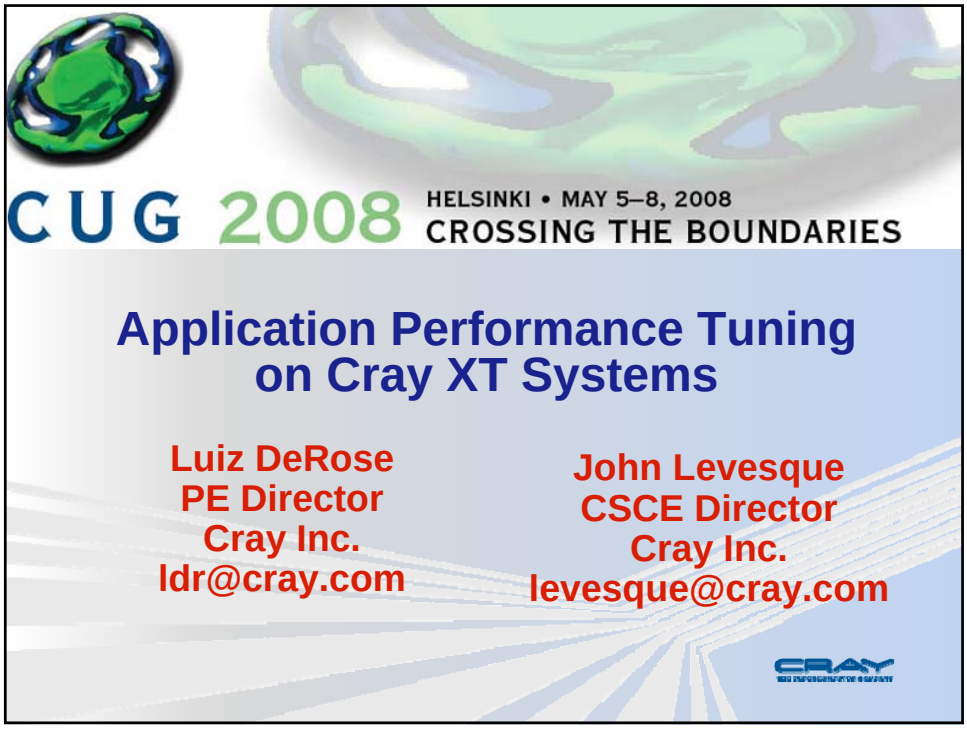
CUG 2008
HELSINKI • MAY 5–8, 2008
CROSSING THE BOUNDARIES
Application Performance Tuning
on Cray XT Systems
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PE Director
Cray Inc.
ldr@cray.com
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CRAY

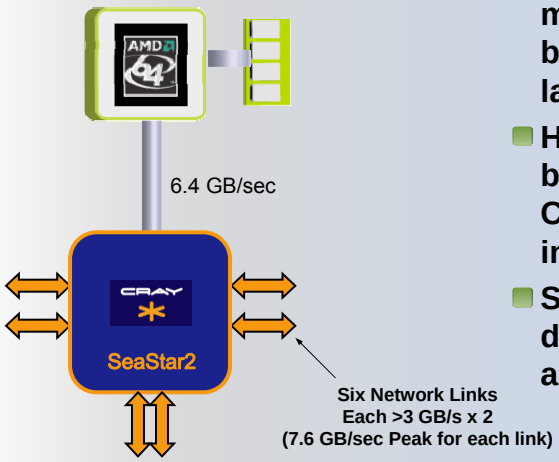

The Cray XT4 System
CRAY

Recipe for a good MPP

1. Select Best Microprocessor
2. Surround it with a balanced or "bandwidth rich" environment
3. "Scale" the System
   - Eliminate Operating System Interference (OS Jitter)
   - Design in Reliability and Resiliency
   - Provide Scaleable System Management
   - Provide Scalable I/O
   - Provide Scalable Programming and Performance Tools
   - System Service Life (provide an upgrade path)

AMD Opteron: Why we selected it

CRAY XT4 PE



- Direct attached local memory for leading bandwidth and latency
- HyperTransport can be directly attached to Cray SeaStar2 interconnect
- Simple two-chip design saves power and complexity

