta) - \frac{\partial}{\partial \tau} P(t, \tau; z, \zeta) = 0, \]

where \((t, \tau)\) varies in \((D, \overline{D})\) and \((z, \zeta)\) is arbitrarily fixed in \((D, \overline{D})\).

Pick a point \( \overline{\zeta}_0 \) on \( \kappa \) and a point \( z \) in \( D \) and join them by a rectifiable curve, \( C \), lying in \( D \). Let \( \overline{C} \) be the conjugate path lying in \( D \) having \( \zeta_0 \) and \( \overline{z} \) as end points. Fix a point \( \zeta \) on \( \overline{C} \), \( \zeta \) not equal to \( \zeta_0 \) or \( \overline{z} \). Denote the part of \( \overline{C} \) joining \( \zeta \) and \( \overline{z} \) by \( \overline{C}_\zeta \). Then \( C_{\zeta} \) is that part of \( C \) joining \( \overline{\zeta} \) and \( z \) (see Figure 1.1). We form the Cartesian product \( S_{\zeta}^2 = C_{\zeta} \times \overline{C}_\zeta \) and define

\[ d_{\zeta} = \{ (t, \overline{t}) : t \in C_{\zeta} \}. \]
We shall refer to $d_\zeta$ as the diagonal of $S_\zeta$.

We now integrate * the functions $\frac{\partial P}{\partial \tau}$ and $\frac{\partial Q}{\partial t}$ which appear in relation (1.15) over the "triangle" whose sides are $d_\zeta$, $(t, \zeta) : t \in C_\zeta$ and $[(z, \tau) : \tau \in \overline{C}_\zeta]$ (see Figure 1.2) in the following way:

\begin{equation}
\int_\zeta^z \frac{\partial P(t, \tau; z, \zeta)}{\partial \tau} d\tau = \int_\zeta^z [P(t, t; z, \zeta) - P(t, z, \zeta)] dt ,
\end{equation}

\begin{equation}
\int_\zeta^z \frac{\partial Q(t, \tau; z, \zeta)}{\partial t} d\tau = \int_\zeta^z [Q(t, t; z, \zeta) - Q(t, z, \zeta)] dt ,
\end{equation}

In view of conditions (1.12) satisfied by the Riemann function, we have

\begin{equation}
\int_\zeta^z P(t, \zeta; z, \zeta) dt = \int_\zeta^z \frac{\partial}{\partial t} [R(t, \zeta; z, \zeta) U(t, \zeta)] dt = U(z, \zeta) - U(t, \zeta) R(t, \zeta; z, \zeta) ,
\end{equation}

and

\begin{equation}
\int_\zeta^z Q(z, \tau; z, \zeta) d\tau = 0 .
\end{equation}

* The steps involving integrations over the triangle pictured in Figure 1.2 can be fully justified by parametrizing the curves $C$ and $\overline{C}$ with respect to two real parameters varying over a common interval and then decomposing the complex line integrals in the usual way as a sum of real integrals.
Figure 1.1
Figure 1.2
Where, subtracting (1.16) from (1.17) and taking into account (1.15), we obtain the formula

\[ (1.18) \quad U(z, \zeta) = U(\zeta, \zeta) R(\zeta, \zeta; z, \zeta) + \int \frac{\partial R}{\partial t} R(t, t; z, \zeta) U(t, \bar{t}) dt + \int P(t, t; z, \zeta) dt + \int Q(t, t; z, \zeta) dt \]

where

\[ (1.19) \quad \int P(t, \bar{t}; z, \zeta) dt + \int Q(t, \bar{t}; z, \zeta) dt = \int P(t, \bar{t}; z, \zeta) dt + \int Q(t, \bar{t}; z, \zeta) dt \]

is a line integral over that part of the diagonal of \( S^2_x \) from \( \zeta, \zeta \) to \( (z, \bar{z}) \), and where we have replaced \( \tau \) by \( \bar{t} \). Reverting to the real variables \( x \) and \( y \) through the transformation

\[ x = \frac{t + \bar{t}}{2}, \quad y = \frac{t - \bar{t}}{2i} \]

and writing \( dt = dx + i dy \), \( d\bar{t} = dx - i dy \), it is seen that (1.19) is actually a line integral over the path \( C_\zeta \) in \( D \). Keeping in mind that

\[ \frac{\partial}{\partial t} = \frac{1}{2} \left( \frac{\partial}{\partial x} - i \frac{\partial}{\partial y} \right), \quad \frac{\partial}{\partial \bar{t}} = \frac{1}{2} \left( \frac{\partial}{\partial x} + i \frac{\partial}{\partial y} \right) \]

it is then easily checked that the condition
is equivalent to the familiar condition that (1.19) be independent of the path. But the truth of (1.20) is immediate from (1.15) when \( \tau \) is restricted to be \( \overline{t} \).

Since \( U(t, \overline{t}) = u(x, y) \) as well as its first partial derivatives are continuous on \( D \cup \kappa \), we may let the variable \( \zeta \) approach \( \zeta_o \) in Formula (1.18) to obtain

\[
U(z, \zeta_o) = U(\zeta_o, \zeta_o) + \int_{\zeta_o}^z \left[ \frac{\partial}{\partial \bar{t}} R(t, \bar{t}; z, \zeta_o) + \frac{\partial}{\partial t} U(t, \bar{t}) \right] \, dt + \int_{\zeta_o}^z U(t, \bar{t}) \left[ \frac{\partial}{\partial \bar{t}} R(t, \bar{t}; z, \zeta_o) - AR \right] \, dt,
\]

where the line integral is independent of the path joining \( \zeta_o \) to \( z \). Formula (1.21) is valid for all \( z \) in \( D \) and shows that \( U(z, \zeta_o) \) is continuous on \( D \cup \kappa \). To verify the analyticity of \( U(z, \zeta_o) \) on \( D \), it suffices to check the Cauchy-Riemann equations, \( \frac{\partial}{\partial \bar{z}} U(z, \zeta_o) = 0 \). Since the first two terms of (1.21) depend analytically on \( z \), their derivatives with respect to \( \overline{z} \) are zero.* Calculating the derivative of the last term we get

\* The line integral \( \int_{\zeta_o}^z P(t, \bar{t}; z, \zeta_o) \, dt + \int_{\zeta_o}^z Q(t, \bar{t}; z, \zeta_o) \, dt \) is independent of the path and \( P \) is a continuous function of \( t \) in \( D \) while \( Q \) is a continuous function of \( t \) in \( D \). Whence, by Morera's theorem, the integral \( \int_{\zeta_o}^z P(t, \bar{t}; z, \zeta_o) \, dt \) is an analytic function of its upper limit and \( P(z, \bar{z}; z, \zeta_o) \) is an analytic function of \( z \), while \( \int_{\zeta_o}^z Q(t, \bar{t}; z, \zeta_o) \, dt \) is an analytic function of its upper limit.
\[ \frac{\partial}{\partial \overline{z}} \int_{\overline{z}_0}^{\overline{z}} U(t, \overline{t}) \left[ \frac{\partial}{\partial \overline{t}} R(t, \overline{t}; z, \overline{\zeta}_0) - A(t, \overline{t}) R(t, \overline{t}; z, \overline{\zeta}_0) \right] \, d\overline{t} \]

\[ = U(z, \overline{z}) \left[ \frac{\partial}{\partial \overline{\zeta}} R(z, \overline{\zeta}; z, \overline{\zeta}_0) - A(z, \overline{\zeta}) R(z, \overline{\zeta}; z, \overline{\zeta}_0) \right] = 0, \]

where the last equality follows from (1.12). Thus \( U(z, \overline{\zeta}_0) \) is indeed an analytic function of \( z \) in \( D \), and therefore so also is \( \frac{\partial U(z, \overline{\zeta}_0)}{\partial \overline{z}} \). Differentiating the right hand side of (1.21) with respect to \( z \) gives

\[ \frac{\partial U(z, \overline{\zeta}_0)}{\partial \overline{z}} = U(\overline{z}_0, \overline{\zeta}_0) \frac{\partial}{\partial \overline{z}} R(\overline{z}_0, \overline{\zeta}_0; z, \overline{\zeta}_0) + P(z, \overline{z}; z, \overline{\zeta}_0) \]

\[ + \int_{\overline{z}_0}^{\overline{z}} \frac{\partial}{\partial \overline{z}} P(t, \overline{t}; z, \overline{\zeta}_0) \, dt + \int_{\overline{z}_0}^{\overline{z}} \frac{\partial}{\partial \overline{z}} Q(t, \overline{t}; z, \overline{\zeta}_0) \, dt, \]

which is a continuous function of \( z \) in \( D \cup K \).

The desired analyticity and continuity of \( U(z_0, \zeta) \) and \( \frac{\partial U(z_0, \zeta)}{\partial \overline{\zeta}} \) may be established by replacing \( z \) with \( z_0 \) in Equation (1.18) and interchanging the limits of integration in (1.19) to get

(1.22) \[ U(z_0, \zeta) = U(\overline{z}_0, \overline{\zeta}) R(\overline{z}_0, \overline{\zeta}; z_0, \zeta) - \int_{z_0}^{\overline{z}} \left[ \frac{\partial}{\partial \overline{t}} \left[ U(t, \overline{t}) R(t, \overline{t}; z_0, \zeta) \right] \right] \]

\[ - U \left( \frac{\partial R}{\partial \overline{t}} - BR \right) \] \[ + \int_{z_0}^{\overline{z}} U(t, \overline{t}) \left[ \frac{\partial R}{\partial \overline{t}} - AR \right] \, dt. \]

This formula shows that \( U(z_0, \zeta) \) is continuous for \( \zeta \) in \( D \cup K \). To check the Cauchy-Riemann equations, differentiate (1.22) with respect to \( \overline{\zeta} \). Taking into account Condition (1.12) and the fact that the last
term on the right hand side is an analytic function of $\zeta$, this calculation gives $\frac{\partial U(z_0, \zeta)}{\partial \zeta} = 0$. Thus, $U(z_0, \zeta)$ as well as $\frac{\partial U(z_0, \zeta)}{\partial \zeta}$ are analytic functions of $\zeta$ in $D$. Finally, differentiating (1.22) with respect to $\zeta$ shows that $\frac{\partial U(z_0, \zeta)}{\partial \zeta}$ is continuous for $\zeta$ in $D \cup \kappa$.

To finish the proof, we point out that when $z_0 \in D$ and $z_0 \in D$, the analyticity of $U(z, \xi)$ and $U(z_0, \zeta)$ follows immediately from the analyticity of $U(z, \zeta)$ in $(D, \bar{D})$. The expressed continuity of $\frac{\partial U(z, \xi)}{\partial z}$ and $\frac{\partial U(z_0, \zeta)}{\partial \zeta}$ is seen by replacing $\xi$ or $z$ by $\xi_0$ or $z_0$, respectively, in Formula (1.18) and then performing the necessary differentiation. This completes the proof of the lemma.

An important property of the solutions of Equation (1.5) in case the coefficients $a(x, y), b(x, y), c(x, y)$ of Equation (1.1) are real-valued functions is given by the following theorem.

**Theorem 1.1** Let $D$ and $\kappa$ be given as in the statement of Lemma 1.1. Assume that the coefficients $a(x, y)$ and $b(x, y)$ of Equation (1.1) are real-valued functions. Let $u(x, y)$ be a real-valued regular solution of (1.1) in $D$ such that $u$ and its first partial derivatives are continuous in $D \cup \kappa$. Let $U(z, \zeta) = u \left( \frac{z + \zeta}{2i}, \frac{z - \zeta}{2i} \right)$. If $z_0$ is a fixed point on $\kappa$, then

$$U(z, z_0) = \frac{U(z_0, \bar{z})}{\frac{\partial U(z_0, \zeta)}{\partial z}} = \frac{\partial U(z_0, \bar{z})}{\partial \bar{z}}$$

for $z$ in $D \cup \kappa$. Whence, the functions $\varphi(z)$ and $\varphi^*(\zeta)$ given by
\begin{align*}
\phi(z) &= \frac{\partial U(z, z_o)}{\partial z} + B(z, z_o)U(z, z_o) \\
\phi^*(\xi) &= \frac{\partial U(z_o', \xi)}{\partial \xi} + A(z_o, \xi)U(z_o, \xi)
\end{align*}

\text{take complex conjugate values when } \xi = \overline{z}.

\textbf{Proof:} We establish the theorem for the case when } z_o \text{ is in } D \text{ and then let } z_o \text{ approach } \kappa.

