Lab 8: Microbenchmarks and SIMD Instructions

1 Membench

The *membench* programs are run to obtain the following plots in **??** to Fig. 3 for the effect of array length and stride length on type of memory access, and time to access.

In this plot, the solid vertical lines indicate the estimated memory sizes, and dashed vertical lines indicate the true memory sizes, with black lines indicating the cache line sizes, and blue lines indicating the total cache sizes. The green solid horizontal lines indicate the approximate cache access times.

In general, it is observed that for a given range of strides, and particularly in regions with plateaus of strides, say between 64B and 4KB, greater array lengths have greater access times. These parallel plateaus can be attributed to filling and then calling the lowest possible caches/accessing the lowest possible level of memory when there are cache misses in the even lower level of memory. This accessing is constant for the given lowest possible memory level.

Here, lowest possible memory level refers to the smallest cache at which the stride is less than the cache size and or line size. At this lowest possible level of memory, there will be the least number of cache misses, as it will be assumed that the array will fill this level of cache with as many full cache lines as possible. Larger arrays will fill more cache lines at that level, up to the level being full (and disregarding space being required for the code/instructions on top of space for the data). This filling also depends on whether a cache miss prompts a cache line to be overwritten, or a new cache line to be filled with data from a higher memory level, This depends on the specific association, inclusivity/exclusivity, hierarchy and relative sizes of the different cache levels.

So for larger arrays, the number of iterations through the array is obviously greater, and must take more time, and more cache misses will occur, regardless of the relative difference in stride size to cache line size. This greater number of misses (and corresponding new cache lines being filled from higher memory levels) is likely linear in the array size. This linear increase in cache misses explains the parallel plateaus at higher accessing times for greater array sizes, even if the time to access each element within a given cache size is roughly constant.

The access times will be measured where there are significant plateaus in the access times, and the *maximum* of these plateaus will be used as an estimate for the access times. The reason there are not sharp increases between plateaus is that as the stride increases, there are less cache hits and more misses as the indexing goes beyond the cache line size, however there are also less indexing calls with greater stride. So the increase up to the next plateau, which corresponds to the memory access time of the next greater memory level, is gradual, as there is a mix of hits in different memory levels.

The following script *calc.sh* in the appendix was used to get the cpu and memory statistics in Code. 1. The average processor core speed for the 36 processors on GreatLakes to be 3000 MHz, and the cache line sizes appear to be constant at 64 Bytes. The cpu core speed will be used to calculate the number of processor clock cycles required to access the various types of memory,

$$\#\text{ cycles per memory access} = \text{clock speed} \times \text{memory access time}.$$

Code 1: CPU and Memory values.

```
Cache Info
Cache L1 Size: 32 kB
Cache L1 Line Size: 64 B

Cache L2 Size: 1024 kB
Cache L2 Line Size: 64 B

Cache L3 Size: 25344 kB
Cache L3 Line Size: 64 B

```

```
Cache L4 Size: 0 kB
Cache L4 Line Size: 0 B




CPU Info
CPU Cores: 36
CPU Speed: 2999.531 MHz
```

1.1 Processor Values

On the Greatlakes compute notes, there are 36 $\times$ Intel(R) Xeon(R) Gold 6140 CPU @ 2.30GHz. From repeated requests for the speed of each core, the average core speed over all cores and samples is 2.99 GHz.

1.2 L_1 Cache Values

For the L_1 cache line size, the true line size is 64B, and from the plots, particularly in Fig. 2, it can be seen that the access times do not start to initially increase until around strides of 64B, before then plateauing. This jump before plateauing indicates that strides greater than this value must start to involve more L_1 misses, and require accessing the L_2 memory.

$$L_1 \text{ Line } = 128B.$$

For the L_1 total cache size, although the true cache size is 32KB, from the plots, particularly in Fig. 2, it can be seen that the access times remain very constant, and at their minimum all way the up to 4KB for arrays with length $\leq$ 32KB, suggesting the entire array, or at least half of the array can be loaded into the L_1 cache. In addition, the next largest 62KB array shows increased access times for up to 32KB strides, suggesting some L_1 cache misses possibly occur, and so the L_1 cache size is likely less than 32KB.

$$16KB \leq L_1 \leq 32KB.$$

For the L_1 access time, given the quite constant access times up to 4KB strides for arrays with length $\leq$ 32KB, the estimated access time is therefore the maximum of the 32KB length array curve:

$$T_1 = 0.57\text{ns} = 2 \text{ cycles}.$$

1.3 L_2 Cache Values

For the L_2 cache line size, the true line size is 64B, and from the plots, particularly in Fig. 3, it can be seen that after the initial increase of access times, there is a slight plateau for strides $\leq$ 512B, and arrays of sizes 64KB-8MB, indicating that possibly the array is being quickly indexed in the L_2 cache with a cache line of between 64B and 512B. There is then a jump in access times, but not a huge jump for arrays up to size 8MB, indicating there are possibly still cache hits in the L_2 cache, but at different lines.

$$64B \leq L_2 \text{ Line } \leq 512B.$$

For the L_2 total cache size, although the true cache size is 1MB, from the plots, particularly in Fig. 3, it can be seen that the access times remain very constant over a large range of array sizes between 64KM to 8MB, with strides between 1KB and 256KB. This suggests lots of these array sizes can be mostly loaded into the L_2 cache on several cache lines. This suggests the L_2 total cache size to be less than 256KB (and greater than the L_1 total cache size); the point where the access times for these array sizes drops dramatically when many less array elements are indexed. The difficulty at finding tighter bounds on the L_2 cache sizes is possibly due to the L_2 cache sometimes being shared by pairs of cores, affecting the timing, depending on which cores the array is being computed on.

$$16KB \leq L_2 \leq 256KB.$$

For the L_2 access time, given the quite constant access times for array sizes between 64KM to 8MB, with strides between 1KB and 256KB, the estimated access time is therefore the maximum of the 8MB size array curve along

this plateau:

$$T_2 = 3.83\text{ns} = 12 \text{ cycles}.$$

1.4 L_3 Cache Values

For the L_3 cache line size, the true line size is 64B, however from the plots, it is difficult to tell where exactly there is a distinct plateau for array indexing with strides within the size of this larger cache's lines. This may be due to the L_3 cache being typically shared between all (36) cores, and so timings may be affected depending how the computations are distributed amongst the cores. However for array sizes of 16MB to 512MB, there is somewhat a plateau between 512B and 4KB, indicating a possible range for the L_3 cache line size. Here, there may be hits due to this larger cache being allowed to store more of these larger arrays, minimising cache misses. The lack of distinct plateau is also possibly attributed to the large arrays being far larger than the cache, and there being many hits and misses while the lines are being filled from the main memory.

