ATLAS Offline Software
Performance Monitoring and Optimization

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ATLAS

THE UNIVERSITY OF IOWA

Contents

Why do we need software performance improvements?

- LHC will run again in 2015 with:
  - ATLAS trigger rate: $\sim 1\,\mathrm{kHz}$ (2012: $\lesssim 400\,\mathrm{Hz}$)
  - 14 TeV and 25 ns bunch spacing
  - average 25 to 40 interactions per bunch crossing
- For reconstruction software:
  - processing time per event needs to be improved substantially
  - memory consumption needs to be decreased
- Several projects for speed improvement are in progress
- Performance studies of two of these projects will be discussed here

Performance measurements

- Profiling shows highest CPU/event consumers are algorithms for track reconstruction
- Several mathematical operations are executed in these algorithms:
  - vector/matrix operations via CLHEP framework
  - trigonometric functions via standard GNU libm mathematical library
- The operations were monitored by:
  - Intel's Pin tool
  - PAPI
- CPU performance comparisons studies between different mathematical libraries were made in a simple test framework

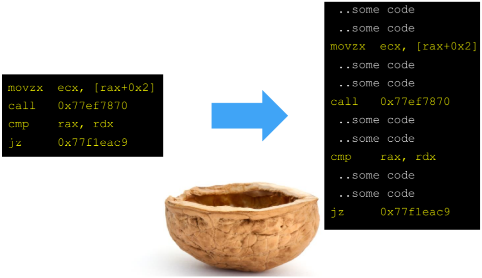
Linear algebra libraries

CLHEP	Eigen	SMatrix	Intel Math Kernel Library
• C++ utility classes for HEP	• C++ templates (headers only) • supports SIMD vectorization	• Implemented in ROOT as expression templates	• BLAS and LAPACK interface • highly optimized
	• expression templates allow removal of temporaries and lazy evaluation		

- All libraries support matrices and vectors with all sizes
- CLHEP is not maintained anymore and not perform well

Pin tool

- Dynamic binary instrumentation framework
  - includes API for abstracting underlying instruction set idiosyncrasies
    $\rightarrow$ no recompilation needed
  - can inject code at the level of functions or instructions



- It is the underlying tool used by Intel Parallel Inspector and Amplifier
- http://www.pintool.org/

Results from monitoring CLHEP functions with Pin

- Monitor calls of CLHEP functions:
    - during reconstruction job
    - with 2012 data sample
      (events passed any Jet, Tau or Missing ET trigger chain)

Five CLHEP functions with highest number of calls:

Function	Calls/Evt
`HepVector::~HepVector()`	3691535
`HepSymMatrix::HepSymMatrix(HepSymMatrix const &)`	1702193
`HepVector::HepVector(int, int)`	1593544
`operator*(HepMatrix const&, HepSymMatrix const&)`	93120
`operator*(HepMatrix const&, HepVector const&)`	42918

Results from monitoring CLHEP functions with Pin

'HepMatrix*HepSymMatrix' arguments with highest number of calls:

1st Argument	2nd Argument	Calls/Evt
3×3	3×3	29333
3×2	2×2	28139
3×5	5×5	13003

'HepSymMatrix*HepVector' arguments with highest number of calls:

1st Argument	2nd Argument	Calls/Evt
5×3	3	23676
3×5	3	11802
1×5	5	4718

- Thanks to pintool,

  now we know how we use CLHEP inside our code,

  with this knowledge we can setup and analyse a realistic test bed
- The results from this testbed are presented in the following slides

PAPI (Performance API)

- Platform-independent interface for hardware performance counters such as: floating point operations, level 1 cache misses, single/double precision vector/SIMD instructions
- Contains low- and high-level sets of routines for accessing counters:

  low level: controls and provides access to all counters

  high level: easily allows one to start, stop and read the counters
- http://icl.cs.utk.edu/papi/

Results from monitoring matrix/vector operations with PAPI

- Monitor floating point operations of several matrix/vector calls with PAPI in a simple test framework
- Compare CLHEP with other classes: Eigen and SMatrix

Floating point operations of 3-dimensional vector/matrix calls:

Operations	CLHEP	Eigen	SMatrix
Matrix allocation	9	9	9
Vector allocation	3	3	3
Vector $+$ Vector	3	3	3
Matrix $\times$ Vector	18	15	n./a.
Matrix $\times$ Matrix	54	47	46

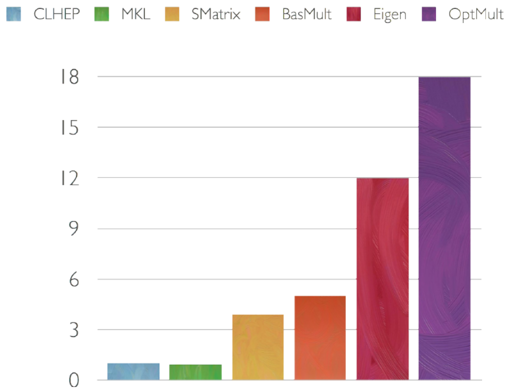
- Matrix $\times$ Vector is not direct available in SMatrix (ROOT v5.34.04)

