Iterative Compilation with Kernel Exploration

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joint work with

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Context

High Performance Computing

- Larger and larger field of application

  simulation (biology, aeronautics, drug design,...), multimedia applications, large data computations

- Higher level of parallelism
  - Numa architectures
  - Hardware accelerators (GPU, clearspeed,...)
  - Multicore
  - Large IPC

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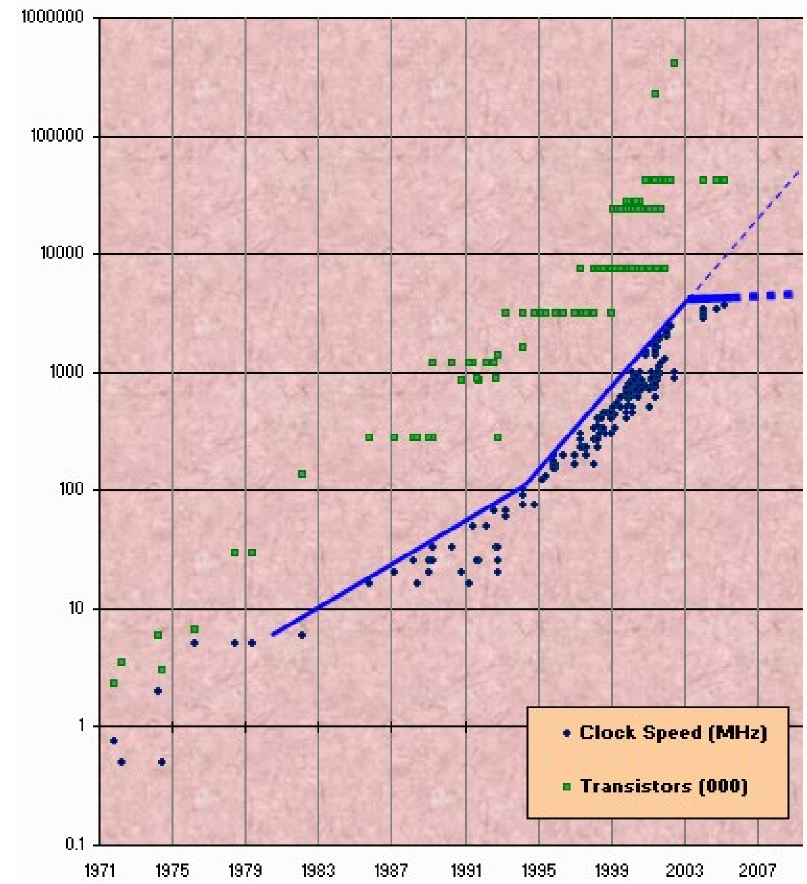
Context

Evolution of Moore's Law:

- end of performance for free ?
- more effort to tap future computational resources
- more need for optimizations



Issues in compilation

Major compiler problems:

- Dealing with more and more complex hardware (ILP, speculation, out of order, multilevel caches)
- → Specific, complex optimizations
- Optimizations not always beneficial for performance (fusion)
- Complex interactions between optimizations
- → Heuristic driven optimization sequences

=> As a result, performance of compiler generated code even for simple matrix multiplication is disappointing

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Experimental setup

- ICC v9.0 (build 20050430)
  - \- O3 – no alias

- Itanium 2 Bull NOVASCALE
  - 1.575 GHz
  - 9MB L3
  - Peak performance = 6300 Mflops (1 FMA every 0.5 cycle)

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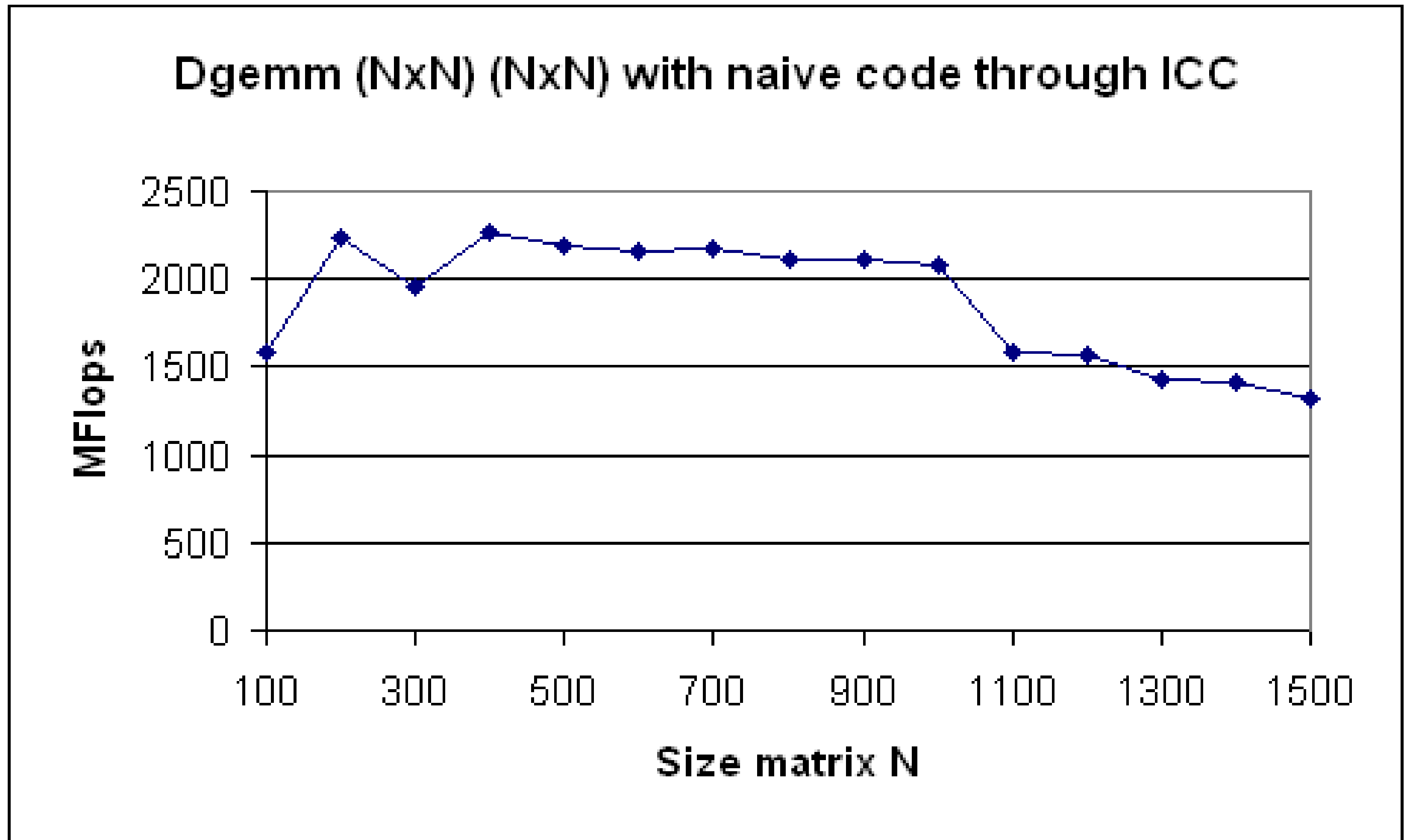
Issues in compilation



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Outline

- Exploring optimization space
  - **Manually: Multistage compilation languages**
  - Automatically: by search or with a model
  - Combine: Kernel decomposition
- Feed-back guided code tuning

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Multistage compilation languages

Goal : **Adapt optimization sequence to application**

Apply transformations to specific code fragments

- pragmas (icc black belts, X language)
- languages manipulating code objects (meta ocaml, `C, Taskgraph, ccg)

Issues

- correction of generated code, debug
- ease of use

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X language

Features:

- Language of pragmas
- Use elementary transformations, with their parameter

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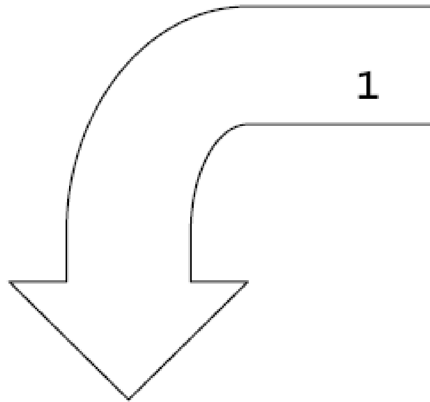
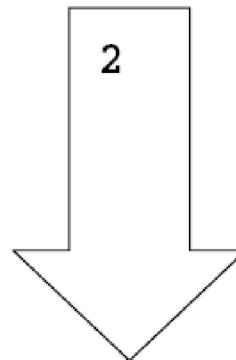
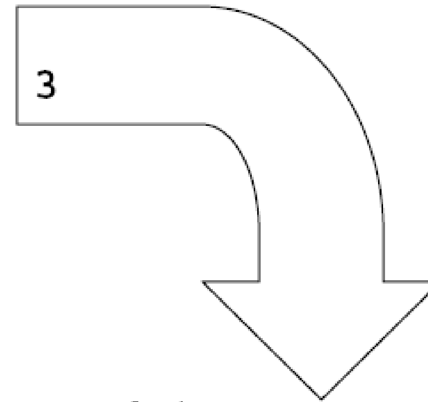
X language

```
do i=1, 100
     a(i)=b(i)+c(i)
end do
```

Unroll








```
do i=1, 100
     a(i)=b(i)+c(i)
end do
```

```
do i=1, 100, 2
     a(i)=b(i)+c(i)
     a(i+1)=b(i+1)+c(i+1)
end do
```

```
do i=1, 99, 3
     a(i)=b(i)+c(i)
     a(i+1)=b(i+1)+c(i+1)
     a(i+2)=b(i+2)+c(i+2)
end do
a(100)=b(100)+c(100)
```

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X language example

```
#pragma xlang parameter U [1:3]
#pragma xlang name loop1
for (i=0; i<100; i++)
  a(i) = b(i) + c(i)
#pragma xlang transform unroll loop1 U
```

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X language

Features:

- Language of pragmas
- Use elementary transformations, with their parameter
- Compose elementary transformations

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X language

```
for (i=0; i<n*2; i++)
  for (j=0; j<m; m++)
    a(i) = a(i) + b(j)
```

outer unroll

```
for (i=0; i<n*2; i++)
  for (j=0; j<m; j++)
    a(i) = a(i) + b(j)
  for (j=0; j<m; j++)
    a(i+1) = a(i+1) + b(j)
```

fusion

```
for (i=0; i<n*2; i++)
  for (j=0; j<m; j++)
    a(i) = a(i) + b(j)
    a(i+1) = a(i+1) + b(j)
```

stripmine

```
for (i=0; i<n*2; i+=2)
  for (ii=i; ii<i+2; ii++)
    for (j=0; j<m; j++)
      a(ii) = a(ii) + b(j)
```

interchange

```
for (i=0; i<n*2; i+=2)
  for (j=0; j<m; j++)
    for (ii=i; ii<i+2; ii++)
      a(ii) = a(ii) + b(j)
```

inner unroll

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X language example

```
#pragma xlang name loopi
for (i=0; i<n*2; i++)
#pragma xlang name loopj
  for (j=0; j<m; j++)
    a(i) = a(i) + b(j)
#pragma xlang transform stripmine loopi 2 loopii
#pragma xlang transform interchange loopii loopj
#pragma xlang transform unroll loopii 2
```

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X language

Features:

- Language of pragmas
- Use elementary transformations, with their parameter
- Compose elementary transformations
- User-defined transformations

X language example

Definition of fusion by pattern matching rule (Prolog)

```
optimize(fusion(I,J),
           for(I,LB,UB,S,B); for (J,LB,UB,S,B2),
          for(I,LB,UB,S,B;B3)):-
       substitute(I/J,B2,B3).
```

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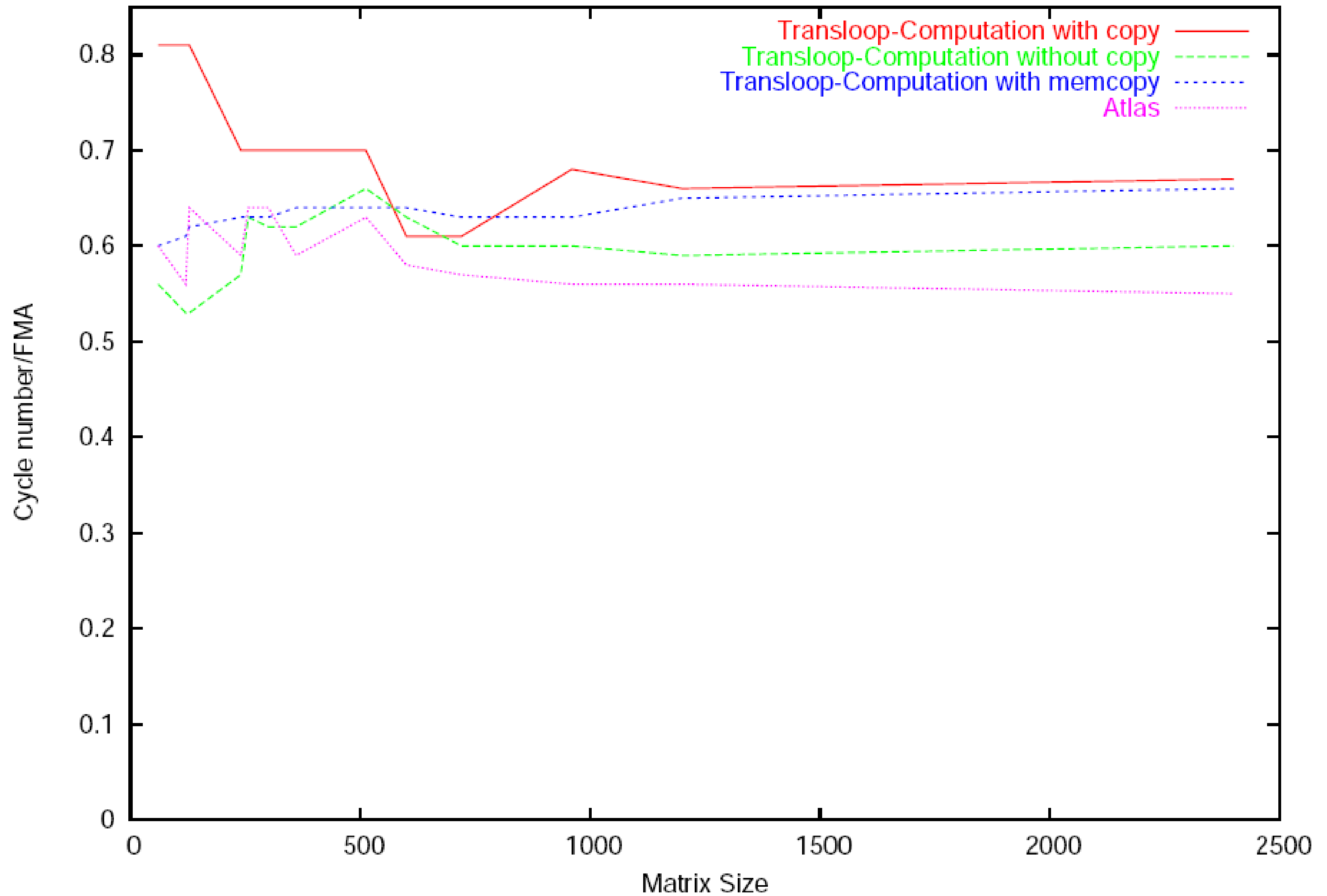
X language applied to dgemm



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X language

Pros:

- Adapt optimization to the application
- New optimizations easily added, pattern matching rules
- Description of the iteration space
- Not application specific, possible to obtain ATLAS performance (not unleashed)

Good language to develop compilation strategies

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X language

Cons:

- Programmer does the job of the compiler! (general to multistage compilation languages)
- Not type safe
- No validation of transformations
- Difficult to read after few lines

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Iterative compilation

Cf previous courses.

- Space of optimizations:
  - optimization sequences
  - parameters (unroll factor, tile sizes, prefetch distance,...)
- Search guided
  - by execution results (Atlas, FFTW, Spiral)
  - by model (Atlas with model)
  - by knowledge of application semantics (all of these)

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Iterative compilation

Pros:

- Source to source transformations (portable)
- May use semantics of the application

Cons:

- Source to source transformation (compiler dependent)
- **Still outperformed by 20% by handtuned codes**

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Kernel decomposition

Objectives:

- Source to source transformations only
- Focus on linear algebra codes
- Close the gap with hand tuned codes

Idea:

Compilers are our friends, use them to their best

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Target typical Code: Matrix Multiplication

Interesting features:

- Contains all of the typical ingredients: ILP, locality, generic shapes,
- Large amount of research work available

Competitors:

- MKL: highly hand tuned library developed by INTEL
- ATLAS: automatically generated library
- GOTO libraries: very high performance assembly coded library
- Close to optimal performance obtained by GOTO and MKL

➔ tough challenge, no performance losses allowed

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General approach

Main steps:

- **High level transformations**, data reuse tiling (if needed)
- **Decompose** data reuse tiles into simple kernels
- → Several decompositions can be obtained
- **Benchmark** all kernels, out of application context
- **Combine** best kernels to generate the code

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Kernel definition

Features of a kernel:

- static control program, constant loop bounds
- bounded loop nest depth
- all working set is in cache
- compact array structures to the working set used in the kernel

→ kernels are simple codes for the compiler to optimize

→ makes kernels executable out of application context

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Kernel decomposition

Search transformations:

- loop interchange, fusion/fission, unroll&jam
- for now, exhaustive search...

Select sub loop nest

- starting from 3 loops, generates kernels of 1,2 and 3 loops

Simplify array structures

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Decomposition applied to dgemm

Starting with a mini mmm tile.

External tiling obtained with X language.

```
for i = 0, N1
    for i = 0, N2
     for k = 0, N3
          C[i][j] = C[i][j] + A[i][k] * B[k][j]
```

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Decomposition applied

1st example: no transformation, select inner loop

```
for i = 0, N1
  for j = 0, N2
     for k = 0, N3
        C[i][j] = C[i][j] + A[i][k] * B[k][j]
```

Simplifies into:

```
for k = 0, N3
  C = C + A[k] * B[k]
```

➔ This is a dot product

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Decomposition applied

2nd example: interchange i,k, unroll k by 2, select inner loop

```
for i = 0, N1
    for k = 0, N3,2
        for j = 0, N2
            C[i][j] = C[i][j] + A[i][k] * B[k][j]
            C[i][j] = C[i][j] + A[i][k+1] * B[k+1][j]
```

Simplifies into:

```
for j = 0, N2
    C[j] = C[j] + A0 * B0[j]
    C[j] = C[j] + A1 * B1[j]
```

Variant of daxpy

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Decomposition applied

All kernels found by decomposition (variants)

- daxpy (1D)
- dotproduct (1D)
- matrix-vector product (2D)
- outer product (2D)
- matrix-matrix product (3D)

Unrolling the kernel itself is also considered.

Implementation:

- decomposition automatic with one elementary transformation of X language
- tiling and other high level transformations with X language

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Benchmarking the kernels

In vitro benchmarking

- In vitro behavior has to be the same than in vivo (inside application)
- All kernel inputs impacting performance are considered.