Recipe for a good MPP

1. ~~Select Best Microprocessor~~
2. Surround it with a balanced or "bandwidth rich" environment
3. ~~"Scale" the System~~
   - Eliminate Operating System Interference (OS Jitter)
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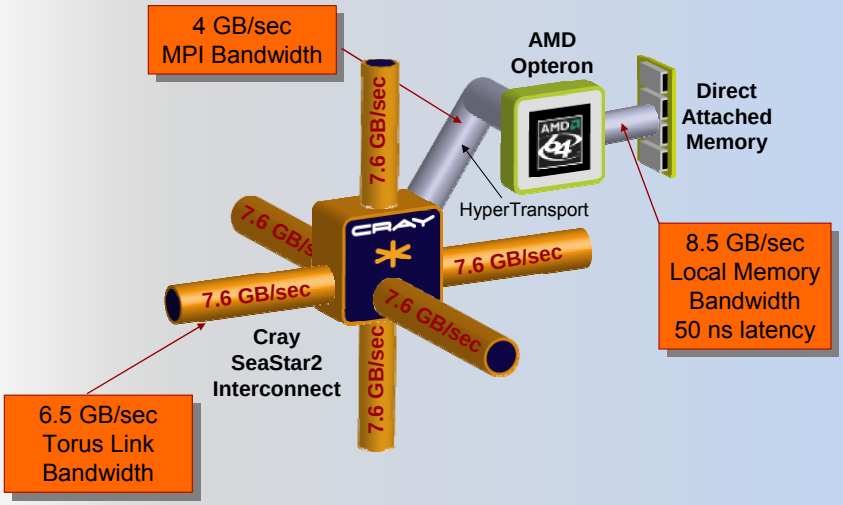
   - Provide Scalable I/O
   - Provide Scalable Programming and Performance Tools
   - System Service Life (provide an upgrade path)

The Cray XT4 Processing Element: Providing a bandwidth-rich environment



Recipe for a good MPP

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   - Provide Scalable Programming and Performance Tools
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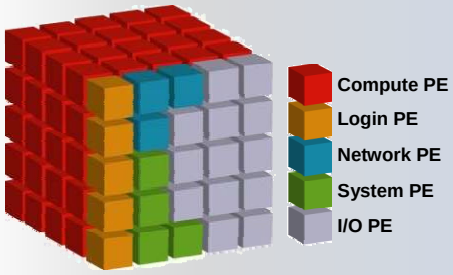
Scalable Software Architecture: UNICOS/lc

"*Primum non nocere*"



Service Partition

Specialized Linux nodes

- Microkernel on Compute PEs, full featured Linux on Service PEs.
- Service PEs specialize by function
- Software Architecture eliminates OS "Jitter"
- Software Architecture enables reproducible run times
- Large machines boot in under 30 minutes, including filesystem

This is the real reason the XT4 will scale to a Petaflop

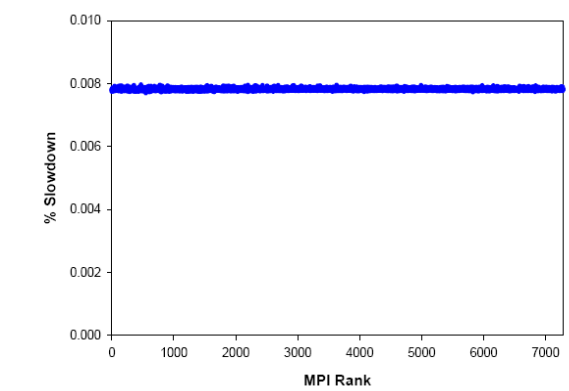


Figure 3: Slowdown caused by computational "noise"