$$64B \leq L_3 \text{ Line } \leq 4KB.$$

For the L_3 total cache size, although the true cache size is 24.75MB, from the plots, particularly in Fig. 4, it can be seen that the plateau between 512B and 4KB, for array sizes of 16MB to 512MB, rises, and then decreases gradually, before plateauing again for strides between 256KB and 8MB. This suggests that the time is not decreasing solely due to there being less elements indexed with greater stride, but there also possibly being effects of the elements still being in the faster L_3 cache compared to the main memory. There are still hits occurring in succession in a cache that are causing this plateau at non-zero access times. There is still though great uncertainty in the exact total size of this L_3 cache.

$$256KB \leq L_3 \leq 8MB.$$

For the L_3 access time, given the two different plateaus present in the access times for the larger arrays, the access time will be estimated as the maximum of these plateaus in Fig. 4.

$$T_3 = 10.36\text{ns} = 32 \text{ cycles}.$$

1.5 Main Memory Values

Only the 1GB array sizes appear to be unable to be stored fully in any caches, and there are enough misses in the lower caches that the main memory must be accessed. It is assumed the upper plateau for the 1GB array are these memory hits, and the access time is assumed to be the maximum of this plateau. This is assumed to be a lower bound, if some of the array is in the L_3 cache, and there are some hits there, and some in the main memory.

$$T_{\text{mem}} \geq 13.69\text{ns} = 42 \text{ cycles}.$$

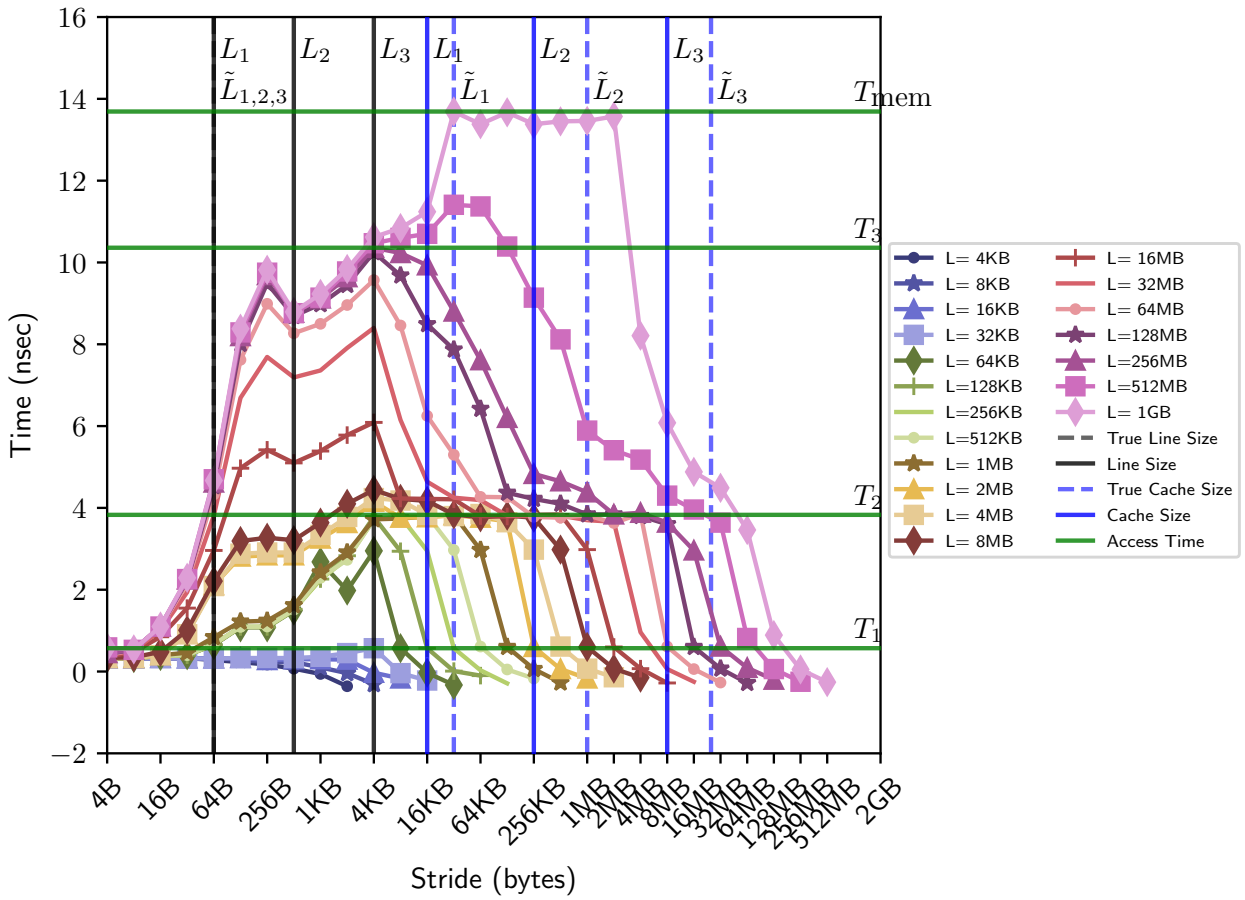

Figure 1: Memory access times for various array sizes, and stride lengths from 4B to 512MB.

