Lab 4 实验分析

从官方文档得知需要完善 `csim.c` 和 `trans.c` 文件，第一个是模拟一个高速缓存的程序并从由 `valgrind` 程序生成的 `trace` 文件中统计 hit, miss 和 eviction 的数量。第二个文件需要优化矩阵转置程序降低程序的不命中度。

PART A

这一部分的核心是使用了一个结构体来模拟一个缓存行：

```
typedef struct {
        int valid;
        ulong tag;
        clock_t time;
} CacheLine;
```

再通过把缓存行在内存中动态分配成一个二维数组，实现模拟缓存的功能。并且使用了`typedef CacheLine *CacheSet;` 和 `typedef CacheSet *CacheHead;` 来让程序更整齐。输入来源于文件和命令行参数。可以用 `getopt()` 函数来解析参数。

各个函数的作用如下：

- `CacheHead CacheInit(int S, int E)` 为缓存动态分配内存；
- `int CacheJudge(CacheHead cache, ulong index, ulong tag)` 判断缓存状态，是否有效，标记匹配；
- `void CacheEvict(CacheHead cache, ulong index, ulong tag)` 执行 eviction 操作；
- `void CacheTouch(CacheHead cache, ulong index, ulong tag)` 执行读取操作，只更新时间戳；
- `void CacheInsert(CacheHead cache, ulong index, ulong tag)` 执行缓存写入操作；
- `void Adder(int type, int num)` 计数器，增加 hit, miss 和 eviction 的数量，并根据配置选择打印信息；
- `void printByte(bytept h, int len)` 逐字节以 16 进制打印内存数据；
- `void Execute(CacheHead cache, char type, ulong address, int len)` 主要的执行函数；
- `int main(int argc, char *args[])` main 函数，读取参数，打开文件；

