

ON COMPUTATION OF EIGENVALUES FOR DIFFERENTIAL EQUATIONS BY NEWTON'S METHOD

BY

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ABSTRACT. Professor Zeev Nehari, in the last months before his untimely death, had been analyzing and developing a new algorithm for computing eigenvalues of selfadjoint boundary value problems of arbitrary order. Apparently, his main goals were Theorems 3.1 and 3.2 below (which incidentally yield the eigenvalues of the given problem, as well as those of a related problem).

Unfortunately, as far as we know, Professor Nehari has not left a proof of the basic Lemma 3.1 which presumably was to be based on §2 or related results. It seems, however, worthwhile to publish this paper since the results of §§1 and 2 are complete and of independent interest and since the question of the validity of Lemma 3.1 is also of interest. While the presentation in §§1 and 2 is in most respects complete, there are a few places where some minor clarifications by selected footnotes were felt to be desirable. Also, Professor Nehari's original incomplete §3 has been replaced by a revised and abbreviated version.

1. Let L be an n th order selfadjoint linear differential operator of the form $Ly = \sum_{\nu=0}^n q_{\nu}(x)y^{(\nu)}$, $q_n > 0$, where, to avoid irrelevant complications, it is assumed that the q_{ν} are of class $C^{(n)}$ on $[0, 1]$. If $p > 0$ and is continuous on $[0, 1]$, we consider the eigenvalue problem

$$Lu + \lambda pu = 0, \quad B_{\nu}(u) = 0, \quad \nu = 1, \dots, n, \quad (1.1)$$

where the B_{ν} are linearly independent linear selfadjoint homogeneous boundary conditions involving the values of $u, u', \dots, u^{(n-1)}$ at 0 and 1, and it is assumed that the B_{ν} do not depend on λ . For these boundary conditions we shall also use the abbreviated notation $B(u) = 0$. We note that it would be sufficient to treat the case $p \equiv 1$, but applied problems are usually of the form (1.1) with $p \neq 1$, and a preliminary transformation changing p into 1 can introduce considerable formal complications.

We shall further assume that the problem (1.1) is positive-definite, i.e., that, for any $u \in C^n$ which satisfies the boundary conditions $B(u) = 0$, we have

$$-\int_0^1 uLu \, dx > 0. \quad (1.2)$$

Under these assumptions, we shall derive an effective algorithm, based on Newton's method, for the computation of the eigenvalues $\lambda_1, \lambda_2, \dots$ (and the corresponding eigenfunctions) of (1.1).

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Many of our considerations do not depend on the positive-definiteness of the problem, and we therefore begin with those aspects of our problem which can be treated without the assumption (1.2).

If $u, v \in C^n[0, 1]$ we have, by Lagrange's identity and the selfadjointness of L ,

$$\int_0^1 (vLu - uLv) dx = P(u, v) \quad (1.3)$$

where $P(u, v)$ is a bilinear form in the variables $u(0), u'(0), \dots, u^{(n-1)}(0), u(1), \dots, u^{(n-1)}(1)$ and $v(0), \dots, v^{(n-1)}(0), v(1), \dots, v^{(n-1)}(1)$. Using the linear independence of the linear forms B_ν , $\nu = 1, \dots, n$, and the selfadjointness it is not difficult to show (see [1, Chapter 11, §3]) that (1.3) may be replaced by

$$\int_0^1 (vLu - uLv) dx = \sum_{\nu=1}^n [B_\nu(v)C_\nu(u) - B_\nu(u)C_\nu(v)] \quad (1.4)$$

where the $C_\nu(u)$ are linear forms in the variables $u(0), u'(0), \dots, u^{(n-1)}(1)$. It may be noted that the C_ν are not uniquely determined by the identity (1.4); clearly, the right-hand side of (1.4) will remain unchanged if C_ν is replaced by $C_\nu + \sum_{\mu=1}^n \alpha_{\nu\mu} B_\mu$, where $\alpha_{\nu\mu} = \alpha_{\mu\nu}$ and the $\alpha_{\nu\mu}$ are otherwise arbitrary. It is not difficult to show that this is the only arbitrariness in the choice of the C_ν . However, since we are not going to make use of this fact, we omit the proof.

We shall describe the relationship between the linear form B_ν and the corresponding form C_ν by saying that C_ν is "associated" with B_ν . Similarly, the boundary condition $C_\nu = 0$ will be said to be associated with the boundary condition $B_\nu = 0$. We note here that the relation between B_ν and C_ν is symmetric except for a sign change: If C_ν is associated with B_ν , then $-B_\nu$ is associated with C_ν . This is an immediate consequence of the fact that the right-hand side of (1.4) remains unchanged under the substitution

$$B_\nu \rightarrow C_\nu, \quad C_\nu \rightarrow -B_\nu.$$

Note that given (1.4), it follows that $B = 0$ is a set of selfadjoint boundary conditions for the operator L . Indeed, if $B_\nu(u) = B_\nu(v) = 0$, $\nu = 1, \dots, n$, we have

$$\int_0^1 vLu dx = \int_0^1 uLv dx \quad (1.5)$$

and the assertion follows. Since, as just pointed out, the substitution $B_\nu \rightarrow C_\nu$, $C_\nu \rightarrow -B_\nu$ does not affect the right-hand side of (1.4), the relation (1.5) will remain valid if B_ν is replaced by C_ν for one or more subscripts ν . We can thus obtain additional sets of selfadjoint boundary conditions for the equation $Lu + \lambda pu = 0$. For instance, if this substitution is carried out only for one subscript, say $\nu = n$, we obtain the selfadjoint boundary value problem

$$Lu + \lambda u = 0, \quad B_\nu(u) = 0, \quad \nu = 1, \dots, n-1, \quad C_n(u) = 0. \quad (1.6)$$