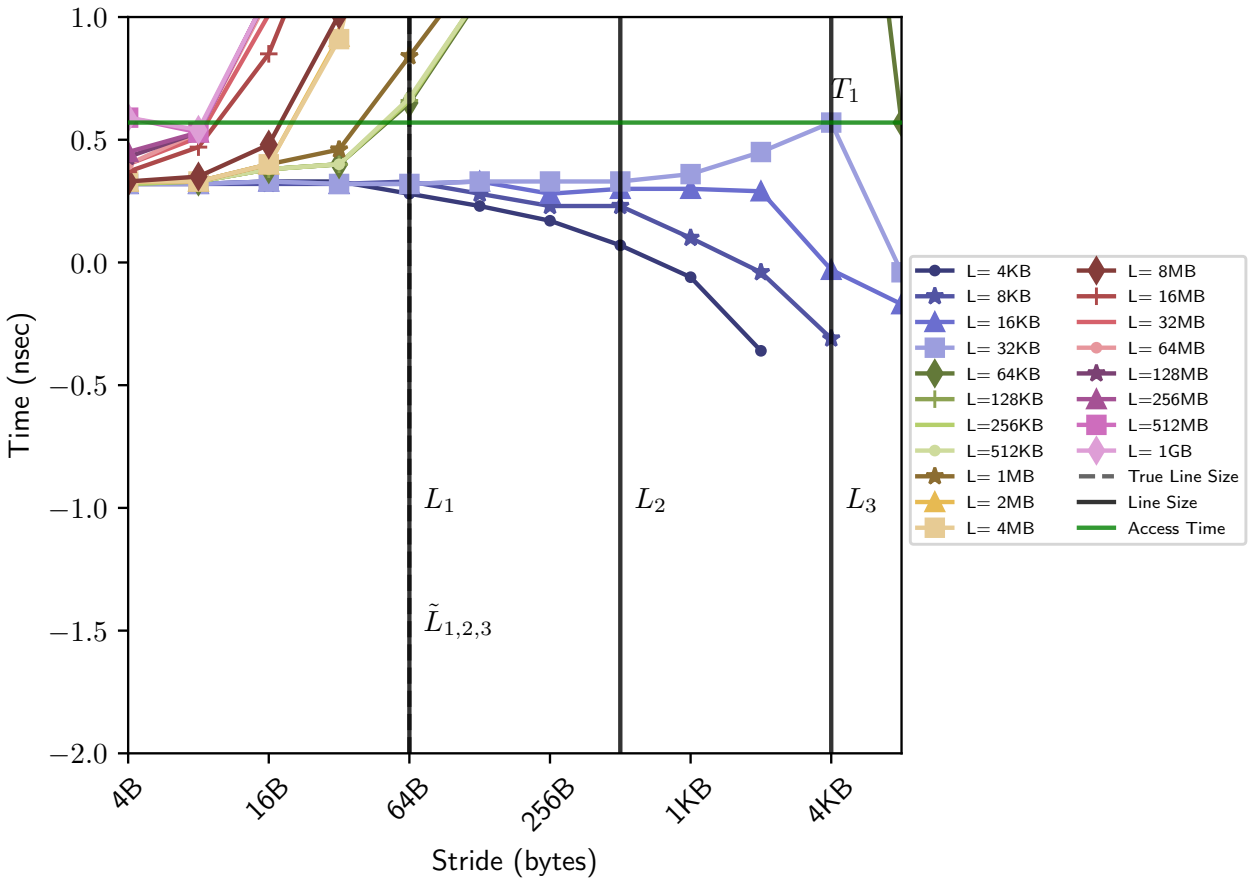

Figure 2: Memory access times for various array sizes, and stride lengths from 4B to 4KB.

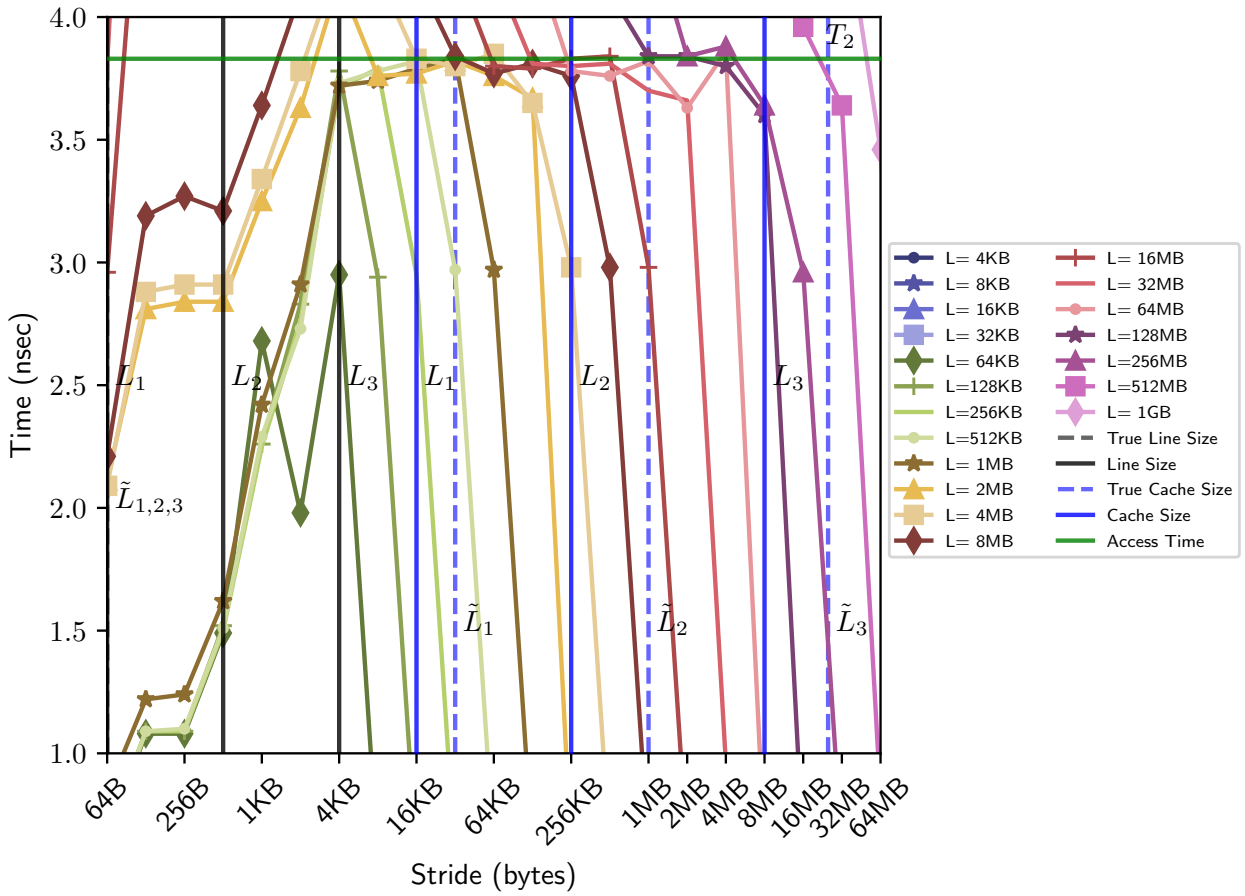

Figure 3: Memory access times for various array sizes, and stride lengths from 16B to 64MB.

