

ITERATIVE METHODS FOR SOLVING PARTIAL DIFFERENCE
EQUATIONS OF ELLIPTIC TYPE

by

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Foreword

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INTRODUCTION

Finite difference methods afford a powerful tool for obtaining approximate numerical solutions for many differential equations whose analytic solutions are not known. The differential equation is replaced by a difference equation which must be satisfied by the values of the unknown function u at a finite set of points in the domain, Ω of the independent variable. This set of points usually consists of the nodes, or net points, of a square network Ω_h contained in Ω . The mesh size is denoted by h (> 0).

It is shown in Chapter I that if N is the number of net points and $u = (u_1, u_2, \dots, u_N)$ is the unknown function, corresponding to a linear self adjoint second order partial differential equation of elliptic type with prescribed boundary values, u must satisfy a system of linear equations of the form

$$(0.1) \quad \sum_{j=1}^N a_{i,j} u_j + d_i = 0 \quad (i=1, 2, \dots, N),$$

where the coefficients $a_{i,j}$ are real and where

$$\begin{aligned}
 (0.2) \quad & \left. \begin{aligned}
 & (a) \quad a_{ii} > 0 \quad (i = 1, 2, \dots, N) \\
 & (b) \quad a_{i,j} \leq 0 \quad (i \neq j; i, j = 1, 2, \dots, N) \\
 & (c) \quad a_{ii} \geq \sum_{\substack{j=1 \\ j \neq i}}^N |a_{i,j}| \quad (i = 1, 2, \dots, N) \quad \text{and for some } i \\
 & \quad \quad a_{ii} > \sum_{\substack{j=1 \\ j \neq i}}^N |a_{i,j}| \\
 & (d) \quad \text{The } N \times N \text{ matrix } (a_{i,j}) \text{ is } \underline{\text{irreducible}}^1, \text{ that is,} \\
 & \quad \quad \text{given any two non empty } \text{complementary} \text{ subsets } \mathcal{I}_E \text{ and } \mathcal{I}_O \\
 & \quad \quad \text{of the set of the first } N \text{ integers there} \\
 & \quad \quad \text{exists } a_{i,j} \neq 0 \text{ such that } i \in \mathcal{I}_E \text{ and } j \in \mathcal{I}_O.
 \end{aligned} \right\}
 \end{aligned}$$

Definition 0.1 A difference equation ^{is} elliptic if, when reduced to the form (0.1), the coefficients of $(a_{i,j})$ satisfy conditions (0.2).

Definition 0.2 An elliptic difference equation is self adjoint, if

$$(0.3) \quad (e) \quad a_{i,j} = a_{j,i} \quad (i, j = 1, 2, \dots, N)$$

Although the finite difference analogue of a self adjoint partial differential equation is self adjoint, if the mesh size is altered, as for example near the boundary, (e)

1. Geiringer [29].

Numbers in brackets, [], refer to the bibliography at the end of the thesis.

will no longer be fulfilled. We shall avoid using (ϵ) whenever possible, and shall always state when it is used.

Geiringer [29] has shown that any system of equations, fulfilling the conditions (0.2) has a unique solution. The proof will be given in Chapter I. Actually obtaining the solution, however, may be very laborious.

It is the purpose of this thesis to consider the practicability of the various methods for solving these equations, with special emphasis on those methods which are adapted to large automatic computing machines. I shall be particularly concerned with the Dirichlet Problem.

Direct methods such as the use of determinants and elimination for solving (0.1) do not appear to be very practical when N is large, and various methods of successive approximation are usually employed, including the iterative methods of Kormes [33] and Liebmann [3] (modified by Shortley and Weller[4]) and the relaxation methods of Southwell [1].

For these methods an arbitrary initial approximation $u^{(0)} = (u_1^{(0)}, u_2^{(0)}, \dots, u_N^{(0)})$ is chosen and successively improved. One obtains a sequence $\{u^{(m)}\}$ such that under the conditions on $(a_{i,j})$

$$(0.4) \quad \lim_{m \rightarrow \infty} u_i^{(m)} = u_i \quad (i = 1, 2, \dots, N)$$

(a) For The Kormes Method, which was applied by Kormes

to a special case of (0.1), the sequence $\{u^{(m)}\}$ is defined by

$$(0.5) \quad u_i^{(m+1)} = - \sum_{\substack{j=1 \\ j \neq i}}^N \frac{a_{ij}}{a_{ii}} u_j^{(m)} - \frac{d_i}{a_{ii}} \quad (i=1, 2, \dots, N)$$

or

$$(0.5a) \quad u^{(m+1)} = \mathcal{K} [u^{(m)}] + c, \quad \text{where}$$

\mathcal{K} is a linear operator on V_N the vector space of N -tuples of complex numbers, and where the vector c is given by

$$(0.6) \quad c = \left(-\frac{d_1}{a_{11}}, -\frac{d_2}{a_{22}}, \dots, -\frac{d_N}{a_{NN}} \right)$$

(b) For The Liebmann Method, which is actually a special case of The Gauss-Seidel Method [27], the equations are taken in a prescribed order, σ , and the sequence $\{u^{(m)}\}$ is defined by

$$(0.7) \quad u_i^{(m+1)} = - \sum_{j=1}^{i-1} \frac{a_{ij}}{a_{ii}} u_j^{(m+1)} - \sum_{j=i+1}^N \frac{a_{ij}}{a_{ii}} u_j^{(m)} - \frac{d_i}{a_{ii}} \quad (i=1, 2, \dots, N)$$

or

$$(0.7a) \quad u^{(m+1)} = L_\sigma [u^{(m)}] + c$$

Clearly, \mathcal{L}_σ is a linear operator on V_N .

In Chapter I, a proof, due to Geiringer, [29] is given for the convergence of The Kormes and Liebmann Methods, using the fact that the matrix $(a_{i,j})$ satisfies conditions (0.2).

(c) For the relaxation methods, one first computes the residuals of $u^{(0)}$ by the formula

$$(0.8) \quad \mathcal{R}_i^{(0)} = - \left[\sum_{j=1}^N a_{i,j} u_j^{(0)} + d_i \right] \quad (i=1,2,\dots,N)$$

If $\mathcal{R}_i^{(0)} = 0$ for all i , $u^{(0)}$ satisfies (0.1).

Otherwise, the values of $u_i^{(0)}$ are adjusted and the residuals are recomputed. This process is continued until all residuals are reduced to a negligible amount. No exact instructions are usually given for doing this; "the former (the relaxation methods) challenges one's intellect at each step to make the best possible guess..." [16]. On the other hand high intellectual powers are not required; by adjusting the coordinates of $u^{(0)}$ one at a time, just enough to remove the corresponding residual, and so that the coordinates are adjusted cyclically in a prescribed order, one has The Liebmann Method. Any one residual $\mathcal{R}_i^{(m)}$ can be removed as follows

$$(0.9) \quad \begin{cases} u_j^{(m+1)} = u_j^{(m)} & (j \neq i) \\ u_i^{(m+1)} = u_i^{(m)} + \frac{\mathcal{R}_i^{(m)}}{a_{ii}} \end{cases}$$

as can be verified directly. This is called relaxing the residual $X_i^{(m)}$. One logical way of relaxing the residuals is to relax the residual of largest magnitude at each stage. In Chapter I a proof due to Temple [15], is given for the convergence of this procedure when $(a_{i,j})$ satisfies (0.2) and (0.3). If only (0.2) is assumed, the method is shown to converge under a weak assumption on the order of relaxing.

Various devices have been introduced to accelerate the convergence, such as block relaxation ([1] page 55) where a group of values $u_i^{(m)}$ are modified simultaneously, and overrelaxation and underrelaxation ([1] page 65), where one modifies $u_i^{(m)}$ by more or less, respectively, than indicated by (0.9). These will be discussed later in this section.

Emmons [16] estimates that by proper use of the relaxation methods, the labor required by the Liebmann Method can be reduced by a factor of 5. However, the effective use of relaxation methods requires scanning of the residuals, a process which is easy for a human computer but which cannot be done efficiently by any large automatic computing machine in existence or being built.

Iterative methods, on the other hand, appear to be best suited for large automatic computing machines. In Chapter II the rates of convergence of The Kormes and Liebmann Methods are studied in detail. The rates of con-

vergence depend on the eigenvalues of the operators \mathcal{K} and \mathcal{L}_σ respectively. For the study of these eigenvalues we make use of the fact that the matrix $(a_{i,j})$ has property (A_ξ) for some ξ . This property is now defined.

Definition 0.3

Let $(a_{i,j})$ An $N \times N$ matrix $(a_{i,j})$ has property (A_ξ) if there exist non empty disjoint subsets T_1, T_2, \dots, T_ξ of \tilde{T} , the set of the first N integers, such that $\bigcup_{l=1}^{\xi} T_l = \tilde{T}$, and such that the T_l can be labeled so that

$$a_{i,j} = 0 \quad \text{unless} \quad i=j \quad \text{or} \\ i \in T_l \quad \text{and} \quad j \in T_{l-1} \cup T_{l+1}.$$

(By convention T_0 and $T_{\xi+1}$ denote the empty set.)

Since $(a_{i,j})$ has property (A_ξ) for some ξ , it is easy to show that if μ is an eigenvalue of \mathcal{K} , $(-\mu)$ is also an eigenvalue. There exist certain orderings σ of the equations, called consistent orderings, such that to each such pair $(\mu, -\mu)$ of eigenvalues of \mathcal{K} corresponds an eigenvalue $\lambda = \mu^2$ of \mathcal{L}_σ . The rate of convergence of \mathcal{L}_σ is exactly twice that of \mathcal{K} . This has been shown to be true asymptotically in N by Shortley and Weller [4]. An explicit expression of the eigenvectors of \mathcal{L}_σ in terms of the eigenvectors of \mathcal{K} is also given. If $a_{i,j} = a_{j,i}$ all eigenvalues of \mathcal{K} and \mathcal{L}_σ are real and the Jordan normal form of the corresponding matrices are diagonal with the possible exception of the subspace associated with $\lambda=0$ for \mathcal{L}_σ .

If, also, $a_{ii} = \text{constant}$, as for the Dirichlet Problem, the eigenvectors of \mathcal{K} are orthogonal. For the Dirichlet Problem the eigenvalues and eigenvectors of \mathcal{K} and \mathcal{L}_σ can be computed exactly for a rectangular region. For one ordering, σ_2 , the normal form of the matrix of \mathcal{L}_σ is diagonal and ^{if} the coordinates of an arbitrary vector in V_N referred to the basis of eigenvectors of \mathcal{K} are known, the coordinates of that same vector referred to the basis of eigenvectors of \mathcal{L}_{σ_1} can be computed at once.

For the symmetric case a conjecture that by The Liebmann Method the rate of convergence can not be increased by using an ordering which is not consistent is proved in one special case. Some numerical studies bear out a conjecture by Shortley and Weller [4] that for large N (hence small h) the rate of convergence of \mathcal{L}_σ is practically independent of σ .

It is also shown that for those methods the number of iterations required to reduce the norm of the initial error function

$$(0.11) \quad \|e^{(0)}\| = \left[\sum_{i=1}^N e^{(0)2}_i \right]^{1/2}, \text{ where}$$

$$(0.12) \quad e^{(0)}_i = u^{(0)}_i - u_i \quad (i=1, 2, \dots, N)$$

to a definite fraction of itself is asymptotically for small h proportional to h^{-2} . For some problems, the time required to obtain an acceptable degree of accuracy, even

with a fast large automatic computing machine such as the UNIVAC, is prohibitive.

In Chapter III it is shown that the required number of iterations can be greatly reduced by using The Successive Overrelaxation Method, where the idea of systematic overrelaxation, first used by L. F. Richardson, [2], is combined with The Liebmann Method. The idea of overrelaxation itself has been used in connection with the relaxation methods by such authors as Hartree, [18], page 120, Southwell, [1] page 65, and Emmons [16]. Overrelaxation is an attempt to "anticipate at each step the effect of later steps in the process," [18]. By Richardson's Method the values of an approximate solution, $u^{(m)}$ of (0.1) are modified simultaneously by the formula

$$(0.13) \quad u_i^{(m+1)} = u_i^{(m)} - \omega \left\{ \sum_{j=1}^N a_{i,j} u_j^{(m)} + d_i \right\} \\ (i=1, 2, \dots, N)$$

or

$$(0.13a) \quad u^{(m+1)} = R_\omega[u^{(m)}] + \omega d$$

where ω is the relaxation factor. If a_{ii} is constant for $i=1, 2, \dots, N$ and $\omega = \frac{1}{a_{ii}}$ we have the Kormes improvement formula (0.5). In general, for The Kormes Method combined with overrelaxation we have the improvement formula

$$(0.14) \quad \mu_i^{(m+1)} = \omega \left[\sum_{\substack{j=1 \\ j \neq i}}^N - \frac{a_{i,j}}{a_{i,i}} \mu_j^{(m)} - \frac{d_i}{a_{i,i}} \right] - (\omega-1) \mu_i^{(m)} \\ (i=1, 2, \dots, N)$$

or

$$(0.14a) \quad \mu^{(m+1)} = \mathcal{K}_\omega [\mu^{(m)}] + \omega C$$

where C is given in (0.6).

Again if $a_{i,i}$ is constant for $i=1, 2, \dots, N$, (0.14) is equivalent to (0.13) for suitable choice of ω .

The gain in convergence rate using a fixed relaxation factor is in general very slight indeed for either (0.13) or (0.14). Richardson used different values of ω for each iteration, but it appears doubtful that a gain of a factor of greater than 5 in the rate of convergence can in general be realized unless one is extremely fortunate in the choice of the values of ω . Shortly and Weller [4], are of the opinion that the gain is even less. This is discussed further in Chapter III.

However, by the simple device of improving the values $\mu_i^{(m)}$ successively in a cyclic order σ and using new values as soon as they are available, one can use a fixed relaxation factor, and, if this single factor is suitably chosen, a large gain in the rate of convergence is possible. For the Dirichlet Problem the gain is of the order of h^{-1} and for the general self adjoint case, if the required number of

iterations with The Liebmann Method is of the order of h^{-k} that number is of the order of $h^{-k/2}$ if this new method, The Successive Overrelaxation Method, is used with the proper value of ω .

The improvement formula for The Successive Overrelaxation Method is

$$(0.16) \quad u_i^{(m+1)} = \omega \left[- \sum_{j=1}^{i-1} \frac{a_{i,j}}{a_{i,i}} u_j^{(m+1)} - \sum_{j=i+1}^N \frac{a_{i,j}}{a_{i,i}} u_j^{(m)} - \frac{d_i}{a_{i,i}} \right] - (\omega - 1) u_i^{(m)} \quad (i=1, 2, \dots, N)$$

or

$$(0.16a) \quad u^{(m+1)} = L_{\sigma, \omega} [u^{(m)}] + w c$$

where the subscripts σ and ω of $L_{\sigma, \omega}$ denote the ordering and the relaxation factor respectively. Clearly $L_{\sigma, \omega}$ is a linear operator, and if $\omega = 1$ we have The Liebmann Method. The Successive Overrelaxation Method is included in a more general class of iterative methods considered by H. Geiringer [29].

It is by using the fact that the matrix $(a_{i,j})$ has property (A_2) that it can be shown, for the first time, that one can obtain the above mentioned remarkable gain in the rate of convergence. We show that, always assuming σ consistent, there is an exact algebraic relation between the eigenvalues and eigenvectors of \mathcal{K} and $L_{\sigma, \omega}$.

If μ is any eigenvalue of \mathcal{K} there exists an eigenvalue $\hat{\lambda}$ of $\mathcal{L}_{\sigma, \omega}$ such that

$$(0.17) \quad \mu \omega \hat{\lambda}^{1/2} = \hat{\lambda} + (\omega - 1)$$

and conversely every eigenvalue of $\mathcal{L}_{\sigma, \omega}$ can be determined by (0.17) for some μ . The eigenvectors of $\mathcal{L}_{\sigma, \omega}$ can also be expressed explicitly in terms of the eigenvectors of \mathcal{K} . If $(a_{i,j})$ is symmetric then the optimum relaxation factor ω_b is given by

$$(0.18) \quad \mu_1^2 \omega_b^2 = 4(\omega_b - 1)$$

where μ_1 is the largest eigenvalue of \mathcal{K} . For all $\omega \geq \omega_b$ every eigenvalue of $\mathcal{L}_{\sigma, \omega}$ has absolute value $(\omega - 1)$ and the Jordan normal form of the matrix of $\mathcal{L}_{\sigma, \omega}$ is diagonal unless $\omega = \omega_b$. In this case the normal matrix form contains precisely one non diagonal element.

For the Dirichlet Problem for small h , μ_1 is very nearly equal to one. μ_1 can be calculated for a rectangle and can be estimated for other regions by comparison theorems. For the general self adjoint case, provided μ_1 is not underestimated (for the Dirichlet Problem a non trivial upper bound for μ_1 can always be found) the relative decrease in the rate of convergence if $\omega' \geq \omega_b$ is used is approximately

$$(0.19) \quad \mathcal{S}^{-1/2} - 1$$

where

$$(0.20) \quad (1 - \mu_1') = \mathcal{S}(1 - \mu_1) \quad (0 < \mathcal{S} \leq 1)$$

and where ω' is determined from (0.18) but with μ_1 replaced by the estimated value μ_1' . Thus a relatively large error in the estimation of $(1-\mu_1)$ can be allowed, and the improvement over The Liebmann Method will not suffer appreciably. This also suggests that The Successive Overrelaxation Method can be successfully applied^{2.} self adjoint equations other than Laplace's Equation.

The Successive Overrelaxation Method can be used with any large automatic computing machine for which The Liebmann Method can be used. The machine time per interaction would not be increased by more than 10%. It is expected that the use of The Successive Overrelaxation Method will considerably augment the class of problems for which the use of large automatic computing machines is practical.

CHAPTER I

Partial Difference Equations of EllipticType

Let Ω be a closed bounded region in Euclidean n -space, with interior R and boundary S . Consider the self adjoint elliptic partial differential equation of second order

$$(I01) \quad (L[\bar{u}] + G)(\kappa) = 0 \quad \kappa \in R$$

$$\bar{u}(\kappa) = g(\kappa) \quad \kappa \in S$$

where

$$(I02) \quad L[\bar{u}] = \sum_{k=1}^m \frac{\partial}{\partial \kappa_k} \left(\alpha^{(k)} \frac{\partial \bar{u}}{\partial \kappa_k} \right) + F \bar{u}$$

and \bar{u} , $\alpha^{(k)}$ ($k=1, 2, \dots, m$), F , and g are functions of the vector κ whose components, (referred to an orthogonal basis e_1, e_2, \dots, e_n of unit coordinate vectors), are $(\kappa_1, \kappa_2, \dots, \kappa_n)$. We assume F ,

$\alpha^{(k)}$ and G are continuous functions of κ with continuous first and second partial derivatives, in Ω , and that g is a continuous function of κ on S . $\alpha^{(k)}$ and F satisfy the conditions

$$(I.03a) \quad \alpha^{(k)} > 0 \quad (k=1, 2, \dots, n)$$

$$(I.03b) \quad F \leq 0$$

If f is any function defined on Ω we write

$$(I.04) \quad f(x) = f(x_1, x_2, \dots, x_n)$$

An important special case of (I.0.2) is the Dirichlet Problem, Kellogg, [5] page 236. In this case

$$(I.05) \quad L[\bar{u}] = \nabla^2 [\bar{u}] = \sum_{k=1}^n \frac{\partial^2 \bar{u}}{\partial x_k^2}$$

§ 1. Basic Facts

For the Dirichlet Problem the existence of a unique solution has been proved for a wide class of regions, see for example Lichtenstein [37] and Kellogg [5], Chapter XI. In [5] page 329 Zaremba's criterion is given for $n=3$: a unique solution exists if each point P of S is the vertex of a right circular cone, which has no points in the portion of R in any sphere about P however small. Phillips and Wiener [11] gave a proof, based on the use of finite difference methods for the existence of a unique solution of the Dirichlet Problem for any region Ω with the following property:

Whenever a point P belongs to S there are positive numbers a and b such that if $r < a$ and an n -sphere Γ of radius r is drawn with P as center, and if Σ is the set of points in Γ but not in R , then the projection of Σ on at least one of the $(n-1)$ dimensional spaces determined by a set of n perpendicular axes exceeds br^{n-1} in content.

Courant Friedrichs, and Lewy, [9] have given a proof for the more general problem (I.o.1) based on finite difference methods. The existence of a unique solution of (I.o.1) is proved for regular regions ([5], page 113), such that

$$(1.1) \quad \lim_{r \rightarrow 0} \frac{1}{r} \int_{S_r} u^2 dx_1 dx_2 \dots dx_n = 0$$

implies $u=0$ on S where S_ν is the set of all points of Ω at a distance less than ν from some point of S and where u is any continuous function. This condition is always fulfilled for $n=2$, [9].

The analytic solution is not known, however, except for the simplest regions. Consequently if one desires numerical results, approximate methods must ordinarily be used. Included among these methods are variational methods [6], the use of orthogonal functions [7] (for $n=2$), conformal mapping (for $n=2$ and for the Dirichlet Problem), and finite difference methods [6].

In this dissertation I shall be concerned with finite difference methods. The region \mathcal{R} is covered by a network \mathcal{R}_h and the differential equation is replaced by a difference equation involving the values of the unknown function at the nodes (net points) of \mathcal{R}_h . The solution of the difference equation differs from the solution of the differential equation by an amount which depends on the fineness of the mesh and on the type of finite difference approximation which is used.

1
Consider a square network whose nodes are the set

of points

1. Triangular and hexagonal networks have been used by Southwell and his collaborators [1]. Square networks are simpler, and have been used almost exclusively in the United States.

$$\begin{aligned} x &= (x_1, x_2, \dots, x_n) && \text{such that} \\ x_k &= p_k h && (k=1, 2, \dots, n) \end{aligned}$$

where h is the mesh size and the p_k are integers.

Two net points x and x' are adjacent if $p_k = p'_k$ for all k except for a single i

$$|p_i - p'_i| = 1$$

where

$$x = (p_1 h, p_2 h, \dots, p_n h)$$

$$x' = (p'_1 h, p'_2 h, \dots, p'_n h)$$

If x is adjacent to x' we write $x \wedge x'$.

Ω_h is the set of all such net points contained in Ω . R_h the interior of Ω_h , is the set of all points x such that all net points adjacent to x belong to Ω_h . All other points of Ω_h belong to S_h the boundary of Ω_h . A segment is a straight line joining two adjacent net points. Ω_h is connected provided any two points of R_h can be joined by an unbroken line consisting of segments contained in R_h . We assume that h is sufficiently small so that Ω_h is connected.

Let N be the number of points of R_h and N_B be the number of points of S_h . The general point of Ω_h may be denoted by

$$(1.2) \quad x^{(i)} = (x_1^{(i)}, x_2^{(i)}, \dots, x_m^{(i)}), \quad (i=1, 2, \dots, N+N_E).$$

where

$$x_k^{(i)} = k_k^{(i)} h.$$

We assume that if $i \leq N$, $x^{(i)} \in R_h$.

Let V_{N+N_E} be the space of all complex valued functions defined on R_h and let V_N be the space of all functions on V_{N+N_E} vanishing on S_h .

