Performance, Portability, and Dreams

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Why Performance Portability?

- HPC is Performance
- A big part of the programming crisis is caused by the challenge of obtaining performance (even) on a single platform
  - This is an unsolved problem
    - Easy example: Implement a barrier. Communicates a single bit of information.
      - Easy to write a simple implementation (e.g., use an atomic counter).
      - Efficient implementations require clever algorithms, attention to memory hierarchies, special instructions, and are still publishable
        - "Algorithms for Scalable Synchronization on Shared-Memory Multiprocessors", ACM TOCS, 1991
        - Recent results such as "Efficient Barrier Implementation on the POWER8 Processor", HiPC 2015
  - Performance portability related to programming productivity
    - And a harder problem that is getting even harder

Platform-specific

NCSA

Why Is Performance Portability so Hard

- Its been hard
  - Predicting performance for a single system is very difficult
    - Systems are complex
    - Behavior has random elements
    - Interactions between parts is hard to predict
- After more than 20 years of stability, processor architectures are diversifying and changing
  - More types of systems – e.g., vectors/streams in GPUs
  - Rapid innovation – new instructions, memory architectures, …
  - Effective* use of these requires someone to adapt to the differences
    - Please make it someone else!
- Even if it is someone else
  - Many costs and risks to maintaining multiple versions

Tradeoffs

- Implicitly, performance portability is intended to reduce the amount of work needed to achieve adequate performance to meet the needs that the computing serves
- How much (programmer re-) work is acceptable to achieve performance portability?
- What constraints or other limitations are acceptable?
  - Choices of data structure, code complexity, reproducibility, compile time, sensitivity to changes in input data, …

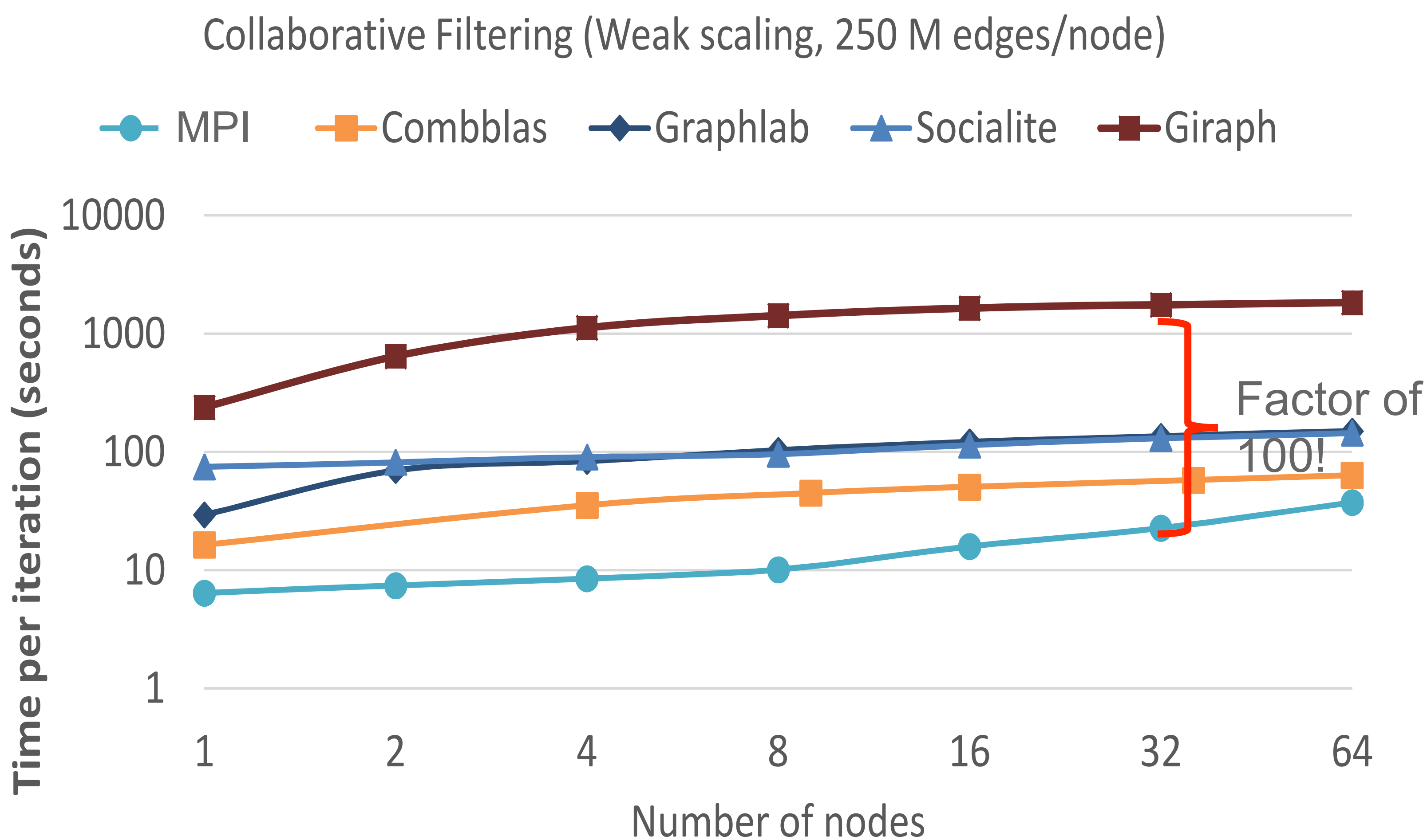
What is the Problem Statement?