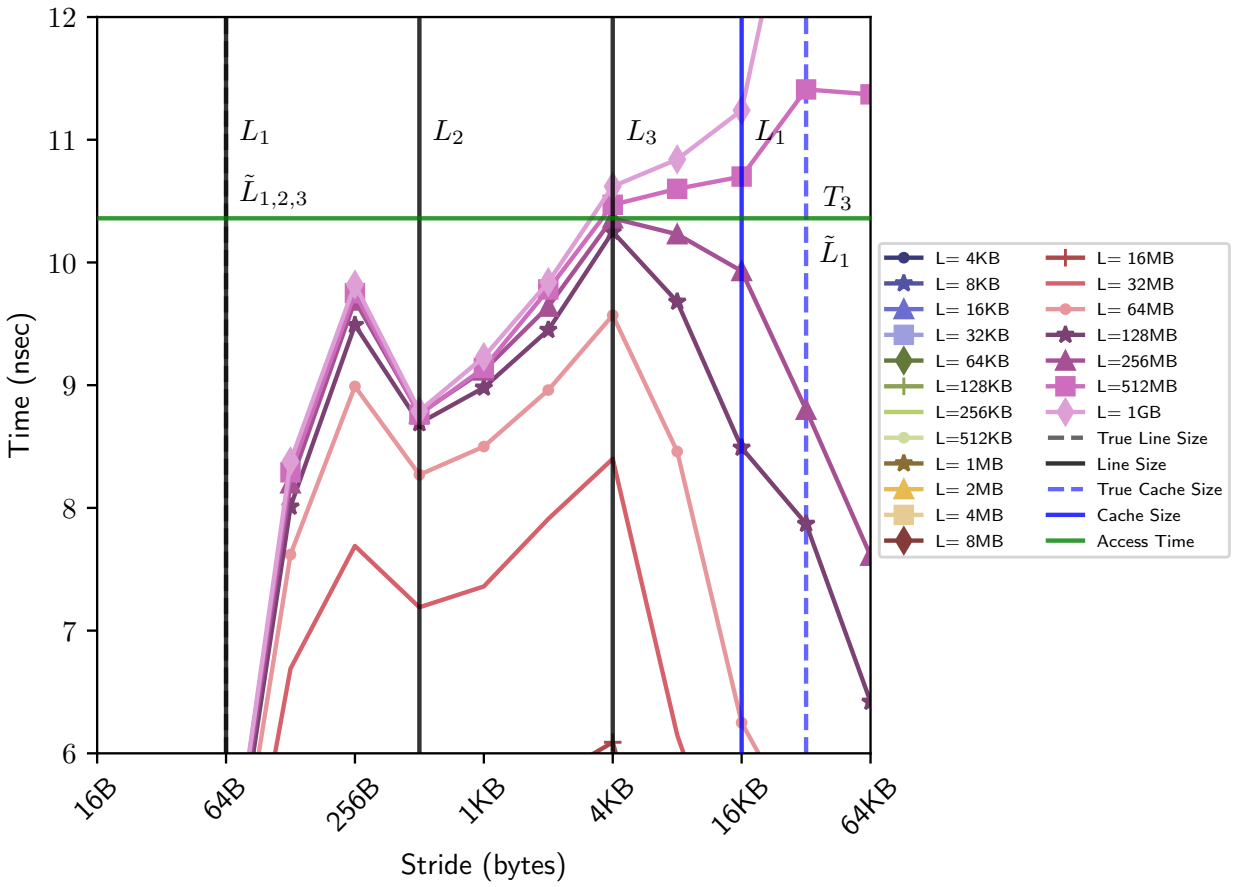

Figure 4: Memory access times for various array sizes, and stride lengths from 16B to 64KB.

2 SIMD Instructions

2.1 AVX Support

- The commands used to verify if the current machine/processor supports AVX are:

  grep -E “avx[^0-9]” /proc/cpuinfo

  and if the current machine/processor supports AVX2 are:

  grep -E “avx2” /proc/cpuinfo

  These searches will show whether the supported AVX fields are in the flags section of the processor info from /proc/cpuinfo. This command will show all processors (36 × Intel(R) Xeon(R) Gold 6140 CPU @ 2.30GHz, for GreatLakes compute nodes).

- The commands used to verify if the current GNU compiler supports AVX or AVX2 by the constants/macros the compiler defines:

  gcc -mavx2 -dM -E - < /dev/null | grep "AVX" | sort

  This command will show the boolean settings for the AVX constants:
  #define __AVX__ 1
  #define __AVX2__ 1

- The commands used to verify if the current Intel compiler supports AVX or AVX2 by the constants/macros the compiler defines:

  icc -march=native -dM -E - < /dev/null | grep "AVX" | sort

  This command will show the boolean settings for the AVX constants:
  #define __AVX__ 1
  #define __AVX2__ 1
  #define __AVX512BW__ 1
  #define __AVX512CD__ 1
  #define __AVX512DQ__ 1
  #define __AVX512F__ 1
  #define __AVX512VL__ 1
  #define __AVX_I__ 1

2.2 dgemm Assembly Instructions

The command to get the assembly instructions is as follows, where the function for the naive *dgemm.cpp* in Code. 6 in the appendix is translated into assembly code, with the avx2 and fast optimizations using the command:

