1 introduction

In science computer simulation has become an important tool. Simulation are becoming more and more advanced which increase the amount of data that are being generated. This data gets stored on harddrive and loaded again when its time to analyze the data. By doing in-situ real-time analysis where the data gets analyzed immediately after being generated. By doing computer simulation this way it may be possible to save time and hardware resources.

2 Hardware

The program have been tested on a server with the following hardware.
Motherboard: Supermicro X11DPU-Z+
CPU: Intel(R) Xeon(R) Gold 6130 CPU @ 2.10GHz, 32 core
DRAM: Samsung RDIMM, 2666 MT/s.
NVDIMM: Micron Technology NV-DIMM , 2933 MT/s

Both CPU have twelve memory slots each. Each CPU have six channels. There are one DRAM and one NVDIMM sharing one channel.

3 Coding with NVDIMM

3.1 Creating pmempool

Before NVDIMM can be used, the user must create whats called a memory pool on the NVDIMM. The NVDIMM has several modes, in order to be able to create a memory pool the mode must be set to fsdax. On a server this must be done by the system administrator. To see what mode the NVDIMM is in can be done by the command ndctl-list. A program called pmempool must also be installed on the server, it is this program that will create the memory pool. The command used for creating the memory pool for this thesis is

```
1 pmempool create --layout my_layout --size=50G obj pool.obj
```

The layout is a string stored in the memory pool. When a program access a memory pool it need to send a string that match the string in the memory pool in order to use it. The user can specify the size of the memory pool, if size is not specified the pmempool will create a pool

with the lowest size allowed. There are three different types of memory pool to choose from, they are obj, log and blk. Which type of memory pool to use depends on which type of library is used in the program. In this thesis the libpmemobj library was used and that is why obj was used in the creating of memory pool. For log and blk are for the libraries libpmemlog and libpmemblk. The last part of the command line is the name and file address of the memory pool.

3.2 Different types of libraries

The libpmemobj library is the main library that most people will use they are programming with NVDIMM.
libpmemlog
libpmemblk

3.3 Opening the memory pool

4 Benchmarks

There are four different benchmarks.

4.1 STREAM DRAM

The stream DRAM benchmark measure the memory speed of the DRAM. The benchmark uses the STREAM[1] benchmark without any changes in order to measure how fast the memory speed is. The benchmark run the test 32 times and only on one socket, every times it restart one extra thread is added. The result is as one would expect, adding more threads in beginning will give a big increase in transfer speed. But at thread 5 there gains in transfer speed will start to diminish and at thread 11 there will be very little increase in transfer speed when adding more threads.

4.2 STREAM NVDIMM

The stream NVDIMM benchmark measure the memory speed of the NVDIMM. This benchmark is the same as the STREAM DRAM benchmark mention above. The different is that the memory type have been changed from DRAM to NVDIMM. The original code looks like this.

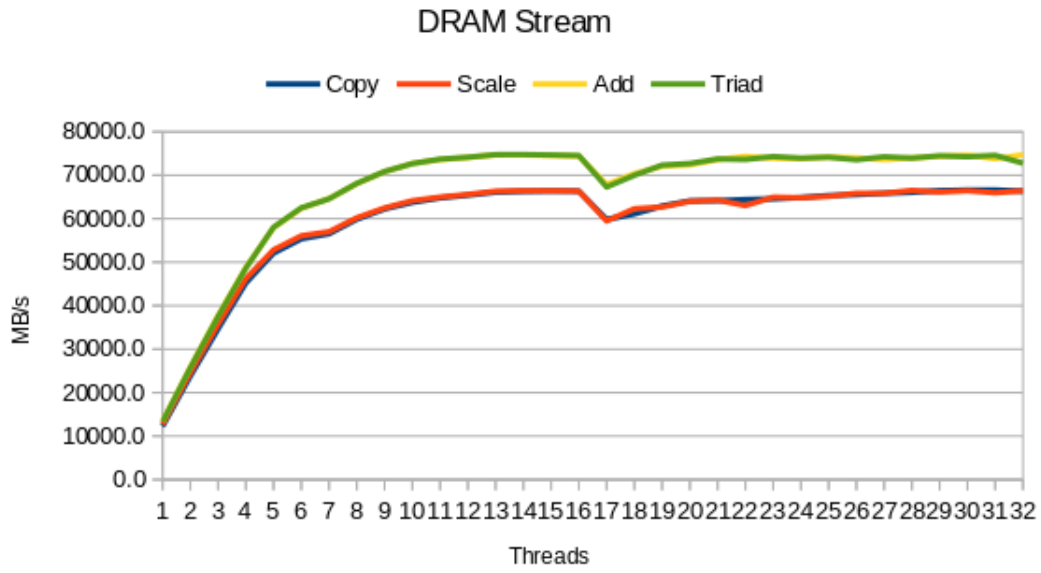


Figure 1: DRAM Stream

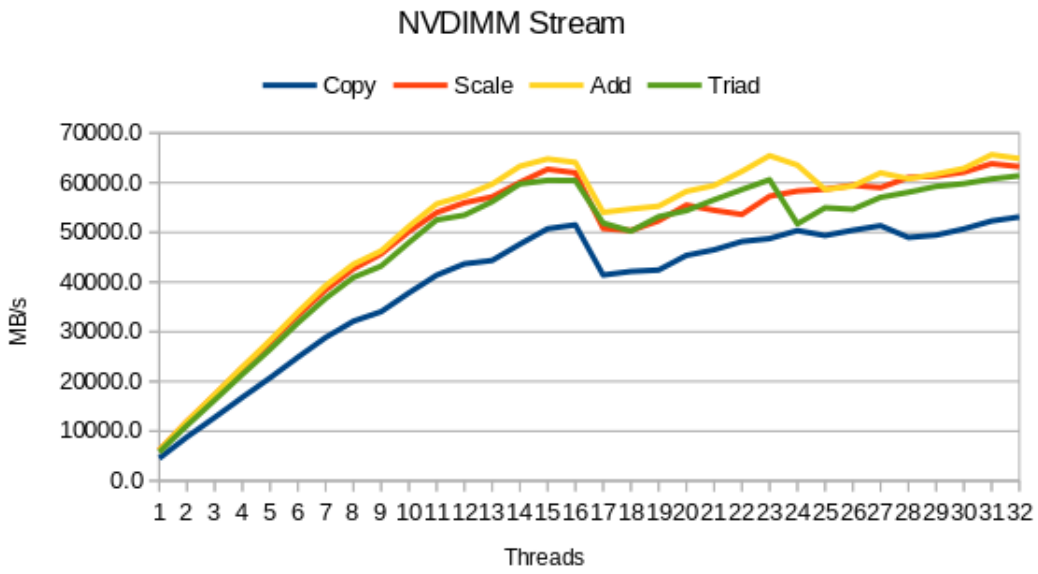
Listing 1: Description

```
#ifndef STREAM_TYPE
#define STREAM_TYPE double
#endif

static STREAM_TYPE a[STREAM_ARRAY_SIZE+OFFSET],
                   b[STREAM_ARRAY_SIZE+OFFSET],
                   c[STREAM_ARRAY_SIZE+OFFSET];
```