Download P-SNAP from the web and try it on your system

Dual Core

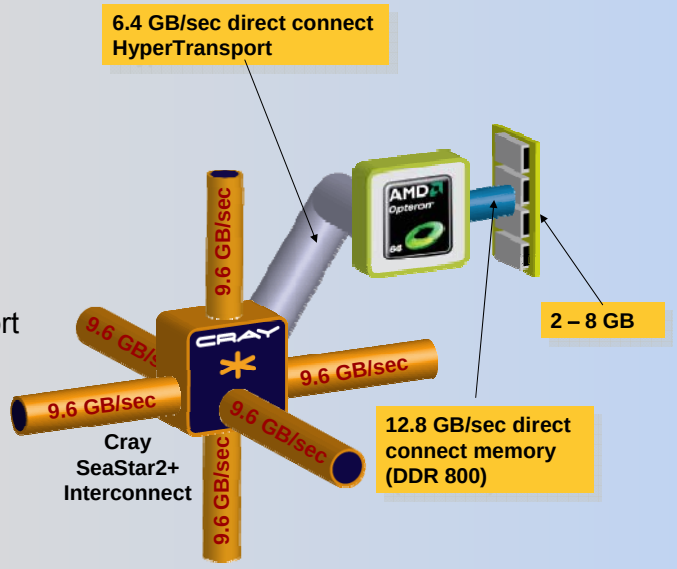
- Core
  - 2.6Ghz clock frequency
  - SSE SIMD FPU (2flops/cycle = 5.2GF peak)
- Cache Hierarchy
  - L1 Dcache/Icache: 64k/core
  - L2 D/I cache: 1M/core
  - SW Prefetch and loads to L1
  - Evictions and HW prefetch to L2
- Memory
  - Dual Channel DDR2
  - 10GB/s peak @ 667MHz
  - 8GB/s nominal STREAMs

Quad Core

- Core
  - 2.2Ghz clock frequency
  - SSE SIMD FPU (4flops/cycle = 8.8GF peak)
- Cache Hierarchy
  - L1 Dcache/Icache: 64k/core
  - L2 D/I cache: 512 KB/core
  - L3 Shared cache 2MB/Socket
  - SW Prefetch and loads to L1,L2,L3
  - Evictions and HW prefetch to L1,L2,L3
- Memory
  - Dual Channel DDR2
  - 10GB/s peak @ 800MHz
  - 10GB/s nominal STREAMs

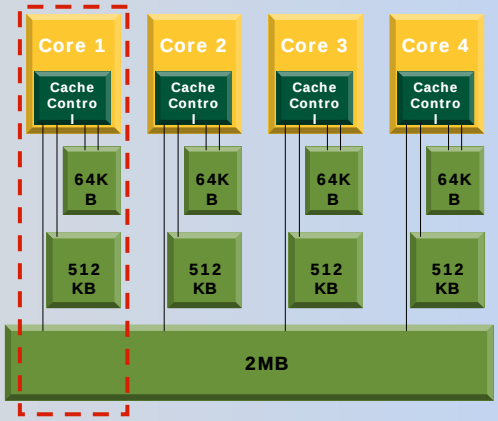
Cray XT4 Node

- 4-way SMP
- >35 Gflops per node
- Up to 8 GB per node
- OpenMP Support within socket



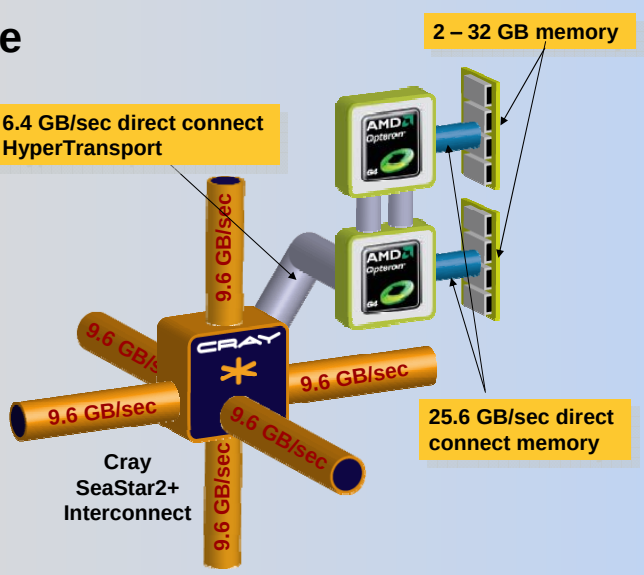
Cache Hierarchy

- Dedicated L1 cache
  - 2 way associativity.
  - 8 banks.
  - 2 128bit loads per cycle.
- Dedicated L2 cache
  - 16 way associativity.
- Shared L3 cache
  - fills from L3 leave likely shared lines in L3.
  - sharing aware replacement policy.