g++ -S -Ofast -mavx2 dgemm.cpp

This command produces the following assembly code in Code. 2

Code 2: Matrix-Matrix multiply assembly with avx2 and fast optimization

```
        .file   "dgemm.cpp"
        .text
        .p2align 4,,15
        .globl   _Z5dgemmccjjjdPKPKdS2_dPPd
        .type   _Z5dgemmccjjjdPKPKdS2_dPPd, @function
_Z5dgemmccjjjdPKPKdS2_dPPd:
.LFB1564:
        .cfi_startproc
        leaq    8(%rsp), %r10
        .cfi_def_cfa 10, 0
        andq    $-32, %rsp
        testl   %ecx, %ecx
        pushq   -8(%r10)
        pushq   %rbp
        .cfi_escape 0x10,0x6,0x2,0x76,0
        movq    %rsp, %rbp
        pushq   %r15
        pushq   %r14
        pushq   %r13
        pushq   %r12
        pushq   %r10
        .cfi_escape 0xf,0x3,0x76,0x58,0x6
        .cfi_escape 0x10,0xf,0x2,0x76,0x78
        .cfi_escape 0x10,0xe,0x2,0x76,0x70
        .cfi_escape 0x10,0xd,0x2,0x76,0x68
        .cfi_escape 0x10,0xc,0x2,0x76,0x60
        pushq   %rbx
```

```
        .cfi_escape 0x10,0x3,0x2,0x76,0x50
        movl        %r8d, -52(%rbp)
        movq        (%r10), %r14
        movq        8(%r10), %rax
        je        .L35
        testl       %edx, %edx
        je        .L35
        subl        $1, %ecx
        leal        -1(%rdx), %r13d
        vbroadcastsd        %xmm1, %ymm3
        leaq        8(%rax,%rcx,8), %r15
        movq        %rax, %rbx
        movl        %ecx, -56(%rbp)
        .p2align 4,,10
        .p2align 3
.L9:
        movq        (%rbx), %r10
        xorl        %r8d, %r8d
        movq        %r10, %rcx
        shrq        $3, %rcx
        negq        %rcx
        andl        $3, %ecx
        leal        3(%rcx), %esi
        cmpl        %r13d, %esi
        ja        .L3
        testl       %ecx, %ecx
        je        .L4
        vmulsd        (%r10), %xmm1, %xmm2
        cmpl        $1, %ecx
        movl        $1, %r8d
        vmovsd        %xmm2, (%r10)
        je        .L4
        vmulsd        8(%r10), %xmm1, %xmm2
        cmpl        $2, %ecx
        movl        $2, %r8d
        vmovsd        %xmm2, 8(%r10)
        je        .L4
        vmulsd        16(%r10), %xmm1, %xmm2
        movl        $3, %r8d
        vmovsd        %xmm2, 16(%r10)
.L4:
        movl        %edx, %r12d
        leaq        (%r10,%rcx,8), %rdi
        xorl        %esi, %esi
        subl        %ecx, %r12d
        xorl        %ecx, %ecx
        movl        %r12d, %r11d
        shrl        $2, %r11d
        .p2align 4,,10
        .p2align 3
.L6:
        vmulpd        (%rdi,%rcx), %ymm3, %ymm2
        addl        $1, %esi
        vmovapd       %ymm2, (%rdi,%rcx)
        addq        $32, %rcx
        cmpl        %esi, %r11d
        ja        .L6
```

```
        movl        %r12d, %ecx
        andl        $-4, %ecx
        addl        %ecx, %r8d
        cmpl        %r12d, %ecx
        je         .L7
.L3:
        movl        %r8d, %ecx
        leaq        (%r10,%rcx,8), %rcx
        vmulsd        (%rcx), %xmm1, %xmm2
        vmovsd        %xmm2, (%rcx)
        leal        1(%r8), %ecx
        cmpl        %ecx, %edx
        jbe        .L7
        leaq        (%r10,%rcx,8), %rcx
        vmulsd        (%rcx), %xmm1, %xmm2
        vmovsd        %xmm2, (%rcx)
        leal        2(%r8), %ecx
        cmpl        %edx, %ecx
        jnb        .L7
        leaq        (%r10,%rcx,8), %rcx
        vmulsd        (%rcx), %xmm1, %xmm2
        vmovsd        %xmm2, (%rcx)
        leal        3(%r8), %ecx
        cmpl        %ecx, %edx
        jbe        .L7
        leaq        (%r10,%rcx,8), %rcx
        vmulsd        (%rcx), %xmm1, %xmm2
        vmovsd        %xmm2, (%rcx)
        leal        4(%r8), %ecx
        cmpl        %ecx, %edx
        jbe        .L7
        leaq        (%r10,%rcx,8), %rcx
        addl        $5, %r8d
        cmpl        %r8d, %edx
        vmulsd        (%rcx), %xmm1, %xmm2
        vmovsd        %xmm2, (%rcx)
        jbe        .L7
        leaq        (%r10,%r8,8), %rcx
        vmulsd        (%rcx), %xmm1, %xmm2
        vmovsd        %xmm2, (%rcx)
.L7:
        addq        $8, %rbx
        cmpq        %r15, %rbx
        jne        .L9
        movl        -52(%rbp), %edx
        testl        %edx, %edx
        je         .L37
        movl        -52(%rbp), %ebx
        leaq        8(,%r13,8), %r13
        movq        %r14, %r15
        leal        -1(%rbx), %edx
        leaq        8(%r14,%rdx,8), %r12
        movl        -56(%rbp), %edx
        leaq        8(,%rdx,8), %r11
        .p2align 4,,10
        .p2align 3
.L12:
```

```
142         movq        (%r15), %rbx
143         movq        %r15, %r10
144         xorl        %edi, %edi
145         subq        %r14, %r10
146         .p2align 4,,10
147         .p2align 3
148 .L11:
149         leaq        (%rbx,%rdi), %r8
150         xorl        %edx, %edx
151         .p2align 4,,10
152         .p2align 3
153 .L10:
154         vmulsd        (%r8), %xmm0, %xmm1
155         movq        (%r9,%rdx), %rsi
156         movq        (%rax,%rdx), %rcx
157         addq        $8, %rdx
158         addq        %rdi, %rcx
159         cmpq        %rdx, %r11
160         vmulsd        (%rsi,%r10), %xmm1, %xmm1
161         vaddsd        (%rcx), %xmm1, %xmm1
162         vmovsd        %xmm1, (%rcx)
163         jne         .L10
164         addq        $8, %rdi
165         cmpq        %r13, %rdi
166         jne         .L11
167         addq        $8, %r15
168         cmpq        %r12, %r15
169         jne         .L12
170 .L37:
171         vzeroupper
172 .L35:
173         popq        %rbx
174         popq        %r10
175         .cfi_def_cfa 10, 0
176         popq        %r12
177         popq        %r13
178         popq        %r14
179         popq        %r15
180         popq        %rbp
181         leaq        -8(%r10), %rsp
182         .cfi_def_cfa 7, 8
183         ret
184         .cfi_endproc
185 .LFE1564:
186         .size         _Z5dgemmccjjjdPKPKdS2_dPPd, .-_Z5dgemmccjjjdPKPKdS2_dPPd
187         .section        .text.startup,"ax",@progbits
188         .p2align 4,,15
189         .type         _GLOBAL__sub_I__Z5dgemmccjjjdPKPKdS2_dPPd, @function
190 _GLOBAL__sub_I__Z5dgemmccjjjdPKPKdS2_dPPd:
191 .LFB2045:
192         .cfi_startproc
193         leaq        _ZStL8__ioinit(%rip), %rdi
194         subq        $8, %rsp
195         .cfi_def_cfa_offset 16
196         call        _ZNSt8ios_base4InitC1Ev@PLT
197         movq        _ZNSt8ios_base4InitD1Ev@GOTPCREL(%rip), %rdi
198         leaq        __dso_handle(%rip), %rdx
```

```
199         leaq        _ZStL8__ioinit(%rip), %rsi
200         addq        $8, %rsp
201         .cfi_def_cfa_offset 8
202         jmp         __cxa_atexit@PLT
203         .cfi_endproc
204 .LFE2045:
205         .size       _GLOBAL__sub_I__Z5dgemmccjjjdPKPKdS2_dPPd,
              .-_GLOBAL__sub_I__Z5dgemmccjjjdPKPKdS2_dPPd
206         .section        .init_array,"aw"
207         .align 8
208         .quad       _GLOBAL__sub_I__Z5dgemmccjjjdPKPKdS2_dPPd
209         .local      _ZStL8__ioinit
210         .comm       _ZStL8__ioinit,1,1
211         .hidden       __dso_handle
212         .ident      "GCC: (Ubuntu 7.5.0-3ubuntu1~18.04) 7.5.0"
213         .section        .note.GNU-stack,"",@progbits
```