Search space:

- loop trip counts,
- unrolling factors,
- array alignment

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DAXPY K kernel

```
for i = 1, 100
    Y[i] = Y[i] + A1*X1[i] + ... + Ak*Xk[i]
```

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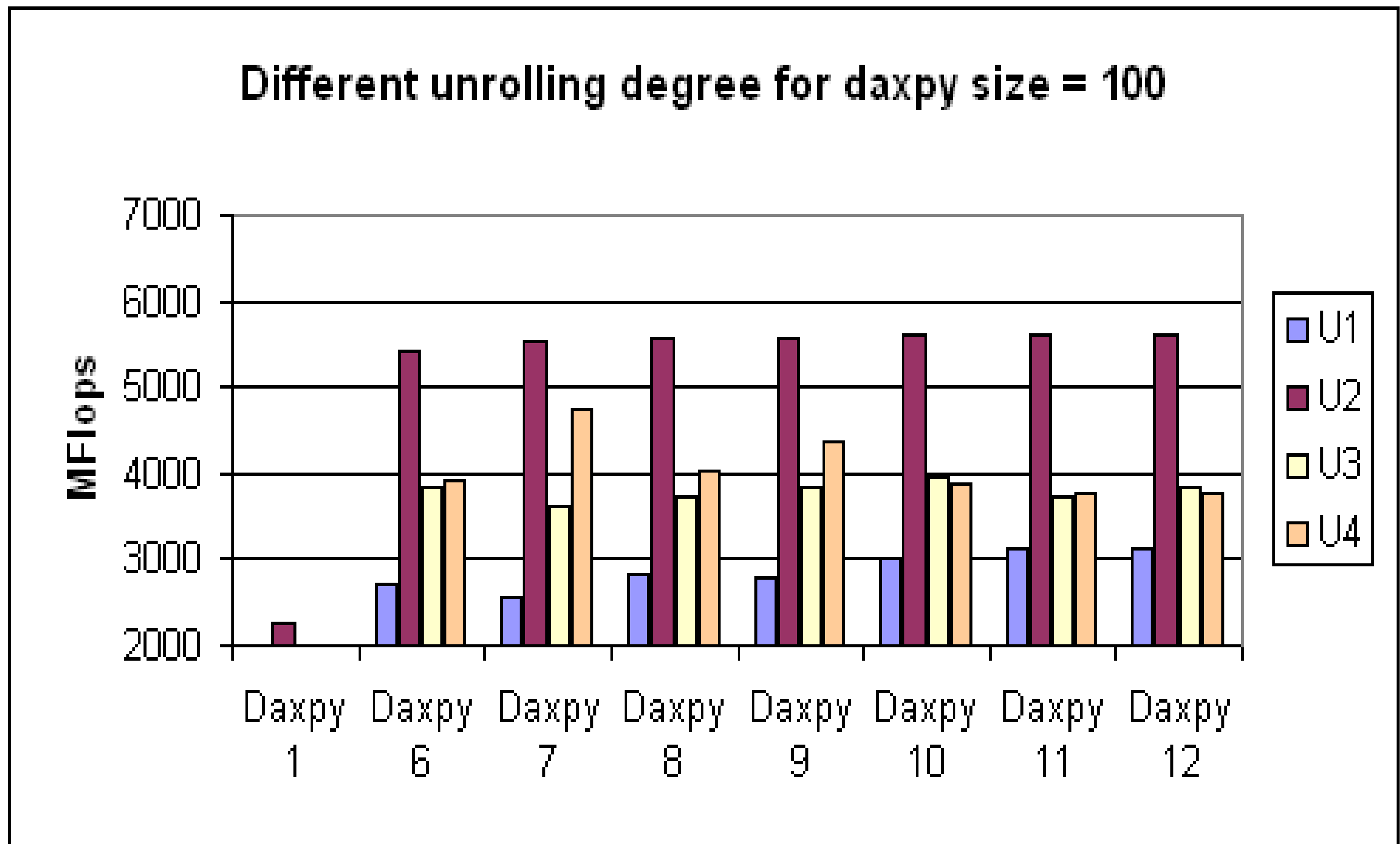
Daxpy_k Performance (N=100)



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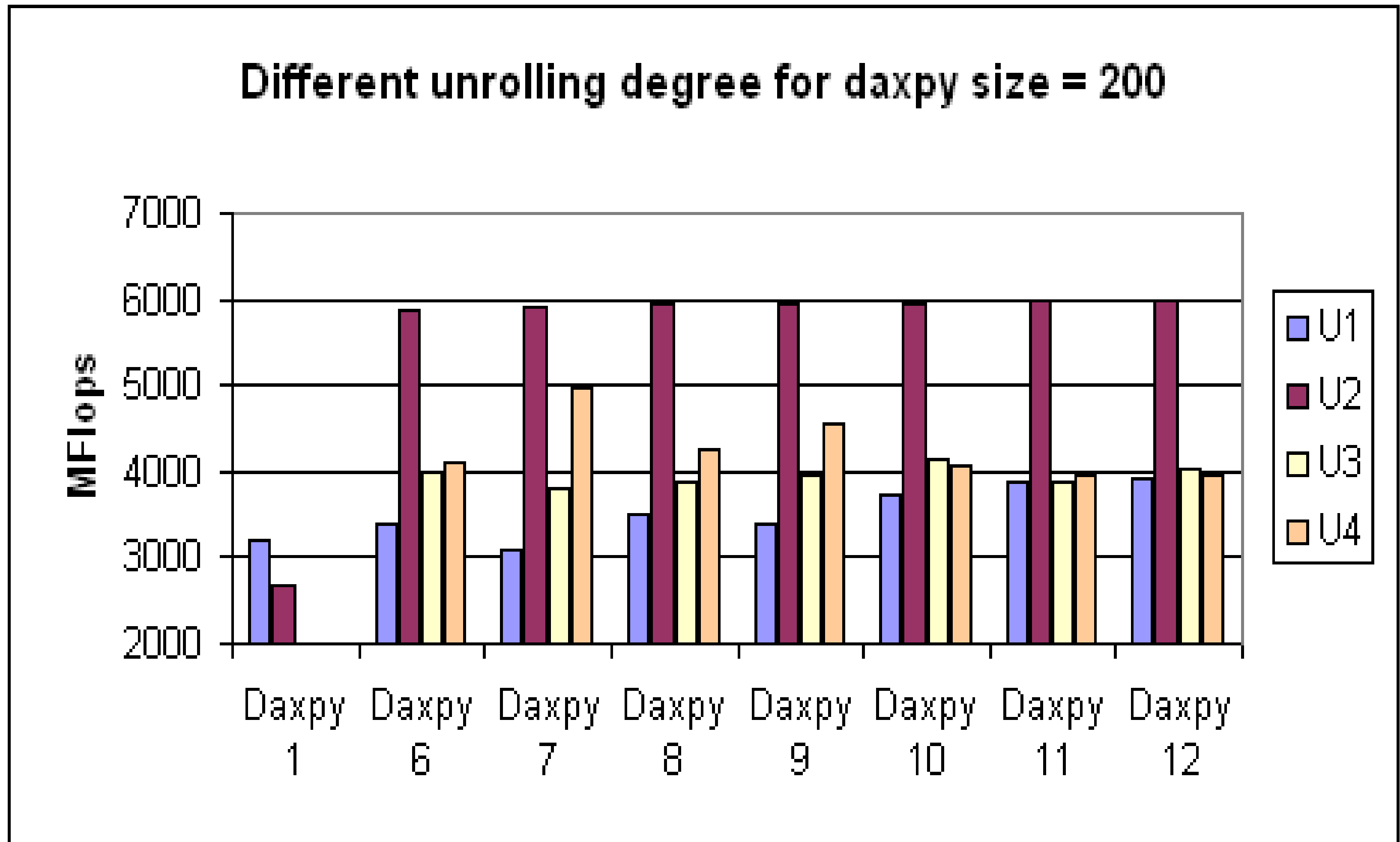
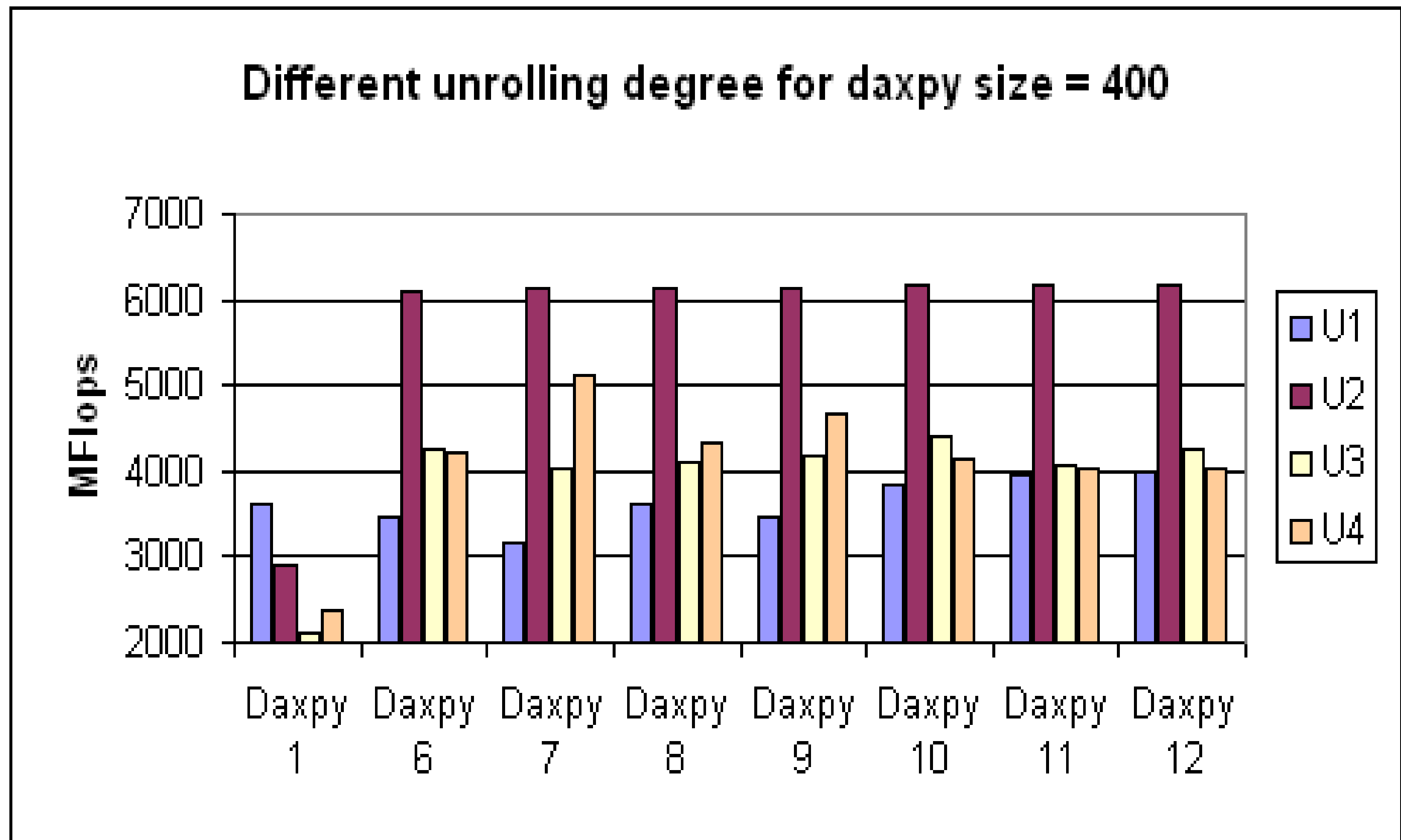
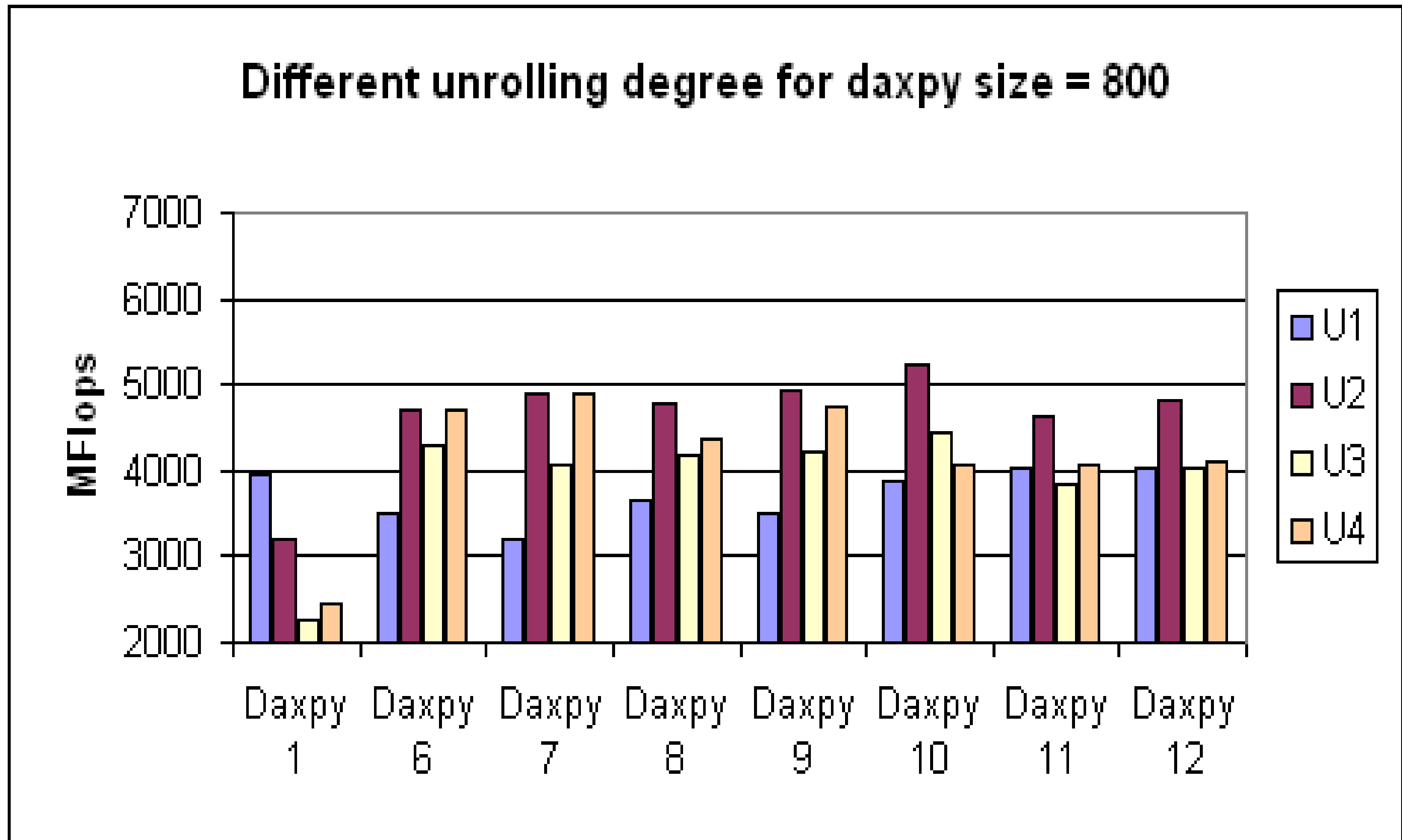
Daxpy_k Performance (N=200)



Daxpy_K Performance (N=400)



Daxpy_k Performance (N=800)



Dot product k kernel

```
For i = 1, 100
   S1 = S1 + X1[i]*Y1[i]
   S2 = S2 + X1[i]*Y2[i]
   S3 = S3 + X2[i]*Y1[i]
   S4 = S4 + X2[i]*Y2[i]
```

Code above will be called (2xn)(nx2) or simpler 2x2

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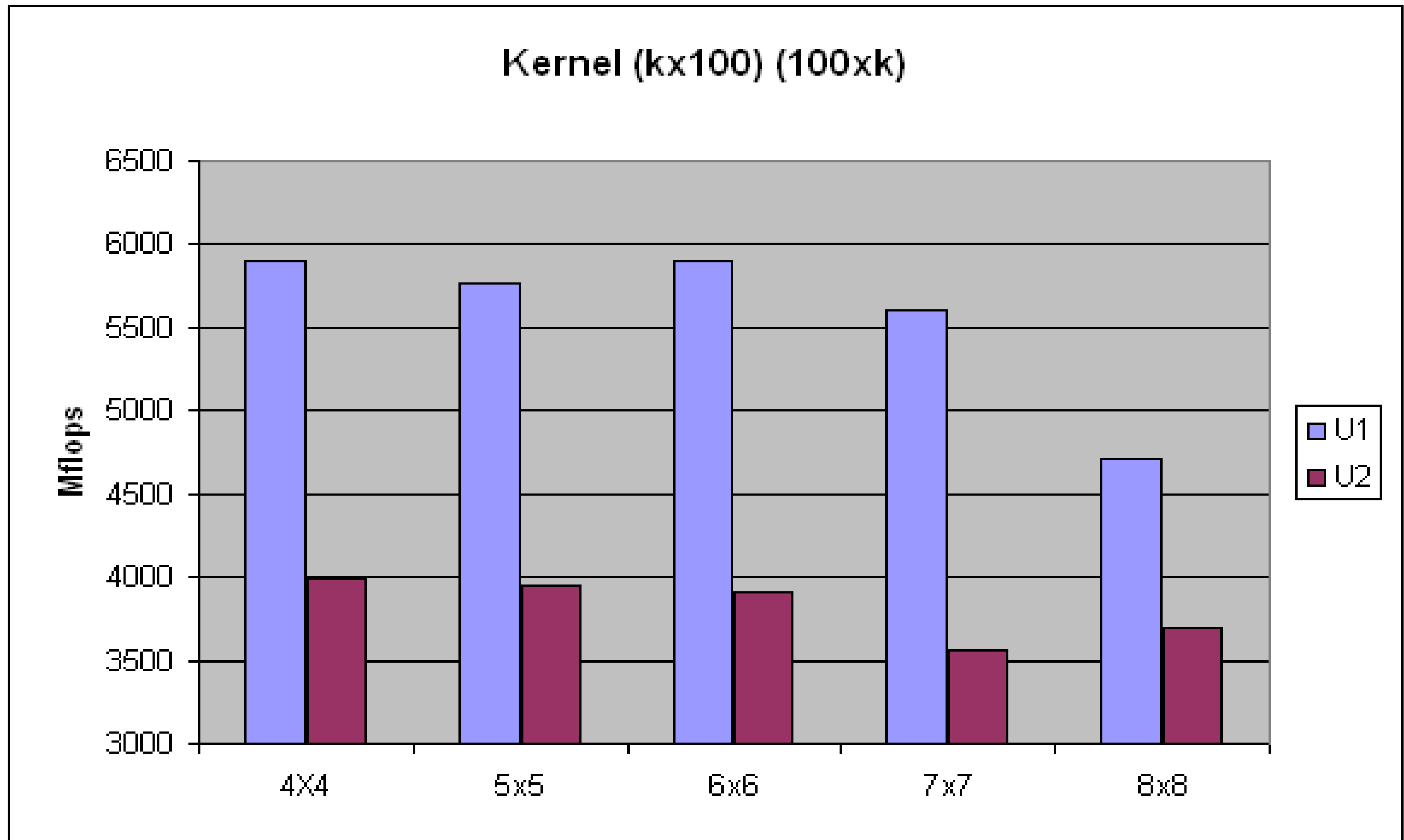
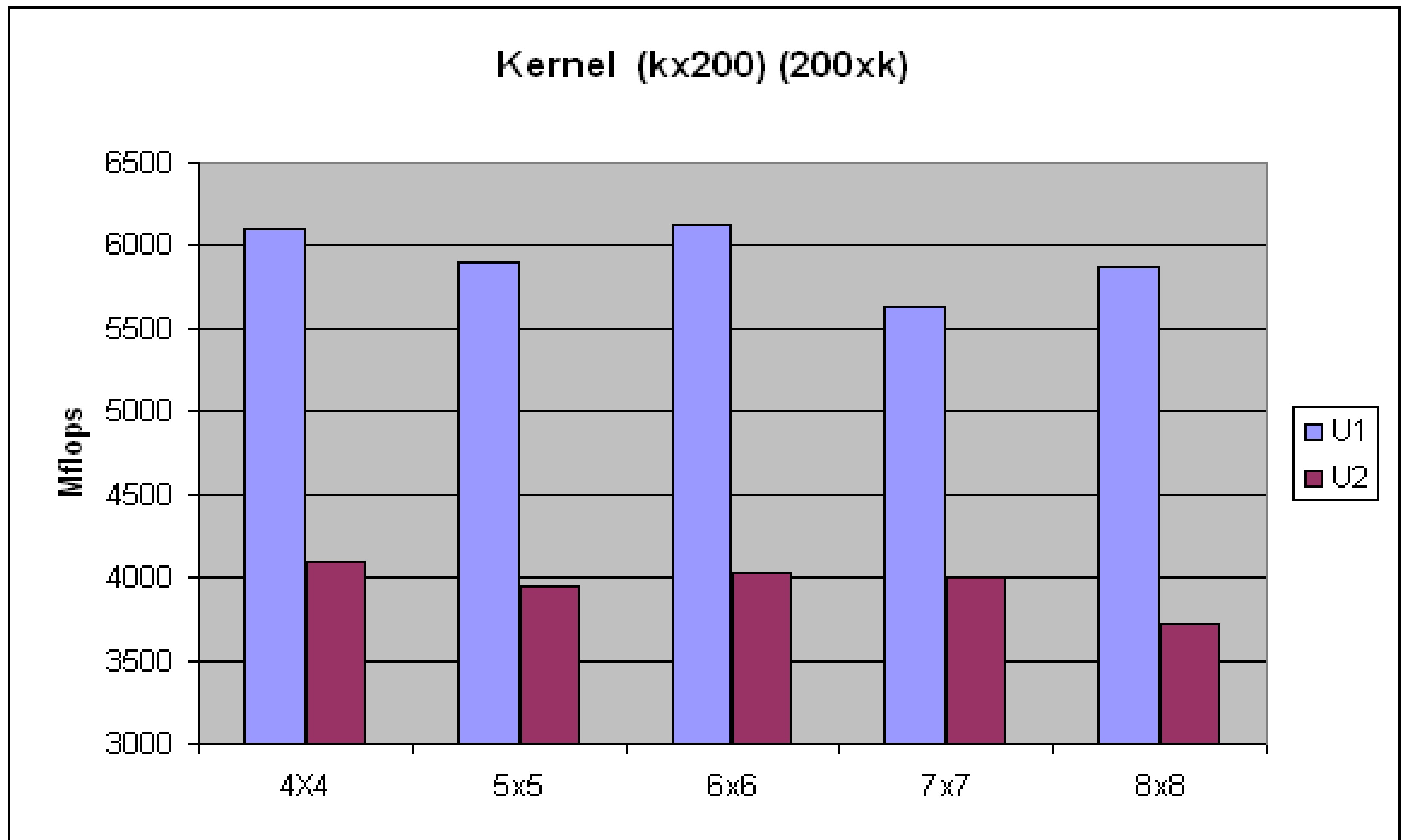
Performance of (kxn) (nxk)



