Notes for Ma221 Lecture 11, Nov 7, 2024

Chapters 6 and 7: Introduction to Iterative Methods for A*x=b and A*x = lambda*x, and the Poisson Equation, our “model problem”

Goals:
Contrast direct and iterative methods
  For Ax=b or least squares: Use iterative methods when direct methods
    are too slow, or use too much memory (from fill-in during factorization),
    or you don't need as much accuracy.
  For eigenproblems or SVD: Use iterative methods for the above reasons,
    or when only a few eigenvalues/vectors are desired.
A good iterative method exploits knowledge of the underlying
physical or mathematical model that gives rise to matrix.
  Large diversity of methods and software tools exist, no one is best.
    See the class web page for pointer to software.
  Model problem to compare methods: Poisson equation in 2D or 3D
    Arises in electrostatics, heat flow, quantum mechanics,
      incompressible fluid mechanics, graph theory, ...
    Summary of iterative methods as applied to Model problem,
      from simple (slow) to sophisticated (fast):
      (1) Simple ones apply to more problems than Model problem
      (2) Simple ones are building blocks for more sophisticated ones

Methods covered:
  (1) "Splitting Methods"
    "Split" A = M - K with M nonsingular, so A*x=b becomes M*x = K*x+b
    Then we iterate: Solve M*x(i+1) = K*x(i) + b for x(i+1).
    To see how it converges, subtract M*x = K*x+b, let e(i) = x(i)-x, so
    M*e(i+1) = K*e(i) or e(i+1)=inv(M)*K*e(i) = (inv(M)*K)^(i+1)*e(0).
    It is easy to implement if solving with M is cheap.
    It converges (fast) if (inv(M)*K)^i -> 0 (fast).
    We will consider 3 classical splitting methods:
    Jacobi, Gauss-Seidel, and Successive Overrelaxation (SOR)
  (2) Krylov Subspace Methods (KSMs):
    What can you do if all you have access to is a subroutine that computes
    A*x for any x? Or if A is so big that A*x is all you can afford to do?
    Then what a KSM does may be described as follows, starting with x(0)
      1) Compute x(1) = A*x(0), x(2) = A*x(1), ... x(k) = A*x(k-1)
        (or a similar set of vectors that span the same subspace).
      2) Choose the linear combination sum_{i=0 to k} a(i)*x(i) that "best"
        approximates the answer (for some definition of "best").
      3) If the approximation is not good enough, increase k and repeat.

Depending on
how the set of vectors is computed,
properties of A (eg symmetry, positive definiteness, ...) and
the definition of "best approximation"
one gets a large number of different algorithms, all used in practice:
Conjugate Gradients (CG), generalized minimum residuals (GMRES), and many
more that we won't discuss in detail.
Instead of asking for the "best approximation" to A*x=b, one can instead
ask for the best approximation to A*x = lambda*x; this yields the eigenvalue
algorithms discussed in Chapter 7.

(3) Preconditioning. How fast do the above methods for A*x=b converge?
It depends on a variety of sometimes subtle properties of A, but it should be`
no surprise that KSMs on well-conditioned matrices generally converge much
faster than on ill-conditioned matrices. But suppose we can find a
"preconditioner", i.e. a matrix M where (1) M*A is well conditioned, and
(2) multiplying by M is cheap. Then one applies the KSM to solve M*A*x = M*b.
Finding good preconditioners can depend in complicated ways on A.
And it is not always straightforward to use them. For example, CG depends on
A being s.p.d., whereas M*A will rarely be symmetric. Still it is possible
to reorganize CG to be able to use preconditioners.

(4) Multigrid: This is one of the most effective preconditioners for problems
with a suitable mathematical structure. If your matrix
arises from solving a physical problem, say Poisson's equation, it is
straightforward to find an approximation with, say, half as many mesh
points in each direction, and use the solution of that smaller, and so
easier, problem (eg 1/4 the dimension in 2D), as a preconditioner.
But if the dimension n is very large, so is n/4. So we just apply the
same idea recursively, using a problem of size n/16 to get a starting guess
for the problem of size n/4, etc. When multigrid works, it can be optimal,
solving an nxn linear system in O(n) flops. But not every problem has the
structure that permits this.

