Run-time code generation in C++ as a foundation for domain-specific optimization

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Joint work with

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Greenwich, November 200

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Mission statement

- Extend optimising compiler technology to challenging contexts beyond scope of conventional compilers
- Another talk:
  - Distributed systems:
    - Across network boundaries
    - Between different security domains
    - Maintaining proper semantics in event of failures
- Another talk:
  - Active libraries for parallel scientific applications
    - Domain-specific optimisations without a DSL
- This talk:
  - Cross-component, domain-specific optimisation in numerical scientific applications, using run-time code generation

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Performance programming

- Performance programming is the discipline of software engineering in its application to achieving performance goals
- This talk introduces one of the performance programming tools we have been exploring

Construction

- What is the role of constructive methods in performance programming?
- **“by construction”**
- **“by design”**
- How can we build performance into a software project?
- How can we build-in the means to detect and correct performance problems?
- As early as possible
- With minimal disruption to the software’s long-term value?

Abstraction

- Most performance improvement opportunities come from adapting components to their context
- So the art of performance programming is to figure out how to design and compose components so this doesn't happen
- Most performance improvement measures break abstraction boundaries
- This talk is about two ideas which can help:
  - Run-time program generation (and manipulation)
  - Metadata, characterising data structures, components, and their dependence relationships

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The TaskGraph library

- “**Multi-stage languages** internalize the notions of runtime program generation and execution”
  - I present a C++ library for multi-stage programming
- “**Metaprogramming** - writing programs which mess with the insides of other programs, eg those it has just generated”
  - That too!
- “**Invasive composition** - writing metaprograms to implement interesting component composition”
  - Future work

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- The TaskGraph library is a portable C++ package for building and optimising code on-the-fly
- Compare:
  - `C (tcc) (Dawson Engler)
  - MetaOCaml (Walid Taha et al)
  - Jak (Batory, Lofaso, Smaragdakis)
- But there's more…

```
#include <TaskGraph>
#include <stdio.h>
#include <stdlib.h>
#include <sys/time.h>

using namespace tg;

int main() {
  int c = 1;
  TaskGraph < Par < int, int >, Ret < int > > T;
  taskgraph( T, tuple2(x, y) ) {
    tReturn( x + y + c );
  }
  T.compile( tg::GCC );
  int a = 2;
  int b = 3;
  printf( "a+b+c = %d\n", T.execute( a, b ) );
}
```

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- A taskgraph is an abstract syntax tree for a piece of executable code
- Syntactic sugar makes it easy to construct
- Defines a simplified sub-language
  - With first-class multidimensional arrays, no alliasing

```
#include <TaskGraph>
#include <stdio.h>
#include <stdlib.h>
#include <sys/time.h>
using namespace tg;
int main() {
  int c = 1;
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  }
  T.compile( tg::GCC );
  int a = 2;
  int b = 3;
  printf( "a+b+c = %d\n", T.execute( a, b ) );
}
```
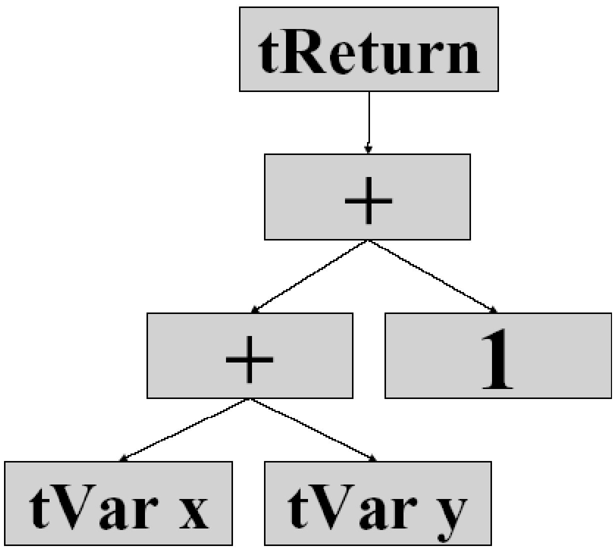

- Binding time is determined by types
- In this example
  - c is static
  - x and y dynamic



- built using value of c at construction time

```
#include <TaskGraph>
#include <stdio.h>
#include <stdlib.h>
#include <sys/time.h>

using namespace tg;

int main() {
  int c = 1;
  TaskGraph < Par < int, int >, Ret < int > > T;
  taskgraph( T, tuple2(x, y) ) {
    tReturn( x + y + c );
  }
  T.compile( tg::GCC );
  int a = 2;
  int b = 3;
  printf( "a+b+c = %d\n", T.execute( a, b ) );
}
```

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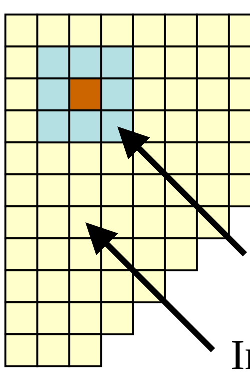
Better example:

- Applying a convolution filter to a 2D image
- Each pixel is averaged with neighbouring pixels weighted by a stencil matrix




```
void filter (float *mask, unsigned n, unsigned m,
                const float *input, float *output,
                unsigned p, unsigned q)
{
  unsigned i, j;
  int      k, l;
  float    sum;
  int half_n = (n/2);
  int half_m = (m/2);

  for (i = half_n; i < p - half_n; i++) {
    for (j = half_m; j < q - half_m; j++) {
      sum = 0;
           // Loop bounds unknown at compile-time
           // Trip count 3, does not fill vector registers
      for (k = -half_n; k <= half_n; k++)
        for (l = -half_m; l <= half_m; l++)
          sum += input[(i + k) * q + (j + l)]
                 * mask[k * n + l];

      output[i * q + j] = sum;
    }
  }
}
```

- TaskGraph representation of this loop nest
- Inner loops are static – executed at construction time
- Outer loops are dynamic
- Uses of mask array are entirely static
- This is deduced from the types of mask, k, m and l.