It have been changed into this. In addition the PMEMobjpool must be initiated in main method.

```
PMEMobjpool *pop;
POBJ_LAYOUT_BEGIN(array);
POBJ_LAYOUT_TOID(array, double);
POBJ_LAYOUT_END(array);
TOID(double) a;
TOID(double) b;
TOID(double) c;

int main()
{
  const char path[] = "/mnt/pmem0-xfs/pool.obj";
  pop = pmemobj_create(path, LAYOUT_NAME, 10737418240,
```

```
        0666);
13    if (pop == NULL)
14          pop = pmemobj_open(path, LAYOUT_NAME);
15
16          if (pop == NULL) {
17                perror(path);
18                exit(1);
19          }
20  }
```



4.3 benchmark 3

Graphs and tables below show the speed of a certain amount of NVDIMM threads while the rest of the threads are from DRAM to DRAM. The test have been conducted by transfer data simultaneously from DRAM-DRAM and NVM-NVM. All the threads are transferring the values of one array to another, all the arrays have 100 million elements of type double. This transfer happens 5000 times and the graphs shows the average of the first 200 iterations. This is done to ensure that all the threads can't finish early and make the remaining threads faster. The sum graphs shows the sum bandwidth of DRAM and NVM. Average graphs shows the average bandwidth of DRAM and NVM.

4.3.1 The code

The benchmark have three different program, the code is mostly the same except for the part where NVDIMM threads from NVDIMM-NVDIMM, DRAM-NVDIMM or NVDIMM-DRAM.

The entire code is run in the main function except when it finds the current time, that is done in a different function. The code begins with creating a memory pool and reads the parameters from command line. The parameters are how many threads are using the NVDIMM, the total amount of threads used and how many time the test will repeat itself. The code will then enter parallel area where one thread will create a 2d array where all the threads will save the time it took to copy the array.

Every threads will then create their two arrays. The thread id will determine if both arrays will be DRAM array, or if one or two arrays will be NVDIMM array. Both arrays will be DRAM if the thread id is lower than the total amount of threads minus the number of NVDIMM threads. Thread ids equal or higher than that will either have one or both arrays stored in NVDIMM. All the arrays in all of the threads will be populated by random numbers. When a thread is done it will wait at a barrier until all the other threads are populating their threads.

Listing 2: Creation of DRAM and NVDIMM arrays

```
1  if(thread_id < totalThreads-nvmThreads){
2    //From DRAM to DRAM
3    drm_read_array =
         (double*)malloc(ARRAY_LENGTH*sizeof(double));
4    drm_write_array =
         (double*)malloc(ARRAY_LENGTH*sizeof(double));
5    #pragma omp critical
6    {
7      for(i=0;i<ARRAY_LENGTH;i++){
8        drm_read_array[i] =
             ((double)rand()/(double)(RAND_MAX));
9        drm_write_array[i] =
             ((double)rand()/(double)(RAND_MAX));
10     }
11   }
12 }
13 else if(thread_id >= totalThreads-nvmThreads){
14   //From NVDIMM to NVDIMM
15   POBJ_ALLOC(pop, &nvm_read_array, double, sizeof(double)
```

```
        * ARRAY_LENGTH, NULL, NULL);
16    POBJ_ALLOC(pop, &nvm_write_array, double, sizeof(double)
        * ARRAY_LENGTH, NULL, NULL);
17    #pragma omp critical
18    {
19      for(i=0;i<ARRAY_LENGTH;i++){
20        D_RW(nvm_read_array)[i] =
            ((double)rand()/(double)(RAND_MAX));
21        D_RW(nvm_write_array)[i] =
            ((double)rand()/(double)(RAND_MAX));
22      }
23    }
24  }
```

Threads with DRAM arrays and threads with one or two NVDIMM array will split into their own part of the code with an if-sentence. All the threads will run the as many times as specified in the parameters and save the time each test takes in the 2d array that was created in the beginning. When they are done they will free up the memory and leave the parallel area.

Listing 3: Threads running their test.

```
1   if(thread_id < totalThreads-nvmThreads){
2     //From DRAM to DRAM
3     for(i=0;i<total_tests;i++){
4       //Time start
5       test_time[thread_id][i] = mysecond();
6       for(j=0;j<ARRAY_LENGTH;j++){
7         drm_write_array[j] = drm_read_array[j];
8       }
9       //Time stop.
10      test_time[thread_id][i] = mysecond() -
          test_time[thread_id][i];
11    }
12  }
13  else if(thread_id >= totalThreads-nvmThreads){
14    //From NVDIMM to NVDIMM
15    for(i=0;i<total_tests;i++){
16      //Time start
17      test_time[thread_id][i] = mysecond2();
18      for(j=0;j<ARRAY_LENGTH;j++)
19        D_RW(nvm_write_array)[j] = D_RO(nvm_read_array)[j];
```

```
20        //Time stop.
21        test_time[thread_id][i] = mysecond2() -
              test_time[thread_id][i];
22    }
23 }
```

The code will then print the entire 2d array where the time measurements are stored to the terminal. Each line represent all the test done by one thread. In the beginning of each line the code will add either DRAM if both arrays are stored on DRAM. Or NVM if one or both arrays are stored on NVDIMM. When the program is done printing it will exit.

4.3.2 NVM-NVM

The tables below shows the result of the benchmark where one group of threads transfer from DRAM-DRAM and another group from NVDIMM-NVDIMM. The test result in the tables are the transfer speed in MB/s. The first table shows the combined transfer speed of all threads that are copying from DRAM-DRAM and the second table shows the combined speed of all the threads that are copying from NVDIMM-NVDIMM.

