

Numerical Matrix Analysis

Notes #12 — Conditioning and Stability Stability of Householder Triangularization

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- Floating Point Axioms
- Stability Definitions
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- Householder QR

2 Stability of Algorithms

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3 Solving $A\vec{x} = \vec{b}$

- Theorem — Householder-Triangularization + Back-Substitution
- Three Major Holes to Patch...

Reference: Key Floating Point Axioms

Axiom (Floating Point Representation)

$\forall x \in \mathbb{R}$, there exists ϵ with $|\epsilon| \leq \epsilon_{\text{mach}}$,
such that $\text{fl}(x) = x(1 + \epsilon)$.

Axiom (The Fundamental Axiom of Floating Point Arithmetic)

For all $x, y \in \mathbb{F}$ (where \mathbb{F} is the set of floating point numbers),
there exists ϵ with $|\epsilon| \leq \epsilon_{\text{mach}}$, such that

$$\begin{aligned} x \oplus y &= (x + y)(1 + \epsilon), & x \ominus y &= (x - y)(1 + \epsilon), \\ x \otimes y &= (x * y)(1 + \epsilon), & x \oslash y &= (x / y)(1 + \epsilon) \end{aligned}$$

Reference: Key Stability Definitions

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Definition (Stable Algorithm)

We say that \tilde{f} is a **stable algorithm** if $\forall \vec{x} \in X$

$$\frac{\|\tilde{f}(\vec{x}) - f(\tilde{\vec{x}})\|}{\|f(\tilde{\vec{x}})\|} = \mathcal{O}(\epsilon_{\text{mach}}),$$

for some $\tilde{\vec{x}}$ with

$$\frac{\|\tilde{\vec{x}} - \vec{x}\|}{\|\vec{x}\|} = \mathcal{O}(\epsilon_{\text{mach}}).$$

“A stable algorithm gives approximately the right answer, to approximately the right question.”

Reference: Key Stability Definitions

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Definition (Backward Stable Algorithm)

An algorithm \tilde{f} is **backward stable** if $\forall \vec{x} \in X$

$$\tilde{f}(\vec{x}) = f(\tilde{\vec{x}}),$$

for some $\tilde{\vec{x}}$ with

$$\frac{\|\tilde{\vec{x}} - \vec{x}\|}{\|\vec{x}\|} = \mathcal{O}(\epsilon_{\text{mach}}).$$

“A backward stable algorithm gives exactly the right answer, to approximately the right question.”

Jump to: accuracy theorem.

Reference: Accuracy — The Goal!

Definition (Accuracy)

We say that the algorithm \tilde{f} is **accurate** if $\forall \vec{x} \in X$

$$\frac{\|\tilde{f}(\vec{x}) - f(\vec{x})\|}{\|f(\vec{x})\|} = \mathcal{O}(\epsilon_{\text{mach}}).$$

This is what we want to do — write algorithms that **accurately** solve problems!

Last time, we finally tied the inherent difficulty of the problem, the **conditioning**, and the quality of the algorithm, the **stability** together in a theorem —

Last Time: Accuracy(stability,conditioning)

Theorem (Computational Accuracy)

Suppose a backward stable algorithm is applied to solve a problem $f : X \rightarrow Y$ with condition number κ in a floating point environment satisfying the floating point representation axiom, and the fundamental axiom of floating point arithmetic.

Then the relative errors satisfy

$$\frac{\|\tilde{f}(x) - f(x)\|}{\|f(x)\|} = \mathcal{O}(\kappa(x)\epsilon_{mach}).$$

Recall: The definition of the **relative condition number**

$$\kappa(\vec{x}) = \sup_{\delta\vec{x}} \left[\frac{\|\delta f\|}{\|f(\vec{x})\|} \middle/ \frac{\|\delta\vec{x}\|}{\|\vec{x}\|} \right]$$

as the ratio of the relative (infinitesimal) change in f induced by an infinitesimal change in \vec{x} .