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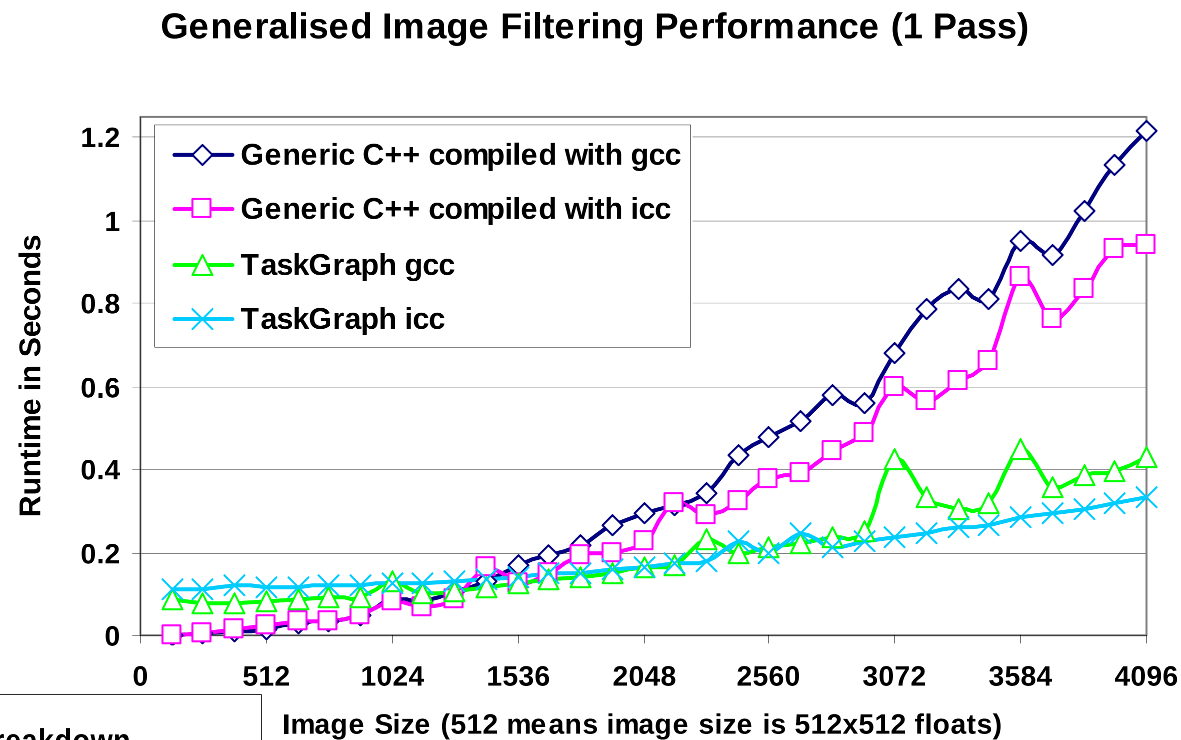
```
void specialize_convolution(
  TaskGraph < Par <float[IMG_SIZE][IMG_SIZE],
                   float[IMG_SIZE][IMG_SIZE]>,
             Ret < void > > &T,
  const int IMGSZ, const int CSZ, const float *mask )
{
  int ci, cj;
  assert( CSZ % 2 == 1 );
  const int c_half = ( CSZ / 2 );
  taskgraph( T, tuple2(tgimg, new_tgimg) ) {
    tVar ( int, i );
    tVar ( int, j );
    // Loop iterating over image
    tFor( i, c_half, IMGSZ - (c_half + 1) ) {
      tFor( j, c_half, IMGSZ - (c_half + 1) ) {
        new_tgimg[i][j] = 0.0;
        // Loop to apply convolution mask
        for( ci = -c_half; ci <= c_half; ++ci ) {
          for( cj = -c_half; cj <= c_half; ++cj) {
            new_tgimg[i][j] +=
              tgimg[i+ci][j+cj] * mask[c_half+ci][c_half+cj];
          } } } }
  }
}
```

