



Hierarchical Matrices and Inexact GMRES

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Chapter 1

Iterative Methods and Krylov's Subspace

1.1 Iterative Methods and motivation

Iterative methods appear as an alternative to exact solution methods, where the true solution is not desired and a good approximation is enough.

The idea is to find, after a certain number of iterations, a sequence x_k that converges to x , the correct solution of the problem 1.1.

$$x = \lim_{k \rightarrow \infty} x_k \quad (1.1)$$

The method stops after k iterations, where x_k is the first element of the sequence to satisfy the condition 1.2.

$$\frac{\|x_k - x\|}{\|x\|} \leq \epsilon \quad (1.2)$$

Where ϵ is a tolerance defined by who is applying the algorithm.

Usually x isn't known, so 1.2 gets modified for 1.3, where A is the system's matrix and b is the RHS(right hand side).

$$\frac{\|Ax_k - b\|}{\|b\|} \leq \epsilon \quad (1.3)$$

The first iterative methods used a decomposition of A as a combination of two matrices 1.4, where A_1 isn't singular, and each iteration is defined as 1.5.

$$A = A_1 - A_2 \quad (1.4)$$

$$A_1 x_{k+1} = b + A_2 x_k \quad (1.5)$$

With a substitution of the others x_k , 1.5 gives 1.6, which converges for every initial solution if and only lff $\rho(A_2 A_1^{-1}) < 1$, or $\rho(X)$ is the spectral radius of X [2].

$$x_{k+1} = A_1^{-1}(b + A_2 x_k) = A_1^{-1}(b + A_2 A_1^{-1}(b + A_2 x_{k-1})) \dots = A_1^{-1} \left[\sum_{i=0}^k (A_2 A_1^{-1})^i b \right] \quad (1.6)$$

If $A_1 = I$ and $A_2 = I - A$ in 1.4, the sequence found in 1.6 is: $x_1 = b, x_2 = 2b - Ab, x_3 = 3b - 3Ab + A^2b, \dots$

Even if the condition $\rho(A - I) \leq 1$ is strong [2], it shows that one approximation x_k could be represented as 1.7.

$$x_k \in \text{span}(b, Ab, A^2b, \dots, A^{k-1}b) \quad (1.7)$$

1.2 Krylov's Subspace

Be $A \in \mathbb{K}^{n \times n}$ a matrix and $b \in \mathbb{K}^n$. To each $k \leq n$ the Krylov's Subspace $\mathcal{K}_k = \mathcal{K}_k(A, b)$ associated to A,b is defined as 1.8.

$$\mathcal{K}_k(A, b) = \text{span}(b, Ab, A^2b, \dots, A^{k-1}b) \quad (1.8)$$

These Subspaces also have the following property: $k < l \rightarrow \mathcal{K}^k \subset \mathcal{K}^l$ [2].

The subspace $\mathcal{K}_k(A, b)$ is also the subspace of all the vectors from \mathbb{R}^m which could be written as $x = p(A)b$, where $p(A)$ is a polynom of degree less than $k - 1$ which $p(0) = 1$.

The problem with using $A^k b, k \in 0, 1, 2, \dots$ as a base comes from the fact that successive products of A make vectors that are *approximately colinears*, since those are really close of the eigenvector with the biggest eigenvalue of A .

1.3 Arnoldi's Method

With the task of obtaining an orthonormal basis to $\mathcal{K}_k(A, b)$, the method searches for a unitary matrix Q for which the expression 1.9 is valid. $H_k = h_{ij}$ is an Hessenberg's matrix.

$$AQ_k = Q_{k+1}H_k \quad (1.9)$$

For each column-vector of Q , q_i , 1.9 could be written as 1.10, where the representation of $\mathcal{K}_k(A, b)$ with an orthonormal basis becomes more evident. In a pratical application, Q est initialized with $q_1 = \frac{b}{\|b\|}$.

$$Aq_m = h_{1m}q_1 + h_{2m}q_2 + \dots h_{m+1,m}q_{m+1} \quad (1.10)$$

An algorithm for the method can be found in 1.