The first line in the first table in figure 2 shows the combined transfer speed of the DRAM-DRAM copying where there are one thread copying from NVDIMM-NVDIMM. That means there are 15 threads that are copying from DRAM-DRAM. The first line in the second table shows the transfer speed of that one thread. The columns shows the the test numbers. The column with name the "1-20" shows the average transfer speed of the first 20 tests. The third table in figure 3 shows the combined transfer speed of all the 16 threads in the first two tables. There is also a graph where all three tables are being represented.

One of the hopes by using NVDIMM and DRAM simultaneously was that there would be an increase in the transfer speed. But by comparing copy on figure 1 with the sum on figure 4 one can see that there has been no increase in transfer speed. Both graphs shows a transfer speed on around 65000 MB/s.

	NVM-NVM					
	DRAM					
Nvm-threads	1	1-20	21-40	41-60	61-80	81-100
1	33979.84	64179.89	64788.61	64951.02	64650.49	64447.29
2	33153.33	60854.29	62114.14	61912.29	61761.77	61872.50
3	32879.35	57643.15	58614.63	58759.60	58625.89	58423.27
4	26839.12	54508.48	55674.22	55682.26	55415.60	55367.41
5	25687.57	51076.28	52241.04	52083.85	51964.28	51955.32
6	24209.41	47721.43	48861.96	48786.82	48552.39	48656.74
7	22425.14	43819.63	45050.64	44975.15	44882.40	44672.94
8	20117.60	40489.02	41752.05	41501.44	41524.94	41286.00
9	17713.80	36687.45	37360.21	37385.79	37156.23	37232.82
10	15212.97	32731.79	33432.15	33379.32	33220.57	33296.06
11	12941.82	28177.13	28767.32	28814.29	28732.10	28833.90
12	9894.49	23814.89	24401.20	24408.00	24416.73	24525.18
13	7341.90	17595.41	18030.92	18359.65	17857.03	18532.65
14	4758.41	12750.63	13284.93	13351.80	13790.00	13569.13
15	2394.31	6834.38	6992.16	7515.33	7445.93	7353.06
	NVM					
Nvm-threads	1	1-20	21-40	41-60	61-80	81-100
1	5114.00	3289.73	3253.33	3250.62	3250.58	3248.86
2	10235.69	6599.16	6520.83	6507.40	6520.58	6500.57
3	15165.52	10119.48	9983.90	9984.04	9966.19	9979.90
4	20114.02	13554.15	13438.86	13435.23	13423.07	13416.59
5	24936.64	17103.23	16991.10	16958.34	16961.03	16933.81
6	29623.07	20662.40	20464.90	20437.07	20468.27	20438.51
7	33972.44	22367.64	22014.43	21953.45	21980.77	22105.95
8	37897.59	27397.05	27264.10	27141.45	27219.06	27083.62
9	41598.76	30795.78	30818.58	30922.06	30851.27	30427.67
10	44808.35	34539.87	34494.76	34500.89	34350.06	34203.29
11	48545.49	37723.50	37394.55	37303.10	37247.85	36857.64
12	51215.90	41988.10	41845.44	41750.50	41731.61	41533.89
13	54109.52	44058.49	43833.39	43794.52	43761.88	42853.98
14	57066.38	48613.84	48218.46	48161.35	48318.21	47953.55
15	58853.11	51816.83	51824.03	51488.10	51789.92	51100.06

Figure 2: NVM-NVM 1-100 iteration, 16 threads total, 3rd version

	SUM					
Nvm-threads	1	1-20	21-40	41-60	61-80	81-100
1	39093.84	67469.62	68041.93	68201.64	67901.07	67696.15
2	43389.02	67453.45	68634.96	68419.69	68282.35	68373.06
3	48044.87	67762.63	68598.53	68743.64	68592.08	68403.17
4	46953.14	68062.63	69113.08	69117.49	68838.67	68784.00
5	50624.21	68179.51	69232.14	69042.18	68925.31	68889.13
6	53832.48	68383.83	69326.86	69223.88	69020.66	69095.26
7	56397.58	66187.27	67065.07	66928.60	66863.17	66778.89
8	58015.19	67886.07	69016.15	68642.89	68744.00	68369.63
9	59312.56	67483.22	68178.79	68307.84	68007.50	67660.49
10	60021.32	67271.67	67926.91	67880.21	67570.63	67499.35
11	61487.31	65900.63	66161.87	66117.39	65979.96	65691.54
12	61110.39	65802.98	66246.64	66158.50	66148.34	66059.07
13	61451.42	61653.90	61864.31	62154.17	61618.91	61386.63
14	61824.79	61364.48	61503.39	61513.15	62108.21	61522.68
15	61247.42	58651.21	58816.19	59003.42	59235.85	58453.12

Figure 3: NVM-NVM 1-100 iteration, 16 threads total, 3rd version

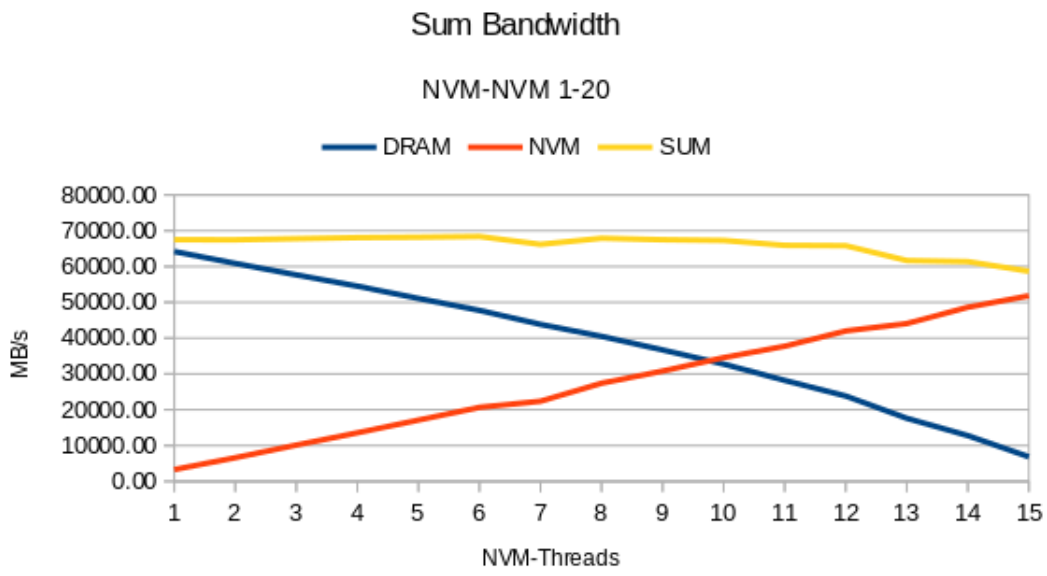


Figure 4: NVM-NVM graph 1-20, 3rd version

4.3.3 NVM-DRAM

This benchmark is similar to the previous benchmark. The only difference is that some threads will transfer data from NVDIMM-DRAM instead of NVDIMM-NVDIMM.

