CHMPR

CENTER FOR HYBRID MULTICORE PRODUCTIVITY RESEARCH

Accelerating a climate physics model with OpenCL

Fahad Zafar, Dibyajyoti Ghosh, Lawrence Sebald, Shujia Zhou

University of Maryland Baltimore County

Introduction

- The demand to increase forecast predictability has been pushing climate and weather models
    - increase model grid resolution
    - include more physical processes.
- Current trends in the computing industry have moved from optimizing performance gains on single-core processors to increasing the overall performance through parallel computing with many-core processors.

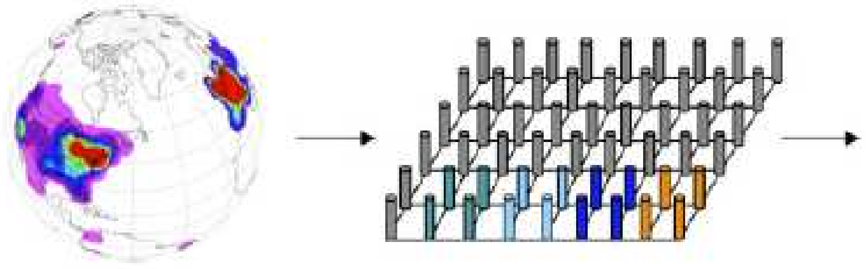
OpenCL

- Open Computing Language (OpenCL) is fast becoming the standard for heterogeneous parallel computing
- Run on CPUs, GPUs, and other accelerator architectures (Cell, Fusion)
- OpenCL puts forward a thread-extensive model for programming

Contributions and Focus

- A complete cross-platform real-world example in OpenCL
  - Evaluate cross-platform performance and portability
- Compare C compilers and execution environments (IBM, Mac OS X)
- Highlight the performance gain achieved by OpenCL CPU implementation over traditional C code on CPUs.

GEOS-5 Climate Model



Compute !!!

- The NASA Goddard Earth Observing System Model, Version 5 (GEOS-5), is a currently operational climate model.
- SOLAR is a solar radiation model component *[Chou et al. 99]* used in GEOS-5 and other climate and weather models.

[Chou et al 99] M. D. Chou and M. J. Suarez, "A solar radiation parameterization (clir-ad-sw) for atmospheric studies," 1999.

SOLAR

- A production-quality climate or weather model code can span up to a few hundred thousand lines.
  - Originally written in FORTRAN
- This particular code was converted to C and ported to the IBM Cell Broadband Engine by [*Zhou et al*] where detailed code structure analysis and performance gains were reported.
- ~20% for SOLAR AND IRRAD, the remaining computing time breaks down as
  - ~25% for dynamics
  - ~25% for input and output data
  - ~30% for other column-physics components.
- We implemented the serial version of the C code in OpenCL version 1.0
  - Platforms: IBM JS21 (PowerPC) and JS22 (Power6) blades, a POWER6 AIX system, and Mac OS X versions 10.6.4 and 10.6.7 with x86 Intel processors.

[Zhou et al] S. Zhou, D. Duffy, T. Clune, M. Suarez, S. Williams, and M. Halem, "The impact of IBM Cell technology on the programming Paradigm in the context of computer systems for climate and weather models," pp. 2176–2186, 2009.

Code Overview

Solar Radiation Initial ()

(Setting up data and arrays)

Solar UV ()

- GetAeroIndex
- Cldscale
- Deledd
- Cldflxv
- Cldflx

Solar IR ()

- GetAeroIndex
- Cldscale
- Deledd
- Cldflxv
- Cldflx

Solar Radiation Final ()

(Finalizing data and output)

Approach

- Extract compute-intensive kernels without changing the overall code structure
- Manually optimized sections of the code to run in a multi-threaded fashion using OpenCL kernels and benchmark them.
- Run in 2 Modes
  - Cross-checking with serial execution
  - Benchmark

Approach

- Compare OpenCL vs. serial GCC
    - IBM (complete)
    - Mac OS X (incomplete)
- Compare auto-vectorization with other compilers for select sections of the code

