

CS601: Software Development for Scientific Computing

Autumn 2022

Week4: Build tool (Make demo), Motifs –
Matrix Computations with Dense Matrices

make – Recap and Demo

- Minimal build
 - What if only `scprod.cpp` changes?
- Special targets (`.phony`)
 - E.g. explicit request to `clean` executes the associated recipe. What if there is a file named `clean`?
- Organizing into folders
 - Use of variables (built-in (`CXX`, `CFLAGS`) and automatic (`$@`, `^`, `<`))

refer to week3_codesamples

Recall Motifs from Week1

Scientific Software - Motifs

noun

1. a decorative image or design, especially a repeated one forming a pattern.
"the colourful hand-painted motifs which adorn narrowboats"

Similar:

design

pattern

decoration

figure

shape

logo

monogram



2. a dominant or recurring idea in an artistic work.
"superstition is a recurring motif in the book"

- | | |
|---------------------------|--------------------------------|
| 1. Finite State Machines | 8. Dynamic Programming |
| 2. Combinatorial | 9. <u>N-Body (/ particle)</u> |
| 3. Graph Traversal | 10. MapReduce |
| 4. <u>Structured Grid</u> | 11. Backtrack / B&B |
| 5. <u>Dense Matrix</u> | 12. Graphical Models |
| 6. <u>Sparse Matrix</u> | 13. <u>Unstructured Grid</u> |
| 7. <u>FFT</u> | |

Matrix Algebra and Efficient Computation

- Pic source: the Parallel Computing Laboratory at U.C. Berkeley: A Research Agenda Based on the Berkeley View (2008)

<i>Motif</i>	Embed	Desktop	Games	DB	ML	HPC	Medicine	Music	Speech	CBIR	Browser	Motif	Desktop	Games	DB	ML	HPC	Medicine	Music	Speech	CBIR	Browser	
1 Finite State Mach.												9 N-Body											
2 Combinational												10 MapReduce											
3 Graph Traversal												11 Backtrack/B&B											
4 Structured Grid												12 Graphical Models											
5 Dense Matrix												13 Unstructured Grid											
6 Sparse Matrix												Temperature Chart of Need					DB = database						
7 Spectral (FFT)												Hot	Warm	Med	Cool	ML = machine learning							
8 Dynamic Prog																HPC = High Perf. Comp.							

Figure 4. Temperature Chart of the 13 Motifs. It shows their importance to each of the original six application areas and then how important each one is to the five compelling applications of Section 3.1. More details on the motifs can be found in (Asanovic, Bodik et al. 2006).

Matrix Multiplication

- Why study?
 - An important “kernel” in many linear algebra algorithms
 - Most studied kernel in high performance computing
 - Simple. Optimization ideas can be applied to other kernels
- Matrix representation
 - Matrix is a 2D array of elements. Computer memory is inherently linear
 - C++ and Fortran allow for definition of 2D arrays. 2D arrays stored row-wise in C++. Stored column-wise in Fortran. E.g.
`// stores 10 arrays of 20 doubles each in C++`
`double** mat = new double[10][20];`

Storage Layout - Example

- Matrix (**2D**): $A = \begin{bmatrix} A(0,0) & A(0,1) & A(0,2) \\ A(1,0) & A(1,1) & A(1,2) \\ A(2,0) & A(2,1) & A(2,2) \end{bmatrix}$

$A(i,j) = A(\text{row}, \text{column})$ refers to the matrix element in the i^{th} row and the j^{th} column

- Row-wise (/Row-major) storage in memory:

$A(0,0)$	$A(0,1)$	$A(0,2)$	$A(1,0)$	$A(1,1)$	$A(1,2)$	$A(2,0)$	$A(2,1)$	$A(2,2)$
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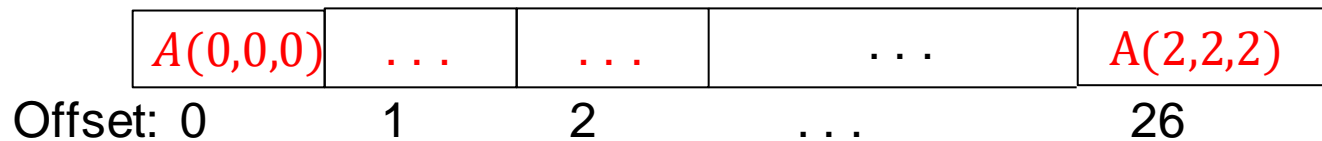
- Column-wise (/Column-major) storage in memory:

$A(0,0)$	$A(1,0)$	$A(2,0)$	$A(0,1)$	$A(1,1)$	$A(2,1)$	$A(0,2)$	$A(1,2)$	$A(2,2)$
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- Generalizing data storage order for ND:** last index changes fastest in row-major. Last index changes slowest in col-major.

Storage Layout - Exercise

- For a 3D array (tensor) assume $A(i, j, k) = A(\text{row}, \text{column}, \text{depth})$



- What is the offset of $A(1, 2, 1)$? as per row-major storage?
- What is the offset of $A(1, 2, 1)$? as per col-major storage?

Matrix Multiplication

- Three fundamental ways to think of the computation

Method 1. Dot product

$$\begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix} \times \begin{bmatrix} 5 & 6 \\ 7 & 8 \end{bmatrix} = \begin{bmatrix} 1.5 + 2.7 & 1.6 + 2.8 \\ 3.5 + 4.7 & 3.6 + 4.8 \end{bmatrix}$$

Method 2. Linear combination of the columns of the left matrix

$$\begin{bmatrix} \textcolor{blue}{1} & \textcolor{green}{2} \\ \textcolor{blue}{3} & \textcolor{green}{4} \end{bmatrix} \times \begin{bmatrix} \textcolor{red}{5} & \textcolor{blue}{6} \\ \textcolor{red}{7} & \textcolor{red}{8} \end{bmatrix} = \left[\textcolor{red}{5} \begin{bmatrix} \textcolor{blue}{1} \\ \textcolor{blue}{3} \end{bmatrix} + 7 \begin{bmatrix} \textcolor{green}{2} \\ \textcolor{green}{4} \end{bmatrix} \quad \textcolor{blue}{6} \begin{bmatrix} \textcolor{blue}{1} \\ \textcolor{blue}{3} \end{bmatrix} + \textcolor{red}{8} \begin{bmatrix} \textcolor{green}{2} \\ \textcolor{green}{4} \end{bmatrix} \right]$$

Method 3. Sum of outer products

$$\begin{bmatrix} \textcolor{blue}{1} & \textcolor{green}{2} \\ \textcolor{blue}{3} & \textcolor{green}{4} \end{bmatrix} \times \begin{bmatrix} \textcolor{red}{5} & \textcolor{blue}{6} \\ \textcolor{red}{7} & \textcolor{red}{8} \end{bmatrix} = \left[\begin{bmatrix} \textcolor{blue}{1} \\ \textcolor{blue}{3} \end{bmatrix} [\textcolor{red}{5} \quad \textcolor{blue}{6}] + \begin{bmatrix} \textcolor{green}{2} \\ \textcolor{green}{4} \end{bmatrix} [\textcolor{red}{7} \quad \textcolor{red}{8}] \right]$$

Common Computational Patterns

Some patterns that we see while doing Matrix-Matrix product:

1. Dot Product or Inner Product: $x^T y$ ← Method 1
2. Scalar **a** times **x** plus **y**: $y = y + ax$ OR saxpy
– Scalar times **x**: αx ← Method 2
3. Matrix times x plus y: $y = y + Ax$ ← Method 1
– generalized axpy OR gaxpy
4. Outer product: $C = C + xy^T$ ← Method 3
5. Matrix times Matrix plus Matrix
– GEMM or generalized matrix multiplication