Performance of (kxn) (nxk)



Outer Product K kernel

```
For i = 1, 100
    Y1[i] = Y1[i] + A1*X[i]
    Y2[i] = Y2[i] + A2*X[i]
    .......
    Yk[i] = Yk[i] + Ak*X[i]
```

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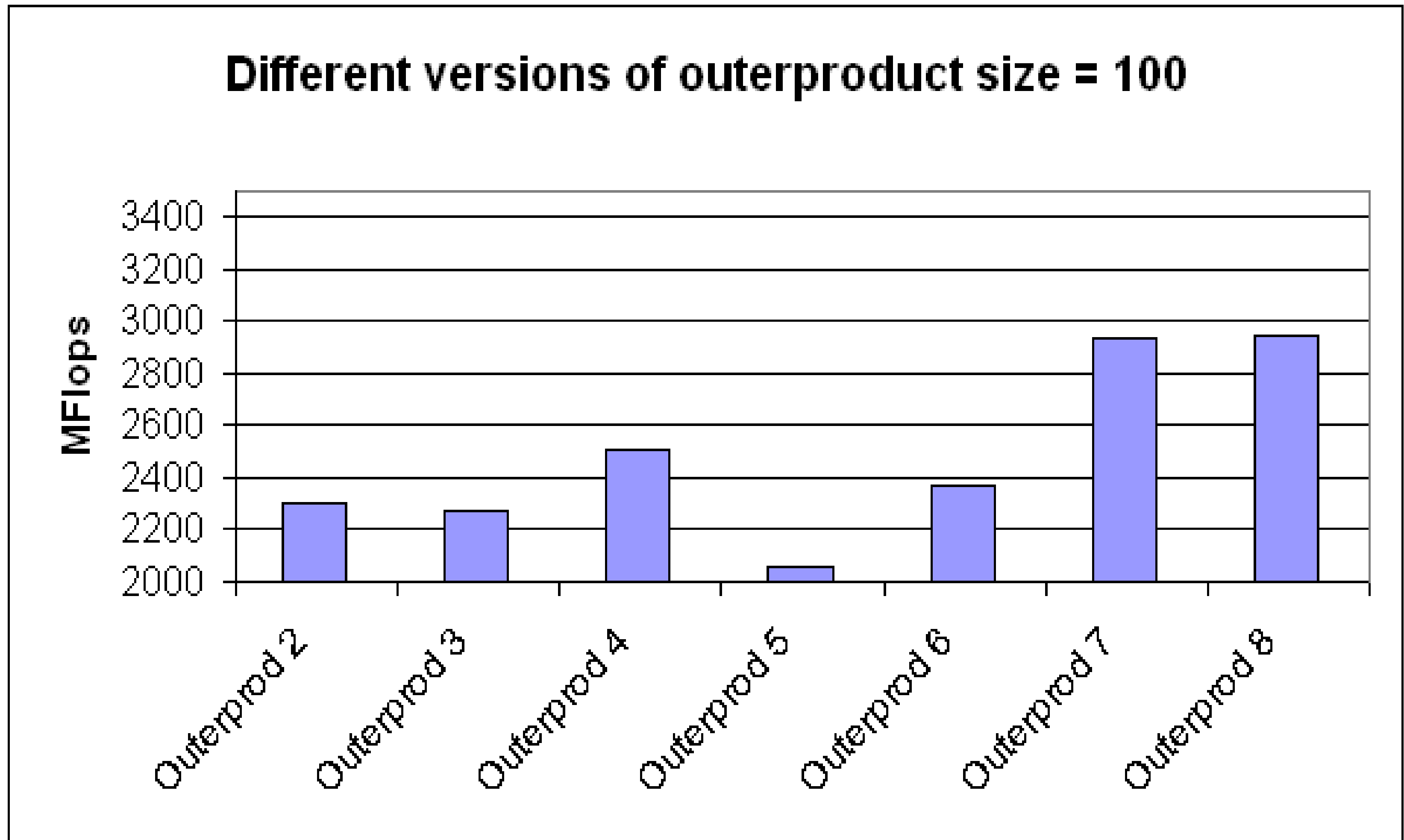
Outer_Product K Performance (N=100)



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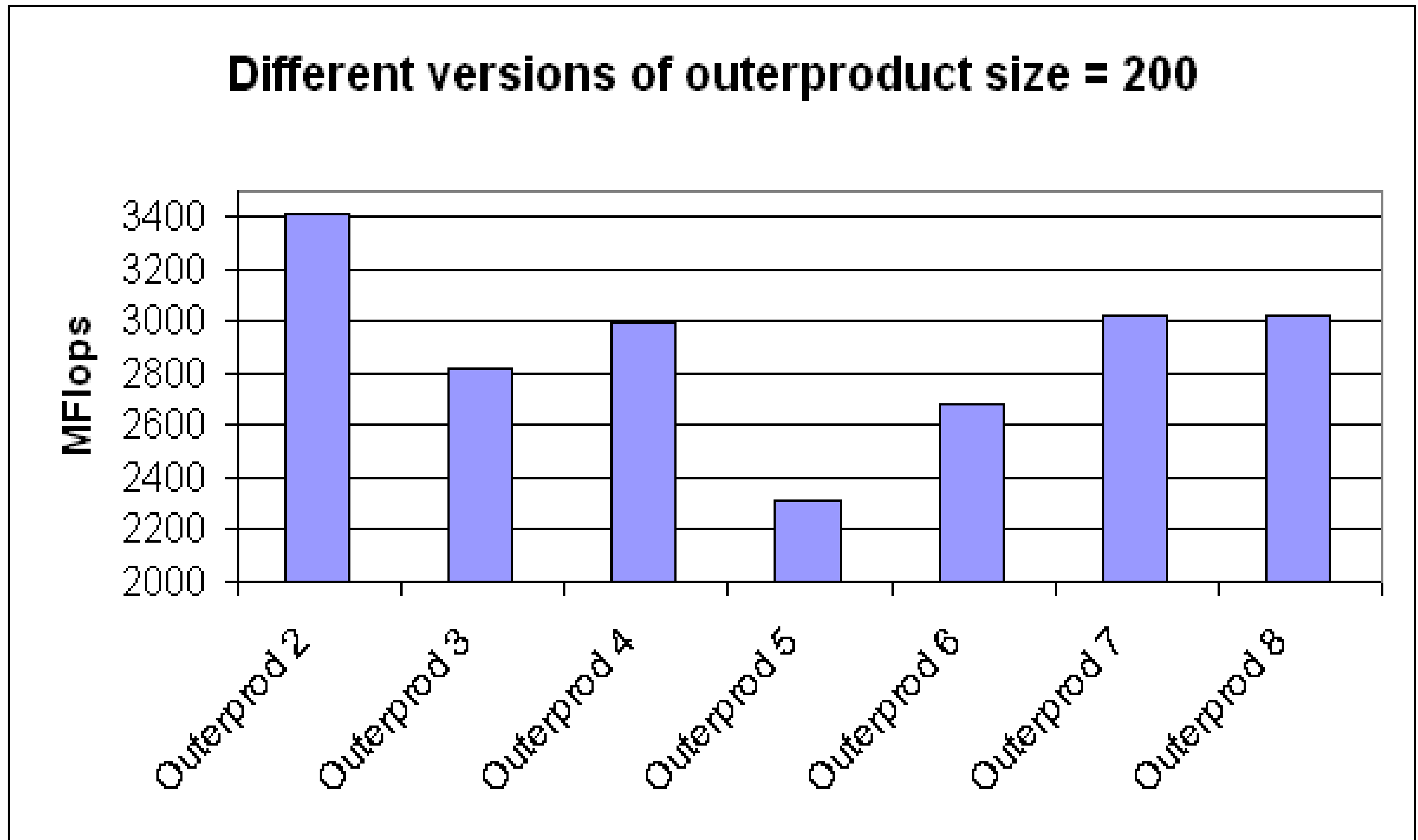
Outer_Product_k Performance (N=200)



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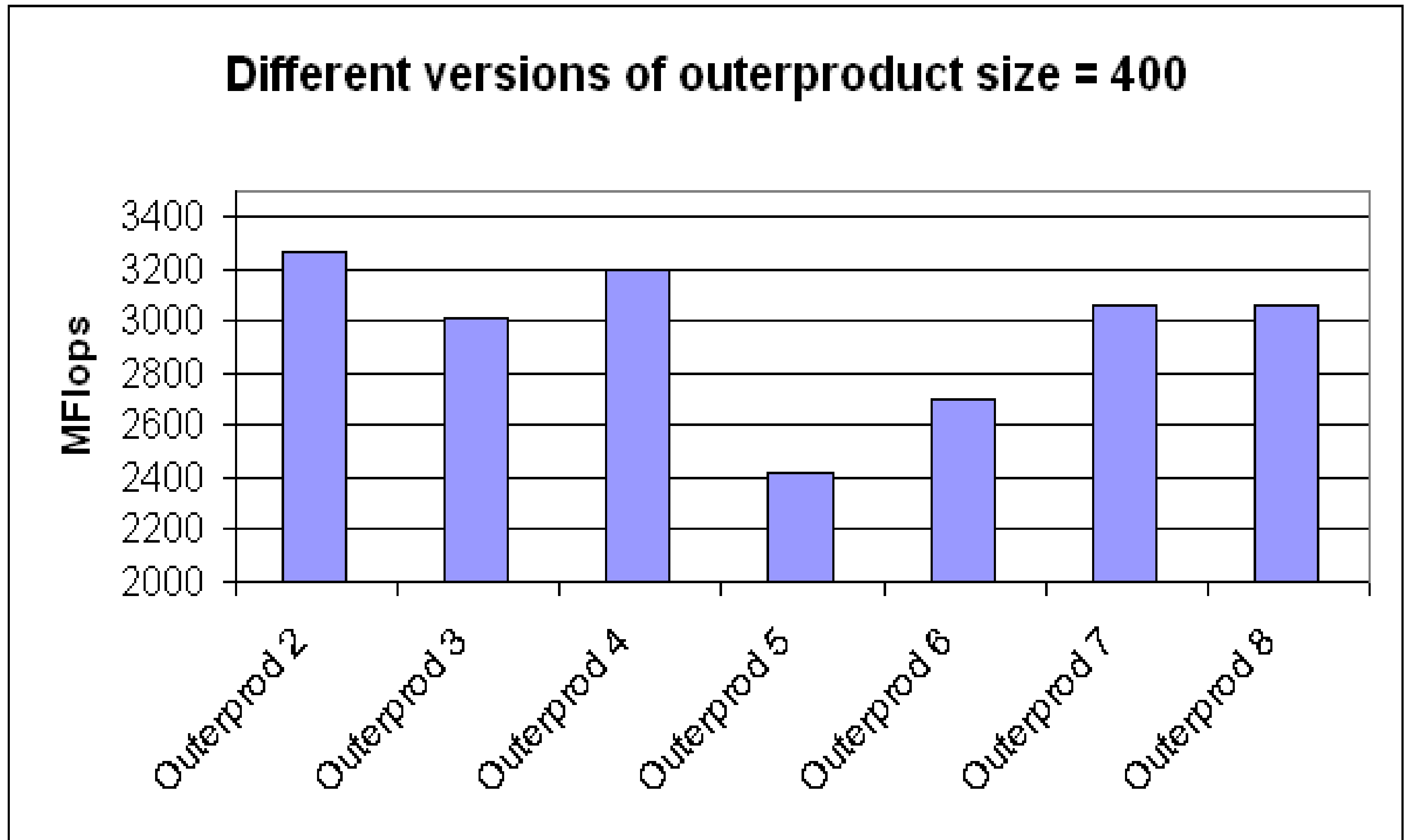
Outer_Product_K Performance (N=400)



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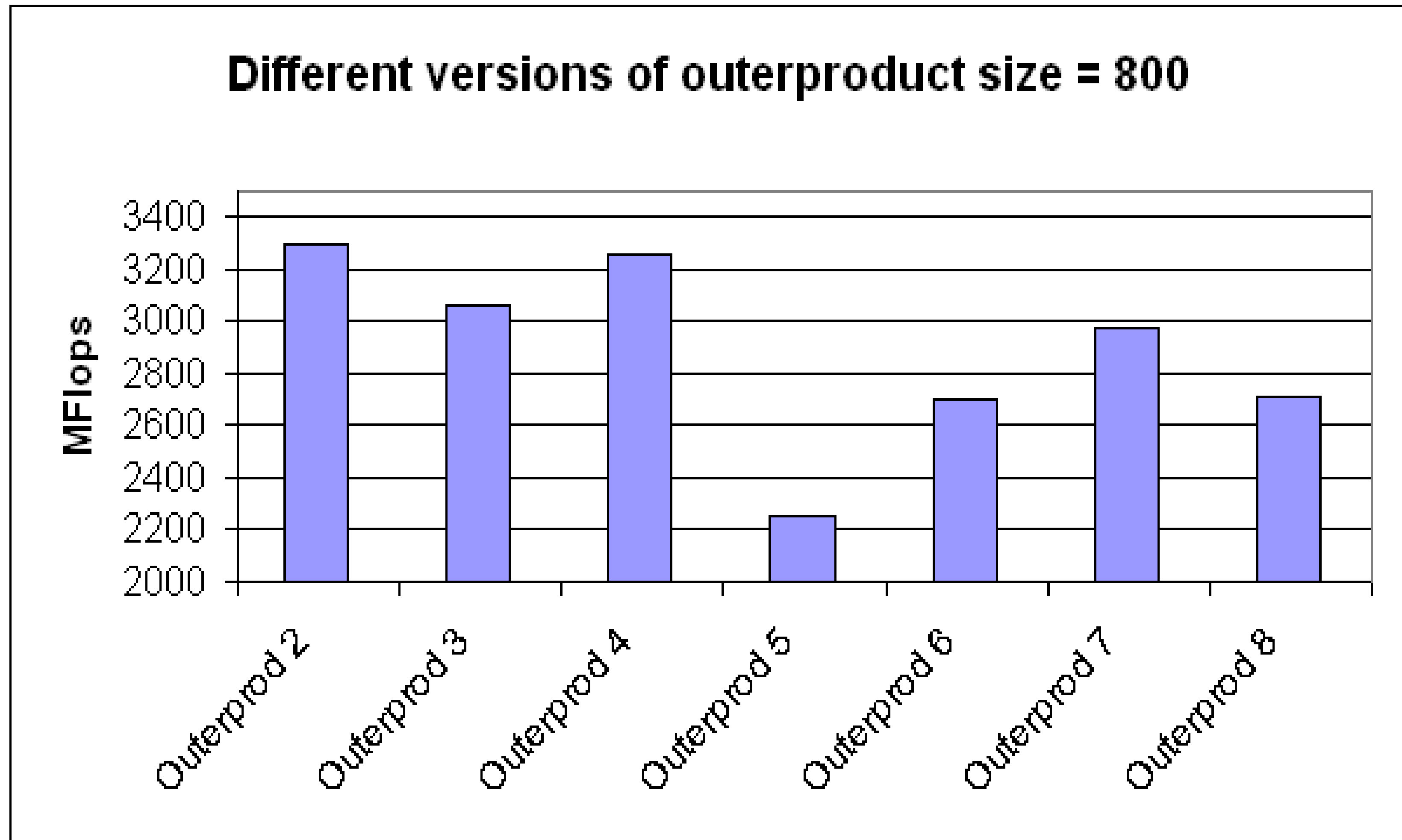
Outer_Product_K Performance (N=800)



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Combining kernels

Copying input/output arrays of kernels

- Ensures stability (array alignment)
- Data in cache, same results expected as in vitro.
- Memcopies are benchmarked (worst case measures)

According tile size:

For all kernels and their appropriate memcopies,

- Find out the best combination according to performance model (trivial)

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Combining kernels for dgemm

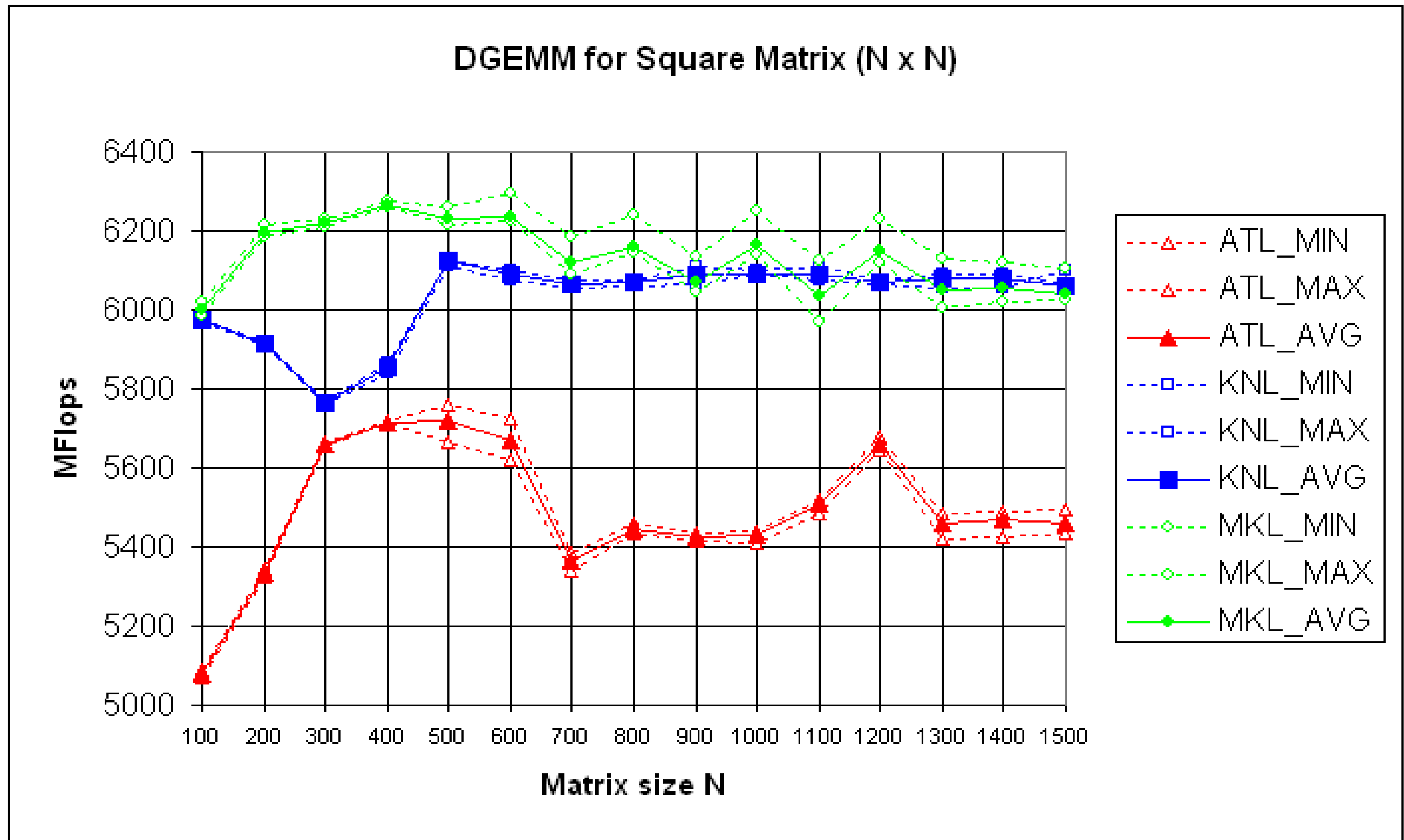
Best decomposition:

- use dotproduct6 kernel
- decompositions found also for degenerate matrix sizes (very thin in one or two dimensions)

The following results are NOT used for the selection of kernels.