Reference: Algorithm — Householder QR

From [NOTES#7]

Algorithm (Householder QR-Factorization, $Q^*\vec{b}$ -Version)

```

1: for  $k \in \{1, \dots, n\}$  do
2:    $\vec{x} \leftarrow A(k:m, k)$ 
3:    $\vec{v}_k \leftarrow \text{sign}(x_1) \|\vec{x}\|_2 \vec{e}_1 + \vec{x}$ 
4:    $\vec{v}_k \leftarrow \vec{v}_k / \|\vec{v}_k\|_2$ 
5:    $A(k:m, k:n) \leftarrow A(k:m, k:n) - 2\vec{v}_k (\vec{v}_k^* A(k:m, k:n))$ 
6:    $\vec{b}(k:m) \leftarrow \vec{b}(k:m) - 2\vec{v}_k (\vec{v}_k^* \vec{b}(k:m))$       /* Compute  $Q^*\vec{b}$  */
7: end for

```

$A(k:m, k)$ Denotes the k th thru m th rows, in the k th column of A — a vector quantity.

$A(k:m, k:n)$ Denotes the k th thru m th rows, in the k th thru n th columns of A — a matrix quantity.

The Road Ahead: Stability of Algorithms

With our new toolbox in hand, we re-visit some of the algorithms previously discussed. This second look will reveal, in a more rigorous way, why the algorithms perform the way they do...

The **Householder Triangularization** method of computing the QR-factorization is a backward stable (HT-QR for short).

First, we look at some numerical experiments showcasing this; and then we combine HT-QR with other backward stable algorithmic fragments to build a stable solver for our fundamental problem

$$A\vec{x} = \vec{b}.$$

Householder Triangularization: Numerics

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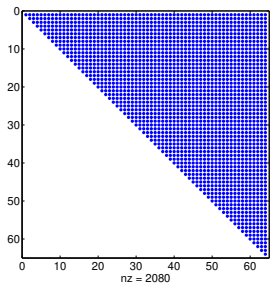


Figure: The non-zero pattern of the matrix R .

We generate a matrix A with known QR-factorization, and compute the Householder QR-factorization using matlab

```
R          = triu(randn(64));  
[Q,X]      = qr(randn(64));  
A          = Q*R;  
[Q2,R2]    = qr(A);
```

Householder Triangularization: Numerics

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It turns out that Q_2 and R_2 are quite far from Q and R :

$$\text{norm}(Q_2 - Q) / \text{norm}(Q) = 0.003427$$

$$\text{norm}(R_2 - R) / \text{norm}(R) = 0.000440$$

It seems like a disaster has occurred

Householder Triangularization: Numerics

2 of 3

It turns out that Q_2 and R_2 are quite far from Q and R :

$$\text{norm}(Q_2 - Q) / \text{norm}(Q) = 0.003427$$

$$\text{norm}(R_2 - R) / \text{norm}(R) = 0.000440$$

It seems like a disaster has occurred, but

$$\text{norm}(A - Q_2 R_2) / \text{norm}(A) = 1.032309\text{e-}15$$

Householder Triangularization: Numerics

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It turns out that Q_2 and R_2 are quite far from Q and R :

$$\begin{aligned}\text{norm}(Q_2 - Q) / \text{norm}(Q) &= 0.003427 \\ \text{norm}(R_2 - R) / \text{norm}(R) &= 0.000440\end{aligned}$$

It seems like a disaster has occurred, but

$$\text{norm}(A - Q_2 R_2) / \text{norm}(A) = 1.032309\text{e-}15$$

Now consider Q_3 and R_3

$$\begin{aligned}Q_3 &= Q + 1\text{e-}4 * \text{randn}(64) \\ R_3 &= R + 1\text{e-}4 * \text{randn}(64) \\ \text{norm}(Q_3 - Q) / \text{norm}(Q) &= 0.001595 \\ \text{norm}(R_3 - R) / \text{norm}(R) &= 0.000129 \\ \text{norm}(A - Q_3 R_3) / \text{norm}(A) &= 1.065451\text{e-}03\end{aligned}$$

Householder Triangularization: Numerics

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The Moral of the Story

The errors in Q_2 and R_2 are known as **forward errors**. Large forward errors are the result of an ill-conditioned problem and/or an unstable algorithm. — In our example it is the former

$$\kappa(A) = \text{cond}(A) = 2.0223\text{e}+16.$$

The error in the result of the matrix product $Q_2 R_2$ is known as the **backward error**, or **residual**.

The fact that the backward error is small **suggests** that Householder Triangularization is backward stable.

Householder Triangularization: Numerics

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Note: Due to the specific way the Householder reflections are performed, the algorithm above may have to be run a couple of times in order to produce (similar) results. A relative error in Q_2 of size ~ 2 indicates that the initial random Q and R could not possibly have come from a HT-QR algorithm (due to “sign-flips.”)