Dot Product

- Vector $x = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}$, Vector $y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix}$ $x_i, y_i \in \mathbb{R}$
- $x^T = [x_1 \quad x_2 \quad \dots \quad x_n]$
- Dot Product or Inner Product: $c = x^T y$ $x^T \in \mathbb{R}^{1 \times n}$, $y \in \mathbb{R}^{n \times 1}$, c is scalar

$$[x_1 \quad x_2 \quad \dots \quad x_n] \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} = [x_1 y_1 + x_2 y_2 + \dots + x_n y_n]$$

- E.g. $[1 \quad 2 \quad 3] \begin{bmatrix} 4 \\ 5 \\ 6 \end{bmatrix} = [1 \times 4 + 2 \times 5 + 3 \times 6] = 32$

AXPY

- Computing the more common (a times x plus y): $y = y + ax$

- $$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} = \begin{bmatrix} y \\ y_2 \\ \vdots \\ y_n \end{bmatrix} + a \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}$$



```
..  
for i=1 to n  
    y[i] = y[i] + a*x[i]  
..
```

- Cost? n multiplications and n additions = **2n** or **O(n)**

Matrix Vector Product

- Computing Matrix-Vector product: $c = c + Ax$, $A \in \mathbb{R}^{m \times r}$, $x \in \mathbb{R}^{r \times 1}$

$$\begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_m \end{bmatrix} = \begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_m \end{bmatrix} + \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1r} \\ a_{21} & a_{22} & \cdots & a_{2r} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mr} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_r \end{bmatrix} = \begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_m \end{bmatrix} + \begin{bmatrix} a_{11}x_1 + a_{12}x_2 + \cdots + a_{1r}x_r \\ a_{21}x_1 + a_{22}x_2 + \cdots + a_{2r}x_r \\ \vdots \\ a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mr}x_r \end{bmatrix}$$

- Rewriting Matrix-Vector product using dot products:

$$\begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_m \end{bmatrix} = \begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_m \end{bmatrix} + \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1r} \\ a_{21} & a_{22} & \cdots & a_{2r} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mr} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_r \end{bmatrix} = \begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_m \end{bmatrix} + \begin{bmatrix} a_1^T x \\ a_2^T x \\ \vdots \\ a_m^T x \end{bmatrix}$$

- Cost? m rows involving dot products and having the form $c_i = c_i + x^T y$ (Per row cost = $2r$ (because $a_i, x \in \mathbb{R}^r$), Total cost = $2mr$ or $O(mr)$)

Matrix-Matrix Product

- Computing Matrix-Matrix product $C = C + AB$, $A \in \mathbb{R}^{m \times r}$, $B \in \mathbb{R}^{r \times n}$, $C \in \mathbb{R}^{m \times n}$

$$\begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ c_{m1} & c_{m2} & \cdots & c_{mn} \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ c_{m1} & c_{m2} & \cdots & c_{mn} \end{bmatrix} + \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1r} \\ a_{21} & a_{22} & \cdots & a_{2r} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mr} \end{bmatrix} \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{r1} & b_{r2} & \cdots & b_{rn} \end{bmatrix}$$

- Consider the AB part first.

$$\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1r} \\ a_{21} & a_{22} & \cdots & a_{2r} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mr} \end{bmatrix} \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{r1} & b_{r2} & \cdots & b_{rn} \end{bmatrix}$$

Matrix-Matrix Product

$$\begin{array}{c} \text{A} \qquad \qquad \qquad \text{B} \\ \left[\begin{array}{cccc} a_{11} & a_{12} & \dots & a_{1r} \\ a_{21} & a_{22} & \dots & a_{2r} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \dots & a_{mr} \end{array} \right] \left[\begin{array}{cccc} b_{11} & b_{12} & \dots & b_{1n} \\ b_{21} & b_{22} & \dots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{r1} & b_{r2} & \dots & b_{rn} \end{array} \right] \\ \\ = \left[\begin{array}{cccc} a_{11}b_{11} + a_{12}b_{21} + \dots + a_{1r}b_{r1} & \dots & \dots & a_{11}b_{1n} + a_{12}b_{2n} + \dots + a_{1r}b_{rn} \\ \vdots & \ddots & \ddots & \vdots \\ a_{m1}b_{11} + a_{m2}b_{21} + \dots + a_{mr}b_{r1} & \dots & \dots & a_{m1}b_{1n} + a_{m2}b_{2n} + \dots + a_{mr}b_{rn} \end{array} \right] \end{array}$$

