

Lecture 6

Householder Reflectors and Givens Rotations

MIT 18.335J / 6.337J

Introduction to Numerical Methods

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Gram-Schmidt as Triangular Orthogonalization

- Gram-Schmidt multiplies with triangular matrices to make columns orthogonal, for example at the first step:

$$\left[\begin{array}{c|c|c|c} v_1 & v_2 & \cdots & v_n \end{array} \right] \begin{bmatrix} \frac{1}{r_{11}} & \frac{-r_{12}}{r_{11}} & \frac{-r_{13}}{r_{11}} & \cdots \\ & 1 & & \\ & & 1 & \\ & & & \ddots \end{bmatrix} = \left[\begin{array}{c|c|c|c} q_1 & v_2^{(2)} & \cdots & v_n^{(2)} \end{array} \right]$$

- After all the steps we get a product of triangular matrices

$$A \underbrace{R_1 R_2 \cdots R_n}_{\hat{R}^{-1}} = \hat{Q}$$

- “Triangular orthogonalization”

Householder Triangularization

- The Householder method multiplies by unitary matrices to make columns triangular, for example at the first step:

$$Q_1 A = \begin{bmatrix} r_{11} & \mathbf{x} & \cdots & \mathbf{x} \\ 0 & \mathbf{x} & \cdots & \mathbf{x} \\ 0 & \mathbf{x} & \cdots & \mathbf{x} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \mathbf{x} & \cdots & \mathbf{x} \end{bmatrix}$$

- After all the steps we get a product of orthogonal matrices

$$\underbrace{Q_n \cdots Q_2 Q_1}_{Q^*} A = R$$

- “Orthogonal triangularization”

Introducing Zeros

- Q_k introduces zeros below the diagonal in column k
- Preserves all the zeros previously introduced

$$\begin{array}{c}
 \left[\begin{array}{ccc} \times & \times & \times \\ \times & \times & \times \end{array} \right] \xrightarrow{Q_1} \left[\begin{array}{ccc} \mathbf{\times} & \mathbf{\times} & \mathbf{\times} \\ \mathbf{0} & \mathbf{\times} & \mathbf{\times} \end{array} \right] \xrightarrow{Q_2} \left[\begin{array}{ccc} \times & \times & \times \\ & \mathbf{\times} & \mathbf{\times} \\ & \mathbf{0} & \mathbf{\times} \\ & \mathbf{0} & \mathbf{\times} \\ & \mathbf{0} & \mathbf{\times} \end{array} \right] \xrightarrow{Q_3} \left[\begin{array}{ccc} \times & \times & \times \\ & \times & \times \\ & & \mathbf{\times} \\ & & \mathbf{0} \\ & & \mathbf{0} \end{array} \right] \\
 A \qquad \qquad \qquad Q_1 A \qquad \qquad \qquad Q_2 Q_1 A \qquad \qquad \qquad Q_3 Q_2 Q_1 A
 \end{array}$$

Householder Reflectors

- Let Q_k be of the form

$$Q_k = \begin{bmatrix} I & 0 \\ 0 & F \end{bmatrix}$$

where I is $(k - 1) \times (k - 1)$ and F is $(m - k + 1) \times (m - k + 1)$

- Create *Householder reflector* F that introduces zeros:

$$x = \begin{bmatrix} \times \\ \times \\ \vdots \\ \times \end{bmatrix} \quad Fx = \begin{bmatrix} \|x\| \\ 0 \\ \vdots \\ 0 \end{bmatrix} = \|x\|e_1$$