These boundary conditions—which we shall denote by the symbol $B^*(u) = 0$ —and the corresponding solutions of the problem (1.6) depend, of course, on the numbering of the original boundary conditions. There are thus n different boundary conditions $B^*(u) = 0$ of this type, all of which are equally suitable for our purposes (although some may be preferable from the point of view of computational convenience).

The proof of our main result will be greatly facilitated by the assumption that the problem

$$Lu + \lambda pu = 0, \quad B_\nu(u) = 0, \quad \nu = 1, \dots, n-1, \quad (1.7)$$

(for given real λ) has a solution which is unique except for a multiplicative constant. (Later, it will be shown that it is sufficient to establish our result under this assumption.)¹ Because of this uniqueness property, the solution of (1.7) can be expressed in an elementary fashion in terms of the solution of the initial value problem (at $x = 0$) for $Lu + \lambda pu = 0$ and some algebraic manipulation. To determine the constant factor, which so far has remained arbitrary, we normalize this solution u by the condition

$$\int_0^1 pu^2 dx = 1 \quad (1.8)$$

and by some sign condition such as the requirement that $u > 0$ in a small right neighborhood of 0.

If λ happens to be an eigenvalue of problem (1.1), we will clearly have $B_\nu(u) = 0$. Conversely, the equation $B_\nu(u) = 0$ implies that λ is an eigenvalue. To emphasize the dependence of $B_\nu(u)$ on the value λ for which the problem (1.7) has been solved (with the normalization (1.8)), we shall set

$$B_\nu(u) = \zeta(\lambda). \quad (1.9)$$

In this terminology, the problem of finding all the eigenvalues of (1.1) is identical with the problem of finding all the solutions of the equation $\zeta(\lambda) = 0$.

Analogously, the eigenvalues λ of problem (1.6) are characterized by the condition $C_\nu(u) = 0$, where u is the corresponding solution of (1.7). If the latter is normalized by (1.8), we set

$$C_\nu(u) = \eta(\lambda). \quad (1.10)$$

Clearly, the zeros of the function $\eta(\lambda)$ coincide with the eigenvalues of problem (1.6). We note here that, as mentioned earlier, the linear form C_ν is not uniquely determined by the forms B_ν . Hence, $\eta(\lambda)$ is not a uniquely determined function either. However, it will soon become apparent that all possible functions η are of the form $A\eta_0 + B\zeta$, where η_0 is one of them and A, B are constants.

Finally, we introduce the function

$$\varphi(\lambda) = \zeta(\lambda)/\eta(\lambda). \quad (1.11)$$

Since, as will be shown presently, no zero of $\zeta(\lambda)$ can coincide with a zero of $\eta(\lambda)$, the zeros of $\varphi(\lambda)$ are the same as the zeros of $\zeta(\lambda)$. Thus, in view of the remark made above concerning the zeros of $\zeta(\lambda)$, the set of eigenvalues of problem (1.1) coincides with the set of zeros of the function $\varphi(\lambda)$. We shall attempt to find these zeros—and thus solve our eigenvalue problem—by applying Newton's method to the equation $\varphi(\lambda) = 0$. However, before we do so, a number of preparations are necessary.

¹This argument was not given in the draft. Note that this assumption is *always* valid for λ not an eigenvalue.

We first remark that, by a standard argument, the solution u of any initial value problem of $Lu + \lambda pu \equiv 0$ is an analytic function of λ for all finite λ . Since, as pointed out before, the conditions $B_\nu(u) = 0$, $\nu = 1, \dots, n-1$, in conjunction with one normalization condition are equivalent to a set of initial conditions, it follows that $B_n(u)$ and $C_n(u)$ —i.e., by (1.9) and (1.10) $\zeta(\lambda)$ and $\eta(\lambda)$ —are analytic functions of λ , provided no extra singularities are introduced by the normalization. This, however, is not the case, at least for real values of λ , since we use the normalization (1.8), and the left-hand side of (1.8) cannot be zero if λ and u are real. We therefore conclude that $\zeta(\lambda)$ and $\eta(\lambda)$ —and also u if regarded as a function of λ for fixed x —are analytic functions of λ if λ is on the real axis.