CPU Experiment Setup

Operating System	Compiler
IBM JS 21 blade	• GCC v4.1.2
IBM JS 22 blade	• GCC v4.1.2
IBM POWER6 AIX	• GCC v4.1.2 • IBM XLC v10.1
Intel 2.66 GHz Core 2 Duo Mac OS X 10.6.7	• GCC v4.2.1 • Intel C++ Compiler v12.0.4

Code Execution and Checking

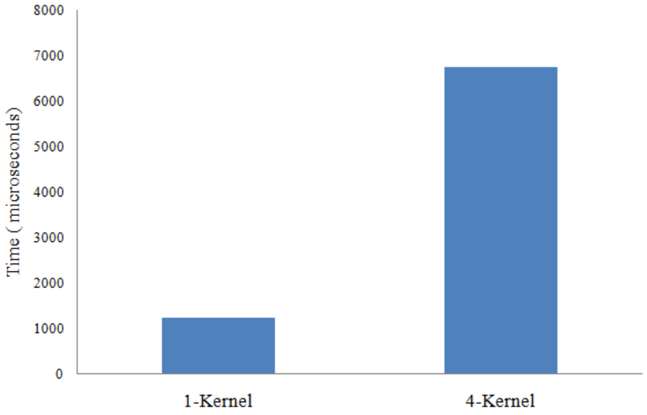
- Parallel code runs side by side
  - Cross-check Compute Device values after every kernel

Code Sample:

```
//----------/
execute_sectionI(df,cnt,so2);



    //--------------------------------------------------------
    //              SECTION - J
    //--------------------------------------------------------


    for (k=0; k<LM; k++)
    {
        for (i=0;i<M_BLOCK; i++)
        {
            //            so2[i][k+1] = so2[i][k] + scal[i][k+1]*cnt[i];
            so2[k+1][i] = so2[k][i] + scal[k+1][i] *cnt[i] ;

            /* LLT increased parameter 145 to 155 to enhance effect */
            //            df[i][k+2] = 0.0633*(1.0 - exp(-0.000155*sqrt(so2[i][k+1])));
            df[k+2][i] = 0.0633*(1.0 - exp(-0.000155*sqrt(so2[k+1][i])));

        }
    }
execute_sectionJ(so2,df);


    /*
    c-----for solar heating due to co2 scaling follows Eq(3.5) with f=1.
    c     unit is (cm-atm)stp. 789 = (1000/980)*(44/28.97)*(22400/44)
    */

    //--------------------------------------------------------
    //              SECTION - K
    //--------------------------------------------------------
    for (i=0; i<M_BLOCK; i++)
    {
        //         so2[i][0] = (789.*co2)*scal[i][0];
        so2[0][i] = (789.*co2)*scal[0][i];
    }


execute_sectionK(so2,scal);
```

Manual Optimization

- Porting C code to OpenCL provides a design decision challenge based on the nested dependency structure of the code.
- Dividing one subroutine with multiple levels of iteration loops and a mix of decision statements can be tricky at times.
- We noticed that splitting some subroutines into multiple kernels at times speed up the processing, while in some cases it reduced performance.



Findings

- Auto vectorization support in OpenCL compiler
  - better than GCC, IBM XLC, Intel ICC

- We found a 3 ~ 4X performance improvement per core over the original serial code compiled with GCC

- OpenCL provides access to a multi-threaded programming and execution model as well as a low-level API for memory and thread management