Further studies: speed comparison measurements

- Evaluated in a small test framework:
  - CPU time of different matrix multiplications
  - comparison studies between: CLHEP, Eigen, SMatrix, MKL and two hand coded C++ routines: BasMult (non-vectorised) and OptMult (vectorised)
- Compiler setup : gcc 4.7.2 and '-O3' for vectorization
- Implemented matrix multiplications:
  - 4×4 with square matrices (including only here BasMult and OptMult)
  - rectangular matrices: $A_{5\times 3} \times B_{3\times 5}$
  - template expression: $C_{5\times 5} = \alpha A_5 B_{3\times 5} + \beta C_{5\times 5}$

Speed comparison with 4×4 square matrices

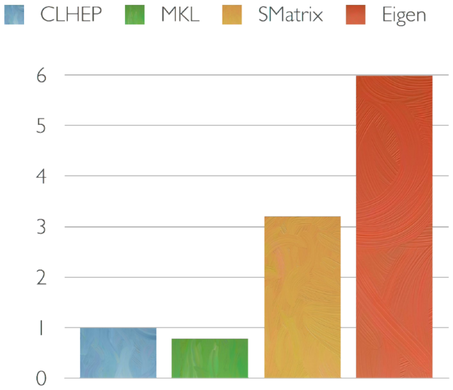
Speedup factor w.r.t. CLHEP:



- Hand vectorized operation is the fastest
- MKL is going though function calls → overhead

Speed comparison with rectangular matrices: $A_{5\times 3} \times B_{3\times 5}$

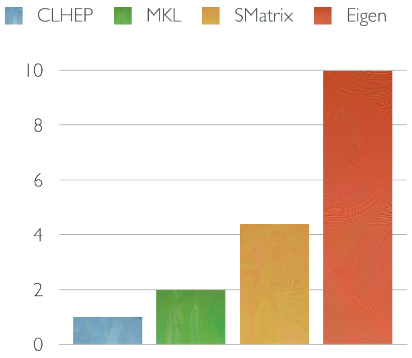
Speedup factor w.r.t. CLHEP:



- Without vectorization
- MKL is going though function calls $\rightarrow$ overhead

Speed comparison with expression templates: $C_{5\times5} = \alpha A_5 B_{3\times5} + \beta C_{5\times5}$

Speedup factor w.r.t. CLHEP:



- Without vectorization
- MKL performs better and overhead is diminished

Conclusion of speed comparison studies: matrix operations

- Hand vectorized operation is the fastest,
  but hand written code is less maintainable and error prone
- Eigen is the fastest linear algebra library
- ATLAS decided to replace CLHEP with Eigen for linear algebra operation for track reconstruction

Trigonometric functions

- GNU libm used as default for trigonometric functions in ATLAS software
- Monitored calls and instructions with Pin during reconstruction job with 2012 data sample

Results with Pin and test framework:

Function	M Call/Evt	Time/Calls [ns]	Time/Evt [s]
exp	3.4	146	0.496
cos	2.5	149	0.373
sin	2.2	149	0.328
atanf	2.1	22	0.0462
sincosf	2.1	24	0.050

- Total times of all trigonometric functions per event: 2.037 s of 14.41 s

CPU time comparison study with alternative math libraries

- VDT
  - developed by CMS
  - designed for auto-vectorization with fast calculations using Padé approximations
  - can be inlined with different API calls, or built into a non-inlined 'drop-in' library (used in this study)
  - further detailed information in Danilo Piparo's talk
- libimf
  - performance optimized library from Intel (Version 2013)
  - can be used as 'drop in' replacement with LD_PRELOAD (use multiple code path for SSE and AVX instructions)
- CPU time comparison study: running reconstruction job with 2012 data sample with GNU libm, VDT and libimf.

CPU time comparison study with alternative math libraries

Results of CPU time comparison study:

Math library	Relative to GNU libm
GNU libm	1.000
VDT	0.923
libimf	0.919

- Reconstruction jobs were running on Sandy Bridge processor with AVX extensions

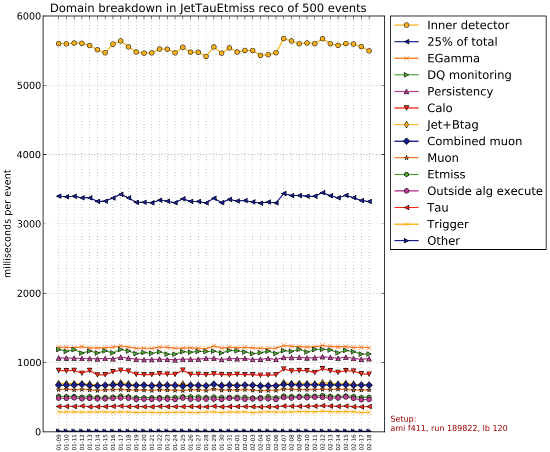
Conclusion:

