Orthogonality

1. Two vectors $u$ and $v$ are orthogonal if $(u, v) = 0$.
2. A system of vectors $\{v_1, \ldots, v_n\}$ is orthogonal if $(v_i, v_j) = 0$ for $i \neq j$; and orthonormal if $(v_i, v_j) = \delta_{ij}$
3. A matrix is orthogonal if its columns are orthonormal
   - Notation: $V = [v_1, \ldots, v_n] = \text{matrix with column-vectors}$ $v_1, \ldots, v_n$.
   - Orthogonality is essential in understanding and solving least-squares problems.

Least-Squares systems

- Given: an $m \times n$ matrix $n < m$. Problem: find $x$ which minimizes:
  $$\|b - Ax\|_2$$
- Good illustration: Data fitting.

Typical problem of data fitting: We seek an unknown function as a linear combination $\phi$ of $n$ known functions $\phi_i$ (e.g. polynomials, trig. functions). Experimental data (not accurate) provides measures $\beta_1, \ldots, \beta_m$ of this unknown function at points $t_1, \ldots, t_m$. Problem: find the ‘best’ possible approximation $\phi$ to this data.

$$\phi(t) = \sum_{i=1}^n \xi_i \phi_i(t), \text{ s.t. } \phi(t_j) \approx \beta_j, j = 1, \ldots, m$$
Question: Close in what sense?

Least-squares approximation: Find $\phi$ such that

$$\phi(t) = \sum_{i=1}^{n} \xi_i \phi_i(t), \quad \& \quad \sum_{j=1}^{m} |\phi(t_j) - \beta_j|^2 = \text{Min}$$

In linear algebra terms: find 'best' approximation to a vector $b$ from linear combinations of vectors $f_i, i = 1, \ldots, n$, where

$$b = \begin{pmatrix} \beta_1 \\ \beta_2 \\ \vdots \\ \beta_m \end{pmatrix}, \quad f_i = \begin{pmatrix} \phi_i(t_1) \\ \phi_i(t_2) \\ \vdots \\ \phi_i(t_m) \end{pmatrix}$$

We want to find $x = \{\xi_i\}_{i=1}^{n}$ such that

$$\left\| \sum_{i=1}^{n} \xi_i f_i - b \right\|_2 \quad \text{Minimum}$$

Define

$$F = [f_1, f_2, \ldots, f_n], \quad x = \begin{pmatrix} \xi_1 \\ \xi_2 \\ \vdots \\ \xi_n \end{pmatrix}$$

This is a Least-squares linear system: $F$ is $m \times n$, with $m \geq n$.

Solution: $\phi_1(t) = 1; \quad \phi_2(t) = t; \quad \phi_3(t) = t^2$

- Evaluate the $\phi_i$'s at points $t_1 = -1; t_2 = 0; t_3 = 1; t_4 = 2$:

$$f_1 = \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \end{pmatrix}, \quad f_2 = \begin{pmatrix} -1 \\ 0 \\ 1 \\ 2 \end{pmatrix}, \quad f_3 = \begin{pmatrix} 1 \\ 0 \\ 1 \\ 4 \end{pmatrix} \rightarrow$$

So the coefficients $\xi_1, \xi_2, \xi_3$ of the polynomial $\xi_1 + \xi_2 t + \xi_3 t^2$ are the solution of the least-squares problem $\min \| b - Fx \|$ where:

$$F = \begin{pmatrix} 1 & -1 & 1 \\ 1 & 0 & 0 \\ 1 & 1 & 1 \\ 1 & 2 & 4 \end{pmatrix}, \quad b = \begin{pmatrix} -1 \\ 1 \\ 2 \\ 0 \end{pmatrix}$$

THEOREM. The vector $x_*$ minimizes $\psi(x) = \| b - Fx \|^2_2$ if and only if it is the solution of the normal equations:

$$F^T F x = F^T b$$
Proof: Expand out the formula for $\psi(x_* + \delta x)$:

$$\psi(x_* + \delta x) = ((b - Fx_*) - F\delta x)^T((b - Fx_*) - F\delta x)$$

$$= \psi(x_*) - 2(F\delta x)^T(b - Fx_*) + (F\delta x)^T(F\delta x)$$

$$= \psi(x_*) - 2(\delta x)^T[F^T(b - Fx_*)] + (F\delta x)^T(F\delta x)$$

Can see that $\psi(x_* + \delta x) \geq \psi(x_*)$ for any $\delta x$, iff the boxed quantity [the gradient vector] is zero. Q.E.D.

Illustration of theorem: $x^*$ is the best approximation to the vector $b$ from the subspace $\text{span}\{F\}$ if and only if $b - Fx^*$ is $\perp$ to the whole subspace $\text{span}\{F\}$. This in turn is equivalent to $F^T(b - Fx^*) = 0$ $\Rightarrow$ Normal equations.