A function (vector), $f \in V_{N+N_E}$ has coordinates

$$f = (f_1, f_2, \dots, f_{N+N_E})$$

referred to a basis of unit functions which equal one at one point of R_h and vanish elsewhere, where

$$(1.3) \quad f_i = f(x^{(i)}) \quad (i=1, 2, \dots, N+N_E)$$

We define the operators ([12], page 4)

$$(1.4) \quad \begin{cases} E_{x_k} f(x) = f(x + h e_k) \\ E_{-x_k} f(x) = f(x - h e_k) \end{cases} \quad (k=1, 2, \dots, n)$$

To derive the finite difference analogue of (I.0.1) we replace the derivatives by difference quotients. Thus as in [9], the differential operator

$$\frac{\partial}{\partial x_k} \left(\alpha^{(k)} \frac{\partial}{\partial x_k} \right)$$

is replaced by

$$(1.5) \quad h^{-2} \left\{ (1 - E - \alpha_k) \left[\alpha^{(k)} (E - \alpha_k - 1) \right] \right\}$$

and the operator (L) is replaced by

$$(1.6) \quad -Lh^{-2} = h^{-2} \left\{ \sum_{k=1}^m \alpha^{(k)} E - \alpha_k - \left[\alpha^{(k)} + E - \alpha_k \alpha^{(k)} \right. \right. \\ \left. \left. + (E - \alpha_k \alpha^{(k)}) E - \alpha_k \right] + h^2 F \right\}$$

The finite difference analogue of (I.0.1) becomes

$$(1.7) \quad \begin{cases} (L[u])_i - h^2 G_i = 0 & (i = 1, 2, \dots, N) \\ u_i = g_i & (i = N+1, \dots, N+N_B) \end{cases}$$

or

$$(1.8) \quad \begin{cases} \sum_{j=1}^{N+N_B} a_{i,j} u_j - h^2 G_i = 0 & (i = 1, 2, \dots, N) \\ u_i = g_i & (i = N+1, \dots, N+N_B) \end{cases}$$

1. Here g_i is taken as the value $g(x)$ where $x \in S$ and x is the nearest point of S to $x^{(i)} \in S_h$. Alternatively one might extend the function g to R and take g_i to be the value of this extended function. Another possibility is to change the mesh size near R whenever $x^{(i)} \in S_h$ does not belong to S , [4]. This does not make the problem essentially more difficult from a practical point of view but does spoil some of the mathematical relationships to be given later. Further discussion of this question will be given later.

where the general element of the $N \times (N + N_B)$ matrix

$(a_{i,j})$ is

$$(1.9) \quad a_{i,j} = \begin{cases} \sum_{k=1}^n [\alpha_i^{(k)} + E - \nu_k \alpha_i^{(k)} - h^2 F_i] & (i=j) \\ -\alpha_i^{(k)} & (x^{(j)} = x^{(i)} + h e_k \text{ for some } k) \\ -E - \nu_k \alpha_i^{(k)} & (x^{(j)} = x^{(i)} - h e_k \text{ for some } k) \\ 0 & (i \neq j \text{ and } x^{(i)} \text{ not adjacent to } x^{(j)}) \end{cases}$$

For the Dirichlet problem we have

$$(1.10) \quad -(l[w])_i = \left[\sum_{k=1}^n (E - \nu_k + E - \nu_k) - 2n \right] [w]_i = 0 \quad (i=1, 2, \dots, N)$$

and

$$(1.10a) \quad a_{ij} = \begin{cases} 2-n & (i=j) \\ -1 & (x^{(i)} \wedge x^{(j)}) \\ 0 & (i \neq j \text{ and } x^{(i)} \text{ not adjacent to } x^{(j)}) \end{cases}$$

Since $u_i = g_i \quad (i = N+1, \dots, N+N_B)$

we have

$$(1.11) \quad \sum_{j=1}^N a_{ij} u_j + d_i = 0 \quad (i=1, 2, \dots, N)$$

I. Other finite difference analogues of the Dirichlet Problem,
with a square net, have been considered by Milne [25] and
Bickley [8].

(also Shortley?)

where

$$(1.12) \quad d_i = \sum_{j=N+1}^{N+N_B} a_{i,j} g_j - h^2 C_i \quad (i=1, 2, \dots, N)$$

We may also at times write (1.11) in the form

$$(1.13) \quad u_i = \sum_{j=1}^N b_{i,j} u_j + C_i \quad (i=1, 2, \dots, N)$$

where

$$(1.14) \quad b_{i,j} = \begin{cases} -\frac{a_{i,j}}{a_{i,i}} & (i \neq j) \\ 0 & (i = j) \end{cases}$$

$$(1.15) \quad C_i = -\frac{d_i}{a_{i,i}} \quad (i=1, 2, \dots, N)$$

Clearly by (1.8) and (I.0.3. a, b) the coefficients of $(a_{i,j})$ have the following properties

$$(1.16) \quad \begin{aligned} (a) \quad & a_{i,i} > 0 && (i=1, 2, \dots, N) \\ (b) \quad & a_{i,j} \leq 0 && (i, j=1, 2, \dots, N) \\ (c) \quad & a_{i,i} \geq \sum_{\substack{j=1 \\ j \neq i}}^N |a_{i,j}| && (i=1, 2, \dots, N), \text{ and for some } i^1. \end{aligned}$$

$$\begin{aligned} & a_{i,i} > \sum_{\substack{j=1 \\ j \neq i}}^N |a_{i,j}| \\ (d) \quad & a_{i,j} < 0 && (x^{(i)} \wedge x^{(j)}) \end{aligned}$$

1. i.e. for all i such that $x^{(i)}$ is adjacent to a point of S_h .

(1.16 cont.) (e) $a_{i,j} = 0$ ($i \neq j$ and $\mathcal{R}^{(i)}$ not adjacent to $\mathcal{R}^{(j)}$).

(1.17) (f) $a_{i,j} = a_{j,i}^{-1}$ ($i, j = 1, 2, \dots, N$).

Theorem 1.1

The matrix $(a_{i,j})$ satisfying (1.16d), (1.16e) is irreducible and has property (A_2) .

Proof: (a) By (1.16d), given any two non empty complementary subsets of \mathcal{R}_h there must exist two adjacent points not belonging to the same subset since \mathcal{R}_h is connected. The irreducibility follows

(b) Let T_2 be the set of integers such that

$$\sum_{k=1}^N p_k^{(i)} \quad \text{is even, and let } T_1 \text{ be}$$

the set of integers such that

$$\sum_{k=1}^N p_k^{(i)} \quad \text{is odd.}$$

1. As already stated we avoid using this fact wherever possible.

For if the mesh size is varied (see (1.18) footnote), this condition is no longer fulfilled.

Then T_1 and T_2 are complementary subsets of T and by (1.16e), if $i \neq j$

$$a_{i,j} = 0$$

unless $i \in T_1$ and $j \in T_2$ or $i \in T_2$ and $j \in T_1$. Thus $(a_{i,j})$ has property (A_2) .

Q. E. D.

Corollary

(1.7) is an elliptic self adjoint difference equation.

The existence of a unique solution of (1.11) has been proved by Gerschgorin [10], without requiring that $(a_{i,j})$ be symmetric but using (1.16d). We shall give a proof for a somewhat more general case, which is due to Geiringer [29].

Theorem 1.2

If the matrix $(a_{i,j})$ satisfies (0.2), then the determinant of $(a_{i,j})$ does not vanish, and there exists a unique solution of (0.1).

Proof: To prove the theorem we need only show that

$d_i = 0, (i = 1, 2, \dots, N)$ implies $u_i = 0, (i = 1, 2, \dots, N)$ is the only solution of (0.1). By linear equation theory, this will imply that the determinant of $(a_{i,j})$ is not zero, and that there exists a unique solution of (0.1).

Thus let $d_i = 0, (i = 1, 2, \dots, N)$ and suppose $u_i > 0$ for some i . Then u must assume a maximum values $u_{i_0} = M$ for some i_0 . By (0.2) this is not possible unless

$$u_j = M \quad \text{for } j \in \mathcal{B}.$$

where S_1 is the set of all integers such that $a_{i_0, j} \neq 0$.

Similarly, by induction $u_j = m$ for all $j \in S_t$,

where S_t is the set of all integers such that

$$a_{i, j} \neq 0 \quad i \in S_{t-1}$$

definition of S_t ?

If we let $S_0 = \{i_0\}$ we have

$$S_0 \subset S_1 \subset S_2 \subset \dots \quad ? ? ?$$

where the inclusion relation is strict by the irreducibility

of $(a_{i, j})$. Therefore we have $u_i = m$, $(i = 1, 2, \dots, N)$

and by (0.2) this is impossible. Therefore

$u_i \leq 0$ $(i = 1, 2, \dots, N)$. Similarly $u_i \geq 0$, $(i = 1, 2, \dots, N)$; therefore

$u_i = 0$ $(i = 1, 2, \dots, N)$.

Q. E. D.

Phillips and Wiener [11] proved that, for the Dirichlet Problem, under the assumptions on Ω stated above $u \rightarrow \bar{u}$ as $h \rightarrow 0$. Courant Friedrichs and Lewy [9] proved the same result for the general problem under their assumptions on Ω already stated.

Gerschgorin [10] derived an error bound for $|u - \bar{u}|$ under the assumption that \bar{u} has continuous partial derivatives of all orders up to and including the fourth. He also obtained an error bound for $|u' - u|$ where u' is any approximate solution of (1.11). For the Dirichlet Problem the proof is relatively simple and is given below.

Theorem 1.3

If

$$(\nabla^2 [\bar{u}])(x) = \sum_{k=1}^m \frac{\partial^2 \bar{u}(x)}{\partial x_k^2} = 0 \quad x \in R$$

and if

$$M_4 = \max_{k=1,2,\dots,m} \left\{ \max_{x \in R} \left| \frac{\partial^4 \bar{u}(x)}{\partial x_k^4} \right| \right\}$$

then

$$(1.18) \quad |(l[\bar{u}])_i| \leq \frac{h^4}{6} M_4 \quad (i=1,2,\dots,N).$$

Proof: By 1.10 we have

$$-(l[\bar{u}])_i = \left(\sum_{k=1}^m E_{x_k} + E_{-x_k} - 2n \right) \bar{u}(x^{(i)})$$

By Taylor's Theorem

$$E_{x_k}(\bar{u}_i) = \bar{u}(x^{(i)} + h e_k) = \bar{u}_i + h \left(\frac{\partial \bar{u}}{\partial x_k} \right)_i \\ + \frac{h^2}{2!} \left(\frac{\partial^2 \bar{u}}{\partial x_k^2} \right)_i + \frac{h^3}{3!} \left(\frac{\partial^3 \bar{u}}{\partial x_k^3} \right)_i + \frac{h^4}{4!} \left(\frac{\partial^4 \bar{u}}{\partial x_k^4} \right) \left(\xi_k^+ \right)$$

where ξ_k^+ is a point on the segment joining $x^{(i)}$ and $x^{(i)} + h e_k$. We have

$$-(l[\bar{u}])_i = \frac{h^2}{2!} (\nabla^2 \bar{u})_i + \frac{h^4}{4!} \left\{ \sum_{k=1}^m \left[\frac{\partial^4 \bar{u}}{\partial x_k^4} \left(\xi_k^+ \right) + \frac{\partial^4 \bar{u}}{\partial x_k^4} \left(\xi_k^- \right) \right] \right\}$$

Hence

$$|(l[\bar{u}])_i| \leq \frac{h^4}{6} M_4. \quad \text{Q. E. D.}$$

Theorem 1.4

For the Dirichlet Problem if r is the radius of any m -sphere containing Ω and if

$$M_1 = \text{Max}_{k=1,2,\dots,n} \left\{ \text{Max}_{x \in \Omega} \left| \frac{\partial \bar{u}(x)}{\partial x_k} \right| \right\}$$

then

$$(1.19) \quad |u_i - \bar{u}_i| \leq \frac{M_1}{24} h^2 r^2 + \sqrt{n} M_1 h \quad (i=1,2,\dots,N)$$

Proof:

Lemma 1: If $(l[u])_i \geq 0$, $(i=1,2,\dots,N)$ and if $u_i \geq 0$ ($i=N+1,\dots,N+N_B$), then $u_i \geq 0$ ($i=1,2,\dots,N$).

Lemma 2:

If $|(l[u])_i| \leq (l[v])_i$, $(i=1,2,\dots,N)$, and if $|u_i| \leq v_i$ ($i=N+1,\dots,N+N_B$) then $|u_i| \leq v_i$ ($i=1,2,\dots,N$)

Lemma 3: Let $x^{(0)} = (x_1^{(0)}, x_2^{(0)}, \dots, x_n^{(0)})$ belongs to R and let $\Omega \subseteq C_r$ where C_r is the closed m -sphere $\sum_{k=1}^m (x_k - x_k^{(0)})^2 \leq r^2$

1. Collatz [31] has shown that by a modification of the difference equations near the boundary, the second term can be made to approach zero with h^{-2} .

Let A be a non negative real constant and let

$$\phi(x) = A \left[1 - \frac{\sum_{k=1}^m (x_k - x_k^{(i)})^2}{r^2} \right] + \sqrt{m} M_1 h$$

then

$$(\ell[\phi])_i = \frac{4h^2}{r^2}$$

We have by the mean value theorem

$$|u_i - \bar{u}_i| \leq \sqrt{m} M_1 h \quad (i = N+1, \dots, N+N_B)$$

since for $x^{(i)} \in S_h$, u_i is taken as the value of $\bar{u}(x)$ on the nearest point of S .

Also by Theorem 1.4 and Lemma 3

$$A = \frac{h^2}{24} r^2 M_4$$

and

$$|(\ell[\bar{u}])_i| = |(\ell[\bar{u} - u])_i| \leq (\ell[\phi])_i \quad (i = 1, 2, \dots, N)$$

$$|u_i - \bar{u}_i| \leq \phi_i \quad (i = N+1, \dots, N+N_B)$$

The theorem follows by Lemma 2.

Q. E. D.

Corollary: For the Dirichlet Problem if u' is an approximate solution of (1.11) and if

$$\max_{i=1,2,\dots,N} \{ |x_i| \} = x'_0$$

where

$$x'_i = -(\ell[u'])_i$$

and u' is the harmonic solution of (1.11) then

$$(1.20) \quad |u_i - u_i| \leq \frac{r^2}{4h^2} x'_0 \quad (i=1,2,\dots,N).$$

Proof: We first note that $|u'_i - u_i| = 0$ ($i = N+1, \dots, N+N_B$)

Also, if we let

$$\phi'(x) = A \left[1 - \frac{\sum_{k=1}^n (x_k - x_k^{(0)})^2}{x^2} \right]$$

Then

$$(\mathcal{L}[\phi'])_i = \frac{4Ah^2}{x^2}$$

If

$$A = \frac{x^2 \mathcal{L}'_0}{4h^2}, \text{ then } (\mathcal{L}[\phi'])_i \geq |(\mathcal{L}[u'])_i| = |(\mathcal{L}[u-u'])_i|$$

Also

$$\phi'_i \geq |u'_i - u_i| = 0 \quad (i = N+1, \dots, N+N_B)$$

therefore the result follows by Lemma 3.

Q. E. D.

A disadvantage of (1.19) is that the derivatives of \bar{u} are not known, in general. However, we may estimate the derivatives by difference quotients of u .

Thus for $n=2$ we replace

$$\frac{\partial^4 \bar{u}}{\partial x_1^4} = \frac{\partial^4 \bar{u}}{\partial x_2^4} = \frac{\partial^4 u}{\partial x_1^2 \partial x_2^2} \quad \text{by}$$

$$D_4(x) = h^{-4} [(E_{x_1} + E_{-x_1})(E_{x_2} + E_{-x_2}) - 4] u(x)$$

If $S_h \subseteq S$ we have by 1.19

$$|u_i - \bar{u}_i| \stackrel{1.}{\leq} \frac{h^2 x^2}{h^4} = \frac{x^2 \bar{D}_4}{2}$$

1. Here the symbol $\stackrel{1.}{\leq}$ means "approximately less than or equal to."

where

$$\bar{D}_4 = \text{Max}_{x \in R_h} D_4(x)$$

For the unit square with $\frac{1}{2}$ intervals on a side we

have

$$h = \frac{1}{2} \quad \text{and} \quad r = \frac{1}{2}\sqrt{2}$$

Then

$$\frac{r^2}{24} \bar{D}_4 h^{-2} = \frac{1}{2} \frac{\bar{D}_4}{24} = .0833 \frac{\bar{D}_4}{4}.$$

Shortley and Weller [4] give

$$.06 \frac{\bar{D}_4}{4}$$

as an asymptotic estimate for the error.

§.2 Numerical Methods

The existence and uniqueness of a solution of (1.11) has already been proved. Thus, from the standpoint of pure mathematics the problem might be considered solved. From the practical, numerical point of view, however, actually solving the equations is the hardest part of the problem.

a. Direct Methods

The formal solution of (1.11) in terms of determinants is of little practical value except for very small N . Direct solution by elimination methods might be practical for large automatic computing machines but the number of operations required increases very rapidly with N .

Runge [32] proposed a method by which one can reduce the number of linear equations by a factor which is of the order of h^{-1} . The simplicity of the original equations is sacrificed. To apply the method one first expresses the u_i , $(x^{(i)} \in R_h)$, in terms of the u_i , $(x^{(i)} \in (S_h^+) \cup S_h)$, where (S_h^+) is the set of points $x^{(i)}$ of R_h such that

$$(x^{(i)} - h) \in S_h$$

For example, consider the Dirichlet Problem for a plane region (figure 1.1).

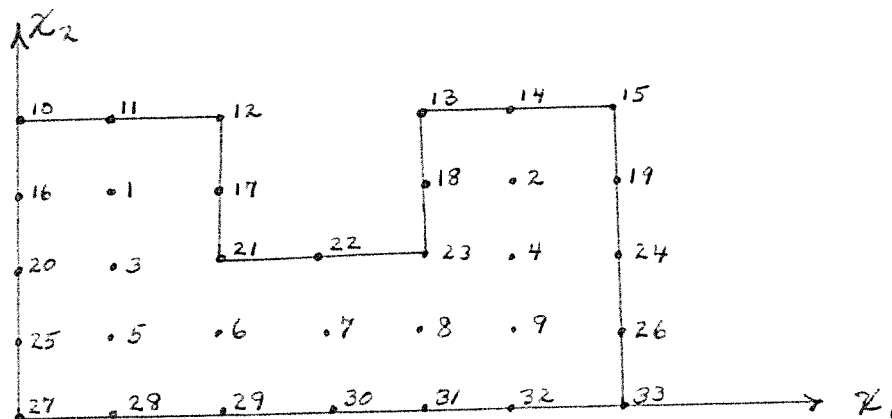


Figure 1.1

Here (S_k^+) , $(k=1)$, consists of the points 1, 3, 5, 2, 4 and (S_k^-) consists of the points 1, 3, 2, 4, 9 where, in general, (S_k^-) is the set of points $x^{(i)}$ of R_k such that

$$(x^{(i)} + h e_k) \in S_k.$$

The $u_i, (x^{(i)} \in R_k)$, can be expressed in terms of $u_i, (x^{(i)} \in S_k \cup (S_k^+))$ by means of the difference equation.

Thus, in figure 1.1. we have

$$u_6 + u_3 + u_{27} + u_{28} - 4u_5 = 0$$

Solving for u_6 we have

$$u_6 = 4u_5 - u_3 - u_{27} - u_{28}.$$

If N_k is the number of points of (S_k^+) , N_k is also the number of points of (S_k^-) . The condition that the difference equation must be satisfied at the points of (S_k^-) gives

\mathcal{N}_k equations and \mathcal{N}_k unknowns. Solving these we have $u_i, (z^{(i)} \in (S_k^+))$, and hence all $u_i, (z^{(i)} \in R_A)$.

The method does not appear well adapted to large automatic computing machines. The complicated equations are not easy to solve either directly or by iterative methods. Moreover, the determination of the coefficients is laborious, especially for large N . In practice one would obtain the non-homogeneous part of the equations by assuming $u_i = 0, (z^{(i)} \in (S_k^+))$, and determining $u_i, (z^{(i)} \in (S_k^-))$ from the boundary values alone. Then, letting the boundary values equal zero, the coefficients of the homogeneous part of the equations λ^{a+c} determined as follows:

Assume $u_i = 1$ at one point of (S_k^+) and zero at all other points of (S_k^+) . Then calculate the values of u at the points of (S_k^-) .

High accuracy in all calculations is very necessary because of the instability of the method. Thus in the example (figure 1.1) an error of ϵ in the final determination of u_5 would result in the following errors:

$$u_6 = 4\epsilon, u_7 = 15\epsilon, u_8 = 56\epsilon, u_9 = 209\epsilon.$$

If \bar{I}_k is the average number of intervals in the \mathcal{N}_k direction, the accumulated error would be about

$$\epsilon \cdot 4^{\bar{I}_k}.$$

Thomas [30] suggests a method for direct solution which he asserts is at least as good as the ordinary methods of iteration for $n=2$. However, the method does not appear to be suitable for large automatic computing machines and is certainly not as good as The Successive Overrelaxation Method of Iteration (Chapter III).

For the Dirichlet Problem and for a rectangle with commensurable sides, an explicit solution in terms of the boundary values is possible. Thus let Ω be a rectangular region with sides $\tau_1, \tau_2, \dots, \tau_n$ where $\tau_k = I_k h$, ($k=1, 2, \dots, n$), and where I_k ($k=1, 2, \dots, n$) are integers.

We assume that on S , $u=0$ except on $\tau_n = \tau_n$ where $u = f(\tau_1, \tau_2, \dots, \tau_{n-1})$. Obviously the general solution can be obtained by linear superposition of such solutions. Using the method of separation of variables for (1.10), as for the continuous case [see Jackson [14] page 95] and noting that

$$\sum_{p_k=1}^{I_k-1} \sin\left(\frac{y_k \pi}{\tau_k} p_k h\right) \sin\left(\frac{y'_k \pi}{\tau_k} p_k h\right) = \begin{cases} \frac{I_k}{2} & y_k = y'_k \\ 0 & y_k \neq y'_k \end{cases}$$

($k=1, 2, \dots, n$).

we obtain by the methods of Phillips and Wiener [11]¹.

¹ I. Phillips and Wiener gave the solution for a unit cube ($n=3$).

$$u(z_1, z_2, \dots, z_n) = \frac{2^{n-1}}{I_1 I_2 \dots I_{n-1}} \sum_{\gamma_1=1}^{I_1-1} \dots \sum_{\gamma_{n-1}=1}^{I_{n-1}-1} \left\{ \sum_{\beta'_1=1}^{I_1-1} \dots \sum_{\beta'_{n-1}=1}^{I_{n-1}-1} \prod_{k=1}^{n-1} \sin\left(\frac{\gamma_k \pi}{L_k} \beta'_k h_k\right) \right. \\ \left. \prod_{k=1}^{n-1} \sin\left(\frac{\gamma_k \pi}{L_k} z_k\right) \frac{\sinh \beta \pi z_n}{\sinh \beta \pi L_n} \right\}$$

where

$$\sinh^2\left(\frac{\beta h}{2}\right) = \sum_{k=1}^{n-1} \sin^2\left(\frac{\gamma_k \pi}{L_k} \frac{h}{2}\right)$$

I have used the above formulas to obtain elementary solutions, (solutions where $g=1$ at one point of S_R and 0 elsewhere), for squares with 4, 6 and 8 intervals on a side. The solution for any boundary values is clearly a linear combination of these solutions. For a rectangle with $\bar{I}_1 \times \bar{I}_2$ intervals on a side, $2(\bar{I}_1 - 1)(\bar{I}_2 - 1)(\bar{I}_1 + \bar{I}_2 - 2)$ multiplications are required, assuming the elementary functions are known.

However, the computation of elementary functions for other regions is in general more difficult, and even for rectangular regions, unless several problems are to be done for the same region, the labor of computing the elementary functions would ordinarily not be justified.

1. Moskovitz [13] has published tables for various rectangular regions whose shortest side contains at most four intervals. Liebmann [3] has given tables to 4 decimals for square regions with 4 and 6 intervals on a side.

For large N and for a region of general shape it seems more practical to proceed by successive approximation methods.

b. Iterative Methods

The Kormes, Liebmann and The Successive Overrelaxation Methods of systematic iteration have been described in the Introduction for general systems of linear equations. We shall give a rather general proof of the convergence of The Kormes and Liebmann Methods which is due to Geiringer [29]. From this the convergence of The Successive Overrelaxation Method follows as will be shown in Chapter III, where this method is discussed.

Theorem 2.1

Given the system of linear equations

$$(0.1) \quad \sum_{j=1}^N a_{i,j} u_j + d_i = 0 \quad (i=1,2,\dots,N)$$

where $(a_{i,j})$ is irreducible and where the elements of $(a_{i,j})$ satisfy (0.2), then the sequences of vectors given by The Kormes Method, (0.5), and The Liebmann Method, (0.6), each converge to the solution of (0.1).