Notice that:

- subscript on a varies from 1 to m in a column (i.e. m rows exist)
- subscript on a varies from 1 to r in a row (i.e. r columns exist)

Suppose that we treat a_i as a vector of size r and there exist m vectors

$$= \left[\begin{array}{cccc} a_1^T b_1 & \dots & \dots & a_1^T b_n \\ \vdots & \ddots & \ddots & \vdots \\ a_m^T b_1 & \dots & \dots & a_m^T b_n \end{array} \right]$$

$$\begin{array}{l} a_i^T \in \mathbb{R}^{1 \times r}, b_j \in \mathbb{R}^{r \times 1} \\ i \text{ ranges from 1 to } m \\ j \text{ ranges from 1 to } n \end{array}$$

Matrix-Matrix Product using Dot Product Formulation

- Pseudocode - Matrix-Matrix product: $C = C + AB$, $A \in \mathbb{R}^{m \times r}$, $B \in \mathbb{R}^{r \times n}$, $C \in \mathbb{R}^{m \times n}$
..
for i=1 to m
 for j=1 to n
 //compute updates involving dot products
 $c_{ij} = c_{ij} + a_i^T b_j$

Matrix-Matrix Product using Dot Product Formulation – Data Access

- Pseudocode - Matrix-Matrix product: $C = C + AB$, $A \in \mathbb{R}^{m \times r}$, $B \in \mathbb{R}^{r \times n}$, $C \in \mathbb{R}^{m \times n}$

..

for i=1 to m

for j=1 to n

//compute updates involving dot products

$$c_{ij} = c_{ij} + a_i^T b_j$$

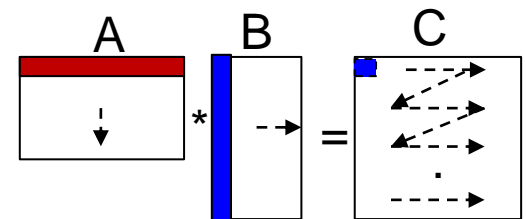
- Expanded: ..

for i=1 to m

for j=1 to n

for k=1 to r

$$c_{ij} = c_{ij} + a_{ik} b_{kj}$$



Elements of C matrix are computed from top to bottom, left to right. Per element computation, you need a row of A and a column of B.

Matrix-Matrix Product using Dot Product Formulation - Cost

- Pseudocode - Matrix-Matrix product: $C = C + AB$, $A \in \mathbb{R}^{m \times r}$, $B \in \mathbb{R}^{r \times n}$, $C \in \mathbb{R}^{m \times n}$
..
for i=1 to m
for j=1 to n
//compute updates involving dot products
 $c_{ij} = c_{ij} + a_i^T b_j$
- Cost?
 - Per dot-product cost = $2r$ ($a_i, b_j \in \mathbb{R}^r$) Total cost = $2mnr$ or $O(mnr)$

Matrix Multiplication Performance

- Experimental Setup
 - Xeon Gold 6240C processor
 - 2.6GHz clock frequency
 - 2 processor chips
 - 18 cores per chip
 - 2 fused multiply-add units per core
(can do two double-precision floating point ops of multiplication and addition combined per cycle)
 - *cache subsystem?*



Matrix Multiplication Performance

$C=C+A*B$, Square matrices, Dimensions = 2048x2048 (INPUT_SIZE = 2048)

	Execution Time	Speedup (w.r.t. Python)
Python	2088.75s	1.0
C++	92.7s	22.53
+ -O3	41.67s	50.13
+ ikj loop ordering	4.71s	443.47
+ utilizing all cores (parallel)	0.147s	14209.18