Example:

1) Approximations by polynomials of degree one:

$\phi_1(t) = 1$, $\phi_2(t) = t$.

$$F = \begin{pmatrix}
1.0 & -1.0 \\
1.0 & -0.5 \\
1.0 & 0 \\
1.0 & 0.5 \\
1.0 & 1.0
\end{pmatrix}$$

$$F^TF = \begin{pmatrix}
5.0 & 0 \\
0 & 2.5
\end{pmatrix}$$

$$F^Tb = \begin{pmatrix}
0.9 \\
-0.15
\end{pmatrix}$$

Best approximation is $\phi(t) = 0.18 - 0.06t$. 
2) Approximation by polynomials of degree 2:
- \( \phi_1(t) = 1, \phi_2(t) = t, \phi_3(t) = t^2. \)
- Best polynomial found: 
  \[
  0.3085714285 - 0.06 \times t - 0.2571428571 \times t^2
  \]

**Finding an orthonormal basis of a subspace**
- Goal: Find vector in \( \text{span}(X) \) closest to \( b \).
- Much easier with an orthonormal basis for \( \text{span}(X) \).

**Problem:** Given \( X = [x_1, \ldots, x_n] \), compute \( Q = [q_1, \ldots, q_n] \) which has orthonormal columns and s.t. \( \text{span}(Q) = \text{span}(X) \).

- Note: each column of \( X \) must be a linear combination of certain columns of \( Q \).
- We will find \( Q \) so that \( x_j \) (\( j \) column of \( X \)) is a linear combination of the first \( j \) columns of \( Q \).

**Algorithm : 1. Classical Gram-Schmidt**
1. For \( j = 1, \ldots, n \) Do:
2. Set \( \hat{q} := x_j \)
3. Compute \( r_{ij} := (\hat{q}, q_i) \), for \( i = 1, \ldots, j - 1 \)
4. For \( i = 1, \ldots, j - 1 \) Do:
5. Compute \( \hat{q} := \hat{q} - r_{ij}q_i \)
6. EndDo
7. Compute \( r_{jj} := \|\hat{q}\|_2 \)
8. If \( r_{jj} = 0 \) then Stop, else \( q_j := \hat{q}/r_{jj} \)
9. EndDo

- All \( n \) steps can be completed iff \( x_1, x_2, \ldots, x_n \) are linearly independent.
- Prove this result
Lines 5 and 7-8 show that
\[ x_j = r_{1j}q_1 + r_{2j}q_2 + \ldots + r_{jj}q_j \]

If \( X = [x_1, x_2, \ldots, x_n] \), \( Q = [q_1, q_2, \ldots, q_n] \), and if \( R \) is the \( n \times n \) upper triangular matrix
\[ R = \{r_{ij}\}_{i,j=1}^{n} \]
then the above relation can be written as
\[ X = QR \]

\( R \) is upper triangular, \( Q \) is orthogonal. This is called the QR factorization of \( X \).

What is the cost of the factorization when \( X \in \mathbb{R}^{m \times n} \)?

Better algorithm: Modified Gram-Schmidt.

**ALGORITHM : 2. Modified Gram-Schmidt**

1. For \( j = 1, \ldots, n \) Do:
2. Define \( \hat{q} := x_j \)
3. For \( i = 1, \ldots, j - 1 \), Do:
4. \( r_{ij} := (\hat{q}, q_i) \)
5. \( \hat{q} := \hat{q} - r_{ij}q_i \)
6. EndDo
7. Compute \( r_{jj} := \|\hat{q}\|_2 \),
8. If \( r_{jj} = 0 \) then Stop, else \( q_j := \hat{q}/r_{jj} \)
9. EndDo

Only difference: inner product uses the accumulated subsum instead of original \( \hat{q} \)

The operations in lines 4 and 5 can be written as
\[ \hat{q} := ORTH(\hat{q}, q_i) \]
where \( ORTH(x, q) \) denotes the operation of orthogonalizing a vector \( x \) against a unit vector \( q \).
Modified Gram-Schmidt algorithm is much more stable than classical Gram-Schmidt in general.

Suppose MGS is applied to $A$ yielding computed matrices $\hat{Q}$ and $\hat{R}$. Then there are constants $c_i$ (depending on $(m, n)$) such that

$$A + E_1 = \hat{Q} \hat{R} \quad \|E_1\|_2 \leq c_1 u \|A\|_2$$

$$\|\hat{Q}^T \hat{Q} - I\|_2 \leq c_2 u \kappa_2(A) + O((u \kappa_2(A))^2)$$

for a certain perturbation matrix $E_1$, and there exists an orthonormal matrix $Q$ such that

$$A + E_2 = Q \hat{R} \quad \|E_2(:, j)\|_2 \leq c_3 u \|A(:, j)\|_2$$

for a certain perturbation matrix $E_2$.