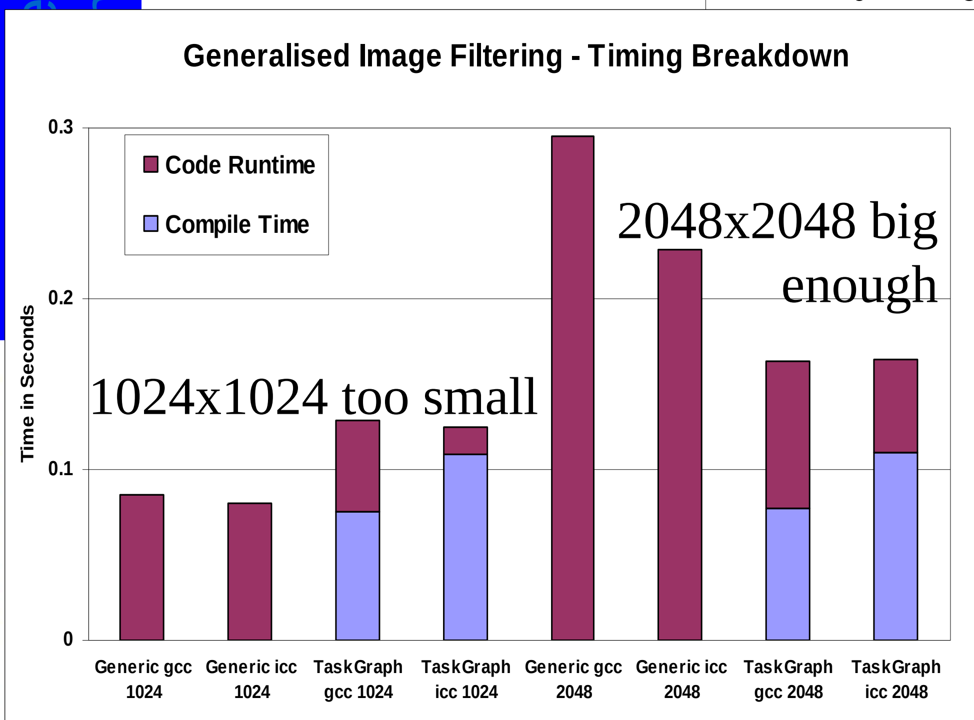
// Inner loops fully unrolled

// j loop is now vectorisable

--\-- Convolution.cc   (C++)--L4--All------------------

Image convolution using TaskGraphs: performance





- We use a 3x3 averaging filter as convolution matrix
- Images are square arrays of single-precision floats ranging in size up to 4096x4096
- Measurements taken on a 1.8GHz Pentium 4-M running Linux 2.4.17, using gcc 2.95.3 and icc 7.0
- Measurements were taken for one pass over the image

(Used an earlier release of the TaskGraph library)

Domain-specific optimisation

- The TaskGraph library is a tool for dynamic code generation and optimisation
- Large performance benefits can be gained from specialisation alone

But there's more:

- TaskGraph library builds SUIF intermediate representation
- Provides access to SUIF analysis and transformation passes
  - SUIF (Stanford University Intermediate Form)
  - Detect and characterise dependences between statements in loop nests
  - Restructure – tiling, loop fusion, skewing, parallelisation etc

Tiling

Example: matrix multiply

```
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typedef float MatrixType[MATRIXSIZE][MATRIXSIZE];
typedef TaskGraph< Par<MatrixType, MatrixType, MatrixType>,
                   Ret<void> > mm_TaskGraph;
float MatrixType a, b, c;

void taskMatrixMult (
  mm_TaskGraph &t,
  TaskLoopIdentifier *loop )
{
  taskgraph ( t, tuple3(a, b, c) ) {
    tVar ( int, x );
    tVar ( int, y );
    tVar ( int, z );

    tGetId ( loop[0] ); // label
    tFor ( x, 0, MATRIXSIZE - 1 ) {
      tGetId ( loop[1] ); // label
      tFor ( z, 0, MATRIXSIZE - 1 ) {
        tGetId ( loop[2] ); // label
        tFor ( y, 0, MATRIXSIZE - 1 ) {
          c[x][y] += a[x][z] * b[z][y];
        }}}}}
--\--  MM.cc          (C++)--L5--Top--
```

Original TaskGraph for matrix multiply

```
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main () {
  int bestTime; int bestSize = 0;
  for (int tsz = 4; tsz <= MATRIXSIZE; ++tsz) {
    int trip3 = { tsz, tsz, tsz };
    TaskLoopIdentifier loop[3];
    mm_TaskGraph MM;

    taskMatrixMult(loop, MM);
    interchangeLoops(loop[1], loop[2]);
    tileLoop(3, &loop[0], trip3);

    MM.compile(TaskGraph::ICC);

    tt3 = time_function();
    MM.execute(A, B, C);
    time = time_function()-tt3;

    if (time < bestTime || bestSize == 0) {
      bestTime = time; bestSize = tsz;
    }}}
--\--  MM.cc          (C++)--L38--Bot--------
```

Loop tries all tile sizes and finds fastest

Loop interchange and tiling

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```
typedef float MatrixType[MATRIXSIZE][MATRIXSIZE];
typedef TaskGraph< Par<MatrixType, MatrixType, MatrixType>,
                   Ret<void> > mm_TaskGraph;
float MatrixType a, b, c;

void taskMatrixMult (
  mm_TaskGraph &t,
  TaskLoopIdentifier *loop )
{
  taskgraph ( t, tuple3(a, b, c) ) {
    tVar ( int, x );
    tVar ( int, y );
    tVar ( int, z );

    tGetId ( loop[0] ); // label
    tFor ( x, 0, MATRIXSIZE - 1 ) {
      tGetId ( loop[1] ); // label
      tFor ( z, 0, MATRIXSIZE - 1 ) {
        tGetId ( loop[2] ); // label
        tFor ( y, 0, MATRIXSIZE - 1 ) {
          c[x][y] += a[x][z] * b[z][y];
        }}}}}

main () {
  int bestTime; int bestSize = 0;
  for (int tsz = 4; tsz <= MATRIXSIZE; ++tsz) {
    int trip3 = { tsz, tsz, tsz };
    TaskLoopIdentifier loop[3];
    mm_TaskGraph MM;

    taskMatrixMult(loop, MM);
    interchangeLoops(loop[1], loop[2]);
    tileLoop(3, &loop[0], trip3);

    MM.compile(TaskGraph::ICC);

    tt3 = time_function();
    MM.execute(A, B, C);
    time = time_function()-tt3;

    if (time < bestTime || bestSize == 0) {
      bestTime = time; bestSize = tsz;
    }}}
```

--\-- MM.cc (C++)--L24--All--------------------