Code 3: membench plotting script.

```python
#!/usr/bin/env python
import matplotlib
import matplotlib.pyplot as plt
import numpy as np

matplotlib.rcParams['text.usetex'] = True
# matplotlib.rcParams['text.latex.preamble'] = [r'\usepackage{ragged2e']

# Routine modified from:
  https://stackoverflow.com/questions/1094841/reusable-library-to-get-human-readable-version-of-file-size
def sizeof_fmt(num, suffix='B'):
    for unit in ['','K','M','G','T']:
        if abs(num) < 1024.0:
            return '%3.0f%s%s' % (num, unit, suffix)
        num /= 1024.0
    return '%.1f%s%s' % (num, 'T', suffix)

def fmt_sizeof(fmt):
    bases={'B':2,'':10}
    units={k:v for k,v in zip(['','K','M','G','T'],[1,10,20,30,40])}
    try:
      base=fmt[-1]
      unit=fmt[-2]
      num = float(fmt[:-2])
    except ValueError:
      try:
        base=fmt[-1]
        unit=''
        num = float(fmt[:-1])
      except:
        try:
          base=''
          unit=''
          num = float(fmt)
        except:
          return fmt
    # print(num,(bases.get(base,10)**units.get(unit,1)))
    # print(num)
    num *= (bases.get(base,10)**units.get(unit,1))
    if int(num) == num:
      num = int(num)
    return num

def indexer(array,sorter,value):
  i = np.where(sorter==value)[0]
  return array[i]


file='membench_4'
cpuspeed=3e9

mbdata = np.genfromtxt('%s.out'%file,usecols=(1,3,5))


```

```
maxunit=10
units=dict(zip(range(0,maxunit*4,maxunit),['','K','M','G']))
sizes = {'%d%s%s'%(b**(i),units[d],u):b**(i+d) for b,u in zip([2],['B']) for d in units for i in range(maxunit)}


xtlabels=[*['4B','16B','64B','256B','1KB','4KB','16KB','64KB','256KB','1MB'],
          *['2MB','4MB','8MB','16MB','32MB','64MB','128MB','256MB','512MB','2GB']]
xtvals = [sizes.get(l,fmt_sizeof(l)) for l in xtlabels]




# k,l,m = '1GB','1MB','512B'
# print((sizes.get(k,fmt_sizeof(k)),indexer(indexer(mbdata[:,2],mbdata[:,0],sizes.get(l,fmt_sizeof(l))),indexer(mbdata[:,1],mbdata[:,0],sizes.get(l,fmt_sizeof(l))),sizes.get(m,fmt_sizeof(m)))[0]))

lims={
       'all':[(xtlabels[0],xtlabels[-1]),(-2,16)],
       'lowerleft':[('4B','8KB'),(-2,1)],
       'middleupper':[('16B','64KB'),(6,12)],
       'middle':[('64B','64MB'),(1,4)],
       }

heights={k:{l:-1 for l in ['h','v']} for k in lims}
heights['all']['v'] =15
heights['lowerleft']['v'] = -1
heights['middle']['v'] = 2.5
heights['middleupper']['v'] = 11
lines={
        'all':{'v': {
                      # **{(sizes.get(k,fmt_sizeof(k))/2,height):r'$\tilde{L}_{1,2,3}\\\textrm{%s}$'%k for i,k in
                        enumerate(['64B'])},
                      # **{(sizes.get(k,fmt_sizeof(k)),height):r'${L}_{%d}\\\textrm{%s}$'%(i+1,k) for i,k in
                        enumerate(['128B'])},
                      # # **{(sizes.get(k,fmt_sizeof(k)),height):r'$\tilde{L}_{%d}$'%(i+1) for i,k in enumerate(['128B','4KB','16KB'])},
                      # **{(sizes.get(k,fmt_sizeof(k)),height):r'$\tilde{L}_{%d}\\\textrm{%s}$'%(i+1,k) for i,k in
                        enumerate(['32KB','1MB','24.75MB'])},

                      **{(sizes.get(k,fmt_sizeof(k)),heights['all']['v']-1):r'$\tilde{L}_{1,2,3}$' for i,k in
                        enumerate(['64B'])},
                      **{(sizes.get(k,fmt_sizeof(k)),heights['all']['v']):r'${L}_{%d}$'%(i+1) for i,k in enumerate(['64B','512B','4KB'])},
                      # **{(sizes.get(k,fmt_sizeof(k)),heights['all']['v']):r'$\tilde{L}_{%d}$'%(i+1) for i,k in
                        enumerate(['128B','4KB','16KB'])},
                      **{(sizes.get(k,fmt_sizeof(k)),heights['all']['v']-1):r'$\tilde{L}_{%d}$'%(i+1) for i,k in
                        enumerate(['32KB','1MB','25MB'])},
```

```
                    **{(sizes.get(k,fmt_sizeof(k)),heights['all']['v']):r'$L_{%d}$'%(i+1) for
                      i,k in enumerate(['16KB','256KB','8MB'])},
                    },

            'h': {
                    # **{(sizes.get(k,fmt_sizeof(k)),np.max(indexer(mbdata[:,2],mbdata[:,0],
                      sizes.get(l,fmt_sizeof(l))))):r'$T_{%d}$'%(i+1) for i,(k,l) in
                      enumerate(zip(['1GB'],['32KB']))},
                    **{(sizes.get(k,fmt_sizeof(k)),np.max(indexer(mbdata[:,2],mbdata[:,0],
                      sizes.get(l,fmt_sizeof(l))))):r'$T_{%d}$'%(i+1) if i<3 else
                      r'$T_{\textrm{mem}}$' for i,(k,l) in
                      enumerate(zip(['1GB','1GB','1GB','1GB'],['32KB','1MB','256MB','1GB']))},
                    # **{(sizes.get(k,fmt_sizeof(k)),indexer(indexer(mbdata[:,2],mbdata[:,0],
                      sizes.get(l,fmt_sizeof(l))),indexer(mbdata[:,1],mbdata[:,0],sizes.get(l,
                      fmt_sizeof(l))),sizes.get(m,fmt_sizeof(m)))[0]):r'$T_{%d}$'%(i+2) for
                      i,(k,l,m) in enumerate(zip(['1GB'],['1MB'],['512B']))},
                    },


            },
        'lowerleft':{'v': {
                            # **{(sizes.get(k,fmt_sizeof(k)),height):r'$\tilde{L}_{1,2,
                              3}\\\textrm{%s}$'%k for i,k in
                              enumerate(['64B'])},
                            # **{(sizes.get(k,fmt_sizeof(k)),
                              height):r'${L}_{%d}\\\textrm{%s}$'%(i+1,k) for i,k in
                              enumerate(['128B'])},

                            **{(sizes.get(k,fmt_sizeof(k)),
                              heights['lowerleft']['v']-0.5):r'$\tilde{L}_{1,2,3}$' for i,k in
                              enumerate(['64B'])},
                            **{(sizes.get(k,fmt_sizeof(k)),
                              heights['lowerleft']['v']):r'${L}_{%d}$'%(i+1) for i,k in
                              enumerate(['64B','512B','4KB'])},


                        },
                    'h': {
                            # **{(sizes.get(k,fmt_sizeof(k)),np.max(indexer(mbdata[:,2],
                              mbdata[:,0],sizes.get(l,fmt_sizeof(l))))):r'$T_{%d}$'%(i+1) for
                              i,(k,l) in enumerate(zip(['256B'],['32KB']))},
                    **{(sizes.get(k,fmt_sizeof(k)),np.max(indexer(mbdata[:,2],mbdata[:,0],
                      sizes.get(l,fmt_sizeof(l))))):r'$T_{%d}$'%(i+1) for i,(k,l) in
                      enumerate(zip(['4KB','4KB'],['32KB','1MB']))},
                        },
                    },
        'middle':{'v': {
                            # **{(sizes.get(k,fmt_sizeof(k)),height):r'$\tilde{L}_{1,2,
                              3}\\\textrm{%s}$'%k for i,k in
                              enumerate(['64B'])},
                            # **{(sizes.get(k,fmt_sizeof(k)),
                              height):r'${L}_{%d}\\\textrm{%s}$'%(i+1,k) for i,k in
                              enumerate(['128B'])},