Findings

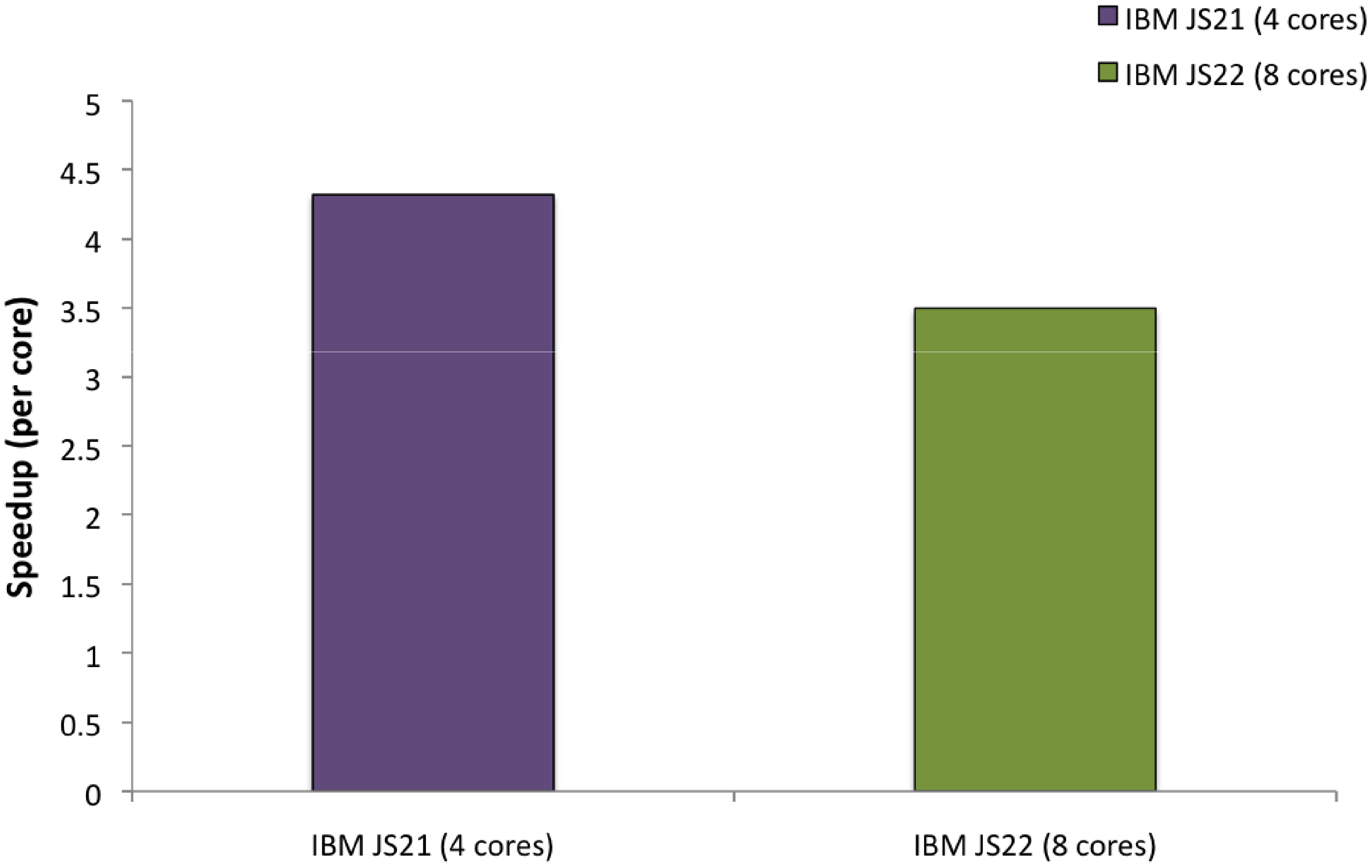
- Similar results were obtained from Intel ICC compiler and IBM XLC compiler for these nested loop constructs

- Efficient vectorization and global optimizations contribute to drastic speedup in OpenCL

