Lecture 25
Linear Algebra Software

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Introduction to Numerical Methods

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1

BLAS

- Basic Linear Algebra Subroutines (BLAS)
  - Standardized interface for simple vector and matrix operations
  - Manufacturers provide optimized implementations for their machines
- History:
  - BLAS1 (1970s) – Vector operations: $\alpha = x^T y, y = \alpha x + y$
  - BLAS2 (mid 1980s) – Matrix-vector operations: $y = Ax + y$
  - BLAS3 (late 1980s) – Matrix-matrix operations: $C = AB + C$
- Efficient cache-aware implementations give almost peak performance for BLAS3 operations
- High level algorithms (Gaussian elimination, etc) use BLAS but no other machine dependent code
  - Performance and portability

2

Memory Hierarchy and High Level BLAS

- Modern computers use a memory hierarchy
- From fast/expensive to cheap/slow: Registers, L1 cache, L2 cache, local memory, remote memory, secondary memory
- Fast algorithms perform many operations on each memory block to minimize memory access (cache reuse)
- Only BLAS3 has potential for very high performance

<table>
<thead>
<tr>
<th>BLAS</th>
<th>Memory Refs</th>
<th>Flops</th>
<th>Flops / Memory Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1 $(y = \alpha x + y)$</td>
<td>$3n$</td>
<td>$2n$</td>
<td>$2/3$</td>
</tr>
<tr>
<td>Level 2 $(y = Ax + y)$</td>
<td>$n^2$</td>
<td>$2n^2$</td>
<td>$2$</td>
</tr>
<tr>
<td>Level 3 $(C = AB + C)$</td>
<td>$4n^2$</td>
<td>$2n^3$</td>
<td>$n/2$</td>
</tr>
</tbody>
</table>

3

BLAS Performance

- For high performance write algorithms in terms of BLAS3 operations

4

Calling BLAS from C

- BLAS standard based on Fortran 77:
  - All memory must be preallocated
  - All variables are passed by reference
- Example: Double precision matrix-matrix multiply ($C = \alpha AB + \beta C$):
  ```c
  dgemm_(&transa,&transb,&m,&n,&k,&alpha,A,&lda,
  B,&ldb,&beta,C,&ldc);
  ```
  - transa, etc: Matrix transpose ('T') or not ('N')
  - lda, etc: Leading dimensions of matrices
  - Some platforms/compilers do not require the trailing underscore
  - In C++, declare functions with extern "C"
- See also C BLAS interface in ATLAS

5

BLAS Implementations

- Vendor provided:
  - Intel Math Kernel Library (MKL), AMD Core Math Library (ACML)
  - Sun Performance Library
  - SGI Scientific Computing Software Library
- Automatically Tuned Linear Algebra Software (ATLAS)
  - Analyzes hardware to produce BLAS libraries for any platform
  - Used in MATLAB, precompiled libraries freely available
  - Sometimes outperforms vendor libraries
- GOTO BLAS (mainly for Intel processors)
  - Manually optimized assembly code, currently the fastest implementation
LAPACK

- Standard library for dense/banded linear algebra
  - Linear systems: $Ax = b$
  - Least squares problems: $\min_x \|Ax - b\|_2$
  - Eigenvalue problems: $Ax = \lambda x$, $Ax = \lambda Bx$
  - Singular value decomposition (SVD): $A = U\Sigma V^T$

- Algorithms use BLAS3 as much as possible
- Used by MATLAB (since version 6)
- LAPACK Search Engine useful for finding routines

LAPACK Performance

- Matrix-matrix multiply and LU factorization as function of matrix size
- About 80% of peak performance for LU factorization of large matrices

Sparse Solver Packages

- UMFpack (Unsymmetric MultiFrontal method)
  - Used in MATLAB (since version 7.1), no parallel version

- PARADISO
  - Serial and shared memory, used in Intel MKL

- SuperLU
  - Versions for serial and parallel computers (shared/distributed)
  - "Static pivoting" for distributed machines (increase small pivots, iterative refinement for accuracy)

- MUMPS (MUltifrontal Massively Parallel sparse direct Solver)
  - Versions for serial and parallel computers (distributed)