Householder Triangularization: Backward Stability

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It turns out that HT-QR is backward stable for **all** matrices A in any floating-point environment satisfying the floating point axioms.

The formal result takes the form

$$\tilde{Q}\tilde{R} = A + \delta A, \quad \delta A \text{ "small,"}$$

where \tilde{R} is the upper triangular matrix constructed by the HT-QR algorithm.

Since the HT-QR algorithm does not explicitly compute \tilde{Q} (in the “fast mode,”) we must define what we mean by \tilde{Q} .

Let \tilde{Q}_k denote the **exactly unitary** reflector defined by the floating point vector $\tilde{\mathbf{v}}_k$

$$\tilde{Q}_k = I - 2 \frac{\tilde{\mathbf{v}}_k \tilde{\mathbf{v}}_k^*}{\tilde{\mathbf{v}}_k^* \tilde{\mathbf{v}}_k}.$$

Householder Triangularization: Backward Stability

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Now, we define \tilde{Q} to be the exactly unitary matrix

$$\tilde{Q} = \tilde{Q}_1 \tilde{Q}_2 \cdots \tilde{Q}_n,$$

this matrix will take the place of the computed Q in our discussion.

This approach is natural since in general the matrix Q is not formed explicitly, but rather used implicitly to get the **action** $Q^* \vec{b}$.

With these definitions, we are ready to state the theorem...

Householder Triangularization: Backward Stability

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Theorem (Backward Stability of Householder QR)

Let the QR-factorization $A = QR$ of a matrix $A \in \mathbb{C}^{m \times n}$ be computed by Householder triangularization in a floating-point environment satisfying the floating-point axioms, and let the computed factors \tilde{Q} and \tilde{R} be as discussed on the previous two slides. Then we have

$$\tilde{Q}\tilde{R} = A + \delta A, \quad \frac{\|\delta A\|}{\|A\|} = \mathcal{O}(\epsilon_{mach})$$

for some $\delta A \in \mathbb{C}^{m \times n}$.

The full proof can be found in: —

Nicholas J. Higham, *Accuracy and Stability of Numerical Algorithms*, 2nd ed., ISBN 0-89871-521-0, SIAM, Philadelphia, 2002. (pp. 357–361)

Solving $A\vec{x} = \vec{b}$, Using Householder QR-Factorization

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Computing the QR-factorization is not an end in itself. Usually it is one of the first steps in trying to solve a system of linear equations, a least squares problem, or an eigenvalue problem.

At this point we know that HT-QR is backward stable, but is that enough?!? As we have seen, the individual factors Q and R may carry large forward errors.

The **good news** is that accuracy of the product QR is sufficient for most purposes.

We consider the following algorithm for solving $A\vec{x} = \vec{b}$

Algorithm (Solution of a Linear System, $A\vec{x} = \vec{b}$)

- | | | |
|----|-------------------------------------|---|
| 1: | $QR \leftarrow A$ | — Compute the QR-factorization by HT-QR |
| 2: | $\vec{y} \leftarrow Q^* \vec{b}$ | — Construct $Q^* \vec{b}$ by HT-QR |
| 3: | $\vec{x} \leftarrow R^{-1} \vec{y}$ | — Solve by back substitution |

Solving $A\vec{x} = \vec{b}$, Using Householder QR -Factorization

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It turns out that this algorithm is backward stable. The three steps are backward stable, for now we state these results without proof, and then combine them to form the larger result.

We have already expressed the backward stability of HT-QR in a previous theorem.

Solving $A\vec{x} = \vec{b}$, Using Householder QR -Factorization

2 of 8

It turns out that this algorithm is backward stable. The three steps are backward stable, for now we state these results without proof, and then combine them to form the larger result.

We have already expressed the backward stability of HT-QR in a previous theorem.