- General case (strong performance portability) – get the fastest solution to the problem on all systems – is far too hard – requires picking model, algorithm, data structure, and implementation
  - Best algorithm/data structure choice often unknown
  - Algorithm may depend on platform
    - Proof – parallel algorithms that trade less synchronization against more work vs. sequential algorithms
- Given a family of data structures and an algorithm, choose the data structure instance and implementation
  - E.g., Array index ordering; Structure of arrays vs array of structures vs structure of arrays of structures; sparse matrix ordering
- Given a data structure and an algorithm, generate "good" code that performs well
  - Problem: choices here are important for performance
  - Problem: Still hard even in simple cases
  - Problem: "Extra" semantics in language – e.g., order of operations for floating point, e.g. in dense matrix-matrix multiply, can limit options even if not intended by programmer

Metrics for Success

- What is success?
- Need to quantify both portability and performance
- Should include impact on productivity
  - A performance portable code that is no longer maintainable or that is too brittle for further development is probably not an improvement
- Not an easy linear function
  - Different users and communities may choose different weights for the metric

Productivity and Performance



Navigating the Maze of Graph Analytics Frameworks using Massive Graph Datasets
Nadathur Satish, Narayanan Sundaram, Md. Mostofa Ali Patwary, Jiwon Seo, Jongsoo Park, M. Amber Hassaan, Shubho Sengupta, Zhaoming Yin, and Pradeep Dubey

Dangers in Performance Portability

- One easy way – make all performance mediocre
  - One vendor did this in the '80s with their vector hardware, to avoid too large a variability in performance
    - Goal was no performance "surprises"
  - Related – predictable performance – a goal and elegant feature of BSP (Bulk Synchronous Programming)
    - How much opportunity for higher but less predictable performance are you willing to give up for predictable performance? Do your users agree with you?
- Another easy way – claim that it can be reduced to a previously solved problem
  - E.g., Claim the compiler can take care of it
  - This is a fantasy
- We clearly need a good definition…

One Definition

- **An application is performance portable if it achieves a consistent ratio of the actual time to solution to either the best-known or the theoretical best time to solution on each platform with minimal platform specific code required.**
  - From http://performanceportability.org/perfport/definition/
  - Note that other definitions are mentioned with different focus and levels of precision

- “Best-known” time to solution is a big loophole
  - For a new system, best known is your own best time
  - If there is only one code, and it runs and there is no theoretical best time, the code is performance portable, regardless of the actual performance
    - That consistent ratio is 1 ☺

- See more on one view of performance portability at
  - http://performanceportability.org/

What Is Performance Portability?

- Is it:
  - A code is performance portable if it achieves at least 100-X% of the achievable performance on all platforms
- Do I need to add constraints?
  - with the same algorithm
  - and the same data structures
  - and the same input and output data organization and format
  - and the same build system (e.g., makefile)
- How large can X be for this definition to be useful?
  - 1? 10? 50? 99? 99.99999?
- Is X the same for all platforms?
  - Alternately, is there an *absolute* performance target, and the code is performance portable if the code meets or exceeds that performance on all platforms of interest?
- Is there a scaling of X based on the cost ($) of the platform?

Defining Performance Portability

- And what about the correctness constraints
  - Is the output strongly or weakly deterministic?
  - Is bitwise identical output required?
- What is the definition of achievable performance?
  - FLOPS?
  - FLOPS and Memory Bandwidth (“roofline” https://dl.acm.org/citation.cfm?id=1498785)
  - FLOPS and Memory Bandwidth and Latency (Execution-Cache-Memory (ECM) model https://link.springer.com/chapter/10.1007%2F978-3-642-14390-8_64)
  - FLOPS and Memory Bandwidth and Instruction Rate (“Achieving high sustained performance in an unstructured mesh CFD application” https://dl.acm.org/citation.cfm?id=331600 , 1999)

What Is Performance Portability?