→ PROOF
(a) For The Liebmann Method if $u^{(m)}$ is the m -th approximation to u defined by (0.7), then the m -th error function

$$e^{(m)} = u^{(m)} - u$$

is given by

$$(2.1) \quad \begin{cases} e_i^{(m)} = -\sum_{j=1}^{i-1} \frac{a_{i,j}}{a_{i,i}} e_j^{(m)} - \sum_{j=i+1}^N \frac{a_{i,j}}{a_{i,i}} e_j^{(m-1)} \\ e^{(0)} = u^{(0)} - u \end{cases} \quad (i=1, 2, \dots, N)$$

Let

$$e_0^{(m)} = \max_{i=1, 2, \dots, N} |e_i^{(m)}|$$

For all i we have by (0.20)

$$|e_i^{(1)}| \leq e_0^{(0)}$$

and for some i_1 by (0.20)

$$|e_{i_1}^{(1)}| < e_0^{(0)}.$$

By the irreducibility of $(a_{i,j})$ we have

$$|e_{i_1}^{(2)}| < e_0^{(0)}$$

$$|e_{i_2}^{(2)}| < e_0^{(0)} \quad \text{for some } i_2 \neq i_1.$$

$$|e_i^{(2)}| \leq e_0^{(0)} \quad (i=1, 2, \dots, N).$$

Continuing this process we have finally

$$|e_i^{(N)}| < e_0^{(0)} \quad (i=1, 2, \dots, N)$$

Letting $\nu_1 = \max_{i=1, 2, \dots, N} \frac{|e_i^{(N)}|}{e_0^{(0)}}$, where

$$e_i^{(N)} = e_0^{(0)} \quad (i=1, 2, \dots, N), \text{ we have}$$

$$e_0^{(N)} \leq \nu_1 e_0^{(0)} \quad (\nu_1 < 1).$$

Similarly

$$e_0^{(mN)} \leq \gamma_1^m e_0^{(0)}, \text{ and hence}$$

$$\lim_{m \rightarrow \infty} e_0^{(m)} = 0, \text{ and}$$

$$\lim_{m \rightarrow \infty} u^{(m)} = u.$$

(b) For The Kormes Method the argument is practically the same.

Q. E. D.

Corollary: For (1.11), The Kormes method and The Liebmann Method each converge

We remark that The Liebmann Method is convergent for any ordering of the equations, and that the ordering may be changed after each total step. [29]

As we shall see in Chapter II, although The Liebmann Method converges exactly twice as fast as The Kormes Method, the rate of convergence in either case is very slow.

Shortley and Weller [4] have introduced two modifications to accelerate the convergence of The Liebmann Method for the Dirichlet Problem for $n = 2$:

(a) The first is the use of formulas by means of which the values of $u_i^{(m)}$ for an entire block are improved simultaneously. Square blocks with 4, 9 and 25 blocks are used. Ordinarily, the gain in convergence would seem to be offset

by the extra work involved in the use of more complicated formulas. However, by a slight modification of the difference equations this extra work is reduced to about 20% using a square block with nine points, while the rate of convergence is improved by a factor of about 3.5.

(b) The second modification is the use of an extrapolation procedure after some iterations have been performed. In most cases the required number of iterations can be reduced by a factor of two or three. Recently Shanks [19] has developed a method which may permit a sufficiently accurate extrapolation after fewer iterations and hence increase the gain somewhat.

Nevertheless the factor of saving, effected by these modifications does not increase appreciably with h^{-1} . The Successive Overrelaxation Method described in Chapter III, on the other hand, affords a gain in convergence which does increase with h^{-1} and for the Dirichlet Problem is proportional to h^{-1} .

(c) Relaxation Methods

Relaxation methods have been described briefly in the Introduction. We shall give below a proof, due to Temple [15], of the convergence of the relaxation methods when applied to any linear system (0.1) assuming that $(a_{i,j})$ is symmetric and positive definite.

Theorem 2.2. For the system of linear equations (0.1), if $(a_{i,j})$ is symmetric and positive definite, and if at each step a largest residual (in absolute value) is relaxed, then the relaxation method converges to the solution of (0.1).

Proof: Obviously, since $(a_{i,j})$ is positive definite a unique solution of (0.1) exists. Let $u^{(0)}$ be an approximate solution of (0.1) and let a largest residual (in absolute value) occur at $r^{(0)}$.

For any two vectors $u, v \in V_N$ we define the following symmetric bilinear form

$$Q(u, v) = \sum_{i,j=1}^N a_{i,j} u_i v_j$$

Since $(a_{i,j})$ is positive definite $Q(u, u) \geq 0$
and $Q(u, u) = 0$ if and only if $u = 0$.

If we now let

$$W(u) = \frac{1}{2} Q(u, u) + \sum_{i=1}^N d_i u_i$$

then

$$\frac{\partial W}{\partial u_i} = \sum_{j=1}^N a_{i,j} u_j + d_i = 0 \quad (i=1,2,\dots,N)$$

and

$$\frac{\partial^2 W}{\partial u_i \partial u_j} = a_{i,j} \quad (i,j=1,2,\dots,N).$$

As is well known, see, for example, Widder ([34] pages 109-112), if u satisfies (0.1), then, since $(a_{i,j})$ is positive definite, W assumes a relative minimum, which we denote by W_0 . If we choose a new orthogonal basis of V_N by an orthogonal transformation ([20] page 247) we have

$$Q(u, u) = \sum_{i=1}^N \lambda_i u_i^{*2} \quad (\lambda_i > 0)$$

where $u_1^*, u_2^*, \dots, u_N^*$ are the coordinates of u referred to the new basis. It is clear that as

$$\sum_{i=1}^N u_i^2$$

becomes very large, $W(u)$ is also very large. Hence W_0 is an absolute minimum for $W(u)$ for all $u \in V_N$.

We have

$$\begin{aligned} W(u^{(1)} + t e_i) &= \frac{1}{2} Q(u^{(1)} + t e_i, u^{(1)} + t e_i) \\ &\quad + \sum_{j=1}^N d_j [u_j^{(1)} + t e_i] \\ &= \frac{1}{2} Q(u^{(1)}, u^{(1)}) + t Q(u^{(1)}, e_i) \\ &\quad + \frac{1}{2} t^2 Q(e_i, e_i) + \sum_{j=1}^N d_j [u_j^{(1)} + t e_i] \end{aligned}$$

$$\begin{aligned} W(u^{(1)} + t e_i) &= W(u^{(1)}) \\ &\quad + t [Q(u^{(1)}, e_i) + \sum_{j=1}^N d_j] + \frac{1}{2} t^2 Q(e_i, e_i). \end{aligned}$$

This expression is minimized by setting

$$t = - \frac{Q(u^{(1)}, e_i) + d_i}{Q(e_i, e_i)} = - \frac{\sum_{j=1}^N a_{i,j} u_j^{(1)} + d_i}{a_{i,i}}$$

If, as in (0.9) we obtain $u^{(2)}$ from $u^{(1)}$ by relaxing the residual at $Z^{(i)}$ we have

$$\begin{cases} u_i^{(2)} = u_i^{(1)} + \frac{-[\sum_{j=1}^N a_{i,j} u_j^{(1)} + d_i]}{a_{i,i}} \\ u_j^{(2)} = u_j^{(1)} \quad (j \neq i) \end{cases}$$

and

$$W^{(2)} = W(u^{(2)}) = W(u^{(1)}) - \frac{(Z_i^{(1)})^2}{a_{i,i}}$$

If this process is repeated we get a decreasing sequence of values of $W^{(m)}$ which approach a limit since $W^{(m)}$ is bounded below by W_0 . Since $a_{i,i} > 0$ ($i = 1, 2, \dots, N$) (because $(a_{i,j})$ is positive definite), the largest residual of $u^{(m)}$ approaches zero; hence for all $i = 1, 2, \dots, N$

$$\lim_{m \rightarrow \infty} \{ Z_i^{(m)} \} = 0$$

Now let $a^{i,j}$ be the cofactor of $a_{i,j}$ in the determinant of $(a_{i,j})$. We have

$$u_i = \sum_{j=1}^N -a^{i,j} d_j \quad (i = 1, 2, \dots, N)$$

$$u_i^{(m)} = \sum_{j=1}^N -a^{i,j} (d_j + Z_j^{(m)}) \quad (i = 1, 2, \dots, N)$$

Therefore for $i = 1, 2, \dots, N$

$$\begin{aligned} \lim_{m \rightarrow \infty} u_i^{(m)} &= \lim_{m \rightarrow \infty} \sum_{j=1}^N -a^{i,j} (d_j + \epsilon_j^{(m)}) \\ &= - \sum_{j=1}^N a^{i,j} d_j = u_i. \end{aligned}$$

Q. E. D.

Theorem 2.3

If $(a_{i,j})$ is an $N \times N$ matrix satisfying (0.2) and (0.3), then $(a_{i,j})$ is positive definite.

Proof: It is well known that if $(a_{i,j})$ is symmetric, then $(a_{i,j})$ is positive definite if and only if

$$\sum_{j=1}^N a_{i,j} u_j^* = \lambda u_i^* \quad (\lambda \leq 0) \quad (i=1, 2, \dots, N)$$

implies $u_i^* = 0, (i=1, 2, \dots, N)$, see for instance [20] pages 245 and 305. Thus, suppose for some $\lambda \leq 0$

$$\sum_{j=1}^N a_{i,j} u_j^* = \lambda u_i^* \quad (i=1, 2, \dots, N)$$

Then

$$(a_{ii} - \lambda) u_i^* + \sum_{\substack{j=1 \\ j \neq i}}^N a_{i,j} u_j^* = 0 \quad (i=1, 2, \dots, N)$$

and by (0.2)

$$(a_{ii} - \lambda) \geq \sum_{\substack{j=1 \\ j \neq i}}^N |a_{i,j}| \quad (i=1, 2, \dots, N)$$

and for some i

$$(a_{ii} - \lambda) > \sum_{\substack{j=1 \\ j \neq i}}^N |a_{i,j}|.$$

By Theorem 1.2, the determinant of $(a_{i,j} - \lambda I)$, (where I is the identity matrix), does not vanish. Therefore

$$u^*_i = 0 \quad (i = 1, 2, \dots, N) .$$

Q. E. D.

Corollary: If $(a_{i,j})$ satisfies (0.2) and (0.3) then the relaxation method converges to the solution of (0.1) if, at each step a largest residual is relaxed.

By the method of Theorem 2.1 it is clear that the relaxation method converges if $(a_{i,j})$ satisfies (0.2) if the residuals are relaxed in any order subject to the following restriction:

There exists a fixed number M such that for all i and m the residual at $x^{(i)}$ is relaxed at least once, on an iteration after the m -th and before the $(m+M)$ th.

We have already observed that relaxation methods are not well suited for large automatic computing machines. However, an electric computing board developed at the Watertown Arsenal Laboratory [17], affords a convenient method of relaxing residuals for the Dirichlet Problem with a plane region S_A which can be inscribed in a square region with 21 intervals on a side. A machine capable of being used with larger regions could be built.

Mounted on a large board is a square lattice of electric terminals, each corresponding to a net point. Each net point is connected to the four adjacent points by fixed re-

sistances. The terminals corresponding to points of S_A are grounded. The residuals of the trial solution $u^{(0)}$ are computed and currents, proportional to these residuals are introduced into the corresponding terminals. The voltages, which are then measured, are approximately to within the accuracy of the electric measuring devices, proportional to the corrections to be added to the $u^{(0)}$. The residuals of $u^{(1)}$, the first improved approximation thus obtained, are then computed and the process repeated if necessary. Any desired accuracy may be obtained.

Through the courtesy of the Watertown Arsenal Laboratory, I was able to use the computing board to solve several problems each involving about 150 net points. I found that the maximum residual was reduced by a factor of from 10 to 50. Each iteration required about 3 hours, with ^{the} greatest part of the time being devoted to computing the residuals (by a desk machine), adjusting the currents and reading the voltages. An experienced operator can perform about three complete iterations with a 20 X 20 region in two eight-hour days.

CHAPTER II

Rates of Convergence of The Kormes Method
and of The Liebmann Method

Shortley and Weller [4] investigated the rapidity of convergence of $\mathcal{L}\sigma$ the transformation defined by the Liebmann Method, see (0.7), for the case of the Dirichlet Problem. They considered the eigenvalues of $\mathcal{L}\sigma$ and derived asymptotic estimates, for small h (for them). In this Chapter I will derive an exact relation for certain σ , between the eigenvalues and eigenvectors of $\mathcal{L}\sigma$ and those of \mathcal{K} , the transformation defined by The Kormes Method, see (0.5). The analysis of \mathcal{K} is relatively easy, and using these relations an exact analysis is made of $\mathcal{L}\sigma$. From this analysis, estimates for the number of iterations required to obtain a specified accuracy are derived.

§ 3. The Rate of Convergence of a Linear Transformation

We shall consider first the rate of convergence of a linear transformation T of an N dimensional complex vector space, V_N , onto itself. If $f = (f_1, f_2, \dots, f_N)$ is any vector of V_N , we define the norm of f by

$$(3.1) \quad \|f\| = \left[\sum_{i=1}^N |f_i|^2 \right]^{1/2}$$

Also, with the inner product

$$(3.2) \quad (f, g) = \sum_{i=1}^N f_i \bar{g}_i$$

V_N is a Euclidean vector space.

Definition 3.1. T is a convergent transformation if for all $f \in V_N$

$$\lim_{m \rightarrow \infty} \|T^m(f)\| = 0$$

Definition 3.2. The rate of convergence of a convergent transformation, T , is

$$(3.3) \quad \phi(T) = -\log \chi(T)$$

where

$$(3.4) \quad \chi(T) = \lim_{m \rightarrow \infty} \left[\text{LUB}_{\substack{f \in V_N \\ m_i > m}} \sqrt[m_i]{\frac{\|T^{m_i}(f)\|}{\|f\|}} \right] \quad \text{why needed}$$

As we shall see later, the number of times T must be applied to a vector f to reduce $\|f\|$ to a specified fraction of itself is, approximately, inversely proportional to the rate of convergence.

It is well known, see for example MacDuffee [30], Chapter VII, that T has M distinct eigenvalues $\lambda_1, \lambda_2, \dots, \lambda_M$ with multiplicities K_1, K_2, \dots, K_M where

$$\sum_{i=1}^M K_i = N$$

Definition 3.3

λ_1 is the dominant eigenvalue of T if

$$|\lambda_1| \geq |\lambda|$$

where λ is any eigenvalue of T .

We shall show below that $|\lambda_1| = \mathcal{N}(T)$.

The Jordan normal matrix form is written in block form,

([36] pages 236 and 241)

$$(3.5) \quad \begin{pmatrix} J_1 & 0 & 0 & \cdot & \cdot & \cdot & 0 \\ 0 & J_2 & 0 & \cdot & \cdot & \cdot & 0 \\ 0 & 0 & J_3 & \cdot & \cdot & \cdot & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & 0 & \cdot & \cdot & \cdot & J_{M_1} \end{pmatrix}$$

where $M_1 \geq M$ and J_i ($i = 1, 2, \dots, M_1$) is a square Jordan matrix of the form

$$(3.6) \quad \begin{pmatrix} \lambda_i & 0 & 0 & \cdot & \cdot & \cdot & 0 \\ 1 & \lambda_i & 0 & \cdot & \cdot & \cdot & 0 \\ 0 & 1 & \lambda_i & \cdot & \cdot & \cdot & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & 0 & \cdot & \cdot & \cdot & \lambda_i \end{pmatrix}$$

Here, not all the λ_i need be distinct. Let the number of rows and columns of the matrix J_i be γ_i , ($i = 1, 2, \dots, M_1$).

Associated with the normal matrix form (3.5) is a basis

$$\{v_{i,k}\} \quad \begin{pmatrix} i=1,2,\dots,M_i \\ k=1,2,\dots,r_i \end{pmatrix}$$

with associated eigenvalue λ_i .

We can normalize the $\{v_{i,k}\}$ so that

$$(3.7) \quad \|v_{i,k}\| = 1 \quad \begin{pmatrix} i=1,2,\dots,M_i \\ k=1,2,\dots,r_i \end{pmatrix}$$

For any $f \in V_N$ we have

$$(3.8) \quad f = \sum_{i=1}^{M_i} \sum_{k=1}^{r_i} A_{i,k} v_{i,k}$$

and

$$(3.9) \quad T^m(v_{i,k}) = \sum_{s=0}^{k-1} m C_s \lambda_i^{m-s} v_{i,k-s} \\ (i=1,2,\dots,M_i); (k=1,2,\dots,r_i)$$

where

$$m C_s = \frac{m!}{s!(m-s)!}$$

By using (3.8) and (3.9), Dresden proved that if $|\lambda_i| < 1$, T is a convergent transformation. The following theorem is obtained in a similar way. It undoubtedly has appeared in the literature although I have been unable to find it.

Theorem 3.1

If T is a convergent transformation and if λ_1 is the dominant eigenvalue of T then

$$(3.10) \quad \mathcal{N}(T) = |\lambda_1|$$

Proof

If we let
$$\alpha_m = \text{LUB}_{\substack{f \in V_N \\ m_1 > m}} \sqrt[m_1]{\frac{\|T^{m_1}(f)\|}{\|f\|}}$$

the sequence $\{\alpha_m\}$ is monotone decreasing, and is bounded below by zero. Therefore $\lim_{m \rightarrow \infty} \alpha_m$ exists.

By the homogeneity of T we can assume $\|f\| = 1$ By

(3.8) and (3.9) we have

$$(3.11) \quad T^{m_1}(f) = \sum_{i=1}^{m_1} \sum_{k=1}^{m_1} \sum_{s=0}^{k-1} A_{i,k} m_1 C_s \lambda_i^{m_1-s} v_{i,k-s}$$

But $s \leq N$ hence $m_1 C_s \leq m_1^s \leq m_1^N$.

By the linear independence of the $v_{i,k}$ the coefficients $A_{i,k}$ of (3.8) are bounded for all $\|f\| = 1$

Let $A = \text{Max}_{i,k} |A_{i,k}|$

We have

$$\|T^{m_1}(f)\| \leq NA m_1^N |\lambda_1|^{m_1-N}$$

and

$$\alpha_m \leq \text{LUB}_{m_1 > m} \left[\left\{ NA m_1^N |\lambda_1|^{m_1-N} \right\}^{1/m_1} \right]$$

$$\kappa_m \leq \text{LUB}_{m_1 > m} \left[(NA)^{1/m_1} m_1^{N/m_1} |\lambda_1|^{1 - \frac{N}{m_1}} \right]$$

But for all $m_1 > \frac{1}{\epsilon}$, m_1^{N/m_1} is a decreasing function of m_1 . Hence

$$\kappa_m \leq (NA)^{1/m} m^{N/m} |\lambda_1|^{1 - \frac{N}{m}}$$

Therefore $\mathcal{N}(\tau) = \lim_{m \rightarrow \infty} \kappa_m \leq |\lambda_1|$

On the other hand if

$$T(f) = \lambda_1 f, \quad \kappa_m = |\lambda_1| \text{ for all } m.$$

Therefore $\mathcal{N}(\tau) \geq |\lambda_1|$ and the theorem follows.

Q. E. D.

Corollary 1

$$(3.12) \quad \phi(\tau) = -\log |\lambda_1|.$$

Corollary 2 T is a convergent transformation if and only if all eigenvalues of T are smaller than one in absolute value.

1. We note that $|\lambda_1| < 1$ since T is convergent. For if f is chosen so that $T(f) = \lambda_1 f$ then $\|T^m(f)\| = |\lambda_1|^m \|f\|$ and would not approach zero unless $|\lambda_1| < 1$.

Theorem 3.2. By similar methods we can prove

(3.13)

$$\mathcal{N}(T) = \lim_{m \rightarrow \infty} \sqrt[m]{\|T^m\|}, \quad \text{where}$$

$$(3.14) \quad \|T^m\| = \text{LUB}_{f \in V_N} \frac{\|T^m(f)\|}{\|f\|}$$

We now consider the number of iterations necessary to reduce $\|f\|$ to a specified fraction of itself.

Definition 3.4.

If T is a convergent transformation on V_N
 $n_f(T, \rho, V_N)$

denotes the smallest number m such that

$$\|T^m(f)\| \leq \rho \|f\|, \quad (0 < \rho < 1).$$

Definition 3.5

$$(3.15) \quad n(T, \rho, V_N) = \text{LUB}_{f \in V_N} n_f(T, \rho, V_N)$$

When no confusion will arise we may drop the third argument for $n(T, \rho, V_N)$.

Theorem 3.3.

$$(3.16) \quad \lim_{\rho \rightarrow 0} \left[n(T, \rho) / \frac{-\log \rho}{-\log |\lambda_1|} \right] = 1$$

Proof:

For all ρ we have

$$n_{\lambda_1}(T, \rho) = \frac{-\log \rho}{-\log |\lambda_1|}$$

where $T(v_i) = \lambda_i v_i$

Hence

$$h(T, \rho) \geq \frac{-\log \rho}{-\log |\lambda_i|}$$

The requirement that $\|f\|$ be reduced to a fraction ρ of itself is equivalent to requiring that

$$\|T^m\| = \text{LUB}_{f \in V_N} \frac{\|T^m(f)\|}{\|f\|} = \rho$$

Obviously as $\rho \rightarrow 0$, $m \rightarrow \infty$.

By Theorem 3.2

$$|\lambda_i| + \epsilon(m) = \sqrt[m]{\|T^m\|}$$

where

$$\lim_{m \rightarrow \infty} \epsilon(m) = 0$$

The condition $\|T^m\| = \rho$ requires that

$$[|\lambda_i| + \epsilon(m)]^m = \|T^m\| = \rho$$

or

$$m = \frac{-\log \rho}{-\log [|\lambda_i| + \epsilon(m)]}$$

$$\frac{m}{-\log \rho} = \frac{-\log |\lambda_i|}{-\log [|\lambda_i| + \epsilon(m)]}$$

By the continuity of the logarithm function for $|\lambda_i| > 0$

$$\lim_{\rho \rightarrow 0} \frac{m}{-\log \rho} = \frac{-\log |\lambda_i|}{-\log |\lambda_i|} = 1$$

Q. E. D.

§ 4. The Kormes Method

The improvement formula for The Kormes Method of iteration is given by (0.5). Using (1.14) and (1.15) we have

$$(4.1) \quad \mu_i^{(m+1)} = \sum_{j=1}^N b_{i,j} \mu_j^{(m)} + C_i \quad (i=1,2,\dots,N)$$

or

$$(4.1a) \quad \mu^{(m+1)} = \mathcal{K} [\mu^{(m)}] + C$$

where C denotes the vector (C_1, C_2, \dots, C_N) . The general element of $(\mathcal{K}_{i,j})$ the matrix of \mathcal{K} is given by

$$(4.2) \quad \mathcal{K}_{i,j} = b_{i,j} \quad (i, j = 1, 2, \dots, N)$$

By (1.16) and (1.14)

$$b_{i,i} = 0 \quad (i = 1, 2, \dots, N)$$

$$b_{i,j} \geq 0 \quad i \neq j \quad (i, j = 1, 2, \dots, N)$$

and the matrix $(b_{i,j})$ is irreducible.

By Theorem 3.1, the rate of convergence of The Kormes Method depends on the dominant eigenvalue of \mathcal{K}

We note that $r = (r_1, r_2, \dots, r_N)$ is an eigenvector of \mathcal{K} with eigenvalue μ if and only if

$$(4.3) \quad \mathcal{K} [r] = \mu r$$

or, equivalently

$$(4.3a) \quad \sum_{j=1}^N b_{i,j} r_j = \mu r_i \quad (i=1,2,\dots,N)$$

Theorem 4.1

If $(a_{i,j})$ is a symmetric $N \times N$ matrix satisfying conditions (0.2), then the normal form of the matrix of \mathcal{K} is a real diagonal matrix; if μ_1 denotes the largest eigenvalue of \mathcal{K} , μ_1 is simple (not repeated).

Lemma 1

The eigenvalues of \mathcal{K} are the same as the eigenvalue of \mathcal{K}' where the general element of $(\mathcal{K}'_{i,j})$ is

$$\mathcal{K}'_{i,j} = b'_{i,j} = \begin{cases} \frac{-a_{i,j}}{\sqrt{a_{i,i}} \sqrt{a_{j,j}}} & (i \neq j) \\ 0 & (i = j) \end{cases}$$

Proof If

$$(4.4) \quad \mathcal{K}(r) = \mu r \quad \text{then}$$

$$\sum_{j=1}^N b_{i,j} r_j = \mu r_i \quad (i=1, 2, \dots, N)$$

$$\sum_{j=1}^N b_{i,j} \sqrt{a_{i,i}} r_j = \mu \sqrt{a_{i,i}} r_i \quad (i=1, 2, \dots, N)$$

Let

$$(4.5) \quad r'_i = \sqrt{a_{i,i}} r_i \quad (i=1, 2, \dots, N)$$

$$\sum_{j=1}^N b_{i,j} \frac{\sqrt{a_{i,i}}}{\sqrt{a_{j,j}}} r'_j = \mu r'_i$$

$$= - \sum_{\substack{j=1 \\ j \neq i}}^N \frac{a_{i,j}}{\sqrt{a_{j,j}} \sqrt{a_{i,i}}} r'_j = - \sum_{j=1}^N b'_{i,j} r'_j$$

Thus

$$(4.6) \quad \mathcal{K}'[r'] = \mu r'$$

Conversely if μ is an eigenvalue of \mathcal{X}' we can show that μ is an eigenvalue of \mathcal{X} . This proves the Lemma.