完整的程序代码如下：

```
// Written By @BillChen
// 2019.5.20
#include "cachelab.h"
#include <getopt.h>
#include <stdio.h>
#include <stdlib.h>
#include <time.h>
#include <unistd.h>
```

```
#define MACHINE_BITS 64
#define NEED_EVICT -1
#define NO_MATCH -2
#define CACHED 1
#define ADD_HIT 1
#define ADD_MISS 2
#define ADD_EVICT 3

int totalMissCount = 0;
int totalHitCount = 0;
int totalEvictCount = 0;

typedef unsigned long ulong;
typedef unsigned char *bytept;
const char *optString = "s:E:b:t:hVv";

struct globalOptions {
        int setIndexBits;
        int associativity;
        int blockBits;
        int verboseFlag;
        int tagBits;
        int superVerboseFlag;
        char *traceDir;
} globalOptions;
struct result {
        int hit;
        int miss;
        int evict;
};
typedef struct {
        int valid;
        ulong tag;
        clock_t time;
} CacheLine;

typedef CacheLine *CacheSet;
typedef CacheSet *CacheHead;

void usage() {
        printf("Usage: ./csim [-hv] -s <s> -E <E> -b <b> -t
<tracefile>\n");
        printf("-h get help info\n");
        printf("-v Optional verbose flag that displays trace info\n");
        printf("-V Optional super verbose flag that displays very detailed
trace info\n");
        printf("-s <s> Number of set index bits\n");
        printf("-E <E> Associativity (number of lines per set)\n");
        printf("-b <b> Number of block bits\n");
        printf("-t <tracefile>: Name of the valgrind trace to replay\n");
}

CacheHead CacheInit(int S, int E) {
```

```
        CacheHead cache;
        cache = calloc(1 << S, sizeof(CacheSet));
        if (cache == NULL) {
                printf("Fail to allocate memory for cache.\n");
                exit(EXIT_FAILURE);
        }
        int i = 0;
        for (i = 0; i < 1 << S; i++) {
                if ((cache[i] = calloc(E, sizeof(CacheLine))) == NULL) {
                        printf("Fail to allocate memory for cache.\n");
                        exit(EXIT_FAILURE);
                }
        }
        for (i = 0; i < 1 << S; i++) {
                int j;
                for (j = 0; j < E; j++) {
                        cache[i][j].valid = 0;
                }
        }
        return cache;
}

int CacheJudge(CacheHead cache, ulong index, ulong tag) {
        int i;
        int fullFlag = 1;
        int matchFlag = 0;
        for (i = 0; i < globalOptions.associativity; i++) {
                if (cache[index][i].valid == 0) {
                        fullFlag = 0;
                }
                if (cache[index][i].tag == tag && cache[index][i].valid ==
1) {
                        matchFlag = 1;
                }
        }
        if (matchFlag == 1)
                return CACHED;
        if (fullFlag == 1)
                return NEED_EVICT;
        else
                return NO_MATCH;
}

void CacheInsert(CacheHead cache, ulong index, ulong tag) {
        int freeLine = 0, i;
        for (i = 0; i < globalOptions.associativity; i++) {
                if (cache[index][i].valid == 0)
                        break;
                freeLine++;
        }
        CacheLine *target = cache[index] + freeLine;
        target->tag = tag;
        target->valid = 1;
        target->time = clock();
```

```
}

void CacheEvict(CacheHead cache, ulong index, ulong tag) {
        int firstLine = 0, i = 0;
        clock_t firstCachedTime = cache[index][i].time;
        for (i = 0; i < globalOptions.associativity; i++) {
                if (cache[index][i].time < firstCachedTime) {
                        firstCachedTime = cache[index][i].time;
                        firstLine = i;
                }
        }
        CacheLine *target = cache[index] + firstLine;
        target->tag = 0;
        target->time = 0;
        target->valid = 0;
}

void CacheTouch(CacheHead cache, ulong index, ulong tag) {
        int touchLine = 0;
        while (cache[index][touchLine].tag != tag)
                touchLine++;
        cache[index][touchLine].time = clock();
}

void Adder(int type, int num) {
        int v = globalOptions.verboseFlag;
        switch (type) {
        case ADD_EVICT:
                totalEvictCount += num;
                if (v && num != 0)
                        printf("eviction ");
                break;
        case ADD_HIT:
                totalHitCount += num;
                if (v && num != 0)
                        printf("hit ");
                break;
        case ADD_MISS:
                totalMissCount += num;
                if (v && num != 0)
                        printf("miss ");
        }
}

void printByte(bytept h, int len) {
        int i;
        for (i = 0; i < len; i++)
                printf("%.2x ", h[i]);
        printf("\n");
}

void Execute(CacheHead cache, char type, ulong address, int len) {
        ulong index = (address << globalOptions.tagBits) >> (MACHINE_BITS
- globalOptions.setIndexBits);
```

```
        ulong tag = address >> (globalOptions.blockBits +
globalOptions.setIndexBits);
        int status = CacheJudge(cache, index, tag);
        if (globalOptions.verboseFlag == 1) {
                if(globalOptions.superVerboseFlag == 1){
                        printf("\n[address:] ");
                        printByte((bytept)&address, sizeof(long));
                        printf("[index:] ");
                        printByte((bytept)&index, sizeof(long));
                        printf("[tag:] ");
                        printByte((bytept)&tag, sizeof(long));
                        printf("(Decimal)[index: %ld, tag: %ld]\n---------
---------------------------------- ", index, tag);
                }
                else{
                        printf("(Decimal)[index: %ld, tag: %ld] ------ ",
index, tag);
                }
        }
        switch (status) {
        case CACHED:
                CacheTouch(cache, index, tag);
                if (type == 'M') {
                        Adder(ADD_HIT, 1);
                        Adder(ADD_HIT, 1);
                } else {
                        Adder(ADD_HIT, 1);
                }
                break;
        case NO_MATCH:
                CacheInsert(cache, index, tag);
                if (type == 'M') {
                        Adder(ADD_MISS, 1);
                        Adder(ADD_HIT, 1);
                } else {
                        Adder(ADD_MISS, 1);
                }
                break;
        case NEED_EVICT:
                CacheEvict(cache, index, tag);
                CacheInsert(cache, index, tag);
                if (type == 'M') {
                        Adder(ADD_MISS, 1);
                        Adder(ADD_EVICT, 1);
                        Adder(ADD_HIT, 1);

                } else {
                        Adder(ADD_MISS, 1);
                        Adder(ADD_EVICT, 1);
                }
                break;
        default:
                printf("Unknown error.\n");
                exit(EXIT_FAILURE);
```

```
        }
        if (globalOptions.verboseFlag == 1) {
                printf("\n");
        }
}

int main(int argc, char *args[]) {
        char ch;
        while ((ch = getopt(argc, args, optString)) != -1) {
                switch (ch) {
                case 's':
                        if (atoi(optarg) < 0) {
                                printf("Unvalid input for <s>. Try
Again.\n");
                                exit(EXIT_FAILURE);
                        }
                        globalOptions.setIndexBits = atoi(optarg);
                        break;
                case 'E':
                        if (atoi(optarg) < 0) {
                                printf("Unvalid input for <E>. Try
Again.\n");
                                exit(EXIT_FAILURE);
                        }
                        globalOptions.associativity = atoi(optarg);
                        break;
                case 'b':
                        if (atoi(optarg) < 0) {
                                printf("Unvalid input for <b>. Try
Again.\n");
                                exit(EXIT_FAILURE);
                        }
                        globalOptions.blockBits = atoi(optarg);
                        break;
                case 't':
                        globalOptions.traceDir = optarg;
                        break;
                case 'v':
                        globalOptions.verboseFlag = 1;
                        break;
                case 'h':
                        usage();
                        exit(EXIT_FAILURE);
                case 'V':
                        globalOptions.verboseFlag = 1;
                        globalOptions.superVerboseFlag = 1;
                        break;
                default:
                        usage();
                        exit(EXIT_FAILURE);
                        break;
                }
        }
        globalOptions.tagBits = MACHINE_BITS - globalOptions.blockBits -
```

```
  globalOptions.setIndexBits;

        FILE *traceFile = fopen(globalOptions.traceDir, "r");
        if (traceFile == NULL) {
                printf("Fail to open file: %s\n", globalOptions.traceDir);
                exit(EXIT_FAILURE);
        }
        CacheHead cache = CacheInit(globalOptions.setIndexBits,
  globalOptions.associativity);
        char traceLine[32];
        while (fgets(traceLine, 32, traceFile) != NULL) {
                char mode;
                ulong address;
                int len;
                sscanf(traceLine, " %c %lx,%d", &mode, &address, &len);
                if (mode == 'I')
                        continue;
                if (globalOptions.verboseFlag == 1) {
                        printf("%c %lx,%d ", mode, address, len);
                }
                Execute(cache, mode, address, len);
        }
        printSummary(totalHitCount, totalMissCount, totalEvictCount);
        free(cache);
        return 0;
  }
```