- Is it:
  - A code is performance portable if it runs with acceptable performance without any source code change (or architecture-specific directives) on the platforms of interest
- This is squishy. What is
  - Acceptable performance
  - Without any source code change
  - Platforms of interest
- What if I make this *more* squishy
  - A code is performance portable if it runs with acceptable performance with no <u>onerous</u> source code or build system changes on <u>most</u> of the platforms of interest

Some Performance Portability Questions

- "How much performance would you be willing to give up by replacing the two optimal applications by a single one?"
  - https://software.intel.com/en-us/blogs/2017/03/30/rainbows-unicorns-and-performance-portability (Robert Geva, Intel)
- How much are you willing to spend to achieve performance portability
  - E.g., if maintaining two codes takes 100 FTE/each and recasting a code in a new system takes 250 FTE, is that acceptable? What if it costs 2500 FTE?
- These ask *quantitative* questions about performance portability
- They also get to the heart of *why* someone might want performance portability

Some Different Approaches to Performance Portability

- Language based
  - Existing languages, possibly with additional information
    - Info from pragmas (e.g., align) or compile flags (assume associative)
  - Extensions, especially for parallelism
    - Directives + runtimes, e.g., OpenMP/OpenCL/OpenACC
    - May also relax constraints, e.g., for operation order, bitwise reproducibility
  - New languages, especially targeted at
    - Specific data structures and operations
    - Specific problem domains
- Library based (define mathematical operators and implement those efficiently)
  - Specific data structure/operations (e.g., DGEMM)
  - Specific operations with families of data structures (e.g., PETSc)
    - This is likely the most practical way to include data-structure and even algorithm choice
    - At the cost of pushing the performance portability problem onto the library developers

Some Different Approaches to Performance Portability

- Tools based
  - Recognize that the user can always write poorly-performing code
  - Support programming in finding and fixing performance problems
  - Example: Early vectorizing compilers gave feedback about missed vectorization opportunities; trained programmer to write "better" code
- Programmer support and solution components
  - Work with programmer to develop code
  - Source-to-source tools to transform and to generate code under programmer guidance
  - Autotuning to select from families of code
  - Database systems to manage architecture and/or system-specific derivatives
- Magic
  - Any sufficiently advanced technology is indistinguishable from magic. (Clarke's 3rd law)
  - Any sufficiently advanced technology is indistinguishable from a rigged demo.
- Note these approaches are not orthogonal
  - Successful performance portability requires many approaches, working together

“Domain-specific” languages

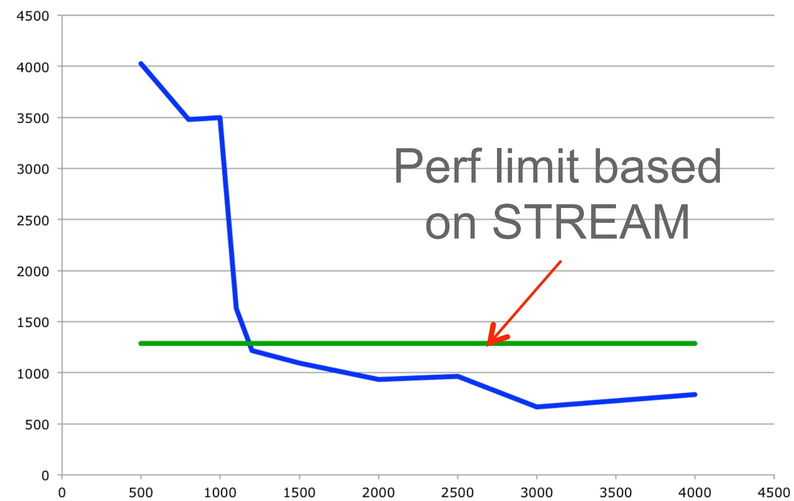
- (First – think abstract data-structure specific, not science domain)
- A possible solution, particularly when mixed with adaptable runtimes
- Exploit composition of software (e.g., work with existing compilers, don’t try to duplicate/replace them)
- Example: mesh handling
  - Standard rules can define mesh
    - Including “new” meshes, such as C-grids
  - Alternate mappings easily applied (e.g., Morton orderings)
  - Careful source-to-source methods can preserve human-readable code
  - In the longer term, debuggers could learn to handle programs built with language composition (they already handle 2 languages – assembly and C/Fortran/…)
- Provides a single “user abstraction” whose implementation may use the composition of hierarchical models
  - Also provides a good way to integrate performance engineering into the application

Let The Compiler Do It

- This is the right answer …
  - If only the compiler *could* do it
- Lets look at one of the simplest operations for a single core, dense matrix transpose
  - Transpose involves only data motion; no floating point order to respect
  - Only a double loop (fewer options to consider)