- libimf provides the fastest trigonometric functions
- ATLAS decided to replace GNU libm with libimf, but keep VDT available in ATLAS software

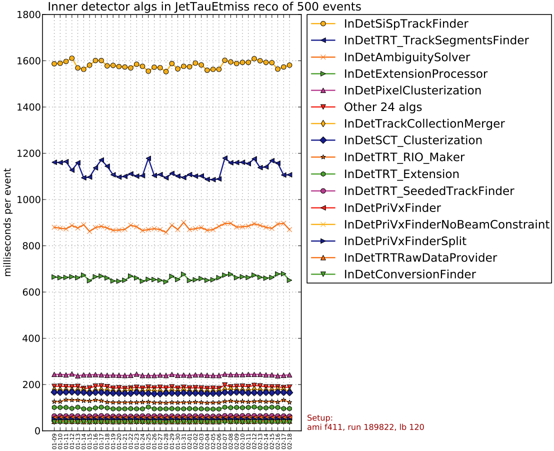
Summary and Conclusion

- Pin provides detailed information about how ATLAS software uses CLHEP and trigonometric functions
- PAPI is an analysis API for hardware performance counters
- Use of these tools has already helped ATLAS achieve significant speed ups in our offline software
- Comparison studies showed:
  - Eigen is the fastest library for matrix and vector operations
  - libimf is the fastest library for trigonometric functions
- ATLAS decided to replace:
  - CLHEP with Eigen for linear algebra operations for track reconstruction
  - GNU libm with libimf for trigonometric functions
- More details about upgrades in tracking algorithms: Talk by Robert Langenberg

Backup slides



- CPU time breakdown per domain depending on the day after the release build during the night
- Measure while processing a data sample from 2011



- CPU time breakdown per domain depending on the day after the release build during the night
- Measure while processing a data sample from 2011

Results with PAPI of matrix/vector operations

- Monitor in a simple test framework floating point operation of several matrix/vector calls with PAPI
- Compare CLHEP with other classes: Eigen and SMatrix

Floating operations of 4-dimensional vector/matrix

Operations	CLHEP	Eigen	SMatrix/SVector
Matrix allocation	16	16	16
Vector allocation	4	4	4
Vector + Vector	4	2	4
Matrix × Vector	32	15	-
Matrix × Matrix	128	58	112

- Matrix × Vector is not availble in SMatrix

Speed comparison with 4×4 square matrices

- Additionally: setup of matrix multiplication with 'std::vectors'
  - basic setup (not vectorized)
  - optimized setup: vectorized without horizontal sums

Basic Multiplication (BasMult):

```
for(int i = 0; i < 16; i+=4){
  for(int j = 0; j < 4; j++){
    z[i+j] = x[i] * y[j] + x[i+1] * y[4 + j] \
    + x[i+2] * y[8 + j] + x[i+3] * y[12 + j];
  }
}
```

Optimized Multiplication (OptMult):

```
for(int i = 0; i < 16; i+=4){
    Vec4d r1 = Vec4d(x[i]) * Vec4d(y);
    for(int j = 1; j < 4; j++){ r1 += Vec4d(x[i+j]) * Vec4d(&y[j*4]); }
    r1.store(&z[i]);
  }
```

CLHEP

- CLHEP - A Class Library for High Energy Physics
- http://proj-clhep.web.cern.ch/proj-clhep/
- A set of HEP-specific utility classes such as random generators, physics vectors, geometry and linear algebra
- CLHEP provides a generic interface for any-dimension matrix/vector
- Problem:
  - Not maintained anymore
  - Not well performed (especially matrix operations)

Eigen

- http://eigen.tuxfamily.org/
- Pure C^{++} template library
  - header only → no binary to compile/install
  - Opensource: MPL2
- It supports:
  - all matrix sizes
  - SIMD vectorization
  - compilers (gcc, icc, clang, ...)
- It is optimized for
  - small fixed-size matrices
  - arbitrarily large dynamic size matrices

SMatrix

- ROOT C^{++} package for high performance vector and matrix computations
- http://root.cern.ch/root/html/MATH_SMATRIX_Index.html
- Implemented as expression templates
- Provide matrix/vector classes of arbitrary dimensions and type
- Classes are templated on the dimension of the matrix/vector and on the scalar type
- Problem:
  - Supports only symmetric matrices
  - Not complete linear algebra package such as Intel MKL or Eigen

Intel Math Kernel Library (MKL)

- http://software.intel.com/en-us/intel-mkl
- Includes:
  - Basic Linear Algebra Subprograms (BLAS)
  - LAPACK routines for solving systems of linear equations
- Optimized:
  - on modern Intel processors
  - for large matrices and BLAS operations: $C = \alpha AB + \beta C$