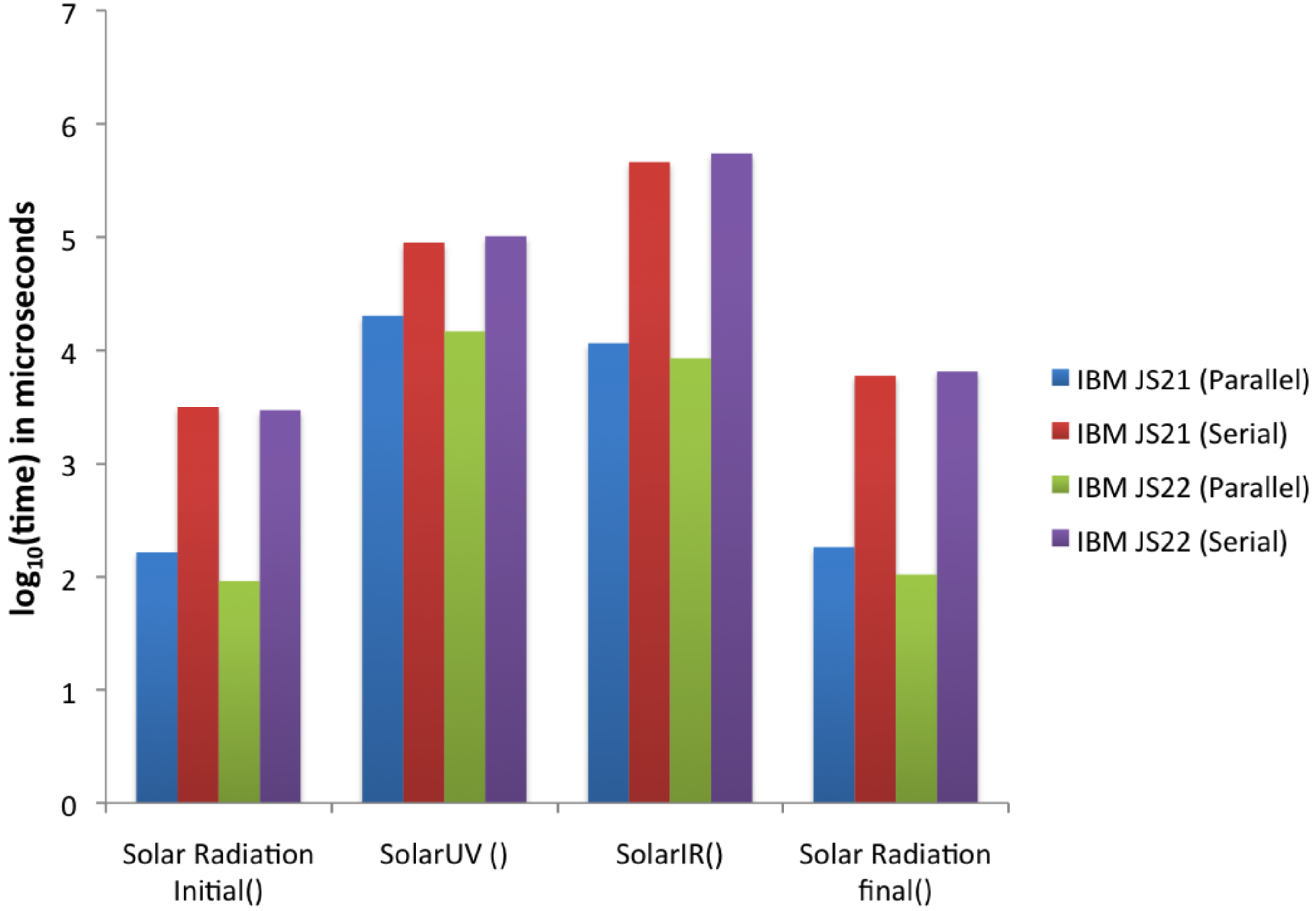
OpenCL Parallel vs. IBM Serial

- Code implementation complete
- Tested and cross checked
- About 70 compute kernels
- The kernels do not have a one-to-one mapping with the serial solar radiation code functions.
- The code uses *integer* and *floating point* data types

