CR10, course 2: Pebble Games 2/2

Outline

Summary on the (black) pebble game

Red-Blue Pebble Game for I/Os

Hong-Kung Lower Bound Method

Tight Lower Bound for Matrix Product

Extensions and Performance Bounds

Pebble game – summary 1/2

Input: Directed Acyclic Graph (=computation)

Rules:

- A pebble may be removed from a vertex at any time.
- A pebble may be placed on a source node at any time.
- If all predecessors of an unpebbled vertex v are pebbled, a pebble may be placed on v.

Objective: put a pebble on each target (not necessary simultaneously) using a minimum number of pebbles

Number of pebbles:

- Number of registers in a processor
- Size of the (fast) memory (together with a large/slow disk)

Pebble game – summary 2/2

Results:

- Hard to find optimal pebbling scheme for general DAGs (NP-hard without recomputation, PSPACE-hard otherwise)
- Recursive formula for trees

Space-Time Tradeoffs:

- Definition of flow and independent function
- (α, n, m, p)-independent function: $\lceil \alpha(S+1) \rceil T \geq mp/4$
- Product of two $N \times N$ matrices:

$$(S+1)T \geq N^3/4$$

(bound reached by the standard algorithm)

Outline

Summary on the (black) pebble game

Red-Blue Pebble Game for I/Os

Hong-Kung Lower Bound Method

Tight Lower Bound for Matrix Product

Extensions and Performance Bounds

What about I/Os

(Black) Pebble game: limit the memory footprint

But usually:

- Memory size fixed
- Possible to write temporary data to the slower storage (disk)
- Data movements take time (Input/Output, or I/O)

NB: same study for any two-memory system:

- (fast, bounded) memory and (slow, large) disk
- (fast, bounded) cache and (slow, large) memory
- (fast, bounded) L1 cache and (slow, large) L2 cache

Red-Blue pebble game (Hong and Kung, 1981)

Two types of pebbles:

- Red pebbles: limited number S (slots in fast memory)
- Blue pebbles: unlimited number, only for storage (disk)

Rules:

(1) A red pebble may be placed on a vertex that has a blue pebble.

(2) A blue pebble may be placed on a vertex that has a red pebble.

(3) If all predecessors of a vertex v have a red pebble, a red pebble may be placed on v.

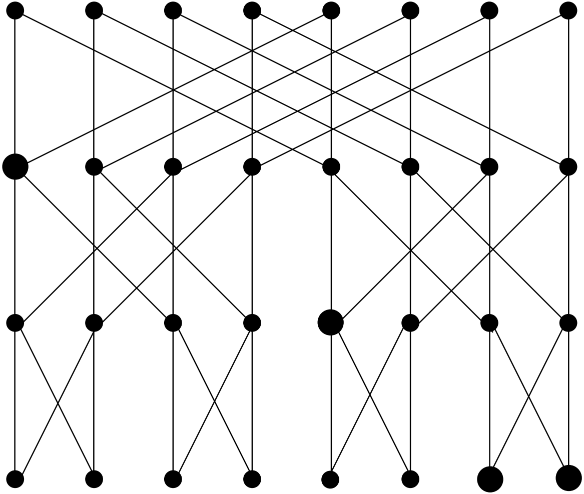
(4) A pebble (red or blue) may be removed at any time.

(5) No more than S red pebbles may be used at any time.

(6) A blue pebble can be placed on an input vertex at any time

Objective: put a red pebble on each target (not necessary simultaneously) using a minimum rules 1 and 2 (I/O operations)

Example: FFT graph



k levels, $n = 2^k$ vertices at each level

Minimum number S of red pebbles ?

How many I/Os for this minimum number S ?

Outline

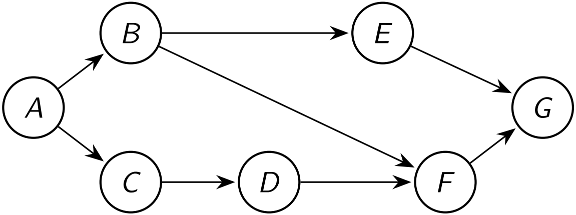
Hong-Kung Lower Bound Method

Objective: Given a number of red pebbles, give a lower bound on the number of I/Os for any pebbling scheme of a graph.

Definition (span).

Given a DAG G, its S-span $\rho(S, G)$, is the maximum number of vertices of G that can be pebbled with S pebbles in the **black** pebble game without the initialization rule, maximized over all initial placements of the S pebbles on G.

Rationale: with large $\rho(S, G)$, you can compute a lot of G with S pebbles (for a given starting point)



Find $\rho(2, G)$

Span of the matrix product

Definition (span).

Given a DAG G, its S-span $\rho(S, G)$, is the maximum number of vertices of G that can be pebbled with S pebbles in the **black** pebble game without the initialization rule, maximized over all initial placements of the S pebbles on G.