Algorithm 1 Arnoldi's iteration

```

1:  $A \in \mathbb{K}^{n \times n}$  et  $b \in \mathbb{K}^n$ 
2:  $x = 0, \beta = \|b\|, q_1 = \frac{b}{\beta}$ 
3: for  $j = 1, 2, \dots, k$  do
4:    $q_{j+1} = Aq_j$ 
5:   for  $i = 1, 2, \dots, j$  do
6:      $h_{ij} = q_{j+1}^t q_i$ 
7:      $q_{j+1} = q_{j+1} - h_{ij} q_i$ 
8:   end for
9:    $h_{j+1,j} = \|q_{j+1}\|$ 
10:   $q_{j+1} = \frac{q_{j+1}}{h_{j+1,j}}$ 
11: end for

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Chapter 2

GMRES

A projection in $\mathcal{K}_k(A, b)$, where the different approximations are taken as in 2.1, where Q_m is the vector in 1.9.

$$x = x_0 + Q_m y \quad (2.1)$$

With 2.1 and 1.9 the residue becomes 2.2, where $x_0 = 0$, $\beta = \|b\|$ and $Q_{m+1}^t b = (\|b\| \ 0 \ 0 \dots)^t$ since the columns of Q_{m+1} are orthonormal vectors and $q_1 = \frac{b}{\|b\|}$.

$$\begin{aligned} r(y) &= \|b - Ax\| \\ &= \|b - A(Q_m y)\| \\ &= \|b - Q_{m+1} H_m y\| \\ &= \|Q_{m+1} (Q_{m+1}^t b - H_m y)\| \\ &= \|\beta e_1 - H_m y\| \end{aligned} \quad (2.2)$$

Thus, y which appears in 2.1, is found as the solution of the residual's minimisation problem in 2.2.

$$y = \min_y \|\beta e_1 - H_m y\| \quad (2.3)$$

An initial version of the GMRES is in 2. The lines 4 to 12 bring the Arnoldi's Method presented in 1.

However, 2 doesn't bring an efficient way of finding the residual in each iteration. To solve this problem and also to find a more efficient way of solving the least squares problem in 2.3, a transformation is applied to H_m , turning it into a triangular matrix.

2.1 Givens's Rotation

Givens's operator, $G(i, i+1)$, is a unitary matrix such that the column vector $a = Gb$ has the elements $a(i) = r \in \mathbb{R}$ and $a(i+1) = 0$. It has a structure as in 2.4. The coefficients c_i, s_i only appear in the rows i et $i+1$.

Algorithm 2 Initial GMRES

```

1:  $A \in \mathbb{K}^{n \times n}$  and  $b \in \mathbb{K}^n$ 
2:  $x = 0, \beta = \|b\|, q_1 = \frac{b}{\beta}$ 
3: for  $k = 1, 2, \dots$  do
4:   for  $j = 1, 2, \dots, k$  do
5:      $q_{j+1} = Aq_j$ 
6:     for  $i = 1, 2, \dots, j$  do
7:        $h_{ij} = q_{j+1}^t q_i$ 
8:        $q_{j+1} = q_{j+1} - h_{ij} q_i$ 
9:     end for
10:     $h_{j+1,j} = \|q_{j+1}\|$ 
11:     $q_{j+1} = \frac{q_{j+1}}{h_{j+1,j}}$ 
12:  end for
13:  Find  $y = \min_y \|\beta e_1 - H_m y\|$ 
14:   $x = Q_k y$ 
15:  Stop if the residual is smaller than the tolerance
16: end for

```

$$G(i, i+1) = \begin{bmatrix} 1 & & & & & & \\ & \ddots & & & & & \\ & & 1 & & & & \\ & & & c_i & s_i & & \\ & & & -s_i & c_i & & \\ & & & & & 1 & \\ & & & & & & \ddots \\ & & & & & & & 1 \end{bmatrix} \quad (2.4)$$

This operator offers a way to transform the columns in H_m , *zeroing* the elements outside the main diagonal. Since a product of unitary operators is still unitary, 2.3 can be written as 2.5, where R_m and g_m are the results from the application of multiple Givens's operators to H_m and βe_1 .

$$y = \min_y \|\beta e_1 - H_m y\| = \min_y \|g_m - R_m y\| \quad (2.5)$$

It can be shown that g_m contains the residual of each iteration [4].

Thus, the new problem 2.5 can be solved with a simple backwards substitution.

(écrire le nouvel algorithme)

2.2 Inexact GMRES

The heaviest part in the code is in the matrix-vector product 1, line 4. Therefore, one approach to accelerate the iterations involves an approximation of Aq , instead of using the exact answer, as shown in 2.6.

$$\mathcal{A}q = (A + E)q \quad (2.6)$$

Where E in 2.6 is a *perturbation matrix* that changes with each iteration and will be written as E_k

for iteration k .

When the matrix-vector product isn't exact, the left side of 1.9 must be changed by 2.7.

$$\begin{aligned} [(A + E_1)q_1, (A + E_2)q_2, \dots, (A + E_k)q_k] &= Q_{k+1}H_k \\ (A + \mathcal{E}_k)Q_k &= Q_{k+1}H_k, \quad \mathcal{E}_k = \sum_{i=1}^k E_i q_i q_i^t \\ \mathcal{A}Q_k &= Q_{k+1}H_k \end{aligned} \tag{2.7}$$

Now the subspace spanned by the vectors of Q_k is not a Krylov's subspace, but these are still orthonormal.

The expression 2.7 also shows that Q_k becomes a basis for a Krylov's subspace, $\mathcal{K}_k(A + \mathcal{E}_k, b)$, made by a big perturbation in A , that gets updated in each iteration.

Using r_k , the exact residue, and \tilde{r}_k , the residue from the Inexact GMRES's k -th iteration, it can be shown [5] that if E_k satisfies the relation 2.8, then the two residues satisfy 2.9.

$$\|E_k\| \leq \frac{\sigma_k(\hat{H}_k)}{k} \frac{1}{\|\tilde{r}_k\|} \epsilon \tag{2.8}$$

$$\|r_k - \tilde{r}_k\| \leq \epsilon \tag{2.9}$$

In 2.8, \hat{H}_k is the upper triangular matrix got after Givens's rotations in H_k and σ_k is the k -th singular value of a given matrix.

Chapter 3

Hierarchical Matrices and ACA Method

3.1 Low-rank Matrices

In reality, most matrices are big, so storing each element is not efficient, or even possible. If $A \in \mathbb{C}^{n \times m}$ has a rank k such that $k \leq m$ and $k(n+m) < n * m$ (A is low-rank), A can be written in outer product form, as a product between the matrices $U \in \mathbb{C}^{n \times k}$ and $V \in \mathbb{C}^{m \times k}$, which can be seen in 3.1, where u_i, v_i are the column vectors of U and V .

$$A = UV^H = \sum_{i=1}^k u_i v_i^* \quad (3.1)$$

Therefore, storing $k(n+m)$ elements to write A , and not $n \times m$. A matrix A that can be represented as 3.1 is an element of $\mathbb{C}_k^{n \times m}$.

The representation in 3.1 also facilitates other operations with A , like matrix-vector products Ab that are always present in methods like GMRES [1] and different kinds of norms, like $\|A\|_F, \|A\|_2$ [1].

However, even full rank matrices can be approximated by matrices with lower rank. A theorem [1] establishes that the closest matrix from $\mathbb{C}_k^{n \times m}$ of a matrix from $\mathbb{C}^{n \times m}$ can be obtained from the SVD $A = U\Sigma V^H$, where Σ contains the singular values $\sigma_1 \geq \sigma_2 \dots \sigma_m \geq 0$ and U, V are unitary. If A_k is the approximation obtained after taking the first k elements of Σ (creating the matrix Σ_k), the error between A and A_k is 3.2.

$$\|A - A_k\| = \left\| U\Sigma V^H - U'\Sigma_k V_H \right\| = \|\Sigma - \Sigma_k\| \quad (3.2)$$

If the spectral norm, $\|\cdot\|_2$ is used instead, the error in 3.2 is given by σ_{k+1} . For Frobenius's norm, $\|\cdot\|_F$, the error becomes $\sum_{l=k+1}^n \sigma_l^2$.

Instead of approximating big matrices entirely, it's better to think in approximations made to each of their blocks. Blocks that appear after the discretization of elliptic operators also have the possibility of being approximated by matrices that decay exponentially with k , S_k , as in 3.3.

$$\|A - S_k\|_2 < q^k \|A\|_2 \quad (3.3)$$

That way, the rank and the precision are related in a logarithmic manner, and the rank required by a certain ϵ is 3.4.

$$k(\epsilon) = \min\{k \in \mathbb{N} : \sigma_{k+1} < \epsilon \sigma_1\} \quad (3.4)$$

3.2 ACA Method(Adaptative Cross Approximation)

As shown in the last section, the SVD methods gives us an approximation of A given a certain ϵ , through the relation in 3.2. Nevertheless, this is an expensive method, where the complexity becomes too big for some calculations.

The algorithm for the method is in 3, where a_{ij} are the elements of a matrix $A \in \mathbb{R}^{n \times m}$. The main objective is to approximate A as $A = S_k + R_k$, $S_k = \sum_{l=1}^k u_l v_l^t$ and R_k is the residue.

Algorithm 3 ACA Method