```
extern void taskGraph_1(void **params)
{
  float (*a)[512];
  float (*b)[512];
  float (*c)[512];
  int i;
  int j;
  int k;
  int j_tile;
  int k_tile;

  a = *params;
  b = params[1];
  c = params[2];
  for (i = 0; i <= 511; i++)
    for (j_tile = 0; j_tile <= 511; j_tile += 64)
      for (k_tile = 0; k_tile <= 511; k_tile += 64)
        for (j = j_tile;
                j <= min(511, 63 + j_tile); j++)
          for (k = max(0, k_tile);
                  k <= min(511, 63 + k_tile); k++)
            c[i][k] = c[i][k] + a[i][j] * b[j][k];
}
```

- Generated code

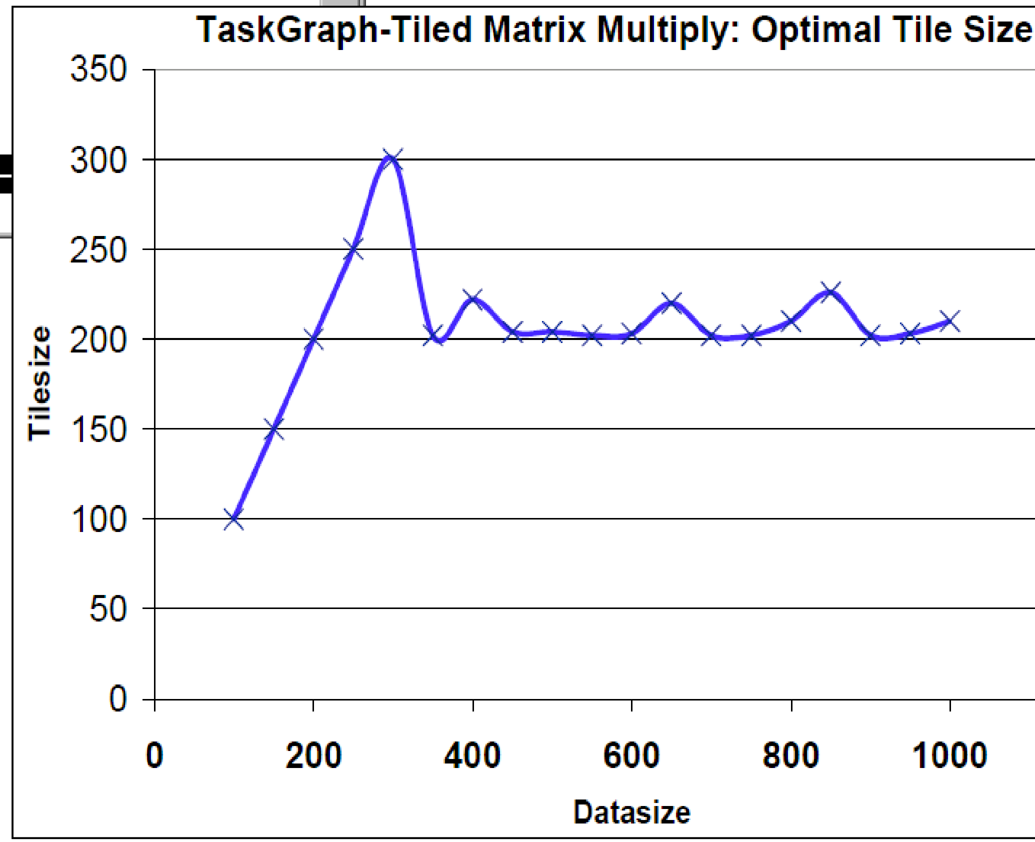
  (Slightly tidied)

Adapting to platform/resources