Since $(\mathcal{X}_{i,j})$ is symmetric by [20] pages 305-6 there exists an orthonormal basis of eigenvectors

$$r^{(1)'}, r^{(2)'}, \dots, r^{(N)'}$$

Such that

$$\mathcal{X}' [r^{(i)'}] = \mu_i r^{(i)'} \quad (i=1,2,\dots,N)$$

where

$$(4.7) \quad \mu_1 \geq \mu_2 \geq \mu_3 \geq \dots \geq \mu_N$$

We show that the corresponding vectors $r^{(i)'}$ satisfying (4.4) are linearly independent even if same μ is repeated k times. In this case let $r^{(1)'}, r^{(2)'}, \dots, r^{(k)'}$ be the linearly independent eigenvalues of \mathcal{X}' such that for $j=1,2,\dots,k$

$$\mathcal{X}' [r^{(j)'}] = \mu_j r^{(j)'}$$

Obviously $r^{(j)'}$ ($j=1,2,\dots,k$) are also linearly independent where

$$r_i^{(j)} = \frac{r_{i,j}^{(j)'}}{\sqrt{a_{ii}}} \quad \left(\begin{array}{l} i=1,2,\dots,N \\ j=1,2,\dots,k \end{array} \right)$$

and $a_{ii} > 0$.

Hence the normal form of $(\mathcal{X}_{i,j})$ is diagonal

Lemma 2

Let $(a_{i,j})$ be a real symmetric $N \times N$ matrix.

(a) μ_1 is the largest eigenvalue of $(a_{i,j})$ if and only if μ_1 is the maximum value of

$$(4.8) \quad Q[w] = \sum_{i,j=1}^N a_{i,j} w_i w_j$$

subject to the condition

$$(4.9) \quad \|w\|^2 = \sum_{i=1}^N w_i^2 = 1$$

(b) If $\|w^{(1)}\|^2 = 1$, then $w^{(1)}$ is an eigenvector associated with μ_1 if and only if

$$Q[w^{(1)}] = \mu_1.$$

Proof: (a) It is well known that any real symmetric matrix is orthogonally equivalent to a real diagonal matrix $(c_{i,j})$, the largest of whose elements is the maximum of $Q[w]$ subject to the requirement $\|w\|^2 = 1$, (see for instance [20] pages 247-250). The maximum clearly exists and is attained because $Q[w]$ is a continuous function on a compact set. The diagonal elements of $(c_{i,j})$ are eigenvalues of $(a_{i,j})$ and conversely (see [20] page 305). Thus (a) is proved.

(b) As in Widder [34] pages 113-115, the maximum problem may be formulated in terms of Lagrange's multipliers. We have the conditions

$$(4.10) \quad \begin{cases} \frac{\partial}{\partial w_i} \left\{ \sum_{i,j=1}^N a_{i,j} w_i w_j - \mu \left[\sum_{i=1}^N w_i^2 - 1 \right] \right\} = 0 \\ \sum_{i=1}^N w_i^2 = 1 \end{cases} \quad (i = 1, 2, \dots, N)$$

where μ is a Lagrange's multiplier. Upon simplification these

conditions become

$$(4.11) \quad \begin{cases} \sum_{j=1}^N a_{i,j} w_j = \mu w_i & (i=1,2,\dots,N) \\ \sum_{i=1}^N w_i^2 = 1 \end{cases}$$

If w satisfies (4.11), we have

$$(4.12) \quad \begin{aligned} Q[w] &= \sum_{i,j=1}^N a_{i,j} w_i w_j = \sum_{i=1}^N w_i \left\{ \sum_{j=1}^N a_{i,j} w_j \right\} \\ &= \sum_{i=1}^N w_i \mu w_i = \mu \end{aligned}$$

Thus if $w^{(1)}$ where $\|w^{(1)}\|^2 = 1$ is an **eigenvector** of $(a_{i,j})$ with eigenvalue μ_1 , $Q[w^{(1)}] = \mu_1$. Conversely, if $Q[w^{(1)}] = \mu_1$ and $\|w^{(1)}\|^2 = 1$, since μ_1 is the maximum of $Q[w]$ subject to $\|w\|^2 = 1$, by (4.11), $w^{(1)}$ is an eigenvector of $(a_{i,j})$ with eigenvalue μ_1 .

Q. E. D.

Lemma 3.

Let $(a_{i,j})$ be a real symmetric $N \times N$ matrix such that

$$a_{i,i} = 0 \quad (i=1,2,\dots,N)$$

$$a_{i,j} \geq 0 \quad (i,j=1,2,\dots,N)$$

and $(a_{i,j})$ is irreducible. If μ_1 is the largest eigenvalue of $(a_{i,j})$ and if $w^{(1)}$ is any eigenvector associated with μ_1 , then either

$$w^{(1)}_i > 0 \quad (i=1,2,\dots,N)$$

or

$$w_i^{(1)} < 0 \quad (i = 1, 2, \dots, N)$$

Moreover μ_1 is simple (not repeated).

Proof: By Lemma 2 for all $w \in V_N$

$$Q[w^{(1)}] \geq Q[w]$$

On the other hand since

$$a_{i,j} \geq 0 \quad (i, j = 1, 2, \dots, N)$$

$$Q[w^{(1)}] \leq Q[\tilde{w}^{(1)}], \quad \text{where}$$

$$(4.13) \quad \tilde{w}^{(1)} = (|w_1^{(1)}|, |w_2^{(1)}|, \dots, |w_N^{(1)}|)$$

Equality can occur only if, whenever $a_{i,j} \neq 0$

$$(4.14) \quad w_i^{(1)} w_j^{(1)} \geq 0$$

By Lemma 2, $\tilde{w}^{(1)}$ is an eigenvalue of $(a_{i,j})$.

Suppose that for some i $w_i^{(1)} = 0$. Then $\tilde{w}_i^{(1)} = 0$ and

$$\sum_{j=1}^N a_{i,j} \tilde{w}_j^{(1)} = \mu_1 \tilde{w}_i^{(1)} = 0$$

and since $a_{i,j} \geq 0$ we have

$$\tilde{w}_j^{(1)} = 0 \quad \text{for all } j \quad \text{such that } a_{i,j} \neq 0$$

Using the irreducibility of $(a_{i,j})$ it can be proved that¹

$$\tilde{w}_i^{(1)} = 0 \quad (i = 1, 2, \dots, N).$$

This contradicts the condition

$$\|w^{(1)}\|^2 = \|\tilde{w}^{(1)}\|^2 = 1$$

1. See the proof of Theorem 1.2.

Therefore $w_i^{(1)} \neq 0$ ($i = 1, 2, \dots, N$)

Again, by the irreducibility of $(a_{i,j})$, since

$w_i^{(1)} w_j^{(1)} \geq 0$ whenever $a_{i,j} \neq 0$ we can show that

$$w_i^{(1)} > 0 \quad (i = 1, 2, \dots, N) \quad \text{or}$$

$$w_i^{(1)} < 0 \quad (i = 1, 2, \dots, N).$$

To show that μ_1 is simple we first note that there exists an orthonormal basis of N eigenvectors for $(a_{i,j})$. If μ_1 is repeated k times then there would exist k linearly independent orthogonal eigenvectors each associated with μ_1 . But since each is non vanishing and one signed it is impossible that they should be orthogonal.

Q. E. D.

From Lemma 3 it follows that the largest eigenvalue of \mathcal{K}' is simple. The Theorem follows at once by Lemma 1.

Q. E. D.

Theorem 4.2

Let $(a_{i,j})$ be a real symmetric $N \times N$ matrix, ($N > 1$) such that

$$a_{ii} = 0 \quad (i = 1, 2, \dots, N)$$

$$a_{i,j} \geq 0 \quad (i, j = 1, 2, \dots, N)$$

and $(a_{i,j})$ is irreducible. Let $(a_{i,j}^*)$ be the $N' \times N'$ matrix obtained from $(a_{i,j})$ by deleting the elements in $(N-N')$ rows and the corresponding columns, where $N' < N$. If μ_1 and μ_1^* denote the largest eigenvalues of $(a_{i,j})$ and $(a_{i,j}^*)$ then

$$\mu_1 < \mu_1^*.$$

Proof Let

$$Q^* [w] = \sum_{i,j=1}^{N'} a_{i,j}^* w_i w_j$$

and

$$Q [w] = \sum_{i,j=1}^N a_{i,j} w_i w_j$$

If $w^{(1)*}$ where $\|w^{(1)*}\|^2 = 1$ is an eigenvector of $(a_{i,j}^*)$ then

$$\mu_1^* = Q^* [w^{(1)*}] = Q [w^{(1)*}]$$

where $w_i^{(1)*}$ in the second expression is taken to be zero if the i th row and column have been deleted. Hence $\mu_1 \geq \mu_1^*$. By Lemma 3, Theorem 4.2, $w^{(1)*}$ is not an eigenvector of $(a_{i,j})$ associated with the largest eigenvalue of $(a_{i,j})$. Hence μ_1^* is not the largest eigenvalue of $(a_{i,j})$. Therefore $\mu_1 > \mu_1^*$.

Q. E. D.

Corollary

If $R_h^{(1)} \subset R_h^{(2)}$ where $R_h^{(1)} \neq R_h^{(2)}$ and $R_h^{(2)}$ is connected, and if $\mu_1^{(1)}$ and $\mu_1^{(2)}$ denote the largest eigenvalue of \mathcal{K} applied to (1.11), for the networks $\mathcal{R}_h^{(1)}$ and $\mathcal{R}_h^{(2)}$ with interiors $R_h^{(1)}$ and $R_h^{(2)}$ respectively, then

$$\mu_1^{(1)} < \mu_1^{(2)}$$

We have already seen, (Theorem 1.1), that $(a_{i,j})$ has property (A_2) . We define the vector $\mathcal{Y} \in V_N$ such that

$$(4.15) \quad \begin{aligned} \gamma_i &= 1 & i \in T_1, \text{ the set where } \sum_{k=1}^m p_k^{(1)} \text{ is odd.} \\ \gamma_i &= 0 & i \in T_2, \text{ the set where } \sum_{k=1}^m p_k^{(1)} \text{ is even.} \end{aligned}$$

Theorem 4.3

If $\mathcal{X}[v] = \mu v$ and if

$$(4.16) \quad v^* = (-1)^r v$$

then

$$(4.17) \quad \mathcal{X}[v^*] = (-\mu)v^*$$

(We do not use the fact that $(a_{i,j})$ is symmetric).Proof:

$$\sum_{j=1}^N b_{i,j} v^*_j = \sum_{j=1}^N b_{i,j} (-1)^{r_j} v_j$$

If $b_{i,j} \neq 0$, $i \in T_1$ and $j \in T_2$ or $i \in T_2$ and $j \in T_1$.

We have

$$\begin{aligned} \sum_{j=1}^N b_{i,j} v^*_j &= -(-1)^{r_i} \sum_{j=1}^N b_{i,j} v_j \\ &= -(-1)^{r_i} \mu v_i = (-\mu)v^* \end{aligned}$$

Hence by (4.3a)

$$\mathcal{X}[v^*] = -\mu v^*$$

Q. E. D.

CorollaryThe eigenvector v^* may be expressed in the form

$$(4.16) \quad v^* = (1 - 2\gamma)v.$$

Now let N_1, N_2 be the number of integers in T_1, T_2 respectively.

Theorem 4.4

Let $\bar{\alpha}$ be the number of non-zero eigenvalues of \mathcal{K} and let

$$(4.19) \quad \alpha' = \text{Min}(N_1, N_2) \quad \alpha'' = \text{Max}(N_1, N_2)$$

If $(a_{i,j})$ is symmetric, then

(a) There are $\bar{\alpha}$ eigenvectors associated with non-zero eigenvalues where $\sigma \leq \bar{\alpha} \leq 2\alpha'$, and $\bar{\alpha}$ is even. The $\bar{\alpha}$ associated eigenvalues do not vanish identically on either T_1 or T_2

(b) The $(N - \bar{\alpha})$ dimensional null space V_0 of \mathcal{K} can be referred to a basis of $(N - \bar{\alpha})$ vectors such that $(N_2 - \frac{\bar{\alpha}}{2})$ of these vectors vanish identically on T_1 and $(N_1 - \frac{\bar{\alpha}}{2})$ vanish identically on T_2

Proof:

(i) If $\mathcal{K}[\mathcal{r}] = \mu \mathcal{r}$, where \mathcal{r} is not identically zero but \mathcal{r} vanishes identically on either T_2 or T_1 , then $\mu = 0$. For, $\mathcal{K}[\mathcal{r}]$ vanishes identically everywhere. Thus if $\mu \neq 0$, \mathcal{r} must not vanish identically on either T_2 or T_1 .

(ii) If $\mathcal{r}^{(1)}$ and $\mathcal{r}^{(2)}$ are any two linearly independent eigenvectors of \mathcal{K} with non-zero eigenvalues it is obvious that $\mathcal{r}^{*(1)} (\neq \mathcal{r}^{(1)})$ and $\mathcal{r}^{*(2)} (\neq \mathcal{r}^{(2)})$ are linearly independent. Therefore $\bar{\alpha}$ is even. Now consider the sets

$$\mathcal{H}_1 = \{ r^{(j)} - r^{*(j)} \} \quad \text{and} \quad \mathcal{H}_2 = \{ r^{(j)} + r^{*(j)} \}, \quad (j=1, 2, \dots, \bar{2}/2).$$

The vectors in \mathcal{H}_1 vanish in T_2 and those in \mathcal{H}_2 vanish in T_1 . On the other hand the \bar{x} vectors of $\mathcal{H}_1 \cup \mathcal{H}_2$ are linearly independent. Hence $\bar{x}/2 \leq \nu'$.

(iii) If $\mathcal{K}[r]=0$ we may write

$$r = r' + r''$$

where r' vanishes identically on T_1 and r'' vanishes identically on T_2 and both r', r'' lie in V_0 . The set of all vectors obtained in this way span V_0 and hence there exists a linearly independent subset spanning V_0 . By (ii), $(N_1 - \bar{x}/2)$ of these vectors vanish identically on T_2 and $(N_2 - \frac{\bar{x}}{2})$ vanish identically on T_1 . Q.E.D.

Given an arbitrary error vector, $e^{(0)}$ in V_N we may write

$$(4.20) \quad e^{(0)} = \sum_{j=1}^N A_j r^{(j)}$$

and by Theorem 4.4, we have

$$(4.2) \quad e^{(0)} = \sum_{j=1}^{\bar{2}/2} A_j r^{(j)} + A^*_{j} r^{*(j)} + \sum_{j=\frac{\bar{2}}{2}+1}^{N-\frac{\bar{2}}{2}} A_j r^{(j)}$$

where

$$\begin{aligned} \mathcal{K}[r^{(j)}] &= \mu_j r^{(j)} & (j=1, 2, \dots, \bar{2}/2) \\ \mu_j &> 0 & (j=1, 2, \dots, \bar{2}/2) \\ r^{(N-j)} &= r^{*(j)} & (j=1, 2, \dots, \bar{2}/2) \\ A^*_j &= A_{N-j} & (j=1, 2, \dots, \bar{2}/2) \\ \mathcal{K}[r^{(j)}] &= 0 & (j = \frac{\bar{2}}{2} + 1, \dots, N - \frac{\bar{2}}{2}) \end{aligned}$$

After m iterations, ($m > 1$), we have

$$(4.22) \quad e^{(m)} = \sum_{j=1}^{N/2} \mu_j^m A_j r^{(j)} + (-\mu_j)^m A_j^* r^{*(j)}$$

For those cases where $a_{ii} = 1$ as in the Dirichlet Problem, the $r^{(j)}$ are orthogonal. If we assume the $r^{(j)}$ have been normalized we have

$$(4.23) \quad A_j = \sum_{i=1}^N e^{(0)}_i r^{(j)}_i \quad (j = 1, 2, \dots, N)$$

and

$$(4.24) \quad \|e^{(0)}\|^2 = \sum_{j=1}^N A_j^2$$

For the Dirichlet Problem we will now show that

$$(4.25) \quad \|e'\|^2 \leq \frac{\|X'\|^2}{(1-\mu_1)^2}$$

where $e' = u' - u$, u' is an approximate solution of (1.11), and where $\|X'\|^2$ is the sum of the squares of the residuals.¹ We have already, in Section 2, given a bound for $|u'_i - u_i|$, ($i = 1, 2, \dots, N$) due to Gerschgorin.

¹ The sum of the squares of the residuals has been used as a measure of convergence by Bowie [26].

To prove (4.25), we use (4.23) to express e' in terms of the eigenvectors of \mathcal{K} . We have

and
$$e' = \sum_{j=1}^N A_j r^{(j)}$$

$$\|e'\|^2 = \sum_{j=1}^N A_j^2$$

Also

$$(\ell[u'])_i = \sum_{j=1}^N a_{i,j} u'_j + d_i \quad (i=1, 2, \dots, N)$$

and

$$0 = \sum_{j=1}^N a_{i,j} u_j + d_i \quad (i=1, 2, \dots, N)$$

Hence

$$(\ell[u'])_i = \sum_{j=1}^N a_{i,j} e'_j \quad (i=1, 2, \dots, N)$$

But since

$$a_{ii} = 1 \quad (i=1, 2, \dots, N), \quad \text{and}$$

$$b_{i,j} = -a_{i,j} \quad (i \neq j)$$

$$(\ell[u'])_i = e'_i - (\mathcal{K}[e'])_i$$

$$= e'_i - \sum_{j=1}^N u_j A_j r_i^{(j)} \quad (i=1, 2, \dots, N)$$

$$(\mathcal{L}[u'])_i = \sum_{j=1}^N (1-\mu_j) A_j r_i^{(j)} \quad (i = 1, 2, \dots, N)$$

$$\|\mathcal{X}'\|^2 = \|(-\mathcal{L}[u'])\|^2 = \sum_{j=1}^N (1-\mu_j)^2 A_j^2 \geq (1-\mu_1)^2 \|e'\|^2$$

Hence (4.25) is proved.

For the Dirichlet Problem with a rectangular region the eigenvalues and eigenvectors of \mathcal{X} can be expressed explicitly. Let I_k be the number of intervals on the k^{th} side. We have

$$(4.26) \quad r_i^{(j)} = \prod_{k=1}^n \sin \frac{l_k(j) \pi p_k^{(i)}}{I_k}$$

where $l_k(j) = 1, 2, \dots, I_k - 1$
 $j = 1, 2, \dots, N$

The corresponding eigenvalue is

$$(4.27) \quad \mu_i = \frac{1}{n} \sum_{k=1}^n \cos \frac{l_k(i) \pi}{I_k}$$

This may be readily verified by (0.5) and (1.10)

In particular

$$(4.28) \quad \mu_1 = \frac{1}{n} \sum_{k=1}^n \cos \frac{\pi}{I_k}$$

For large I_k ($k=1, 2, \dots, m$)

$$(4.29) \quad \mu_1 \sim 1 - \frac{\pi^2}{4} \sum_{k=1}^m \frac{1}{I_k^2}$$

and

$$(4.30) \quad \phi(\chi) \sim \frac{\pi^2}{4} \sum_{k=1}^m \frac{1}{I_k^2} .$$

The rate of convergence is therefore very slow for large I_k . We remark that μ_1 , and hence the rate of convergence can be estimated for non rectangular regions by using Theorem (4.2), Corollary.

Number of Iterations

Theorem 4.5

For the Dirichlet Problem

$$(4.31) \quad \mathcal{N}(\chi, \rho) = \frac{-\log \rho}{-\log \mu_1}$$

where $\mathcal{N}(\chi, \rho)$ is defined by Definition 3.4, (the third argument has been omitted).

Proof: For all $f \in V_N$ by (4.22) and (4.24)

$$\| \chi^m [f] \| \leq \mu_1^m \| f \|$$

But

$$\mu_1^m \| f \| \leq \rho \| f \|$$

provided

$$m \geq \frac{-\log \rho}{-\log \mu_1}$$

Hence
$$\mathcal{N}(\chi, \rho) \leq \frac{-\log \rho}{-\log \mu_1}$$

On the other hand if $f = r^{(1)}$

$$\| \mathcal{X}^m [f] \| = \| \mu,^m f \| = \mu, \| f \|.$$

Therefore

$$\eta(\mathcal{X}, \rho) \geq \frac{-\log \rho}{-\log \mu,}$$

and the theorem follows.

Q. E. D.

Theorem 4.6

Let \mathcal{R}_h enclose a bounded region Ω , and let \mathcal{R}_h be connected. Let $\mathcal{R}_{h_1}, \mathcal{R}_{h_2}, \dots$ be nets covering Ω obtained from \mathcal{R}_h by subdividing the mesh by a factor of $2^1, 2^2, \dots$, then for the Dirichlet Problem, there exist positive constants m_1 and M_1 and a mesh size h_0 such that for all $h = h_0 \bar{r}^{-i}$ with $0 < h \leq h_0$

$$(4.32) \quad m_1 \leq h^2 \eta(\mathcal{X}, \rho, V_{N_h}) \leq M_1$$

where V_{N_h} denotes the vector space of all functions defined on \mathcal{R}_h .

Proof

Let \square_2 and \square_1 be rectangular regions circumscribing and inscribed in Ω . Let the sides of \square_1 and \square_2 be $\gamma_k^{(1)}$ and $\gamma_k^{(2)}$ respectively, ($k=1, 2, \dots, n$) and let the $\gamma_k^{(j)}$ be chosen so they are multiples of h . Let $R_h^{(1)}$ and $R_h^{(2)}$ be the set of net points interior to \square_1 and \square_2 respectively. If $\mu_1^{(1)}(h)$, $\mu_1(h)$ and $\mu_1^{(2)}(h)$ denote the largest eigenvalue of \mathcal{X} for $R_h^{(1)}$, R_h and $R_h^{(2)}$ respectively we have by Theorem 4.2, Corollary

$$(4.33) \quad \mu_1^{(1)}(h) \leq \mu_1(h) \leq \mu_1^{(2)}(h)$$

By (4.28)

$$\begin{aligned} \mu_1^{(1)} &= 1 - \frac{\pi^2 h^2}{4} \sum_{k=1}^n (\gamma_k^{(1)})^{-2} + \mathcal{O}(h^4). \\ -\log \mu_1^{(1)} &= \frac{\pi^2 h^2}{4} \sum_{k=1}^n (\gamma_k^{(1)})^{-2} + \mathcal{O}(h^4) \\ -\log \mu_1^{(2)} &= \frac{\pi^2 h^2}{4} \sum_{k=1}^n (\gamma_k^{(2)})^{-2} + \mathcal{O}(h^4) \end{aligned}$$

where $\mathcal{O}(h^4)$ vanishes with h^4 .

Therefore by (4.31)

$$\frac{-\log \rho}{-h^2 \frac{\pi^2}{4} \sum_{k=1}^n (\gamma_k^{(1)})^{-2} + \mathcal{O}(h^4)} \leq \mathcal{N}(\mathcal{X}, \rho, V_{N_h}) \leq \frac{-\log \rho}{-h^2 \frac{\pi^2}{4} \sum_{k=1}^n (\gamma_k^{(2)})^{-2} + \mathcal{O}(h^4)}$$

and the theorem follows.

Q. E. D.

In the above sense we may state that as $h \rightarrow 0$ the required number of iterations is asymptotically proportional to h^{-2} . In symbols

$$(4.34) \quad n(x, \rho) = O(h^{-2})$$

§.5 The Liebmann Method with a Consistent Ordering

The improvement formula for The Liebmann Method has been given in (0.7) . Using (1.14) and (1.15) we have

$$(5.1) \quad u_i^{(m+1)} = \sum_{j=1}^{i-1} b_{i,j} u_j^{(m+1)} + \sum_{j=i+1}^N b_{i,j} u_j^{(m)} + C_i$$

or

$$(5.1a) \quad u^{(m+1)} = \mathcal{L}\sigma [u^{(m)}] + C$$

where σ denotes the ordering of the equations and C denotes the vector (C_1, C_2, \dots, C_N) .