A Simple Example: Dense Matrix Transpose

- do j=1,n
      do i=1,n
          b(i,j) = a(j,i)
      enddo
  enddo
- No temporal locality (data used once)
- Spatial locality only if (words/cacheline) * n fits in cache



- Performance plummets when matrices no longer fit in cache

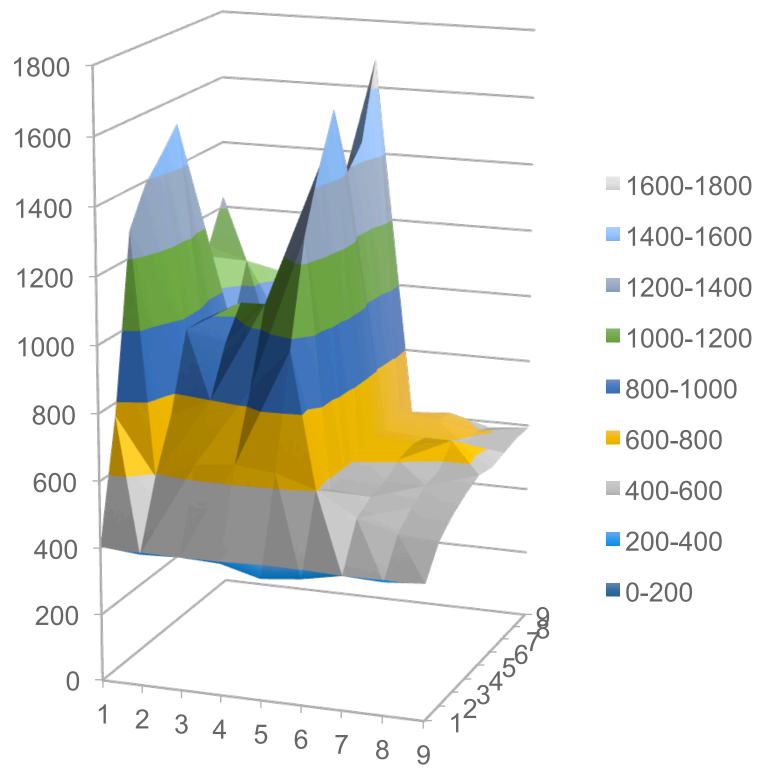
Blocking for cache helps

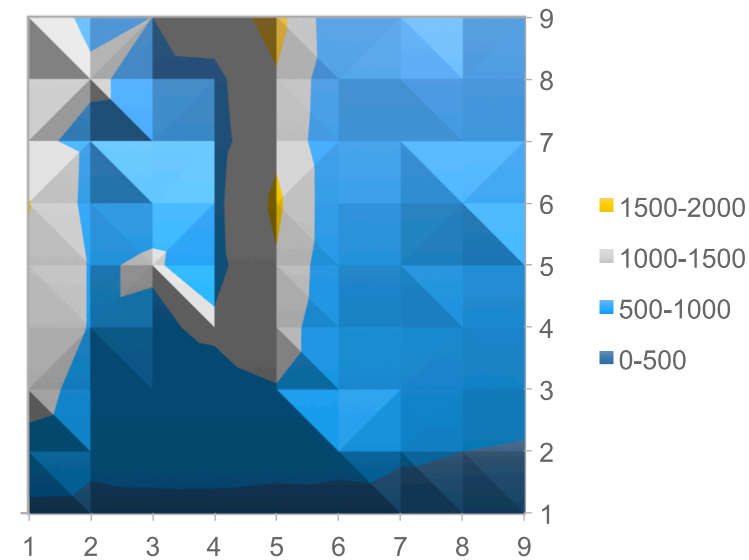
- do jj=1,n,stridej

```
do jj=1,n,stridej
   do ii=1,n,stridei
      do j=jj,min(n,jj+stridej-1)
         do i=ii,min(n,ii+stridei-1)
            b(i,j) = a(j,i)
```

- Good choices of stridei and stridej can improve performance by a factor of 5 or more
- But what are the choices of stridei and stridej?

