Scaling Symmetric Positive Definite Matrices to Prescribed Row Sums

Dianne P. O'Leary

Computer Science Department, University of Maryland, College Park, MD 20742 USA; oleary@cs.umd.edu

Abstract

We show that any symmetric positive definite matrix can be symmetrically scaled by a positive diagonal matrix, or by a diagonal matrix with arbitrary signs, to have arbitrary positive rows sums. The scaling can be constructed by solving an ordinary differential equation.

Key words: positive definite matrices, matrix scaling, diagonal preconditioning, homotopy.
PACS: 65F35

7 September 2001

1 Introduction

We consider the following problem: Given a matrix $W \in R^{n \times n}$ and an n-vector $u > 0$, find a diagonal matrix X so that the scaled matrix XWX has row-sums equal to the elements of u. In other words, given W and u, solve the nonlinear equation

$$XWXe = u\,,$$

where e is an n-vector with all entries equal to one.

Scaling problems have been a topic of intense investigation. Brualdi [1] gave necessary and sufficient conditions for the existence of such a diagonal scaling when W is symmetric with nonnegative elements. Other authors have considered scalings of nonsymmetric matrices, allowing different diagonal matrices on the left and the right; see, for example, [2–4] and the references therein. The inverse problem of finding matrices of given sign patterns with given row and column sums has also been investigated, for example, in [5,6].

In this paper, we prove that if W is symmetric and positive definite, then a solution X exists. In fact, there are 2^n solutions, one for each sign pattern for X.

2 A Constructive Existence Proof

Suppose we are given a symmetric positive definite matrix $W \in R^{n \times n}$ and an n-vector $u > 0$. We want to show that there exists a positive diagonal matrix X so that the scaled matrix XWX has row-sums equal to the elements of u.

We will prove this result by considering the matrix

$$V(t) = (1-t)I + tW\,.$$

Then $V(0) = I$, and $V(1) = W$. The notation $\|.\|$ will denote the 2-norm for vectors and matrices.

We will study the mapping

$$H(t,x) = X(t)V(t)X(t)e - u = 0\,,$$

where $X(t)$ is a positive diagonal matrix with entries x_i. For $t = 0$, we have a unique positive solution $x(0) = \hat{x}$ with $\hat{x}_i = \sqrt{u_i}$.

If we can find a positive solution vector x for $t = 1$, then the solution to our scaling problem is the corresponding matrix $X(1)$.

Differentiating our mapping, we obtain

$$\partial_x H(t,x) x'(t) + \partial_t H(t,x) = 0\;, \quad x(0) = \hat{x}\,, \tag{1}$$

where

$$\begin{aligned} \partial_x H(t,x) &= X(t)V(t) + \mathrm{diag(V(t)X(t)e)}\,, \\ \partial_t H(t,x) &= X(t)(W-I)X(t)e\,. \end{aligned}$$

The matrix $V(t)$ is positive definite on some interval $(-\sigma, \tau)$ where $\sigma > 0$ and $\tau > 1$. Let $2\epsilon = \min(\sigma, \tau - 1)$. Then $V(t)$ is uniformly positive definite on the interval $(-\epsilon, 1+\epsilon)$, with eigenvalues $(1-t)+t$ times the eigenvalues of W, and we define the bounds on its eigenvalues to be $\lambda_{min} > 0$ and $\lambda_{max} < \infty$.

The proof of our theorem relies on three lemmas, one establishing the boundedness of $X(t)$, one showing Lipschitz continuity of $f(t,x) = \partial_x H(t,x)^{-1}\partial_t H(t,x)$, and one rather standard result concerning existence of solutions to initial value problems.

Lemma 1: There exist scalars $\xi_\ell > 0$ and $\xi_u < \infty$, independent of t, such that if $x(t) > 0$ satisfies (1) for some value of $t \in [-\epsilon, 1+\epsilon]$, then

$$\xi_\ell \leq \min_i x_i(t) \leq \max_i x_i(t) \leq \xi_u \,.$$

Proof: The matrix $X(t)$ satisfies $X(t)V(t)X(t)e - u = 0$, so

$$e^T X(t)V(t)X(t)e = e^T u > 0\,.$$

Since $Xe = x$, we know that

$$e^T u \geq \lambda_{min}(V)\|x\|^2 \geq \lambda_{min}\, x_i^2\,, i = 1, \ldots, n,$$

so

$$x_i^2 \leq \frac{e^T u}{\lambda_{min}} \equiv \xi_u^2.$$

This means that the elements of $X(t)$ are uniformly bounded above for $t \in [-\epsilon, 1+\epsilon]$.