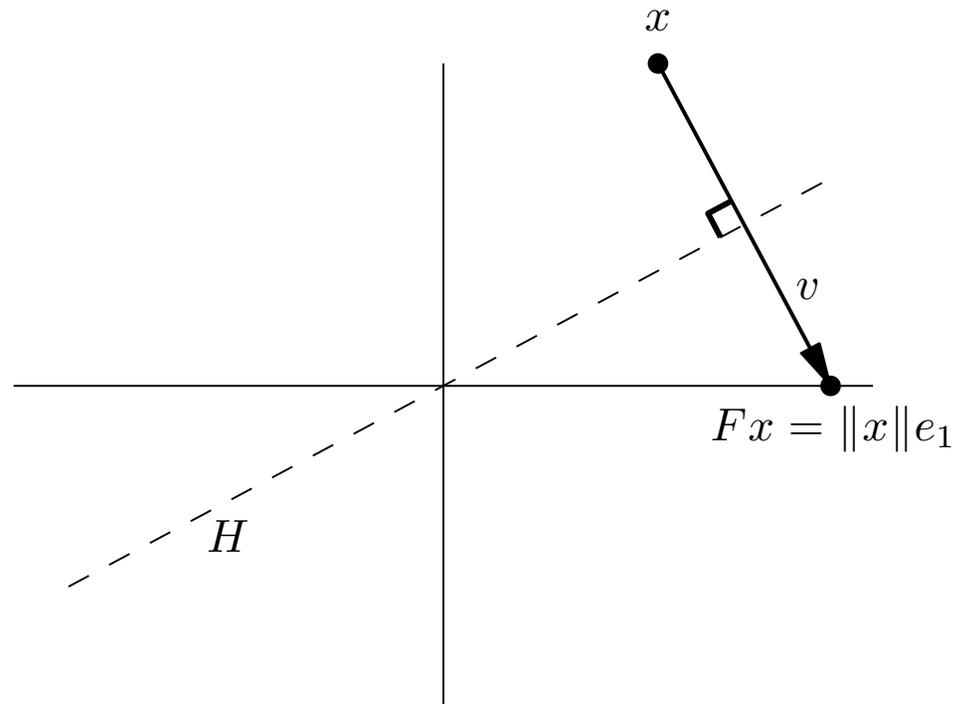
Householder Reflectors

- Idea: Reflect across hyperplane H orthogonal to $v = \|x\|e_1 - x$, by the unitary matrix

$$F = I - 2 \frac{vv^*}{v^*v}$$

- Compare with projector

$$P_{\perp v} = I - \frac{vv^*}{v^*v}$$

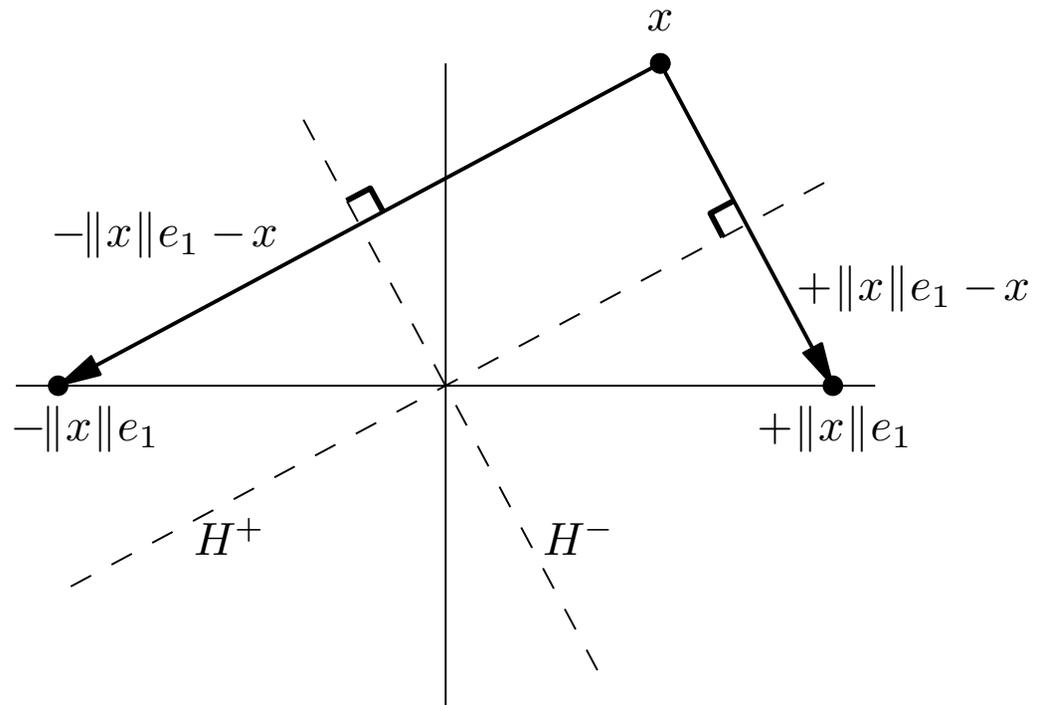


Choice of Reflector

- We can choose to reflect to any multiple z of $\|x\|e_1$ with $|z| = 1$
- Better numerical properties with large $\|v\|$, for example

$$v = \text{sign}(x_1)\|x\|e_1 + x$$

- Note: $\text{sign}(0) = 1$, but in MATLAB, $\text{sign}(0) == 0$



The Householder Algorithm

- Compute the factor R of a QR factorization of $m \times n$ matrix A ($m \geq n$)
- Leave result in place of A , store reflection vectors v_k for later use