Consider now the solution u of

$$Lu + \lambda pu = 0, \quad (1.12)$$

subject to the boundary conditions $B_\nu(u) = 0$, $\nu = 1, \dots, n-1$, and the normalization (1.8). This solution is unique and, as just seen, analytic in λ . It is thus permissible to differentiate (1.12) with respect to λ . Setting

$$v = \partial u / \partial \lambda, \quad (1.13)$$

we find that v is a solution of the differential equation

$$Lv + \lambda pv + pu = 0. \quad (1.14)$$

Since, regardless of the value of λ , $B_\nu(u) = 0$, $\nu = 1, \dots, n-1$, we also have $B_\nu(v) = 0$, $\nu = 1, \dots, n-1$. Hence, by (1.4),

$$\int_0^1 (vLu - uLv) dx = B_n(v)C_n(u) - B_n(u)C_n(v).$$

By (1.9), (1.10) and (1.13), the right-hand side is equivalent to $\zeta'(\lambda)\eta(\lambda) - \zeta(\lambda)\eta'(\lambda)$. Since, by (1.12), (1.14) and (1.8), the left-hand side is equal to 1, we obtain the relation

$$\zeta'(\lambda)\eta(\lambda) - \eta'(\lambda)\zeta(\lambda) = 1. \quad (1.15)$$

Since both $\zeta(\lambda)$ and $\eta(\lambda)$ are analytic for real λ this proves, incidentally, our earlier assertion that ζ and η cannot have common real zeros.

Differentiating this with respect to λ , we have $\zeta''\eta - \eta''\zeta = 0$, i.e., $\zeta''/\zeta = \eta''/\eta$. If we denote this common value by $-q(\lambda)$, we thus have

$$\zeta''(\lambda) + q(\lambda)\zeta(\lambda) = 0, \quad \eta''(\lambda) + q(\lambda)\eta(\lambda) = 0. \quad (1.16)$$

Both $\zeta(\lambda)$ and $\eta(\lambda)$ are thus found to be solutions of the same linear second-order differential equation. This, incidentally, proves the assertion made earlier that all possible functions $\eta(\lambda)$ associated with a given $\zeta(\lambda)$ are of the form $\eta(\lambda) = A\eta_0(\lambda) + B\zeta(\lambda)$, where $\eta_0(\lambda)$ is one of them and A, B are constants.

We now prove that the coefficient $q(\lambda)$ of equation (1.16) must be positive, a fact which will later be found of crucial importance. Differentiating (1.14) with respect to λ and setting

$$\partial v / \partial \lambda = w \quad (1.17)$$

we find that w satisfies the equation

$$Lw + \lambda pw + 2pv = 0 \quad (1.18)$$

and, of course, the boundary conditions $B_\nu(w) = 0$, $\nu = 1, \dots, n-1$. Thus, by (1.4), (1.14) and (1.18),

$$B_n(w)C_n(v) - B_n(v)C_n(w) = -\int_0^1 p u w \, dx + 2 \int_0^1 p v^2 \, dx.$$

By (1.9), (1.10), (1.13) and (1.17), the left-hand side is equal to $\zeta''(\lambda)\eta'(\lambda) - \eta''(\lambda)\zeta'(\lambda)$. Since, by twice differentiating (1.8) and observing (1.13) and (1.17), we obtain

$$0 = 2 \int_0^1 p u w \, dx + 2 \int_0^1 p v^2 \, dx,$$

we thus arrive at the identity

$$\zeta''(\lambda)\eta'(\lambda) - \eta''(\lambda)\zeta'(\lambda) = 3 \int_0^1 p v^2 \, dx.$$

By (1.16) and (1.15),

$$\zeta''(\lambda)\eta'(\lambda) - \eta''(\lambda)\zeta'(\lambda) = q(\lambda)[\zeta'(\lambda)\eta(\lambda) - \eta'(\lambda)\zeta(\lambda)] = q(\lambda),$$

and our identity simplifies to

$$q(\lambda) = 3 \int_0^1 p v^2 \, dx. \quad (1.19)$$

The coefficient $q(\lambda)$ in the differential equation (1.16) is thus indeed found to be positive, as asserted.

We are now ready to begin our attempt to solve the equation $\varphi(\lambda) = 0$ (where φ is the function in (1.11)) by means of Newton's method. If λ is a tentative value for a zero of $\varphi(\lambda)$, we replace it by a modified value λ_1 defined by

$$\lambda_1 = \lambda - \varphi(\lambda)/\varphi'(\lambda). \quad (1.20)$$

Iterating this procedure, we obtain a sequence $\lambda, \lambda_1, \lambda_2, \dots$ which will rapidly converge to a zero $\bar{\lambda}$ of $\varphi(\lambda) = 0$ if the initial guess λ was "close enough" to $\bar{\lambda}$. This last remark is of course of no practical value, since we do not know even approximately where the zeros of $\varphi(\lambda)$ are located. We shall, however, see that considerable information concerning the behavior of such sequences $\lambda, \lambda_1, \lambda_2, \dots$ can be extracted from the definition (1.20) of the basic step, without having any prior information regarding the location of the zeros.

The definition (1.20) of λ_1 , can be cast into a simpler and more suggestive form. Since, by (1.11) and (1.15),

$$\varphi'(\lambda) = 1/\eta^2(\lambda), \quad (1.21)$$

it follows, by another use of (1.11), that (1.20) is equivalent to

$$\lambda_1 = \lambda - \zeta(\lambda)\eta(\lambda). \quad (1.22)$$

We note that, by (1.21), $\varphi(\lambda)$ is increasing from $-\infty$ to $+\infty$ if λ increases from one zero of $\eta(\lambda)$ to the adjacent zero on the right. Thus, between two adjacent zeros of $\eta(\lambda)$ there will be precisely one zero of $\varphi(\lambda)$ (or, equivalently of $\zeta(\lambda)$). This, of course, also follows from the Sturm separation theorem if it is observed that both $\zeta(\lambda)$ and $\eta(\lambda)$ are solutions of the equation (1.16).

