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Minimum-Length Covering by Intersecting Intervals*

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This paper considers the problem: Given a sequence $\{I_i\}_1^n$ of intervals on the real axis, find a sequence $\{J_i\}_1^n$ of closed intervals which minimizes the sum-of-lengths $S=\Sigma_1^n|J_i|$ subject to $I_i \subseteq J_i$ and $J_i \cap J_{i+1} \neq \phi$ for all i. The paper gives a simple algorithm for determining the J_i and notes that linear programming can be applied to the more complicated problem where S is changed to $\Sigma_1^n \alpha_i|J_i|$, $\alpha_i > 0$.

Key Words: Covering problems; Manhattan metric.

1. Introduction

This paper deals with the following problem: Given a sequence $\{I_i\}_1^n$ of intervals on the real axis, find a sequence $\{J_i\}_1^n$ of closed intervals which minimizes the sum-of-lengths

$$S=\Sigma_1^n|J_i| \tag{1.1}$$

subject to the constraints

$$I_i \subseteq J_i \qquad (i=1, 2, \ldots, n), \tag{1.2}$$

$$J_i \cap J_{i+1} \neq \phi \qquad (i=1, 2, \ldots, n-1). \tag{1.3}$$

Interest in this problem arose while studying the determination of shortest length networks consisting only of vertical or horizontal lines connecting a set of points in the plane. If the points form "clusters," where each cluster lies on some vertical line, and if the clusters are far enough apart so that it is clear that only one horizontal line joins any two successive clusters, then the above problem arises as follows. For each cluster, it is clear that a vertical interval containing its highest (greatest ordinate) and lowest (smallest ordinate) point will be necessary and sufficient to cover the given cluster minimally. These vertical intervals correspond to the I_i, above. Since horizontal lines will be used to connect successive intervals, the intervals may need to be enlarged to some new intervals J_i, so that any two successive J_i have overlapping ordinates. Since the length of horizontal connecting lines is constant, a minimization of the above type results.

A simple solution algorithm for this problem is presented in section 2 and justified in section 3.

2. The Algorithm

Set $J_1=I_1$. Given $\{J_j\}_1^i$, J_{i+1} is found as follows:

(a) If $J_i \cap I_{i+1} \neq \phi$, set $J_{i+1}=I_{i+1}$.
(b) If $\max J_i < \min I_{i+1}$, set

$$J_{i+1}=[\max J_i, \max I_{i+1}].$$

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(c) If $\max I_{i+1} < \min J_i$, set

$$J_{i+1} = [\min I_{i+1}, \min J_i].$$

The process clearly yields a sequence $\{J_i\}_1^n$ which is *feasible*, i.e., satisfies (1.2) and (1.3). It remains to show that this sequence is also *optimal*, i.e., minimizes S over all feasible sequences.

3. Justification

The dependence of S on its arguments will be indicated by writing $S(\{J_i\}_1^n)$, while the minimum value of S for the problem with data $\{I_i\}_1^n$ will be denoted $S_{\min}(\{I_i\}_1^n)$.

The proof of optimality will be by induction on n. Clearly the algorithm yields an optimal result for $n=1$. Suppose this is true for $n=N$, and let $\{J_i\}_1^{N+1}$ be the result of applying the algorithm to data $\{I_i\}_1^{N+1}$. There are two cases to be considered.

CASE I: $I_1 \cap I_2 \neq \phi$. Then $J_2 = I_2$ holds, in addition to $J_1 = I_1$. Hence $\{J_i\}_2^{N+1}$ would result from applying the algorithm to $\{I_i\}_2^{N+1}$, so by the induction hypothesis

$$\Sigma_2^{N+1} |J_i| = S_{\min}(\{I_i\}_2^{N+1}).$$

Consider *any* $\{J_i^*\}_1^{N+1}$ feasible for $\{I_i\}_1^{N+1}$. J_1^* will cover I_1, and $\{J_i^*\}_2^{N+1}$ will be feasible for $\{I_i\}_2^{N+1}$, so that

$$\begin{aligned} S(\{J_i^*\}_1^{N+1}) &= |J_1^*| + \Sigma_2^{N+1} |J_i^*| \\ &\geqslant |I_1| + S_{\min}(\{I_i\}_2^{N+1}) = S(\{J_i\}_1^{N+1}), \end{aligned}$$

proving that $\{J_i\}_1^{N+1}$ is optimal.

CASE II: $I_1 \cap I_2 = \phi$. Let $\{J_i^o\}^{N+1}$ be *any* sequence optimal for $\{I_i\}_1^{N+1}$. Define a sequence $\{J_i'\}_1^{N+1}$ as follows: $J_1' = I_1$, J_2' is the smallest interval covering J_2^o and meeting I_1, and $J_i' = J_i^o$ for $i > 2$. Clearly $\{J_i'\}_1^{N+1}$ is feasible for $\{I_i\}_1^{N+1}$, and it will be shown below that

$$|J_1'| + |J_2'| = |I_1| + |J_2'| = |J_1^o| + |J_2^o|, \tag{3.1}$$

implying $S(\{J_i'\}_1^{N+1}) = S(\{J_i^o\}_1^{N+1})$. Since $\{J_i^o\}_1^{N+1}$ is optimal, the same must be true of $\{J_i'\}_1^{N+1}$.