(5) Domain decomposition. This can be thought of as a way to hybridize the
above methods, using different methods in different "domains" or submatrices,
where A may be easier to work with than as a whole.

Optimizing performance

Most methods assume the only thing you can afford to do is y=A*x.
Computing A*x is generally the bottleneck, and usually because of communication:
For example, if A is too large to fit in cache, it needs to be read out of
main (slow) memory every iteration, with only one multiplication and addition
per entry. So recent work has addressed communication-avoiding KSMs, where methods
like CG are redesigned to take s>1 steps for each access of A, instead of 1 step.
See links on the class webpage for details.

Our Model Problem: Poisson's Equation
1D with Dirichlet boundary conditions
  -d^2 v(x)/d x^2 = f(x) on (0,1) with v(0)=v(1)=0
Recalling Lecture 6 (on Gaussian elimination for matrices with structure),
discretizing this yields
  T_N * [v_1;...;v_N] = T_N * v = h^2*[f_1;...;f_N] = h^2*f
where T_N is tridiagonal with diagonals = 2 and offdiagonals = -1.
This is often referred to as a "stencil" on a 1D mesh. (draw)

Eigenvalues and eigenvectors of T_N
Lemma: T_N * z_j = lambda_j * z_j where lambda_j = 2*(1 - cos(pi*j/(N+1)))
  z_j(k) = sqrt(2/(N+1)) * sin(j*k*pi/(N+1)) and ||z_j||_2 = 1
  Proof: Trigonometry (homework Question 6.1)
Corollary: The matrix Z where Z_jk = sqrt(2/(N+1))*sin(j*k*pi/(N+1))
  is orthogonal (related to FFT-Fast Fourier Transform matrix later)

(see Fig 6.1 in text (graph711.eps) for eigenvalues,
Fig 6.2 in text (graph712.eps) for eigenvectors)

Eigenvalues range from smallest lambda_j ~ (pi*j/(N+1))^2 for small j
to largest lambda_N ~ 4

This tells us the condition number of T_N,
  lambda_N/lambda_1 ~ (2(N+1)/pi)^2 = (2/pi)^2*h^(-2)

2D with Dirichlet boundary conditions
  -d^2 v(x,y) / dx^2 - d^2 v(x,y) / dy^2 = f(x,y) on square (0,1)^2,
  with v(x,y)=0 on boundary of square
Discretizing as before and writing v_ij for v(i*h,j*h) we get
  4*v_ij - v_i-1,j - v_i+1,j - v_i,j-1 - v_i,j+1 = h^2*f_ij
This is often referred to as a "stencil" on a 2D mesh. (draw)
Letting V be the NxN matrix of v_ij, we can also write
  2*v_ij - v_i-1,j - v_i+1,j = (T_N*V)_ij
  2*v_ij - v_i,j-1 - v_i,j+1 = (V*T_N)_ij
or
  4*v_ij - v_i-1,j - v_i+1,j - v_i,j-1 - v_i,j+1 = (T_N*V + V*T_N)_ij
and
  T_N*V + V*T_N = h^2*F
a system of N^2 linear equations for the N^2 entries of V, though
not in the usual "A*x=b" form. (See Q4.6 in the text, on the Sylvester Equation.)

We can ask about the corresponding eigenvalues and eigenvectors
in the analogous form

```
        T_N*V + V*T_N = lambda*V
```
Suppose that T_N*z_i = lambda_i*z_i and T_N*z_j = lambda_j*z_j
are any two eigenpairs of T_N. Letting V = z_i * z_j^T , we get
```
        T_N*V + V*T_N = T_N*z_i*z_j^T + z_i*z_j^T*T_N
                      = (T_N*z_i)*z_j^T + z_i*(z_j^T*T_N)
                      = (lambda_i*z_i)*z_j^T + z_i*(z_j^T*lambda_j)
                      = (lambda_i + lambda_j)*(z_i*z_j^T)
                      = ( lambda_i + lambda_j ) * V
```
so that V is an "eigenvector". Since there are N^2 unknowns,
we expect N^2 eigenpairs, for all possible sums of pairs lambda_i + lambda_j.