```

```
                        **{(sizes.get(k,fmt_sizeof(k)),
                          heights['middle']['v']-0.5):r'$\tilde{L}_{1,2,3}$' for i,k in
                          enumerate(['64B'])},
                        **{(sizes.get(k,fmt_sizeof(k)),
                          heights['middle']['v']):r'${L}_{%d}$'%(i+1) for i,k in
                          enumerate(['64B','512B','4KB'])},
                        **{(sizes.get(k,fmt_sizeof(k)),
                          heights['middle']['v']-1):r'$\tilde{L}_{%d}$'%(i+1) for i,k in
                          enumerate(['32KB','1MB','25MB'])},
                         **{(sizes.get(k,fmt_sizeof(k)),
                           heights['middle']['v']):r'$L_{%d}$'%(i+1) for i,k in
                           enumerate(['16KB','256KB','8MB'])},
                    },
                'h': {
                      # **{(sizes.get(k,fmt_sizeof(k)),np.max(indexer(mbdata[:,2],
                        mbdata[:,0],sizes.get(l,fmt_sizeof(l))))):r'$T_{%d}$'%(i+1) for
                        i,(k,l) in enumerate(zip(['256B'],['32KB']))},
                **{(sizes.get(k,fmt_sizeof(k)),np.max(indexer(mbdata[:,2],mbdata[:,0],
                  sizes.get(l,fmt_sizeof(l))))):r'$T_{%d}$'%(i+1) for i,(k,l) in
                  enumerate(zip(['16MB','16MB'],['32KB','1MB']))},
                      },
                },
    'middleupper':{'v': {
                        # **{(sizes.get(k,fmt_sizeof(k)),height):r'$\tilde{L}_{1,2,
                          3}\\\textrm{%s}$'%k for i,k in
                          enumerate(['64B'])},
                        # **{(sizes.get(k,fmt_sizeof(k)),
                          height):r'${L}_{%d}\\\textrm{%s}$'%(i+1,k) for i,k in
                          enumerate(['128B'])},

                        **{(sizes.get(k,fmt_sizeof(k)),
                          heights['middleupper']['v']-0.5):r'$\tilde{L}_{1,2,3}$' for i,k
                          in enumerate(['64B'])},
                        **{(sizes.get(k,fmt_sizeof(k)),
                          heights['middleupper']['v']):r'${L}_{%d}$'%(i+1) for i,k in
                          enumerate(['64B','512B','4KB'])},
                        **{(sizes.get(k,fmt_sizeof(k)),
                          heights['middleupper']['v']-1):r'$\tilde{L}_{%d}$'%(i+1) for i,k
                          in enumerate(['32KB','1MB','25MB'])},
                         **{(sizes.get(k,fmt_sizeof(k)),
                           heights['middleupper']['v']):r'$L_{%d}$'%(i+1) for i,k in
                           enumerate(['16KB','256KB','8MB'])},
                    },
                'h': {
                      # **{(sizes.get(k,fmt_sizeof(k)),np.max(indexer(mbdata[:,2],
                        mbdata[:,0],sizes.get(l,fmt_sizeof(l))))):r'$T_{%d}$'%(i+1) for
                        i,(k,l) in enumerate(zip(['256B'],['32KB']))},
                **{(sizes.get(k,fmt_sizeof(k)),np.max(indexer(mbdata[:,2],mbdata[:,0],
                  sizes.get(l,fmt_sizeof(l))))):r'$T_{%d}$'%(i+1) for i,(k,l) in
                  enumerate(zip(['16MB','16MB','32KB'],['32KB','1MB','256MB']))},
                      },
                },
    # 'middle':{'v': {**{(sizes.get(k,fmt_sizeof(k)),-4.5):'L%d\\LineSize:\\%s'%(i+1,k) for
      i,k in enumerate(['4KB','16KB'])}}}
    }