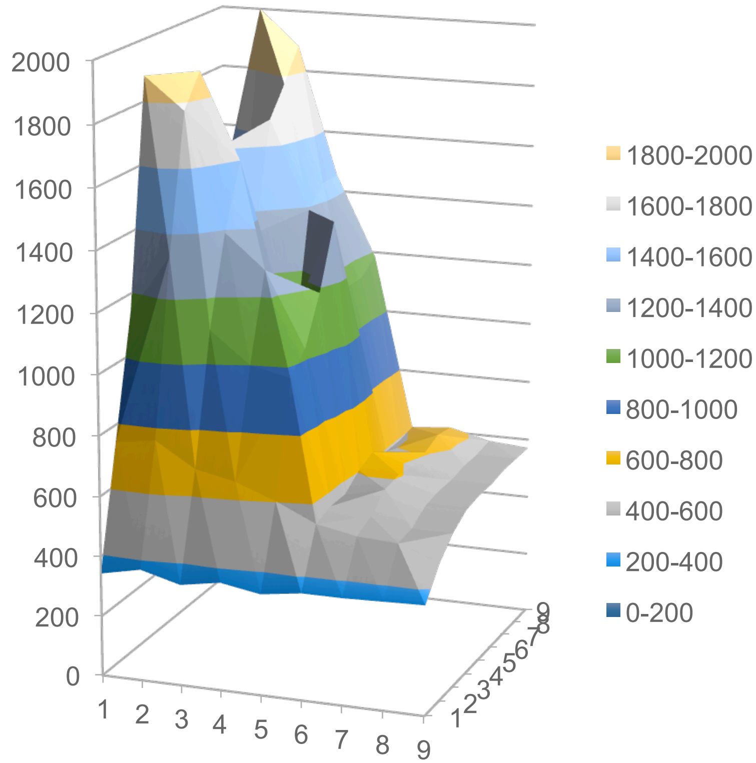
Results: Blue Waters O1

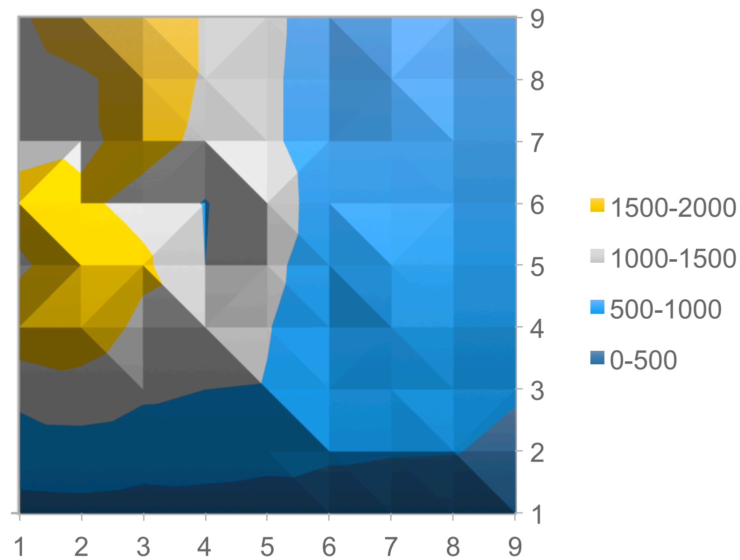




Results: Blue Waters O3

Simple, unblocked code compiled with O3 – 709MB/s





An Example: Stencil Code from a Real Application

- Stencil for CFD code
- Supports 2D and 3D
- Supports different stencil widths
- Matches computational scientists' view of the mathematics

```
! @ICE block=StrainRate
do i = 1,ND
  do k = 1,ND ! diagonal components first
    do ii = 1, Nc
      StrnRt(ii,i) = StrnRt(ii,i) + &
        MT1(ii,i+k*ND-2) * VelGradIst(ii,i+k*ND-2)
    end do
  end do ! k
  do j = i+1,ND ! upper-half part of strain-rate tensor due to symmetry
    do k = 1,ND
      do ii = 1, Nc
        StrnRt(ii,i+j+ND-2) = StrnRt(ii,i+j+ND-2) + &
          MT1(ii,k+j+ND-2) * VelGradIst(ii,i+k+ND-2) + &
          MT1(ii,k+i+ND-2) * VelGradIst(ii,j+k+ND-2)
      end do
    end do ! k
    do ii = 1, Nc
      StrnRt(ii,i+j+ND-2) = 0.5_rfreal * StrnRt(ii,i+j+ND-2)
    end do
  end do ! j
end do ! i
do k = 1,size(StrnRt,2)
  do ii = 1, Nc
    StrnRt(ii,k) = JAC(ii) * StrnRt(ii,k)
  end do
end do ! k
! @ICE endblock
```