	NVM-DRAM					
	DRAM					
Nvm-threads	1	1-20	21-40	41-60	61-80	81-100
1	32437.33	51729.43	53490.40	54419.38	56626.69	57295.70
2	31785.84	58694.61	59123.37	59135.90	58803.95	59160.35
3	27089.46	55323.72	55359.79	55449.94	55124.84	55079.11
4	26523.71	51565.09	51498.67	51032.22	50944.45	51155.26
5	23943.39	47390.53	47067.10	47291.86	46960.13	47119.51
6	21332.19	43205.17	43003.44	43143.48	42653.83	42962.85
7	18079.52	38801.31	38958.62	38995.27	38681.43	39000.71
8	18219.63	34652.20	34829.29	34582.21	34809.29	34763.03
9	15716.34	30244.85	30604.89	30504.82	30347.98	30531.90
10	12959.49	25984.54	26132.58	26116.43	26282.85	25981.46
11	11550.12	21756.54	21772.80	21935.54	21740.99	21776.18
12	8936.14	17175.26	17608.93	17216.47	17843.56	17341.46
13	6236.36	12779.91	13194.20	13003.21	13181.25	13119.76
14	3603.24	8669.61	8644.75	8731.08	8916.27	8621.84
15	1793.63	4250.55	4490.40	4267.18	4502.44	4260.46
	NVM					
Nvm-threads	1	1-20	21-40	41-60	61-80	81-100
1	2170.83	3635.35	3940.80	4127.15	4313.01	4234.35
2	4446.39	7927.66	7856.40	7977.52	7974.72	7800.26
3	6524.15	12018.48	11973.65	11978.96	11956.69	11868.26
4	8968.17	16245.16	16145.53	16224.22	16169.83	15979.78
5	11227.93	20004.18	20569.08	20226.56	20499.64	20114.15
6	13267.48	24362.23	24984.69	24557.47	24613.37	24477.62
7	15471.30	28739.42	29026.57	28754.67	28980.22	28589.24
8	18094.36	32833.01	33428.60	33380.75	33069.79	33033.76
9	20805.37	37368.77	37715.52	37628.86	37511.17	37290.54
10	22740.89	41319.93	41966.16	42139.10	42023.48	41966.67
11	25533.28	45907.61	46625.38	46449.12	46306.21	46181.20
12	28124.41	50396.18	50722.28	51065.63	50556.47	50735.26
13	30225.94	54592.24	55465.44	55422.83	55294.43	55153.29
14	32659.06	58440.82	59868.63	59725.88	59542.50	59570.12
15	35484.88	63168.26	64013.14	64235.39	63940.74	64110.34

Figure 5: NVM-DRAM 1-100 iteration, 3rd version

	SUM					
Nvm-threads	1	1-20	21-40	41-60	61-80	81-100
1	34608.16	55364.78	57431.19	58546.53	60939.70	61530.05
2	36232.23	66622.28	66979.77	67113.41	66778.68	66960.61
3	33613.61	67342.20	67333.44	67428.90	67081.53	66947.36
4	35491.88	67810.25	67644.20	67256.43	67114.28	67135.04
5	35171.32	67394.71	67636.19	67518.42	67459.77	67233.66
6	34599.67	67567.40	67988.12	67700.95	67267.20	67440.47
7	33550.82	67540.73	67985.19	67749.94	67661.65	67589.95
8	36313.99	67485.21	68257.89	67962.96	67879.08	67796.79
9	36521.71	67613.62	68320.41	68133.69	67859.15	67822.43
10	35700.38	67304.47	68098.74	68255.52	68306.33	67948.13
11	37083.40	67664.15	68398.18	68384.66	68047.19	67957.39
12	37060.55	67571.44	68331.21	68282.10	68400.02	68076.72
13	36462.30	67372.15	68659.64	68426.04	68475.68	68273.05
14	36262.30	67110.42	68513.38	68456.96	68458.77	68191.96
15	37278.51	67418.81	68503.54	68502.57	68443.18	68370.81

Figure 6: NVM-DRAM 1-100 iteration, 3rd version

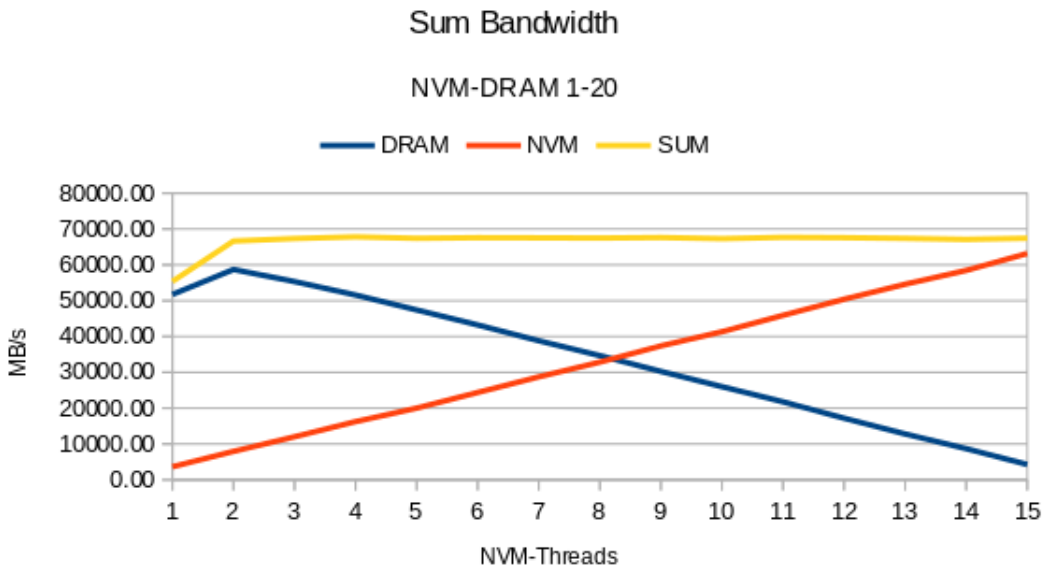


Figure 7: NVM-DRAM graph 1-20, 3rd version

4.3.4 DRAM-NVM

This benchmark is also similar to the other two benchmarks. This time some of the threads will transfer from DRAM-NVDIMM.