最终在 `./driver.py` 的测试下，该程序和 `csim-ref` 的运行结果一致。

```
billchen@bill-ubuntu:/media/psf/Home/OneDrive/Workspace/LearningRepo/Course/CSAPP/LAB4$ ./driver.py
Part A: Testing cache simulator
Running ./test-csim
                        Your simulator     Reference simulator
Points (s,E,b)    Hits  Misses  Evicts    Hits  Misses  Evicts
     3 (1,1,1)       9       8       6       9       8       6  traces/yi2.trace
     3 (4,2,4)       4       5       2       4       5       2  traces/yi.trace
     3 (2,1,4)       2       3       1       2       3       1  traces/dave.trace
     3 (2,1,3)     167      71      67     167      71      67  traces/trans.trace
     3 (2,2,3)     201      37      29     201      37      29  traces/trans.trace
     3 (2,4,3)     212      26      10     212      26      10  traces/trans.trace
     3 (5,1,5)     231       7       0     231       7       0  traces/trans.trace
     6 (5,1,5)  265189   21775   21743  265189   21775   21743  traces/long.trace
    27
```

PART B

按照官方文档的说明，需要在 `trans.c` 中写入一个优化的矩阵转置函数。尽可能地降低不命中率。使用命令 `./test-trans -M <rol> -N <col>` 可以查看这一转置函数的不命中数。生成的 `trace.fi` 文件还可以利用 PART A 写的缓存模拟器检查命中情况。

Your performance score for each matrix size scales linearly with the number of misses, m, up to some threshold:

- 32×32: 8 points if $m < 300$, 0 points if $m > 600$
- 64×64: 8 points if $m < 1,300$, 0 points if $m > 2,000$
- 61×67: 10 points if $m < 2,000$, 0 points if $m > 3,000$

从官方文档得知要在 PART B 中得到分数需要完成三个测试并满足对应的不命中数条件。

Test I: 32 * 32

由于程序使用的缓存 block size 为 5，也就是有 2^5 的块大小，为32字节。`sizeof(int) = 4`，所以可以存储下 8 个整数。

先研究原始的一个简单的矩阵转置函数：

```
int i, j, tmp;
for (i = 0; i < N; i++) {
    for (j = 0; j < M; j++) {
        tmp = A[i][j];
        B[j][i] = tmp;
    }
}
```