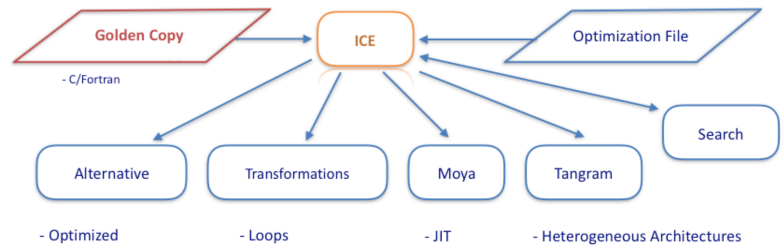
Another Version of the Same Code

- This version is 4X as fast as the simpler, easier to read code
- Less general code (subset to stencil, problem dimension)
- Same algorithm, data structure, and operations, but transformed to aid compiler in generating fast (and vectorized) code

```
if( ND == 2 ) then
  do ii = 1, Nc
    ! diagonal components first
    StrnRt(ii,1) = JAC(ii) * (                     &
      MT1(ii,1) * VelGradist(ii,1)                 &
      + MT1(ii,2) * VelGradist(ii,3) )
    StrnRt(ii,2) = JAC(ii) * (                     &
      MT1(ii,3) * VelGradist(ii,2)                 &
      + MT1(ii,4) * VelGradist(ii,4) )
    StrnRt(ii,3) = JAC(ii) * 0.5_rfreal * ( &
      MT1(ii,3) * VelGradist(ii,1)                 &
      + MT1(ii,1) * VelGradist(ii,2)               &
      + MT1(ii,4) * VelGradist(ii,3)               &
      + MT1(ii,2) * VelGradlst(ii,4) )
  end do
else if( ND == 3 ) then
  do ii = 1, Nc
    ! diagonal components first
    StrnRt(ii,1) = JAC(ii)    * (                  &
      MT1(ii,1) * VelGradlst(ii,1)                 &
      + MT1(ii,2) * VelGradlst(ii,4)               &
      + MT1(ii,3) * VelGradlst(ii,7) )
    StrnRt(ii,4) = JAC(ii) * 0.5_rfreal * ( &
      MT1(ii,4) * VelGradlst(ii,1)                 &
      + MT1(ii,1) * VelGradlst(ii,2)               &
      + MT1(ii,5) * VelGradlst(ii,4)               &
      + MT1(ii,2) * VelGradlst(ii,5)               &
      + MT1(ii,6) * VelGradlst(ii,7)               &
      + MT1(ii,3) * VelGradlst(ii,8) )
  end do
  do ii = 1, Nc
    StrnRt(ii,2) = JAC(ii) * (                     &
      MT1(ii,4) * VelGradlst(ii,2)                 &
      + MT1(ii,5) * VelGradist(ii,5)               &
      + MT1(ii,6) * VelGradist(ii,8) )
    StrnRt(ii,6) = JAC(ii) * 0.5_rfreal * ( &
      MT1(ii,7) * VelGradist(ii,2)                 &
      + MT1(ii,4) * VelGradist(ii,3)               &
      + MT1(ii,8) * VelGradist(ii,5)               &
      + MT1(ii,5) * VelGradist(ii,6)               &
      + MT1(ii,9) * VelGradist(ii,8)               &
      + MT1(ii,6) * VelGradist(ii,9) )
  end do
  do ii = 1, Nc
    StrnRt(ii,3) = JAC(ii) * (                     &
      MT1(ii,7) * VelGradist(ii,3)                 &
      + MT1(ii,8) * VelGradist(ii,6)               &
      + MT1(ii,9) * VelGradist(ii,9) )
    StrnRt(ii,5) = JAC(ii) * 0.5_rfreal * ( &
      MT1(ii,7) * VelGradist(ii,1)                 &
      + MT1(ii,1) * VelGradlst(ii,3)               &
      + MT1(ii,8) * VelGradlst(ii,4)               &
      + MT1(ii,2) * VelGradlst(ii,6)               &
      + MT1(ii,9) * VelGradlst(ii,7)               &
      + MT1(ii,3) * VelGradlst(ii,9) )
  end do
end if
```

Illinois Coding Environment (ICE)

- One pragmatic approach
- Assumptions
  - Fast code requires some expert intervention
  - Can't all be done at compile time
  - Original code (in standard language) is maintained as reference
  - Can add information about computation to code
- Center for Exascale Simulation of Plasma-Coupled Combustion
  - http://xpacc.illinois.edu



- Approach
  - Annotations provide additional descriptive information
    - Block name, expected loop sizes, etc.
  - Source-to-source transformations used to create code for compiler
    - Exploit tool ecosystem – interface to existing tools
    - Original "Golden Copy" used for development, correctness checks
  - Database used to manage platform-specific versions; detect changes that invalidate transformed versions