An equivalent version:

**ALGORITHM : 3, Modified Gram-Schmidt - 2 -**

0. Set $\hat{Q} := X$
1. For $i = 1, \ldots, n$ Do:
   2. Compute $r_{ii} := \|\hat{q}_i\|_2$, 
   3. If $r_{ii} = 0$ then Stop, else $q_i := \hat{q}_i / r_{ii}$
   4. For $j = i + 1, \ldots, n$, Do:
      5. $r_{ij} := (\hat{q}_j, q_i)$
      6. $\hat{q}_j := \hat{q}_j - r_{ij} q_i$
   7. EndDo
8. EndDo

Does exactly the same computation as previous algorithm, but in a different order.

Example:

Orthonormalize the system of vectors:

$$X = [x_1, x_2, x_3] = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 0 \\ 1 & 0 & -1 \\ 1 & 0 & 4 \end{pmatrix}$$

Answer:

$$q_1 = \begin{pmatrix} 1 \\ \frac{1}{2} \\ -\frac{1}{2} \\ \frac{1}{2} \end{pmatrix} \quad ; \quad \hat{q}_2 = x_2 - (x_2, q_1)q_1 = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} - 1 \times \begin{pmatrix} 1 \\ \frac{1}{2} \\ -\frac{1}{2} \end{pmatrix} = \begin{pmatrix} \frac{1}{2} \\ -\frac{1}{2} \\ \frac{1}{2} \end{pmatrix}$$

$$\hat{q}_2 = \begin{pmatrix} \frac{1}{2} \\ \frac{1}{2} \\ -\frac{1}{2} \\ -\frac{1}{2} \end{pmatrix} \quad ; \quad q_2 = \begin{pmatrix} \frac{1}{2} \\ \frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}$$
\[ \hat{q}_3 = x_3 - (x_3, q_1)q_1 = \begin{pmatrix} 1 \\ 0 \\ -1 \\ 4 \end{pmatrix} - 2 \times \begin{pmatrix} 1/2 \\ 1/2 \\ 1/2 \end{pmatrix} = \begin{pmatrix} 0 \\ -1 \\ -2 \\ 3 \end{pmatrix} \]

\[ \hat{q}_3 = \hat{q}_3 - (\hat{q}_3, q_2)q_2 = \begin{pmatrix} 0 \\ -1 \\ -2 \\ 3 \end{pmatrix} - (-1) \times \begin{pmatrix} 1/2 \\ 1/2 \\ 1/2 \end{pmatrix} = \begin{pmatrix} 1/2 \\ -1/2 \\ -2.5 \\ 2.5 \end{pmatrix} \]

\[ \|\hat{q}_3\|_2 = \sqrt{13} \rightarrow q_3 = \frac{\hat{q}_3}{\|\hat{q}_3\|_2} = \frac{1}{\sqrt{13}} \begin{pmatrix} 1/2 \\ -1/2 \\ -2.5 \\ 2.5 \end{pmatrix} \]

For this example: what is \( Q \)? what is \( R \)? Compute \( Q^T Q \).

Result is the identity matrix.

Recall: For any orthogonal matrix \( Q \), we have

\[ Q^T Q = I \]

(In complex case: \( Q^H Q = I \)).

Consequence: For an \( n \times n \) orthogonal matrix \( Q \), \( Q^{-1} = Q^T \).

\( Q \) is orthogonal/ unitary)

Use of the QR factorization

Problem: \( Ax \approx b \) in least-squares sense

\( A \) is an \( m \times n \) (full-rank) matrix. Let

\[ A = QR \]

the QR factorization of \( A \) and consider the normal equations:

\[ A^T Ax = A^T b \rightarrow R^T Q^T QRx = R^T Q^T b \rightarrow R^T Rx = R^T Q^T b \rightarrow Rx = Q^T b \]

\( (R^T \) is an \( n \times n \) nonsingular matrix). Therefore,

\[ x = R^{-1} Q^T b \]
Also observe that for any vector $w$

$$w = QQ^Tw + (I - QQ^T)w$$

and that $QQ^Tw \perp (I - QQ^T)w \rightarrow$

Pythagoras theorem $\rightarrow$

$$\|w\|_2^2 = \|QQ^Tw\|_2^2 + \|(I - QQ^T)w\|_2^2$$

Min is reached when 2nd term of r.h.s. is zero.

Method:
- Compute the QR factorization of $A$, $A = QR$.
- Compute the right-hand side $f = QTb$.
- Solve the upper triangular system $Rx = f$.
- $x$ is the least-squares solution.

As a rule it is not a good idea to form $AT A$ and solve the normal equations. Methods using the QR factorization are better.

Total cost?? (depends on the algorithm used to get the QR decomposition).

Using matlab find the parabola that fits the data in previous data fitting example (p. 7-9) in L.S. sense [verify that the result found is correct.]
Application: another method for solving linear systems.

\[ Ax = b \]

\( A \) is an \( n \times n \) nonsingular matrix. Compute its QR factorization.

- Multiply both sides by \( QT \) → \( QTQRx = QTb \) → 

\[ Rx = QTb \]

Method:

- Compute the QR factorization of \( A, A = QR \).
- Solve the upper triangular system \( Rx = QTb \).

Cost??