	DRAM-NVM					
	DRAM					
Nvm-threads	1	1-20	21-40	41-60	61-80	81-100
1	18762.63	62678.30	63604.73	63196.58	63136.35	63599.61
2	27382.09	58321.86	59823.75	59850.20	59792.36	59717.87
3	25055.31	55650.92	55734.25	56127.18	55630.90	55935.54
4	24531.82	51279.78	52005.76	52282.87	51782.02	52177.37
5	23933.44	46555.25	48391.69	47941.57	48093.38	47839.01
6	18038.64	43432.14	44116.64	44225.90	43685.08	44094.70
7	16733.09	38827.55	39930.92	39448.07	39906.00	39483.39
8	14948.52	35285.18	35922.06	35737.11	35492.87	35796.48
9	12648.41	31228.15	31784.53	31492.60	31380.92	31454.26
10	11685.27	26830.40	27658.00	27610.40	27050.44	27021.04
11	9125.40	22445.38	23500.71	22790.09	22663.17	22910.98
12	6988.07	18442.56	18641.75	18849.18	18429.07	18354.52
13	5241.80	13668.18	14290.47	14034.79	14232.71	13744.87
14	3489.73	9087.65	9672.94	9461.29	9476.61	9276.00
15	1706.71	4273.06	4665.14	4342.46	4592.38	4610.87
	NVM					
Nvm-threads	1	1-20	21-40	41-60	61-80	81-100
1	3375.57	4094.13	3968.66	4013.27	4024.96	3937.43
2	5969.30	8738.95	8141.12	7939.10	8120.81	7879.02
3	14655.50	12710.47	12200.25	12147.26	12139.38	12124.44
4	12183.05	16846.06	16447.48	16153.87	16528.34	16083.88
5	15414.28	21516.95	20524.82	20689.27	20457.96	20526.30
6	23350.53	25835.47	24888.70	24740.28	25046.00	24538.40
7	24810.32	30042.63	29430.07	29410.65	29124.31	29382.89
8	25246.16	34903.09	33344.27	33607.80	33385.67	33247.98
9	29498.49	38826.97	37916.57	38188.18	37813.69	37219.56
10	36784.96	43563.46	42352.29	42525.81	42036.90	42070.58
11	39799.65	47967.83	46875.74	47224.03	46257.64	46424.18
12	38783.93	52752.69	51908.85	51408.20	51339.13	50338.82
13	43481.73	56883.56	56624.74	55455.89	55879.32	56058.91
14	49369.10	61602.79	60907.89	60678.79	60065.98	60171.88
15	49133.33	67153.54	66972.79	63557.38	63874.03	63521.86

Figure 8: DRAM-NVM 1-100 iteration, 3rd version

	SUM					
Nvm-threads	1	1-20	21-40	41-60	61-80	81-100
1	22138.20	66772.43	67573.40	67209.85	67161.31	67537.04
2	33351.39	67060.81	67964.86	67789.29	67913.17	67596.89
3	39710.81	68361.39	67934.50	68274.44	67770.28	68059.98
4	36714.87	68125.85	68453.24	68436.74	68310.35	68261.24
5	39347.72	68072.20	68916.50	68630.84	68551.33	68365.32
6	41389.17	69267.61	69005.34	68966.18	68731.08	68633.10
7	41543.41	68870.19	69360.99	68858.72	69030.31	68866.28
8	40194.68	70188.28	69266.33	69344.90	68878.54	69044.46
9	42146.90	70055.12	69701.09	69680.78	69194.61	68673.83
10	48470.23	70393.86	70010.29	70136.21	69087.34	69091.62
11	48925.05	70413.21	70376.45	70014.13	68920.81	69335.17
12	45772.00	71195.25	70550.60	70257.38	69768.20	68693.34
13	48723.53	70551.74	70915.22	69490.69	70112.04	69803.78
14	52858.83	70690.44	70580.83	70140.07	69542.59	69447.88
15	50840.04	71426.60	71637.93	67899.84	68466.41	68132.72

Figure 9: DRAM-NVM 1-100 iteration, 3rd version

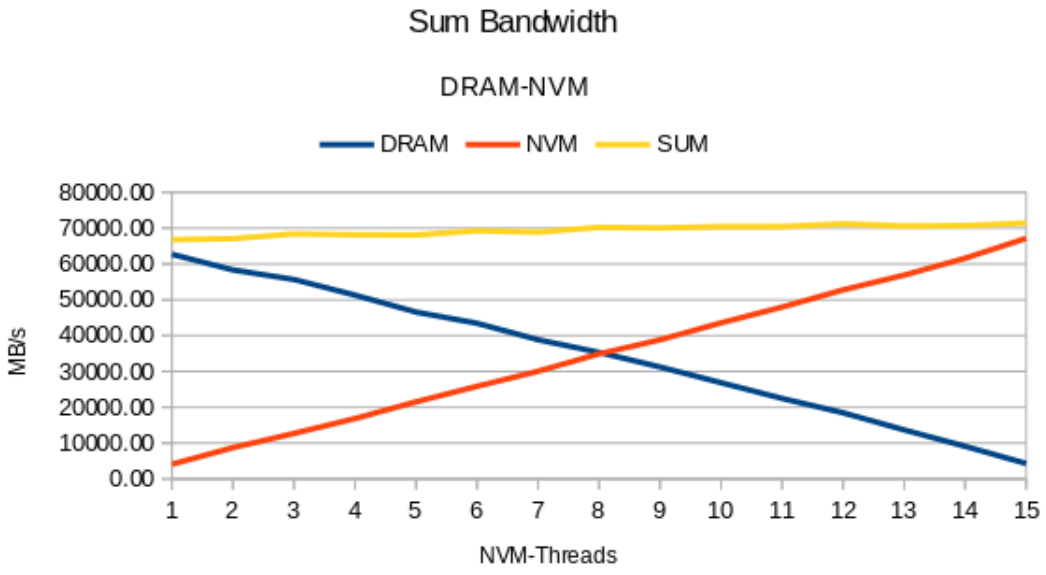


Figure 10: DRAM-NVM graph 1-20, 3rd version

5 Simulation

5.1 DRAM only

Threads	Total time	Iteration time	Calculation time
1	1217.624747	747.345183	470.279564
2	641.937113	399.266812	242.670301
3	442.936486	275.083333	167.853153
4	339.788006	211.632944	128.155062
5	276.30993	171.953573	104.356358
6	233.895282	146.63456	87.260722
7	204.532469	129.058858	75.473611
8	186.792502	118.626586	68.165916
9	174.884702	111.713336	63.171366
10	164.146195	107.15154	56.994655
11	156.103916	103.946944	52.156971
12	151.490592	102.12569	49.364902
13	147.958949	100.005358	47.953591
14	143.513119	98.887134	44.625985
15	140.027579	98.30932	41.718259
16	137.833572	98.451276	39.382296