\text{Fix } z_o = x_o + i y_o \text{ in } D. \text{ Then } u \text{ has a Taylor series representation in a neighborhood of the point } (x_o, y_o) \text{ given by}

\[ u(x, y) = \sum_{m, n=0}^{\infty} a_{mn} (x-x_o)^m (y-y_o)^n, \]

\text{where the } a_{mn} \text{ are real constants dependent upon } (x_o, y_o). \text{ From this, we obtain}

\[ U(z, \xi) = u\left(\frac{z+\xi}{2}, \frac{z-\xi}{2i}\right) = \sum_{m, n=0}^{\infty} a_{mn} \left(\frac{z+\xi - z_o + \overline{z_o}}{2}\right)^m \left(\frac{z-\xi - z_o + \overline{z_o}}{2i}\right)^n \]

\[ = \sum_{m, n=0}^{\infty} a_{mn} \frac{1}{2^{m+n}} \left(\frac{1}{i}\right)^n \frac{1}{z-z_o} + (\xi - \overline{\xi}) \frac{m}{z-z_o} - (\xi - \overline{\xi}) \frac{n}{z-z_o} \]

\text{which is absolutely and uniformly convergent for } (z, \xi) \text{ in some poly-cylindrical neighborhood of } (z_o, \overline{z_o}). \text{ In particular,}

\[ (1.23) \quad U(z, \overline{z_o}) = \sum_{m+n=0}^{\infty} a_{mn} \frac{1}{2^{m+n}} \left(\frac{1}{i}\right)^n (z - z_o)^{m+n} \]

\text{and}

\[ (1.24) \quad U(z_o, \overline{z}) = \sum_{m+n=0}^{\infty} a_{mn} \frac{1}{2^{m+n}} \left(-\frac{1}{i}\right)^n (z - z_o)^{m+n} . \]
Whence,

\[ U(z_0, \overline{z}) = \sum_{m+n=0}^{\infty} a_{mn} \frac{1}{2^{m+n}} \left( \frac{-1}{i} \right)^n (z - z_0)^{m+n} \]

\[ = \sum_{m+n=0}^{\infty} a_{mn} \frac{1}{2^{m+n}} \left( \frac{1}{i} \right)^n (\overline{z} - z_0)^{m+n} \]

\[ = U(z, \overline{z_0}) \]

for all \( z \) in some neighborhood for \( z_0 \). Since \( U(z, \overline{z_0}) \) and \( U(z_0, \overline{z}) \) are analytic for \( z \) in \( D \) (\( U(z_0, \overline{z}) \) is an antianalytic function of an antianalytic function) and since they agree on a set with a limit point, we may conclude that \( U(z, \overline{z_0}) = U(z_0, \overline{z}) \) throughout all of \( D \). By Lemma 1.1 we can let \( z_0 \) approach \( K \) to conclude that \( U(z, \overline{z_0}) = U(z_0, \overline{z}) \) for \( z_0 \) on \( K \) and \( z \) in \( D \cup K \).

After differentiating expressions (1.23) and (1.24) with respect to \( z \) and \( \overline{z} \), respectively, we may apply the same argument as above to establish that

\[ \frac{\partial U(z, \overline{z}_0)}{\partial z} = \frac{\partial U(z_0, \overline{z})}{\partial \overline{z}} \]

for \( z_0 \) on \( K \) and \( z \) in \( D \cup K \).

To prove the last part of the theorem, let \( \tilde{a}(z, \zeta) = a \left( \frac{z + \zeta}{2}, \frac{z - \zeta}{2i} \right) \) and \( \tilde{b}(z, \zeta) = b \left( \frac{z + \zeta}{2}, \frac{z - \zeta}{2i} \right) \). Then \( \tilde{a}(z, \overline{z}) = \tilde{a}(x, y) \) and \( \tilde{b}(z, \overline{z}) = \tilde{b}(x, y) \) are real analytic functions and so the same argument as above may be used to establish that \( \tilde{a}(z, \overline{z}_0) = \tilde{a}(z_0, z) \) and \( \tilde{b}(z, \overline{z}_0) = \tilde{b}(z_0, \overline{z}) \).
Whence, by the definition of $A(z, \zeta)$ and $B(z, \zeta)$ given in (1.4),

$$4 A(z_0, \bar{z}) = \tilde{a}(z_0, \bar{z}) + i \tilde{b}(z_0, \bar{z})$$

and

$$4 A(z, z) = \tilde{a}(z_0, z) - i \tilde{b}(z_0, z)$$

$$= \tilde{a}(z, z_0) - i \tilde{b}(z, z_0)$$

$$= 4 B(z, z_0).$$

It is now an easy matter to check that $\varphi(z) = \varphi^*(z)$. This completes the proof of the theorem.

We are now ready to write down a representation for the solutions of Equation (1.1) in terms of analytic functions of a complex variable.

**Theorem 1.2.** Let $D$ be a simply-connected domain adjacent to an arc $\kappa$ such that $D \cup \kappa$ is contained in a fundamental domain for Equation (1.1). If $u(x, y)$ is a regular solution of (1.1) in $D$ and if $u$ and its first partial derivatives are continuous in $D \cup \kappa$ and if

$$U(z, \zeta) = u \left( \frac{z + \zeta}{2} , \frac{z - \zeta}{2i} \right),$$

then

$$u(x, y) = \alpha_0 R(z_0, z_0; z, \bar{z}) + \int_{z_0}^{z} \varphi(t) R(t, z_0; z, \bar{z}) \, dt$$

$$+ \int_{z_0}^{\bar{z}} \varphi^*(\tau) R(z_0, \tau; z, \bar{z}) \, d\tau,$$
where \( z = x + iy \) is in \( D \), \( z_0 = x_0 + iy_0 \) is a fixed point on \( \kappa \),
\[
\alpha_0 = U(z_0, \overline{z_0}),
\]
\( R \) is the Riemann function for (1.1) and
\[
\varphi(z) = \frac{\partial U(z, \overline{z_0})}{\partial z} + B(z, \overline{z_0}) U(z, \overline{z_0}),
\]
\[
\varphi^*(\zeta) = \frac{\partial U(z_0, \zeta)}{\partial \zeta} + A(z_0, \zeta) U(z_0, \zeta),
\]
which are analytic functions of \( z \) and \( \zeta \) in \( D \) and \( \overline{D} \) and continuous
in \( D \cup \kappa \) and \( \overline{D \cup \kappa} \) respectively.

Conversely, if \( \alpha_0 \) is an arbitrary constant and \( \varphi(z) \) and \( \varphi^*(\zeta) \)
are arbitrary analytic functions in \( D \) and \( \overline{D} \), continuous in \( D \cup \kappa \) and
\( \overline{D \cup \kappa} \), respectively, then Formula (1.26) represents the regular
solutions of Equation (1.1), continuous in \( D \cup \kappa \).

Remark: If the coefficients \( a(x, y), b(x, y) \) and \( c(x, y) \) of Equation
(1.1) are real-valued functions and if \( u(x, y) \) is a real regular solution of (1.1), then \( \alpha_0 \)
is a real constant, \( R(z_0, \overline{z_0}, z, \overline{z}) \) is a real-valued function and from Theorem 1.1, \( \varphi^*(\zeta) = \varphi(\overline{\zeta}) \) and
\[
R(t, \overline{z_0}; z, \overline{z}) = R(z_0, t; z, \overline{z}).
\]
In this case, Formula (1.26)
may be written as
\[
u(x, y) = \alpha_0 R(z_0, \overline{z_0}; z, \overline{z}) + 2 \Re \left[ \int_{z_0}^{z} \varphi(t) R(t, \overline{z_0}; z, \overline{z}) dt \right].\]
Proof of theorem: In identity (1.7), replace \( V \) by the Riemann function \( R(z, \zeta; t, \tau) \), interchange the ordered pairs \( (z, \zeta) \) and \( (t, \tau) \) and use the fact that \( U(t, \tau) \) satisfies (1.5) in \( t \) and \( \tau \) to get

\[
(1.27) \quad \frac{\partial^2}{\partial t \partial \tau} \left[ U(t, \tau)R(t, \tau; z, \zeta) \right] = \frac{\partial}{\partial t} \left[ U(t, \tau) \left( \frac{\partial R}{\partial \tau} - AR \right) \right] \\
+ \frac{\partial}{\partial \tau} \left[ U(t, \tau) \left( \frac{\partial R}{\partial t} - BR \right) \right].
\]

We wish to integrate the above expression with respect to \( t \) from \( z_o \) to \( z \) and with respect to \( \tau \) from \( \bar{z}_o \) to \( \zeta \). Note that because of Lemma 1.1, \( z_o \) may be taken to be on \( \kappa \).

In view of Conditions (1.12), the above integrals may be evaluated as follows:

\[
(1.28) \quad \int_{z_o}^{z} dt \int_{z_o}^{\zeta} \frac{\partial^2}{\partial t \partial \tau} \left[ U(t, \tau)R(t, \tau; z, \zeta) \right] d\tau
\]

\[
= \int_{z_o}^{z} \frac{\partial}{\partial t} \left[ U(t, \zeta)R(t, \zeta; z, \zeta) - U(t, \bar{z}_o)R(t, \bar{z}_o; z, \zeta) \right] dt
\]

\[
= U(z, \zeta) - U(z, \bar{z}_o)R(z, \bar{z}_o; z, \zeta) - U(z_o, \zeta)R(z_o, \zeta; z, \zeta)
\]

\[
+ U(z_o, \bar{z}_o)R(z_o, \bar{z}_o; z, \zeta),
\]
\[ \int_{z_0}^{z} dt \int_{z_0}^{\zeta} \frac{\partial}{\partial t} \left[ U(t, \tau) \left( \frac{\partial R}{\partial \tau} - AR \right) \right] d\tau \] 

\[ = - \int_{z_0}^{\zeta} U(z_0, \tau) \left( \frac{\partial}{\partial \tau} R(z_0, \tau, z, \zeta) - AR \right) d\tau \] 

\[ = - \int_{z_0}^{\zeta} \frac{\partial}{\partial \tau} \left[ U(z_0, \tau) R(z_0, \tau, z, \zeta) \right] d\tau \] 

\[ + \int_{z_0}^{\zeta} \left( \frac{\partial U}{\partial \tau} + AU \right) R(z_0, \tau, z, \zeta) d\tau \] 

and

\[ \int_{z_0}^{z} dt \int_{z_0}^{\zeta} \frac{\partial}{\partial t} \left[ U(t, \tau) \left( \frac{\partial R}{\partial t} - BR \right) \right] d\tau \] 

\[ = - \int_{z_0}^{\zeta} U(t, z_0) \left( \frac{\partial}{\partial t} R(t, z_0, z, \zeta) - BR \right) dt \] 

\[ = - \int_{z_0}^{\zeta} \frac{\partial}{\partial t} \left[ U(t, z_0) R(t, z_0, z, \zeta) \right] dt \] 

\[ + \int_{z_0}^{\zeta} \left( \frac{\partial U}{\partial t} + BU \right) R(t, z_0, z, \zeta) dt \] 

\[ = - U(z_0, z_0) R(z, z_0, z, \zeta) + U(z_0, z_0) R(z, z_0, z, \zeta) \] 

\[ + \int_{z_0}^{z} \left( \frac{\partial U}{\partial t} + BU \right) R(t, z_0, z, \zeta) dt . \]
Combining (1.28), (1.29), and (1.30) according to the identity (1.27), we obtain

\[ U(z, \zeta) = U(z_0, \zeta_0) \cdot R(z_0, \zeta_0; z, \zeta) + \int_{z_0}^{z} \left[ \frac{\partial}{\partial t} U(t, \zeta_0) + B \cdot U(t, \zeta_0) \right] R(t, \zeta_0; z, \zeta) dt \]

\[ + \int_{z_0}^{\zeta} \left[ \frac{\partial}{\partial \tau} U(z_0, \tau) + A \cdot U(z_0, \tau) \right] R(z_0, \tau; z, \zeta) d\tau. \]

Restricting \( \zeta = \overline{z} \) in this expression gives Formula (1.26). And, the desired analyticity and continuity of \( \Phi(z) \) and \( \Phi^*(\zeta) \) follow directly from Lemma 1.1.

The second half of the theorem is easily verified by directly substituting Formula (1.26) into Equation (1.5) with \( \zeta = \overline{z} \) and keeping in mind Conditions (1.13). This completes the proof of the theorem.

Consider the nonhomogeneous equation associated with (1.1),

\[ L[u] = f(x, y), \]

where \( f(x, y) \) is an analytic function of \( x \) and \( y \) in some simply-connected domain of the \( x, y \)-plane. The equivalent complex form of this equation is

\[ \mathcal{L}[U] = F(z, \zeta), \]

where \( F(z, \zeta) = \frac{1}{4} f \left( \frac{z+\zeta}{2}, \frac{z-\zeta}{2i} \right) \). As is well known, the general
solution of a linear nonhomogeneous differential equation is obtained by
adding a particular solution of the nonhomogeneous equation to the
general solution of the homogeneous equation. Taking into account
Conditions (1.13), it is easily shown by direct substitution that the
function

\[ U_p(z, \zeta) = \int_{z_0}^{z} \int_{\zeta_0}^{\zeta} R(t, \tau; z, \zeta) F(t, \tau) \, d\tau \, dt \]

is a particular solution of (1.32). Restricting \( \zeta = \bar{z} \) gives \( U_p(z, \bar{z}) \)
as a particular solution of (1.31). We are thus led to state the fol-
lowing corollary.