Results: Speedup per core

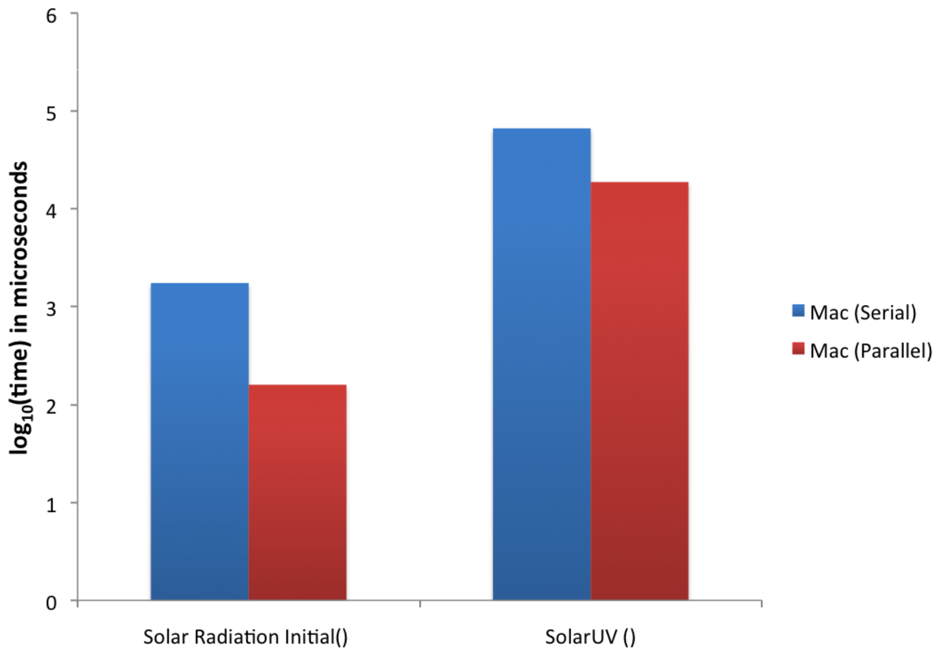


Results: Performance gain per section



OpenCL Parallel vs. Mac OS X Serial

- Code Implementation Incomplete
  - First two sections tested and running
- Performance is portable to some extent



Portability Issues

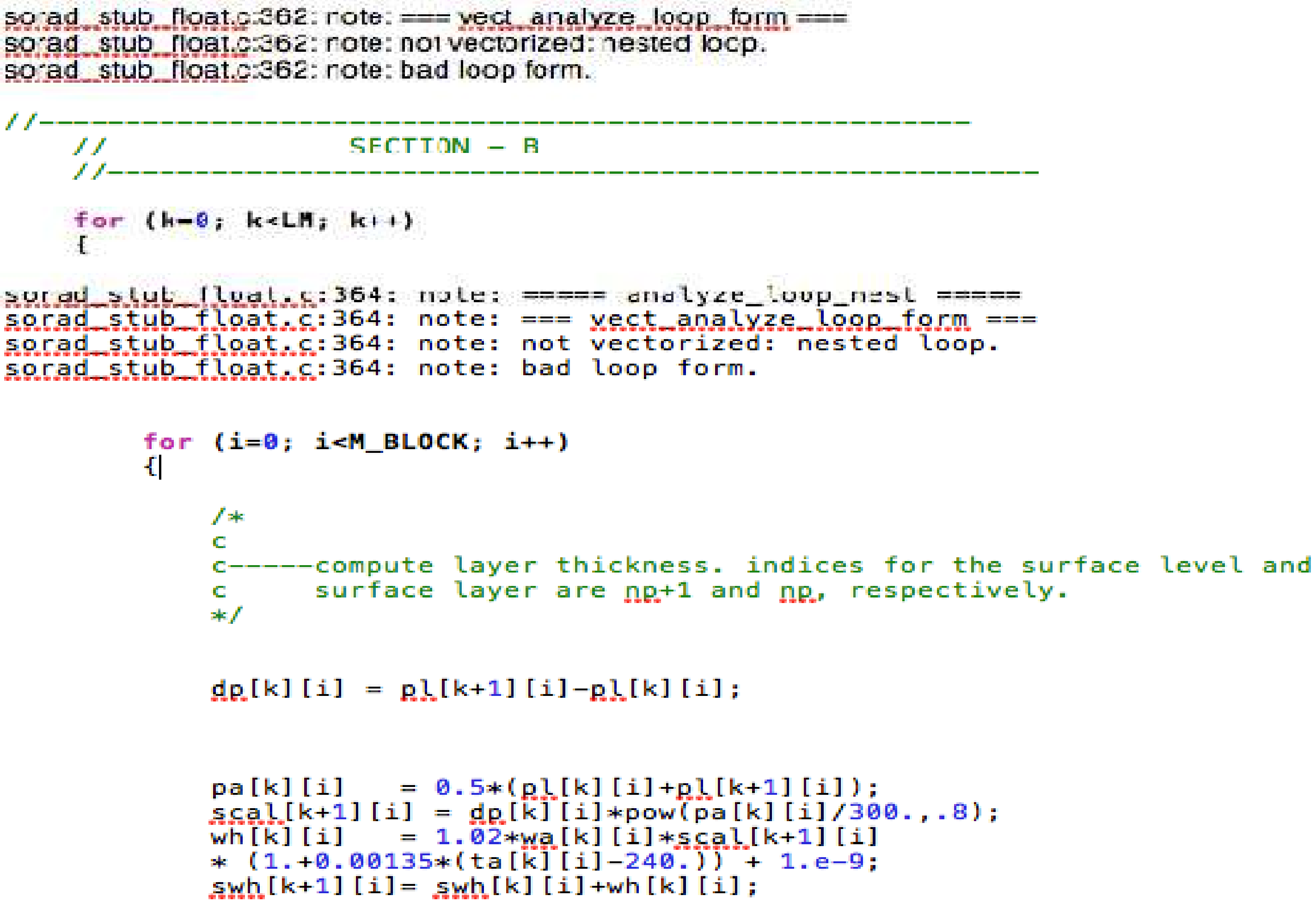
- The code implemented with OpenCL 1.0 compiled correctly and executed accurately with cross-checked values in IBM JS21 and JS22 blades did not run on Mac OS X "as is".
- Thread scheduling identified as an issue.
- Platform detection functions would crash for one platform while ran correctly for the other.