Now $\{J_i\}_2^{N+1}$ would result from applying the algorithm to the sequence $(J_2, \{I_i\}_3^{N+1})$, and so it is optimal for this sequence, by the induction hypothesis. But $\{J_i'\}_2^{N+1}$ is feasible with respect to this same sequence, since J_2' meets I_1 and covers I_2, while the algorithm generates J_2 as the smallest interval covering I_2 and meeting I_1. Hence

$$S(\{J_i\}_2^{N+1}) \leqslant S(\{J_i'\}_2^{N+1}),$$

and since $J_1 = J_1' = I_1$, it follows that

$$S(\{J_i\}_1^{N+1}) \leqslant S(\{J_i'\}_1^{N+1}).$$

Because $\{J_i'\}_1^{N+1}$ is optimal with respect to $\{I_i\}_1^{N+1}$, as noted above, the same must be true of $\{J_i\}_1^{N+1}$, as desired.

It only remains to prove (3.1). Since $\{J_i^o\}_1^{N+1}$ is optimal, J_1^o must be the smallest interval which covers I_1 and meets J_2^o. Recall that J_2' is the smallest interval which covers J_2^o and meets I_1.

Assume without loss of generality that $\max I_1 < \min I_2$. Then $\max I_1 < \max J_2^o$. If I_1 and J_2^o meet, then we must have $J_1^o = I_1$ and $J_2' = J_2^o$ so that (3.1) holds. Therefore, suppose $\max I_1 < \min J_2^o$.

Then

$$J_1^o = [\min I_1, \min J_2^o], \quad J_2' = [\max I_1, \max J_2^o],$$

and so

$$\begin{aligned}|I_1| + |J_2'| &= (\max I_1 - \min I_1) + (\max J_2^o - \max I_1) \\ &= \max J_2^o - \min I_1 \\ &= (\max J_2^o - \min J_2^o) + (\min J_2^o - \min I_1) \\ &= |J_2^o| + |J_1^o|.\end{aligned}$$

This completes the justification of the algorithm.

4. Differently Weighted Intervals

A problem similar to the above but slightly more complicated is the following. Minimize

$$S = \Sigma_1^n \alpha_i |J_i| \tag{4.1}$$

subject to constraints (1.2) and (1.3) of section 1, where all $\alpha_i > 0$.

Although no algorithm as simple as the above has been found to solve this case, it is worth noting that the minimization can be performed by a linear program, as follows.

Let $I_i = [a_i, b_i]$ and $J_i = [A_i, B_i]$. Then the problem is minimized when

$$S = \Sigma_1^n \alpha_i (B_i - A_i)$$

is minimized, subject to

$$A_i \leqslant a_i, B_i \geqslant b_i (i = 1, 2, . . ., n), \tag{4.2}$$

and

$$A_i \leqslant B_{i+1}, B_i \geqslant A_{i+1} (i = 1, 2, . . ., n-1), \tag{4.3}$$

where (4.2) is equivalent to (1.2) and (4.3) is equivalent to (1.3). It is clear that this formulation results in a linear program in the variables A_i and B_i.

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Publications of the National Bureau of Standards*

Selected Abstracts

Mather, J. N., **Invariance of the homology of a lattice,** *Proc. Am. Math. Soc.* **17,** *No. 5, 1120–1124 (Oct. 1966).*
Rota, Kan, Peterson and Whitehead have developed a homology theory for finite lattices which *a priori* depends upon the choice of a cross-cut of the lattice. It is shown here that the different cross-cuts of a lattice lead to simplicial complexes which have the same homotopy type and are therefore homology equivalent.

Key Words: Homology; lattice; combinatorics; cross-cut; simplicial complex; homotopy.

Newman, M., **A bound for the number of conjugacy classes in a group,** *J. London Math. Soc.* **43,** *108–110 (1968).*
It is shown that if the group G is of order h and has k conjugacy classes, then $k \geqslant \log \log h / \log 4$.

Key Words: Conjugacy classes; bounds; groups; matrix representations.

Olver, F. W. J., **An extension of Millers's algorithm,** *Aplikace Mat.* **13,** *174–176 (1968).*
A new algorithm is described for computing the solution of any second-order linear difference equation which is applicable when simple recurrence procedures cannot be used because of instability.

Key Words: Chebyshev series; difference equations; error analysis; Miller algorithm; recurrence methods; special functions.

Other NBS Publications

J. Res. NBS 73A (Phys. and Chem.), No. 1 (Jan.-Feb. 1969), $1.00.

Specific heats of oxygen at coexistence. R. D. Goodwin and L. A. Weber.

Specific heats C_v of fluid oxygen from the triple point to 300 K at pressures to 350 atmospheres. R. D. Goodwin and L. A. Weber.

Thermodynamic properties of fluid oxygen at temperatures to 250 K and pressures to 350 atmospheres on isochores at 1.3 to 3.0 times critical density. R. D. Goodwin.

Two new standards for the pH scale. B. R. Staples and R. G. Bates.

Calculation of diffusion coefficients in ternary systems from diaphragm cell experiments. P. R. Patel, E. C. Moreno, and T. M. Gregory.

Calculated line strength for the transition array $(3d^3+3d^24s)-3d^24p$ in Ti II. H. Mendlowitz.

Morphological stability of a cylinder. S. R. Coriell and S. C. Hardy.

Distorted tetrahedra in strontium copper åkermanite. J. Ito and H. S. Peiser.

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A survey of blemishes on processed microfilm. C. S. McCamy, S. R. Wiley, and J. A. Speckman.

J. Res. NBS 72C (Engr. and Instr.), No. 4 (Oct.-Dec. 1968), 75 cents.

Theoretical and experimental study on longitudinal impact of tapered rods. L. R. Hettche.

Analytical studies of probe conduction errors in ground temperature measurements. B. A. Peavy.

Nonlinear constrained optimization by a nonrandom complex method. R. A. Mitchell and K. L. Kaplan.

Carter, G. C., Bennett, L. H., Cuthill, J. R., Kahan, D. J., The NBS alloy data center: Function, bibliographic system, related data centers, and reference books, Tech. Note 464 (Aug. 1968), $1.25.

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