**Corollary:** Let \( D \) and \( \kappa \) be given as in the statement of Theorem
1.2. Assume \( F(z, \zeta) \) is analytic in \((D, \overline{D})\) and that it is continuous in
each variable separately up to and including the boundary \( \kappa \), or \( \overline{\kappa} \),
as the case may be. If \( u(x, y) \) is a regular solution of the nonhom-
geneous Equation (1.31) in \( D \) and if it and its first partial derivatives
are continuous on \( D \cup \kappa \) and if \( U(z, \zeta) = u\left(\frac{z+\zeta}{2}, \frac{z-\zeta}{2i}\right) \), then

\[ u(x, y) = \alpha R(z_0, \bar{z}_0 ; z, \bar{z}) + \int_{z_0}^{z} \int_{\zeta_0}^{\zeta} \varphi(\tau) R(t, \bar{z}_0 ; z, \bar{z}) \, d\tau \, dt \]
\[ + \int_{z_0}^{z} \int_{\zeta_0}^{\zeta} \varphi(\tau) R(z_0, \tau ; z, \bar{z}) \, d\tau \, d\tau \]
\[ + \int_{z_0}^{z} dt \int_{\zeta_0}^{\zeta} R(t, \tau ; z, \bar{z}) F(t, \tau) \, d\tau , \]
where \( z = x + iy \) is in \( D \), \( z_0 = x_0 + iy_0 \) is a fixed point on \( \kappa \),

\[ \alpha_o = U(z_0, \overline{z}_0), \quad F(z, \zeta) = \frac{1}{4} f \left( \frac{z + i\zeta}{z} \right), \quad \text{and} \]

\[ \varphi(z) = \frac{\partial U(z, \overline{z})}{\partial z}, \quad \beta(z, \overline{z}) U(z, \overline{z}), \]

\[ \varphi^*(\zeta) = \frac{\partial U(z_0, \zeta)}{\partial \zeta}, \quad \alpha(z_0, \zeta) U(z_0, \zeta), \]

which are analytic functions of \( z \) and \( \zeta \) in \( D \) and \( \overline{D} \) and continuous in \( D \cup \kappa \) and \( \overline{D \cup \kappa} \), respectively.

Conversely, if \( \alpha_o \) is an arbitrary constant and \( \varphi(z) \) and \( \varphi^*(\zeta) \) are arbitrary analytic functions in \( D \) and \( \overline{D} \), continuous in \( D \cup \kappa \) and \( \overline{D \cup \kappa} \), respectively, then (1.34) represents the regular solutions of Equation (1.31), continuous in \( D \cup \kappa \).

**Proof:** If \( u(x, y) \) is given as a solution of (1.31), then the function

\[ u_h(x, y) = U_h(z, \overline{z}) = U(z, \overline{z}) - U_p(z, \overline{z}) \]

satisfies \( L[u_h] = 0 \). Therefore, from Theorem 1.2,

\[ U(z, \overline{z}) = U_h(z, \overline{z}) + U_p(z, \overline{z}) \]

(1.35)

\[ = U_h(z_0, \overline{z}_0) R(z_0, \overline{z}_0; z, \overline{z}) + \int \varphi(T) R(t, \overline{z}_0; z, \overline{z}) \, dt \]

\[ + \int \varphi^*(T) R(z_0, \overline{z}_0; z, \overline{z}) \, dT + \int \int \int R(t, \tau; z, \overline{z}) F(t, \tau) \, dt \, d\tau, \]

where
\[ \varphi(z) = \frac{\partial U_h(z, \bar{z})}{\partial z} + B(z, \bar{z}_o) U_h(z, \bar{z}_o) \]

and

\[ \varphi^*(\bar{\zeta}) = \frac{\partial U_h(z_o, \bar{\zeta})}{\partial \bar{\zeta}} + A(z_o, \zeta) U_h(z_o, \zeta) \].

But, from (1.33) it is seen that \( U_p(z_o, \bar{z}_o) = 0 \) and that

\[ \begin{align*}
U_p(z, \bar{z}_o) &= 0, \\
\frac{\partial U_p(z, \bar{z}_o)}{\partial z} &= 0, \\
U_p(z_o, \zeta) &= 0, \\
\frac{\partial U_p(z_o, \zeta)}{\partial \zeta} &= 0.
\end{align*} \]

Therefore, \( U_h(z_o, \bar{z}_o) = U(z_o, \bar{z}_o) \) and

\[ \begin{align*}
U_h(z, \bar{z}_o) &= U(z, \bar{z}_o), \\
\frac{\partial U_h(z, \bar{z}_o)}{\partial z} &= \frac{\partial U(z, \bar{z}_o)}{\partial z}, \\
U_h(z_o, \zeta) &= U(z_o, \zeta), \\
\frac{\partial U_h(z_o, \zeta)}{\partial \zeta} &= \frac{\partial U(z_o, \zeta)}{\partial \zeta}.
\end{align*} \]

Thus, Formula (1.35) is identical to Formula (1.34). The second half of the corollary may be verified by direct substitution. This completes the proof.
CHAPTER II

§ 1. Geometric Reflection Across an Analytic Arc.

If \( z = x + iy \) is a point in the complex plane, then reflecting \( z \) across the \( x \)-axis corresponds to the familiar notion of taking its complex conjugate, \( \bar{z} = x - iy \). We would like to extend this notion of reflection to more general types of arcs; in particular, to those analytic arcs treated by Sloss in [6] and [7].

Let \( \kappa \) be an open analytic arc in the \( xy \)-plane defined by the relation \( F(x, y) = 0 \), where \( F \) is a real analytic function in some neighborhood of \( \kappa \) and where \( \frac{\partial^2}{\partial x^2} F(x, y) + \frac{\partial^2}{\partial y^2} F(x, y) \neq 0 \) along \( \kappa \). By \( \kappa \) being open, we mean that it can be considered as a homeomorphic image of an open interval. Make the substitutions \( z = x + iy \), \( \zeta = x - iy \) to obtain

\[
g(z, \zeta) = F \left[ \frac{z + \zeta}{2}, \frac{z - \zeta}{2i} \right]
\]

as an analytic function in some polycylindrical neighborhood \( |z - z_o| < r, \)

\( |\zeta - z_o| < r \) of \((z_o, \overline{z_o})\) for every \( z_o = x_o + iy_o \) on \( \kappa \). Moreover,

\[
g(z_o, \overline{z_o}) = F \left[ \frac{z_o + \overline{z_o}}{2}, \frac{z_o - \overline{z_o}}{2i} \right] = F(x_o, y_o) = 0,
\]

\[
\frac{\partial g}{\partial \zeta} \bigg|_{z=z_o, \zeta=\overline{z_o}} = \frac{1}{2} \left[ F_x(x_o, y_o) + i F_y(x_o, y_o) \right] \neq 0,
\]
and
\[ \frac{\partial g}{\partial z} \bigg|_{z = z_o, \zeta = \overline{z_o}} = \frac{1}{2} \left[ F_x(x_o, y_o) - i F_y(x_o, y_o) \right] \neq 0. \]

Therefore, by the implicit function theorem of complex variables, there exists a unique function, \( \zeta = G(z) \), defined on a neighborhood, \( N(z_o) \), of each point \( z_o \) on \( \kappa \), whose range is a neighborhood of \( \overline{z_o} \) and which satisfies the relation \( g[z, G(z)] = 0 \) for all \( z \in N(z_o) \). Also, \( G(z) \) is single-valued and analytic in a neighborhood of \( \kappa \) and
\[ G(z_o) = \overline{z_o} \text{ for all } z_o \in \kappa. \]
Because \( \frac{\partial g}{\partial z}(z_o, \overline{z_o}) \neq 0 \) and \( \frac{\partial g}{\partial \zeta}(z_o, \overline{z_o}) \neq 0 \), \( G(z) \) is also one-to-one in some neighborhood of \( \kappa \).

**Definition 2.1.** The function \( G(z) \) introduced above will be referred to as the reflection function relative to the arc \( \kappa \).

**Definition 2.2.** Let \( D \) be a simply-connected domain adjacent to an analytic arc \( \kappa \) such that the reflection function, \( G \), is defined, analytic and one-to-one in \( D \). If \( z \) is a point in \( D \), we define the point \( \hat{z} = \overline{G(z)} \) to be the reflection of \( z \) across \( \kappa \).

Note that \( \hat{z} = \overline{G(z)} = z \) for all points \( z \) on \( \kappa \). We let \( \hat{D} = \overline{G(D)} \) denote the reflection of \( D \) across \( \kappa \).
To justify the above definition of reflection, we show that if $z$ is not a point of $\kappa$, but lies in a sufficiently small neighborhood of $\kappa$, then $z$ must lie on that side of $\kappa$ not containing $z$. Toward this end, let $\kappa$ be given as the image of an open interval $(a, b)$ under a mapping $h(\xi) = x(\xi) + iy(\xi)$ which is analytic and one-to-one. Then $h$ can be extended as a one-to-one analytic function of a complex variable into some sufficiently small simply-connected neighborhood, $R$, of $(a, b)$ which is symmetric with respect to the real axis, i.e., $R = \overline{R}$. Let $R_+$ denote that portion of $R$ which lies in the upper half-plane, $y > 0$, and let $R_-$ be that portion which lies in the lower half-plane, $y < 0$. Let $N_+ = h(R_+)$ and $N_- = h(R_-)$. Then $N_+$ and $N_-$ are domains lying on opposite sides of $\kappa$, since $N_+ \cap N_- = \emptyset$ and $\kappa$ is contained in the boundaries of $N_+$ and $N_-$. 

Without loss of generality, assume $G$ is one-to-one and analytic in $N_+ \cup \kappa \cup N_-$. We wish to show that if $z$ is in $N_-$, say, then its reflected image, $\bar{z}$, must lie in $N_+$. It is clear that the latter will be established if we can show that $\bar{z} = h(\zeta)$, where $\zeta$ is in $R_-$ and $h(\zeta) = z$. However, notice that $\bar{z} = h(\zeta)$ is equivalent to the expression

$$G[h(\zeta)] = \overline{h(\zeta)},$$

since $z = G[h(\zeta)]$. But $G[h(\zeta)]$ and $\overline{h(\zeta)}$ are analytic functions of $\zeta$ in
R and they agree along \((a, b)\). Indeed, if \(\xi \in (a, b)\) then \(h(\xi) \in \kappa\) and 
\[G[h(\xi)] = h(\xi)\] or \(G[h(\xi)] = h(\xi) = h(\xi)\). The last equality follows because \(\xi\) is real. Thus, \((2.1a)\) must be valid for all \(\xi\) in \(R\) and so 
\[\hat{z} = h(\xi)\] lies in \(N_+\).

Intuitively speaking, the above shows that points close to \(\kappa\) have reflected images on the opposite side of \(\kappa\). We will extend this further by assuming throughout the remainder of the paper that whenever \(D\) is given as in Definition 2.2, then \(D \cap \hat{D}\) is empty.

Later, it will be useful to know how the reflection function acts on the reflected region \(\hat{\kappa}\). Toward this end, consider the function \(H(\hat{z}) = \bar{z}\) defined for \(\hat{z}\) in \(\hat{D} \cup \kappa\). By examining the difference quotient for \(H(\hat{z})\) it is easily seen that \(H\) has a derivative at every point of \(D\); in fact, \(H'(\hat{z}) = \frac{G'(z)}{G(z)}\). Thus, \(H\) is analytic in \(D\) and it is continuous on \(\hat{D} \cup \kappa\) and agrees with \(G\) for \(z\) on \(\kappa\). Therefore, \(H\) is the analytic continuation of \(G\) into \(D\); i.e., 
\[G(\hat{z}) = H(\hat{z}) = \bar{z}\] for \(\hat{z}\) in \(\hat{D} \cup \kappa\). As a consequence, we have that \(\hat{z} = z\) in \(D \cup \kappa \cup D\). Thus, \(G(z)\) is analytic and \(G'(z) \neq 0\) in \(D \cup \kappa \cup \hat{D}\) and \(G(\hat{D}) = D\).

Of particular interest are the cases where it is possible to obtain an explicit expression for the reflection function. When \(\kappa\) is a segment of the \(x\)-axis, we set \(F(x, y) = y\) and obtain
\[ g(z, \zeta) = \frac{z - \zeta}{2i}. \]

Setting the right hand side equal to zero and solving for \( \zeta \), we get that \( \zeta = G(z) = z \) and that \( z = \bar{G(z)} = \bar{z} \). Thus, for the case of the \( x \)-axis, the generalized notion of reflection agrees with the usual notion of reflecting a point by taking its complex conjugate.

For the case when \( \kappa \) is a circle or a circular arc of radius \( r \) centered at the origin, we set \( F(x, y) = x^2 + y^2 - r^2 \). Make the complex substitutions to get

\[ g(z, \zeta) = \left( \frac{z + \zeta}{2} \right)^2 + \left( \frac{z - \zeta}{2i} \right)^2 - r^2 \]

and then solve \( g(z, \zeta) = 0 \) for \( \zeta \) to obtain \( \zeta = G(z) = r^2 z - 1 \) and \( z = \bar{G(z)} = \bar{r^2 z - 1} \). We see that the reflected point, \( z \), obtained by means of the reflection function corresponds to the familiar notion of the inverse point of \( z \) relative to the circle of radius \( r \) centered at the origin.