The second step computes $\tilde{Q}^* \vec{b}$, due to floating-point errors, the result \tilde{y} is not equal to $\vec{y} = \tilde{Q}^* \vec{b}$, but the operation is backward stable

$$(\tilde{Q} + \delta Q)\tilde{y} = \vec{b}, \quad \|\delta Q\| = \mathcal{O}(\epsilon_{\text{mach}}).$$

The solution \tilde{x} of the back substitution in the third step satisfies

$$(\tilde{R} + \delta R)\tilde{x} = \tilde{y}, \quad \frac{\|\delta R\|}{\|\tilde{R}\|} = \mathcal{O}(\epsilon_{\text{mach}}).$$

Solving $A\vec{x} = \vec{b}$, Using Householder QR-Factorization

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With these unproven (for now) building blocks, we are ready to state and prove the following theorem

Theorem

The three step algorithm described above for solving $A\vec{x} = \vec{b}$ is backward stable, satisfying

$$(A + \Delta A)\tilde{x} = \vec{b}, \quad \frac{\|\Delta A\|}{\|A\|} = \mathcal{O}(\epsilon_{mach}),$$

for some $\Delta A \in \mathbb{C}^{m \times m}$.

Solving $A\vec{x} = \vec{b}$, Using Householder QR -Factorization

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Proof: From step #2 and step #3 we have

$$(\tilde{Q} + \delta Q)\tilde{y} = \vec{b}, \quad \text{and} \quad (\tilde{R} + \delta R)\tilde{x} = \tilde{y},$$

combining the two gives

$$\vec{b} = (\tilde{Q} + \delta Q)(\tilde{R} + \delta R)\tilde{x} = \left[\tilde{Q}\tilde{R} + (\delta Q)\tilde{R} + \tilde{Q}(\delta R) + (\delta Q)(\delta R) \right] \tilde{x}.$$

Solving $A\vec{x} = \vec{b}$, Using Householder QR-Factorization

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Now, using the result for step #1

$$\tilde{Q}\tilde{R} = A + \delta A$$

we get

$$\vec{b} = \left[A + \underbrace{\delta A + (\delta Q)\tilde{R} + \tilde{Q}(\delta R) + (\delta Q)(\delta R)}_{\Delta A} \right] \tilde{x}.$$

Solving $A\vec{x} = \vec{b}$, Using Householder QR -Factorization

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Next, we must show that the perturbation

$$\Delta A = \delta A + (\delta Q)\tilde{R} + \tilde{Q}(\delta R) + (\delta Q)(\delta R)$$

is small relative to A .

Solving $A\vec{x} = \vec{b}$, Using Householder QR -Factorization

5 of 8

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is small relative to A .

Since $\tilde{Q}\tilde{R} = A + \delta A$, and \tilde{Q} is unitary we have

$$\frac{\|\tilde{R}\|}{\|A\|} \leq \|\tilde{Q}^*\| \frac{\|A + \delta A\|}{\|A\|} = \mathcal{O}(1), \quad \epsilon_{\text{mach}} \rightarrow 0.$$

Solving $A\vec{x} = \vec{b}$, Using Householder QR -Factorization

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$$\frac{\|\tilde{R}\|}{\|A\|} \leq \|\tilde{Q}^*\| \frac{\|A + \delta A\|}{\|A\|} = \mathcal{O}(1), \quad \epsilon_{\text{mach}} \rightarrow 0.$$

Hence, the relative size of the second term is bounded

$$\frac{\|(\delta Q)\tilde{R}\|}{\|A\|} \leq \|(\delta Q)\| \frac{\|\tilde{R}\|}{\|A\|} = \mathcal{O}(\epsilon_{\text{mach}}).$$

Solving $A\vec{x} = \vec{b}$, Using Householder QR -Factorization

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Now, consider the third term

$$\Delta A = \delta A + (\delta Q)\tilde{R} + \tilde{Q}(\delta R) + (\delta Q)(\delta R)$$

$$\frac{\|\tilde{Q}(\delta R)\|}{\|A\|} \leq \|\tilde{Q}\| \frac{\|(\delta R)\|}{\|A\|} = \|\tilde{Q}\| \frac{\|(\delta R)\|}{\|\tilde{R}\|} \frac{\|\tilde{R}\|}{\|A\|}.$$

Solving $A\vec{x} = \vec{b}$, Using Householder QR -Factorization

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$$\Delta A = \delta A + (\delta Q)\tilde{R} + \tilde{Q}(\delta R) + (\delta Q)(\delta R)$$

$$\frac{\|\tilde{Q}(\delta R)\|}{\|A\|} \leq \|\tilde{Q}\| \frac{\|(\delta R)\|}{\|A\|} = \|\tilde{Q}\| \frac{\|(\delta R)\|}{\|\tilde{R}\|} \frac{\|\tilde{R}\|}{\|A\|}.$$