这一函数的运行结果出现了 1000 多个 miss。提取一小部分原始的文件，利用 csim 查看详细的 miss 和 eviction 信息，可以发现在读取的时候发生了严重的抖动，导致了大量 miss 的出现。

```
14c400,4 (Decimal)[index: 0, tag: 1329] ------ miss
10c0a0,4 (Decimal)[index: 5, tag: 1072] ------ miss eviction
14c480,4 (Decimal)[index: 4, tag: 1329] ------ miss eviction
10c0a4,4 (Decimal)[index: 5, tag: 1072] ------ hit
14c500,4 (Decimal)[index: 8, tag: 1329] ------ miss eviction
10c0a8,4 (Decimal)[index: 5, tag: 1072] ------ hit
14c580,4 (Decimal)[index: 12, tag: 1329] ------ miss eviction
10c0ac,4 (Decimal)[index: 5, tag: 1072] ------ hit
14c600,4 (Decimal)[index: 16, tag: 1329] ------ miss eviction
10c0b0,4 (Decimal)[index: 5, tag: 1072] ------ hit
14c680,4 (Decimal)[index: 20, tag: 1329] ------ miss eviction
10c0b4,4 (Decimal)[index: 5, tag: 1072] ------ hit
14c700,4 (Decimal)[index: 24, tag: 1329] ------ miss eviction
10c0b8,4 (Decimal)[index: 5, tag: 1072] ------ hit
14c780,4 (Decimal)[index: 28, tag: 1329] ------ miss eviction
10c0bc,4 (Decimal)[index: 5, tag: 1072] ------ hit
14c800,4 (Decimal)[index: 0, tag: 1330] ------ miss eviction
10c0c0,4 (Decimal)[index: 6, tag: 1072] ------ miss
14c880,4 (Decimal)[index: 4, tag: 1330] ------ miss eviction
10c0c4,4 (Decimal)[index: 6, tag: 1072] ------ hit
```

所以可以利用矩阵分块的思想。每一行数组都可以被存入 4 个缓存行中，一共有 32 个缓存行，所以**每过 8 行就会出现一次和前面相同的组索引**，发生 miss 和 eviction。所以考虑将 32 * 32 的矩阵分成 16 个 8 * 8 的矩

阵，每一次都将一行的 8 个 int 分别存储进 t1 - t4。

即，将矩阵划分成如下结构：

1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16

其中每一个小块都是 8 * 8，每一行能够完整存储到缓存行中的矩阵。这种情况在 `transpose_submit()` 中的代码如下：

```
if(N == 32 && M == 32){
    int i, j, k;
    int t1, t2, t3, t4, t5, t6, t7, t8;
    for (i = 0; i < 32; i += 8) {
        for (j = 0; j < 32; j += 8) {
            for (k = 0; k < 8; k++) {
                t1 = A[i + k][j];
                t2 = A[i + k][j + 1];
                t3 = A[i + k][j + 2];
                t4 = A[i + k][j + 3];
                t5 = A[i + k][j + 4];
                t6 = A[i + k][j + 5];
                t7 = A[i + k][j + 6];
                t8 = A[i + k][j + 7];
                B[j][i + k] = t1;
                B[j + 1][i + k] = t2;
                B[j + 2][i + k] = t3;
                B[j + 3][i + k] = t4;
                B[j + 4][i + k] = t5;
                B[j + 5][i + k] = t6;
                B[j + 6][i + k] = t7;
                B[j + 7][i + k] = t8;
            }
        }
    }
}
```