By Theorem 3.1 the rate of convergence of The Liebmann Method depends on the dominant eigenvalue of $\mathcal{L}\sigma$. The following has been noted by Geiringer [29] and by Stein and Rosenberg [28]

Theorem 5.0

$$\mathcal{L}\sigma [v] = \lambda v \quad \text{if and only if}$$

$$(5.2) \quad \sum_{j=1}^{i-1} b_{i,j} \lambda v_j + \sum_{j=i+1}^N b_{i,j} v_j = \lambda v_i \quad (i=1, 2, \dots, N)$$

Moreover if the matrix $(\xi_{i,j})$ is given by

$$(5.3) \quad \xi_{i,j} = \begin{cases} b_{i,j} & j > i \\ \lambda b_{i,j} & j < i \\ -\lambda & j = i \end{cases}$$

then $|\mathcal{L}_\sigma - \lambda I|$, the characteristic determinant of \mathcal{L}_σ , is equal to the determinant of $(f_{i,j})$.

Clearly, the determinant of $(f_{i,j})$ can be obtained from $|\mathcal{K} - \lambda I|$ by multiplying the elements of the latter determinant which are below the main diagonal by λ .

Consistent Orderings

Because $(a_{i,j})$ has property (A_2) it is possible to order the equations in such a way that there is an exact relation between the eigenvalues and eigenvectors of \mathcal{K} and \mathcal{L}_σ . Such orderings will be called consistent orderings. Before defining them, however, we shall first define and show that there exists an ordering vector.

Theorem 5.1:

An $N \times N$ matrix $(a_{i,j})$ has property (A_2) if and only if there exists a vector γ in V_N with integral coordinates such that

$$a_{i,j} \neq 0 \text{ and } i \neq j \text{ imply } |\gamma_i - \gamma_j| = 1,$$

and such that γ assumes q distinct values.

Proof:

(a) If $(a_{i,j})$ has property (A_2) there exist non empty disjoint sets T_1, T_2, \dots, T_q such that $\bigcup_{l=1}^q T_l = \mathcal{N}$.

We assume the sets T_l ordered so that $i \in T_l$ and $i \neq j$ implies $a_{i,j} = 0$ or $j \in T_{l-1} \cup T_{l+1}$. As

before (T_0 and T_{q+1} are empty sets). We can define

γ such that $i, j \in T_l$ implies $\gamma_i = \gamma_j$ and so that if $i \in T_l$ and $j \in T_{l+1} \cup T_{l-1}$, $|\gamma_i - \gamma_j| = 1$. γ will have the

required properties. We note that γ is not uniquely determined.

(b) If γ exists, on the other hand, we denote by $T_1, T_2, \dots, T_{\tilde{q}}$ sets on which γ_i is a constant arranged in ascending order and where $\tilde{q} = \max \gamma_i - \min \gamma_i$

Clearly if $a_{i,j} \neq 0, i \in T_l$ and $i \neq j$ we have

$$|\gamma_i - \gamma_j| = 1 \quad \text{and} \quad j \in T_{l-1} \cup T_{l+1}.$$

Hence if q is the number of distinct values of γ, q of the sets $T_1, T_2, \dots, T_{\tilde{q}}$ will be non empty. Thus $(a_{i,j})$ has property (A_q) .

Q. E. D.

Corollary 1:

If $(a_{i,j})$ has property $(A_q), (q \geq 2)$ it has property $(A_{q'})$ where $2 \leq q' \leq q$.

Proof:

If $(a_{i,j})$ has property (A_q) we can let

$$\begin{aligned} \gamma(T_1) &= 1, \quad \gamma(T_2) = 2, \quad \dots, \quad \gamma(T_{q'}) = q' \\ \gamma(T_{q'+1}) &= q'-1, \quad \gamma(T_{q'+2}) = q' \end{aligned}$$

etc. getting only

q' distinct values $2 \leq q' \leq q$. ($\gamma(T_l)$ denotes γ_i for $i \in T_l$).

Hence new sets $T'_1, T'_2, \dots, T'_{q'}$ are obtained as in the

Theorem and $(a_{i,j})$ has property $(A_{q'})$

Q. E. D.

Corollary 2

If $(a_{i,j})$ is irreducible, and has property (A_q) then

$$q = \tilde{q} = \max \gamma_i - \min \gamma_i.$$

Proof: We need only prove that if $\gamma_i = a, \gamma_j = a+2$ then there exists i' such that $\gamma_{i'} = a+1$

Let J_1 be the set of all i such that $\gamma_i \leq a$,
and J_2 be the set of all i such that $\gamma_i \geq a+2$.

By the irreducibility of $(a_{i,j})$ there exists $i \in J_1, j \in J_2$ such that $a_{i,j} \neq 0$. But this implies $|\gamma_i - \gamma_j| = 1$, which is impossible if $J_1 \cup J_2 = T$.

Q. E. D.

Definition 5.1: γ is called the ordering vector of $(a_{i,j})$.

Definition 5.2:

An ordering σ of the rows and columns of a matrix $(a_{i,j})$ with property (A_φ) is consistent, if for some ordering vector $\gamma, \gamma_i > \gamma_j$ ^{and $a_{i,j} \neq 0$} implies $i > j$ ¹ under σ , for all $i, j \in T$.

When we speak of a consistent ordering, it is implied that $(a_{i,j})$ has property (A_φ) for some φ . It is obvious that if a matrix $(a_{i,j})$ has property (A_φ) then at least one consistent ordering of the rows and columns of $(a_{i,j})$ exists.

Corollary 1:

If σ is a consistent ordering and if $a_{i,j} \neq 0$ and $i > j$

1. " $i > j$ under σ " means that under the ordering the i th row follows the j th row of $(a_{i,j})$.

then $\gamma_i > \gamma_j$

Examples of Orderings

We first define equivalent orderings.

Definition 5.3

Two orderings σ, σ' are equivalent if wherever $a_{i,j} \neq 0$ and $i \neq j$

$i > j$ under σ if and only if $i > j$ under σ' .

Corollary: If σ is equivalent to σ' , σ is consistent if and only if σ' is consistent.

Clearly, if σ is consistent one may interchange the i th and the j th row of $(a_{i,j})$, where $\gamma_i = \gamma_j$ and the new ordering obtained will be consistent.

For R_h we need only define the ordering relation for adjacent net points by (1.16e). We now define some typical orderings.

Definition 5.4:

$$(a) \underline{\sigma_0} \quad x > x' \text{ if } \left\{ \begin{array}{l} p_n > p'_n \text{ or} \\ p_n = p'_n, \text{ and } p_{n-1} > p'_{n-1} \text{ or} \\ \dots \\ p_m = p'_m, \dots, p_1 = p'_1, p_1 > p'_1 \end{array} \right.$$

$$(b) \underline{\sigma_1} \quad x > x' \text{ if } \sum_{i=1}^n p_i > \sum_{i=1}^n p'_i$$

$$(c) \sigma_2 \quad x > x' \quad \text{if} \quad \begin{cases} \sum_{i=1}^n p_i \text{ is odd and} \\ \sum_{i=1}^n p_i' \text{ is even} \end{cases}$$

$$(d) \sigma_3 \quad x > x' \quad \text{if} \quad \begin{cases} p_2 \text{ is even, } p_2' \text{ is odd, or} \\ p_2 = p_2' \text{ and } p_1 > p_2 \end{cases}$$

($n=2$)

$$(e) \sigma_4 \quad x > x' \quad \text{if} \quad \begin{cases} p_2 > p_2' \\ p_2 \text{ is odd and } p_1 > p_1' \\ p_2 \text{ is even and } p_1 < p_1' \end{cases}$$

($n=2$)

It is evident that σ_0 is equivalent to σ_1 . σ_0 is the most common ordering although σ_2 has certain advantages.

Theorem 5.2

The orderings σ_0 , σ_1 , σ_2 and σ_3 are consistent. The ordering σ_4 is not consistent for all networks.

Proof :

(a) We have already noted that σ_0 is equivalent to σ_1 . We define the ordering vector by

$$(5.4) \quad \tau_i = \sum_{k=1}^n p_k^{(i)} \quad (i = 1, 2, \dots, N)$$

Clearly $a_{i,j} \neq 0$ and $i \neq j$ implies $|\tau_i - \tau_j| = 1$

Hence by theorem (5.1), $(a_{i,j})$ has property (A_q) where q is the number of distinct values of γ_i .

σ_1 is consistent since $\gamma_i > \gamma_j$ implies under $x^{(i)} > x^{(j)}$ under σ_1 .

(b) We have already seen that $(a_{i,j})$ has property (A_2) where T_1, T_2 are the sets where $\sum_{k=1}^n p_k^{(i)}$ is odd or even, respectively.

The ordering vector is given by

$$(5.5) \quad \gamma_i = \begin{cases} 1 & \text{if } \sum_{k=1}^n p_k^{(i)} \text{ is odd} \\ 0 & \text{if } \quad \quad \quad \text{is even} \end{cases}$$

Clearly $a_{i,j} \neq 0, i \neq j$ implies $|\gamma_i - \gamma_j| = 1$.

Also $\gamma_i > \gamma_j$ implies $x^{(i)} > x^{(j)}$ under σ_2 . Hence σ_2 is consistent.

(c) For σ_3 we let the ordering vector be given by

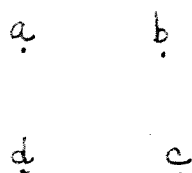
$$(5.6) \quad \gamma_i = \begin{cases} p_1^{(i)} & \text{if } p_2^{(i)} \text{ is odd} \\ p_1^{(i)} - 1 & \text{if } p_2^{(i)} \text{ is even} \end{cases}$$

Again $a_{i,j} \neq 0$ and $i \neq j$ imply $|\gamma_i - \gamma_j| = 1$, and

$\gamma_i > \gamma_j$ implies $x^{(i)} > x^{(j)}$ under σ_3 . Thus σ_3 is consistent. We note that $(a_{i,j})$ has property (A_q) where

q is the number of distinct values of γ_i .

(d) Let R_h consist of the vertices of a square



Under σ_4 the ordering is

a, b, c, d .

If σ_4 were consistent we could define an ordering vector τ such that $\tau(a)=1$. By the required properties of τ we would have

$$\tau(b)=2 \quad \tau(c)=3 \quad \tau(d)=4.$$

$$\therefore |\tau(d) - \tau(a)| > 1, \text{ a contradiction} \\ \text{Q. E. D.}$$

Theorem 5.3

Let $(a_{i,j})$ be an $N \times N$ matrix with property (A_4) where the ordering of the rows and columns of $(a_{i,j})$ is consistent. Let the general element of $(a'_{i,j})$ be given by

$$a'_{i,j} = a_{i,j} \quad (i=j \text{ or } i < j)$$

$$a'_{i,j} = \lambda a_{i,j} \quad (i > j)$$

Then, the determinant $| (a'_{i,j}) |$ equals $| (a''_{i,j}) |$ where the general element of $(a''_{i,j})$ is given by

$$a''_{i,j} = a_{i,j} \quad (i=j)$$

$$a''_{i,j} = \sqrt{\lambda} a_{i,j} \quad (i \neq j)$$

Proof:

Each term of $| (a'_{i,j}) |$ is of the form

$$t(j(i)) = \prod_{i=1}^N a'_{i,j(i)} \quad , \text{ where}$$

$j(i)$ is a permutation of the first N integers.

$$t(j(i)) = \prod_{\substack{i=1 \\ j(i)=i}}^N a_{i,j(i)} \prod_{\substack{i=1 \\ j(i) < i}}^N \lambda a_{i,j(i)} \prod_{\substack{i=1 \\ j(i) > i}}^N a_{i,j(i)}$$

But since $(a_{i,j})$ and hence $(a''_{i,j})$ has property (A₂) if $a_{i,j} \neq 0$, $i < j(\omega)$ implies $r_{j(\omega)} - r_i = 1$, and $i < j(i)$ implies $r_i - r_{j(i)} = 1$ where the ordering vector, r , exists by Theorem (5.1). We have

$$t(j(\omega)) = \prod_{\substack{i=1 \\ j(i)=i}}^N a_{i,j(\omega)} \prod_{\substack{i=1 \\ r_i > r_{j(i)}}}^N \lambda a_{i,j(i)} \prod_{\substack{i=1 \\ r_i < r_{j(i)}}}^N a_{i,j(i)}$$

Let β_1 be the number of factors with $r_i > r_{j(i)}$ and β_2 be the number of factors with $r_i < r_{j(i)}$.

$$\beta_1 = \sum_{\substack{i=1 \\ r_i > r_{j(i)}}}^N r_i - r_{j(i)}$$

$$\beta_2 = \sum_{\substack{i=1 \\ r_i < r_{j(i)}}}^N r_{j(i)} - r_i$$

$$\beta_1 - \beta_2 = \sum_{\substack{i=1 \\ r_i \neq r_{j(i)}}}^N r_i - r_{j(i)} = 0$$

Therefore

$$t(j(\omega)) = \prod_{\substack{i=1 \\ j(i)=i}}^N a_{i,j(\omega)} \prod_{\substack{i=1 \\ j(i) \neq i}}^N \sqrt{\lambda} a_{i,j(i)}$$

which is the general term of $| (a''_{i,j}) |$.

Q. E. D.

Theorem 5.4

If μ is a k -fold non zero eigenvalue of \mathcal{K} and if σ is a consistent ordering, then $\lambda = \mu^2$ is a k -fold eigenvalue of \mathcal{L}_σ . If \bar{x} is the number of non zero eigenvalues of \mathcal{K} , then zero is an $(N - \bar{x}/2)$ -fold eigenvalue of \mathcal{L}_σ .

Proof:

By Theorem 5.0 and Theorem 5.3 the characteristic determinant of \mathcal{L}_σ equals

$$|\mathcal{L}_\sigma - \lambda I| = |\sqrt{\lambda} \mathcal{K} - \lambda I| = \lambda^{N/2} |\mathcal{K} - \sqrt{\lambda} I|$$

By Theorem 5.3

$$|\mathcal{K} - \lambda I| = \prod_{i=1}^{\bar{x}/2} (\lambda - \mu_i^2) (\sqrt{\lambda})^{N-\bar{x}}, \text{ hence}$$

$$|\mathcal{L}_\sigma - \lambda I| = \lambda^{N-\bar{x}/2} \prod_{i=1}^{\bar{x}/2} (\lambda - \mu_i^2)$$

Q. E. D.

Corollary 1: If σ is consistent, then the rate of convergence of \mathcal{L}_σ is exactly twice the rate of convergence of \mathcal{K} .

Corollary 2: If $(a_{i,j})$ is symmetric and if σ is consistent, then the eigenvalues of \mathcal{L}_σ are real and non negative.

Theorem 5.5

If σ is a consistent ordering and if $\mathcal{L}[r] = \mu r$
and if

$$(5.7) \quad \lambda = \mu^2$$

$$(5.8) \quad v = \lambda^{n/2} r$$

then

$$(5.9) \quad \mathcal{L}_\sigma[v] = \lambda v$$

Proof: By Theorem 5.4, $\lambda = \mu^2$ is an eigenvalue of \mathcal{L}_σ . We have

$$\begin{aligned} & \sum_{j=1}^{i-1} b_{i,j} \lambda v_j + \sum_{j=i+1}^N b_{i,j} v_j \\ &= \sum_{j=1}^{i-1} b_{i,j} \lambda^{\frac{r_j}{2} + 1} r_j + \sum_{j=i+1}^N b_{i,j} \lambda^{\frac{r_j}{2}} r_j. \end{aligned}$$

But for $b_{i,j} \neq 0$

$$r_j = \begin{cases} r_{i+1} & j > i \\ r_{i-1} & j < i \end{cases}$$

since the ordering is consistent, by Definition 5.2, Corollary,

The last expression becomes

$$\lambda^{\frac{r_i+1}{2}} \sum_{\substack{j=1 \\ j \neq i}}^N b_{i,j} r_j = \lambda^{\frac{r_i+1}{2}} \mu r_i = (\lambda^{1/2} \mu) v_i = \lambda v_i.$$

By Theorem 5.0 $\mathcal{L}_\sigma[v] = \lambda v$.

Q. E. D.

Theorem 5.6

If $(a_{i,j})$ is symmetric and if σ is consistent, the normal form of the matrix of \mathcal{L}_σ is diagonal except possibly for the submatrix associated with the eigenvalue zero.

Proof:

If $\lambda \neq 0$ is a k -fold root of $|\mathcal{L}_\sigma - \lambda I| = 0$ $\mu = \sqrt{\lambda}$ is a k fold root of $|\mathcal{K} - \lambda I| = 0$ by Theorem 5.4. Since $(a_{i,j})$ is symmetric, the normal form of the matrix of \mathcal{K} is diagonal by Theorem 4.1 and hence there exists k linearly independent eigenvectors of \mathcal{K}

$$r^{(j)} \quad (j = 1, 2, \dots, k).$$

The eigenvectors

$$v^{(j)} \quad (j = 1, 2, \dots, k)$$

of \mathcal{L}_σ given by (5.8), are also linearly independent.

Otherwise there would exist constants v_1, v_2, \dots, v_k not all zero such that

$$\sum_{j=1}^k v_j v^{(j)} = 0$$

For all $i = 1, 2, \dots, N$

$$\sum_{j=1}^k v_j v_i^{(j)} = \sum_{j=1}^k v_j \lambda_j \frac{v_i}{\lambda_j} r_i^{(j)} = 0$$

Since $\lambda_j \neq 0$ this implies

$$\sum_{j=1}^k v_j r_i^{(j)} = 0 \quad (i = 1, 2, \dots, N)$$

or
$$\sum_{j=1}^k v_j r^{(j)} = 0$$

This contradicts the fact that the $r^{(j)}$ are linearly independent.

Q. E. D.

Theorem 5.7

If $(a_{i,j})$ is symmetric, the normal form of L_{σ_2} is diagonal.

Proof:

By Theorems 5.4 and 5.6 we need only show that there exist $N - \frac{I}{2}$ linearly independent vectors in the null space of L_{σ_2} . There are N_2 linearly independent vectors in the null space of L_{σ_2} whose components are zero except for one $i \in T_2$ as may be seen easily. By Theorem 4.4 there are $N_1 - \frac{I}{2}$ linearly independent vectors in the null space of \mathcal{K} which vanish identically on T_2 . Obviously, these vectors are also in the null space of L_{σ_2} . Thus the total number of linearly independent vectors in the null space of L_{σ_2} is

$$N_2 + (N_1 - \frac{I}{2}) = N - \frac{I}{2}.$$

Q. E. D.

That Theorem 5.7 cannot be extended to all consistent orderings can be shown easily. Thus consider a region with four points $x^{(1)} = (1,1)$, $x^{(2)} = (1,2)$, $x^{(3)} = (2,1)$ and $x^{(4)} = (2,2)$ with the ordering σ_0 : $x^{(1)}, x^{(2)}, x^{(3)}, x^{(4)}$. We have for the Dirichlet Problem

$$L_{\sigma_0}(0, 2, 2, -1) = (1, 0, 0, 0)$$

where

$$L_{\sigma_0}(1, 0, 0, 0) = 0.$$

Thus a nilpotent vector exists. It can be easily shown [4] that the normal form of the matrix of $\mathcal{L}\sigma_0$ is

$$\begin{pmatrix} 1/4 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

with corresponding basis

$$\begin{aligned} &(4, 2, 2, 1) \\ &(1, 0, 0, 0) \\ &(0, 2, 2, -1) \\ &(0, 1, -1, 0) \end{aligned}$$

Footnote

I have not yet been able to prove the following conjectures which are suggested by numerical results with square regions with 3, 4 and 5 intervals on a *side*.

(a) For the Dirichlet Problem and for a square region with I intervals on a *side* there are $(I-z)$ nilpotent vectors of degree z ($I-1 > z \geq 1$), for the ordering σ_0 .

(b) For any region the highest degree of nilpotency does not exceed the number distinct values of γ_i , for σ_0 .

In the following, we assume $(a_{i,j})$ is symmetric.

Given an arbitrary error vector

$$(5.10) \quad e^{(0)} = u^{(0)} - u$$

we can expand $e^{(0)}$ in eigenvectors and nilpotent vectors of \mathcal{L}_σ (σ -consistent), by Theorem 5.6. We have

$$(5.11) \quad e^{(0)} = \sum_{j=1}^{I/2} B_j v^{(j)} + \mathcal{N}$$

where

$$\mathcal{L}_\sigma [v^{(j)}] = \lambda_j v^{(j)}$$

and where \mathcal{N} is a suitable linear combination of nilpotent vectors. After m iterations the error vector becomes

$$(5.12) \quad e^{(m)} = \sum_{j=1}^{I/2} \lambda_j^m B_j v^{(j)} + \mathcal{L}_\sigma^m [\mathcal{N}]$$

where for some M , $m > M$ implies $\mathcal{L}_\sigma^m [\mathcal{N}] = 0$.

If the coefficients A_j of (4.23) for the expansion of $e^{(0)}$ in eigenvectors of \mathcal{K} are known the B_j of (5.11) may be computed easily for the ordering σ_2 . We have by (5.8 and 5.9)

$$v^{(j)} = \lambda_j^{I/2} z^{(j)} \quad (j = 1, 2, \dots, I/2)$$

where

$$\mathcal{K}[z^{(j)}] = \mu_j z^{(j)} \quad ; \mu_j > 0 \quad (j = 1, 2, \dots, I/2)$$

and where

$$\mathcal{L}\sigma_2[v^{(j)}] = \lambda_j v^{(j)} = \mu_j^{1/2} v^{(j)} \quad (j = 1, 2, \dots, \bar{N}/2)$$

From (5.5) we have, since

$$\begin{aligned} \lambda_j^{1/2} &= (1-\tau) + \lambda_j^{1/2} \tau & (j = 1, 2, \dots, \bar{N}/2) \\ (5.13) \quad v^{(j)} &= \left[(1-\tau) + \tau \lambda_j^{1/2} \right] r & (j = 1, 2, \dots, \bar{N}/2) \end{aligned}$$

If we set

$$(5.14) \quad v^*(j) = (1-\tau)r^{(j)} \quad (j = 1, 2, \dots, \bar{N}/2)$$

It can be easily verified that

$$\mathcal{L}\sigma_2[v^*(j)] = 0 \quad (j = 1, 2, \dots, \bar{N}/2)$$

By (4.18) we have

$$(5.15) \quad \begin{cases} \tau r^{(j)} = \frac{1}{2} [r^{(j)} - r^*(j)] \\ (1-\tau)r^{(j)} = \frac{1}{2} [r^{(j)} + r^*(j)] \end{cases} \quad (j = 1, 2, \dots, \bar{N}/2)$$

therefore

$$(5.16) \quad \begin{cases} v^{(j)} = \frac{1 + \lambda_j^{1/2}}{2} r^{(j)} + \frac{1 - \lambda_j^{1/2}}{2} r^*(j) \\ v^*(j) = \frac{1}{2} r^{(j)} + \frac{1}{2} r^*(j) \end{cases} \quad (j = 1, 2, \dots, \bar{N}/2)$$

Solving these equations for $r^{(j)}$ and $r^{*(j)}$ we get

$$(5.17) \quad \begin{cases} r^{(j)} = \lambda_j^{-1/2} [v^{(j)} + (1 - \lambda_j^{1/2}) r^{*(j)}] = \lambda_j^{-1/2} v^{(j)} + \kappa_1 \\ r^{*(j)} = \lambda_j^{-1/2} [-v^{(j)} + (1 + \lambda_j^{1/2}) r^{(j)}] = -\lambda_j^{-1/2} v^{(j)} + \kappa_2 \end{cases}$$

($j = 1, 2, \dots, I/2$)

where

$$\mathcal{L}\sigma_2[\kappa_1] = \mathcal{L}\sigma_2[\kappa_2] = 0$$

By (4.21) an arbitrary error vector $e^{(0)}$ can be written in the form

$$e^{(0)} = \sum_{j=1}^{\bar{x}/2} A_j r^{(j)} + A_j^* r^{*(j)} + \sum_{j=\frac{\bar{x}}{2}+1}^{\bar{x}-\frac{\bar{x}}{2}} A_j r^{(j)}$$

Using (5.17) and the fact that

$$\kappa[r^{(j)}] = 0 \quad \text{implies} \quad \mathcal{L}\sigma_2[r^{(j)}] = 0$$

we have

$$(5.18) \quad e^{(0)} = \sum_{j=1}^{\bar{x}/2} \lambda_j^{-1/2} (A_j - A_j^*) v^{(j)} + \kappa$$

where

$$\mathcal{L}\sigma_2[\kappa] = 0$$

In Section 7 we shall use this expansion to get an upper bound for the number of iterations required to solve the finite difference analogue of The Dirichlet Problem using $\mathcal{L}\sigma_2$.

For a general consistent ordering, σ , however, even if the A_j and $r^{(j)}$ of (4.20) are known, the determination of the B_j of (5.11) could only be done by solving a set of linear equations. This is true even though the eigenvectors, $v^{(j)}$ of L_σ are known explicitly in terms of the $r^{(j)}$.