Since

$$\|\tilde{Q}\| = \mathcal{O}(1), \quad \frac{\|(\delta R)\|}{\|\tilde{R}\|} = \mathcal{O}(\epsilon_{\text{mach}}), \quad \text{and} \quad \frac{\|\tilde{R}\|}{\|A\|} = \mathcal{O}(1),$$

Solving $A\vec{x} = \vec{b}$, Using Householder QR -Factorization

6 of 8

Now, consider the third term

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Since

$$\|\tilde{Q}\| = \mathcal{O}(1), \quad \frac{\|(\delta R)\|}{\|\tilde{R}\|} = \mathcal{O}(\epsilon_{\text{mach}}), \quad \text{and} \quad \frac{\|\tilde{R}\|}{\|A\|} = \mathcal{O}(1),$$

we have

$$\frac{\|\tilde{Q}(\delta R)\|}{\|A\|} = \mathcal{O}(\epsilon_{\text{mach}}).$$

Solving $A\vec{x} = \vec{b}$, Using Householder QR -Factorization

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Finally, the fourth term

$$\Delta A = \delta A + (\delta Q)\tilde{R} + \tilde{Q}(\delta R) + (\delta Q)(\delta R)$$

$$\frac{\|(\delta Q)(\delta R)\|}{\|A\|} \leq \|(\delta Q)\| \frac{\|(\delta R)\|}{\|A\|}$$

Solving $A\vec{x} = \vec{b}$, Using Householder QR-Factorization

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Finally, the fourth term

$$\Delta A = \delta A + (\delta Q)\tilde{R} + \tilde{Q}(\delta R) + (\delta Q)(\delta R)$$

$$\frac{\|(\delta Q)(\delta R)\|}{\|A\|} \leq \|(\delta Q)\| \frac{\|(\delta R)\|}{\|A\|}$$

We know

$$\|(\delta Q)\| = \mathcal{O}(\epsilon_{\text{mach}}), \quad \text{and} \quad \frac{\|(\delta R)\|}{\|A\|} = \mathcal{O}(\epsilon_{\text{mach}})$$

So,

$$\frac{\|(\delta Q)(\delta R)\|}{\|A\|} = \mathcal{O}(\epsilon_{\text{mach}}^2)$$

Solving $A\vec{x} = \vec{b}$, Using Householder QR -Factorization

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We collect our findings, and note that as required

$$\frac{\|\Delta A\|}{\|A\|} \leq \frac{\|\delta A\|}{\|A\|} + \frac{\|(\delta Q)\tilde{R}\|}{\|A\|} + \frac{\|\tilde{Q}(\delta R)\|}{\|A\|} + \frac{\|(\delta Q)(\delta R)\|}{\|A\|} = \mathcal{O}(\epsilon_{\text{mach}}).$$

This completes the proof. \square

Solving $A\vec{x} = \vec{b}$, Using Householder QR-Factorization

8 of 8

We collect our findings, and note that as required

$$\frac{\|\Delta A\|}{\|A\|} \leq \frac{\|\delta A\|}{\|A\|} + \frac{\|(\delta Q)\tilde{R}\|}{\|A\|} + \frac{\|\tilde{Q}(\delta R)\|}{\|A\|} + \frac{\|(\delta Q)(\delta R)\|}{\|A\|} = \mathcal{O}(\epsilon_{\text{mach}}).$$

This completes the proof. \square

If we combine this result with the accuracy theorem we showed last time, we get the following result about the **accuracy** of solutions of $A\vec{x} = \vec{b}$ using the *Householder-Triangularization + Back-substitution algorithm*:

Accuracy of the Solution to $A\vec{x} = \vec{b}$ using Householder QR and Back-substitution

Theorem (Accuracy of the Solution to $A\vec{x} = \vec{b}$ using Householder QR-factorization and Back-substitution)

The solution \tilde{x} computed by the Householder-Triangularization + Back-substitution algorithm satisfies

$$\frac{\|\tilde{x} - \vec{x}\|}{\|\vec{x}\|} = \mathcal{O}(\kappa(A)\epsilon_{mach})$$

Patching Some Holes...

We have left three major holes in the argument — the statement, without proof, that the individual steps are backward stable.

It is instructive to see at least one such proof from “scratch.” —
Next, we turn our attention to the back-substitution algorithm.

Even though back substitution is one of the easiest problems of numerical linear algebra, the stability proof is quite lengthy... and provides the general structure / workflow for all such proofs.