```

1:  $k = 1$  et  $\mathbf{Z} = \emptyset$ 
2: repeat
3:   TFind  $i_k$ 
4:    $\hat{v}_k = a_{i_k, 1:m}$ 
5:   for  $l = 1, \dots, k-1$  do
6:      $\hat{v}_k = \hat{v}_k - (u_l)_{i_k} v_l$ 
7:   end for
8:    $Z = Z \cup \{i_k\}$ 
9:   if  $\hat{v}_k$  doesn't disappear then
10:     $j_k = \operatorname{argmax}_j |(\hat{v}_k)_j|$  ;  $v_k = (\hat{v}_k)_{j_k}^{-1} \hat{v}_k$ 
11:     $u_k = a_{1:n, j_k}$ 
12:    for  $l = 1, \dots, k-1$  do
13:       $u_k = u_k - (v_l)_{j_k} u_l$ 
14:    end for
15:     $k = k + 1$ 
16:  end if
17: until  $\|u_k\| \|v_k\| \leq \epsilon$ 

```

Considering $I, J \in \mathbb{N}$ the index set of a given matrix and $\mathbf{T}_{I \times J}$ the cluster block tree that contains an admissible partition P of $I \times J$ in its leaves, $\mathfrak{L}(\mathbf{T}_{I \times J})$. The set of hierarchical matrices in $\mathbf{T}_{I \times J}$ rank k for each block A_b defined in 3.5.

$$\mathfrak{H}(\mathbf{T}_{I \times J}, k) = \{A \in \mathbb{C}^{I \times J} : \operatorname{rank} A_b \leq k, \forall b \in P\} \quad (3.5)$$

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