```
int bestTime;
int bestSize = 0;
for (int tsz = 4; tsz <= MATRIXSIZE; ++tsz) {
  int trip3 = { tsz, tsz, tsz };
  TaskLoopIdentifier loop[3];
  TaskGraph MM;
  taskMatrixMult(loop, MM);
  interchangeLoops(loop[1], loop[2]);
  tileLoop(3, &loop[0], trip3);
  MM.compile(TaskGraph::ICC, false);
  tt3 = time_function();
  MM.execute("A",A, "B",B, "C",C, NULL);
  time = time_function()-tt3;
  if (time < bestTime || bestSize == 0) {
    bestTime = time; bestSize = tsz;
  }
}
```

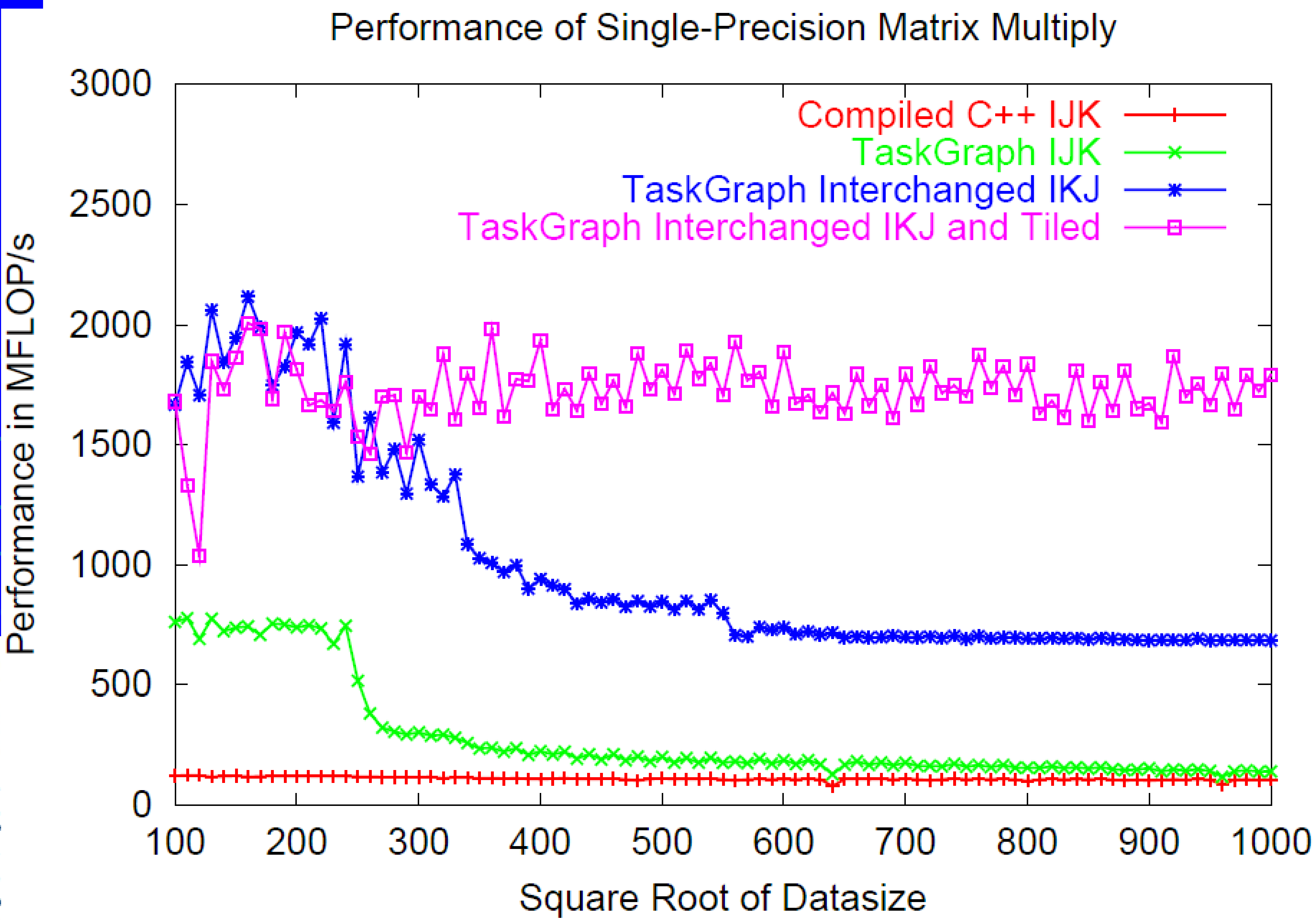
--\-- IterativeMM.cc   (C++)--L2-- 2%---

- We can program a search for the best implementation for our particular problem size, on our particular hardware

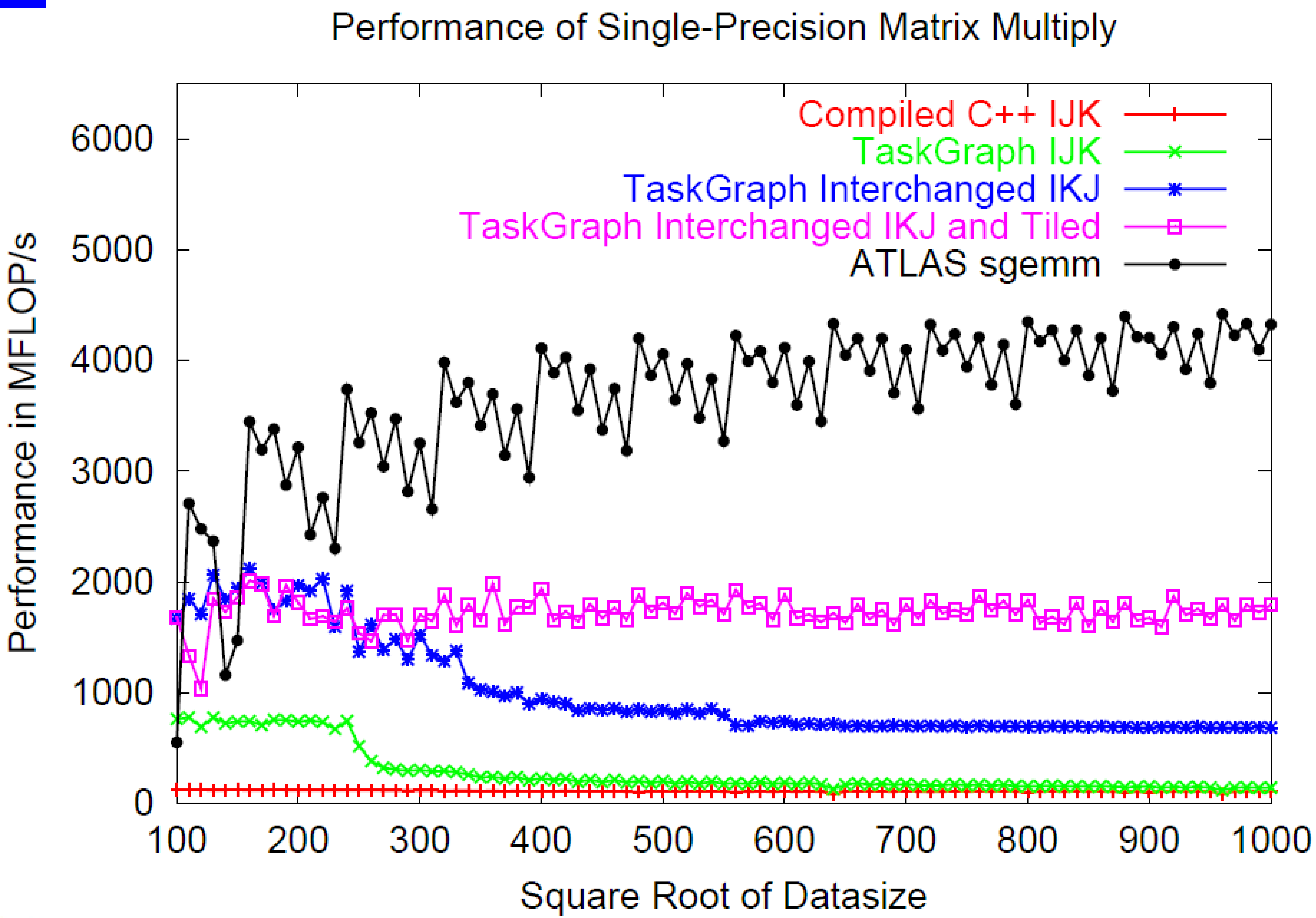


On Pentium 4-M, 1.8 GHz, 512KB L2 cache, 256 MB, running Linux 2.4 and icc 7.1.

Adapting to platform/resources



Adapting to platform/resources



Potential for user-directed restructuring

- Programmer controls application of sophisticated transformations
- Performance benefits can be large – in this example >8x
- Different target architectures and problem sizes need different combinations of optimisations
  - ijk or ikj?
  - Hierarchical tiling
  - 2d or 3d?
  - Copy reused submatrix into contiguous memory?
- Matrix multiply is a *simple* example

Cross-component loop fusion