To get a more accurate idea of the behavior of $\varphi(\lambda)$ between two adjacent zeros of $\eta(\lambda)$, we compute the Schwarzian derivative

$$\{\varphi, \lambda\} = \left(\frac{\varphi''}{\varphi'}\right)' - \frac{1}{2}\left(\frac{\varphi''}{\varphi'}\right)^2 = \frac{\varphi'''}{\varphi'} - \frac{3}{2}\left(\frac{\varphi''}{\varphi'}\right)^2. \quad (1.23)$$

Since, by (1.21), $\varphi''/\varphi' = -2\eta'/\eta$ we easily obtain

$$\{\varphi, \lambda\} = -2\eta''/\eta = 2q(\lambda) \quad (1.23')$$

(the last equality following from (1.16)). As shown before (cf. (1.19)), $q(\lambda) > 0$. Hence, $\{\varphi, \lambda\} > 0$, and we can conclude from (1.23) and (1.21) that $\varphi''' > 0$ i.e., $\varphi''(\lambda)$ is increasing in an interval I between two adjacent zeros of $\eta(\lambda)$. Since, by (1.15), η and η' cannot be zero simultaneously, it follows from $\varphi'' = -2\eta'/\eta^3$ that φ'' increases from $-\infty$ to $+\infty$ in this interval. As a result, the interval I contains a point λ_0 such that $\varphi''(\lambda_0) = 0$, $\varphi''(\lambda) > 0$, for $\lambda > \lambda_0$, $\lambda \in I$, and $\varphi''(\lambda) < 0$ for $\lambda < \lambda_0$, $\lambda \in I$.

We saw earlier that the function $\varphi(\lambda)$ is likewise increasing from $-\infty$ to $+\infty$ as λ traverses the interval I and that, as a result, there exists a unique point in I , say α , such that $\varphi(\alpha) = 0$. Our aim is to find the point α . It would therefore be very satisfactory if we could show that a Newton algorithm based on the iteration of the step (1.22) and starting with a value $\lambda \in I$ will invariably converge to α . While this does not seem to be true, the following, less general result is easily established.

THEOREM A. *Let I be the open interval between two consecutive zeros of $\eta(\lambda)$, and denote by α the unique zero of $\zeta(\lambda)$ in I . Then one of the two open intervals—say I_0 —into which I is divided by α has the following property. If λ_1 is any point of I_0 , and $\lambda_2, \lambda_3, \dots$ are defined by the iteration*

$$\lambda_{k+1} = \lambda_k - \zeta(\lambda_k)\eta(\lambda_k), \quad (1.24)$$

then λ_k converges monotonically (and quadratically) to α .

Before we prove this, we point out that, by (1.8), (1.9), and (1.10), (1.24) is equivalent to

$$\lambda_{k+1} = \lambda_k - \frac{B_n(u_k)C_n(u_k)}{\int_0^1 p u_k^2 dx}, \quad (1.25)$$

where u_k is a solution of $Lu_k + \lambda_k p u_k = 0$ which satisfies the boundary conditions $B_\nu(u_k) = 0$, $\nu = 1, \dots, n-1$.

The interval I_0 in which the iteration (1.24) converges can be characterized in terms of the point $\lambda_0 \in I$ at which $\varphi''(\lambda_0) = 0$: I_0 is the subinterval of I bounded by α , which does *not* contain λ_0 as an interior point. To prove that I_0 indeed has the property stated above, suppose first that $\lambda_0 \leq \alpha$ and that, as a result, I_0 is at the right of α . By the definition of λ_0 and α we then have $\varphi(\lambda) > 0$ and $\varphi''(\lambda) > 0$ if $\lambda \in I_0$. Hence, if $\lambda_1 \in I_0$ and λ_2 is defined by

$$\lambda_2 = \lambda_1 - \varphi(\lambda_1)/\varphi'(\lambda_1) = \lambda_1 - \zeta(\lambda_1)\eta(\lambda_1), \quad (1.26)$$

we have

$$\varphi(\lambda_2) \geq \varphi(\lambda_1) + \varphi'(\lambda_1)(\lambda_2 - \lambda_1) = \varphi'(\lambda_1)[\lambda_2 - \lambda_1 + \varphi(\lambda_1)/\varphi'(\lambda_1)]$$

i.e., by (1.26), $\varphi(\lambda_2) \geq 0$, and this implies $\lambda_2 \geq \alpha$. On the other hand, since $\varphi(\lambda_1) > 0$ and (by (1.21)), $\varphi'(\lambda_1) > 0$, (1.26) shows that $\lambda_2 \leq \lambda_1$. Thus, $\lambda_1 \in I_0$ implies $\lambda_2 \in I_0$, and λ_2 is closer to α than λ_1 . Hence, the indefinite iteration of the step (1.26) will converge to a point $\geq \alpha$. It is obvious from (1.26) that this point must be a zero of either $\zeta(\lambda)$ or $\eta(\lambda)$. Since $\eta(\lambda) \neq 0$ in I and the only zero of $\zeta(\lambda)$ in I is α , it follows that the iteration converges to α , as asserted. If $\lambda_0 < \alpha$, the result follows by a trivial modification of the same argument.