Now since $x_i(t)(V(t)X(t)e)_i = u_i$, $i = 1, \ldots, n$, we have

$$x_i(t) = \frac{u_i}{(V(t)X(t)e)_i} \geq \frac{u_i}{\|V(t)\|\|X(t)\|\sqrt{n}}\,,$$

so we can define

$$\xi_\ell = \frac{\min_i u_i}{\lambda_{max}\xi_u\sqrt{n}}\,.$$

[]

Lemma 2: Let

$$\Omega = \{(t,x) : -\epsilon < t < 1+\epsilon, \frac{1}{2}\xi_\ell e < x(t) < 2\xi_u e, V(t)x(t) > 0, \}\,.$$

For a fixed value of t, the function $f(t,x)$ is Lipschitz continuous on Ω, where f is defined by

$$\partial_x H(t,x) f(x) = -\partial_t H(t,x)\,. \tag{2}$$

Proof: The matrix $\partial_x H(t,x)X(t)$ is symmetric and positive definite on Ω, so the inverse of $\partial_x H(t,x)$ must exist, and it is a continuous function of x and t. The right-hand side $-X(t)(W-I)X(t)e$ is continuous on Ω, Therefore, $f(x)$ is continuous.

Now, for a fixed $t \in [-\epsilon, 1+\epsilon]$, we show that $f(t,x)$ satisfies a Lipschitz condition in x.

Let (t,x) and $(t,\hat{x})$ be two points in Ω. Let $Y = X(W-I)Xe$ and $Z = XVX + \text{diag(XVx)}$, and define $\hat{Y}$ and $\hat{Z}$ by substituting $\hat{X}$ for X in these expressions. Then we have these bounds:

$$\begin{aligned}
\|\hat{X}\|\,,\ \|X\| &\le \xi_u\,,\\
\|\hat{Y}\|\,,\ \|Y\| &\le \sqrt{n}\|W-I\|\xi_u^2\,,\\
\|\hat{Z}^{-1}\|\,,\ \|Z^{-1}\| &\le \frac{1}{\xi_\ell^2\lambda_{min}}\,.
\end{aligned}$$

We compute

$$\begin{aligned}
\|f(t,\hat{x}) - f(t,x)\| &= \|\hat{X}\hat{Z}^{-1}\hat{Y} - XZ^{-1}Y\\
&= \|(\hat{X}-X)\hat{Z}^{-1}\hat{Y} + X\hat{Z}^{-1}(\hat{Y}-Y) + X(\hat{Z}^{-1}-Z^{-1})Y\|\\
&\le \|(\hat{X}-X)\|\,\|\hat{Z}^{-1}\|\,\|\hat{Y}\| + \|X\|\,\|\hat{Z}^{-1}\|\,\|\hat{Y}-Y\|\\
&\quad + \|X\|\,\|\hat{Z}^{-1}-Z^{-1}\|\,\|Y\|\,.
\end{aligned}$$

We already have bounds on many of these norms, so to conclude that f is Lipschitz continuous, it suffices to bound $\|\hat{Y}-Y\|$ and $\|\hat{Z}^{-1}-Z^{-1}\|$ in terms of $\|\hat{X}-X\|$, since $\|\hat{X}-X\| \le \|\hat{x}-x\|$.

We compute the Y bound by noting that

$$\hat{Y} - Y = \hat{X}(W-I)\hat{X}e - X(W-I)Xe = (\hat{X}-X)(W-I)\hat{X}e + X(W-I)(\hat{X}-X)e\,,$$

so

$$\|\hat{Y} - Y\| \leq 2\|W - I\|\xi_u\sqrt{n}\|\hat{X} - X\|\,.$$

Now we bound the Z term. Let $D = \text{diag(XVx)}$, and similarly for $\hat{D}$, and note that

$$\begin{aligned}\hat{Z}^{-1} - Z^{-1} &= (\hat{X}V\hat{X} + \hat{D})^{-1} - (XVX + D)^{-1} \\ &= (\hat{X}V\hat{X} + \hat{D})^{-1}[-\hat{X}V(\hat{X} - X) + (\hat{X} - X)VX - \hat{D} + D](XVX + D)^{-1}\end{aligned}$$

The norms of the first and last factors are bounded, so we just need to bound the norm of the middle expression:

$$\| - \hat{X}V(\hat{X} - X) + (\hat{X} - X)VX - \hat{D} + D\| \leq 2\xi_u\lambda_{max}\|\hat{X} - X\| + \|\hat{D} - D\|\,.$$

Focusing on the last term gives

$$\begin{aligned}(\hat{D} - D)_i &= \hat{x}_i \sum_j w_{ij}\hat{x}_j - x_i \sum_j w_{ij}x_j \\ &= (\hat{x}_i - x_i)\sum_j w_{ij}\hat{x}_j + x_i \sum_j w_{ij}(\hat{x}_j - x_j)\end{aligned}$$

so

$$|(\hat{D} - D)_i| \leq \lambda_{max}\xi_u|\hat{x}_i - x_i| + \xi_u\lambda_{max}\|\hat{x}_j - x_j\|$$

and thus we have a bound on every term in terms of $\|\hat{x} - x\|$, yielding a conclusion of Lipschitz continuity for f. []

Lemma 3: Let Ω be a bounded domain in R^{n+1} with $(0, x_0) \in \Omega$. If f is continuous in Ω and locally satisfies a Lipschitz condition in the x variables, then there exists a solution of the initial value problem

$$x'(t) = f(t, x)\ , \quad x(0) = x_0$$

that can be uniquely extended arbitrarily close to the boundary of Ω.