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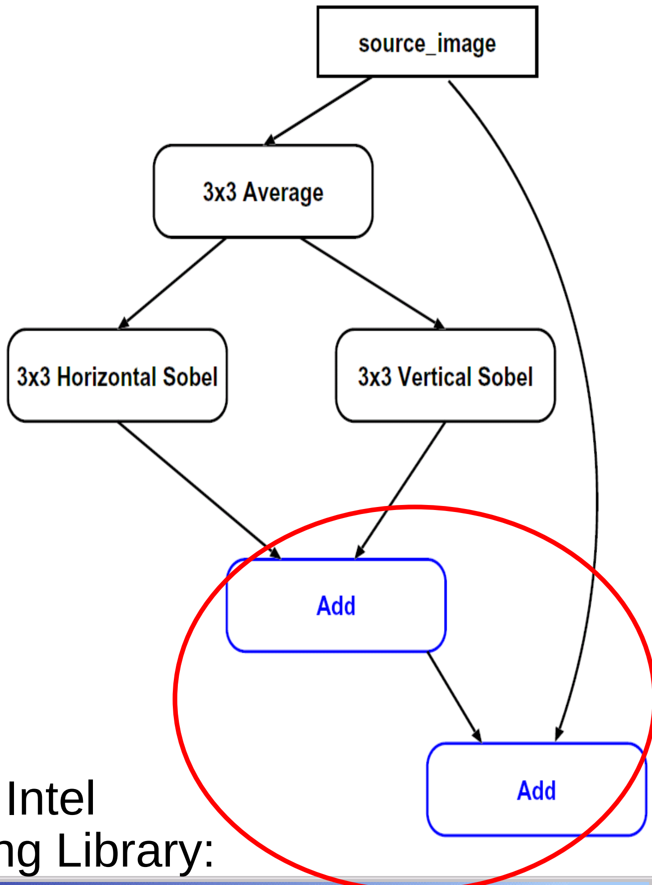
```
  TaskGraph T;
  taskgraph( T ) {
    unsigned int ds[] = fsz, szg;
    tParameter(tArrayFromList(float, dstimg, 2, ds));
    tParameter(tArrayFromList(float, srcimg, 2, ds));
    tArrayFromList( float, blur , 2, ds );
    // ...
    instantiateBlur (blur , srcimg, i , j , sz, sz , 3);
    instantiateSobelHoriz(horiz , blur , i , j , sz, sz);
    instantiateSobelVert (vert , blur , i , j , sz, sz);
    instantiateAdd(both, vert , horiz , i , j , sz, sz);
    instantiateAdd(dstimg, blur , both, i , j , sz, sz);
  }
  T.applyOptimisation ("fusion");
  T.compile(TaskGraph::ICC, true);
  T.execute("dstimg", result , "srcimg" , image, NULL);
}
--\--  Filter.cc          (C++)--L10--Bot-----------------
```



- Image processing example
- Blur, edge-detection filters then sum with original image
- Final two additions using Intel Performance Programming Library:

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```
  // Ipp Domain Specific Library
  ippiAdd_32f_C1R( horiz, length , vert , length,
                   both, length , whole );
  ippiAdd_32f_C1R( image, length, both, length,
                   result , length , whole );

--\--  FilterIPP.cc       (C++)--L5--All----------
```