We were led to Theorem A in an attempt to solve the eigenvalue problem (1.1) by applying Newton's method to the equation $\varphi(\lambda) = 0$, where

$$\varphi(\lambda) = \frac{\zeta(\lambda)}{\eta(\lambda)} = \frac{B_n(u)}{C_n(u)}$$

(cf. (1.9), (1.10), (1.11)). The same procedure may be applied to the eigenvalue problem (1.6), which is obtained from (1.1) if the boundary condition $B_n = 0$ is replaced by $C_n = 0$. Since, as shown before, the linear form "associated with" C_n is $-B_n$ (if C_n was associated with B_n) the only change necessary to adapt our analysis to the present case is the substitution of $\eta(\lambda)$ for $\zeta(\lambda)$, and of $-\zeta(\lambda)$ for $\eta(\lambda)$. In accordance with (1.11), the function $\varphi(\lambda)$ will then be replaced by

$$\psi(\lambda) = -\frac{\eta(\lambda)}{\zeta(\lambda)} = -\frac{1}{\varphi(\lambda)}, \quad (1.27)$$

and, by (1.15), its derivative is found to be

$$\psi'(\lambda) = \frac{1}{\zeta^2(\lambda)}. \quad (1.28)$$

Thus $\psi(\lambda)$ is increasing from $-\infty$ to $+\infty$ if λ traverses an interval K between two consecutive zeros of $\zeta(\lambda)$ and ψ is found to have precisely one zero, say β , in K . Since, as noted before, $\zeta(\lambda)$ and $\eta(\lambda)$ have no zeros in common, this is also the only zero of $\eta(\lambda)$ in K .

The Schwarzian derivative (1.23) remains unchanged if $\varphi(\lambda)$ is replaced by $-1/\varphi(\lambda)$. Thus, by (1.23') and (1.16), $\{\psi, \lambda\} = 2q(\lambda) > 0$, and we have (cf. (1.23))

$$\frac{\psi'''}{\psi'} - \frac{3}{2} \left(\frac{\psi''}{\psi'} \right)^2 > 0.$$

Hence, by (1.28), $\psi''' > 0$ and—as in the case of the function φ —we conclude from this that ψ'' grows from $-\infty$ to $+\infty$ as λ traverses the interval K . A comparison with the proof of Theorem A shows that the properties of ψ are identical with the properties of φ used in proving Theorem A. If we note that, by (1.27) and (1.28),

$$\lambda - \frac{\psi(\lambda)}{\psi'(\lambda)} = \lambda + \zeta(\lambda)\eta(\lambda),$$

we have established the following companion result to Theorem A.

THEOREM B. Let K be the open interval between two consecutive zeros of $\zeta(\lambda)$, and denote by β the unique zero of $\eta(\lambda)$ in K . Then one of the two open intervals—say K_0 —into which K is divided by β has the following property: If λ_1 is any point of K_0 , and $\lambda_2, \lambda_3, \dots$ are defined by the iteration

$$\lambda_{k+1} = \lambda_k + \zeta(\lambda_k)\eta(\lambda_k), \quad (1.29)$$

then λ_n converges monotonically (and quadratically) to β .

2. As mentioned earlier, Lagrange's identity can be written in the form

$$\int_0^1 (vLu - uLv) dx = \sum_{\nu=1}^n [B_\nu(v)C_n(u) - B_\nu(u)C_n(v)].$$

If the functions u and v satisfy the $n-1$ boundary conditions $B_1 = \dots = B_{n-1} = 0$ —or, as we shall occasionally say, $u, v \in B_{(n-1)}$ —this reduces to

$$\int_0^1 (vLu - uLv) dx = B_n(v)C_n(u) - B_n(u)C_n(v), \quad (2.1)$$

or

$$\mathcal{J}(u, v) = \mathcal{J}(v, u) \quad (2.1')$$

where

$$\mathcal{J}(u, v) = B_n(u)C_n(v) - \int_0^1 uLv dx. \quad (2.2)$$

As follows from (2.2), the symmetric bilinear form $\mathcal{J}(u, v)$ can be written—after some preliminary integrations by parts—as an integral of a bilinear form in $u, u', \dots, u^{(n/2)}, v, v', \dots, v^{(n/2)}$, and, possibly, a number of boundary terms (in many of the classical problems these boundary terms are absent).

From now on, we shall restrict our considerations to operators L and boundary conditions B_ν for which the quadratic form $\mathcal{J}(u, u)$ is positive-definite for $u \in B_{(n-1)}$. We thus assume

ASSUMPTION A_3 .

$$\mathcal{J}(u, u) \equiv B_n(u)C_n(u) - \int_0^1 uLu dx > 0 \quad (2.3)$$

if u satisfies the boundary conditions $B_1(u) = \dots = B_{n-1}(u) = 0$ and does not vanish identically.