§ 6. Other Orderings

We have seen that the rate of convergence of The Liebmann Method with a consistent ordering is exactly twice the rate of convergence of The Kormes Method. It is logical to ask whether the rate of convergence of The Liebmann Method could not be increased by using orderings which are not consistent.

Shortley and Weller [4] state that, except for small N the rate of convergence of The Liebmann Method applied to the Dirichlet Problem is practically independent of the order in which the points are traversed. Numerical evidence, given in Table 6.1 indicates that the effect of the ordering on the rate of convergence is small, not exceeding 12% in the most extreme case treated, and decreases rapidly as N increases. Furthermore in these cases, the consistent orderings were found to give the best convergence. It is my conjecture that the consistent orderings always give the best convergence. I have not found a proof of this except for one special case. If the ordering relationship between any one given point and one or more adjacent points is changed, a consistent ordering will in general be made non consistent; it is proved for the self adjoint case that in any such case the rate of convergence is not increased.

Before giving the proof for this fact we shall first give an example to show that the results of Section 5 are not valid for all orderings.

6 A. An Ordering for Which the Results of Theorem 5.4
Are Not Valid

Consider the Dirichlet Problem for a square region with four interior points. If the order of improvement is σ_0

$$\begin{bmatrix} .1 & .2 \\ .3 & .4 \end{bmatrix}$$

the characteristic equation for The Liebmann Method is

$$(6.1) \quad \frac{1}{256} [256\lambda^4 - 64\lambda^3] = 0 \quad \text{and the}$$

eigenvalues are $\lambda = 0, 0, 0, 1/4$.

For The Kormes Method the eigenvalues are

$$\mu = 0, 0, 1/2, -1/2.$$

This agrees with Theorem 5.4.

On the other hand with the ordering σ_4 $\begin{bmatrix} 1. & 2. \\ 4. & 3. \end{bmatrix}$ the characteristic equation for The Liebmann Method is

$$(6.2) \quad \frac{1}{256} [256\lambda^4 - 65\lambda^3 + 2\lambda^2 - \lambda] = 0, \text{ and the}$$

eigenvalues are $\lambda = 0, -.0115 + .1185i, -.0115 - .1185i, .277$.

Since $.277 > 1/4$ the rate of convergence of $\mathcal{L}\sigma_4$ is less than the rate of convergence of $\mathcal{L}\sigma_0$ for this region.

We observe that the rate of convergence is independent of a cyclic permutation of the ordering. Hence the essentially different orderings are

$$\sigma_0 \begin{bmatrix} .1 & .2 \\ .3 & .4 \end{bmatrix}$$

$$\sigma_2 \begin{bmatrix} .1 & .3 \\ .4 & .2 \end{bmatrix}$$

$$\sigma_2' \begin{bmatrix} .1 & .4 \\ .3 & .2 \end{bmatrix}$$

$$\sigma_4 \begin{bmatrix} .1 & .2 \\ .4 & .3 \end{bmatrix}$$

$$\sigma_0' \begin{bmatrix} .1 & .3 \\ .2 & .4 \end{bmatrix}$$

$$\sigma_4' \begin{bmatrix} .1 & .4 \\ .2 & .3 \end{bmatrix}$$

The orderings σ_0 , σ_0' , σ_2 and σ_2' are consistent. By symmetry it is evident that σ_4 is equivalent to σ_4' . Thus for this region we have shown that for no ordering can the rate of convergence of The Liebmann Method exceed that for a consistent ordering.

2. 63. The Effect of Changing the Relative Position of One Equation in a Consistent Ordering

We now prove a special case of the conjecture that for $(a_{i,j})$ symmetric, the rate of convergence of The Liebmann Method for any ordering does not exceed that for a consistent ordering.

Theorem 6.1

Let σ be a consistent ordering of the rows and columns of the symmetric $N \times N$ matrix $(a_{i,j})$ satisfying (0.2). If σ' is a new ordering obtained by changing the relative position of any single row and the corresponding column under σ , then the rate of convergence of $\mathcal{L}_{\sigma'}$ does not exceed the rate of convergence of \mathcal{L}_{σ} .

Proof: By Theorem 5.0

$$|\mathcal{L}_{\sigma} - \lambda I| = |(\xi_{i,j})|, \text{ where}$$

$$\xi_{i,j} = \begin{cases} b_{i,j} & (j > i) \\ \lambda a_{i,j} & (j < i) \\ -\lambda & (j = i) \end{cases}$$

and where, by (1.4)

$$b_{i,j} = \begin{cases} 0 & (i = j) \\ -\frac{a_{i,j}}{a_{j,i}} & (i \neq j) \end{cases}$$

It is easily verified that

$$|(\Sigma'_{i,j})| = |(\bar{\Sigma}'_{i,j})|, \text{ where}$$

$$\bar{\Sigma}'_{i,j} = \begin{cases} b'_{i,j} & (j > i) \\ \lambda b'_{i,j} & (j < i) \\ -\lambda & (j = i) \end{cases}$$

and where

$$b'_{i,j} = \begin{cases} 0 & (i = j) \\ -\frac{a_{i,j}}{\sqrt{a_{i,i}} \sqrt{a_{j,j}}} & (i \neq j) \end{cases}$$

We note that $\bar{\Sigma}'_{i,j}$ is symmetric.

Lemma 1:

Let N be even and let λ_1 be the largest eigenvalue of Z_T . Then all subdeterminants, obtained from the matrix $\bar{\Sigma}'_{i,j}$ by deleting an even number of rows and the corresponding columns are positive, when $\lambda = \lambda_1$.

Proof:

We first remark that if since Γ is consistent for $(b'_{i,j})$ it is also consistent for any submatrix of the above type. By Theorem 4.2 the largest eigenvalue of The Kormes Method for the submatrix is smaller than for the entire matrix. But by Theorem 5.4 the same is true for Z_T . Since N is even $|Z_T - \lambda I| > 0$ for the submatrix and the matrix is positive for sufficiently large λ ; therefore $|Z_T - \lambda_1 I| > 0$ for the submatrix.

Q. E. D.

Now let the rows and columns of $|\mathcal{L}' - \lambda \mathbf{I}| = |(\xi'_{i,j})|$ be arranged so that they are in the order σ' . If the i_0 th equation was originally displaced we have

$$(6.3) \quad \xi'_{i,j} = \begin{cases} b'_{i,j} & (j > i) \\ \lambda b'_{i,j} & (j < i) \\ -\lambda & (j = i) \end{cases}$$

except that for some k we may have

$$(6.4) \quad \begin{cases} \begin{cases} \sum_{i_0} \xi'_{k,i_0} = b'_{k,i_0} \text{ and} & (i_0 < k) \\ \sum_{i_0} \xi'_{i_0,k} = \lambda b'_{i_0,k} \end{cases} \\ \text{or} \\ \begin{cases} \sum_{i_0} \xi'_{k,i_0} = \lambda b'_{k,i_0} \text{ and} & (i_0 > k) \\ \sum_{i_0} \xi'_{i_0,k} = b'_{i_0,k} \end{cases} \end{cases}$$

If no such k exists

$$|\mathcal{L} - \lambda \mathbf{I}| = |\mathcal{L}' - \lambda \mathbf{I}|$$

and the Theorem follows at once.

By (6.3) and (6.4), the determinants $|(\xi'_{i,j})|$ and $|(\xi_{i,j})|$ can differ only in terms containing the factors $(\xi'_{i_0,k} \xi'_{j,i_0})$ where $i_0 \neq j, k$ and $k \neq j$.

Typical sets of such terms for $|(\xi'_{i,j})|$ are

$$\tau(j(i)) = - \xi'_{i_0,i_1} \xi'_{i_1,i_2} \cdots \xi'_{i_{r-1},i_r} \bar{\alpha}(j(i))$$

and the complementary set

$$\tau(j \neq i) = - \xi'_{i_1,i_0} \xi'_{i_2,i_1} \cdots \xi'_{i_r,i_{r-1}} \bar{\alpha}(j(i))$$

where $i_1, i_2, \dots, i_k, i_0$ are distinct integers, and $\bar{z}(j(i))$ is the subdeterminant obtained from $(\bar{z}'(i, j))$ by removing the rows and columns containing i_0, i_1, \dots, i_k . Such subdeterminants are positive for $\lambda = \lambda_1$ by Lemma 1.

Similar formulas can be given for the corresponding sets of terms $\bar{z}(j(i))$ and $\bar{z}(j^*(i))$ for $|(z'(i, j))|$.

We note that since $(a_{i, j})$ has property $(A_2)_\Delta$, Δ must be odd. Moreover for each set of terms, the set of second subscripts is obtained from the set of first subscripts by an odd number of transpositions, hence we have a negative sign.

By Theorem 5.3

$$\bar{z}(j(i)) = \bar{z}(j^*(i))$$

Also for $\lambda = \lambda_1$ we have $\bar{z}(j(i)) \leq 0$

On the other hand by (6.4)

$$\bar{z}(j(i)) = \lambda^{\bar{n}} \bar{z}(j(i))$$

$$\bar{z}(j^*(i)) = \lambda^{-\bar{n}} \bar{z}(j(i))$$

for some integer \bar{n}

Therefore

$$\begin{aligned} & [\bar{z}(j(i)) + \bar{z}(j^*(i)) - 2 \bar{z}(j(i))] / \lambda = \lambda_1 \\ & = [(\lambda_1^{\bar{n}/2} - \lambda_1^{-\bar{n}/2})^2 \bar{z}(j(i))] / \lambda = \lambda_1 \leq 0 \end{aligned}$$

Summing over all such sets of terms we get

$$|\mathcal{L}_{\sigma'} - \lambda_1 \Gamma| = |\mathcal{L}_{\sigma} - \lambda_1 \Gamma| = 0$$

Since N is even $|\mathcal{L}_{\sigma'} - \lambda \Gamma|$ is positive for sufficiently large λ . Therefore for some $\lambda_1' \geq \lambda_1$ we have

$$|\mathcal{L}_{\sigma'} - \lambda_1' \Gamma| = 0$$

A similar argument can be used when N is odd.

Q. E. D.

The author has so far not been able to extend the proof to the case where more than one change is made in the ordering.

The following numerical results for The Dirichlet Problem are given to show that the effect of a change ordering is small, in all probability. Except for examples 1, 2 and 3 the eigenvalues for the non consistent orderings were obtained experimentally, [4]. We note that for any region, ^{with} no more than three points every ordering is consistent. Hence on the plausible assumption that the effect of different orderings decreases as N increases it would appear that it is largest in example 1.

Table 6.1

Region and Ordering		λ_1	$\lambda_1^{(1)}$ (consistent ordering)
1.	1. 2. 4. 3.	.277 ⁽¹⁾	.250
2.	1. 2. 3. 5. 4.	.307 ⁽¹⁾	.285
3.	1. 2. 3. 6. 5. 4.	.393 ⁽¹⁾	.363
4.	1. 2. 3. 6. 5. 4. 7. 8. 9.	.519 ± .003	.500
5.	1. 2. 3. 8. 9. 4. 7. 6. 5.	.520 ± .001	.500
6.	1. 2. 4. 3. 5. 6. 8. 7.	.445 ± .004	.428
7.	1. 2. 3. 6. 5. 4. 7. 8. 9. 12. 11. 10.	.587 ± .005	.5745

1. Exact values, to number of decimals given.

8.

1.	2.	3.	4.
8.	7.	6.	5.
9.	10.	11.	12.
16.	15.	14.	13.

 $.664 \pm .007$

.655

§ 7. The Use of Large Automatic Computing Machines

One might suppose that, if a large automatic computing machine can be used with The Liebmann Method, the slow rate of convergence would be compensated by the speed of the machine. A more careful analysis reveals however that the number of iterations required may be so large that even with a fast machine the time is prohibitive.

For example, in [21], F. Snyder and H. Livingston propose a set of coding instructions for solving a "Laplace Boundary Value Problem" for a plane region by means of the UNIVAC,¹ and using The Liebmann Method.² The authors state that problems for a square region with 300 intervals on a side, and, of course, smaller regions, are easily programmed. On the other hand the authors make no estimate of the number of iterations required. As we shall see, for the Dirichlet Problem for a 300 x 300 interval square, the UNIVAC would require about 2 years to reduce the error of the original estimated solution by a factor of 1000.

-
1. When the paper [21] was written the construction of the UNIVAC had not yet been completed.
 2. The Liebmann Method is clearly preferable to The Kormes Method. Not only is the rate of convergence twice as large, but the storage problem is simplified.

For the number of iterations required to reduce $\|e^{(0)}\|$ to a definite fraction ρ of its original value we have by Definition 3.5 and Theorem 3.3.

$$(7.1) \quad \lim_{\rho \rightarrow} \left[\mathcal{N}(\mathcal{L}_0, \rho) / \frac{-\log \rho}{-\log |d_1|} \right] = 1$$

By Theorem 4.6 and Theorem 5.4, Corollary 1, we have

$$(7.2) \quad \mathcal{N}(\mathcal{L}_\sigma, \rho) = O(h^{-2})$$

provided σ is consistent. By the considerations of Section 6, this is almost certainly true for any ordering.

For the ordering σ_2 we can make a more exact statement about the required number of iterations.

Theorem 7.1

For all ρ ($0 < \rho < 1$)

$$(7.3) \quad \mathcal{N}(\mathcal{L}_{\sigma_2}, \rho) \leq \frac{-\log \rho / 2}{-\log \lambda_1} + 1$$

Proof: By (5.18) we have

$$e^{(0)} = \sum_{j=1}^{\bar{n}/2} \left[\frac{A_j - A_j^*}{\lambda_j^{1/2}} \right] v^{(j)} + \mathcal{N}$$

1. The ordering σ_0 was used for the coding for the UNIVAC given in [21]. The coding for the ordering would be only slightly more difficult and approximately half as many storage registers would be required. This is due to the fact that the values of $\mu_i^{(m)}$ where $\sum_{k=1}^2 p_k^{(i)}$ is odd completely determine $\mu_i^{(m+1)}$, ($i = 1, 2, \dots, N$).

where $\mathcal{L}_{\sigma_2} [n] = 0$.

Then for $m \geq 1$

$$e^{(m)} = \sum_{j=1}^{\bar{n}/2} \left(\frac{A_j - A_j^*}{\lambda_j^{1/2}} \right) \lambda_j^m v^{(j)}$$

By (5.16)

$$v_i^{(j)} = \frac{1 + \lambda_j^{1/2}}{2} r_i^{(j)} + \frac{1 - \lambda_j^{1/2}}{2} r_i^{(j)}$$

Hence

$$\begin{aligned} \|\mathcal{L}_{\sigma_2}^m [e^{(0)}]\|^2 &= \sum_{j=1}^{\bar{n}/2} \lambda_j^{2m} \left(\frac{A_j - A_j^*}{\lambda_j^{1/2}} \right)^2 \left(\frac{1 + \lambda_j}{2} \right) \\ &\leq 2 \lambda_1^{2m-1} \sum_{j=1}^N A_j^2 = 2 \lambda_1^{2m-1} \|e^{(0)}\|^2 \end{aligned}$$

$$(7.4) \quad \|\mathcal{L}_{\sigma_2}^m [e^{(0)}]\| \leq \sqrt{2} \lambda_1^{m-1/2} \|e^{(0)}\|$$

Therefore

$$(7.5) \quad \mathcal{N}(\mathcal{L}_{\sigma_2, \rho}) \leq \frac{-\log \rho/2}{-\log \lambda_1} + 1$$

Q. E. D.

No matter what ordering is used, the rate of convergence of The Liebmann Method is very slow. For $n=2$ the time per iteration, as well as the number of iterations is of the order of h^{-2} . Hence, the total time is of the order of h^{-4} .

Consider, for example the unit square with $h^{-1} = 300$. We have by (4.30)

$$\mu_1 \approx 1 - \frac{\pi^2}{2} (300)^{-2}$$

and

$$\lambda_1 \approx 1 - \pi^2 (300)^{-2}$$

Setting $\rho = 10^{-3}$ we have by (7.1)

$$N(L_0, 10^{-3}) \approx \frac{-3 \log_{10} \rho}{\pi^2 300^{-2}} = 63,300 \text{ iterations.}$$

For the UNIVAC, the estimate of the time required (in seconds) per iteration given in [21] is $\frac{I_1 + I_2}{100}$ where I_1, I_2

are the number of intervals on the sides of a plane rectangle. In our case 900 seconds are required per iteration.

The total time required is

$$\frac{63,300 \times 900}{3600} \text{ seconds} \approx 15,800 \text{ hours}$$

$$\approx 660 \text{ days}$$

Numerical estimates for other mesh sizes will be given in Section 9.

Obviously, for large N a more rapidly converging method is needed. In the next Chapter it is shown that The Liebmann Method can be modified in such a way that the number of iterations required is proportional to h^{-1} instead of h^{-2} .

CHAPTER III

The Successive Overrelaxation Method

L. F. Richardson's method of systematic overrelaxation has already been described in the Introduction. Using a fixed relaxation factor ω , the rate of convergence cannot in general be appreciably increased. Consider the Dirichlet Problem for example. In the notation of (1.14) and (1.15) the improvement formula (0.13) becomes, (if we replace $\omega a_{i,i}$ by ω),

$$(III.0.1) \quad u_i^{(m+1)} = \omega \sum_{j=1}^N b_{i,j} u_j^{(m)} + \omega C_i - (\omega - 1) u_i^{(m)} \quad (i = 1, 2, \dots, N)$$

or

$$(III.0.1a) \quad u^{(m+1)} = \mathcal{R}_\omega [u^{(m)}] + \omega C$$

We observe that a vector \hat{r} is an eigenvector of \mathcal{R}_ω with eigenvalue $\hat{\mu}$ if and only if

$$(III.0.2) \quad \hat{\mu} \hat{r}_i = \omega \sum_{j=1}^N b_{i,j} \hat{r}_j - (\omega - 1) \hat{r}_i \quad (i = 1, 2, \dots, N)$$

But if

$$\mathcal{K}[r] = \lambda r$$

$$\begin{aligned}
 \text{(III.0.3)} \quad \omega \sum_{j=1}^N b_{i,j} r_j - (\omega-1) r_i &= \omega \mu r_i - (\omega-1) r_i \\
 &= r_i [\omega \mu - (\omega-1)] = r_i [1 - \omega(1-\mu)] \\
 &\quad (i = 1, 2, \dots, N)
 \end{aligned}$$

Therefore

$$\text{(III.0.4)} \quad R_\omega [r] = [1 - \omega(1-\mu)] r$$

and

$[1 - \omega(1-\mu)]$
is an eigenvalue of R_ω .

By Theorem 3.1, Corollary 2 R_ω will converge if and only if

$$\text{(III.0.5)} \quad |1 - \omega(1-\mu)| < 1$$

for all eigenvalues μ of \mathcal{K} .

For the Dirichlet Problem all μ are real. Moreover if μ_1 is the largest eigenvalue of \mathcal{K} , $(-\mu_1)$ is the smallest by Theorem 4.3 and the above requirement is equivalent to the condition

$$\text{(III.0.6)} \quad 0 < \omega < \frac{2}{1+\mu_1}$$

Therefore the rate of convergence cannot be increased by a factor of more than $\frac{2}{1+\mu_1}$, which is very slightly greater than one, since μ_1 is in general very nearly one.

As stated previously Richardson varied ω on each

iteration. For the Dirichlet Problem the improvement formula may be written

$$(III.0.7) \quad u_i^{(m+1)} = \omega_m \sum_{j=1}^N b_{i,j} u_j^{(m)} + \omega_m C_i - (\omega_m - 1) u_i^{(m)}.$$

or ($i = 1, 2, \dots, N$).

$$(III.0.7a) \quad u^{(m+1)} = \omega_m [B u^{(m)}] + \omega_m C$$

If

$$(III.0.8) \quad e^{(0)} = u^{(0)} - u = \sum_{k=1}^N A_k r^{(k)}$$

where $\{r^{(k)}\}$ is the orthonormal set of eigenvectors of \mathcal{K} , then it can be easily verified that

$$(III.0.9) \quad e^{(m)} = u^{(m)} - u = \sum_{k=1}^N A_k r^{(k)} \prod_{\nu=1}^m (1 - \omega_\nu (1 - \mu_k))$$

and

$$(III.0.10) \quad \|e^{(m)}\|^2 = \sum_{k=1}^N A_k^2 \prod_{\nu=1}^m (1 - \omega_\nu (1 - \mu_k))^2$$

Thus the effect of using $\omega > \frac{2}{1+\mu_1}$ on one iteration is compensated by using $\omega < 1$ on other iterations. By (III.0.9) we note that if an eigenvalue μ_k is known exactly the coefficient A_k of the corresponding eigenvector can be removed on one iteration by setting

$$\omega = \frac{1}{1 - \mu_k}$$

In fact, if all μ_k , ($k=1, 2, \dots, N$), were known, the error could be reduced to zero after N iterations.

In practice however, all the μ_k are seldom known and even if they were, the number of iterations would be prohibitive by the above method. Richardson chose values of ω approximately evenly spaced in the range

$$0 < \omega < \frac{1}{1-\mu}$$

in an attempt to reduce

$$\prod_{r=1}^m (1 - \omega_r (1 - \mu_k))$$

as uniformly as possible for all μ_k .

However, from numerical studies for a square region with 20 intervals on a side (where all μ_k are known) it appears doubtful that the gain in convergence rate could be made to exceed a factor of five, except by a very fortunate choice of the ω_r .

As stated in the Introduction one can, by successively modifying the values of $\mu_i^{(m)}$ and using new values as soon as they are available use just one fixed relaxation factor, and yet obtain a large increase in the rate of convergence. The improvement formula for The Successive Overrelaxation Method is, in the notation of (1.14) and (1.15), by (0.16)

$$(III.0.11) \quad u_i^{(m+1)} = \omega \left[\sum_{j=1}^{i-1} b_{i,j} u_j^{(m+1)} + \sum_{j=i+1}^N b_{i,j} u_j^{(m)} \right] \\ - (\omega - 1) u_i^{(m)} + \omega C_i$$

or

$$(III.0.11a) \quad u^{(m+1)} = \mathcal{L}_{\sigma, \omega} [u^{(m)}] + \omega C$$

§ 8. Eigenvalues and Eigenvectors

In order to study the rate of convergence of The Successive Overrelaxation Method we shall analyze the eigenvalues and eigenvectors of $\mathcal{L}_{\sigma, \omega}$. We restrict ourselves to the case where $(a_{i,j})$ has property (A_q) and where the ordering σ is consistent.

Theorem 8.1

$$(8.1) \quad \mathcal{L}_{\sigma, \omega} [\hat{v}] = \hat{\lambda} \hat{v}$$

if and only if

$$(8.2) \quad \omega \left\{ \sum_{j=1}^{i-1} b_{i,j} \hat{\lambda} \hat{v}_j + \sum_{j=i+1}^N b_{i,j} \hat{v}_j \right\} - (\omega-1) \hat{v}_i = \hat{\lambda} \hat{v}_i \quad (i = 1, 2, \dots, N)$$

The proof is immediate by (III.0.11).

Theorem 8.2.

$$\text{If } \mathcal{K} [r] = \mu r$$

$$(8.3) \quad \hat{\lambda} + (\omega-1) = \omega \mu \hat{\lambda}^{1/2}$$

$$(8.4) \quad \hat{v} = \hat{\lambda}^{\frac{r}{2}} r$$

then

$$(8.5) \quad \mathcal{L}_{\sigma, \omega} [\hat{v}] = \hat{\lambda} \hat{v},$$

where τ is the ordering vector, (see Section 5).

Proof: If $\hat{v}_i = \lambda^{\frac{\gamma_i}{2}} \pi_i$ ($i = 1, 2, \dots, N$) and if $\hat{\lambda} + (\omega - 1) = \omega \mu \hat{\lambda}^{\frac{1}{2}}$, then

$$\begin{aligned} & \omega \left\{ \sum_{j=1}^{i-1} b_{i,j} \hat{\lambda} \hat{v}_j + \sum_{j=i+1}^N b_{i,j} \hat{v}_j \right\} - (\omega - 1) \hat{v}_i \\ &= \omega \left\{ \sum_{j=1}^{i-1} b_{i,j} \hat{\lambda} \cdot \lambda^{\frac{\gamma_j}{2}} \pi_j + \sum_{j=i+1}^N b_{i,j} \lambda^{\frac{\gamma_j}{2}} \pi_j \right\} \\ & \quad - (\omega - 1) \lambda^{\frac{\gamma_i}{2}} \pi_i \end{aligned}$$

But for $b_{i,j} \neq 0$ we have

$$\gamma_j = \begin{cases} \gamma_i + 1 & (j > i) \\ \gamma_i - 1 & (j < i) \end{cases}$$

Hence we have for the last expression

$$\begin{aligned} & \omega \lambda^{\frac{\gamma_i+1}{2}} \left\{ \sum_{j=i+1}^N b_{i,j} \pi_j \right\} - (\omega - 1) \lambda^{\frac{\gamma_i}{2}} \pi_i \\ &= [\omega \mu \hat{\lambda}^{\frac{1}{2}} - (\omega - 1)] \lambda^{\frac{\gamma_i}{2}} \pi_i, \text{ by (4.3a), and} \\ &= \hat{\lambda} \hat{v}_i \quad (i = 1, 2, \dots, N) \text{ by (8.3)} \end{aligned}$$

Hence \hat{v} is an eigenvector and $\hat{\lambda}$ is an eigenvalue of $L_{\sigma, \omega}$ by Theorem 8.1.