Table 1: Simulation with only DRAM, n=16M

The generation of data happens inside a while-loop that will repeat the generation and analyzing of data 5000 times. The total time is measured by taking the time before and after the while-loop. The analyzing time is measured the same way by taking the time before and after the analyzing part of the program. Data generation time is measured by subtracting the analyze time from the total time. All the time measurements are made inside a pragma omp singel so there are no reason to be worried if the mysecond-method is thead-safe. The mysecond-method have been copied from the original stream benchmark. All the arrays used in the code have been subjected to first touch before the time is measured.

Listing 4: while-loop

```
1 #pragma omp single
2 {
3   data_generation_time, = mysecond();
4 }
5 while( n<5000 ){
6   #pragma omp barrier
7   #pragma omp single
```

```
8     {
9       n++;
10      diff=0.0;
11      average = 0;
12      //completes the first part of the formula.
13      Wk_1_product = (omd + (d*Wk_1))*iN;
14    }
15
16    Data generation, see chapter 5.1.1
17
18    #pragma omp barrier
19    #pragma omp single
20    {
21      temp_x = xk_1;
22      xk_1 = x;
23      x = temp_x;
24      //starting time measurement of calculation.
25      temp_calc=mysecond();
26    }
27
28    Analyzing the data, see chapter 5.1.2
29
30    #pragma omp barrier
31    #pragma omp single
32    {
33      average *= iN;
34      analyze_time+=mysecond()-temp_calc;
35    }
36  }
37  #pragma omp single
38  {
39    data_generation_time, = mysecond() -
        data_generation_time;
40  }
```

Listing 5: while-loop

```
1   double mysecond(){
2     struct timeval tp;
3     struct timezone tzp;
4     int i;
5     i = gettimeofday(&tp,&tzp);
6     return ( (double) tp.tv_sec + (double) tp.tv_usec *
```

```
      1.e-6 );
}
```

5.1.1 Data generation

The arrays x and xk_1 are double arrays that have the length of 4'000'000 elements. CRS_row_ptr and CRS_col_idx are int arrray that have the length of 31'976'004 elements, CRS_'values have the same length and a double array. The code run through the x-array one time and xk_1 twice. It also runs through CRS_row_ptr, CRS_col_idx and CRS_values once. The formula for calculating memory traffic is 3*4'000'000+2*31'976'004 this would amount to 607 MB per iteration of the while-loop.

Listing 6: Generation of data.

```
#pragma omp for reduction(max:diff)
for( i=0; i<nodes; i++){
  x[i] = 0;
  for( j=CRS_row_ptr[i]; j<CRS_row_ptr[i+1]; j++)
    x[i] += CRS_values[j] * xk_1[CRS_col_idx[j]];
  x[i] *= d;
  x[i] += Wk_1_product;
  //Comuting the difference between x^k and x^k-1
  //and adds the biggest diff to diffX[thread_id]
  if( x[i]-xk_1[i] > diff ){
    diff = x[i] - xk_1[i];
  }
}
```

Calculation					
		Factor	repeated	total	total MB
n	16,000,000	2.5	5000	200,000,000,000	1,600,000.00
edges	127,952,004	1.5	5000	959,640,030,000	7,677,120.24
	Benchmark	Predicted	Data generated		
Threads	DRAM speed	time	time measurement		
1	13265.2	699.36	747.35		
2	26431.7	350.98	399.27		
3	38557.2	240.61	275.08		
4	49447.8	187.61	211.63		
5	58565.4	158.41	171.95		
6	62627.3	148.13	146.63		
7	66290.8	139.95	129.06		
8	69130.7	134.20	118.63		
9	71409.6	129.91	111.71		
10	73271.5	126.61	107.15		
11	74191.2	125.04	103.95		
12	74211.4	125.01	102.13		
13	74659.4	124.26	100.01		
14	74715.4	124.17	98.89		
15	74486	124.55	98.31		
16	74328.7	124.81	98.45		

Table 2: Prediction of time taken for data generation, n=16M

5.1.2 Analyze

The analyze part run through the nodes array five times and add all the elements to the average variable. The average variable is divided by the number of elements in array, this is shown in the code in chapter 5.1. The memory traffic will amount of 160MB per while-loop iteration.

Listing 7: Analyzing the data.

```
1  //Analyse part
2  #pragma omp for reduction(+ : average)
3    for(i=0;i<nodes;i++){
4    average += xk_1[i];
5  }
6  #pragma omp for reduction(+ : average)
7    for(i=0;i<nodes;i++){
8    average += xk_1[i];
9  }
10 #pragma omp for reduction(+ : average)
11   for(i=0;i<nodes;i++){
12   average += xk_1[i];
13 }
14 #pragma omp for reduction(+ : average)
15 for(i=0;i<nodes;i++){
16   average += xk_1[i];
17 }
18 #pragma omp for reduction(+ : average)
19 for(i=0;i<nodes;i++){
20   average += xk_1[i];
21 }
```

Calculation For analyze					
		Factor	MB	repeated	total MB
n	16,000,000.00	5	640	5000	3,200,000
	Benchmark		Analyze		Analyze time
Threads	DRAM speed		Prediction		Measurement
1	6665.4		480.09		470.279564
2	13183.1		242.74		242.670301
3	18704.7		171.08		167.853153
4	24971.9		128.14		128.155062
5	31169.6		102.66		104.356358
6	37259.5		85.88		87.260722
7	42771.7		74.82		75.473611
8	47211.9		67.78		68.165916
9	50706.4		63.11		63.171366
10	56235.2		56.90		56.994655
11	61401		52.12		52.156971
12	65062		49.18		49.364902
13	66645		48.02		47.953591
14	71518.7		44.74		44.625985
15	76423.3		41.87		41.718259
16	81259.4		39.38		39.382296