结果如下图所示：

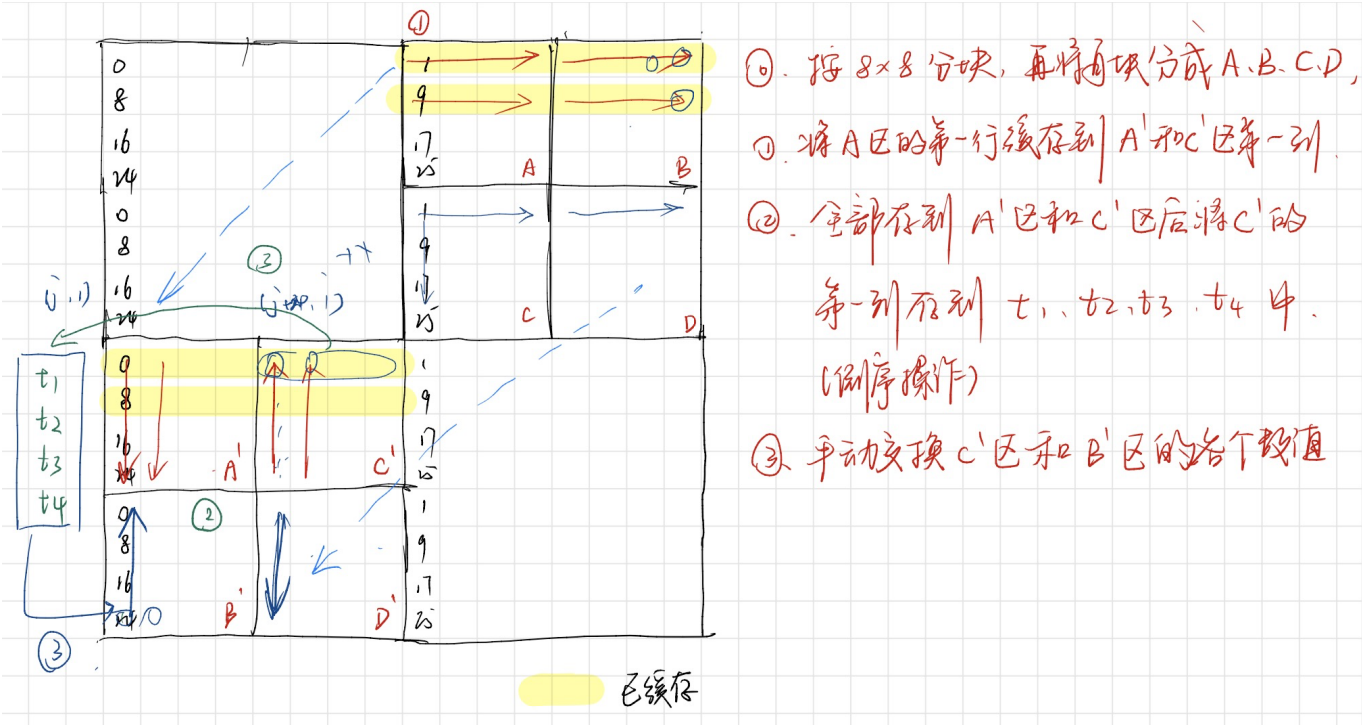
```
trans.c
billchen@bill-ubuntu:/media/psf/Home/OneDrive/Workspace/LearningRepo/Course/CSAPP/LAB4$ ./test-trans -M 32 -N 32

Function 0 (1 total)
Step 1: Validating and generating memory traces
Step 2: Evaluating performance (s=5, E=1, b=5)
func 0 (Transpose submission): hits:1766, misses:287, evictions:255

Summary for official submission (func 0): correctness=1 misses=287

TEST_TRANS_RESULTS=1:287
```

Test II: 64 * 64

和第一种情况测试类似。但是由于大小变成了 64 * 64，每过 4 行就会出现一次冲突的情况。所以可以先分成 8 * 8 的块，然后再把 8 * 8 的块分成 4 个 4 * 4 的块。读取一行，但存储进的位置如图所示。逆序存储之后再逐行处理 C' 和 B' 处的数据。

由于之前是逆序存储的，所以在 C' 会把 0 加载进缓存，而在 B' 会把 24 加载进缓存，再利用 t1, t2, t3, t4 四个变量作临时变量存储，交换 0 行和 24 行的位置。