We want to write V as a single vector in a way that easily extends
to higher dimensional Poisson equations:
In the 3x3 case, write V columnwise from left to write as:
```
         v = [ v_11; v_21; v_31; v_12; v_22; v_32; v_13; v_23; v_33 ]
```
and T_NxN as
```
        [  4 -1  0 -1                ]
        [ -1  4 -1    -1             ]
        [  0 -1  4       -1          ]
        [ -1        4 -1  0 -1       ]
        [    -1    -1  4 -1    -1    ]
        [       -1  0 -1  4       -1 ]
        [          -1        4 -1  0 ]
        [             -1    -1  4 -1 ]
        [                -1  0 -1  4 ]
```
The pattern is that in each row, the
```
          4  on the diagonal multiplies v_ij,
         -1s next to the diagonal multiply v_i-1,j and v_i+1,j
         -1s N away from the diagonal multiply v_i,j-1 and v_i,j+1
```
Note that some rows have fewer than 4 -1s, when these are
on the boundary of the square. One may confirm that
```
        T_NxN * v = h^2*f
```
Another way to write T_NxN is
```
        T_NxN = [ T_N + 2*I_N    -I_N                        ]
                [      -I_N     T_N + 2*I_N   -I_N           ]
                [                   ...                      ]
                [                     -I_N    T_N + 2*I_N    ]
```
a pattern we will generalize to arbitrary dimensions, using Kronecker products.

Poissons's equation in d dimensions.

We need to convert arrays most naturally indexed by 2 or more indices
(like V above) into vectors.

Def: Let X be mxn, then vec(X) is the m*n x 1 vector gotten by stacking
the columns of X atop one another, from left to right.
(In Matlab, vec(X) = reshape(X,m*n,1))

Def: Let A be mxn and B be pxq, then A kron B is the m*p x n*q matrix

```
[ A_11*B   A_12*B   ... A_1n*B  ]
[ A_21*B   A_22*B   ... A_2n*B  ]
[                   ...         ]
[ A_m1*B  A_m2*B    ... A_mn*B ]
```

which is called the Kronecker product of A and B. In Matlab, A kron B = kron(A,B).

Lemma: Let A be mxm, B be nxn and X be mxn, then
1. vec(A*X) = (I_n kron A) * vec(X)
2. vec(X*B) = (B^T kron I_m) * vec(X)
3. The 2D Poisson equation T_N*V + V*T_N = h^2*F may be written
   (I_N kron T_N + T_N kron I_N) * vec(V) = h^2*vec(F)

Proof of 1: I_n kron A = diag(A,A,...,A) n times so (I_n kron A) * vec(X)
= diag(A,A,...,A)*[X(:,1); X(:,2); ... ; X(:,n)]
= [A*X(:,1); A*X(:,2); ... ; A*X(:,n)]
= vec(A*X)

Proof of 2: similar (homework, question 6.4)

Proof of 3: Apply part 1 to T_N*V and part 2 to V*T_N, noting that T_N is
symmetric.

Note that

```
I_N kron T_N  +  T_N kron I_N  =
  [ T_N                ] + [ 2*I_N    -I_N                ]
  [        T_N         ]   [   -I_N  2*I_N   -I_N         ]
  [              ...   ]   [                   ...        ]
  [                T_N ]   [                  -I_N  2*I_N ]
```

In Matlab, this is two lines:

```
TN = 2*eye(N) - diag(ones(N-1,1),-1) - diag(ones(N-1,1),+1)
TNN = kron(eye(N),TN) + kron(TN,eye(N))
```

Lemma (homework, question 6.4)
(1) Assume that A*C and B*D are well defined.
Then (A kron B)*(C kron D) = (A*C) kron (B*D)
(2) If A and B are invertible then (A kron B)^(-1) = A^(-1) kron B^(-1)
(3) (A kron B)^T = A^T kron B^T