As another example, we take the ellipse given by \( F(x, y) = b^2 x^2 + a^2 y^2 - a^2 b^2 = 0 \) and calculate the reflection function to be

\[ G(z) = \frac{(a^2 + b^2) z - 2ab \sqrt{z^2 + b^2 - a^2}}{a^2 - b^2} \]

where the principle branch of the square root function is used; i.e. \( \sqrt{z^2 + b^2 - a^2} = \sqrt{|z^2 + b^2 - a^2|} \exp[\arg(z^2 + b^2 - a^2) \cdot 2^{-1}] \).
Finally, for the parabola $F(x, y) = x^2 - y = 0$ we find that

$$G(z) = (i - z) - i \sqrt{4iz + 1},$$

where again, the principle branch of the square root is used.

§ 2. Statement of the Problem and Notation.

Consider the elliptic partial differential equation

$$Q[u] = \sum_{i+j=2n}^{\infty} c_{ij} \frac{\partial^{2n}}{\partial x^i \partial y^j} u(x, y) = 0$$

of order $2n$ where the $c_{ij}$ are real constants. Ellipticity implies that $c_{2n, 0} \neq 0$ and so, without loss of generality, we take $c_{2n, 0} = 1$.

Further, the elliptic nature of the operator $Q$ allows it to be decomposed as a product of $2n$ linear factors as

$$Q = \prod_{k=1}^{n} \left( \frac{\partial}{\partial x} - \alpha_k \frac{\partial}{\partial y} \right) \left( \frac{\partial}{\partial x} - \overline{\alpha_k} \frac{\partial}{\partial y} \right)$$

where $\alpha_k = \beta_k + i \delta_k$ and $\overline{\alpha_k} = \beta_k - i \delta_k$, with $\delta_k \neq 0$, are the roots of the associated characteristic polynomial

$$P(\xi) = \sum_{k=0}^{2n} c_{2n-k, k} \xi^{2n-k} = 0.$$

Since $\delta_k \neq 0$ and since $\alpha_k$ and $\overline{\alpha_k}$ are both involved in the decomposition of $Q$, we may choose $\delta_k$ to always be positive.

Finally, we shall assume that the characteristics of (2.1) are
distinct; that is to say, we shall assume that $\alpha_i \neq \alpha_j$ if $i \neq j$.

For each $k = 1, 2, \ldots, n$, introduce the nonsingular coordinate transformation

\[
(2.2) \quad x_k = x, \quad y_k = \delta_k^{-1}(y + \beta_k x)
\]

whose inverse is given by

\[
(2.3) \quad x = x_k, \quad y = \delta_k y_k - \beta_k x_k.
\]

Under this transformation, observe that

\[
\left(\frac{\partial}{\partial x} - \alpha_k \frac{\partial}{\partial y}\right)\left(\frac{\partial}{\partial x} - \alpha_k \frac{\partial}{\partial y}\right) = \frac{\partial^2}{\partial x_k^2} + \frac{\partial^2}{\partial y_k^2} = \Delta_k,
\]

which is just the Laplacian with respect to the coordinates, $x_k, y_k$.

Thus, (2.1) may be written as

\[
(2.4) \quad Q[u] = \left(\prod_{k=1}^{n} \Delta_k\right) u(x,y) = 0.
\]

In [7], Sloss showed that it is possible to analytically continue solutions of Equation (2.4) across analytic arcs by means of reflection provided the solution satisfies certain analytic boundary conditions along the arc. Furthermore, he was able to explicitly describe a region into which the solution could be extended. The region of reflection turned out to be dependent only on the original domain, the analytic arc and the coefficients, $c_{ij}$ of Equation (2.1).
In this chapter, we would like to examine to what extent Sloss' results carry over to the case when (2.1) has lower order terms present. Because of the reason mentioned in the introduction, we shall limit our examination to sixth order elliptic equations that can be factored as

\[
L[u] = \prod_{k=1}^{3} \left[ \Delta_k + a_k(x_k, y_k) \frac{\partial}{\partial x_k} + b_k(x_k, y_k) \frac{\partial}{\partial y_k} + c_k(x_k, y_k) \right] u(x, y) = 0,
\]

where the coefficients \(a_k, b_k, c_k\) are complex-valued analytic functions of their arguments, \(x_k\) and \(y_k\). Before proceeding with an investigation of this equation, we introduce some transformations and notation that will be used repeatedly throughout what follows.

Let \(z = x + iy\) and set \(z_k = x_k + iy_k\) where \(x_k\) and \(y_k\) are given by (2.2), \(k = 1, 2, 3\). Solve for \(z_k^*\) and \(\bar{z}_k\) in terms of \(z\) and \(\bar{z}\) to obtain the transformations

\[
\begin{align*}
    z_k &= \tau_k(z) = A_k z + B_k \bar{z} \\
    \bar{z}_k &= \tau_k^*(\bar{z}) = B_k \bar{z} + A_k z
\end{align*}
\]

where the coefficients are uniquely determined as

\[
\begin{align*}
    A_k &= \frac{1}{2} \left[ (1 + \delta_k^{-1}) + i \delta_k^{-1} \beta_k \right] \\
    B_k &= \frac{1}{2} \left[ (1 - \delta_k^{-1}) + i \delta_k^{-1} \beta_k \right].
\end{align*}
\]
Though $\tau_k(z)$ and $\tau_k^*(z)$ are not analytic functions of their arguments, they are continuous one-to-one transformations having continuous inverses given by

$$z = \tau_k^{-1}(z_k) = \delta_k (A_k z_k - B_k z_k)$$

(2.7)

$$\zeta = \tau_k^*^{-1}(\zeta_k) = \delta_k (-B_k z_k + A_k \zeta_k)$$

for all $z_k$.

We now continue $\tau_k$ and $\tau_k^*$ into the domain of two independent complex variables. Replace $z$ by $\zeta$ in (2.6) to get

$$z_k = A_k z + B_k \zeta_k$$

(2.8)

$$\zeta_k = A_k z + B_k \zeta_k$$

as a nonsingular continuous linear transformation between the variables $(z, \zeta)$ and $(z_k, \zeta_k)$ whose inverse is given by

$$z = \delta_k (A_k z_k - B_k \zeta_k)$$

(2.9)

$$\zeta = \delta_k (-B_k z_k + A_k \zeta_k).$$

From (2.8) and (2.9) the relationship between the pairs $(z_k, \zeta_k)$ and $(z_j, \zeta_j), k \neq j$, can easily be established as a result of straightforward algebraic manipulations to be
\[ z_k = T_k(z_j, \zeta_j) = a_{kj} z_j + b_{kj} \zeta_j \]

\[ \zeta_k = T_k^{*}(\zeta_j, z_j) = b_{kj} z_j + a_{kj} \zeta_j , \]

where

\[ a_{kj} = \delta_j (A_k A_j - B_k B_j) \]

\[ b_{kj} = \delta_j (B_k A_j - A_k B_j) . \]

Again, this is a continuous nonsingular linear change of variables and \( T_k \) and \( T_k^{*} \) are entire functions of \( z_j \) and \( \zeta_j \). We remark that when \( \zeta_j = z_j \), then \( T_k(z_j, z_j) = \tau_k \tau_j^{-1}(z_j) = z_k \) and \( T_k^{*}(z_j, z_j) = \tau_k^{*} \tau_j^{*-1}(z_j) = z_k^{*} \). This notation will be used interchangeably.

Finally, let \( D \) denote a simply-connected domain in the \( x,y \)-plane adjacent to an open analytic arc \( \kappa \). For each \( j \), let

\[ D_j = \left\{ z_j = \tau_j(z) : z \in D \right\} , \]

\[ \kappa_j = \left\{ z_j = \tau_j(z) : z \in \kappa \right\} . \]

Since \( \tau_j \) is a homeomorphism, \( D_j \) will be a simply-connected domain adjacent to \( \kappa_j \). Moreover, the relations defining transformation (2.3) are analytic and for this reason \( \kappa_j \) will also be an analytic arc. For example, if \( \kappa \) is part of a nondegenerate conic given by

\[ F(x, y) = ax^2 + bxy + cy^2 + dx + ey + f = 0 , \]
then \( K_j \) will also be part of a nondegenerate conic of the same type as \( K \).

§ 3. Equation (2.5) as a System.

We return now to Equation (2.5) and define operators

\[
L_k = \Delta_k + a_k(x_k, y_k) \frac{\partial}{\partial x_k} + b_k(x_k, y_k) \frac{\partial}{\partial y_k} + c_k(x_k, y_k), \quad k = 1, 2, 3
\]

where, from (2.3),

\[
\frac{\partial}{\partial x_k} = \frac{\partial}{\partial x} - \beta_k \frac{\partial}{\partial y}, \quad \frac{\partial}{\partial y_k} = \delta_k \frac{\partial}{\partial y}.
\]

Then (2.5) may be written as

\[
(2.11) \quad L[u] = L_1 L_2 L_3 u(x, y) = 0.
\]

Set

\[
u_3(x, y) = u(x, y),
\]
\[
(2.12) \quad u_2(x, y) = L_3[u_3],
\]
\[
\quad u_1(x, y) = L_2[u_2].
\]

Then (2.11) may be written as the system

\[
L_3[u_3] = u_2(x, y)
\]
\[
L_2[u_2] = u_1(x, y)
\]
\[
L_1[u_1] = 0.
\]
From the coordinate transformation (2.3), we have

\[(2.14)\quad u_k(x, y) = u_k(x, j, y_j - j, x_j)\]

\[= \nu_{kj}(x, j, y_j)\]

\[= \nu_{kj}\left(\frac{x_j + z_j}{2}, \frac{z_j - z_j}{2i}\right)\]

\[= V_{kj}(z_j, z_j).\]

If we now introduce the operations

\[
\frac{\partial}{\partial z_k} = \frac{1}{2} \left(\frac{\partial}{\partial x_k} - i \frac{\partial}{\partial y_k}\right), \quad \frac{\partial}{\partial \bar{z}_k} = \frac{1}{2} \left(\frac{\partial}{\partial x_k} + i \frac{\partial}{\partial y_k}\right),
\]

then system (2.13) takes the form

\[
\left[\frac{\partial^2}{\partial z_3 \partial \bar{z}_3} + A_3(z_3, \bar{z}_3)\frac{\partial}{\partial z_3} + B_3(z_3, \bar{z}_3)\frac{\partial}{\partial \bar{z}_3} + C_3(z_3, \bar{z}_3)\right]V_{33}(z_3, \bar{z}_3) = \frac{1}{4} V_{23}(z_3, \bar{z}_3)
\]

(2.15)

\[
\left[\frac{\partial^2}{\partial z_2 \partial \bar{z}_2} + A_2(z_2, \bar{z}_2)\frac{\partial}{\partial z_2} + B_2(z_2, \bar{z}_2)\frac{\partial}{\partial \bar{z}_2} + C_2(z_2, \bar{z}_2)\right]V_{22}(z_2, \bar{z}_2) = \frac{1}{4} V_{12}(z_2, \bar{z}_2)
\]

\[
\left[\frac{\partial^2}{\partial z_1 \partial \bar{z}_1} + A_1(z_1, \bar{z}_1)\frac{\partial}{\partial z_1} + B_1(z_1, \bar{z}_1)\frac{\partial}{\partial \bar{z}_1} + C_1(z_1, \bar{z}_1)\right]V_{11}(z_1, \bar{z}_1) = 0,
\]

where
$A_k(z_k, \bar{z}_k) = \frac{1}{4} \left[ a_k \left( \frac{z_k + \bar{z}_k}{2}, \frac{z_k - \bar{z}_k}{2i} \right) + i b_k \left( \frac{z_k + \bar{z}_k}{2}, \frac{z_k - \bar{z}_k}{2i} \right) \right]$, \\

$B_k(z_k, \bar{z}_k) = \frac{1}{4} \left[ a_k \left( \frac{z_k + \bar{z}_k}{2}, \frac{z_k - \bar{z}_k}{2i} \right) - i b_k \left( \frac{z_k + \bar{z}_k}{2}, \frac{z_k - \bar{z}_k}{2i} \right) \right]$, \\

$C_k(z_k, \bar{z}_k) = \frac{1}{4} c_k \left( \frac{z_k + \bar{z}_k}{2}, \frac{z_k - \bar{z}_k}{2i} \right)$.

It is System (2.15) which we shall use to reflect the solutions of Equation (2.5). We point out that $V_{kk}(z_k, \bar{z}_k)$ and $V_{kj}(z_j, \bar{z}_j)$, $j = k+1$, $k = 1, 2$, are equal to the same function $u_k(x, y)$ and that they are related by the expression

\[(2.16) \quad V_{kj}(z_j, \bar{z}_j) = V_{kk} [\tau_k^{-1}(z_j), \tau_k^{*} \tau_k^{-1}(\bar{z}_j)]
= V_{kk} [T_k(z_j, \bar{z}_j), T_k^{*}(\bar{z}_j, z_j)]
= V_{kk}(z_k, \bar{z}_k),\]

where $z_j = \tau_k^{-1}(z_k)$. If $u(x, y)$ is given as a solution of (2.5), then $V_{kk}(x_k, y_k) = V_{kk}(z_k, \bar{z}_k)$ becomes a known analytic function of $x_k, y_k$ and is a solution of the $k^{th}$ equation of (2.15), $k = 1, 2, 3$.

§4. Reflecting solutions of Equation (2.5).