Vectorization test

- IBM
  - Implement a subset of the code using Altivec Instruction set.
  - Speedup = 2x
- Intel
  - Use Intel OpenCL viewer to look at the assembly code

Vectorization Analysis - I

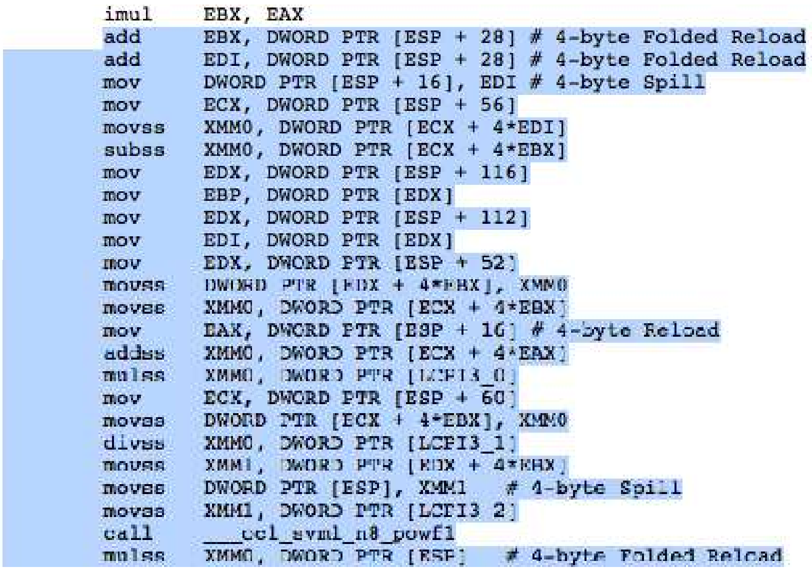
A part of the serial code with GCC vectorization error output



```
sorad_stub_float.c:362: note: === vect_analyze_loop_form ===
sorad_stub_float.c:362: note: not vectorized: nested loop.
sorad_stub_float.c:362: note: bad loop form.

//----------------------------------------------------------
    //                SECTION - B
    //----------------------------------------------------------

    for (k=0; k<LM; k++)
    {

sorad_stub_float.c:364: note: ===== analyze_loop_nest =====
sorad_stub_float.c:364: note: === vect_analyze_loop_form ===
sorad_stub_float.c:364: note: not vectorized: nested loop.
sorad_stub_float.c:364: note: bad loop form.


        for (i=0; i<M_BLOCK; i++)
        {

            /*
            c
            c-----compute layer thickness. indices for the surface level and
            c     surface layer are np+1 and np, respectively.
            */


            dp[k][i] = pl[k+1][i]-pl[k][i];


            pa[k][i]    = 0.5*(pl[k][i]+pl[k+1][i]);
            scal[k+1][i] = dp[k][i]*pow(pa[k][i]/300.,.8);
            wh[k][i]    = 1.02*wa[k][i]*scal[k+1][i]
            * (1.+0.00135*(ta[k][i]-240.)) + 1.e-9;
            swh[k+1][i]= swh[k][i]+wh[k][i];
```