(EXAMPLES.² If $Lu \equiv u''$, $B_1(u) = u(0)$, then $\mathcal{J}(u, u) = \int_0^1 (u')^2 dx$. If $Lu \equiv -u^{iv}$, $B_1(u) = u(0)$, $B_2(u) = u'(0)$, $B_3(u) = u(1)$ then $\mathcal{J}(u, u) = \int_0^1 (u'')^2 dx$.)

Our final restriction on L —and this is a very mild one—is the following:³ We

²In the first example, the expression $\mathcal{J}(u, u)$ will be as given if one selects, say, $B_2(u) = u(1)$ and, correspondingly, $C_2(u) = u'(1)$.

In the second example, one may take $B_4(u) = u'(1)$, $C_4(u) = u''(1) + \beta u(1)$, to obtain the given formula for $\mathcal{J}(u, u)$.

³Under the *present* hypotheses on the coefficients of L , this appears to follow from Assumption A_3 and the hypothesis described in (1.7).

assume that, within the class of functions u satisfying $B_\nu(u) = 0$, $\nu = 1, \dots, n-1$, $C_n(u) + \mu B_n(u) = 0$ ($\mu > 0$ is fixed but arbitrary), the equation $Lu = w$ (w continuous) has a unique inverse $u = Gw$, where G is a compact operator. (Equivalently, this property may be expressed in terms of the existence of a Green's function of $Lu = 0$ with the above boundary conditions.)

Under all these assumptions we can prove the following result:

Let $u \in C^n[0, 1]$, and let u be subject to the boundary conditions $B_\nu(u) = 0$, $\nu = 1, \dots, n-1$. Then

$$\min_u [\mathcal{J}(u, u) + \mu B_n^2(u)] = \mathcal{J}(w, w) + \mu B_n^2(w) = \lambda, \quad (2.4)$$

where $\mu > 0$ and w is a solution of the differential equation

$$Lw + \lambda pw = 0 \quad (2.5)$$

which satisfies, in addition to the boundary conditions imposed on u , the condition $C_n(w) + \mu B_n(w) = 0$ and λ is the smallest eigenvalue of (2.5) associated with these boundary conditions.

We shall further show that the higher eigenvalues of (2.5) for these boundary conditions can be defined by the classical max-min characterization associated with the minimum problem (2.4).

Suppose now that u is a function subject to the boundary conditions $B_\nu(u) = 0$, $\nu = 1, \dots, n-1$, and the normalization

$$\int_0^1 pu^2 dx = 1. \quad (2.6)$$

We define a function w for which

$$Lw = -\lambda pu \quad (2.7)$$

and for which $B_\nu(w) = 0$, $\nu = 1, \dots, n-1$, $C_n(w) + \mu B_n(w) = 0$. By our assumptions, there exists such a function w for any λ . We determine λ , and thus determine the function w completely, by the normalization

$$\int_0^1 pw^2 dx = 1. \quad (2.8)$$

From (2.7), we have

$$-\int_0^1 wLw dx = \lambda \int_0^1 puw dx,$$

and thus, by (2.6), (2.8) and (2.3),

$$\mathcal{J}(w) - B_n(w)C_n(w) \leq \lambda \quad (\mathcal{J}(w) = \mathcal{J}(w, w)). \quad (2.9)$$

Again by (2.7) and (2.6),

$$-\int_0^1 uLw dx = \lambda$$

and therefore, by (2.2),

$$\lambda = \mathcal{J}(u, w) - B_n(u)C_n(w).$$

Since the quadratic form $\mathcal{J}(u) \equiv \mathcal{J}(u, u)$ is positive-definite we have

$$\mathcal{J}^2(u, w) \leq \mathcal{J}(u)\mathcal{J}(w),$$

and it follows from the last identity that, for arbitrary positive μ ,

$$\lambda \leq \sqrt{\mathcal{J}(u) + \mu B_n^2(u)} \sqrt{\mathcal{J}(w) + \frac{1}{\mu} C_n^2(w)}. \quad (2.10)$$

The function w is subject to the condition $C_n(w) + \mu B_n(w) = 0$. If we use this number μ in (2.10), we have

$$\mathcal{J}(w) + \frac{1}{\mu} C_n^2(w) = \mathcal{J}(w) - B_n(w)C_n(w) \leq \lambda$$

(the last inequality following from (2.9)), and (2.10) is seen to imply the right half of the inequality

$$\mathcal{J}(w) + \mu B_n^2(w) \leq \lambda \leq \mathcal{J}(u) + \mu B_n^2(u). \quad (2.11)$$

The left half of this inequality follows from (2.9) and the fact that $C_n(w) + \mu B_n(w) = 0$.