→ They are experimental results of the decompositions.

(NxN) (NxN) DGEMM Performance



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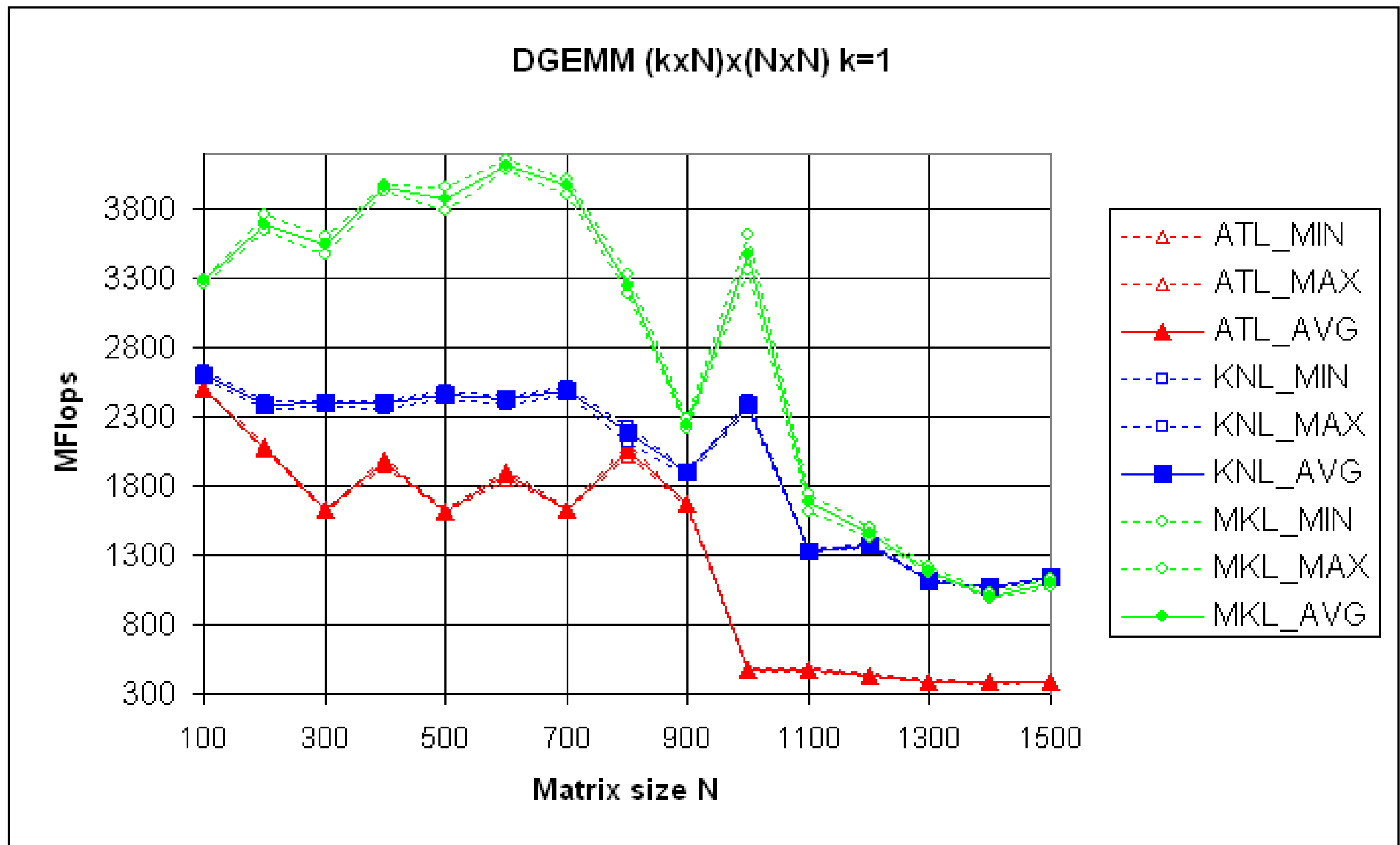
(1xN)(NxN) DGEMM Performance



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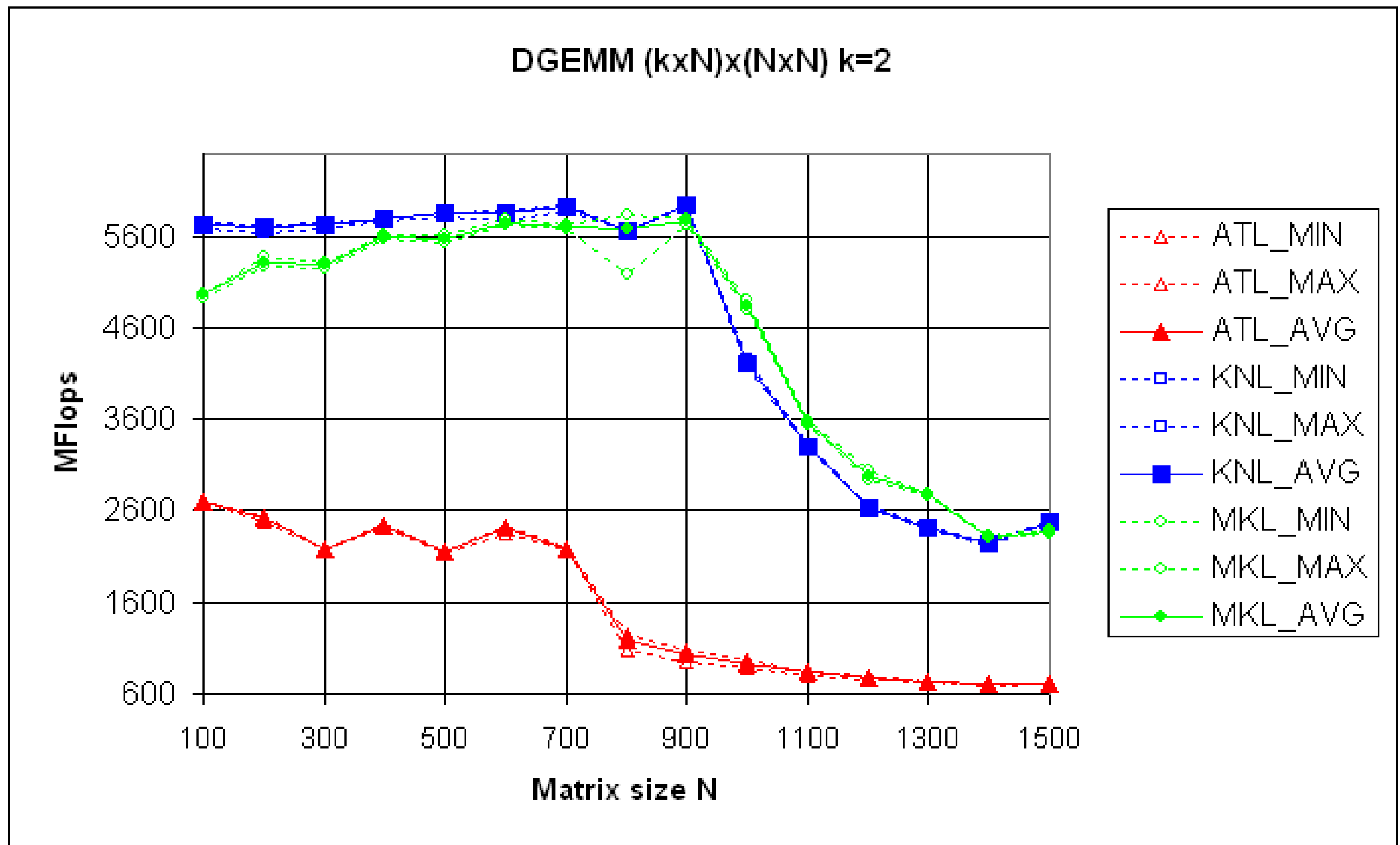
(2xN)(NxN) DGEMM Performance



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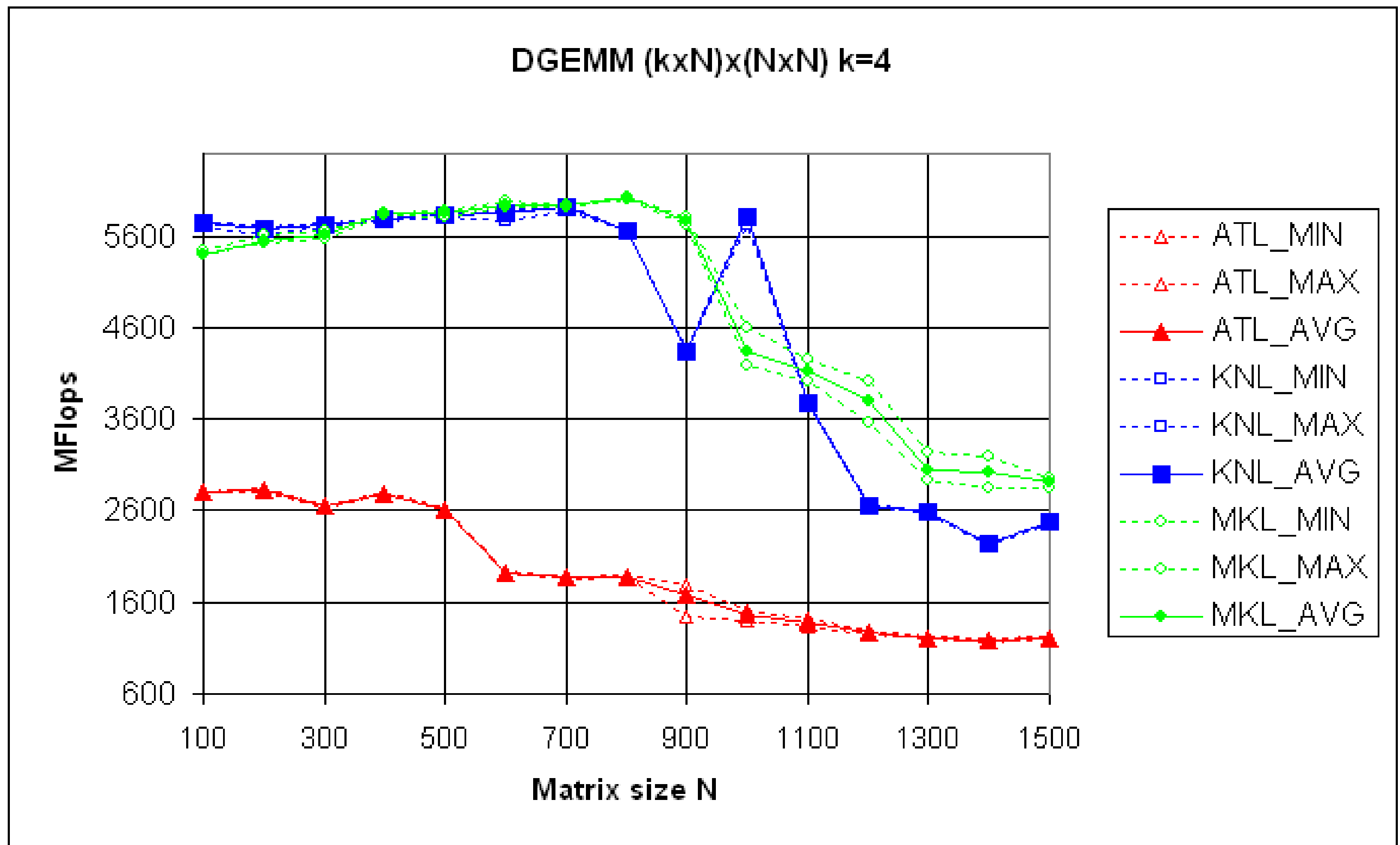
(4xN)(NxN) DGEMM Performance



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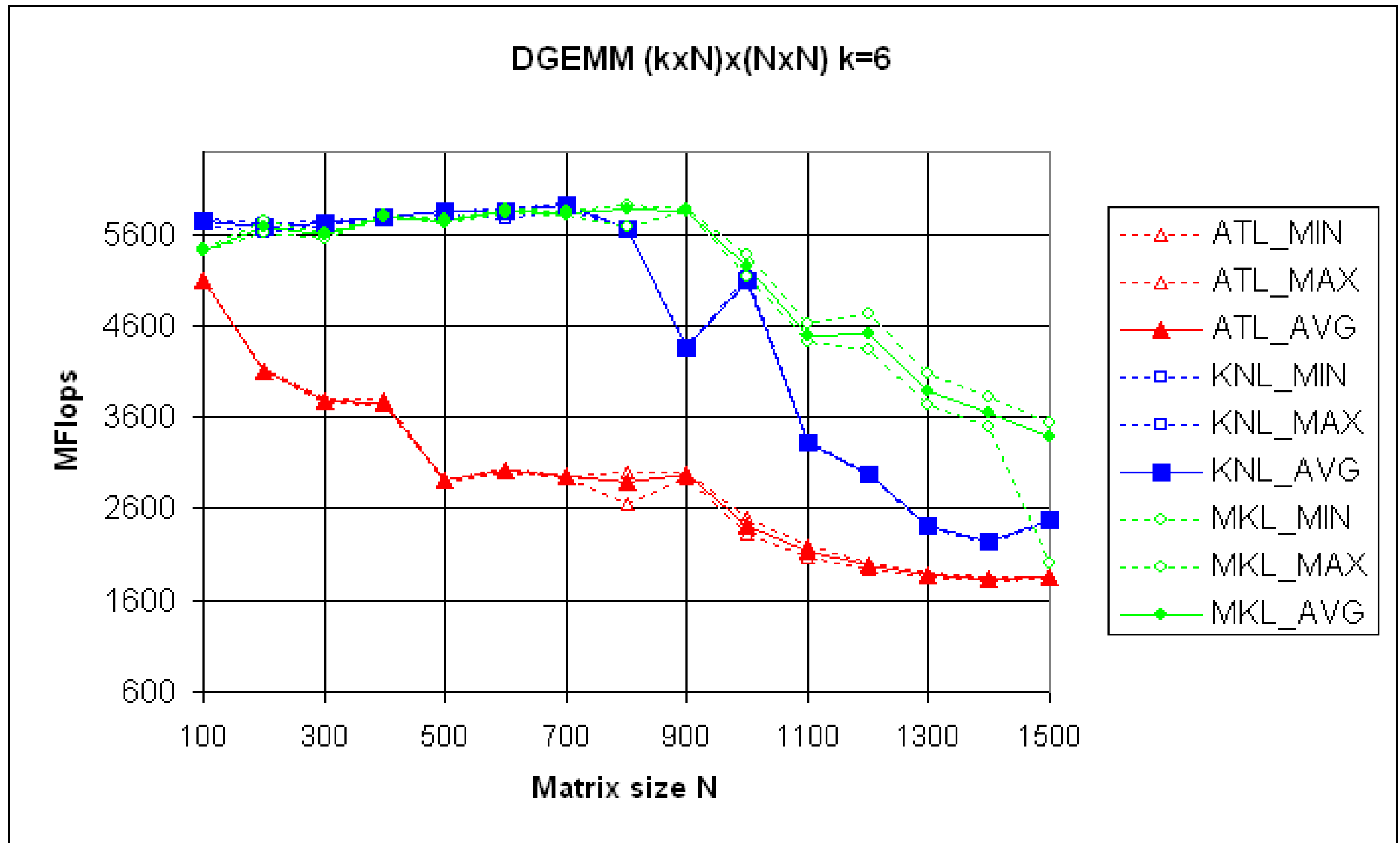
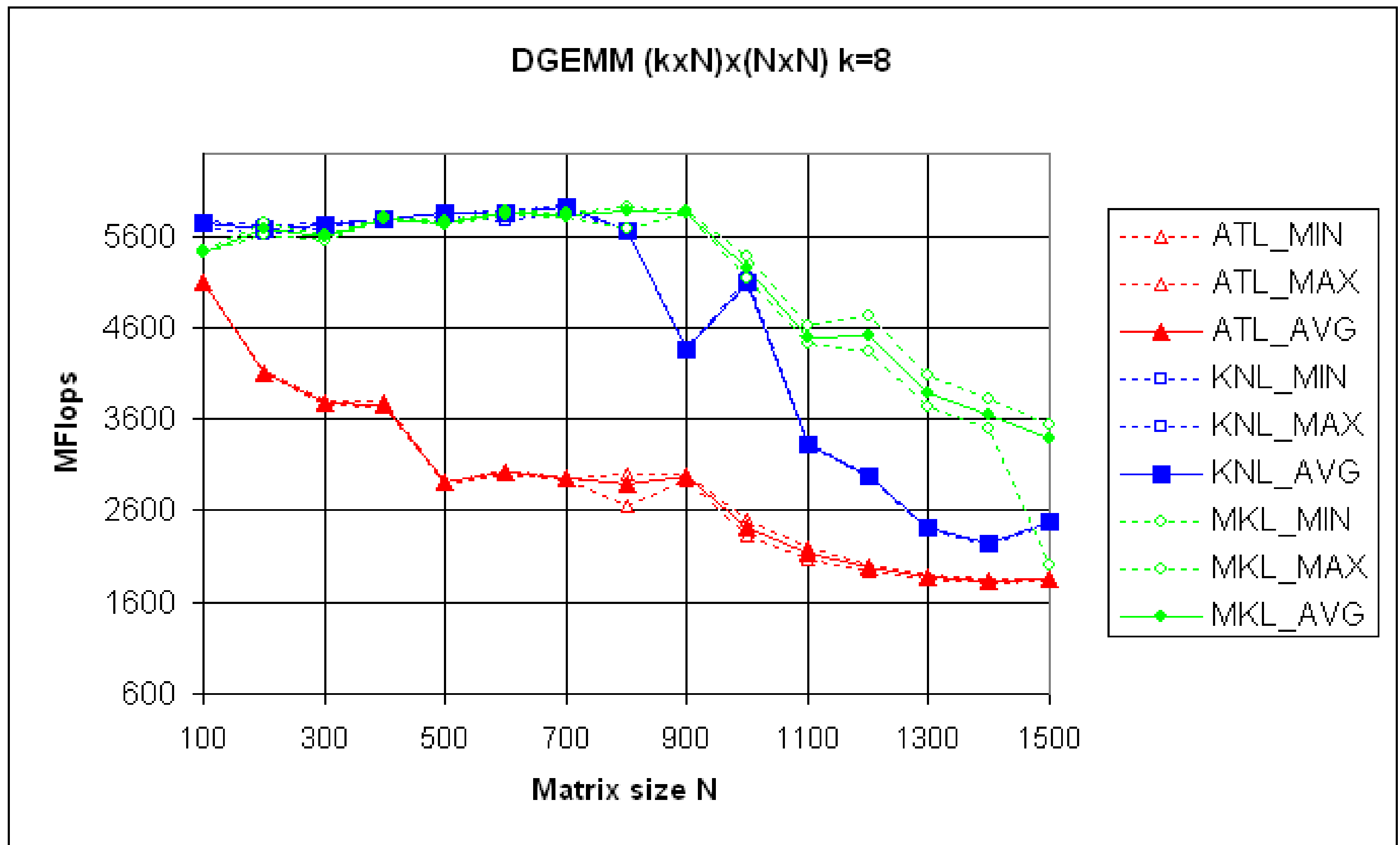
(6xN)(NxN) DGEMM Performance