Suppose $f(x_1, y_1) = F(z_1, \bar{z}_1)$ is a known function defined for all $z_1$ in $D_1$ such that $F(z_1, \xi_1)$ is an analytic function of the two complex variables $z_1 \in D_1$, $\xi_1 \in \overline{D}_1$. Upon performing the
coordinate transformation

\[ F(z_1, \bar{z}_1) = F[T_1(z_2', \bar{z}_2), \ T_1^*(\bar{z}_2', z_2)] = \tilde{F}(z_2, \bar{z}_2), \]

where \( z_2 = \tau_2 \tau_1^{-1}(z_1) = T_2(z_1, \bar{z}_1) \), we obtain a function \( \tilde{F}(z_2, \bar{z}_2) \)
defined for all \( z_2 \) in \( D_2 = \tau_2 \tau_1^{-1}(D_1) \). However, the function

\[ \tilde{F}(z_2, \zeta_2) = F[T_1(z_2, \zeta_2), \ T_1^*(\zeta_2, z_2)] \]

will not, in general, be analytic for all \( z_2 \in D_2 \), \( \zeta_2 \in \overline{D_2} \) as the
following example suggests.

Take \( D_1 \) to be the square whose corners are the points \((0, 0), (1, 0), (1, 1)\) and \((0, 1)\) and take \( \delta_1 = \delta_2 = 1, \ \beta_1 = 0, \ \beta_2 = 1 \). Then

\[ z_2 = T_2(z_1, \zeta_1) = (1 + \frac{1}{2} i) z_1 + \frac{1}{2} i \zeta_1, \]

\[ \zeta_2 = T_2^*(\zeta_1, z_1) = -\frac{1}{2} i z_1 + (1 - \frac{1}{2} i) \zeta_1, \]

and the inverse of this coordinate transformation is

\[ z_1 = T_1(z_2, \zeta_2) = (1 - \frac{1}{2} i) z_2 - \frac{1}{2} i \zeta_2 \]

\[ \zeta_1 = T_1^*(\zeta_2, z_2) = \frac{1}{2} i z_2 + (1 + \frac{1}{2} i) \zeta_2. \]

The set \( D_2 \) is just \( \{ z_2 = (1 + \frac{1}{2} i) z_1 + \frac{1}{2} i \bar{z}_1 : z_1 \in D_1 \} \) and is shown
in Figure 2.1.
Figure 2.1
Consider the pair \( z_2 = \frac{3}{4} + i \frac{7}{8}, \xi_2 = \frac{1}{8} - i \frac{1}{4} \) in \( D_2 \times \bar{D}_2 \). Then

\[
z_1 = T_1 \left( \frac{3}{4} + i \frac{7}{8}, \frac{1}{8} - i \frac{1}{4} \right) = \frac{17}{16} + i \frac{7}{16}
\]

\[
\xi_1 = T_1 \left( \frac{1}{8} - i \frac{1}{4}, \frac{3}{4} + i \frac{7}{8} \right) = -\frac{3}{16} + i \frac{3}{16}
\]

and this pair is not in \( D_1 \times \bar{D}_1 \). Thus \( \tilde{F} \left( \frac{3}{4} + i \frac{7}{8}, \frac{1}{8} - i \frac{1}{4} \right) \) is not even defined. However, given any point \( z_2 \) in \( D_2 \), there does exist a neighborhood, \( N \), of \( z_2 \) contained in \( D_2 \) such that \( \tilde{F}(z_2, \xi_2) \) is defined and is an analytic function of the two complex variables

\( z_2 \in N, \xi_2 \in \bar{N} \). It is the purpose of the following lemma to establish this fact and to give some idea about the size of \( N \).

We use the notation \( N(z, \rho) \) to designate an open disc in the \( x, y \)-plane whose boundary is a circle of radius \( \rho \) centered at \( z = x + iy \).

**Lemma 2.1.** Let \( \Omega_j \) be an open connected set in the complex plane and

\[
\Omega_k = \left\{ T_k(z_j, \bar{z}_j) = z_k : z_j \in \Omega_j \right\}.
\]

Let \( F(z_j, \xi_j) \) be a known analytic function of two complex variables for \( (z_j, \xi_j) \in (\Omega_j, \bar{\Omega}_j) \). Then, for every point \( z_{k0} \) in \( \Omega_k \), there exists an open disc, \( N(z_{k0}, r) \), centered at \( z_{k0} \) and of radius \( r \) contained in \( \Omega_k \) such that the function \( \tilde{F}(z_{k0}, \xi_{k0}) \) defined by
\[ F(z_k, \zeta_k) = F[T_j(z_k, \zeta_k), T_j^*(\zeta_k, z_k)] = F(z_j, \zeta_j) \]

is an analytic function of the two complex variables \( z_k \in N(z_{ko}, r) \), 
\( \zeta_k \in N(\zeta_{ko}, r) \). Moreover, the radius, \( r \), of the largest such disc 
can be determined explicitly from the choice of the point \( z_{ko} \) 
and from the coefficients \( a_{jk} \) and \( b_{jk} \) of the transformation 
\( T_j(z_k, \zeta_k) \) to be

\[
r(z_{ko}) = \frac{m(z_{ko})}{|a_{jk}| + |b_{jk}|},
\]

where \( m(z_{ko}) = \inf \left| |z_j - z_{jo}| : z_j = T_j(z_{ko}, \zeta_{ko}), z_j \in \partial \Omega \right| \).

**Proof.** Arbitrarily fix a point \( z_{ko} \) in \( \Omega \) and let \( z_{jo} \) be the point 
in \( \Omega_j \) defined by

\[
z_{jo} = T_j(z_{ko}, \zeta_{ko}) = a_{jk} z_{ko} + b_{jk} \zeta_{ko}.
\]

Let \( N(z_{ko}, r) \) and \( N(\zeta_{ko}, r) \) be open discs of radius \( r \) centered at 
\( z_{ko} \) and \( \zeta_{ko} \) respectively. We proceed to find an \( r \) satisfying the 
conclusions of the lemma.

Replace \( z_j \) by \( z_{ko} \) and \( \zeta_j \) by \( \zeta_k \) in the coordinate transforma-
tion (2.10) and observe that the resulting mappings

\[
T_j(z_{ko}, \zeta_k) = a_{jk} z_{ko} + b_{jk} \zeta_k = z_j
\]
and

\[ T_j^*(\zeta, z_{ko}) = \overline{b_{jk} z_{ko} + a_{jk} \zeta} = \overline{\zeta_j} \]

are linear with respect to the single complex variable \( \zeta_k \) and so map circles onto circles. Furthermore,

\[ |z_j - z_{jo}| = |T_j^*(z_{ko}, \zeta) - T_j^*(z_{ko}, \overline{z_{ko}})| \]

\[ = |a_{jk} z_{ko} + b_{jk} \zeta - a_{jk} z_{ko} - b_{jk} \overline{z_{ko}}| \]

\[ = |b_{jk}| \left| \zeta - \overline{z_{ko}} \right| , \]

and

\[ |\zeta_j - \overline{z_{jo}}| = |T_j^*(\overline{\zeta}, z_{ko}) - T_j^*(\overline{z_{ko}}, z_{ko})| \]

\[ = |b_{jk} z_{ko} + a_{jk} \overline{\zeta} - b_{jk} z_{ko} - a_{jk} \overline{z_{ko}}| \]

\[ = |a_{jk}| \left| \zeta - \overline{z_{ko}} \right| . \]

From this, it is seen that \( T_j^*(z_{ko}, \zeta) \) maps \( N(z_{ko}, r) \) onto an open disc, \( N(z_{jo}, |b_{jk}| r) \), of radius \( |b_{jk}| r \) centered at \( z_{jo} \) and that \( T_j^*(\overline{\zeta}, z_{ko}) \) maps \( N(z_{ko}, r) \) onto an open disc, \( N(z_{jo}, |a_{jk}| r) \), of radius \( |a_{jk}| r \) centered at \( \overline{z_{jo}} \). Thus, transformation (2.10) maps the set \( \{z_{ko}\} \times N(z_{ko}, r) \) onto a subset of \( N(z_{jo}, |b_{jk}| r) \times N(z_{jo}, |a_{jk}| r) \).
For the next step, arbitrarily pick a point $\xi_k$ in $N(z_{ko}, r)$.

Then, transformation (2.10) maps the pair $(z_{ko}, \xi_k)$ onto the pair $(z_j', \xi_j')$ in $N(z_{jo}, |b_{jk}| r) \times N(z_{jo}, |a_{jk}| r)$ given by

$$z_j' = T_j(z_{ko}, \xi_k) = a_{jk} z_{ko} + b_{jk} \xi_k$$

$$\xi_j' = T_j^*(\xi_k, z_{ko}) = \overline{b_{jk}} z_{ko} + \overline{a_{jk}} \xi_k$$

Consider now the set $N(z_{ko}, r) \times \{\xi_k\}$ and the linear mappings $T_j(z_{ko}, \xi_k)$ and $T_j^*(\xi_k, z_{ko})$. As functions of $z_k$, they map circles onto circles and in particular they map $N(z_{ko}, r)$ onto open discs centered at $z_j'$ and $\xi_j'$ respectively (see Figure 2.2). Furthermore,

$$|z_j - z_j'| = |T_j(z_k, \xi_k') - T_j(z_{ko}, \xi_k')|$$

$$= |a_{jk} z_k + b_{jk} \xi_k - a_{jk} z_{ko} - b_{jk} \xi_k|$$

$$= |a_{jk}||z_k - z_{ko}|$$

and

$$|\xi_j - \xi_j'| = |T_j^*(\xi_k', z_k) - T_j^*(\xi'_{ko}, z_{ko})|$$

$$= |\overline{b_{jk}} z_k + \overline{a_{jk}} \xi_k' - \overline{b_{jk}} z_{ko} - \overline{a_{jk}} \xi_k'|$$

$$= |\overline{b_{jk}}||z_k - z_{ko}|.$$
Figure 2.2
Thus, $T_j(z_{j'k}, \zeta_{j'k}')$ maps $N(z_{j'k}, r)$ onto an open disc $N(z_{j'k}, a_{j'k}^1 r)$, of radius $a_{j'k}^1 r$ centered at $z_{j'}$ and $T_j(z_{j'k}, \zeta_{j'k})$ maps $N(z_{j'k}, r)$ onto an open disc $N(\zeta_{j'k}, b_{j'k}^1 r)$, of radius $b_{j'k}^1 r$ centered at $\zeta_{j'}$. And so, transformation (2.10) maps the set $N(z_{j'k}, r) \times N(\zeta_{j'k}, b_{j'k}^1 r)$ onto a subset of $N(z_{j}, a_{j'k}^1 r) \times N(\zeta_{j}, b_{j'k}^1 r)$.

Now form the union of all the open discs $N(z_{j'}, a_{j'k}^1 r)$ whose center, $z_{j'}$, lies in the disc $N(z_{j'k}, b_{j'k}^1 r)$ to get an open disc centered at $z_{j'}$ and of radius $(a_{j'k}^1 + b_{j'k}^1) r$; i.e.,

$$\bigcup_{z_{j'} \in N(z_{j'k}, b_{j'k}^1 r)} N(z_{j'}, a_{j'k}^1 r) = N(z_{j'k}, (a_{j'k}^1 + b_{j'k}^1) r).$$

Similarly,

$$\bigcup_{\zeta_{j'} \in N(z_{j'k}, b_{j'k}^1 r)} N(\zeta_{j'}, b_{j'k}^1 r) = N(z_{j'k}, (a_{j'k}^1 + b_{j'k}^1) r).$$

From the preceding construction it is seen that transformation (2.10), being a homeomorphism, maps the open set $N(z_{j'k}, r) \times N(z_{j'k}, r)$ onto an open subset of

$$(2.17) \quad N[z_{j'k}, (a_{j'k}^1 + b_{j'k}^1) r] \times N[z_{j'k}, (a_{j'k}^1 + b_{j'k}^1) r].$$

If we define $m(z_{j'k})$ as in the conclusion of the lemma and pick $r$ such that $(a_{j'k}^1 + b_{j'k}^1) r \leq m(z_{j'k})$, then (2.17) will be contained in $\Omega_j \times \Omega_j$. It is easily seen that $r(z_{j'k}) = \frac{m(z_{j'k})}{a_{j'k}^1 + b_{j'k}^1}$ is the
largest such value for $r$ possible and that for $r$ equal to this quantity, $N[z_{ko}, r (z_{ko})]$ is contained in $\Omega_k$.

It is now a simple matter to check that the function $\tilde{F}(z_k, \zeta_k)$

$= F[T_j(z_k, \zeta_k), T_j^*(\zeta_k, z_k)]$ is defined for all $(z_k, \zeta_k) \in N(z_{ko}, r)$

$\times N(z_{ko}, r)$, where $r \leq \frac{|a_j| l + |b_j| l}{j k}$. Furthermore, for each fixed

$\zeta_k$ in $N(z_{ko}, r)$, $\tilde{F}$ is analytic in the single variable $z_k$ in a neighborhood of each point of $N(z_{ko}, r)$ and for each fixed $z_k$ in $N(z_{ko}, r)$, $\tilde{F}$ is analytic in the single variable $\zeta_k$ in a neighborhood of each point of $N(z_{ko}, r)$. Therefore, by Hartog's theorem on the analyticity of functions of several complex variables (see [2] Ch. VII), $\tilde{F}(z_k, \zeta_k)$ is analytic as a function of two complex variables on the domain $N(z_{ko}, r) \times N(z_{ko}, r)$, where $r \leq \frac{|a_j| l + |b_j| l}{j k}$. This completes the proof of the lemma.