Proof: See, for example, Hurewicz [7, Theorem 11]. []

Now we use our three lemmas to prove that the scaling matrix exists.

Theorem: Given a symmetric positive definite matrix $W \in R^{n\times n}$ and an n-vector $u > 0$, there exists a positive diagonal matrix X so that the scaled matrix XWX has row-sums equal to the elements of u.

Proof: To construct our scaling X, we use Lemma 3 to show that (1) has a solution at $t = 1$.

It is clear that $(0, x_0) \in \Omega$, and Lemma 2 assures us that the function f defined by (2) is Lipschitz continuous on Ω. Thus, the assumptions of Lemma 3 are satisfied, so a solution to (1) can be extended to the boundary of Ω.

Now, consider any solution point $(t, x(t))$ for $t \in [-\epsilon, 1+\epsilon]$ with $x > 0$. By Lemma 1, $\xi_\ell e \le x \le \xi_u e$, and thus, since $XV(t)x = u > 0$, we must have

$$V(t)x \ge \frac{1}{\xi_u} u > 0\,.$$

Therefore, any solution point $(t, x(t))$ with $t \in [-\epsilon, 1+\epsilon]$ has x bounded away from the constraints

$$\frac{1}{2}\xi_\ell e < x(t) < 2\xi_u e,\;\; V(t)x(t) > 0$$

that define Ω. Therefore, we must be able to extend the solution from $t = 0$ to the boundary $t = 1+\epsilon$, and thus the solution exists for $t = 1$. []

By replacing $V(t)$ by the positive definite matrix $EV(t)E$, where E is a diagonal matrix with entries ± 1, we can see that there are actually 2^n scaling matrices, one for each quadrant, that give the prescribed row sums. For $t = 1$, the equation $XVXe = u$ is a polynomial system of degree 2^n, so this accounts for all possible solutions.

Corollary: The equation $XWXe = u$, with W symmetric positive definite and X a diagonal matrix, has 2^n solutions, one per quadrant, so we can scale the matrix W by a diagonal matrix with arbitrary signs, so that it has prescribed row sums.

3 Conclusions and Remarks

We have presented an existence proof showing that any symmetric positive definite matrix can be scaled by a positive diagonal matrix, or by a diagonal matrix with arbitrary signs, to have arbitrary positive row sums.

The proof is constructive in that it leads to algorithms for computing such a scaling: apply an ordinary differential equation solver to (1). This is one particular homotopy method applied to the solution of the nonlinear equation $XWXe - u = 0$; other methods for solution of nonlinear equations could also be applied.

If the matrix is not positive definite, then the homotopy breaks down at values t for which $(1-t)I + tW$ is singular.

4 Acknowledgements

I am grateful to Roger Horn, John E. Osborn, Hans Schneider, G. W. Stewart, and Ilya Zavorin for helpful discussions. This work was supported in part by the National Science Foundation under Grant CCR-97-32022.

References

[1] R. A. Brualdi, The dad theorem for arbitrary row sums, Proc. AMS 45 (1974) 189–194.

[2] R. Sinkhorn, Diagonal equivalence to matrices with prescribed row and column sums. ii, Proc. AMS 45 (1974) 195–198.

[3] R. A. Brualdi, S. V. Parter, H. Schneider, The diagonal equivalence of a nonnegative matrix to a stochastic matrix, J. Math. Anal. and Appl. 16 (1966) 31–50.

[4] U. G. Rothblum, H. Schneider, Scalings of matrices which have prespecified row sums and column sums via optimisation, Lin. Alg. Appl. 114/115 (1989) 737–764.

[5] D. Hershkowitz, A. J. Hoffman, H. Schneider, On the existence of sequences and matrices with prescribed partial sums of elements, Lin. Alg. Appl. 265 (1997) 71 – 92.

[6] C. R. Johnson, S. A. Lewis, D. Y. Yau, Possible line sums for a qualitative matrix, Lin. Alg. Appl. 327 (2001) 53–60.

[7] W. Hurewicz, Lectures on Ordinary Differential Equations, John Wiley and Sons, New York, 1958.