Vectorization Analysis - II

A part of the OpenCL code with vectorized instruction set for the loop-construct in the last slide



```
imul    EBX, EAX
add     EBX, DWORD PTR [ESP + 28] # 4-byte Folded Reload
add     EDI, DWORD PTR [ESP + 28] # 4-byte Folded Reload
mov     DWORD PTR [ESP + 16], EDI # 4-byte Spill
mov     ECX, DWORD PTR [ESP + 56]
movss   XMM0, DWORD PTR [ECX + 4*EDI]
subss   XMM0, DWORD PTR [ECX + 4*EBX]
mov     EDX, DWORD PTR [ESP + 116]
mov     EBP, DWORD PTR [EDX]
mov     EDX, DWORD PTR [ESP + 112]
mov     EDI, DWORD PTR [EDX]
mov     EDX, DWORD PTR [ESP + 52]
movss   DWORD PTR [EDX + 4*EBX], XMM0
movss   XMM0, DWORD PTR [ECX + 4*EBX]
mov     EAX, DWORD PTR [ESP + 16] # 4-byte Reload
addss   XMM0, DWORD PTR [ECX + 4*EAX]
mulss   XMM0, DWORD PTR [LCPI3_0]
mov     ECX, DWORD PTR [ESP + 60]
movss   DWORD PTR [ECX + 4*EBX], XMM0
divss   XMM0, DWORD PTR [LCPI3_1]
movss   XMM1, DWORD PTR [EDX + 4*EBX]
movss   DWORD PTR [ESP], XMM1    # 4-byte Spill
movss   XMM1, DWORD PTR [LCPI3_2]
call    ___ocl_svml_n8_powf1
mulss   XMM0, DWORD PTR [ESP]    # 4-byte Folded Reload
```

pshufd, paddd, movaps, movups are special SIMD instructions belonging to Intel Advanced Vector Extensions.

Why is OpenCL Faster on the CPU?

- The current IBM implementation is based around a modified version of their XLC compiler.
  - XLC is designed specifically for the POWER architecture. The use of XLC by IBM in their implementation of OpenCL should come as no surprise and it explains why XLC is capable of sophisticated Altivec code generation.

- The OpenCL implementation in Mac OS X is based on Low Level Virtual Machine (LLVM) with the Clang front-end. LLVM was designed as an infrastructure for building compilers, with a large focus on optimized code generation. LLVM supports the Intel architecture quite well, explaining why it creates such well-optimized code from the OpenCL kernel functions that we have implemented on Mac OS X thus far.

Why is OpenCL Faster on the CPU?

- Better automatic vectorization
  - The OpenCL compiler on IBM architectures uses the Altivec instruction set, while the OpenCL compiler on Intel architectures uses Streaming SIMD Extensions 4.1
- Light weight OpenCL threads
  - Better memory management ?
- It should be noted that the OpenCL compiler might make certain assumptions that GCC cannot afford to make for naive C code.
  - The OpenCL compiler can assume that the given computation is meant to be run as a many-threaded piece of code