大概的逻辑如下图所示：

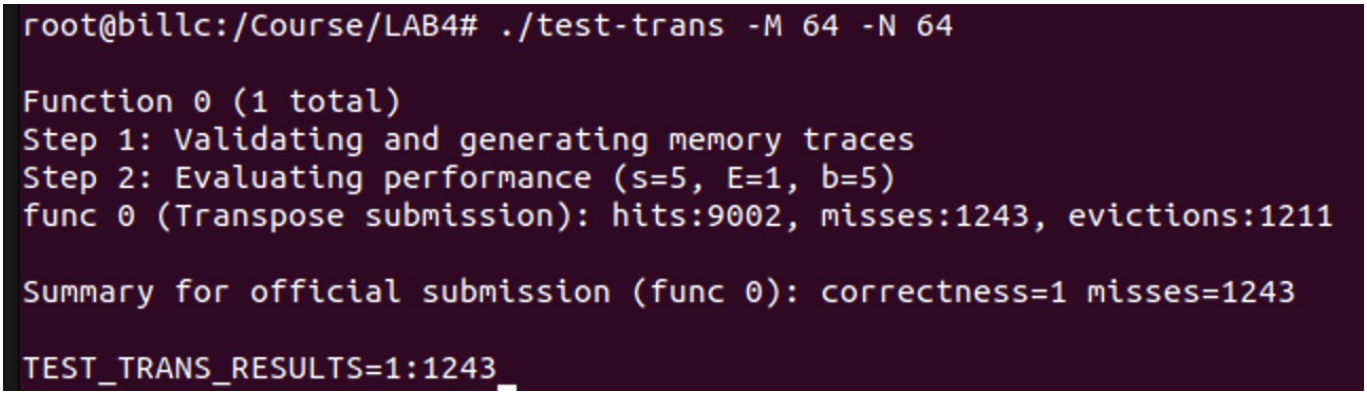


具体的代码实现如下：

```
else if (N == 64 && M == 64) {
    int t0, t1, t2, t3, t4, t5, t6, t7;
    for (int i = 0; i < N; i += 8) {
        for (int j = 0; j < M; j += 8) {
            for (int k = i; k < i + 4; k++) {
                t0 = A[k][j];
                t1 = A[k][j + 1];
                t2 = A[k][j + 2];
                t3 = A[k][j + 3];
                t4 = A[k][j + 4];
                t5 = A[k][j + 5];
                t6 = A[k][j + 6];
                t7 = A[k][j + 7];
                B[j][k] = t0;
                B[j + 1][k] = t1;
                B[j + 2][k] = t2;
                B[j + 3][k] = t3;
                B[j + 0][k + 4] = t7;
                B[j + 1][k + 4] = t6;
```

```
                B[j + 2][k + 4] = t5;
                B[j + 3][k + 4] = t4;
            }
            for (int h = 0; h < 4; h++) {
                t0 = A[i + 4][j + 3 - h];
                t1 = A[i + 5][j + 3 - h];
                t2 = A[i + 6][j + 3 - h];
                t3 = A[i + 7][j + 3 - h];
                t4 = A[i + 4][j + 4 + h];
                t5 = A[i + 5][j + 4 + h];
                t6 = A[i + 6][j + 4 + h];
                t7 = A[i + 7][j + 4 + h];
                B[j + 4 + h][i + 0] = B[j + 3 - h][i + 4];
                B[j + 4 + h][i + 1] = B[j + 3 - h][i + 5];
                B[j + 4 + h][i + 2] = B[j + 3 - h][i + 6];
                B[j + 4 + h][i + 3] = B[j + 3 - h][i + 7];
                B[j + 3 - h][i + 4] = t0;
                B[j + 3 - h][i + 5] = t1;
                B[j + 3 - h][i + 6] = t2;
                B[j + 3 - h][i + 7] = t3;
                B[j + 4 + h][i + 4] = t4;
                B[j + 4 + h][i + 5] = t5;
                B[j + 4 + h][i + 6] = t6;
                B[j + 4 + h][i + 7] = t7;
            }
        }
    }
}
```

得到如下结果：



Test III: 61 * 67

这一测试中由于矩阵不规则，而且也不是 8 的倍数，所以在行与行之间没有特别明显的冲突不命中的关系。可以尝试用分块矩阵的方式优化。经过尝试 8 * 8 的分块和 16 * 16 的分块后，发现使用 16 * 16 的分块方式可以将 miss 数降低到 2000 以下。

这一部分的代码如下：

```
else {
    int i, j, k, h;
    for (i = 0; i < N; i += 16) {
        for (j = 0; j < M; j += 16) {
            for (k = i; k < i + 16 && k < N; k++) {
                for (h = j; h < j + 16 && h < M; h++) {
                    B[h][k] = A[k][h];
                }
            }
        }
    }
}
```

可以得到 1992 的 miss 数。

```
root@billc:/Course/LAB4# ./test-trans -M 61 -N 67

Function 0 (1 total)
Step 1: Validating and generating memory traces
Step 2: Evaluating performance (s=5, E=1, b=5)
func 0 (Transpose submission): hits:6187, misses:1992, evictions:1960

Summary for official submission (func 0): correctness=1 misses=1992
```

最终在 `./driver.py` 的运行结果中，Part B 获得如下结果：

```
Part B: Testing transpose function
Running ./test-trans -M 32 -N 32
Running ./test-trans -M 64 -N 64
Running ./test-trans -M 61 -N 67

Cache Lab summary:
                        Points   Max pts      Misses
Csim correctness          27.0        27
Trans perf 32x32           8.0         8         287
Trans perf 64x64           8.0         8        1243
Trans perf 61x67          10.0        10        1992
          Total points    53.0        53
```

> 一如既往地，现在又是凌晨了 orz.
>
> 2019.5.22