Our statement is now a direct consequence of the inequalities (2.11). If $\{u_k\}$ is a sequence of admissible functions for which

$$\lim_{k \rightarrow \infty} \mathcal{J}(u_k) + \mu B_n^2(u_k) = \lambda_0 = \inf[\mathcal{J}(u) + \mu B_n^2(u)], \quad (2.12)$$

then, by (2.11), the sequence of functions w_k determined from the u_k by means of (2.7) and the prescribed boundary conditions also has the minimum property expressed by (2.12). By Assumption A_3 , the w_k belong to a compact set S , and it is easy to see that there exists a subsequence of the sequence w_k which converges to a function $w_0 \in S$ for which

$$\mathcal{J}(w_0) + \mu B_n^2(w_0) = \lambda_0. \quad (2.13)$$

Identifying w_0 with the function u in (2.7) and defining a new function w by (2.7), we find that the minimum property (2.13) of w_0 will be contradicted unless w and w_0 are proportional. From this it follows immediately that w_0 must be a solution of (2.5), and that the eigenvalue λ appearing in (2.5) has the meaning expressed in (2.4).

To establish the statement concerning the max-min characterization of the higher eigenvalues, it is sufficient to show that the minimum problem (2.4) will yield the k th eigenvalue, say λ_k , of the differential equation (2.5) if u is restricted by the conditions

$$\int_0^1 p u w_\nu dx = 0, \quad \nu = 1, \dots, k-1, \quad (2.14)$$

where w_ν is the ν th eigenfunction of (2.5). This, in turn, will follow by a simple argument if we can show that the transformation $u \mapsto w$ given by (2.7) and the appropriate boundary conditions does not affect the orthogonality conditions (2.14). To do so, we note that, by (2.7) and (2.14),

$$\int_0^1 w_\nu L w dx = 0.$$

Hence, by (2.1),

$$\int_0^1 w L w_\nu dx = B_n(w) C_n(w_\nu) - C_n(w) B_n(w_\nu).$$

Because of $C_n(w) + \mu B_n(w) = 0$ and $C_n(w_\nu) + \mu B_n(w_\nu) = 0$, this reduces to

$$\int_0^1 w L w_\nu dx = 0.$$

Finally, since w_ν satisfies the equation (2.5) (with $\lambda = \lambda_\nu$), we obtain

$$\int_0^1 p w w_\nu dx = 0, \quad \nu = 1, \dots, k-1.$$

Thus, w is found to be subject to the same orthogonality relations as u . The rest of the argument establishing our assertion is elementary.

3. [This is a completely revised and abbreviated version of Professor Nehari's original §3.]

The assertion in Theorem B has an interesting extension when the following lemma is valid.

LEMMA 3.1. *Let α_m, α_{m+1} be two consecutive zeros of $\zeta(\lambda)$ ($\alpha_m < \alpha_{m+1}$) and let β_{m+1} be the unique zero of $\eta(\lambda)$ in (α_m, α_{m+1}) . If $\lambda_0 \in (\beta_{m+1}, \alpha_{m+1})$, then*

$$\lambda_0 + \zeta(\lambda_0)\eta(\lambda_0) > \alpha_m. \quad (3.1)$$

For notation see (1.9) and (1.10) and recall that Assumption A_3 is in effect (see (2.3)).

It is not difficult to see that if Lemma 3.1 holds then Theorem B implies

THEOREM 3.1. *Let λ_1 be a positive number larger than the smallest zero of $\eta(t)$. If $\zeta(\lambda_1)\eta(\lambda_1) < 0$, then the iteration*

$$\lambda_{k+1} = \lambda_k + \zeta(\lambda_k)\eta(\lambda_k), \quad k = 1, 2, \dots, \quad (3.2)$$

converges (quadratically) to the largest zero of $\eta(t)$ at the left of λ_1 .

Relative to Theorem A the analogous assertion would be

LEMMA 3.1*. *If $\lambda_0 \in (\alpha_m, \beta_{m+1})$ ($m > 1$) then*

$$\lambda_0 - \zeta(\lambda_0)\eta(\lambda_0) > \beta_m.$$

If this is valid then Theorem A implies the following

THEOREM 3.2. *Let λ_1 be a positive number larger than the smallest zero of $\zeta(t)$. If $\zeta(\lambda_1)\eta(\lambda_1) > 0$, then the iteration*

$$\lambda_{k+1} = \lambda_k - \zeta(\lambda_k)\eta(\lambda_k), \quad k = 1, 2, \dots, \quad (3.3)$$

converges (quadratically) to the largest zero of $\zeta(t)$ at the left of λ_1 .

Thus, these algorithms always converge to the nearest zero of $\zeta(\lambda)$ or $\eta(\lambda)$, respectively, at the left of the starting value. Since the zeros of $\zeta(\lambda)$ and $\eta(\lambda)$ alternate, it is possible to combine these procedures into one algorithm which gives, in descending order, all the zeros of $\zeta(\lambda)$ and $\eta(\lambda)$ which are smaller than the starting value λ_1 . If, say, the algorithm (3.1) converges to a zero α of $\zeta(\lambda)$, we start the algorithm (3.2) with a value $\alpha - \epsilon$, where ϵ is a small positive number (replacing $\alpha - \epsilon$ by $\alpha - \epsilon/2$ if it should be found that $\zeta(\alpha - \epsilon)\eta(\alpha - \epsilon) > 0$). A similar step is taken at a zero β of $\eta(\lambda)$ to which the iteration (3.2) converges. This

method may, of course, miss some eigenvalues whenever a zero of $\zeta(\lambda)$ is very close to a zero of $\eta(\lambda)$ or, equivalently, if ε is not taken small enough.