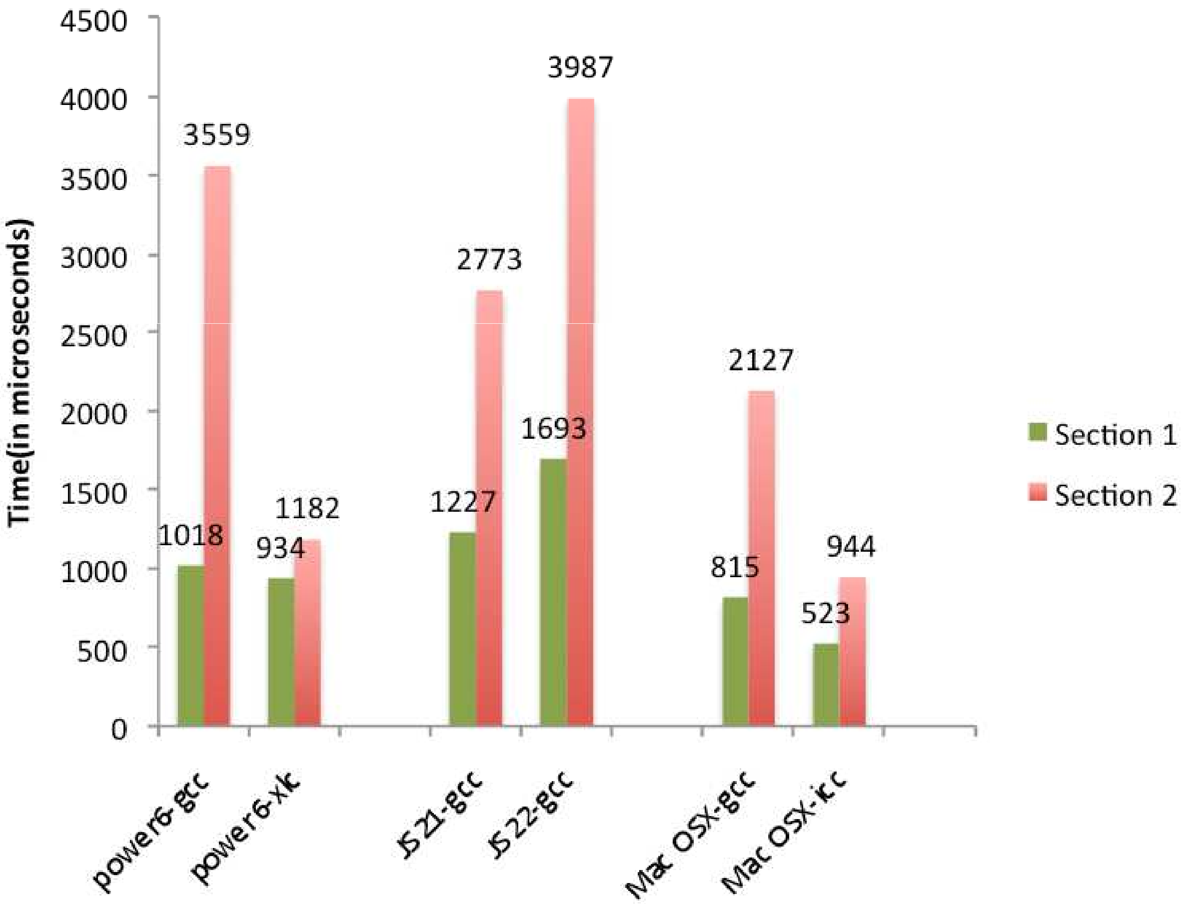
Benchmarking Other Compilers

Select two sections of SOLAR with complex nested loop constructs

Compile and run serial sections on GCC, IBM XLC, Intel C++ compiler

Compared timing data

Timing compilers on different platforms



Conclusion

- Multithreaded programming and execution models of OpenCL can significantly increase the performance
  - IBM POWER and PowerPC and POWER6 CPU architectures
  - Similar performance improvement has also been obtained in Intel CPUs

- Performance improvement in CPUs arises from a much better implicit vectorization support provided by the OpenCL compiler infrastructure as compared to auto-vectorization support provided by popular compilers like GCC, ICC and IBM XLC.

- Across complier infrastructure Intel ICC on Mac OS X 10.6.7 fares best followed by IBM XLC on POWER6 AIX

Future Work

- We plan to modify the OpenCL code appropriately to run on GPU.
- Apply OpenMP optimization to serial code and compare to OpenCL version.
- Identify programming practices that work best/worst on GPU and CPU platforms

Questions ?

Thank You