Algorithm: Householder QR Factorization

for $k = 1$ **to** n

$$x = A_{k:m,k}$$

$$v_k = \text{sign}(x_1) \|x\|_2 e_1 + x$$

$$v_k = v_k / \|v_k\|_2$$

$$A_{k:m,k:n} = A_{k:m,k:n} - 2v_k(v_k^* A_{k:m,k:n})$$

Applying or Forming Q

- Compute $Q^*b = Q_n \cdots Q_2Q_1b$ and $Qx = Q_1Q_2 \cdots Q_nx$ implicitly
- To create Q explicitly, apply to $x = I$

Algorithm: Implicit Calculation of Q^*b

for $k = 1$ to n

$$b_{k:m} = b_{k:m} - 2v_k(v_k^*b_{k:m})$$

Algorithm: Implicit Calculation of Qx

for $k = n$ downto 1

$$x_{k:m} = x_{k:m} - 2v_k(v_k^*x_{k:m})$$

Operation Count - Householder QR

- Most work done by

$$A_{k:m,k:n} = A_{k:m,k:n} - 2v_k(v_k^* A_{k:m,k:n})$$

- Operations per iteration:

- $2(m - k)(n - k)$ for the dot products $v_k^* A_{k:m,k:n}$
- $(m - k)(n - k)$ for the outer product $2v_k(\dots)$
- $(m - k)(n - k)$ for the subtraction $A_{k:m,k:n} - \dots$
- $4(m - k)(n - k)$ total

- Including the outer loop, the total becomes

$$\begin{aligned} \sum_{k=1}^n 4(m - k)(n - k) &= 4 \sum_{k=1}^n (mn - k(m + n) + k^2) \\ &\sim 4mn^2 - 4(m + n)n^2/2 + 4n^3/3 = 2mn^2 - 2n^3/3 \end{aligned}$$

Givens Rotations

- Alternative to Householder reflectors

- A Givens rotation $R = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix}$ rotates $x \in \mathbb{R}^2$ by θ

- To set an element to zero, choose $\cos \theta$ and $\sin \theta$ so that

$$\begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} x_i \\ x_j \end{bmatrix} = \begin{bmatrix} \sqrt{x_i^2 + x_j^2} \\ 0 \end{bmatrix}$$

or

$$\cos \theta = \frac{x_i}{\sqrt{x_i^2 + x_j^2}}, \quad \sin \theta = \frac{-x_j}{\sqrt{x_i^2 + x_j^2}}$$

Givens QR

- Introduce zeros in column from bottom and up

$$\begin{array}{ccc}
 \begin{bmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{bmatrix} & \xrightarrow{(3,4)} & \begin{bmatrix} \times & \times & \times \\ \times & \times & \times \\ \mathbf{\times} & \mathbf{\times} & \mathbf{\times} \\ \mathbf{0} & \mathbf{\times} & \mathbf{\times} \end{bmatrix} & \xrightarrow{(2,3)} & \begin{bmatrix} \times & \times & \times \\ \mathbf{\times} & \mathbf{\times} & \mathbf{\times} \\ \mathbf{0} & \mathbf{\times} & \mathbf{\times} \\ & \times & \times \end{bmatrix} & \xrightarrow{(1,2)} & \begin{bmatrix} \times & \times & \times \\ & \times & \times \\ & \times & \times \\ & \times & \times \end{bmatrix} \\
 \begin{bmatrix} \mathbf{\times} & \mathbf{\times} & \mathbf{\times} \\ \mathbf{0} & \mathbf{\times} & \mathbf{\times} \\ & \times & \times \\ & \times & \times \end{bmatrix} & \xrightarrow{(3,4)} & \begin{bmatrix} \times & \times & \times \\ & \times & \times \\ & \mathbf{\times} & \mathbf{\times} \\ & \mathbf{0} & \mathbf{\times} \end{bmatrix} & \xrightarrow{(2,3)} & \begin{bmatrix} \times & \times & \times \\ & \times & \times \\ & \mathbf{\times} & \mathbf{\times} \\ & \mathbf{0} & \mathbf{\times} \end{bmatrix} & \xrightarrow{(3,4)} & \begin{bmatrix} \times & \times & \times \\ & \times & \times \\ & \mathbf{\times} & \mathbf{\times} \\ & \mathbf{0} & \mathbf{\times} \\ & & \times \end{bmatrix} & \xrightarrow{(3,4)} & R
 \end{array}$$

- Flop count $3mn^2 - n^3$ (or 50% more than Householder QR)

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