Performance Engineering of Software Systems
Massachusetts Institute of Technology 6.172
Prof. Charles E. Leiserson and Prof. Julian Shun Handout 13

Homework 8: Cache-Oblivious Algorithms

Then, answer the writeup questions in this handout and submit an *individual* writeup. See the following paper for more information on cache-oblivious algorithms: `https:// dl.acm.org/citation.cfm?id=2071383`.

For this homework, assume that all matrices are stored in row-major layout.

1 Cache Complexity of Matrix Multiplication

During Lecture 14 we discussed the cache complexity of matrix multiplication of dimension n, with tall cache assumption of size $\mathcal{M}$ and cache line size $\mathcal{B}$. For the naive approach, there were two cases: 1) If $n > \mathcal{M}/\mathcal{B}$, then $\Theta(n^3)$ cache misses occur, and 2) if $\mathcal{M}^{1/2} < n < \mathcal{M}/\mathcal{B}$, then $\Theta(n^3/\mathcal{B})$ cache misses occur. For the blocking approach, with block size $s < \mathcal{M}^{1/2}$, $\Theta(n^3/\mathcal{B}\mathcal{M}^{1/2})$ cache misses occur. The cache-oblivious approach achieves the same complexity as the blocking approach without the need of the voodoo parameter s.

> **Checkoff Item 1:** Assume we want to multiply two rectangular matrices: $m \times n$ with $n \times r$. Given the same tall cache assumption, please analyze the complexity for one of the following four cases: the two cases for the naive approach ($n > \mathcal{M}/\mathcal{B}$ and $\mathcal{M}/r < n < \mathcal{M}/\mathcal{B}$), the block approach, and the cache-oblivious approach. You may pick whichever case you want to analyze.

2 Tableau Construction

Consider the tableau-construction problem from Lecture 8. The problem involves filling an $N \times N$ tableau, where each entry of the tableau is calculated as a function of some of its neighbors. To be specific, the equation to fill an element of the tableau would take the form

$$A[i][j] = f(A[i-1][j-1], A[i][j-1], A[i-1][j])$$

where f is an arbitrary function.

2.1 Iterative Formulation

Consider the code snippet in Figure 1 below.

```
#define A(i, j) A[N + (i) - (j) - 1]

void tableau(double *A, size_t N) {
  for (size_t i = 1; i < N; i++) {
    for (size_t j = 1; j < N; j++) {
      A(i, j) = f(A(i-1, j-1), A(i, j-1), A(i-1, j));
    }
  }
}
```

Figure 1: A simple, iterative loop for filling a tableau.

In this problem, we are only interested in computing the final value of the tableau, stored in `A(N-1,N-1)`, and hence we really only need $2N - 1$ amount of space during computation. Thus, the algorithm declares `A` as an array of size $2N - 1$.

The algorithm initializes the first row and first column of the tableau, and invokes the `tableau` function as shown in Figure 2.

```
for (size_t i = 0; i < N; i++) {
  A(i, 0) = INIT_VAL;
}
for (size_t j = 0; j < N; j++) {
  A(0, j) = INIT_VAL;
}
tableau(A, N);
res = A(N - 1, N - 1);
```

Figure 2: Initializing and calling the iterative `tableau` function.

Write-up 1: Explain why $2N - 1$ space is sufficient and how the `tableau` function utilizes the $2N - 1$ space.

Recall the tall cache assumption, which states that $\mathcal{B}^2 < \alpha\mathcal{M}$, where $\mathcal{B}$ is the size of the cache line, $\mathcal{M}$ is the size of the cache, and $\alpha \leq 1$ is a constant.

Write-up 2: Assuming that an optimal replacement strategy holds and that the cache is tall, give a tight upper bound on the cache complexity $Q(n)$ for each of the following cases using O notation, where $c \le 1$ is a sufficiently small constant:

1. $n \ge c\mathcal{M}$
2. $n < c\mathcal{M}$

2.2 Recursive Formulation

Now consider the code snippet for a recursive tableau implementation, as shown in Figure 3. This

```
#define A(i, j) A[N + (i) - (j) - 1]

void recursive_tableau(double *A, size_t rbegin, size_t rend, size_t cbegin,
                       size_t cend) {
  if (rend-rbegin == 1 && cend-cbegin == 1) {
    size_t i = rbegin, j = cbegin;
    A(i, j) = f(A(i-1, j-1), A(i, j-1), A(i-1, j));
  } else {
    size_t rmid = rend-rbegin > 1 ? (rbegin + (rend-rbegin) / 2) : rend;
    size_t cmid = cend-cbegin > 1 ? (cbegin + (cend-cbegin) / 2) : cend;
    recursive_tableau(A, rbegin, rmid, cbegin, cmid);
    if (cend > cmid)
      recursive_tableau(A, rbegin, rmid, cmid, cend);
    if (rend > rmid)
      recursive_tableau(A, rmid, rend, cbegin, cmid);
    if (rend > rmid && cend > cmid)
      recursive_tableau(A, rmid, rend, cmid, cend);
  }
}
```

Figure 3: A recursive implementation for filling in a tableau.

algorithm similarly uses only $2N-1$ amount of space, initializes the array `A`, and invokes the `recursive_tableau` function as shown in Figure 4. This recursive algorithm divides the tableau into four quadrants to compute. As discussed in Lecture 8 (slide 88), after the first quadrant is done computing, we can then compute the second and third quadrants in parallel. Parallelizing this way gives us work as $\Theta(n^2)$ and span as $\Theta(n^{\lg 3})$ with parallelism as $\Theta(n^{2-\lg 3})$. We also discussed (slide 92) a more parallel construction that divides up the tableau 9 ways.

```
for (size_t i = 0; i < N; i++) {
  A(i, 0) = INIT_VAL;
}
for (size_t j = 0; j < N; j++) {
  A(0, j) = INIT_VAL;
}
if (N > 1) {
  recursive_tableau(A, 1, N, 1, N);
}
res = A(N-1, N-1);
```

Figure 4: Initializing and calling the `recursive_tableau` function.

Write-up 3: Derive the general formula for work and span, assuming a k^2-way tableau construction (i.e., the tableau is divided up into k^2 pieces of size $n/k \times n/k$).

Write-up 4: Answer the following questions assuming that an optimal replacement strategy holds and that the cache is tall.

1. Show the recurrence relation for the cache complexity $Q(n)$ using the 4-way construction of the `recursive_tableau` function.
2. Draw the recursion tree and label the internal nodes and leaves with their cache complexity $Q(n)$. What's the height of the recursion tree?
3. How many leaves are in the recursion tree?
4. Using the recursion tree and the recurrence relation, derive a simplified expression for $Q(n)$.

Write-up 5: Answer the following question assuming that an optimal replacement strategy holds and that the cache is tall. Assuming a k^2-way tableau construction, show that if we are "unlucky," where a subpiece is just slightly above the cache size, then we have $Q(n) = \Theta(n^2 k/\mathcal{M}\mathcal{B})$. Also show that if we are lucky and this situation does not arise, then we have $Q(n) = \Theta(n^2/\mathcal{M}\mathcal{B})$.

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