(8xN)(NxN) DGEMM Performance



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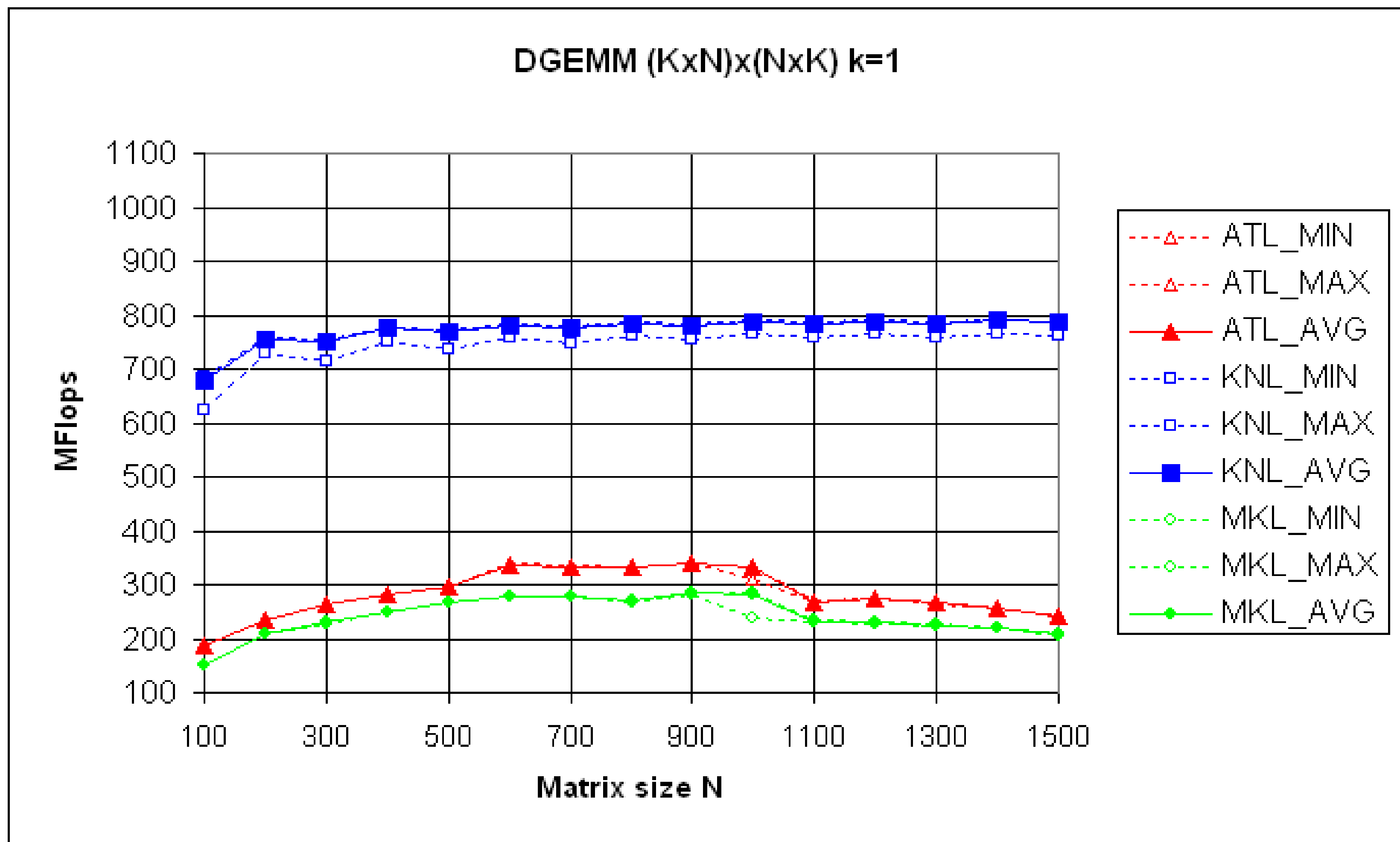
(1xN)(Nx1) DGEMM Performance



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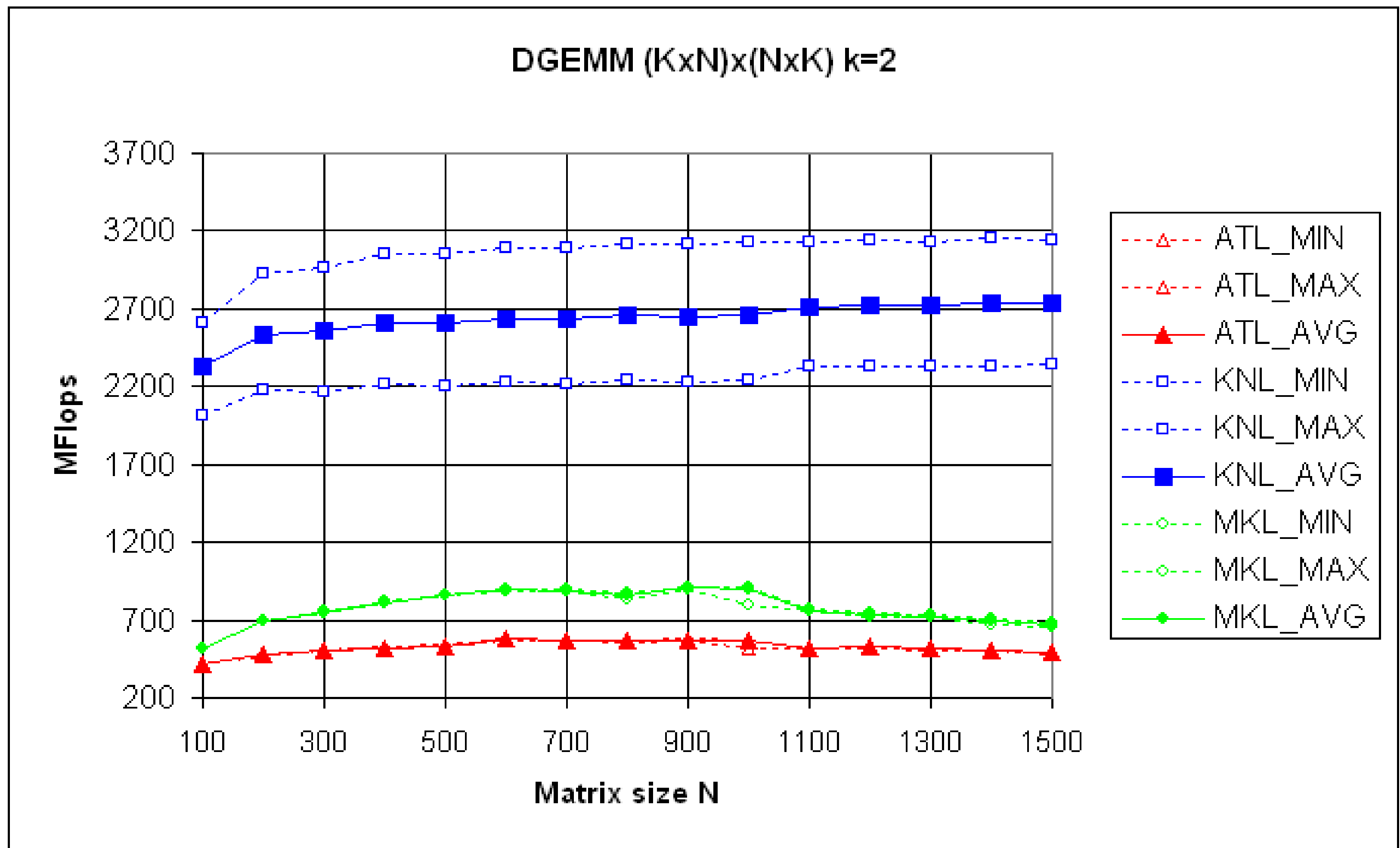
(2xN)(Nx2) DGEMM Performance



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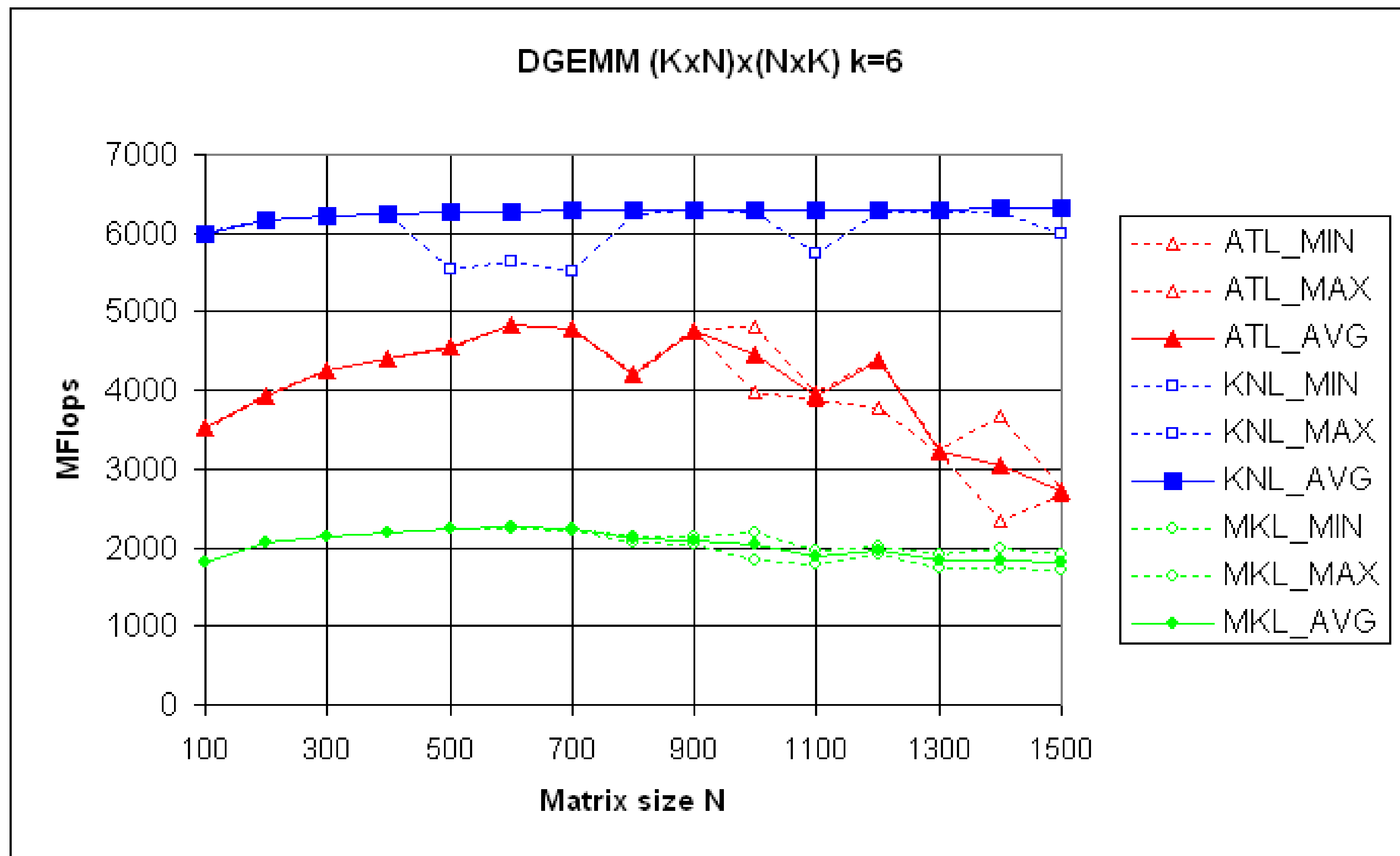
(6xN)(Nx6) DGEMM Performance



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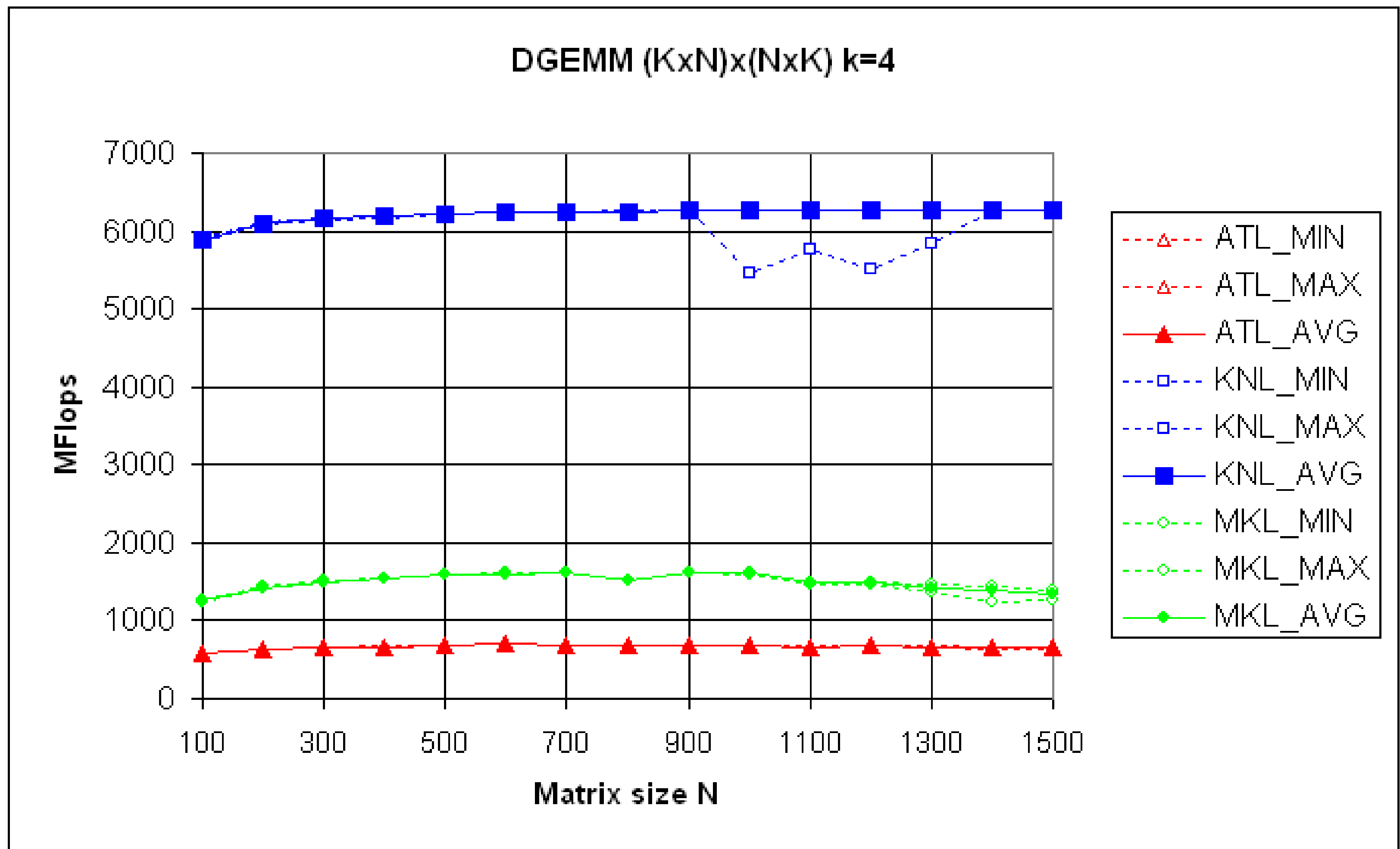
(4xN)(Nx4) DGEMM Performance



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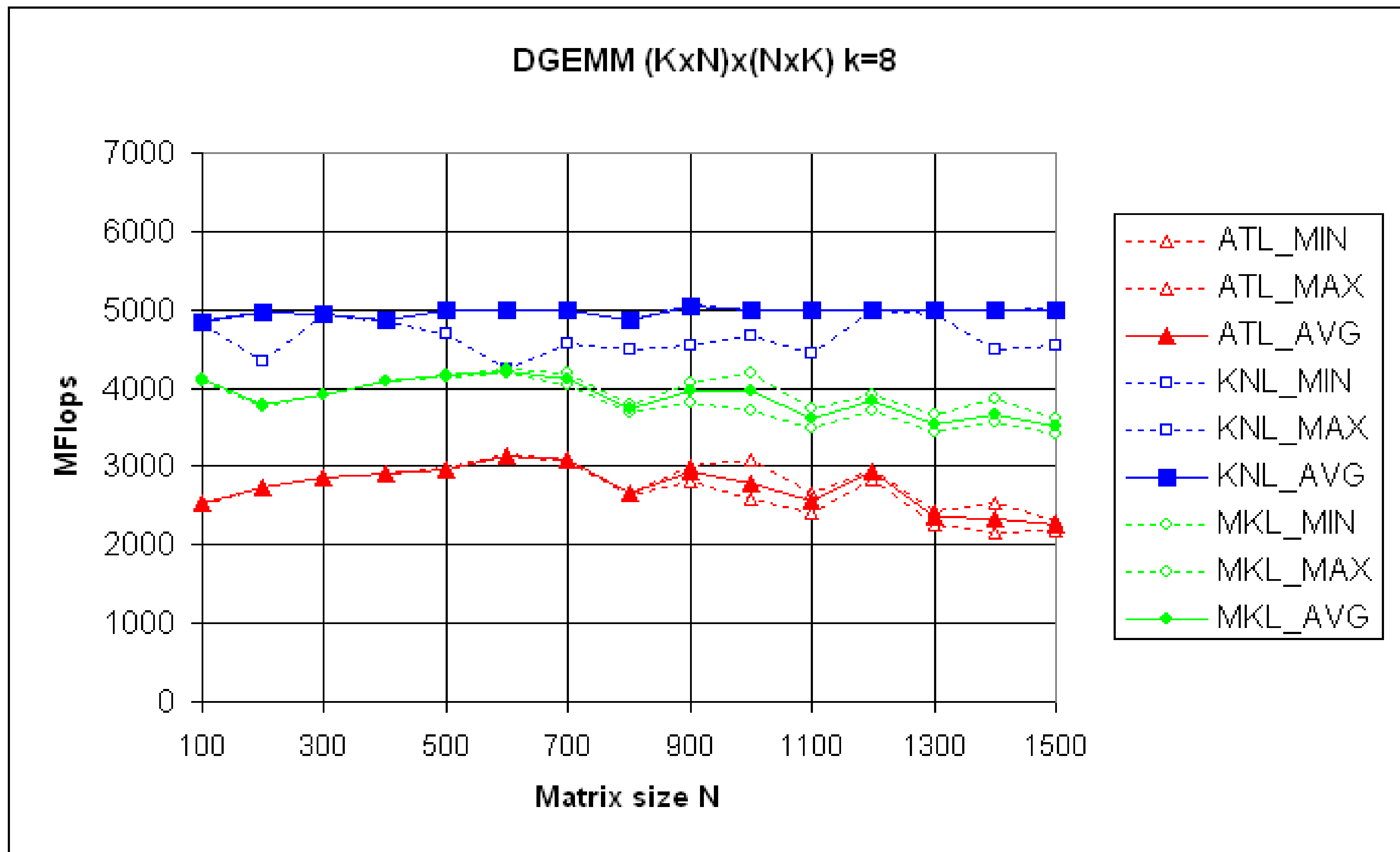
(8xN)(Nx8) DGEMM Performance