Theorem.

For every DAG G to compute the product of two $N \times N$ matrices in a regular manner (performing the N^3 products), the span is bounded by $\rho(S, G) \leq 2S\sqrt{S}$ for $S \leq N^2$.

Lemma.

Let T be a binary (in-)tree representing a computation, with p **black** pebbles on some vertices and an unlimited number of available pebbles. At most $p - 1$ vertices can be pebbled in the tree without pebbling new inputs.

(proofs on the board, available in the notes)

From Span to I/O Lower Bound

$T_{I/O}(S, G)$: number of I/O steps (red $\leftrightarrow$ blue)

Theorem (Hong & Kung, 1981).

For every pebbling scheme S of a DAG $G = (V, E)$ in the red-blue pebble-game using at most S red pebbles, the number of I/O steps satisfies the following lower bound:

$$\lceil T_{I/O}(S, G)/S \rceil \rho(2S, G) \geq |V| - |Inputs(G)|$$

Recall that for matrix product $\rho(S, G) \leq 2S\sqrt{S}$, hence:

$$T_{I/O} \geq \frac{N^3 - N^2}{4\sqrt{2}S} = \Theta\left(\frac{N^3}{\sqrt{S}}\right)$$

Outline

Tight Lower Bound for Matrix Product

$b \leftarrow \sqrt{M/3}$
for $i = 0, \rightarrow n/b - 1$ **do**
  for $j = 0, \rightarrow n/b - 1$ **do**
    for $k = 0, \rightarrow n/b - 1$ **do**
      Simple-Matrix-Multiply($n, C^b_{i,j}, A^b_{i,k}, B^b_{k,j}$)

- Blocked algorithm: $3\sqrt{3}N^3/\sqrt{M}$
- Previous bound on I/Os $\sim N^3/4\sqrt{2M}$
- Many improvements needed to close the gap
- Presented here for $C \leftarrow C + AB$, square matrices

New operation: Fused Multiply Add

- Perform $c \leftarrow c + a \times b$ in a single step
- No temporary storage needed (3 inputs, 1 output)

Step 1: Use Only FMAs (Fused Multiply Add)

Theorem.

Any algorithm for the matrix product can be transformed into using only FMA without increasing the required memory or the number of I/Os.

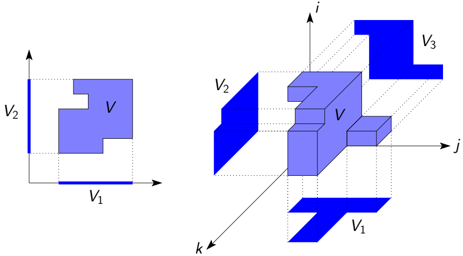
Transformation:

- If some $c_{i,j,k}$ is computed while $c_{i,j}$ is not in memory, insert a read before the multiplication
- Replace the multiplication by a FMA
- Remove the read that must occur before the addition $c_{i,j} \leftarrow c_{i,j} + c_{i,j,k}$, remove the addition
- Transform occurrences of $c_{i,j,k}$ into $c_{i,j}$
- If $c_{i,j,k}$ and $c_{i,j}$ were both in memory in some time-interval, remove operations with $c_{i,j,k}$ in this interval

Step 2: Concentrate on Read Operations

Theorem (Irony, Toledo, Tiskin, 2008).

Using N_A elements of A, N_B elements of B and N_C elements of C, we can perform at most $\sqrt{N_A N_B N_C}$ distinct FMAs.



Theorem (Discrete Loomis-Whitney Inequality).

Let V be a finite subset of $\mathbb{Z}^D$ and V_1, V_2, V_3 denotes the orthogonal projections of V on each coordinate planes, we have

$$|V|^2 \leq |V_1| \cdot |V_2| \cdot |V_3|,$$

Step 3: Use Phases of R Reads ($\neq M$)

Theorem.

During a phase with R reads with memory M, the number of FMAs is bounded by

$$F_{M+R} \leq \left(\frac{1}{3}(M+R)\right)^{3/2}$$

Number F_{M+R} of FMAs constrained by:

$$\begin{cases} F_{M+R} \leq \sqrt{N_A N_B N_C} \\ 0 \leq N_A, N_B, N_C \\ N_A + N_B + N_C \leq M + R \end{cases}$$

Using Lagrange multipliers, maximal value obtained when $N_A = N_B = N_C$

Step 4: Choose R and add write operations

in one phase, nb of computations: $F_{M+R} \leq \left(\frac{1}{3}(M+R)\right)^{3/2}$

Total volume of reads:

$$V_{\text{read}} \geq \left\lfloor \frac{N^3}{F_{M+R}} \right\rfloor \times R \geq \left(\frac{N^3}{F_{M+R}} - 1\right) \times R$$

Valid for all values of R, maximized when $R = 2M$:

$$V_{\text{read}} \geq 2N^3/\sqrt{M} - 2M$$

Each element of C written at least once: $V_{\text{write}} \geq N^2$

Theorem.