Q. E. D.

Theorem 8.3

If $K[\pi] = \mu \pi$, and

$$(8.6) \quad \mu^2 \omega^2 - 4(\omega - 1) = 0$$

$$\begin{aligned} \mathcal{L}_{\sigma, \omega}[\hat{v}] &= \hat{\lambda} \hat{v} \\ \hat{\lambda} + (\omega - 1) &= \omega \mu \hat{\lambda}^{\frac{1}{2}} \\ \hat{v} &= \hat{\lambda}^{\frac{\omega}{2}} \pi \end{aligned}$$

$$(8.7) \quad \hat{v}' = \frac{d}{d\lambda} \hat{v} = \left(\frac{\omega}{2} - 1\right) \hat{\lambda}^{\frac{\omega}{2} - 1} \pi$$

then

$$(8.8) \quad \mathcal{L}_{\sigma, \omega}[\hat{v}'] = \hat{\lambda} \hat{v}' + \hat{v}.$$

We call \hat{v}' an invariant vector of $\mathcal{L}_{\sigma, \omega}$.

Proof:

Lemma 1: If $\mathcal{L}_{\sigma, \omega}[\hat{v}] = \hat{\lambda} \hat{v}$ then

$$\mathcal{L}_{\sigma, \omega}[\hat{v}'] = \hat{\lambda} \hat{v}' + \hat{v}$$

if and only if

$$(8.9) \quad \hat{\lambda} \hat{v}'_i + \hat{v}_i = \omega \left\{ \sum_{j=1}^{i-1} b_{ij} (\hat{\lambda} \hat{v}'_j + \hat{v}_j) + \sum_{j=i+1}^N b_{ij} \hat{v}'_j \right\} - (\omega - 1) \hat{v}'_i, \quad (i = 1, 2, \dots, N).$$

The proof is immediate from (III.0.II)

We have for all $i = 1, 2, \dots, N$

$$\begin{aligned} & \omega \left\{ \sum_{j=1}^{i-1} b_{ij} (\hat{\lambda} \hat{\sigma}_j + \hat{\sigma}_j) + \sum_{j=i+1}^N b_{ij} \nu_j \right\} - (\omega-1) \hat{\nu}_i \\ &= \omega \left\{ \sum_{j=1}^{i-1} b_{ij} \hat{\lambda}^{\frac{\gamma_j}{2}} \left(\frac{\gamma_j}{2}\right) r_j + \sum_{j=i+1}^N b_{ij} \left(\frac{\gamma_j}{2} - 1\right) \hat{\lambda}^{\frac{\gamma_j}{2} - 1} r_j \right\} \\ & \quad - (\omega-1) \left(\frac{\gamma_i}{2} - 1\right) \hat{\lambda}^{\frac{\gamma_i}{2} - 1} r_i \end{aligned}$$

Since

$$\gamma_j = \begin{cases} \gamma_i + 1 & j > i \\ \gamma_i - 1 & j < i \end{cases}$$

the last expression becomes

$$\omega \hat{\lambda}^{\frac{\gamma_i-1}{2}} \left(\frac{\gamma_i-1}{2}\right) \sum_{j=1}^N b_{ij} r_j - (\omega-1) \hat{\lambda}^{\frac{\gamma_i}{2} - 1} \left(\frac{\gamma_i}{2} - 1\right) r_i$$

By (4.3a) we have

$$\hat{\lambda}^{\frac{\gamma_i-1}{2}} \left\{ \omega \frac{\gamma_i-1}{2} \mu \hat{\lambda}^{\frac{1}{2}} - (\omega-1) \left(\frac{\gamma_i}{2} - 1\right) \right\} r_i$$

Setting $\omega \mu \hat{\lambda}^{\frac{1}{2}} = (\omega-1) + \hat{\lambda}$ and

$$\mu^2 \omega^2 = 4(\omega-1) = 0$$

we get

$$\hat{\lambda} = (\omega - 1) \quad \text{and}$$

$$\mu \omega = 2 \hat{\lambda}^{\frac{1}{2}}$$

Hence we have

$$\begin{aligned}
 & \left\{ 2\hat{\lambda}^{\frac{\alpha_i-1}{2}} - \hat{\lambda}^{\left(\frac{\alpha_i}{2}-1\right)} \right\} \hat{\lambda}^{\frac{\alpha_i}{2}-1} r_i \\
 &= \left\{ \hat{\lambda}^{\left(\frac{\alpha_i}{2}-1\right)} + \hat{\lambda} \right\} \hat{\lambda}^{\frac{\alpha_i}{2}-1} r_i \\
 &= \hat{\lambda} \hat{v}_i' + \hat{v}_i \quad (i=1, 2, \dots, N)
 \end{aligned}$$

The theorem follows by Lemma 1.

Q. E. D.

Corollary 1: If (a_{ij}) is symmetric and if μ is a k -fold root of $|K - \mu I| = 0$ and satisfies (8.6), then there exist k linearly independent eigenvectors and k linearly independent invariant vectors of $L_{\sigma, \omega}$ associated with the eigenvalue $\hat{\lambda}$ given by (8.3).

Theorem 8.4

If μ_i , $i=1, 2, \dots, N$, are the eigenvalues of K and if $\omega > 1$, then all the eigenvalues of $L_{\sigma, \omega}$ are given by

$$(8.10) \quad \hat{\lambda} + (\omega - 1) = \omega \mu_i \hat{\lambda}^{\frac{1}{2}}$$

Multiplicities of the eigenvalues are preserved.

Proof:

$$\text{Let } |\mathcal{L}_{\sigma, \omega} - \hat{\lambda} I| = \left| \sum_{i,j}^{\wedge} c_{ij} \right|,$$

where by Theorem 8.1.

$$\sum_{i,j}^{\wedge} c_{ij} = \begin{cases} -(\omega-1) - \hat{\lambda} & i=j \\ \omega \theta_{i,j} & i < j \\ \hat{\lambda} \omega \theta_{i,j} & i > j \end{cases}$$

By Theorem 5.3

$$\left| \left(\sum_{i,j}^{\wedge} c_{ij} \right) \right| = \left| \left(\sum_{i,j}^{\wedge} c_{ij}'' \right) \right|$$

$$\sum_{i,j}^{\wedge} c_{ij}'' = \begin{cases} -(\omega-1) - \hat{\lambda} & (i=j) \\ \hat{\lambda}^{\frac{1}{2}} \theta_{i,j} & (i \neq j) \end{cases} \quad \begin{matrix} \text{where} \\ (i=1, 2, \dots, N.) \\ (i=1, 2, \dots, N.) \end{matrix}$$

Therefore

$$\begin{aligned} |\mathcal{L}_{\sigma, \omega} - \hat{\lambda} I| &= \omega^N \hat{\lambda}^{\frac{N}{2}} \left| \kappa - \frac{(\omega-1) + \hat{\lambda}}{\omega \hat{\lambda}^{\frac{1}{2}}} I \right| \\ &= \omega^N \hat{\lambda}^{\frac{N}{2}} \prod_{i=1}^N \left(\mu_i - \frac{(\omega-1) + \hat{\lambda}}{\omega \hat{\lambda}^{\frac{1}{2}}} \right) \\ &= \prod_{i=1}^N (\omega \mu_i \hat{\lambda}^{\frac{1}{2}} - [(\omega-1) + \hat{\lambda}]) \end{aligned}$$

Therefore $|\mathcal{L}_{\sigma, \omega} - \hat{\lambda} I|$ vanishes if and only if

$$\omega \mu_i \hat{\lambda}^{\frac{1}{2}} = (\omega-1) + \hat{\lambda},$$

with multiplicities preserved.

Q. E. D.

Theorem 8.5

For $\omega > 1$ if (a_{ij}) is symmetric the normal form of the matrix of $\mathcal{L}_{\sigma, \omega}$ is diagonal except for the submatrix associated with $\hat{\lambda}(\mu)$ defined by (8.3) where $\mu^2 \omega^2 - 4(\omega - 1) = 0$. In the latter case, if μ is a k -fold root of $|\mathcal{K} - \mu I| = 0$ in the normal form, the associated submatrix has $2k$ diagonal elements equal to $\hat{\lambda}(\mu)$ and has alternating zeros and ones in the diagonal immediately below the main diagonal.

Proof: Solving (8.3) for $\hat{\lambda}^{\frac{1}{2}}$ we get

$$(8.11) \quad \hat{\lambda}(\mu_i)^{\frac{1}{2}} = \frac{\omega \mu_i \pm \sqrt{\omega^2 \mu_i^2 - 4(\omega - 1)}}{2}$$

If $\omega > 1$ and if $\omega^2 \mu_i^2 - 4(\omega - 1) \neq 0$ we get two distinct solutions

$$(8.12) \quad \hat{\lambda}'(\mu_i)^{\frac{1}{2}} = \frac{\omega \mu_i + \sqrt{\omega^2 \mu_i^2 - 4(\omega - 1)}}{2}$$

$$(8.13) \quad \hat{\lambda}''(\mu_i)^{\frac{1}{2}} = \frac{\omega \mu_i - \sqrt{\omega^2 \mu_i^2 - 4(\omega - 1)}}{2}$$

By Theorem (4.3) the non zero eigenvalues of \mathcal{K} occur in pairs. We note that

$$(8.14) \quad \hat{\lambda}'(\mu_i)^{\frac{1}{2}} = -\hat{\lambda}''(-\mu_i)^{\frac{1}{2}}$$

$$(8.15) \quad \hat{\lambda}''(\mu_i)^{\frac{1}{2}} = -\hat{\lambda}'(-\mu_i)^{\frac{1}{2}}$$

There are three cases to consider

$$(a) \quad \omega^2 \mu_i^2 - 4(\omega - 1) > 0$$

We get two distinct, real positive values $\lambda^1(\mu_i)$ and $\lambda^2(\mu_i)$, and two distinct eigenvectors defined by (8.4). The pair of eigenvectors associated with μ_i are clearly identical with the pair associated with those associated with $-\mu_i$ by (8.4), (4.16) and (8.11). Thus for each pair $(\mu_i, -\mu_i)$ satisfying (4.3) we get two linearly independent eigenvectors of $\mathcal{L}_{\sigma, \omega}$. Of course if $\omega > 1, \mu_i \neq 0$ since $\omega^2 \mu_i^2 > 4(\omega - 1)$

$$(b) \quad \omega^2 \mu_i^2 - 4(\omega - 1) < 0$$

In this case we get two distinct complex eigenvalues λ^1 and λ^2 unless $\mu_i = 0$. If $\mu_i = 0$ is a k -fold eigenvalue of \mathcal{K} we get by (8.4), k linearly independent eigenvectors of $\mathcal{L}_{\sigma, \omega}$ with eigenvalue $\lambda = -(\omega - 1)$. If $\mu_i \neq 0$

$$\lambda^1(\mu_i)^{\frac{1}{2}} = \frac{\omega \mu_i + i \zeta_i}{2} \quad \lambda^2(\mu_i)^{\frac{1}{2}} = \frac{\omega \mu_i - i \zeta_i}{2}$$

where $\zeta_i^2 = 4(\omega - 1) - \omega^2 \mu_i^2 > 0$

As in (a) we obtain exactly two distinct complex eigenvectors of $\mathcal{L}_{\sigma, \omega}$ for each pair of eigenvalues (μ_i, μ_j) of \mathcal{K} . If μ_i is a k -fold eigenvalue we obtain k such pairs.

(c) If $\omega^2 \mu_i^2 - 4(\omega - 1) = 0$

We obtain in this case invariant vectors by Theorem 8.3. If μ_i is repeated k times, there are k linearly independent eigenvalues associated with $\hat{\lambda}(\mu_i)$ and k invariant vectors by Corollary 1 of Theorem 8.3.

Q. E. D.

Let us replace $\hat{\lambda}^{1/2}$ of equation 8.3 by Z and μ by w . We obtain the Joukowski transformation

$$(8.16) \quad Z + (\omega - 1) Z^{-1} = \omega w.$$

Solving for Z we have

$$(8.17) \quad Z = Z_\omega(w) = \frac{\omega w \pm \sqrt{\omega^2 w^2 - 4(\omega - 1)}}{2}$$

Let

$$(8.17a) \quad \begin{cases} Z'_\omega(w) = \frac{\omega w + \sqrt{\omega^2 w^2 - 4(\omega - 1)}}{2} \\ Z''_\omega(w) = \frac{\omega w - \sqrt{\omega^2 w^2 - 4(\omega - 1)}}{2} \end{cases}$$

and

$$(8.17b) \quad a_\omega(w) = \max(|Z'_\omega(w)|, |Z''_\omega(w)|)$$

We note that $a_\omega(w) = a_\omega(-w)$.

Theorem 8.6. If A is a positive real constant and if $|AK|$, and if

$$(8.18) \quad \omega_b = 1 + \left[\frac{1 - \sqrt{1 - A^2}}{A} \right]^2$$

then

$$(8.18a) \quad |Z_{\omega_b}(w)|^2 = |\omega_b - 1| \quad \text{for all real } w, (|w| \leq A),$$

and

$$(8.18b) \quad \xi_A(w) = \text{LUB}_{\substack{-A \leq w \leq A \\ w \text{ real}}} |a_w(w)|^2 > |\omega_b - 1|$$

if $w \neq \omega_b$.

Proof: We assume throughout that w is real.

Lemma 1: If

$$w^2 < \frac{4(\omega - 1)}{\omega^2}$$

$Z_{\omega}(w)$ is

complex and $|Z_{\omega}(w)|^2 = |\omega - 1|$.

Proof: The proof follows from (8.17).

Lemma 2: If

$$w_1^2 > w_2^2 > \frac{4(\omega - 1)}{\omega^2}$$

then

$$a_{\omega}(w_1) > a_{\omega}(w_2).$$

Proof: By (8.17a) and (8.17b) we may assume w_1, w_2 positive, if we take the sign of the radical as plus.

$$a_{\omega}(w_1) - a_{\omega}(w_2) = \frac{\omega(w_1 - w_2) + \sqrt{\omega^2 w_1^2 - 4(\omega - 1)} - \sqrt{\omega^2 w_2^2 - 4(\omega - 1)}}{2}$$

$$= \frac{\omega}{2} (w_1 - w_2) + \frac{\omega^2 (w_1^2 - w_2^2)}{\sqrt{\omega^2 w_1^2 - 4(\omega - 1)} + \sqrt{\omega^2 w_2^2 - 4(\omega - 1)}}$$

> 0

Q.E.D.

Lemma 3: If $2 > \omega_1 > \omega_2 > 0$, then

$$\frac{4(\omega_1 - 1)}{\omega_1^2} > \frac{4(\omega_2 - 1)}{\omega_2^2}$$

Proof:

$$\begin{aligned} & \frac{4(\omega_1 - 1)}{\omega_1^2} - \frac{4(\omega_2 - 1)}{\omega_2^2} \\ &= \frac{4}{\omega_1^2 \omega_2^2} (\omega_1 - \omega_2) \left[\frac{\omega_1}{2} (2 - \omega_2) + \frac{\omega_2}{2} (2 - \omega_1) \right] > 0 \end{aligned}$$

Q.E.D.

Lemma 4: If $2 > \omega_1 > \omega_2 > 0$ and if $w^2 \geq \frac{4(\omega_1 - 1)}{\omega_1^2}$, then

$$a_{\omega_1}(w) < a_{\omega_2}(w)$$

Proof: By Lemma 3

$$w^2 > \frac{4(\omega_2 - 1)}{\omega_2}$$

$$\begin{aligned} a_{\omega_1}(w) - a_{\omega_2}(w) &= \frac{\omega_1 - \omega_2}{2} w + \frac{\sqrt{\omega_1^2 w^2 - 4(\omega_1 - 1)} - \sqrt{\omega_2^2 w^2 - 4(\omega_2 - 1)}}{2} \\ &= \frac{(\omega_1 - \omega_2)}{2} w + \frac{w^2(\omega_1^2 - \omega_2^2) + 4(\omega_2 - \omega_1)}{2 \sum_{i=1}^2 \sqrt{\omega_i^2 w^2 - 4(\omega_i - 1)}} \\ &= \frac{(\omega_1 - \omega_2)}{2} w + \frac{(\omega_1 - \omega_2) \{ w^2(\omega_1 + \omega_2) - 4 \}}{2 \sum_{i=1}^2 \sqrt{\omega_i^2 w^2 - 4(\omega_i - 1)}} \\ &= \frac{\omega_1 - \omega_2}{2} \left[\frac{\sum_{i=1}^2 \sqrt{\omega_i^2 w^4 - 4w^2(\omega_i - 1)} + (w^2 \omega_1 - 2)}{\sum_{i=1}^2 \sqrt{\omega_i^2 w^2 - 4(\omega_i - 1)}} \right] \end{aligned}$$

$$\text{But } \left\{ \sqrt{\omega_i^2 w^4 - 4w^2(\omega_i - 1)} \right\}^2 = (2 - \omega_i w^2)^2 + 4(w^2 - 1) \quad (i = 1, 2)$$

Since $2 - \omega_i w^2 > 0$, we have

$$\sqrt{\omega_i^2 w^4 - 4w^2(\omega_i - 1)} - (2 - \omega_i w^2) < 0 \quad (i = 1, 2)$$

and $a_{\omega_1}(w) - a_{\omega_2}(w) < 0$. This proves the Lemma.

Q.E.D.

The theorem now follows from the lemmas.

Q.E.D.

Theorem 8.7: If $(a_{i,j})$ is symmetric, and if the relaxation factor $\omega = \omega_b$ is used, where

$$(8.19) \quad \omega_b = 1 + \left[\frac{1 - \sqrt{1 - \mu_1^2}}{\mu_1} \right]^2$$

then the rate of convergence of $\mathcal{L}_{\sigma, \omega}$ is maximized. The rate of convergence of $\mathcal{L}_{\sigma, \omega_b}$ is

$$(8.20) \quad \rho(\mathcal{L}_{\sigma, \omega_b}) = -\log(\omega_b - 1)$$

Moreover for all i

$$(8.20a) \quad |\hat{\lambda}(\mu_i)| = \omega_b - 1.$$

Proof: The proof follows from Theorem 3.1, Corollary 1, and Theorem 8.6, and the fact that because $(a_{i,j})$ is symmetric the eigenvalues of \mathcal{K} are real.

Corollary 1: $1 \leq \omega_b < 2$.

Proof: Since $0 \leq \mu_i < 1$ we can let

$$\mu_i = \cos \theta, \text{ where } 0 < \theta \leq \frac{\pi}{2}$$

$$\omega_b = 1 + \left[\frac{1 - \sin \theta}{\cos \theta} \right]^2$$

Then
$$\frac{1 - \sin \theta}{\cos \theta} = \tan \left(\frac{\pi}{4} - \frac{\theta}{2} \right).$$

Therefore
$$0 \leq \frac{1 - \sin \theta}{\cos \theta} < 1.$$

Q.E.D.

Theorem 8.7. If $(a_{i,j})$ is symmetric with the value ω_b given by 8.19 then the normal form of $\mathcal{L}_{\sigma, \omega_b}$ contains precisely one non diagonal element associated with the repeated eigenvalue $(\omega_b - 1)$. The submatrix is of the form

$$(8.21) \quad \begin{pmatrix} \omega_b - 1 & 0 \\ 1 & \omega_b - 1 \end{pmatrix}$$

Proof: The proof follows from Theorem 8.4, Theorem 8.5 and Theorem 4.1.

Theorem 8.9. If $(a_{i,j})$ is symmetric, then for all $\omega > \omega_b$, $\omega < 2$

$$|\hat{\lambda}(\mu_i)| = (\omega - 1) \quad (i = 1, 2, \dots, N)$$

for all i , and the normal form of the matrix of $\mathcal{L}_{\tau, \omega}$ is diagonal.

Proof: The proof follows from Theorem 8.5 and Lemma 1 of Theorem 8.6.

Thus, for $(a_{i,j})$ symmetric the operator $\mathcal{L}_{\tau, \omega}$ has been analyzed completely. Even if $(a_{i,j})$ is not symmetric we have shown, Theorem 8.4 how the eigenvalues of $\mathcal{L}_{\tau, \omega}$ can be determined from the eigenvalues of \mathcal{K} when these are known.

We shall now show that for properly chosen ω the rate of convergence of $\mathcal{L}_{\tau, \omega}$ is of the order of the square root of the rate of convergence of The Liebmann Method, for $(a_{i,j})$ symmetric.

§ 9 The Superiority Over The Liebmann Method

A. Rates of Convergence

If N is large, μ_1 is very nearly one. We have
 Theorem 9.1. If $(a_{i,j})$ is symmetric, then

$$(9.1) \quad \lim_{\mu_1 \rightarrow 1} \frac{\phi(\mathcal{L}_\sigma, \omega_b)}{\phi(\mathcal{L}_\sigma)} \sqrt{1-\mu_1} = \sqrt{2},$$

where ϕ is the rate of convergence defined in Definition 3.2, and where ω_b is given by (8.19).

Proof: By (8.20a), using ω_b the optimum value of ω , the dominant eigenvalue of $\mathcal{L}_{\sigma, \omega_b}$ is given by

$$(9.2) \quad |\hat{\lambda}(\mu_1)| = \omega_b^{-1} = \left[\frac{1 - \sqrt{1-\mu_1^2}}{\mu_1} \right]^2$$

But

$$-\log(1 - \sqrt{1-\mu_1^2}) = \sqrt{2(1-\mu_1)} + (1-\mu_1) + O_1((1-\mu_1)^{3/2})$$

$$-\log \mu_1 = (1-\mu_1) + O_2((1-\mu_1)^{3/2})$$

$$-\log \left[\frac{1 - \sqrt{1-\mu_1^2}}{\mu_1} \right] = \sqrt{2(1-\mu_1)} + O((1-\mu_1)^{3/2})$$

Therefore by (3.3) and (5.7)

$$\frac{\phi(\mathcal{L}_\sigma, \omega_b)}{\phi(\mathcal{L}_\sigma)} = \frac{-\log |\hat{\lambda}(\mu_1)|}{-2 \log \mu_1} = \frac{\sqrt{2}}{\sqrt{1-\mu_1}} + O((1-\mu_1)^{1/2}),$$

and the theorem follows.

Q.E.D.

Corollary

$$(9.3) \quad \phi(\mathcal{L}_\sigma, \omega_b) \approx \sqrt{2} \left[\phi(\mathcal{L}_\sigma) \right]^{1/2}$$

Proof: This follows since

$$\phi(\mathcal{L}_\sigma) = -2 \log \mu_1 = -2(1-\mu_1) - 2 O_2((1-\mu_1)^{3/2}).$$

B. Number of Iterations Necessary to Reduce the Error by a Specified Amount.

If the best overrelaxation factor, ω_b is used, the number of iterations necessary to reduce the error to a specified fraction of itself is, by Theorem (3.3), approximately for small ρ

$$(9.4) \quad N(\mathcal{L}_\sigma, \omega_b, \rho) \approx \frac{-\log \rho}{-\log(\omega_b - 1)}$$

For μ_1 nearly equal to one we have

$$-\log(\omega_b - 1) \approx 2\sqrt{2} \sqrt{1-\mu_1}$$

Therefore

$$(9.5a) \quad N(\mathcal{L}_\sigma, \omega_b, \rho) \approx \frac{-\log \rho}{2\sqrt{2} \sqrt{1-\mu_1}}$$

and for The Liebmann Method

$$(9.5b) \quad N(\mathcal{L}_\sigma, \rho) \approx \frac{-\log \rho}{2(1-\mu_1)}$$

Hence, as already stated in the Introduction, if the required number of iterations is of the order of h^{-k} by The Liebmann Method, that number is of the order of $h^{-k/2}$ by The Successive Overrelaxation Method. For the Dirichlet Problem by (7.2) $k=2$.