```

```
151
152
153 print(lines)
154
155
156 cmap = 'tab20b'
157 lengths=np.array(list(sorted(set(mbdata[:,0]))))
158
159 kwargs={}
160 kwargs['marker']  = ['.','*','^','s','d','+','']
161
162 kwargs['color'] = {k:v for k,v in zip(lengths,plt.get_cmap(cmap)(np.linspace(0, 1,
      len(lengths))).tolist())}
163 kwargs['label'] = {k:'L=%s'%(sizeof_fmt(k)) for k in lengths }
164
165 kwargs['marker'] = {k: kwargs['marker'][i%len(kwargs['marker'])] for i,k in enumerate(lengths)}
166 kwargs['inds'] = {k: np.where(mbdata[:,0]==k)[0] for k in lengths}
167
168
169
170 kwargs['lines'] = {k: {'linestyle':s,'color':c,'label':l,'alpha':a,'zorder':z} for k,l,c,s,a,z
      in zip(
171                                                                                 ['tilde{L}_{1,2,
                                                                                    3}',
                                                                                    'tilde{L}',
                                                                                    '{L}_','L_',
                                                                                    'T_','Mem',
                                                                                    None],
172                                                                                 ['True Line
                                                                                    Size','True
                                                                                    Cache
                                                                                    Size','Line
                                                                                    Size','Cache
                                                                                    Size','Access
                                                                                    Time','Access
                                                                                    Time',''],
173                                                                                 ['k','b','k',
                                                                                    'b','g','g',
                                                                                    None],
174                                                                                 ['--','--','-',
                                                                                    '-','-','-',
                                                                                    None],
175                                                                                 [0.6,0.6,0.8,
                                                                                    0.8,0.8,0.8,
                                                                                    None],
176                                                                                 [-1,-1,10,10,10,
                                                                                    10,None],
177                                                                                 )}
178
179 for lim in lims:
180
181
182   fig,ax = plt.subplots()
183
184   # Plots
185
186   #for i in range(9,27):
```

```
187   for L in lengths:
188     #ax.plot(mbdata[istt:istt+i,1],mbdata[istt:istt+i,2],
189     ax.plot(mbdata[kwargs['inds'][L],1],mbdata[kwargs['inds'][L],2],**{k:kwargs[k][L] for k in
          ['color','marker','label']})
190     #istt=istt+i+1
191
192   ax.set_ylabel('Time (nsec)')
193   ax.set_xlabel('Stride (bytes)')
194   ax.set_xscale('log',base=2)
195   ax.set_xticks(xtvals)
196   ax.set_xticklabels(xtlabels,rotation=45)
197   ax.set_ylim(*[l for l in lims[lim][1]])
198   ax.set_xlim(*[sizes.get(l,fmt_sizeof(l)) for l in lims[lim][0]])
199
200   # Lines
201   plotlines={k:lambda line,k=k,i=i,**kwargs: getattr(ax,'ax%sline'%k)(line[i],**kwargs) for i,k
        in enumerate(['v','h'])}
202   annotatelines={k:lambda line,text,k=k,i=i,**kwargs:
        getattr(plt,'annotate')(text=text,xy=line,**kwargs) for i,k in enumerate(['v','h'])}
203   for k in lines.get(lim,[]):
204     plotline=plotlines[k]
205     annotateline=annotatelines[k]
206     for line in lines[lim][k]:
207       text = lines[lim][k][line]
208       _kwargs = kwargs['lines'][None]
209       for x in kwargs['lines']:
210         if str(x) in text:
211           _kwargs = kwargs['lines'][x]
212           break
213       textline=list(line)
214       if 0 and (_kwargs['color'] == 'k' and _kwargs['linestyle'] == '-'):
215         textline[0] /=8
216       elif (_kwargs['color'] == 'g') and (lim=='all'):
217         textline[1] += 0.25
218       elif (_kwargs['color'] == 'g') and (lim=='lowerleft'):
219         textline[1] += 0.1
220       elif (_kwargs['color'] == 'g') and (lim=='middle'):
221         textline[0] *= 1.5
222         textline[1] += 0.06
223       elif (_kwargs['color'] == 'g') and (lim=='middleupper'):
224         textline[0] *= 1.2
225         textline[1] += 0.1
226       elif lim not in ['lowerleft']:
227         textline[0] *= 1.15
228       else:
229         textline[0] *= 1.15
230       # if lim == 'lowerleft':
231       #   textline[1] = -0.5
232
233       plotline(line,**_kwargs)
234       annotateline(textline,text)
235
236   handles,labels = ax.get_legend_handles_labels()
237   handles,labels = [h for i,(h,l) in enumerate(zip(handles,labels)) if l not in labels[:i]],[l
        for i,(h,l) in enumerate(zip(handles,labels)) if l not in labels[:i]]
238   fig.legend(handles=handles,labels=labels,bbox_to_anchor=(0.7,0.5),loc='center
        left',ncol=2,prop = {"size": 6},)
```

```
239  fig.subplots_adjust(right=0.7,bottom=0.15)
240  fig.savefig('../../figures/%s_%s.pdf'%('_'.join(file.split('_')[:-1]),lim))
```

Code 4: CPU Info script.

```
#!/bin/bash

prog="/proc/cpuinfo"
field="cpu MHz"
pattern="s%.*: \([^ ]*\).*$%\1%"
trials=5000

file=tmp1234.tmp
rm -f ${file}


for i in $(seq 1 ${trials})
do
        #echo Trial: $i
        grep "${field}" ${prog} | sed "${pattern}" >> ${file}
        sleep 0.00000001
done

N=$(wc -l ${file} | sed "s:\([^ ]*\).*:\1:")
avg=$(paste -sd+ ${file} | bc)
avg=$(echo "scale=3 ; $avg / $N" | bc)

echo Avg\(N=${N},Trials=${trials}\)  :  ${avg}

rm ${file}
```

Code 5: membench job script.

```
#!/bin/bash

#SBATCH --account=ners570f20_class
#SBATCH --job-name=NERS570_Lab8
#SBATCH --partition=standard
#SBATCH --mail-user=mduschen@umich.edu
#SBATCH --mail-type=END
#SBATCH --nodes=1
#SBATCH --mem-per-cpu=8000m
#SBATCH        --time=01:00:00
#SBATCH        --ntasks-per-node=3


./run.sh
```

Code 6: Matrix-Matrix multiply

```
#include <cstdio>
#include <iostream>



void dgemm( char transa, char transb,
              unsigned int m, unsigned int n, unsigned int k,
              double alpha, const double * const * a,
              const double * const * b,
              double beta, double **c)
{
    for(unsigned int i=0; i<n; i++){
            for(unsigned int j=0; j<m; j++){
                c[i][j] *= beta;
                }
        };
    for(unsigned int l=0; l<k; l++){
               for(unsigned int j=0; j<m; j++){
                    for(unsigned int i=0; i<n; i++){
                     c[i][j] += alpha*a[i][l]*b[l][j];
                        }
                }
        };


}
```