Example: Dense Matrix Multiply

- Matrix Multiplication

```
#pragma @ICE loop=matmul
  for (i = 0; i < n; i++)
    for (j = 0; j < n; j++)
      for (k = 0; k < n; k++)
         mC[i][j] += mA[i][k] * mB[k][j];
#pragma @ICE endloop
```

+

```
---
#Compilation command before tests
buildcmd: make realclean;  make CC={compiler} COPT={params}

search:
  tool: opentuner
  time-limit: 30000
  variants-limit: 1000

buildoptions:
   gcc:
        params:{'-O':{'default': 3, 'min': 0, 'max': 3}}

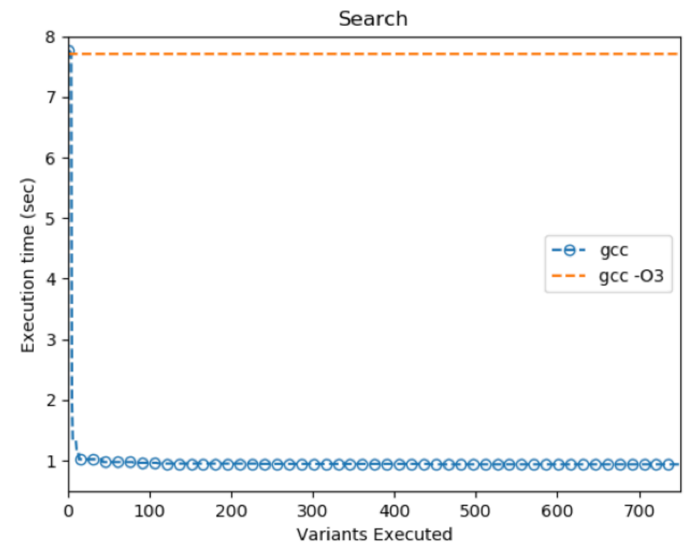
#Command call for each test
runcmd: ./mmc

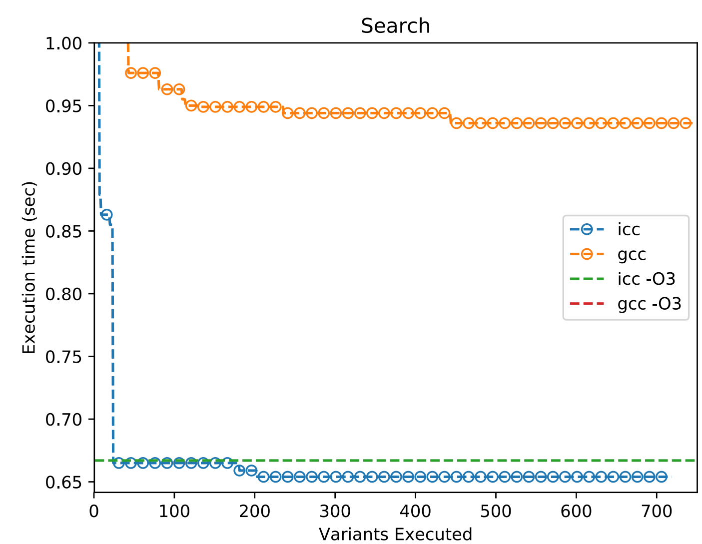
tuning: on

matmul:
      rose_uiuc:
          - stripmine+:
              loop: 3
              factor: 2..36
          - stripmine+:
              loop: 2
              factor: 2..48
          - interchange+:
              order: 1,3,0,2,4
          - unroll*:
              loop: 5
              factor: 2..24
…
```

Performance Results

- Dense matrix-matrix multiply
  - 302,680 total variants
  - Subset evaluated (based on results-so-far)
  - 8.2x speedup over gcc compiler with optimization
  - Small but consistent speedup over icc –O3
- Different parameters can be selected/remembered for each platform
  - Within the constraints of the performance parameters considered