Table 3: Prediction of time taken for analyzing the data, n=16M

5.1.3 Stream benchmark, sum

This benchmark is the STREAM benchmark with an added benchmark. The sum is found by adding all the elements into a single variable. The STREAM benchmark was changed by increasing several array from four to five and added the sum benchmark after the four other benchmark. The STREAM benchmark for NVDIMM is the same as the one described above, but the code has been changed so the benchmark will read and write to the NVDIMM.

	copy	scale	add	triad	Average
1	13072.2	14053.7	13810.8	13821.3	6652.3
2	24586.2	25448.2	26622	25639.9	12920.8
3	35144.7	36424.1	38554.9	38323.4	18936.7
4	45261.6	46928	49559	49473.3	25020.5
5	52061.5	52960.9	58313.3	58783.2	31049.9
6	55459.1	55960	62524.6	62896.5	37123.1
7	57928.9	58281.5	65642	66144.9	42689.6
8	59714.4	60302.5	68166.4	68608.6	47295.1
9	61802.5	62368.3	70859.2	71188.9	50991.5
10	63482.1	63966.8	72520.9	72851	56010.9
11	64636.5	65069.6	73669.4	73741.7	61519.2
12	65450.4	65659.8	74202.1	74163.3	64427.4
13	66145.8	66209.1	74432.5	74503.6	66549.8
14	66337.4	66343.3	74314.9	74386.3	71372.7
15	66439.8	66274.5	74195	74232.2	76140.7
16	66417.5	66115.8	74067.2	74154.5	80702.4

Table 4: New Stream benchmark, DRAM

NVM sum test cpu 0-15					
threads	copy	scale	add	triad	Sum
1	6455.2	4492.9	6134.2	5451.6	5422.2
2	12606.9	8783.7	11978.3	10631.0	10423.9
3	18284.2	12732.8	17392.6	15414.4	15141.5
4	24033.7	16760.6	22869.3	20280.1	19841.8
5	29584.8	20683.6	28242.3	25052.1	24489.6
6	35355.3	24818.6	33865.8	30064.3	29347.0
7	37564.9	24631.4	29185.7	26727.6	34074.4
8	45400.6	31945.8	43520.9	38752.7	37750.0
9	48372.0	33983.1	46176.0	41174.1	40607.1
10	52953.8	37741.9	51064.9	45665.5	45129.2
11	56689.4	41441.1	55640.6	50013.6	49416.7
12	58537.3	43532.5	56954.3	51616.4	52280.9
13	59904.7	44258.9	59200.8	53467.5	53727.5
14	62678.7	47558.2	63158.1	57325.7	57790.7
15	50577.2	36717.5	49718.4	44182.5	45334.0
16	66047.5	52866.6	66134.0	60444.3	65552.6

Table 5: New Stream benchmark, NVM

5.1.4 Calculation only

Calculation					
		Factor	repeated	total	total MB
n	16,000,000	2.5	5000	200,000,000,000	1,600,000.00
edges	127,952,004	1.5	5000	959,640,030,000	7,677,120.24
	Benchmark	Predicted	Data generated		
Threads	DRAM speed	time	time measurement		
1	13265.2	699.36	727.54		
2	26431.7	350.98	383.48		
3	38557.2	240.61	268.12		
4	49447.8	187.61	208.36		
5	58565.4	158.41	168.77		
6	62627.3	148.13	146.18		
7	66290.8	139.95	126.40		
8	69130.7	134.20	116.22		
9	71409.6	129.91	110.54		
10	73271.5	126.61	105.72		
11	74191.2	125.04	102.53		
12	74211.4	125.01	101.56		
13	74659.4	124.26	99.68		
14	74715.4	124.17	98.92		
15	74486	124.55	99.10		
16	74328.7	124.81	98.76		

Table 6: Prediction of time taken for calculation of the data, with a code that only do calculation

5.2 NVDIMM Analyze only

1	912.95
2	417.38
3	277.17
4	217.33
5	174.67
6	188.40
7	233.93
8	234.64
9	220.51
10	207.10
11	188.31
12	188.65
13	174.08
14	168.63
15	161.06
16	162.10

Table 7: Mearsurement of analyzations only on NVDIMM.

5.3 NVM simulation

5.3.1 Locks

The program are divided into two parts, the calculation of data and the analyzing of the data that have been generated. The two parts synchronize by using two locks called lock_a and lock_b, lock_a will start in unlocked state and lock_b in locked state. When the two parts starts the analyzing part is put on hold by lock_b until the calculation part has generated the first set of data. Then the calculation part will lock lock_a, swap the pointers x and xk_1 and then unlock lock_b. The calculation part will then start the calculation of the next set of data, but wont swap pointers until analyzing part has transferred the content in xk_1 to NVDIMM and unlocked lock_a.

When the calculation part unlocks lock_b the analyzing will start transferring data from xk_1 to NVDIMM and unlock lock_a when it's done with the transfer. The analyzing part will then start analyzing the data on NVDIMM. When its done it will encounter lock_b and will wait there until calculation has a new set of data ready and has swapped the pointers.

Before and after the set lock in calculation and analyze part there is a time measurement that measure how long the threads have waited for the lock to be unlocked by the other part. All the individual times the threads have waited in calculation or analyze gets added to a variable called iteration_idle_time or transfer_idle_time that will be the total time the threads have waited.

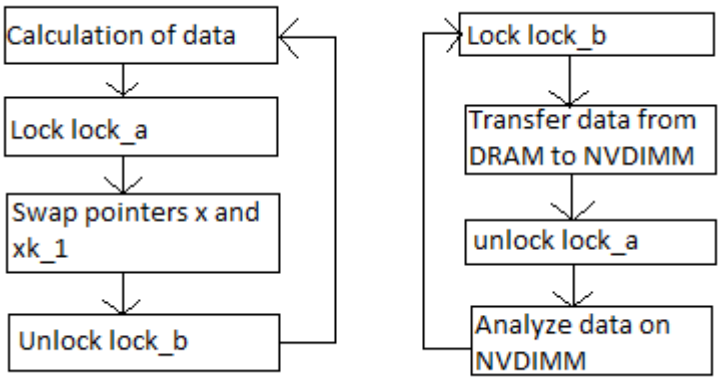


Table 8: A simplified version of how lock works.