Cross-component loop fusion

```
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// TaskGraph Generated Code
  for ( i = 0; i <= 1199; i++) {
    for ( j = 0; j <= 1599; j++) {
      both[ i ][ j ] = vert [ i ][ j ] + horiz [ i ][ j ];
    }
  }
  for ( i = 0; i <= 1199; i++) {
    for ( j = 0; j <= 1599; j++) {
      tgimage[i ][ j ] = blur [ i ][ j ] + both[ i ][ j ];
    }
  }
}
--\--  FilterGenerated.cc      (C++)--L2--Bot-------------
```

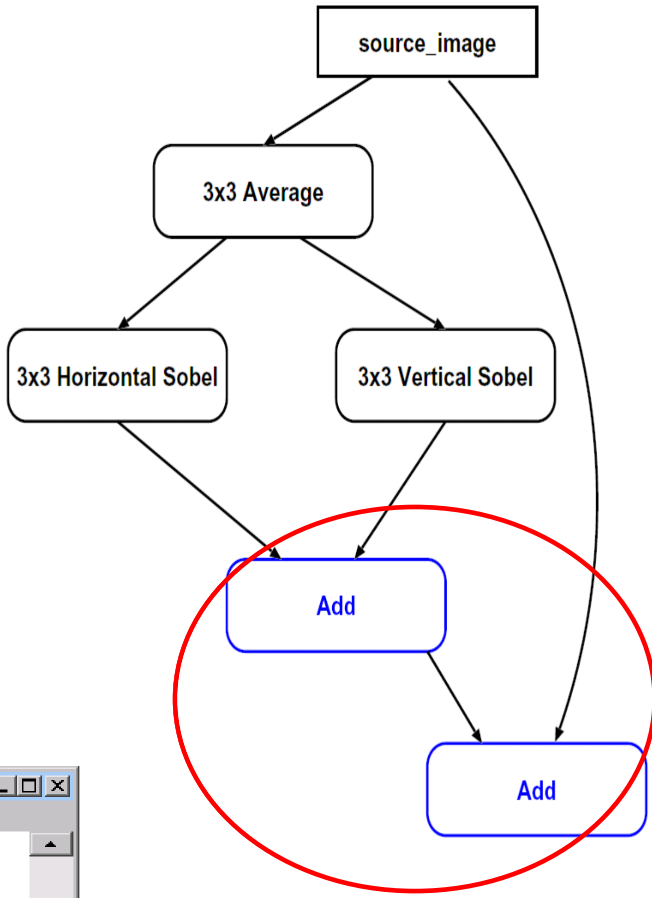

- After loop fusion:

```
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// TaskGraph Optimised Generated Code
  for ( i = 0; i <= 1199; i++) {
    for ( j = 0; j <= 1599; j++) {
      both[ i ][ j ] = vert [ i ][ j ] + horiz [ i ][ j ];
      tgimage[i ][ j ] = blur [ i ][ j ] + both[ i ][ j ];
    }
  }
}
--\--  FilterGenerated.cc      (C++)--L16--Bot------------
```
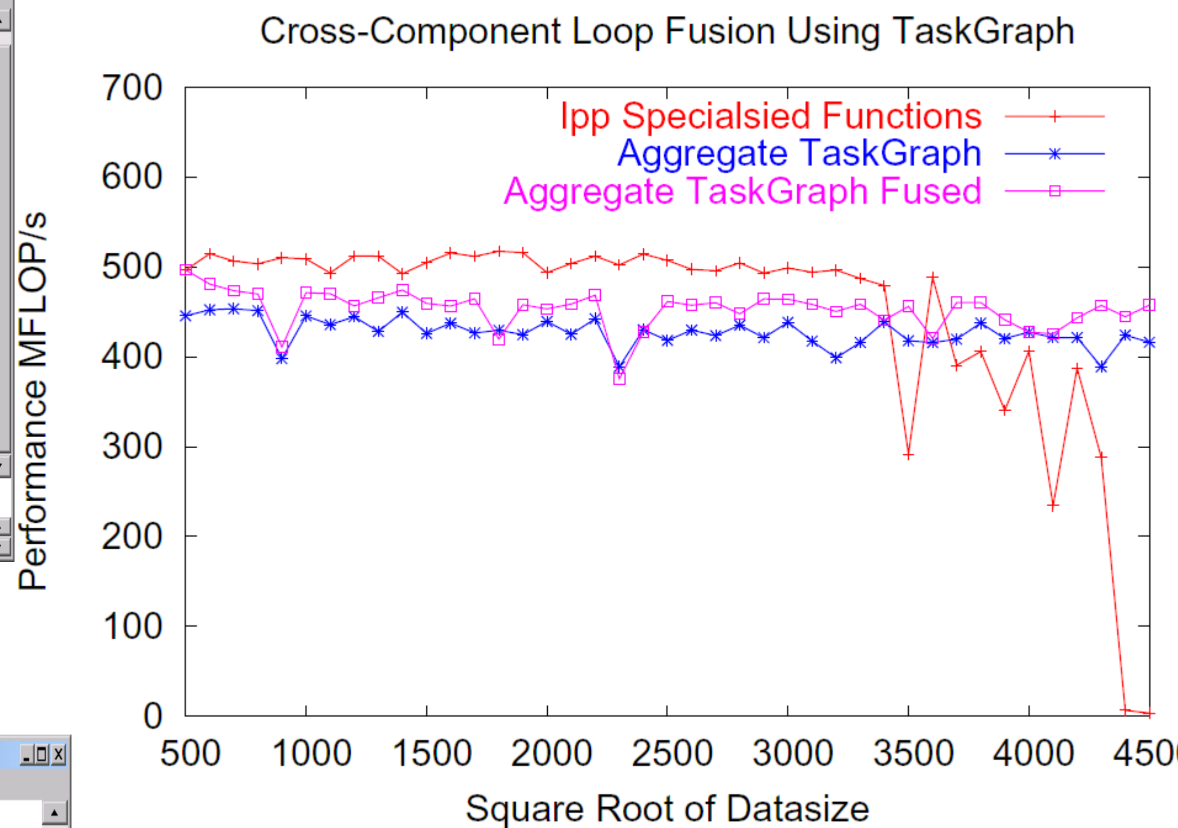

Cross-component loop fusion

```
// TaskGraph Generated Code
for ( i = 0; i <= 1199; i++) {
  for ( j = 0; j <= 1599; j++) {
    both[ i ][ j ] = vert [ i ][ j ] + horiz [ i ][ j ];
  }
}
for ( i = 0; i <= 1199; i++) {
  for ( j = 0; j <= 1599; j++) {
    tgimage[i ][ j ] = blur [ i ][ j ] + both[ i ][ j ];
  }
}
}
--\--  FilterGenerated.cc      (C++)--L2--Bot------------
```