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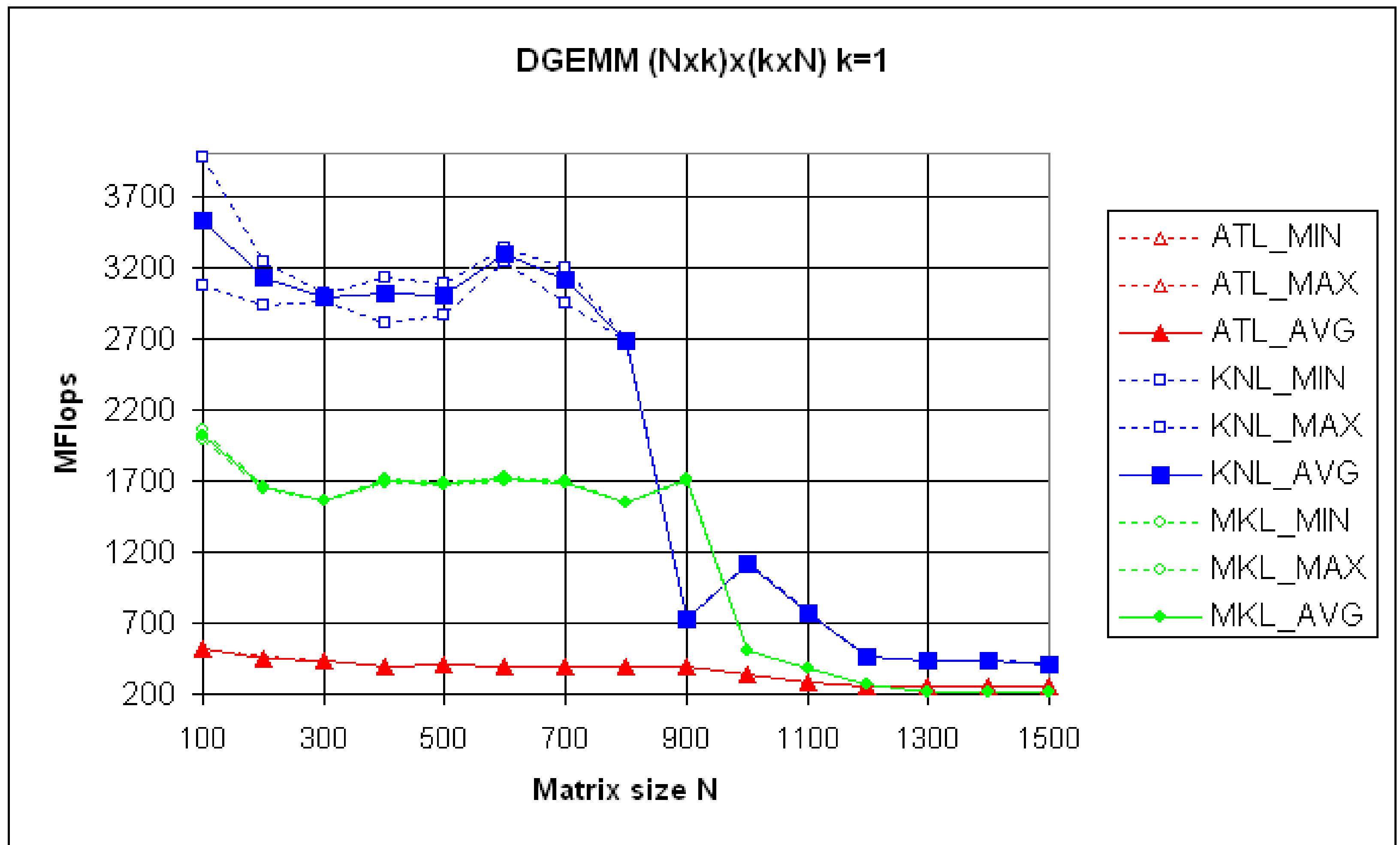
(Nx1)(1xN) DGEMM Performance



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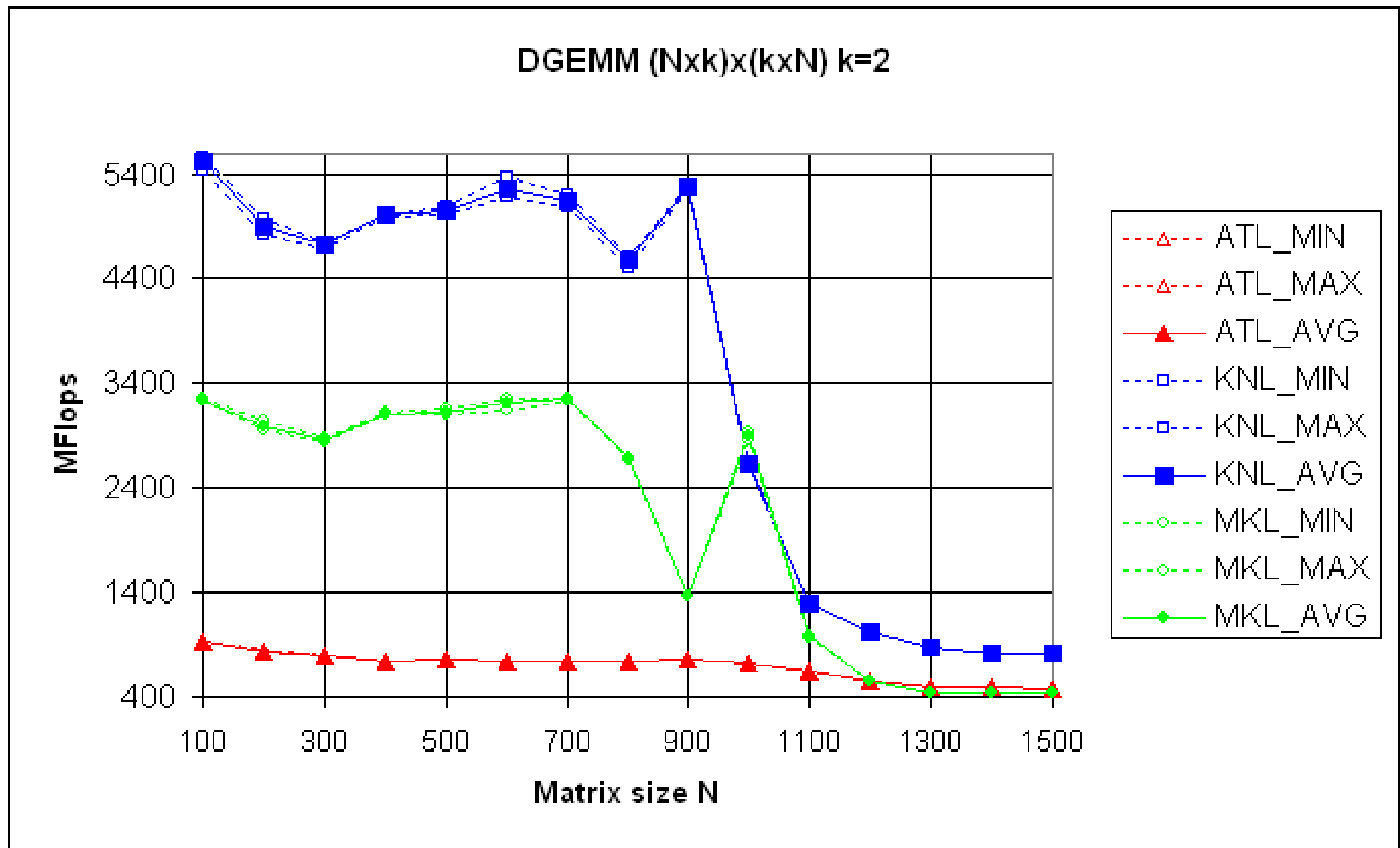
(Nx2)(2xN) DGEMM Performance



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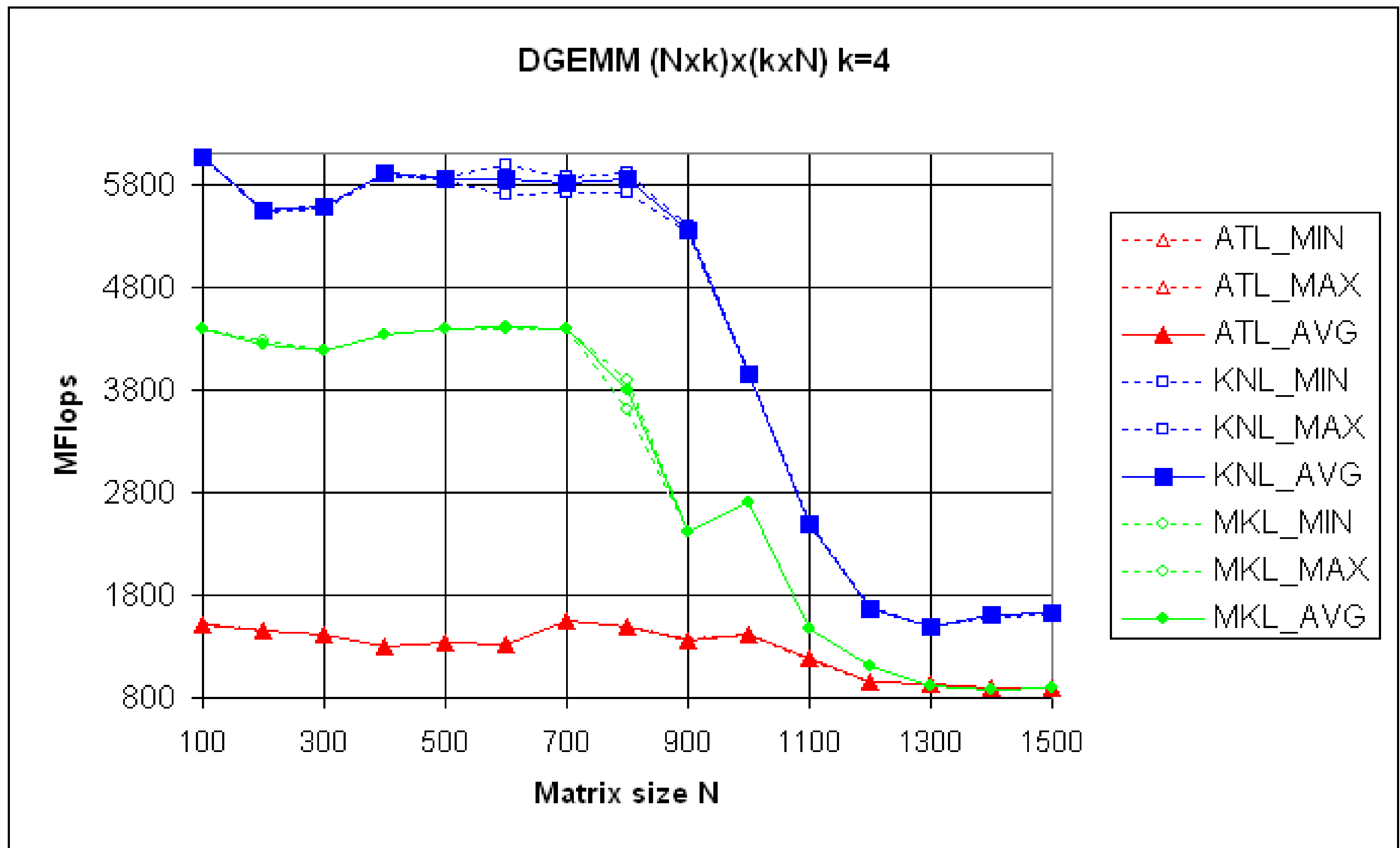
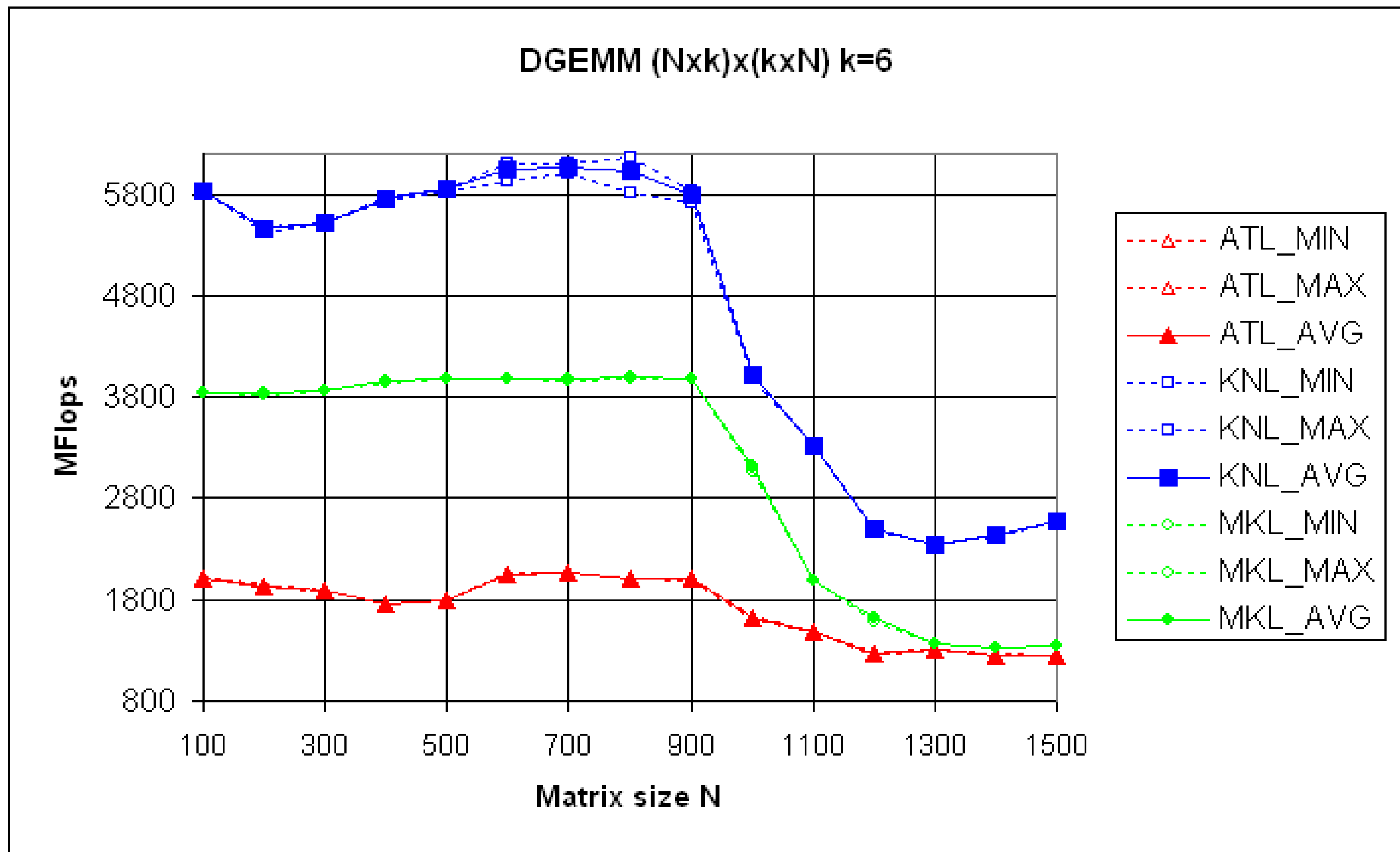
(Nx4)(4xN) DGEMM Performance



(Nx6)(6xN) DGEMM Performance



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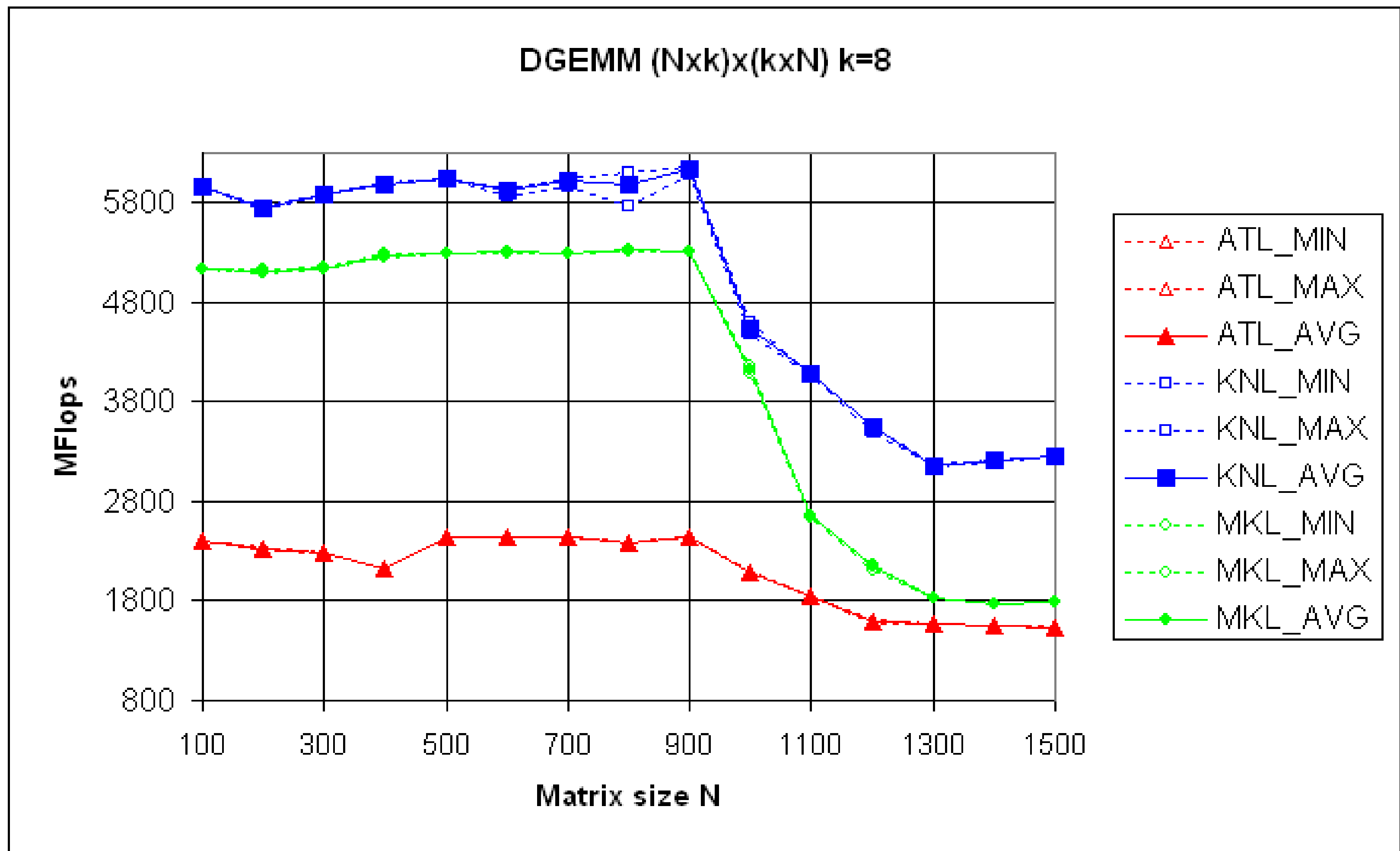
(Nx8)(8xN) DGEMM Performance



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Dealing with L2/L3

Trying to minimize systematically the number of misses is the wrong approach

- What matters is the overall cost:

  Σ miss x cost of this miss,

  where the cost is the bubbles generated

- Itanium has an interesting L3: for example computing a dot product for which one array is in L2, while the second one is in L3 is as fast as if the two operands are in L2