In dealing with System (2.15), the approach will be to work with each equation separately, extending first the function $V_{11}$, then $V_{22}$ and finally $V_{33}$. To avoid needless repetition, the process we use to reflect solutions of a single second order equation is presented in the following lemma.

**Lemma 2.2.** Let $\Omega$ be a simply-connected domain in the $x, y$-plane adjacent to an open analytic arc $\kappa$ such that the reflection function, $G$, relative to $\kappa$ is defined, analytic and $G'(z) \neq 0$ on $\Omega \cup \kappa \cup \Omega$,
where \( \Omega = \overline{G(\Omega)} \). Let \( V(z, \bar{z}) \), for \( z = x + iy \) in \( \Omega \), be given as a regular solution of the equation

\[
\frac{\partial^2 V}{\partial z \partial \bar{z}} + A(z, \bar{z}) \frac{\partial V}{\partial z} + B(z, \bar{z}) \frac{\partial V}{\partial \bar{z}} + C(z, \bar{z})V = F(z, \bar{z})
\]

which has \( \Omega \cup \kappa \cup \overline{\Omega} \) as a fundamental domain. Assume that \( V(z, \bar{z}) \) is in \( C^1(\Omega \cup \kappa) \) and that along \( \kappa \) it satisfies the condition

\[
A(z, \bar{z}) \frac{\partial V}{\partial z} + B(z, \bar{z}) \frac{\partial V}{\partial \bar{z}} + C(z, \bar{z})V + F(z, \bar{z}) = 0,
\]

where \( A_0(z, \zeta), B_0(z, \zeta), C_0(z, \zeta), F_0(z, \zeta) \) as well as \( \Gamma(z, \zeta) \) are analytic functions for \( z \in \Omega \cup \kappa \cup \overline{\Omega} \), \( \zeta \in \Omega \cup \kappa \cup \overline{\Omega} \) and \( A_0(z, \zeta) \neq 0 \), \( B_0(z, \zeta) \neq 0 \). Then \( V(z, \bar{z}) \) can be extended as a solution of Equation (2.18) across \( \kappa \) into all of \( \overline{\Omega} \). Replacing \( \bar{z} \) by \( \zeta \) gives \( V(z, \zeta) \) as an analytic function of the two complex variables \( z \in \Omega \cup \kappa \cup \overline{\Omega}, \zeta \in \Omega \cup \kappa \cup \overline{\Omega} \).

**Proof:** By the corollary to Theorem 1.2, \( V(z, \bar{z}) \) may be expressed as

\[
V(z, \bar{z}) = V(z_0, \bar{z}_0) R(z_0, \bar{z}_0; z, \bar{z}) + \int_{z_0}^{z} \Phi(t) R(t, \bar{z}_0; z, \bar{z}) dt
\]

\[
+ \int_{\overline{z}_0}^{\overline{z}} \Phi^*(\tau) R(z_0, \tau; z, \bar{z}) d\tau + \int_{z_0}^{z} \int_{\overline{z}_0}^{\overline{z}} R(t, \tau; z, \bar{z}) F(t, \tau) d\tau,
\]

where \( z_0 \) is a fixed point on \( \kappa \) and \( \Phi(z), \Phi^*(\zeta) \) are uniquely determined from \( V(z, \bar{z}) \) as analytic functions on \( \Omega, \overline{\Omega} \) and continuous on
Our aim is to analytically continue the functions \( \phi(z) \), \( \phi(\zeta) \) across \( \kappa, \bar{\kappa} \) into \( \hat{\Omega}, \hat{\Omega} \), respectively. Then, since \( F(t, \tau) \) and the Riemann function \( R(t, \tau; z, \bar{z}) \) are known for \( z, t \in \Omega \cup \kappa \cup \hat{\Omega} \) and \( \tau \in \Omega \cup \kappa \cup \hat{\Omega} \), Formula (2.20) will provide the unique continuation of the given solution, originally known only in \( \Omega \), into \( \Omega \cup \kappa \cup \hat{\Omega} \).

The extension of \( \phi(z) \) across \( \kappa \) is carried out with the help of Condition (2.19). Keeping in mind that

\[
\frac{\partial V(z, \bar{z})}{\partial z} = \frac{\partial V(z, \zeta)}{\partial z} \bigg|_{\zeta = z}, \quad \frac{\partial V(z, \bar{z})}{\partial \zeta} = \frac{\partial V(z, \zeta)}{\partial \zeta} \bigg|_{\zeta = z}
\]

and in view of Property (1.9) of the Riemann function, Formula (2.20) gives rise to the following expressions:

\[
(2.21) \quad \frac{\partial V(z, \bar{z})}{\partial z} = V(z_o, \bar{z}_o) \frac{\partial}{\partial z} R(z_o, \bar{z}_o; z, \bar{z}) + \phi(z) \exp \left[ \int_{\bar{z}}^{\bar{z}_o} A(z, \eta) d\eta \right]
\]

\[
+ \int_{z_o}^{z} \phi(t) \frac{\partial}{\partial z} R(t, \bar{z}_o; z, \bar{z}) dt
\]

\[
+ \int_{z_o}^{z} \phi^*(\tau) \frac{\partial}{\partial z} R(z_o, \tau; z, \bar{z}) d\tau
\]

\[
+ \frac{\partial}{\partial z} \int_{z_o}^{z} dt \int_{z_o}^{z} R(t, \tau; z, \bar{z}) F(t, \tau) d\tau ,
\]

and
(2.22) \[ \frac{\partial V(z, z)}{\partial z} = V(z, z) \frac{\partial}{\partial z} R(z, z; z, z) \]

\[ + \int_{z_0}^{z} \varphi(t) \frac{\partial}{\partial z} R(t, z_0; z, z) \, dt \]

\[ + \varphi^*(z) \exp \left[ \int_{z}^{z_0} B(\xi, z) \, d\xi \right] \]

\[ + \int_{z_0}^{z} \varphi^*(\tau) \frac{\partial}{\partial z} R(z_0, \tau; z, z) \, d\tau \]

\[ + \frac{\partial}{\partial z} \int_{z_0}^{z} \frac{\partial}{\partial z} R(t, z; z) \, dt \int_{z_0}^{z} R(t, z; z) \, dt . \]

For \( z \) varying in \( \Omega \), substitute Formulas (2.20), (2.21) and (2.22) into the left hand side of (2.19). Without loss of generality, take \( A_o(z, \zeta) = 1 \). Then, the resulting expression may be written as

\[ \text{(2.23)} \quad \exp \left[ \int_{z}^{z_0} A(z, \eta) d\eta \right] \left\{ \varphi(z) - \int_{z_0}^{z} K(t, z_0; z, z) \varphi(t) \, dt \right. \]

\[ + g(z, z) \varphi^*(z) \]

\[ - \int_{z_0}^{z} K(z_0, \tau; z, z) \varphi^*(\tau) \, d\tau - f(z, z) \right\} , \]

where we have set
\[ K(t, \tau; z, \xi) = \exp \left[ \int_{z_0}^{\xi} A(z, \eta) d\eta \right] \left\{ \frac{\partial}{\partial z} R(t, \tau; z, \xi) \right\}, \]

\[ + B_0(z, \xi) \frac{\partial}{\partial \zeta} R(t, \tau; z, \xi) + C_0(z, \xi) R(t, \tau; z, \xi) \]}

\[ g(z, \xi) = B_0(z, \xi) \exp \left[ \int_{z_0}^{z} B(\xi, \zeta) d\xi \right] \exp \left[ \int_{z_0}^{\xi} A(z, \eta) d\eta \right], \]

\[ f(z, \xi) = \exp \left[ \int_{z_0}^{\xi} A(z, \eta) d\eta \right] V(z_0, \overline{z}_0) \frac{\partial}{\partial z} R(z_0, \overline{z}_0; z, \xi) \]

\[ + \frac{\partial}{\partial z} \int_{z_0}^{z} dt \int_{z_0}^{\xi} R(t, \tau; z, \xi) F(t, \tau) d\tau \]

\[ + B_0(z, \xi) \left[ V(z_0, \overline{z}_0) \frac{\partial}{\partial \zeta} R(z_0, \overline{z}_0; z, \xi) \right] \]

\[ + \frac{\partial}{\partial \zeta} \int_{z_0}^{z} dt \int_{z_0}^{\xi} R(t, \tau; z, \xi) F(t, \tau) d\tau \]

\[ + C_0(z, \xi) \left[ V(z_0, \overline{z}_0) R(z_0, \overline{z}_0; z, \xi) \right] \]

\[ + \int_{z_0}^{z} dt \int_{z_0}^{\xi} R(t, \tau; z, \xi) F(t, \tau) d\tau \]

\[ + F_0(z, \xi) \]}

Note that \( K(t, \tau; z, \xi), g(z, \xi) \) and \( f(z, \xi) \) are analytic functions for \( z, t \) in \( \Omega \cup \mathcal{K} \cup \overline{\Omega} \) and \( \zeta, \tau \) in \( \Omega \cup \mathcal{K} \cup \overline{\Omega} \).
To put Expression (2.23) into a form suitable for reflection, we need to introduce an analytic mapping of a single complex variable which will establish a one-to-one correspondence between the points of $\Omega$ and the reflected region $\hat{\Omega}$ and which will map points $z$ on $\kappa$ onto the corresponding points $\bar{z}$ on $\kappa$. The reflection function, $G$, relative to $\kappa$ provides this desired connection, since, as seen in §1 of this chapter, if $z$ is a point in $\Omega$, then $G(z) = \bar{z}$ and $G(z) = z$ for all $z$ on $\kappa$.

Substitute for $\bar{z}$ in (2.23) to obtain the following expression for the left hand side of (2.19):

$$\exp \left[ \int_{G(z)}^{z} \frac{A(z, \eta)}{G(z)} \, d\eta \right] \left[ \varphi(z) - \int_{z_{0}}^{z} K[t, G(z_{0}); z, G(z)] \varphi(t) \, dt \right]$$

$$+ g[z, G(z)] \varphi'[G(z)]$$

$$- \int_{z_{0}}^{z} K[z_{0}, G(\xi); z, G(z)] \varphi'[G(\xi)] G'(\xi) \, d\xi$$

$$- f[z, G(z)] \right].$$

In view of Condition (2.19) and the fact that $\varphi(z)$ and $\varphi'[G(z)]$ are continuous functions of $z$ in $\Omega \cup \kappa$ and that $\lim_{z \to \kappa} G(z) = G(z)$, we can let $z$ approach $\kappa$ to get the identity.
(2.24) \[ \Phi(z) = \int_{z_0}^{z} K(t, G(z_0); z, G(z)) \varphi(t) \, dt \]

\[ = f[z, G(z)] - g[z, G(z)] \Phi[G(z)] \]

\[ + \int_{z_0}^{z} K[z_0, G(\xi); z, G(z)] \Phi[G(\xi)] G'(\xi) \, d\xi \]

along \( \kappa \). Thus, along \( \kappa \), \( \Phi(z) \) satisfies the Volterra integral equation

(2.25) \[ h(z) = \int_{z_0}^{z} K(t, G(z_0); z, G(z)) h(t) \, dt \]

\[ = f[z, G(z)] - g[z, G(z)] \Phi[G(z)] \]

\[ + \int_{z_0}^{z} K[z_0, G(\xi); z, G(z)] \Phi[G(\xi)] G'(\xi) \, d\xi \]

in which \( h(z) \) plays the role of the unknown.

Because \( \Phi[G(z)] \) is defined and analytic in \( \hat{\Omega} \) and continuous in \( \hat{\Omega} \cup \kappa \), the right hand side of Equation (2.25) is actually a known analytic function for \( z \) in \( \hat{\Omega} \) and is continuous up to and including \( \kappa \). Similarly, the kernel \( K[t, G(z_0); z, G(z)] \) is analytic in \( \hat{\Omega} \) and is continuous in \( \hat{\Omega} \cup \kappa \). Hence, Equation (2.25) may be solved by the usual method of successive approximations to obtain the unique solution in \( \hat{\Omega} \cup \kappa \) given by
(2.26) \[ \psi(z) = R(z) + \int_{z_0}^{z} \Gamma(t, z) \, R(t) \, dt , \]

where \( R(z) \) denotes the right hand side of (2.25) and \( \Gamma(t, z) \) is the so-called resolvent kernel defined by the series

\[ \Gamma(t, z) = \sum_{n=1}^{\infty} K^{(n)}(t, z) . \]

By definition,

\[ K^{(1)}(t, z) = K[t, G(z_0); z, G(z)] \]

\[ K^{(n)}(t, z) = \int_{t}^{z} K^{(1)}(t, \eta) K^{(n-1)}(\eta, z) \, d\eta , \quad n = 2, 3, \ldots \]

and it can be shown that the series defining \( \Gamma(t, z) \) is absolutely and uniformly convergent on compact subsets of \( \hat{\Omega} \cup \kappa \) and that \( \Gamma(t, z) \) is an analytic function for \( z, t \) in \( \hat{\Omega} \) and continuous in \( \hat{\Omega} \cup \kappa \) (see [8]). Therefore, \( \psi(z) \) is analytic in \( \hat{\Omega} \) and is continuous in \( \Omega \cup \kappa \). Moreover, \( \psi(z) \) satisfies Equation (2.25) along \( \kappa \). But, as seen earlier, the function \( \varphi(z) \) also satisfies (2.25) along \( \kappa \). Hence, by the uniqueness theorem for Volterra integral equations, the functions \( \varphi(z) \) and \( \psi(z) \) must assume the same values at points of \( \kappa \), and so \( \psi(z) \) is indeed the unique analytic continuation of \( \varphi(z) \) into \( \hat{\Omega} \).