For the Dirichlet Problem and for the ordering σ_2 we can derive an upper bound for $\mathcal{N}(\mathcal{L}_{\sigma_2}, \omega, \rho)$.

Theorem 9.2.

For the Dirichlet Problem if

$$|\hat{\lambda}_1| = \omega^{-1}, \quad \text{where} \\ \omega \geq \omega_b = 1 + \left[\frac{1 - \sqrt{1 - \omega_1^2}}{\omega_1} \right]^2$$

then $\mathcal{N}(\mathcal{L}_{\sigma_2}, \omega_b, \rho)$ is not greater than the largest solution m of

$$(9.6) \quad m |\hat{\lambda}_1|^{m-1} = \rho/\sigma.$$

Proof: By (4.21) and (4.24) we have for any $f \in V_N$

$$f = \sum_{j=1}^{\bar{N}/2} A_j r^{(j)} + A_j^* r^{*(j)} + \sum_{j=\bar{N}/2+1}^{N-\frac{\bar{N}}{2}} A_j r^{(j)}$$

and

$$\|f\|^2 = \sum_{j=1}^N A_j^2.$$

By (8.4), since $\hat{\lambda}_j^{\frac{r}{2}} = (1-r) + \hat{\lambda}_j^{1/2} r$ we have

$$(9.7) \quad \begin{cases} \hat{v}^{(j)} = [(1-r) + \hat{\lambda}_j^{1/2} r] r^{(j)} \\ \hat{v}^{*(j)} = [(1-r) + \hat{\lambda}_j^{*1/2} r] r^{(j)} \end{cases}$$

where

$$(9.7a) \quad \begin{cases} \hat{\lambda}_j^{1/2} = \frac{\omega \mu_j + \sqrt{\omega^2 \mu_j^2 - 4(\omega-1)}}{2} \\ \hat{\lambda}_j^{*1/2} = \frac{\omega \mu_j - \sqrt{\omega^2 \mu_j^2 - 4(\omega-1)}}{2} \end{cases}$$

and

$$(9.7) \quad \begin{cases} \mathcal{L}_{\sigma_2, \omega} [\hat{v}^{(j)}] = \hat{\lambda}_j \hat{v}^{(j)} \\ \mathcal{L}_{\sigma_2, \omega} [\hat{v}^{*(j)}] = \hat{\lambda}_j^* \hat{v}^{*(j)} \end{cases}$$

Since

$$(9.8) \quad v^{*(j)} = (1-2r) r^{(j)} \quad (j=1, 2, \dots, \bar{x}/2)$$

we have

$$(9.9) \quad \begin{cases} \hat{v}^{(j)} = \frac{1+a_j}{2} r^{(j)} + \frac{1-a_j}{2} r^{*(j)} \\ \hat{v}^{*(j)} = \frac{1+a_j^*}{2} r^{(j)} + \frac{1-a_j^*}{2} r^{*(j)} \end{cases} \quad (j=1, 2, \dots, \bar{x}/2)$$

where, for convenience we let

$$(9.10) \quad \begin{aligned} a_j &= \hat{\lambda}_j^{1/2} \\ a_j^* &= \hat{\lambda}_j^{*/2} \end{aligned} \quad (j=1, 2, \dots, \bar{\alpha}/2)$$

Conversely we have

$$(9.11) \quad r^{(j)} = \frac{1-a_j^*}{a_j-a_j^*} v^{(j)} + \frac{-1+a_j}{a_j-a_j^*} v^{*(j)}$$

$$r^{*(j)} = \frac{-1-a_j^*}{a_j-a_j^*} v^{(j)} + \frac{1+a_j}{a_j-a_j^*} v^{*(j)}$$

($j=1, 2, \dots, \bar{\alpha}/2$).

Moreover, if $\frac{\bar{\alpha}}{2} < j \leq N - \frac{\bar{\alpha}}{2}$, $r^{(j)} = r^{*(j)}$ and $\hat{v}^{(j)}$ and $\hat{v}^{*(j)}$ are linearly dependent.

For $N - \frac{\bar{\alpha}}{2} \geq j > \frac{\bar{\alpha}}{2}$ $\kappa[r^{(j)}] = 0$, and

$$\mathcal{L}_{\sigma_2, \omega}[r^{(j)}] = -(\omega-1)r^{(j)}.$$

Thus we may let

$$\hat{v}^{(j)} = \hat{v}^{*(j)} = r^{(j)}$$

$$(j = \frac{\bar{\alpha}}{2} + 1, \dots, N - \frac{\bar{\alpha}}{2}).$$

We have

$$(9.12) \quad f = \sum_{j=1}^{\bar{n}/2} \frac{1}{a_j - a_j^*} \left[\left\{ A_j (1 - a_j^*) + A_j^* (-1 - a_j^*) \right\} \hat{v}(j) \right. \\ \left. + \left\{ A_j (-1 + a_j) + A_j^* (1 + a_j) \right\} \hat{v}^*(j) \right] \\ + \sum_{j=\frac{\bar{n}}{2}+1}^{N-\frac{\bar{n}}{2}} A_j \hat{v}(j)$$

and

$$\mathcal{L}_{\sigma, \omega}^m [f] = \sum_{j=1}^{\bar{n}/2} \left[\frac{a_j^{2m} - a_j^{*2m}}{2(a_j - a_j^*)} \left\{ A_j^* (-1 - a_j^*) (1 + a_j) + A_j (1 - a_j a_j^*) \right\} \right. \\ \left. + \frac{a_j^{2m} + a_j^{*2m}}{2} A_j \right] r(j) + \left[\frac{a_j^{2m} - a_j^{*2m}}{2(a_j - a_j^*)} \right. \\ \left. \left\{ A_j (1 - a_j^*) (1 - a_j) + A_j^* (-1 + a_j a_j^*) \right\} + \frac{a_j^{2m} + a_j^{*2m}}{2} A_j^* \right] r^*(j) \\ + \sum_{j=\frac{\bar{n}}{2}+1}^{N-\frac{\bar{n}}{2}} a_j^{2m} A_j r(j) \\ = \sum_{j=1}^{\bar{n}/2} A_j^{(m)} r(j) + A_j^{*(m)} r^*(j) \\ + \sum_{j=\frac{\bar{n}}{2}+1}^{N-\frac{\bar{n}}{2}} a_j^{2m} A_j^{(m)} r(j)$$

By (8.11) and (9.10) either a_j and a_j^* are each real and positive or else they are complex conjugates, with positive real parts. Moreover $|a_j| < 1$ and $|a_j^*| < 1$. Thus we have

$$\left\{ \begin{array}{l} \left| \frac{a_j^{2m} - a_j^{*2m}}{a_j - a_j^*} \right| \leq 2^m |\bar{a}_j|^{2m-1} \\ |1 - a_j a_j^*| \leq 1 \\ |(1 - a_j)(1 - a_j^*)| \leq 2 \\ |(1 + a_j^*)(1 + a_j)| \leq 4 \end{array} \right.$$

where

$$|\bar{a}_j| = \max(|a_j|, |a_j^*|).$$

Therefore

$$(9.12a) \quad \left\{ \begin{array}{l} |A_j^{(m)}| \leq m |\bar{a}_j|^{2m-1} (4|A_j^*| + |A_j|) + |\bar{a}_j|^{2m} |A_j| \\ |A_j^{*(m)}| \leq m |\bar{a}_j|^{2m-1} (2|A_j| + |A_j^*|) + |\bar{a}_j|^{2m} |A_j^*| \end{array} \right.$$

By the same method it can be shown that the above inequality holds even if $a_j = a_j^*$ which is possible for $\omega = \omega_b$. In this case $a_1 = a_1^*$ and $\hat{v}^{*(1)}$ is replaced by the invariant vector (see Theorem 8.3)

$$v^{(1)} = \lim_{a_1^* \rightarrow a_1} \frac{\hat{v}^{(1)} - \hat{v}^{*(1)}}{a_1 - a_1^*} = \frac{1}{2} a_1^{-1} \gamma \lambda^{(1)}$$

where

$$v^{(1)} = ((1-\gamma) - a_1 \gamma) \lambda^{(1)}$$

Thus the inequality (9.12a) is valid for all $\omega \geq \omega_b$.

We now have

$$\begin{aligned} \|\mathcal{L}_{\sigma_2, \omega}^m [f]\|^2 &\leq \sum_{j=1}^{\bar{\lambda}/2} \left\{ m^2 |\bar{a}_j|^{2(2m-1)} [17|A_j^*| + 5|A_j|^2 \right. \\ &\quad \left. + 12|A_j||A_j^*| + |\bar{a}_j|^{4m} [|A_j|^2 + |A_j^*|^2]] \right\} \\ &+ \sum_{j=\frac{\bar{\lambda}}{2}+1}^{N-\frac{\bar{\lambda}}{2}} |A_j|^2 |a_j|^{2m} \end{aligned}$$

Therefore

$$\|\mathcal{L}_{\sigma_2, \omega}^m [f]\|^2 \leq 20 |\hat{\lambda}_1|^{2(m-1)} m^2 \|f\|^2$$

or

(9.13)

$$\|\mathcal{L}_{\sigma_2, \omega}^m [f]\| \leq 5 m |\hat{\lambda}_1|^{m-1} \|f\|$$

Hence if n is the largest solution of

$$m |\hat{\lambda}_1|^{m-1} = \rho/5$$

for all $m > n$

$$\|L_{\sigma_2, \omega}^m\| \leq \rho \|f\|$$

Q. E. D.

The reduction of the number of iterations required using The Successive Overrelaxation Method is seen by (9.6) to be in general not as large as the gain in the rate of convergence. However, when ρ is very small the gains in each case are approximately equal. For small ρ and for μ , nearly one

$$N(L_{\sigma_2, \rho}) \approx \frac{-\log \rho}{-\log \lambda_1}$$

and by Theorem (9.1)

$$N(L_{\sigma_2, \omega_b, \rho}) \approx \frac{-\log \rho}{\sqrt{-\log \lambda_1}}$$

For the Dirichlet Problem for ^a unit square with $h = \frac{1}{I}$ we have by (4.30) and Theorem (5.4)

$$\lambda_1 \approx 1 - \frac{\pi^2}{I^2} ; \quad -\log \lambda_1 \approx \frac{\pi^2}{I^2}$$

By Theorem (8.7)

$$\hat{\lambda}_1 |_{\omega=\omega_b} = \omega_b^{-1} \approx 1 - \frac{2\pi}{I}$$

$$-\log \hat{\lambda}_1 |_{\omega=\omega_b} \approx \frac{2\pi}{I}$$

$$\frac{-\log \hat{\lambda}_1 |_{\omega=\omega_b}}{-\log \lambda_1} \approx \frac{2I}{\pi}$$

Thus the gain in the rate of convergence by using The Successive Overrelaxation Method is of the order of I .

C. The Use of Large Automatic Computing Machines

The large reduction in the required number of iterations makes The Successive Overrelaxation method much more practical for use with large automatic computing machines. A study of the coding for the UNIVAC for a Dirichlet Problem to be solved by means of The Liebmann Method [21] (see also section II.4) reveals that only two additional memory locations would be required to use The Successive Overrelaxation Method and that the time per iteration would not be increased by more than 10%. For both methods the stored values which are used on each operation are the values of u at the same set of net points.

The following table gives a comparison of the estimated number of iterations required using The Liebmann Method and The Successive Overrelaxation Method for the Dirichlet Problem with the unit square with I intervals on a side. Time estimates for the UNIVAC are also given [See Table next page.]

TABLE (9.1)

I	THE LIEBMANN METHOD			THE SUCCESSIVE OVERRELAXATION METHOD			
	λ_1	$n(\mathcal{L}, \rho)^1$	Time ² .	ω_b	$\hat{\lambda}_1$	$n(\mathcal{L}, \omega_b, \rho)^1$	Time ² .
20	.9754	280	.31	1.755	.755	45	.05
50	.99605	1750	12.15	1.882	.882	106	.74
100	.999015	7010	195.0	1.940	.940	227	7.95
300	.999890	63300	15,750	1.980	.980	756	186.5

In the above estimates ρ was assumed to be 10^{-3} . For smaller ρ the advantage of The Successive Overrelaxation Method would be greater.

1. $n(\mathcal{L}, \omega_b, \rho)$ is the solution of $m(\omega_b - 1)^{m-1} = \rho/5$
 $n(\mathcal{L}, \rho)$ " " " " $\lambda_1^m = \rho$

2. The estimated time is in hours computing time for the UNIVAC. The number of seconds per iteration was assumed to be $\frac{I^2}{100}$, [21].

§ 10. The Determination of the Optimum Relaxation Factor.

By (8.19) the optimum relaxation factor ω_b is given by

$$\omega_b = 1 + \left[\frac{1 - \sqrt{1 - \mu_1^2}}{\mu_1} \right]^2$$

where μ_1 is the largest eigenvalue of the Kormes Method.

For the Dirichlet Problem μ_1 can be expressed in terms of μ_1^T , the smallest eigenvalue of the finite difference analogue of

$$(10.1) \quad \left\{ \begin{array}{l} \sum_{k=1}^m \frac{\partial^2 u(x)}{\partial x_k^2} = -\Delta u(x) \quad x \in R \\ u(x) = 0 \quad x \in S \end{array} \right.$$

which is given by

$$(10.2) \quad \left(\left[\sum_{k=1}^m E_{x_k} + E - x_k - 2m \right] u \right)_i = -u^T u_i \quad (x^{(i)} \in R_h) \\ u_i = 0 \quad (x^{(i)} \in S_h)$$

By (10.2) and (4.3a) we have

$$(10.3) \quad 2m(1 - \mu_1) = \mu_1^T.$$

Also, by [9]

$$(10.4) \quad \lim_{h \rightarrow 0} \frac{\mu, T}{h^2} = \Lambda_1.$$

where Λ_1 is the smallest eigenvalue of (10.1).

The relation between $\mu, T/h^2$ and Λ_1 has been investigated by Collatz ([22], page 280-297) and the agreement has been shown to be remarkably close for some regions even with coarse meshes. Λ_1 can be computed exactly for some regions including the circle ([23] page 260), and the ellipse [24]. Of course μ , itself can be computed exactly for square or rectangular regions, (4.28).

For the case of a rectangular region with side lengths $I_k h = \tau_k$ ($k=1, 2, \dots, n$) we have

$$(10.5) \quad \Lambda_1 = \frac{\pi^2}{h^2} \sum_{k=1}^n \frac{1}{I_k^2} = \pi^2 \sum_{k=1}^n \frac{1}{\tau_k^2}$$

By (10.3) and (4.28)

$$\begin{aligned} \mu, T/h^2 &= \frac{1}{h^2} \left\{ 2n - 2 \sum_{k=1}^n \cos \frac{\pi}{I_k} \right\} \\ &= \frac{\pi^2}{h^2} \left\{ \sum_{k=1}^n \frac{1}{I_k^2} - \frac{1}{12} \sum_{k=1}^n \frac{1}{I_k^4} + O(h^6) \right\} \end{aligned}$$

$$(10.6) \quad \mu_1^T/h^2 = \pi \left\{ \sum_{k=1}^{\infty} \frac{1}{r_k^2} - \frac{h^2}{12} \sum \frac{1}{r_k^4} \right\} + o(h^6)$$

Hence, the convergence of $\frac{\mu_1^T}{h^2}$ to Λ , is, in this case very rapid.

In any case, for the Dirichlet Problem, a lower bound to μ_1^T can be found by computing μ_1^T for a circumscribing rectangular region, because of the Theorem 4.2, Corollary

We now show that for the general self adjoint case, if $(1-\mu_1)$ is not overestimated, the relative decrease in the rate of convergence is, asymptotically, for small errors in $(1-\mu_1)$ and for small $(1-\mu_1)$, equal to one half the relative error in the estimation of $(1-\mu_1)$

Definition 10.1.

The relative change, or error, of y' with respect to y is $\left\{ \frac{|y' - y|}{|y|} \right\}$ ($y \neq 0$)

Theorem 10.1.

Let μ_1 be the dominant eigenvalue of \mathcal{K} and let μ_1' be the estimated value of μ_1 , such that

$$\mu_1 \leq \mu_1' < 1$$

Then

$$(10.7) \quad \lim_{\mu_1 \rightarrow 1} \left\{ \lim_{\mu_1' \rightarrow \mu_1} \frac{\left| \frac{\phi(\mathcal{L}\sigma, \omega') - \phi(\mathcal{L}\sigma, \omega)}{\phi(\mathcal{L}\sigma, \omega)} \right|}{\left| \frac{(1-\mu_1') - (1-\mu_1)}{1-\mu_1} \right|} \right\} = \frac{1}{2}$$

where ω, ω' are determined from (8.19) based on μ_1 and μ_1' respectively, and where $\phi(\mathcal{L}\sigma, \omega)$ and $\phi(\mathcal{L}\sigma, \omega')$ are the rates of convergence of $\mathcal{L}\sigma, \omega$ and $\mathcal{L}\sigma, \omega'$ respectively.

Proof: The left member of (10.7) equals

$$(10.8) \quad \lim_{\mu_1 \rightarrow 1} \frac{-\frac{d}{d\mu_1} [\log \phi(\mathcal{L}\sigma, \omega)]}{-\frac{d}{d\mu_1} [\log (1-\mu_1)]}$$

provided the derivatives exist

Now let $\mu_1 = \cos \theta$ by (8.19)

$$(\omega-1)^{1/2} = \frac{1-\sin \theta}{\cos \theta} = \tan \left(\frac{\pi}{4} - \frac{\theta}{2} \right)$$

$$\frac{d}{d\theta} (\omega-1)^{1/2} = -\frac{1}{2} \sec^2 \left(\frac{\pi}{4} - \frac{\theta}{2} \right)$$

$$\begin{aligned}
-\frac{d}{d\mu_1} [\log \phi(\mathcal{L}\sigma, \omega)] &= -\frac{d}{d\mu_1} [\log (-\log (\omega-1))] \\
&= \frac{\frac{d}{d\mu_1} (-\log (\omega-1))}{-\log (\omega-1)} = \frac{-2 \frac{d}{d\mu_1} (\omega-1)^{1/2}}{-\log (\omega-1) \cdot (\omega-1)^{1/2}} \\
&= \frac{-2 \frac{d}{d\theta} (\omega-1)^{1/2} \frac{d\theta}{d\mu_1}}{-\log (\omega-1) \cdot (\omega-1)^{1/2}} \\
&= \frac{\sec^2 \left(\frac{\pi}{4} - \frac{\theta}{2} \right)}{-\log \tan^2 \left(\frac{\pi}{4} - \frac{\theta}{2} \right) \cdot \tan \left(\frac{\pi}{4} - \frac{\theta}{2} \right)} \frac{d\theta}{d\mu_1}
\end{aligned}$$

$$(10.9) \quad -\frac{d}{d\mu_1} [\log \phi(\mathcal{L}\sigma, \omega)] = \frac{1}{-\log \tan \left(\frac{\pi}{4} - \frac{\theta}{2} \right) \cdot \cos \theta} \frac{d\theta}{d\mu_1}$$

Also

$$(10.9a) \quad -\frac{d}{d\mu_1} \log (1-\mu_1) = \frac{1}{1-\mu_1} \frac{d\mu_1}{d\theta} \frac{d\theta}{d\mu_1} = \cot \frac{\theta}{2} \frac{d\theta}{d\mu_1}$$

The left member of (10.7) equals

$$(10.10) \quad \lim_{\theta \rightarrow 0} \frac{\tan \frac{\theta}{2}}{-\log \tan \left(\frac{\pi}{4} - \frac{\theta}{2} \right) \cdot \cos \theta} = \frac{1}{2}$$

by l'Hospital's rule.

Q. E. D.

Theorem 10.2.

$$(10.11) \quad \lim_{\mu_1 \rightarrow 1} \frac{\phi(\mathcal{L}\sigma, \omega')}{\phi(\mathcal{L}\sigma, \omega)} = \sqrt{\xi}$$

where

$$(1 - \mu_1') = \xi (1 - \mu_1) \quad (0 < \xi \leq 1),$$

and where ω, ω' are determined from (8.19) using μ_1 and μ_1' respectively.

Proof:

$\omega' > \omega$, hence all eigenvalues of $\mathcal{L}\sigma, \omega'$ have absolute value $|\omega' - 1|$,

$$\frac{\phi(\mathcal{L}\sigma, \omega')}{\phi(\mathcal{L}\sigma, \omega)} = \frac{-\log(\omega' - 1)}{-\log(\omega - 1)}$$

Let $\mu_1 = \cos \theta$, $\mu_1' = \cos \theta'$ where $\theta' < \theta$.

$$1 - \cos \theta' = \xi (1 - \cos \theta)$$

$$\sin^2 \frac{\theta'}{2} = \xi \sin^2 \frac{\theta}{2}$$

But as in Theorem 10.1.

$$(10.12) \quad (\omega-1)^{1/2} = \frac{1-\sin \Theta}{\cos \Theta} = \tan \left(\frac{\pi}{4} - \frac{\Theta}{2} \right)$$

$$(10.13) \quad (\omega'-1)^{1/2} = \frac{1-\sin \Theta'}{\cos \Theta'} = \tan \left(\frac{\pi}{4} - \frac{\Theta'}{2} \right)$$

Neglecting terms in Θ and Θ' of degree higher than the first have

$$(10.14) \quad \Theta' = \sqrt{3} \Theta + o(\Theta) \quad , \text{ and}$$

$$-2 \log (\omega-1)^{1/2} = 2 \Theta + o(\Theta)$$

$$-2 \log (\omega'-1)^{1/2} = 2 \Theta' + o(\Theta)$$

where $o(\Theta)$ vanishes with Θ .

Hence the theorem follows.

Q. E. D.

From this it can be seen that even if $(1-\mu_1)$ is underestimated by as much as 50% the rate of convergence will be decreased by less than 30%. Since the gain in the rate of convergence of The Successive Overrelaxation Method is of an order of magnitude μ^{-1} however, such an increase is relatively unimportant.

On the other hand if $\beta > 1$ we have

$$\phi(\mathcal{L}_\sigma, \omega') = -\log \left\{ \frac{\omega' \mu_1}{2} \left(1 + \sqrt{\omega'^2 \mu_1^2 - 4(\omega' - 1)} \right) \right\}$$

where $\omega'^2 \mu_1^2 - 4(\omega' - 1) = 0$ by (8.19).

Therefore

$$\phi(\mathcal{L}_\sigma, \omega') = -\log \left\{ \frac{\omega'}{2} \left[\mu_1 + \sqrt{\mu_1^2 - \mu_1'^2} \right] \right\}$$

If

$$\mu_1 = \cos \theta', \text{ by (10.13)}$$

$$(\omega' - 1)^{1/2} = \frac{1 - \sin \theta'}{\cos \theta'} = \tan \left(\frac{\pi}{4} - \frac{\theta'}{2} \right)$$

$$\omega' = \sec^2 \left(\frac{\pi}{4} - \frac{\theta'}{2} \right)$$

Neglecting terms in θ' higher than the first and setting $\theta' = \sqrt{5} \theta + o(\theta)$ as in (10.14)

$$\phi(\mathcal{L}_\sigma, \omega') = \theta \left[\sqrt{5} - 2\sqrt{5-1} \right] + o(\theta)$$

Since $\phi(\mathcal{L}_\sigma, \omega) = \theta + o(\theta)$

we have

$$(10.15) \quad \left[\frac{\phi(\mathcal{L}_\sigma, \omega')}{\phi(\mathcal{L}_\sigma, \omega)} \right] = \sqrt{5} - 2\sqrt{5-1} + o(\theta).$$

Because of the presence of the term $\sqrt{S-1}$ the derivative of the above ratio with respect to S becomes large as S approaches one. Thus it is always better to underestimate $(1-\mu_1)$ i.e. be sure $S \leq 1$.

As stated in the Introduction the fact that the gain in rate of convergence is not very sensitive to relative changes in $(1-\mu_1)$ (as long as $(1-\mu_1)$ is not overestimated), suggests that not only for the Dirichlet Problem but for other self adjoint equations the relaxation factor can be chosen so that the problems can be solved much more rapidly. For equations of the type (1.11) where $(a_{i,j})$ is not symmetric, however, the eigenvalues of \mathcal{K} are not in general real and the gain in convergence which could be obtained, even with the best relaxation factor, is much less. Nevertheless the relation between the eigenvalues of $\mathcal{K}, L\sigma$ and $L\sigma, \omega$ are valid. The study of the convergence of $L\sigma$ and $L\sigma, \omega$ is therefore simplified.

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