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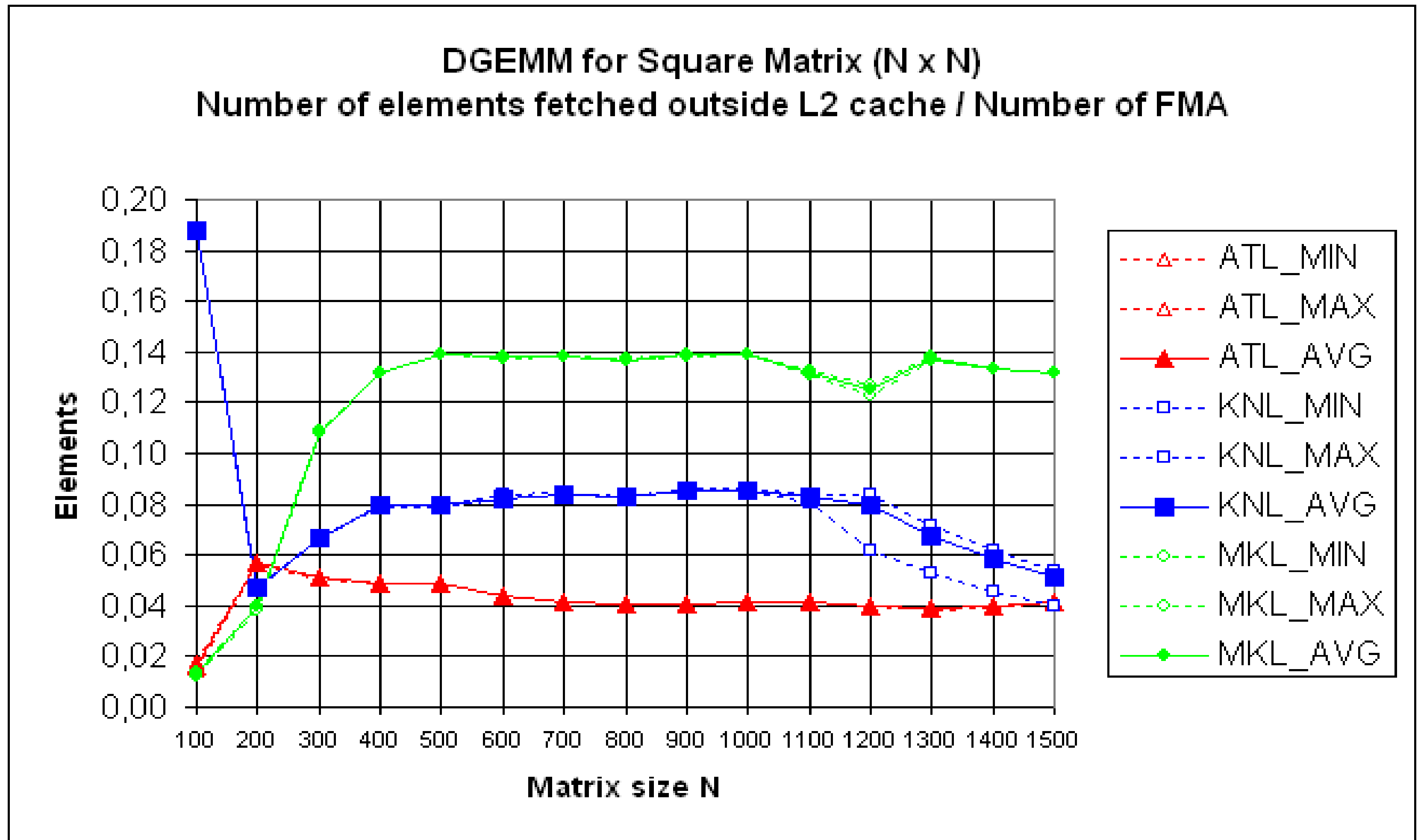
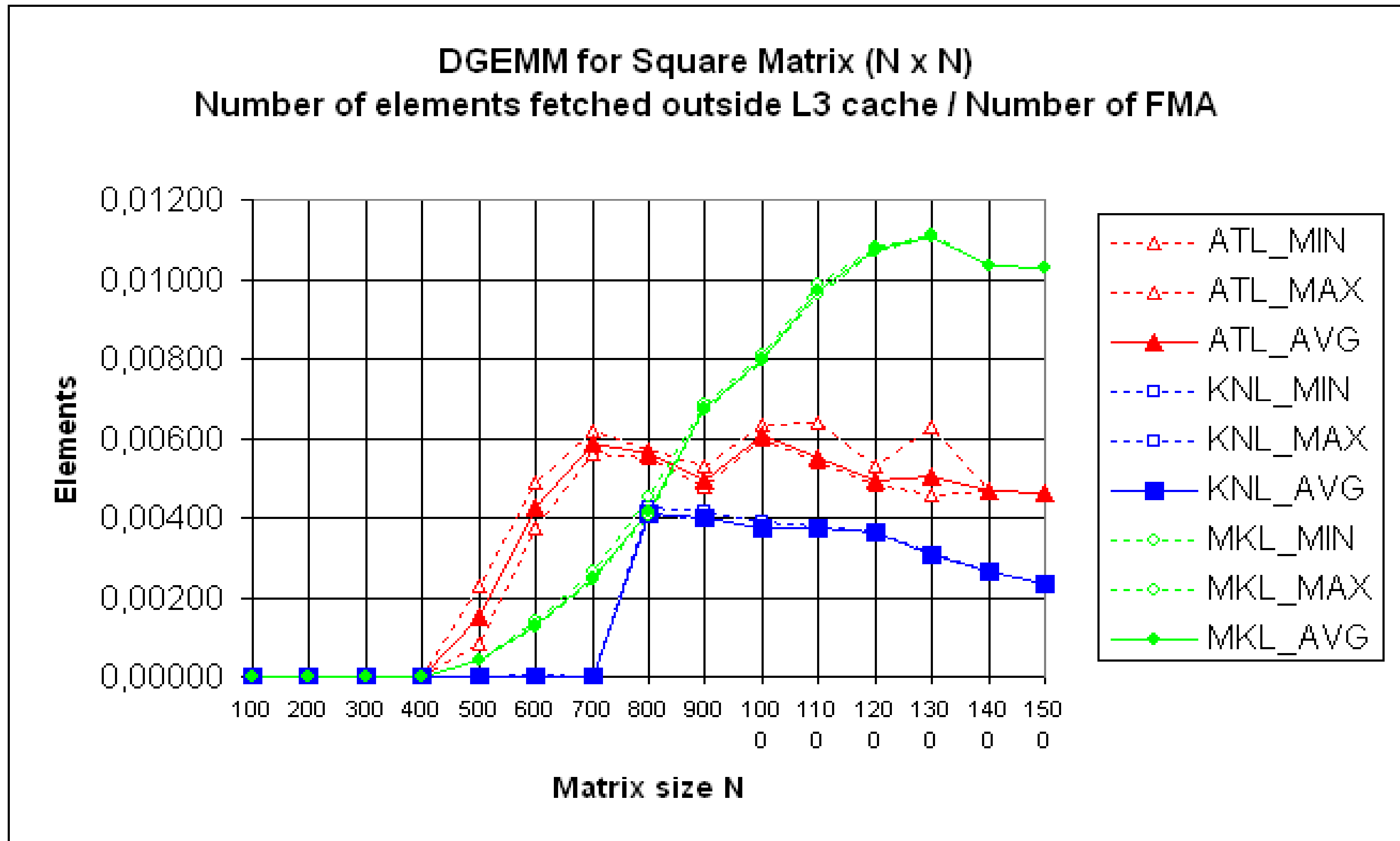
(NxN)(NxN) DGEMM L2 Behavior



DGEMM (NxN) (NxN) L3 Behavior



Stability issues

- **Performance are unstable**
  - bank conflicts
  - Load Store Queue problems
- SOLUTION: use the copy operation before each kernel

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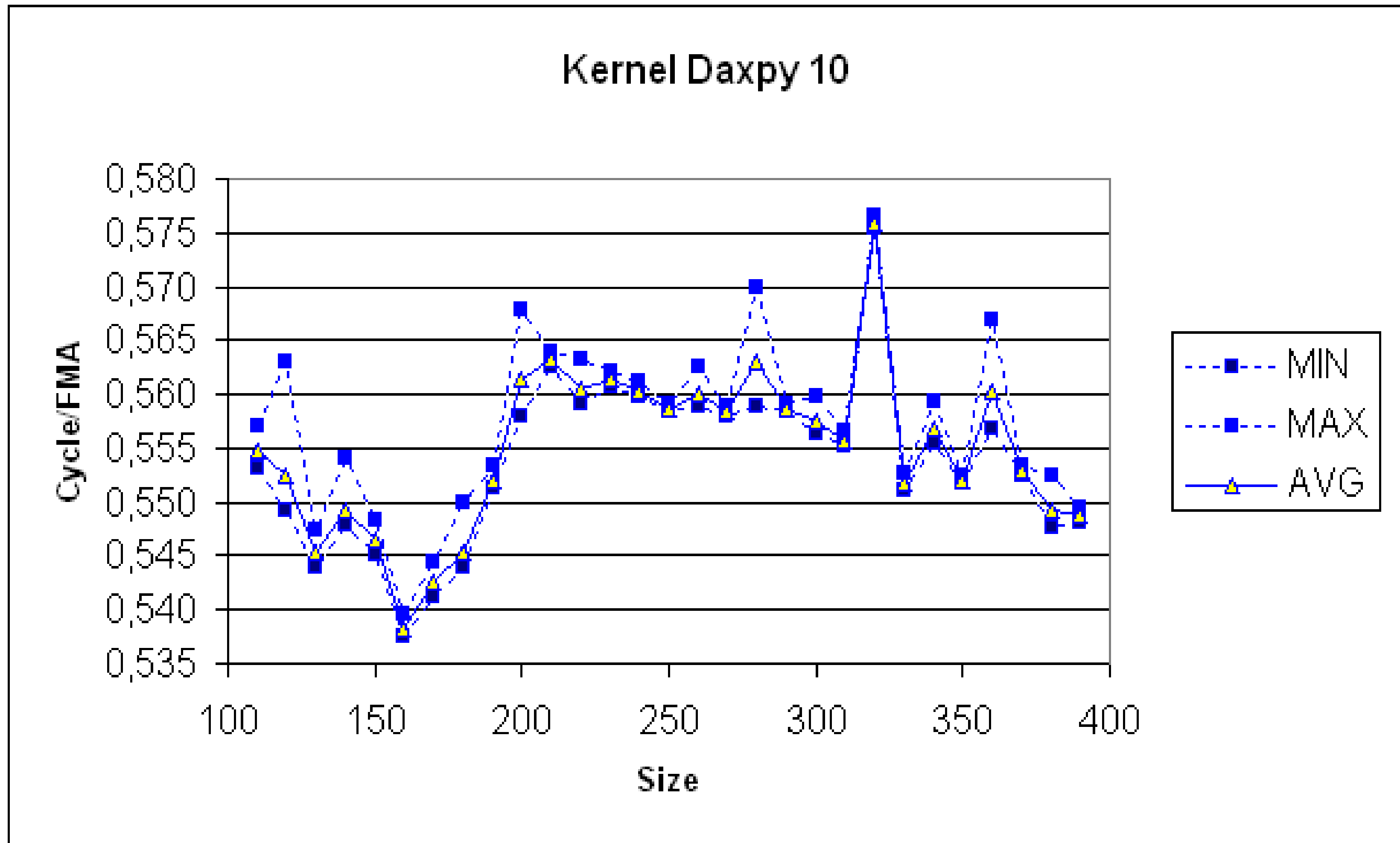
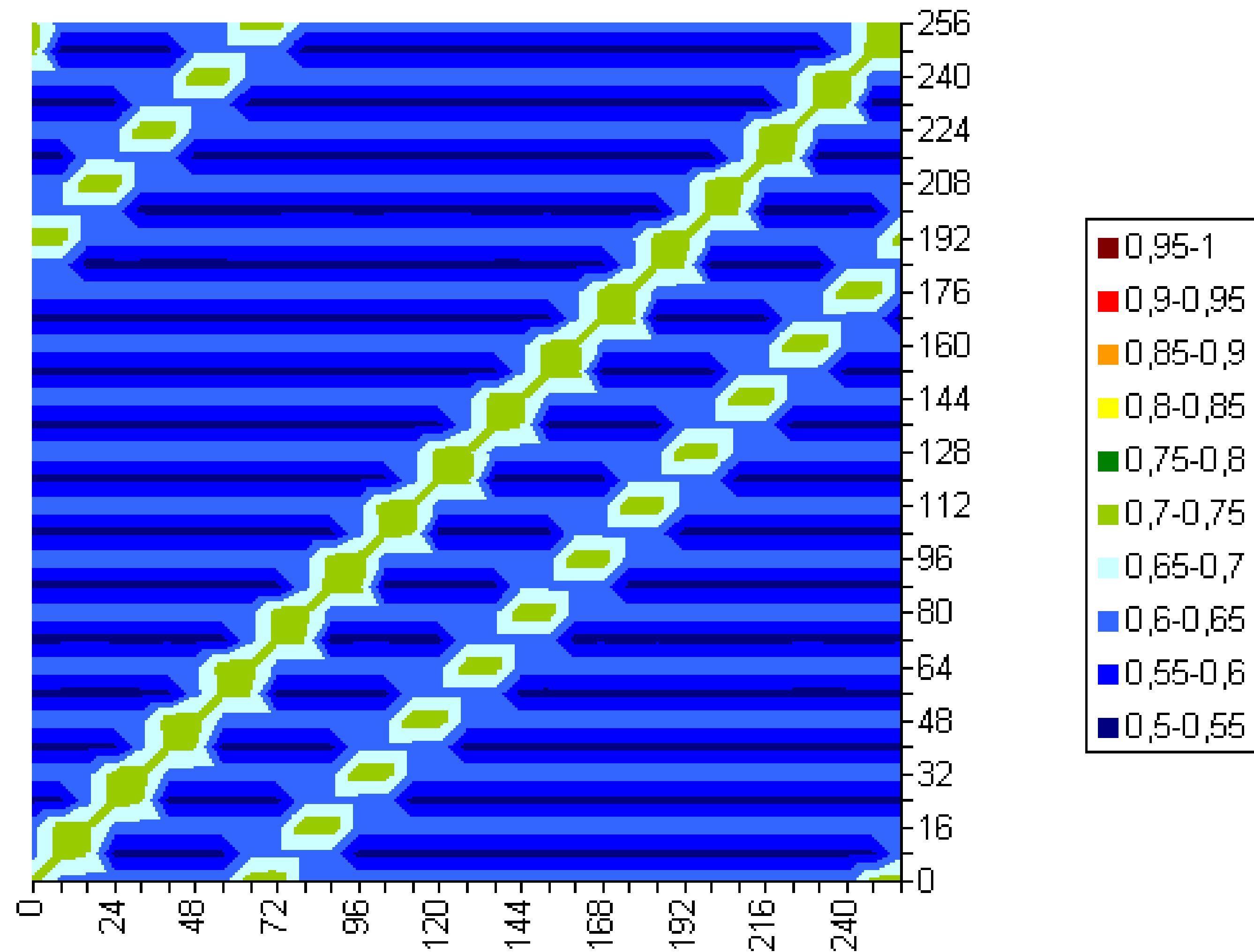
Daxpy10 Stability issues



Impact of Array Offset on Daxpy10 U2 N = 200



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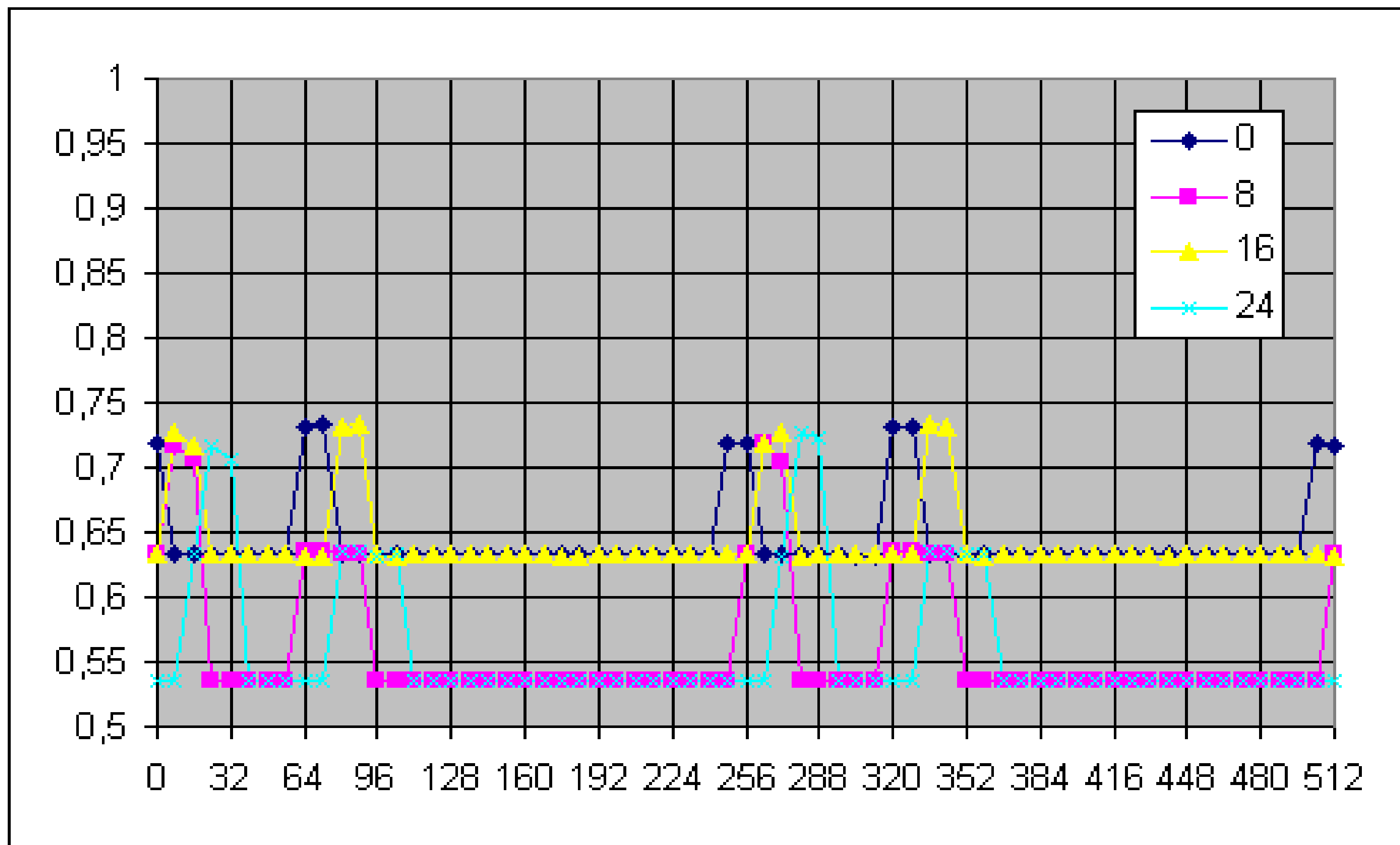
Impact of Array Offset on Daxpy10 U2 (N=200)



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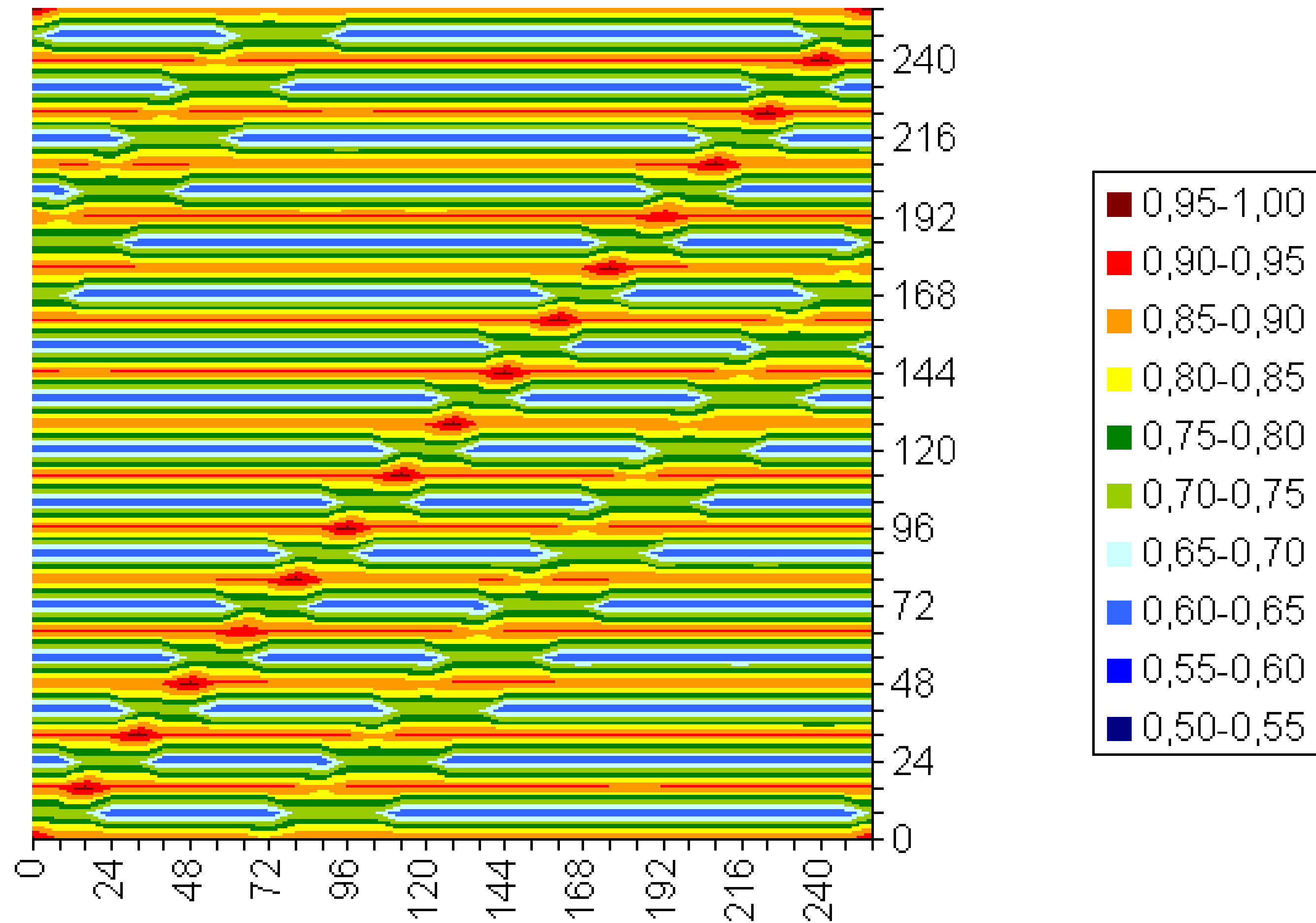
Impact of Array Offset on Daxpy10 U2 (N=800)