If the coefficients \( A(z, z), B(z, z) \) and \( C(z, \overline{z}) \) of Equation...
(2.18) are real-valued functions, then by Theorem 1.1, \( \Phi^*(z) = \Phi(\zeta) \) and the function \( \Psi^*(z) = \Psi(\zeta) \) gives the unique analytic continuation of \( \Phi^* \) across \( \kappa \) into \( \Omega \). Otherwise, rewrite Expression (2.23) in the form

\[
2.27 \quad \exp \left[ \int_{z}^{z_0} B(\xi, \zeta) \, d\xi \right] \left| \Phi^*(z) \right|
- \int_{z_0}^{z} \tilde{K}(z_o, \tau; z, \zeta) \Phi^*(\tau) \, d\tau
+ \tilde{g}(z, \zeta) \Phi(z)
- \int_{z_0}^{z} \tilde{K}(t, \zeta; z, \zeta) \Phi(t) \, dt - \tilde{f}(z, \zeta)
\]

where \( \tilde{K}, \tilde{g} \) and \( \tilde{f} \) differ from \( K, g \) and \( f \) only by an exponential factor. Recall that for \( z \) in \( \Omega \), \( G(z) = z \); whence, \( G(z) = G(z) \) \( = \tilde{z} \) and \( z = G^{-1}(z) \). Substitute for \( z \) in (2.27) and then let \( z \) approach \( \kappa \) to get that \( \Phi^*(z) \) satisfies a Volterra integral equation analogous to (2.25) along \( \kappa \). Now proceed as before to obtain the unique analytic continuation of \( \Phi^*(z) \) across \( \kappa \) into \( \Omega \).

Finally, in Formula (2.20), replace the functions \( \Phi(z) \) and \( \Phi^*(\zeta) \) by their extensions defined in \( \Omega \cup \kappa \cup \Omega \) and \( \Omega \cup \kappa \cup \Omega \).
respectively, to obtain \( V(z, \bar{z}) \) as the unique solution of Equation (2.18) in \( \Omega \cup \kappa \cup \bar{\Omega} \) which is identical to the original solution throughout \( \Omega \). And, replacing \( \bar{z} \) by \( \zeta \) in Formula (2.20) gives \( V(z, \zeta) \) as an analytic function of two complex variables in \( (\Omega \cup \kappa \cup \bar{\Omega}, \Omega \cup \kappa \cup \bar{\Omega}) \). This completes the proof.

Remark: Lemma 2.2 is also valid if the condition \( A_o(z, \zeta) \neq 0, B_o(z, \zeta) \neq 0 \) is replaced by the condition \( A_o(z, \zeta) = B_o(z, \zeta) = 0 \) and \( C_o(z, \zeta) = 1 \).

In preparation for the next theorem, let \( a_{k, o}(x, y), b_{k, o}(x, y), c_{k, o}(x, y) \) and \( f_{k, o}(x, y) \) be analytic functions in some region of the real \( x, y \)-plane. Apply the change of coordinates (2.3) and then replace \( x_k \) and \( y_k \) by the expressions \( \frac{z_k + \zeta}{2} \) and \( \frac{z_k - \zeta}{2i} \), respectively, to obtain the four new functions

\[
A_{k, o}(z_k, \zeta_k) = a_{k, o}(\frac{z_k + \zeta_k}{2}, \frac{z_k - \zeta_k}{2i}) + ib_{k, o}
\]

\[
B_{k, o}(z_k, \zeta_k) = a_{k, o}(\frac{z_k + \zeta_k}{2}, \frac{z_k - \zeta_k}{2i}) - ib_{k, o}
\]

(2.28)

\[
C_{k, o}(z_k, \zeta_k) = c_{k, o}(\frac{z_k + \zeta_k}{2}, \frac{z_k - \zeta_k}{2i})
\]

\[
F_{k, o}(z_k, \zeta_k) = f_{k, o}(\frac{z_k + \zeta_k}{2}, \frac{z_k - \zeta_k}{2i})
\]

We are now ready to present the main reflection theorem.
Theorem 2.1. Let $D$ be a simply-connected domain in the $x,y$-plane adjacent to an open analytic arc $\kappa$ such that the reflection function, $G_k$, relative to the arc $\kappa_k = \{ z_k = \tau_k(z) : z \in \kappa \}$ ($\tau_k(z)$ given by (2.6)) is defined, analytic and $G_k'(z_k) \neq 0$ on $D_k \cup \kappa_k \cup D_k^A$, $k = 1, 2, 3$. Let $u(x,y)$ be in $C^6(D) \cap C^5(D \cup \kappa)$ and satisfy
\begin{equation}
(2.29) \quad \bigg\{ \sum_{k=1}^{3} \left[ \Delta_k + a_k(x_k,y_k) \frac{\partial}{\partial x_k} + b_k(x_k,y_k) \frac{\partial}{\partial y_k} + c_k(x_k,y_k) \right] u_k(x,y) \bigg\} = 0
\end{equation}
in $D$, where the coefficients $a_k$, $b_k$ and $c_k$ are nonzero analytic complex-valued functions of their arguments and where $D_k \cup \kappa_k \cup D_k^A$ is a fundamental domain for the operator
\[ L_k = \Delta_k + a_k(x_k,y_k) \frac{\partial}{\partial x_k} + b_k(x_k,y_k) \frac{\partial}{\partial y_k} + c(x_k,y_k), \]
k = 1, 2, 3. Along $\kappa$, let $u(x,y)$ satisfy the conditions
\begin{equation}
(2.30) \quad a_k, o(x,y) \frac{\partial u_k}{\partial x} + \left[ \delta_k b_k, o(x,y) - \beta_k a_k, o(x,y) \right] \frac{\partial u_k}{\partial y} + c_k, o(x,y) u_k + f_k, o(x,y) = 0,
\end{equation}
k = 1, 2, 3, where $u_3 = u$, $u_2 = L_3[u_3]$, $u_1 = L_2[u_2]$ and $\beta_k$ and $\delta_k$ are the same numbers that appear in the coordinate transformation (2.2). The functions $a_k, o, b_k, o, c_k, o$ and $f_k, o$ are assumed to be analytic in $x$ and $y$ and to be such, that the functions $A_k, o(z_k, \zeta_k)$,
B\(_k\), \(o(z_k, \xi_k)\), C\(_k\), \(o(z_k, \xi_k)\) and F\(_k\), \(o(z_k, \xi_k)\) given in (2.28) are analytic for \(z_k\) in \(D_k \cup \hat{\kappa} \cup \hat{D}_k\), \(\xi_k\) in \(D_k \cup \hat{\kappa} \cup \hat{D}_k\), and

\[A_k, o(z_k, \xi_k) \neq 0, B_k, o(z_k, \xi_k) \neq 0\] for \(k = 1, 2, 3\). Then, \(u(x, y)\) can be analytically continued as a solution of (2.29) across \(\kappa\) into a simply-connected domain, \(\hat{\kappa}\), adjacent to \(\kappa\). The region \(\hat{\kappa}\) can be explicitly determined and is seen to depend only on the coefficients of the highest order terms of (2.29) as given in (2.1), on the original domain \(D\), on the arc \(\kappa\) and, possibly, on the choice of a finite number of simply-connected domains. Thus, the extension is global in nature.

**Remark:** Theorem 2.1 remains valid if the condition \(A_k, o \neq 0, B_k, o \neq 0\) is replaced by the condition \(A_k, o = B_k, o = 0, C_k, o = 1\) for any \(k\).

**Proof of theorem:** As seen in §3 of this chapter, Equation (2.29) may be written as the system

\[
(2.31a) \left[ \frac{\partial^2}{\partial z_3^2} + A_3(z_3, \vec{z}_3) \frac{\partial}{\partial z_3} + B_3(z_3, \vec{z}_3) \frac{\partial}{\partial \vec{z}_3} \right] V_{33}(z_3, \vec{z}_3) = \frac{1}{4} V_{23}(z_3, \vec{z}_3), z_3 \in D_3,
\]


\[
(2.31b) \left[ \frac{\partial^2}{\partial \vec{z}_2^2} + A_2(z_2, \vec{z}_2) \frac{\partial}{\partial \vec{z}_2} + B_2(z_2, \vec{z}_2) \frac{\partial}{\partial \vec{z}_2} \right] V_{22}(z_2, \vec{z}_2) = \frac{1}{4} V_{12}(z_2, \vec{z}_2), z_2 \in D_2,
\]
To rewrite Conditions (2.30), rearrange the first two terms as

\[ a_k, o (x, y) \left( \frac{\partial u_k}{\partial x} - \beta_k \frac{\partial u_k}{\partial y} \right) + b_k, o (x, y) \frac{\partial u_k}{\partial y}, \]

and then refer to (2.14) to see that

\[ \frac{\partial v_{kk}(x'_k, y'_k)}{\partial x'_k} = \frac{\partial u_k(x, y)}{\partial x} - \beta_k \frac{\partial u_k(x, y)}{\partial y}, \]

\[ \frac{\partial v_{kk}(x'_k, y'_k)}{\partial y'_k} = \delta_k \frac{\partial u_k(x, y)}{\partial y}. \]

Thus, with respect to the variables \( x_k \) and \( y_k \), Conditions (2.30) become

\[ a_k, o (x_k, y_k) \delta_k x_k - \beta_k x_k \frac{\partial v_{kk}}{\partial x'_k} + b_k, o \frac{\partial v_{kk}}{\partial y'_k} + c_k, o v_{kk} + f_k, o = 0. \]

Introducing the transformation

\[ x_k = \frac{z_k + z_{\bar{k}}}{2}, \quad y_k = \frac{z_k - z_{\bar{k}}}{2i}, \]

into this last expression, we see that when \( z_k \) is on \( K_k' \),

\[ V_{kk}(z_k, z_{\bar{k}}) \] must satisfy the condition
\[ (2.32) \quad A_k, o(z_k, \overline{z}_k) \frac{\partial V}{\partial z_k} + B_k, o(z_k, \overline{z}_k) \frac{\partial V}{\partial \overline{z}_k} + C_k, o(z_k, \overline{z}_k) V + F_k, o(z_k, \overline{z}_k) = 0, \]

\[ k = 1, 2, 3. \]

We begin the reflection process with \( V_{11}(z_1, \overline{z}_1) \), a known function satisfying Equation (2.31c) for \( z_1 \) in \( D_1 \) and Condition (2.32) along \( \kappa_1 \). Apply Lemma 2.2 to extend \( V_{11}(z_1, \overline{z}_1) \) as a solution of (2.31c) into the entire reflected domain \( D_1 \) adjacent to \( \kappa_1 \).

Refering to (2.14) and (2.7), transform \( V_{11}(z_1, \overline{z}_1) \) back to the \( x, y \) coordinates to obtain \( u_1(x, y) \) as defined and satisfying \( L_1[u_1] = 0 \) in \( D \cup \kappa \cup \tau_1^{-1}(D_1) \), where \( \tau_1^{-1}(D_1) \) is a simply-connected domain adjacent to \( \kappa \) and disjoint from \( D \).

Next, we consider the function \( V_{22}(z_2, \overline{z}_2) \), which is known and satisfies (2.31b) in \( D_2 \) and Condition (2.32) along \( \kappa_2 \). The function \( V_{12}(z_2, \overline{z}_2) = V_{11}[T_1(z_2, \overline{z}_2), \overline{T_1'(z_2, \overline{z}_2)}] \) appearing in the right hand side of (2.31b), which is originally known only for \( z_2 \) in \( D_2 \), is now defined for \( z_2 \) in \( \tau_2 \tau_1^{-1}(D_1 \cup \kappa_1 \cup \overline{D_1}) = D_2 \cup \kappa_2 \cup \tau_2 \tau_1^{-1}(D_1) \), where \( \tau_2 \tau_1^{-1}(D_1) \) is a simply-connected domain adjacent to \( \kappa_2 \) and disjoint from \( D_2 \). Since \( V_{11}(z_1, \zeta_1) \) is analytic for \( (z_1, \zeta_1) \in (D_1 \cup \kappa_1 \cup \overline{D_1}, D_1 \cup \kappa_1 \cup \overline{D_1}) \), then, by Lemma 2.1, for each \( z_{20} \) on \( \kappa_2 \) there is an open disc,
\[ N[z_{20}, r(z_{20})], \] of maximum radius \( r(z_{20}) \) and centered at \( z_{20} \), contained in \( D_2 \cup \kappa_2 \cup \tau_2^{-1}(D_1) \) such that \( \hat{V}_{12}(z_2, \zeta_2) \)

\[ = V_{11}[T_1(z_2, \zeta_2), T_1^{*}(\zeta_2, z_2)] \] is analytic for \( z_2 \in N[z_{20}, r(z_{20})] \), \( \zeta_2 \in N[z'_{20}, r(z_{20})] \). For simplicity, we limit \( r(z_{20}) \) so that the boundary of \( N[z_{20}, r(z_{20})] \) meets \( \kappa_2 \) in at most two points. Restricting our attention to the domain \( N[z_{20}, r(z_{20})] \), we use Lemma 2.2 to extend \( V_{22}(z_2, z_2) \) as a solution of (2.31b) into that simply-connected component, \( \hat{R}(z_{20}) \), of \( N[z_{20}, r(z_{20})] \cap D_2 \cap N[z_{20'}, r(z_{20'})] \) which is adjacent to that portion of \( \kappa_2 \) contained in \( N[z_{20}, r(z_{20})] \) (see Figure 2.3).