Geometrically speaking, the relation (3.1) refers to the amount by which the Newtonian iterate calculated at λ_1 for the nearby zero β_{m+1} of $\psi(\lambda)$ can overshoot this zero. Of course no overshooting at all is possible when the inflection point of the curve $\psi(\lambda)$ lies in the subinterval (α_m, β_{m+1}) since in that case ψ is convex throughout $(\beta_{m+1}, \alpha_{m+1})$. This is the context of Theorem B.

In seeking how to prove Lemma 3.1 it may be worth noting the following variational description of relation (3.1). First of all, a minimax comparison permits one to deduce that under the present hypotheses the family of quadratic forms $\{\mathcal{J}^\mu\}_{\mu \geq 0}$ defined on the subspace $B_{(n-1)}$ (notation introduced in §2) by

$$\mathcal{J}^\mu(u) = \mu B_n^2(u) + B_n(u)C_u(u) - \int uLu \, dx, \quad u \in B_{(n-1)},$$

all possess eigenvalues which interweave one another. (Note that $\mathcal{J}^0 = \mathcal{J}$.) That is, denoting eigenvalues of \mathcal{J}^μ by λ_i^μ , $i \geq 1$, we have in addition to the obvious relation

$$0 < \mu_1 < \mu_2 \Rightarrow \lambda_i^0 \leq \lambda_i^{\mu_1} \leq \lambda_i^{\mu_2}, \quad i = 1, 2, \dots, \quad (1)$$

the further relation

$$\lambda_i^\mu < \lambda_{i+1}^0, \quad 0 \leq \mu. \quad (2)$$

Thus by reference to (2.4) and (2.5) we see that the eigenvalues of the selfadjoint operator L relative to the sets of boundary conditions

$$C_n(u) + \mu B_n(u), \quad \mu \geq 0, \quad B_k(u) = 0, \quad 1 \leq k \leq n-1, \quad (3)$$

fill out disjoint intervals on the positive real axis. In fact, if we use λ_j^∞ to refer to the eigenvalues associated with what is formally obtained from (3) when $\mu = \infty$:

$$B_n(u) = 0, \quad B_k(u) = 0, \quad 1 \leq k \leq n-1, \quad (3')$$

then it follows that the nonoverlapping intervals of the positive λ axis denoted by

$$I_j = [\lambda_j^0, \lambda_j^\infty], \quad j = 1, 2, \dots,$$

consist entirely of eigenvalues of the forms $\{\mathcal{J}^\mu\}_{0 \leq \mu < \infty}$. (Similarly, the gaps between the intervals I_j are intervals consisting of eigenvalues of the quadratic forms $\{\mathcal{J}^\mu\}_{\mu < 0}$.)

Utilizing this information we see that the point λ_1 occurring in Lemma 3.1 can be described as the eigenvalue λ_{m+1}^μ for some $\mu > 0$ and is thus associated with a normalized eigenfunction u_{m+1}^μ of the quadratic form \mathcal{J}^μ [and hence of the operator L]. In this description the iteration (3.1) can be expressed by noting that

$$\lambda_0 + \zeta(\lambda_0)\eta(\lambda_0) = - \int u_{m+1}^\mu L u_{m+1}^\mu \, dx + B_n(u_{m+1}^\mu)C_n(u_{m+1}^\mu) = \mathcal{J}(u_{m+1}^\mu).$$

Thus we have the alternate "variational" formulation

$$\mathcal{J}^0(u_{m+1}^\mu) > \alpha_m = \mathcal{J}^0(u_m^\infty). \quad (3.1')$$

A point that was contributed by the referee is the observation that the variational Assumption A_3 is crucial to the possible validity of Lemma 3.1. Otherwise as he indicated one could simply select η as *any* solution of $\zeta'' + q\zeta = 0$ subject to the

condition

$$\zeta' \eta - \zeta \eta' = 1$$

and arrange for its zero $\beta \in (\alpha_m, \alpha_{m+1})$ to be located so close to α_m that $\zeta(\lambda_0)\eta(\lambda_0) = -\zeta^2(\lambda_0) \int_{\beta}^{\lambda_0} d\lambda / \zeta^2(\lambda)$ would be a very large negative number.

Finally, we note that under the transition $B_n \rightarrow C_n$, $C_n \rightarrow -B_n$ the form $\mathcal{J}(u, v)$ is replaced by

$$\mathcal{J}_*(u, v) = -B_n(v)C_n(u) - \int_0^1 uLv \, dx,$$

which is also selfadjoint on $B_{(n-1)}$. Setting

$$\mathcal{J}_*^\mu = C_n^2(u)/\mu + \mathcal{J}_*(u), \quad \mu > 0,$$

one finds that eigenfunctions of \mathcal{J}_*^μ are eigenfunctions of L which satisfy the (previously omitted) boundary conditions

$$C_n(u) - \mu B_n(u) = 0, \quad \mu > 0.$$

It should be noted that the quadratic form

$$\mathcal{J}_*(u) = -B_n(u)C_n(u) - \int_0^1 uLu \, dx$$

cannot be positive-definite on $B_{(n-1)}$, if A_3 holds.

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