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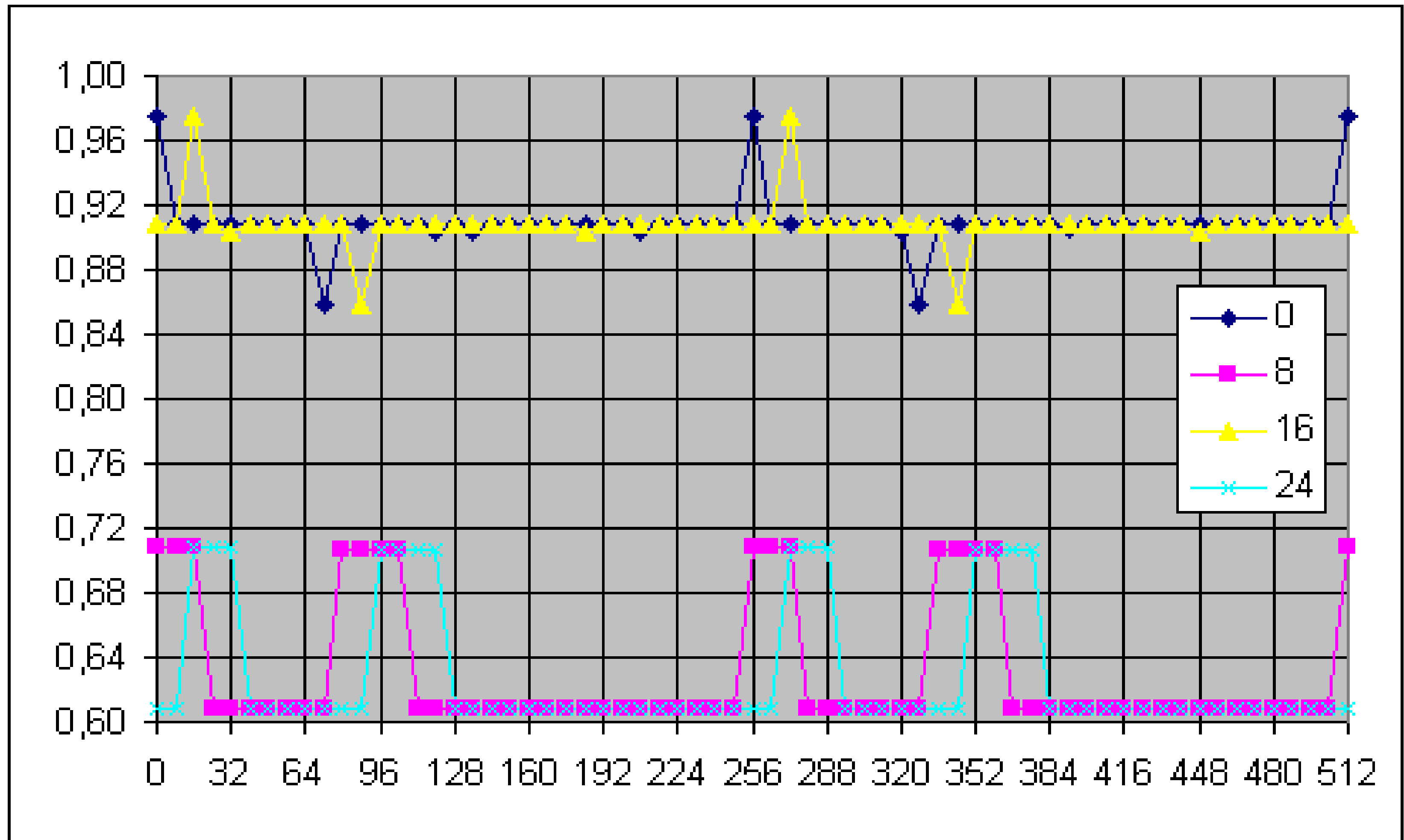
Impact of Array Offset on Daxpy10 U2 (N=800)



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Sum up for kernel decomposition

A method to generate efficient codes with source to source transformations

- Search is limited to kernels
- → Seems necessary due to complexity of hardware mechanisms at this level
- Low level optimizations taken care of by the compiler
- Still need for more complex models to reduce high level optimization search

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Perspectives

- Extend the approach to other library codes (banded case, finite difference codes)
- Apply same approach to application loop nests
- First results on Pentium confirm those on Itanium (with SSE vectorization)
- More complex high level transformations needed, as well as a performance model...

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Outline

- Exploring optimization space
  - Manually: Multistage compilation languages
  - Automatically: by search or with a model
  - Combine: Kernel decomposition
- **Feed-back guided code tuning**

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Tools for code tuning

- Performance code tuning
  - Vtune, HPCView, MAQAO...
- Why not use the expertise of these tools as feed back to limit search ?
  - first step: Ocean project, in the 90's
  - nature of feed back:
    - assessment of performance bottle neck
    - identify the limits of the compiler
    - propose optimization paths to improve performance

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MAQAO: a modular assembly code quality analyzer and optimizer

- Analysis of assembly codes
  - structures (loops, call graph,...)
  - static performance model (compiler and resource bound)
  - identify poor performance patterns
  - find optimizations applied (versioning, inlining, unrolling,...)
- Instrumentation and analyses
  - compute hotpath, value profiling (prefetch distances, bank conflicts, opportunities for versioning)

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Feed back for iterative compilation

- No execution needed
  - static analysis of assembly performance can avoid some executions
  - comparison between assemblies
- Guiding the search
  - proposing modifications (pragmas or compiler flags)
  - identifying when the code hits the limits of the compiler

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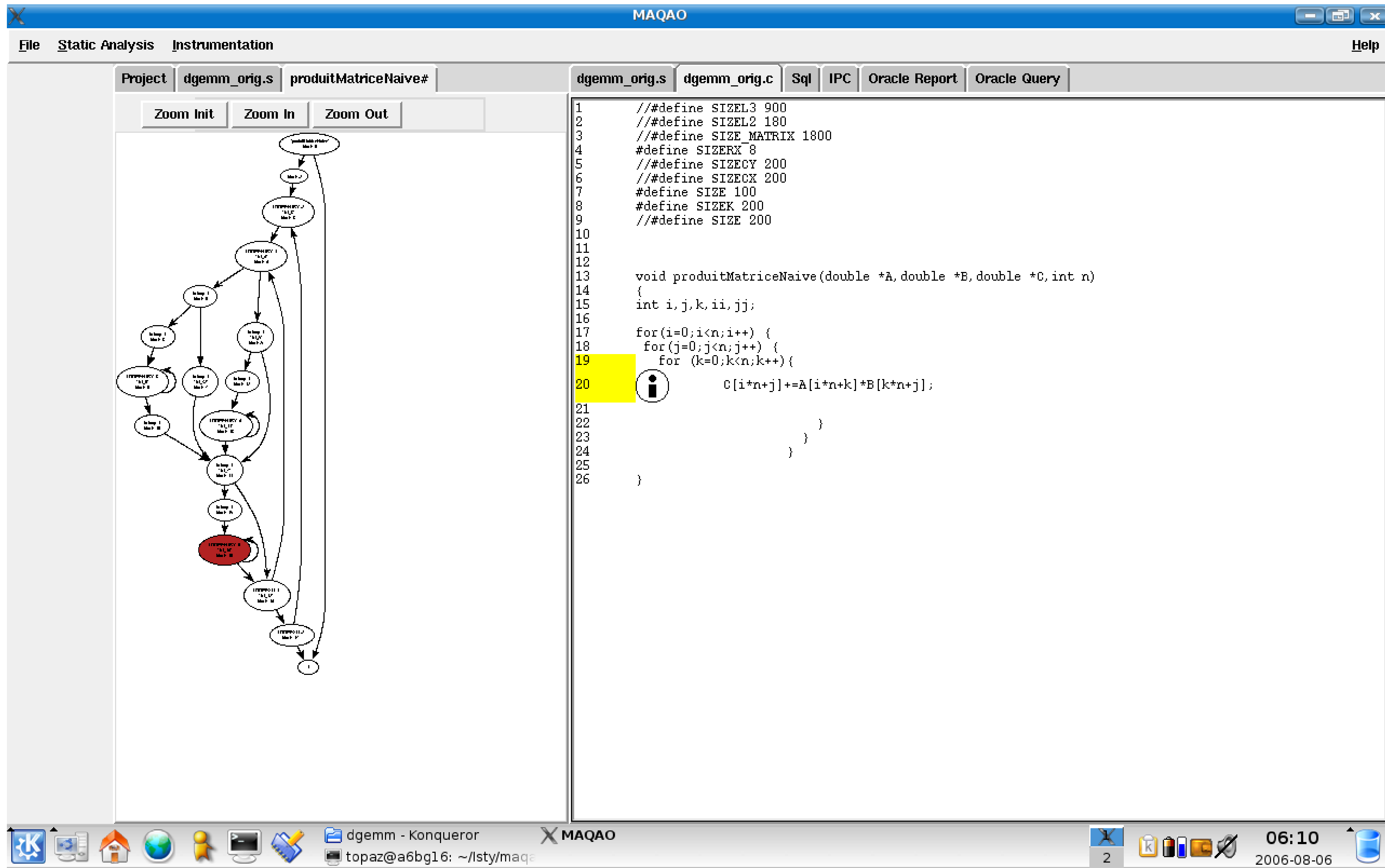
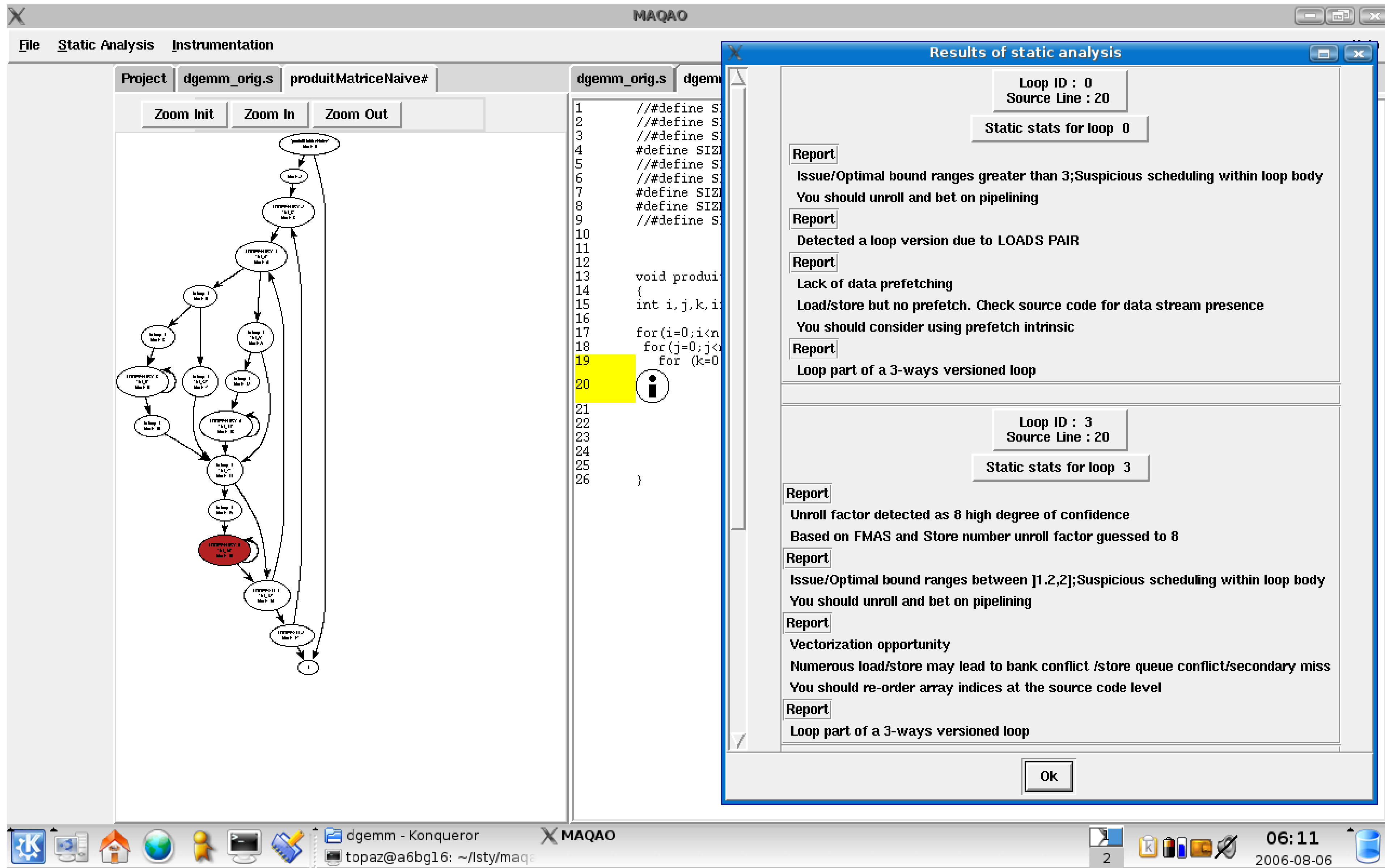
MAQAO feed back on dgemm



MAQAO feed back on dgemm



MAQAO feed back on dgemm

MAQAO

File Static Analysis Instrumentation Help

Project | dgemm_orig.s | produitMatriceNaive#

Zoom Init | Zoom In | Zoom Out

dgemm_orig.s | dgemm_orig.c | Sql | IPC | Oracle Report | Oracle Query

```
1        //#define SIZEL3 900
2        //#define SIZEL2 180
3        //#define SIZE_MATRIX 1800
4        #define SIZERX 8
5        //#define SIZECY 200
6        //#define SIZECX 200
7        #define SIZE 100
8        #define SIZEK 200
9        //#define SIZE 200
10
11
12
13       void produitMatriceNaive(double *A,double *B,double *C,int n)
14       {
15       int i,j,k,ii,jj;
16
17       for(i=0;i<n;i++) {
18        for(j=0;j<n;j++) {
19          for (k=0;k<n;k++){
20                    C[i*n+j]+=A[i*n+k]*B[k*n+j];
21
22                         }
23                       }
24                     }
25
26       }
```

Filter

Static

Loop id	Static estimated cycles	Issues/Bound ra
0	7*N	7
3	8*N + 16	1.6
4	8*N + 16	1.33

Ok

dgemm - Konqueror | MAQAO | topaz@a6bgl6: ~/lsty/maqa

06:12 2006-08-06

MAQAO feed back on dgemm

MAQAO

File Static Analysis Instrumentation Help

Project | dgemm_orig_mod.s | produitMatriceNaive#

Zoom Init | Zoom In | Zoom Out

dgemm_orig_mod.s | dgemm_orig_mod.c | Sql | IPC | Oracle Report | Oracle Query

```
1       //#define SIZEL3 900
2       //#define SIZEL2 180
3       //#define SIZE_MATRIX 1800
4       #define SIZERX 8
5       //#define SIZECY 200
6       //#define SIZECX 200
7       #define SIZE 100
8       #define SIZEK 200
9       //#define SIZE 200
10
11
12
13      void produitMatriceNaive(double **A,double **B,double **C,int n)
14      {
15      int i,j,k,ii,jj;
16
17      for(i=0;i<n;i++) {
18       for(j=0;j<n;j++) {
19         for (k=0;k<n;k++){
20             //C[i*n+j]+=A[i*n+k]*B[k*n+j];
21                  C[i][j]+=A[i][k]*B[k][j];
22
23                              }
24                            }
25                          }
26
27      }
```

images - Konqueror | MAQAO | My Way - Mozilla Firefox

otomaz@allaoua:~/dgemm | Session par défaut: file:///hc

06:24 2006-08-06

MAQAO feed back on dgemm

MAQAO

File   Static Analysis   Instrumentation   Help

Project | dgemm_orig_mod.s | produitMatriceNaive#

Zoom Init | Zoom In | Zoom Out

dgemm_orig_mod.s

```
1        //#define SIZ
2        //#define SIZ
3        //#define SIZ
4        #define SIZEF
5        //#define SIZ
6        //#define SIZ
7        #define SIZE
8        #define SIZEF
9        //#define SIZ
10
11
12
13       void produitM
14       {
15       int i,j,k,ii,
16
17       for(i=0;i<n;i
18        for(j=0;j<n;
19          for (k=0;k
20              //C[i*
21                  C
22
23
24
25
26
27       }
```

Results of static analysis

Loop ID : 2
Source Line : 21

Static stats for loop 2

Report
Issue/Optimal bound ranges greater than 3;Suspicious scheduling within loop body
You should unroll and bet on pipelining

Report
Check.s detected, possible code speculation
Speculative code may harms performance ; Check source code for while loop
You should turn off speculation

Report
Detected a loop version due to LOADS PAIR

Report
Loop part of a 3-ways versioned loop

Loop ID : 4
Source Line : 21

Static stats for loop 4

Report
Issue/Optimal bound ranges greater than 3;Suspicious scheduling within loop body
You should unroll and bet on pipelining

Report
Check.s detected, possible code speculation
Speculative code may harms performance ; Check source code for while loop
You should turn off speculation

Report
Detected a loop version due to LOADS PAIR

Report
Loop part of a 3-ways versioned loop

Ok

images - Konqueror | otomaz@allaoua:~/dgemm | MAQAO | Session par défaut: file:///hc | My Way - Mozilla Firefox | 06:25 2006-08-06

MAQAO feed back on dgemm

MAQAO

File Static Analysis Instrumentation Help

Project | dgemm_orig_mod.s | produitMatriceNaive#

Zoom Init | Zoom In | Zoom Out

dgemm_orig_mod.s | dgemm_orig_mod.c | Sql | IPC | Oracle Report | Oracle Query

```
1        //#define SIZEL3 900
2        //#define SIZEL2 180
3        //#define SIZE_MATRIX 1800
4        #define SIZERX 8
5        //#define SIZECY 200
6        //#define SIZECX 200
7        #define SIZE 100
8        #define SIZEK 200
9        //#define SIZE 200
10
11
12
13       void produitMatriceNaive(double **A,double **B,double **C,int n)
14       {
15       int i,j,k,ii,jj;
16
17       for(i=0;i<n;i++) {
18        for(j=0;j<n;j++) {
19          for (k=0;k<n;k++){
20               //C[i*n+j]+=A[i*n+k]*B[k*n+j];
21                    C[i][j]+=A[i][k]*B[k][j];
22
23                                   }
24                                 }
25                               }
26
27       }
```

Filter

Static

Loop id	Static estimated cycles	Issues/Bound ra
4	164*N	16.4
2	37*N	9.25
6	5*N	5

Ok

images - Konqueror | otomaz@allaoua:~/dgemm | MAQAO | Session par défaut: file:///hc | My Way - Mozilla Firefox | 2 | 06:25 2006-08-06

Conclusion

- Search is necessary due to complex architecture
- Possible to limit this search to lower level of optimizations and use of performance tuning tools
- Model necessary to eliminate combinatorial explosion for other transformations

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