Prop: Let T = Z*Lambda*Z^T be the eigendecomposition
of the NxN symmetric matrix T. Then the eigendecomposition of
I kron T + T kron I

```
       = (Z kron Z) * (I kron Lambda + Lambda kron I) * (Z^T kron Z^T)
     where I kron Lambda + Lambda kron I is a diagonal matrix whose
     ((i-1)*N+j)th diagonal entry is lambda_i + lambda_j, and
     Z kron Z is orthogonal with ((i-1)*N+j)th column z_i kron z_j.

  Proof: Multiply out the factorization using the last lemma to get
      (Z kron Z) * (I kron Lambda + Lambda kron I) * (Z^T kron Z^T)
        = (Z*I kron Z*Lambda + Z*Lambda kron Z*I) * ( Z^T kron Z^T)
        = (Z*I*Z^T kron Z*Lambda*Z^T + Z*Lambda*Z^T kron Z*I*Z^T)
        = (I kron T + T kron I)  as desired

   Similarly, Poisson's equation in 3D leads to the matrix
     T_NxNxN = ( T_N kron I_N kron I_N ) +
               ( I_N kron T_N kron I_N ) +
               ( I_N kron I_N kron T_N )
   with eigenvalue matrix
               ( Lambda_N kron    I_N       kron        I_N     ) +
               ( I_N           kron Lambda_N kron        I_N     ) +
               ( I_N           kron    I_N       kron Lambda_N )
i.e. N^3 eigenvalues lambda_i + lambda_j + lambda_k for all triples (i,j,k),
and corresponding eigenvector matrix Z kron Z kron Z.
Poisson's equation equation in d dimensions is similarly represented.

We now know enough to describe how to solve Poisson's equation with the FFT.  This
is a direct method, not iterative, but we want to compare it to the other methods.
We describe it first for 2D Poisson, and then how to extend to higher dimensions.
Start with 2D Poisson written as T_N*V + V*T_N = F; this is a special case of the
Sylvester equation described in HW Question 4.6: We substitute the eigendecomposition
    T_N = Z*Lambda*Z^T
yielding
    Z*Lambda*Z^T*V + V*Z*Lambda*Z^T = F
Premultiply by Z^T and postmultiply by Z, yielding
    Lambda*Z^T*V*Z + Z^T*V*Z*Lambda = Z^T*F*Z
Rename V' = Z^T*V*Z and F' = Z^T*F*Z, yielding
    Lambda*V' + V'*Lambda = F'
Since Lambda is diagonal, this is a diagonal system of equations, with
    (Lambda*V' + V'*Lambda)(i,j) = lambda(i)*V'(i,j) + V'(i,j)*lambda(j) = F'(i,j)
or
    V'(i,j) = F'(i,j) / (lambda(i) + lambda(j))
This yields the overall algorithm:
  (1) compute F' = Z^T*F*Z
  (2) compute V'(i,j) = F'(i,j) / (lambda(i) + lambda(j)) for all (i,j)
  (3) compute V = Z*V'*Z^T
The main costs are the matrix multiplications by Z and Z^T in (1) and (3), which
```

would cost O(N^3) if done straightforwardly. But they can be done in O(N^2*log N)
operations (recall N^2 is the number of unknowns) by noting that Z is closely
related to the Fast Fourier Transform matrix:
 FFT(i,j) = exp(sqrt(-1)*pi*i*j/N) = cos(pi*i*j/N) + sqrt(-1)*sin(pi*i*j/N)
for which there are O(N*log N) methods for multiplication by a vector.

The same idea extends to high dimensions by using Kronecker product notation:
I kron T + T kron I = (Z kron Z) * (I kron Lambda + Lambda kron I) * (Z^T kron Z^T)
so
inv(I kron T + T kron I)
 = inv((Z kron Z) * (I kron Lambda + Lambda kron I) * (Z^T kron Z^T))
 = inv(Z^T kron Z^T) * inv(I kron Lambda + Lambda kron I) * inv(Z kron Z)
 = (Z kron Z) * inv(diagonal matrix D) * (Z^T kron Z^T)
where the diagonal entries of D are sums lambda_i + lambda_j.
For 3D Poisson we would get
 (Z kron Z kron Z) * inv(diagonal matrix D) * (Z^T kron Z^T kron Z^T)
where the diagonal entries of D are sums lambda_i + lambda_j + lambda_k.

Summary of performance of methods for solving the Poisson equation in 2D (and 3D).

We will count #Flops, Memory used, #Parallel Steps, and #Processors.
"Parallel Steps" is the fewest possible, on a machine with as many processors as needed
(#Procs), and so it refers only to the available parallelism, not how you would actually
implement it on a real machine with a smaller number of processors.

The algorithms are sorted in two related orders: from slowest to fastest for the Poisson
Equation, and (roughly) from most general (fewest assumptions about the matrix) to least
general.