Listing 8: Calculation

```
while( n<5000 ){
  #pragma omp barrier
  /*
    Calculation of Data
  */
  #pragma omp single
  {
    temp_time = mysecond();
    omp_set_lock(&lock_a);
    iteration_idle_time += mysecond() - temp_time;

    temp_x = xk_1;
    xk_1 = x;
    x = temp_x;

    omp_unset_lock(&lock_b);
  }
}//end of while-loop
```

Listing 9: Analyze

```
while(1==1){
  #pragma omp single
  {
    temp_time = mysecond();
    omp_set_lock(&lock_b);
    transfer_idle_time += mysecond() - temp_time;
    temp_time = mysecond();
    average=0.0;
  }
  /*
    Transfer of array from DRAM to NVDIMM
  */
  #pragma omp single
  {
    DRAM_to_NVM_time += mysecond() - temp_time;
    omp_unset_lock(&lock_a);
    temp_time = mysecond();
  }
  /*
    Analyzations of data
  */
```

```
22      }
23      #pragma omp barrier
24      #pragma omp single
25      {
26        Analyse_time += mysecond() - temp_time;
27      }
28      //if sentence for exiting while-loop.
29      if(iteration_ongoing==0){
30        break;
31      }
32  }
```

Total Threads	DataGen Threads	Analyze Threads	DataGen Time	DataGen Idle Time	Transfer Idle Time	DRAM-NVM Time	Analyze Time	Total Time
16	15	1	106.48	851.99	0.04	170.84	787.73	958.63
16	14	2	107.57	396.76	0.03	86.31	418.06	504.42
16	13	3	111.85	249.67	0.03	61.27	300.26	361.58
16	12	4	137.93	300.53	0.03	167.58	270.87	438.50
16	11	5	147.57	218.52	0.03	142.66	223.43	366.14
16	10	6	162.87	158.12	0.03	130.22	190.75	321.03
16	9	7	171.85	90.88	0.03	102.66	160.03	262.76
16	8	8	199.35	51.40	0.66	95.37	154.62	250.78
16	7	9	235.15	42.02	9.91	105.50	161.31	277.18
16	6	10	235.51	31.83	35.55	93.38	138.33	267.39
16	5	11	240.33	15.70	19.51	89.37	147.13	256.06
16	4	12	288.71	0.73	73.63	83.42	132.35	289.49
16	3	13	351.75	0.00	177.44	70.45	103.91	351.81
16	2	14	464.62	0.00	338.75	48.58	77.36	464.72
16	1	15	823.71	0.00	738.35	21.70	63.65	823.76

Table 9: Simulation with both NVDIMM and DRAM

Calculation					
		Factor	repeated	total	total MB
n	16,000,000	2.5	5000	200,000,000,000.00	1,600,000.00
edges	127,952,004	1.5	5000	959,640,030,000.00	7,677,120.24
	Benchmark	Predicted	Data generated		
Nvm-threads	DRAM speed	time	time measurement		
1	74486.0	124.55	106.48		
2	74715.4	124.17	107.57		
3	74659.4	124.26	111.85		
4	74211.4	125.01	137.93		
5	74191.2	125.04	147.57		
6	73271.5	126.61	162.87		
7	71409.6	129.91	171.85		
8	69130.7	134.20	199.35		
9	66290.8	139.95	235.15		
10	62627.3	148.13	235.51		
11	58565.4	158.41	240.33		
12	49447.8	187.61	288.71		
13	38557.2	240.61	351.75		
14	26431.7	350.98	464.62		
15	13265.2	699.36	823.71		

Table 10: Time prediction, data generation

Analyze						
		Factor	repeated	total	total MB	
n	16,000,000	5	5000	400,000,000,000.00	3,200,000.00	
DRAM-NVM	16,000,000	1	5000	80,000,000,000.00	640,000.00	
	Benchmark	DRAM-NVM	DRAM-NVM	Benchmark	Analyze	Analyze time
Nvm-threads	NVM speed	Predicted	transfer time	NVM sum	Prediction	Measurement
1	3937.43	162.54	170.84	5449	587.26	787.73
2	7879.02	81.23	86.31	10216.5	313.22	418.06
3	12124.44	52.79	61.27	14921.8	214.45	300.26
4	16083.88	39.79	167.58	19562.3	163.58	270.87
5	20526.30	31.18	142.66	24142.1	132.55	223.43
6	24538.40	26.08	130.22	28837.2	110.97	190.75
7	29382.89	21.78	102.66	33421.1	95.75	160.03
8	33247.98	19.25	95.37	37228.5	85.96	154.62
9	37219.56	17.20	105.50	40080.3	79.84	161.31
10	42070.58	15.21	93.38	44540.9	71.84	138.33
11	46424.18	13.79	89.37	48703.0	65.70	147.13
12	50338.82	12.71	83.42	51520.0	62.11	132.35
13	56058.91	11.42	70.45	53418.7	59.90	103.91
14	60171.88	10.64	48.58	57326.6	55.82	77.36
15	63521.86	10.08	21.70	61542.9	52.00	63.65

Table 11: Time prediction, transfer and analyze

5.4 2D-array test

Listing 10: Kildekode

```
1 https://github.com/SveinGunnar/Master_Thesis_2020/tree/master/ArrayCopyTest
```

4000*4000		
Threads	Time	Speed
1	138.47	4621.91
2	71.90	8901.87
3	49.98	12805.97
4	37.97	16854.35
5	30.83	20759.23
6	26.20	24426.96
7	23.37	27388.78
8	22.03	29050.67
9	21.13	30290.55
10	20.28	31558.77
11	19.77	32372.93
12	19.53	32769.09
13	19.95	32072.81
14	18.87	33919.44
15	18.83	33997.04
16	18.90	33864.18
10000*10000		
Threads	Time	Speed
1	856.44	4670.51
2	445.47	8979.21
3	306.34	13057.28
4	237.02	16876.45
5	195.01	20511.92
6	165.48	24172.77
7	153.00	26143.97
8	147.82	27059.68
9	146.34	27334.50
10	137.83	29021.36
11	134.70	29695.01
12	133.70	29917.48
13	131.01	30533.18
14	127.94	31263.72
15	128.40	31153.04
16	128.13	31217.93

Table 12: 2D-Array test

References

[1] John D. McCalpin. *STREAM source code*. URL: https://www.cs.virginia.edu/stream/FTP/Code/stream.c (visited on 12/20/2020).