The total volume of I/Os is bounded by:

$$V_{I/O} \geq \frac{2N^3}{\sqrt{M}} + N^2 - 2M$$

Outline

Extension to the Memory Hierarchy Pebble Game

Generalization for a memory/cache hierarchy of L levels:

- Level 1: fastest/most limited memory
- Level L: slow/unlimited memory
- p_l available pebbles at level $l < L$:
- Computation steps only with level-1 pebbles
- Initialization only with level-L pebbles
- Input from level l: if level-l pebble, put level-$(l-1)$ pebble
- Output to level l: if level-$(l-1)$ pebble, put level-l pebble

Cumulated number of pebbles up to level l: $s_l = \sum_{i=1}^{l} p_i$.
Number of inputs from/outputs to level l:

$$T_l = \begin{cases} \Theta(N^3/\sqrt{s_{l-1}}) & \text{if } s_{l-1} < 3N^2 \\ \Theta(N^2) & \text{otherwise} \end{cases}$$

Recent Developments of Pebble Games

Restrict to pebbling without recomputation:

- Add white pebbles with red pebbles when computing
- White pebbles stay on vertices
- No computation possible if white pebble already present
- All nodes must be white-pebbled at the end

This restriction increases the number of red pebbles and I/Os by at most a $log^{3/2}n$ factor

Towards automatic derivation of lower bounds:

- Extend bounds for composite graphs
- Use special min-cuts instead of span

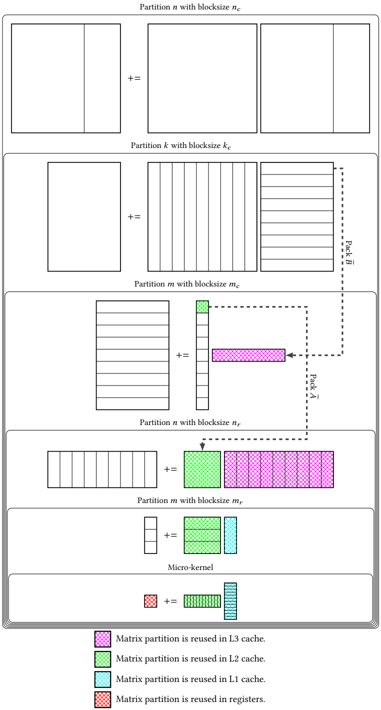
Parallel Red-Blue-White Pebble Game (cf. memory hierarchies)

Still an inspiring model!

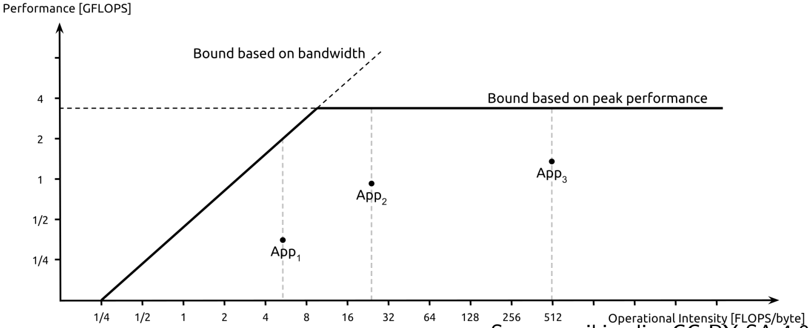
Why so much fuss about matrix product?

BLAS: Basic Linear Algebra Subprograms

- Introduced in the 80s as a standard for LA computations
- Written first in FORTRAN
- Library provided by the vendor to ease use of new machines
- Organized by levels:
  - Level 1: vector/vector operations ($x \cdot y$)
  - Level 2: vector/matrix (Ax)
  - Level 3: matrix/matrix (AB^T, blocked algorithms)
- Implementations:
  - Vendors (MKL from Intel, CuBLAS from NVidia, etc.)
  - Automatic Tuning: ATLAS
  - GotoBLAS
- Matrix product: still a large share of LA computations


Partition n with blocksize n_c
+=
Partition k with blocksize k_c
+=
Pack $\widetilde{B}$
Partition m with blocksize m_c
+=
Pack $\widetilde{A}$
Partition n with blocksize n_r
+=
Partition m with blocksize m_r
+=
Micro-kernel
+=
Matrix partition is reused in L3 cache.
Matrix partition is reused in L2 cache.
Matrix partition is reused in L1 cache.
Matrix partition is reused in registers.

Summary: Performance Bounds & Rooftop Model



Computation ceilings:

- Theoretical peak,
- Matrix-Matrix product (DGEMM)
- LINPACK (Top 500 ranking)

Bandwidth ceilings:

- Cache bandwidth
- Memory bandwidth
- NUMA (Non Uniform Memory Access)