Stencil 3D

```
#pragma @ICE loop=stencil
for(i = 1; i < x-1; i++) {
  for(j = 1; j < y-1; j++) {
    for(k = 1; k < z-1; k++) {
      B[i][j][k] = C0 * A[i][j][k] + C1 * (
                   A[i+1][j][k] + A[i-1][j][k] +
                   A[i][j+1][k] + A[i][j-1][k] +
                   A[i][j][k+1] + A[i][j][k-1]);
    }
  }
}
#pragma @ICE endloop
```

+

```
---
#Built command before compilation
prebuildcmd:

#Compilation command before tests
buildcmd:
    make realclean;  make CC={compiler} COPT={params}

buildoptions:
   gcc:
        params:{'-O':{'default': 3,'min': 0,'max': 3}}
   icc:
        params:{'-O':{'default': 3,'min': 0,'max': 3}}

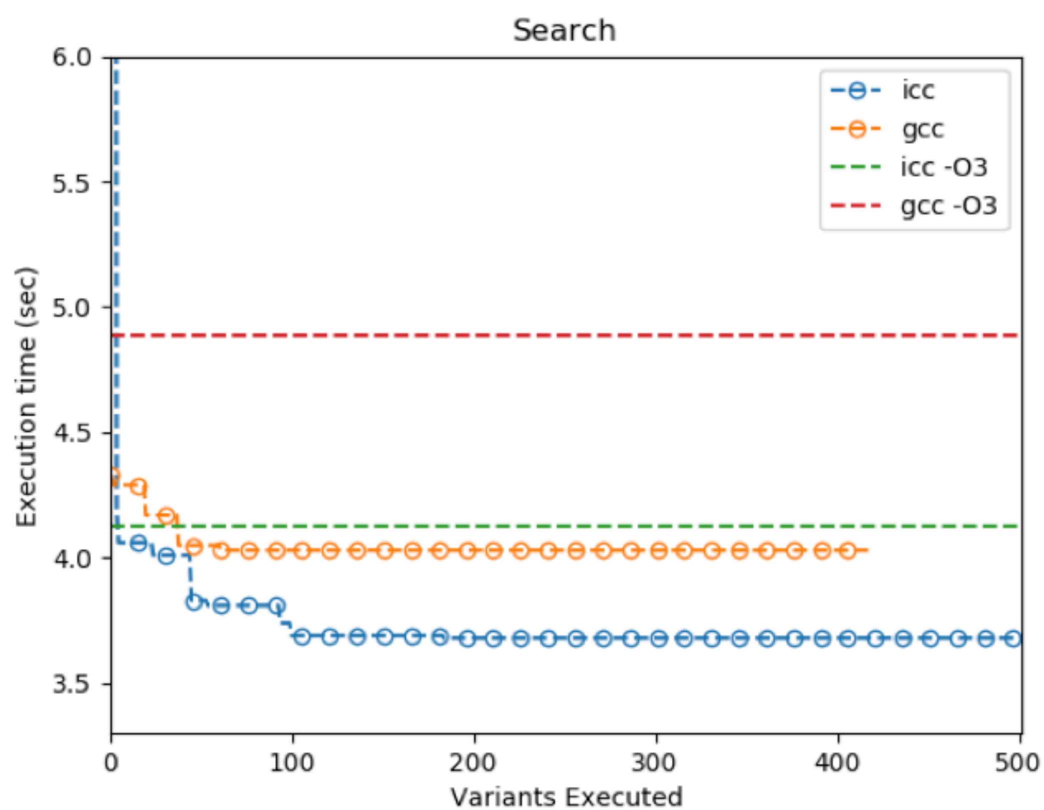
#Command call for each test
runcmd: ./sten3d 1024 20

tuning: on

stencil:
       rose_uiuc:
          - stripmine+:
              loop: 4
              factor: 16..1024
                type: poweroftwo
          - stripmine+:
              loop: 3
              factor: 16..1024
                type: poweroftwo
          - stripmine+:
              loop: 2
              factor: 16..1024
                type: poweroftwo
          - interchange+:
              order:0,1,3,5,2,4,6
...
```

Performance Results

- 3-D Stencil
  - 11,664 variants
  - Max 12.6 sec
  - Min 3.68 sec
  - Speedup over simple code
    - icc: 1.12x
    - gcc: 1.21x



Other Dangers

- How do we know that the performance portable code is correct?
  - Or even if it will compute the same result as the original code
    - And what is “the same result”?
- It is *not enough* to prove that any code transformations are correct
  - MPICH used to test whether the compiler returned the same result in a and c for these two statements:
    - ```
      a = joe->array[OFF+b+1];
      c = joe->array[OFF+1+b];
      ```
  - Because one major vendor compiler got this ***wrong***.
- And you still need to prove that the hardware implements all of the operations correctly
  - And vectorization is already likely to produce results that are not bitwise identical to the non-vector version (which might depend on how data is aligned at runtime)
- Question: How do you test that the performance portable code is computing what is intended?
- Proving code transformations correct is *necessary* but not *sufficient*
      ```

So What Is Performance Portability?

- Rather than define whether a code is (or is not) performance portable, look at the goals
  - Make it easier for end users to run an application code effectively on different systems
    - for some set of systems – not necessarily every possible system
    - May focus on the workflow or the I/O performance, rather than any single code
  - Make it easier for developers to write, tune, and maintain an application for multiple systems
    - Allows a tradeoff between one code and several, based on what's *easier*

Summary

- Don't underestimate the difficulty
  - I don't believe "strong" performance portability is possible
- Don't give up
  - There is a lot that can be done to support users and improve performance resilience
- Accept different approaches
  - Different communities, expectations, goals
- Be precise about your goal and accomplishment
  - Let this be a No Hype zone