We proceed to show that if \( \hat{R}(z_{20}) \cap \hat{R}(z_{20'}) \) is nonempty and simply-connected for two distinct points \( z_{20} \) and \( z_{20'} \) on \( \kappa_2 \), then the extensions of \( V_{22}(z_2, z_2) = V_{22}(x_2, y_2) \) into \( \hat{R}(z_{20}) \) and \( \hat{R}(z_{20'}) \) agree on \( \hat{R}(z_{20}) \cap \hat{R}(z_{20'}) \). First, note that if \( \hat{R}(z_{20}) \cap \hat{R}(z_{20'}) \) is nonempty, then the assumption that \( G_2(z_2) \neq 0 \) on \( D_2 \cup \kappa_2 \cup \hat{D}_2 \) implies that \( N[z_{20}, r(z_{20})] \cap N[z_{20'}, r(z_{20'})] \cap D_2 \) is nonempty.

Indeed, let \( \eta \) be a point in \( \hat{R}(z_{20}) \cap \hat{R}(z_{20'}) \). Then, the fact that

\[ \eta \in \hat{R}(z_{20}) \subseteq \left[ N[z_{20}, r(z_{20})] \cap D_2 \right] \cap N[z_{20}, r(z_{20})] \]

and

\[ \eta \in \hat{R}(z_{20'}) \subseteq \left[ N[z_{20'}, r(z_{20'})] \cap D_2 \right] \cap N[z_{20'}, r(z_{20'})] \]
Figure 2.3
implies that there exist points \( \xi \) and \( \xi' \) in \( N[z_{20}, r(z_{20})] \cap D_2 \) and \( N[z'_{20}, r(z'_{20})] \cap D_2 \), respectively, such that \( G_2(\xi) = \xi = \eta = \xi' = G_2(\xi') \). But by assumption, \( G_2 \) is one-to-one on \( D_2 \cup \kappa \cup \overset{\wedge}{D}_2 \). Whence

\[
\xi = \xi' \in N[z_{20}, r(z_{20})] \cap N[z'_{20}, r(z'_{20})] \cap D_2
\]

(see Figure 2.4).

Also, note that the set

\[
\left\{ N[z_{20}, r(z_{20})] \cap N[z'_{20}, r(z'_{20})] \cap (D_2 \cup \kappa_2) \cup \overset{\wedge}{R}(z_{20}) \right\}
\]

is a simply-connected domain.

Now let \( v_{z_{20}}(x_2, y_2) \) and \( v'_{z_{20}}(x_2, y_2) \) be the extensions of \( V_{2n}(z_2, z_2) = v_2(x_2, y_2) \) in the domain

\[
\left\{ N[z_{20}, r(z_{20})] \cap (D_2 \cup \kappa_2) \right\} \cup \overset{\wedge}{R}(z_{20})
\]

and in the domain

\[
\left\{ N[z'_{20}, r(z'_{20})] \cap (D_2 \cup \kappa_2) \right\} \cup \overset{\wedge}{R}(z'_{20})
\]

respectively. Then \( v_{z_{20}}(x_2, y_2) \) and \( v'_{z_{20}}(x_2, y_2) \) are analytic functions of \( x_2 \) and \( y_2 \) which agree on the open set

\[
N[z_{20}, r(z_{20})] \cap N[z'_{20}, r(z'_{20})] \cap D_2
\]

and so they must also agree on \( \overset{\wedge}{R}(z_{20}) \cap \overset{\wedge}{R}(z'_{20}) \).
Figure 2.4
We form the set \( \bigcup_{z_{20} \in \kappa_2} \hat{R}(z_{20}) \), which is adjacent to \( \kappa_2 \).

If it is simply-connected, then we set \( \hat{R}_2 \) equal to it. Otherwise, we let \( \hat{R}_2 \) be a simply-connected subdomain of \( \bigcup_{z_{20} \in \kappa_2} \hat{R}(z_{20}) \) adjacent to \( \kappa_2 \). Now use the preceding argument to analytically continue \( V_{22}(z_2, \bar{z}_2) = v_{22}(x_2, y_2) \) throughout \( \hat{R}_2 \). Then \( V_{22}(z_2, \bar{z}_2) \) becomes defined throughout \( D_2 \cup \kappa_2 \cup \hat{R}_2 \) as a solution of Equation (2.31b) and \( V_{22}(z_2, \bar{z}_2) \) is an analytic function of two complex variables whenever \( z_{20} \in \kappa_2 \) and

\[
\begin{align*}
z_2 & \in \left[ N[z_{20}, r(z_{20})] \cap (D_2 \cup \kappa_2) \right] \cup \left[ \hat{R}(z_{20}) \cap \hat{R}_2 \right], \\
\zeta_2 & \in \left[ N[z_{20}, r(z_{20})] \cap (D_2 \cup \kappa_2) \right] \cup \left[ \hat{R}(z_{20}) \cap \hat{R}_2 \right].
\end{align*}
\]

Again, referring to (2.14) and (2.7), we can transform \( V_{22}(z_2, \bar{z}_2) \) back to the \( x, y \) coordinates to obtain \( u_2(x, y) \) as defined and satisfying \( L_2[u_2] = u_1(x, y) \) in \( D \cup \kappa \cup \tau_2^{-1}(\hat{R}_2) \). Note, since \( \hat{R}_2 \subset \hat{R}_1 \subset \tau_2^{-1}(D_1) \), then \( \tau_2^{-1}(\hat{R}_2) \subset \tau_2^{-1}(D_1) \).

Finally, repeat the same argument for \( V_{33}(z_3, \bar{z}_3) \) as we did for the function \( V_{22}(z_2, \bar{z}_2) \) to obtain a simply-connected domain \( \hat{R}_3 \) adjacent to \( \kappa_3 \) into which \( V_{33}(z_3, \bar{z}_3) = v_{33}(x_3, y_3) \) can be extended as a solution of (2.31a). We remark that when applying Lemma 2.1, the set \( \Omega_j \) becomes \( \left[ N[z_{20}, r(z_{20})] \cap (D_2 \cup \kappa_2) \right] \).
and the image of this latter set under the mapping \( \tau_3 \tau_2^{-1} \) becomes \( \Omega_k \). Again, perform a change of variables from the \( x_3, y_3 \) coordinates to the original \( x, y \) coordinates to get \( u_3(x, y) \) as being defined and satisfying \( L_3[u_3] = u_2(x, y) \) in \( D \cup \kappa \cup \tau_3^{-1}(R_3) \). As before, \( \tau_3^{-1}(R_3) \subset \tau_2^{-1}(R_2) \subset \tau_1^{-1}(D_1) \); thus, keeping in mind that \( u_3(x, y) = u(x, y) \), it is seen that \( u(x, y) \) satisfies Equation (2.29) in \( D \cup \kappa \cup \hat{R} \) and agrees with the original solution in \( D \cup \kappa \), where \( \hat{R} = \tau_3^{-1}(R_3) \) is a simply-connected domain adjacent to \( \kappa \) and disjoint from \( D \). This completes the proof.

§ 5. **Concluding Remarks and Illustrations.**

Conceptually, it is not difficult to see that the process involved in the proof of Theorem 2.1 may be continued to include equations of order higher than six. Thus, with the obvious modifications in the hypotheses, an inductive argument may be adapted to establish the conclusions of the reflection theorem for elliptic equations of the form

\[
\left( \prod_{k=1}^{n} L_k \right) u(x, y) = 0 ,
\]

where the operators \( L_k \) are defined in § 3 of this chapter.

We would like now to point out a couple of differences between the cases treated here and by Sloss in [7]. First, unlike
the method used in [7], the reflection process of Theorem 2.1 does not depend on the characteristics of the differential equation being distinct. That is, it is not necessary that \( \alpha_j \neq \alpha_k \) if \( j \neq k \) (see §2).

The second and most outstanding difference between the two cases lies in the Riemann functions used to represent solutions of second order elliptic equations with analytic coefficients (see Theorem 1.2). If the given differential equation has no lower order terms and is of the type considered by Sloss, then it can be decomposed as a system of second order equations whose Riemann functions are all identically equal to unity. On the other hand, for equations of the type considered in this paper, where lower order terms are present, the Riemann functions depend nontrivially on four independent complex variables. The introduction of these independent complex variables complicates the geometry of the problem considerably by requiring computations to always be performed in certain fundamental domains, namely those which are determined by Lemma 2.1.

When the differential equation has no lower order terms present, the computations necessary for reflection involve analytic functions of a single complex variable. In this case, there is a
method whereby a relatively simple and explicit formula may be
derived for the domain of reflection. In fact, let \( D \) be a simply-
connected domain adjacent to an open analytic arc \( \kappa \) such that the
reflection function, \( G \), relative to \( \kappa \) is defined, analytic and
\( G'(z) \neq 0, \ G'(z) \neq -A_j/B_j \) for \( z \) in \( D \cup \kappa \cup \hat{D} \). Here, \( A_j \) and
\( B_j \) are the constants given in (2.6a). Let \( \tau_j(z) \) be given as in
(2.6) and let

\[
\sigma_j(z) = A_j z + B_j G(z)
\]

The function \( \sigma_j(z) \) is analytic in \( D \cup \kappa \cup \hat{D} \) and \( \sigma'(z) \neq 0 \) there,
and so it has an inverse. If \( u(x, y) \) is given in \( D \) to be a solution
of the differential equation

\[
\Delta_1 \Delta_2 \ldots \Delta_n u(x, y) = 0
\]

where \( u(x, y) \) satisfies certain analytic boundary conditions along \( \kappa \),
then Sloss has shown in [7] that it is possible to continue \( u \) as a
solution of the differential equation into the region

\[
R_0 = \bigcap_{j=1}^{n} \tau_j^{-1} \left\{ \sigma_j(R) \cap \tau_j(D) \right\} \subset D
\]

where \( R = R_1 \cap R_2 \cap \ldots \cap R_n \), \( R_j = \sigma_j^{-1} \left\{ \sigma_j(D) \cap \tau_j(D) \right\} \) and
\( R = G(R) \).

The following four figures were obtained with the invaluable
aid of the U.C.S.B. on-line system. They were photographed from
the display scope and then drawn from an enlarged print. The first three illustrate the region of reflection for solutions of the specific equation

$$\frac{\partial^6 u}{\partial x^6} + 2 \frac{\partial^5 u}{\partial x^5 \partial y} + 3 \frac{\partial^4 u}{\partial x^4 \partial y^2} + 6 \frac{\partial^3 u}{\partial x^3 \partial y^3} + 6 \frac{\partial^2 u}{\partial x^2 \partial y^4} - 8 \frac{\partial^6 u}{\partial x \partial y^5} + 40 \frac{\partial^6 u}{\partial y^6} = 0$$

for various choices of the arc. Here, $\alpha_1 = 1 + i$, $\alpha_2 = 2i$ and $\alpha_3 = -2 + i$. The last illustration is for the differential equation having $\alpha_1 = 1 + 1.5i$, $\alpha_2 = i$ and $\alpha_3 = .5 + .5i$. Each figure shows the original domain $D$, the arc $\kappa$, the reflected domain $D$, and the region of reflection, $R_o$, which is the shaded portion of the drawing. In Figure 2.5, $\kappa$ is the interval $(-1, 1)$ of the $x$-axis and $D$ is the region between the curve whose equation is $y^2 = x^2 + .5$ and $\kappa$. Figure 2.6 shows reflection across a portion of an ellipse. The domain $D$ is the intersection of the open circular disc centered at $(0, -.7)$ of radius one with the inside of the ellipse $\cos \theta + i \frac{1}{2} \sin \theta$, $-\pi \leq \theta \leq \pi$. In Figure 2.7, $\kappa$ is part of a parabola whose equation is $y = x^2$ for $1 \leq x \leq \sqrt{7}$. Finally, in Figure 2.8, $D$ is the annular domain bounded by the circle of radius .7 centered at the origin and $\kappa$, which is the
unit circle. In this case, since $D$ is not simply-connected, we must restrict our attention to the single valued solutions of the differential equation. We emphasize that in these illustrations $\hat{D}$ contains $R_0$ and is adjacent to $\kappa$. 
Figure 2.6
Figure 2.3
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