Some explanations and abbreviations:
Explicit inverse assumes we have precomputed the exact inverse of the matrix (and
are not counting the cost of doing this!) and only need to multiply by it.
SOR = Successive overrelaxation
SSOR/Chebyshev = Symmetric SOR with Chebyshev Acceleration
FFT = Fast Fourier Transform
BCR = Block Cyclic Reduction
Lower Bound is a lower bound that assumes one flop per
 component of the output vector
SpMV means sparse-matrix times dense-vector multiplication.

For 2D Poisson on an nxn mesh, we let N = n^2 = #unknowns
For 3D Poisson on an nxnxn mesh, we let N = n^3 = #unknowns
If the table entry for 3D Poisson differs from 2D, it is shown in parentheses.
All table entries are meant in a Big-Oh sense.

```
Method              Direct or  #Flops      Mem       #Parallel   #Procs
                    Iterative                         Steps
Dense Cholesky          D      N^3         N^2        N           N^2
  works on any spd matrix
------------------------------------------------------------------------------
Explicit Inverse        D      N^2         N^2        log N        N^2
------------------------------------------------------------------------------
Band Cholesky           D      N^2         N^(3/2)   N             N
                             (N^(7/3)) (N^(5/3))                  (N^(4/3))
  Works on any spd band matrix with cost O(N*bw^2),
     2D: bw = n = N^(1/2)
     3D: bw = n^2 = N^(2/3)
------------------------------------------------------------------------------
Jacobi                   I      N^2          N          N              N
        3D case: Homework!  (N^(5/3)               (N^(2/3))
  #Flops = O(#Flops(SpMV)* #iterations), where #Flops(SpMV) = O(#nonzeros in A)
    and #iterations ~ cond(A) = n^2 in 2D and 3D
  Works on any diagonally dominant matrix, convergence rate depends on cond(A)
------------------------------------------------------------------------------
Gauss-Seidel             I      N^2          N          N              N
        3D case: Homework!  (N^(5/3)               (N^(2/3))
  cost analogous to Jacobi (constants differ)
  Works on any diagonally dominant or spd matrix
------------------------------------------------------------------------------
Sparse Cholesky          D      N^(3/2)   N*log N   N^(1/2)      N
                               (N^2)     (N^(4/3)) (N^(2/3))   (N^(4/3))
  Assumes we are using the best ordering known (nested dissection)
  Works on any spd matrix; complexity arises from cost of dense Cholesky
    on trailing nxn submatrix (in 2D) or n^2xn^2 submatrix (in 3D)
------------------------------------------------------------------------------
Conjugate Gradients      I      N^(3/2)    N          N^(1/2)*log N   N
        3D case: Homework!   (N^(4/3))              (N^(1/3))*log N)
  #Flops =O(#Flops(SpMV)* #iterations), where cost(SpMV) = O(#nonzeros in A)
    and #iterations = O(sqrt(cond(A)))
  Works on any spd matrix
------------------------------------------------------------------------------
SOR                      I      N^(3/2)   N           N^(1/2)      N
        3D case: Homework!   (N^(4/3))              (N^(1/3))
  SOR = Successive Overrelaxation
  Cost analysis analogous to Conjugate Gradients.
  Works on any spd matrix, convergence rate depends on cond
------------------------------------------------------------------------------
SSOR/Chebyshev           I      N^(5/4)   N          N^(1/4)      N
```

```
        3D case: Homework!    (N^(7/6))              (N^(1/6))
  #Flops = O(#Flops(SpMV) * #iterations), where #flops(SpMV) = O(#nonzeros in A)
    and #iterations = (cond(A))^(1/4)
  Works on any spd matrix, but need to know range of eigenvalues
---------------------------------------------------------------------------------
FFT                            D      N*log N   N         log N          N
  Works on model problem
---------------------------------------------------------------------------------
BCR                            D      N*log N   N            ?              ?
  BCR = Block Cyclic Reduction
           3D case: Homework!
  Works on problems slightly more general than model problem
---------------------------------------------------------------------------------
Multigrid                       I       N          N         log^2 N       N
  Many variants of this algorithm, which work quite generally on
   problems arising from elliptic PDE and FEM models
---------------------------------------------------------------------------------
Lower bound                             N          N         log N
---------------------------------------------------------------------------------
```