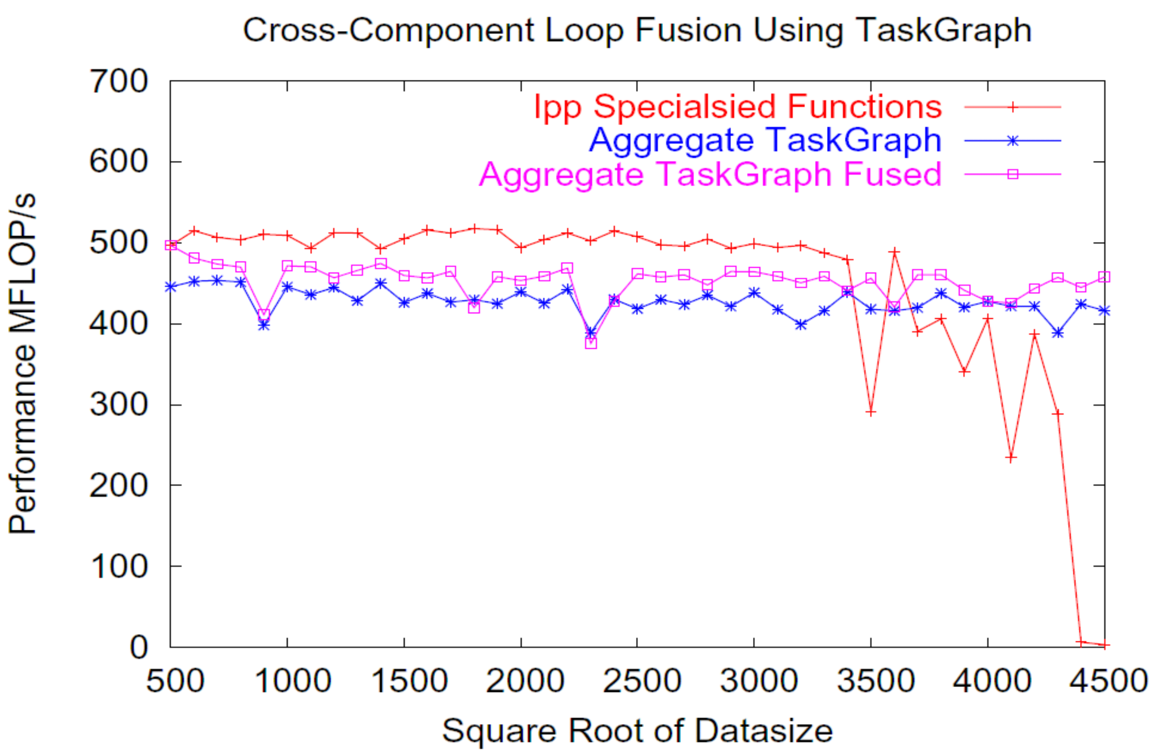
After loop fusion:

```
// TaskGraph Optimised Generated Code
for ( i = 0; i <= 1199; i++) {
  for ( j = 0; j <= 1599; j++) {
    both[ i ][ j ] = vert [ i ][ j ] + horiz [ i ][ j ];
    tgimage[i ][ j ] = blur [ i ][ j ] + both[ i ][ j ];
  }
}
}
--\--  FilterGenerated.cc      (C++)--L16--Bot------------
```

- Simple fusion leads to small improvement
- Beats Intel library only on large images
- Further fusion opportunities require skewing/retiming

Performance metadata informs cross-component optimisation

- We know we *can* fuse the two image addition loops
- However our performance results show this is only sometimes faster
  - For small images it's faster to call the Intel Performance library functions one-at-a-time
  - On this machine, fusion is a huge benefit – but only for images > 4000x4000



- How can we tell what to do?
  - Could use static rule "on a Pentium4 fuse if size >4000"
  - Could experiment at runtime, measure whether fusion is faster, roll-back if not
  - Could use hardware performance counters – if TLB and L2 cache miss rate are low, fusion unlikely to win

Conclusions

- TaskGraph library delivers run-time code generation (as found in `C, Jak, MetaOCaml etc) as a library, rather than a language extension
- SUIF offers the metaprogrammer full power of a restructuring compiler
- Aggressive compiler techniques can be especially effective:
  - The TaskGraph language is simple and clean
  - TaskGraphs are usually small
  - Compilation effort can be directed by the programmer
  - Domain knowledge can direct the focus and selection of optimisations
  - Programmers can build and share domain-specific optimisation components
- Domain-specific optimisation components have lots of potential

Restructuring loops by metaprogramming

- The taskgraph library is still at the prototype stage
- We have ambitious plans for this work:
  - Combining specialisation with dependence analysis and restructuring
    - cf inspector-executor
  - Domain-specific optimisation components
    - Build collection of optimisation components specialised to computational kernels of particular kinds
    - Eg stencil loops (Jacobi, red-black, Gauss-Seidel etc)
  - Combine
    - domain-specific information (eg algebraic properties of tensor operators)
    - Problem-specific information (eg sizes and shapes of data)
    - Context-specific information (the application's control and data dependence structure)

TaskGraph – open issues...

- Types
  - TaskGraph library currently limited to scalars+arrays. How can we use calling program's data types, in an efficient and type safe way?
  - How can we check that the generated code is being used in a safe way?
- Compilation overhead
  - Building and compiling small code fragments takes ~100ms. Mostly in C compiler (not TGL or SUIF). This is a major problem in some applications, eg JIT
- Metaprogramming API
  - Much more work is needed on designing a flexible representation of the dependence information we have (or need) about a TaskGraph (eg Dan Quinlan's ROSE)
  - Fundamental issue is to make metadata smaller than the data
- Introspection and naming
  - Need to think more about how a metaprogrammer refers to the internal structures of the subject code – "which loop did I mean?"

Domain-specific optimisation – open issues

- Domain-specific *optimisation* is surprisingly hard to find
- Domain-specific information is hard to use
  - How to capture a software component's characteristics, so that the component can be optimised to its context (or mode) of use.
  - How to represent the space of possible optimisation alternatives for a component, so that the best combination of optimisations can be chosen when the component is used.
  - How to represent the relevant internal structure of a component so that domain-specific optimisations can be implemented at a sufficiently abstract level to be re-usable and easy to construct.

Components for performance programming

- Component's functional interface
- Component's adaptation interface
- Component metadata
  - Characterizes how the component can adapt
  - Provides performance model
  - Provides elements from which composite optimisation formulation can be assembled
- Composition metaprogramming
  - Uses components' metadata to find optimal composite configuration
  - Uses component adaptation interfaces to implement it
  - May also deploy and use instrumentation to refine its decision

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