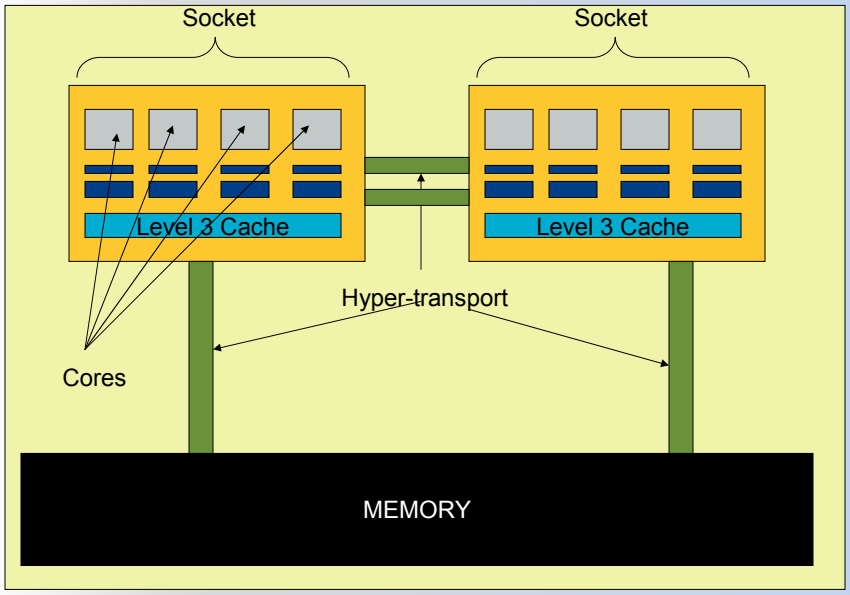


Cray XT5 Node

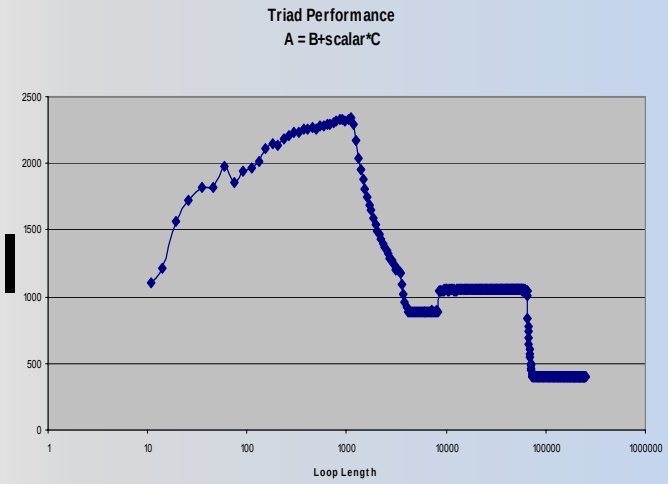
- 8-way SMP
- >70 Gflops per node
- Up to 32 GB of shared memory per node
- OpenMP Support



The Barcelona Node (XT5)



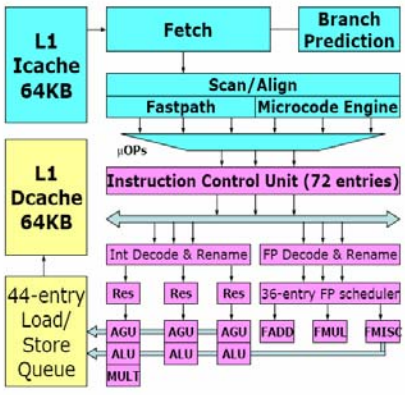
Performance = F(Cache Utilization)



Core IPC improvements

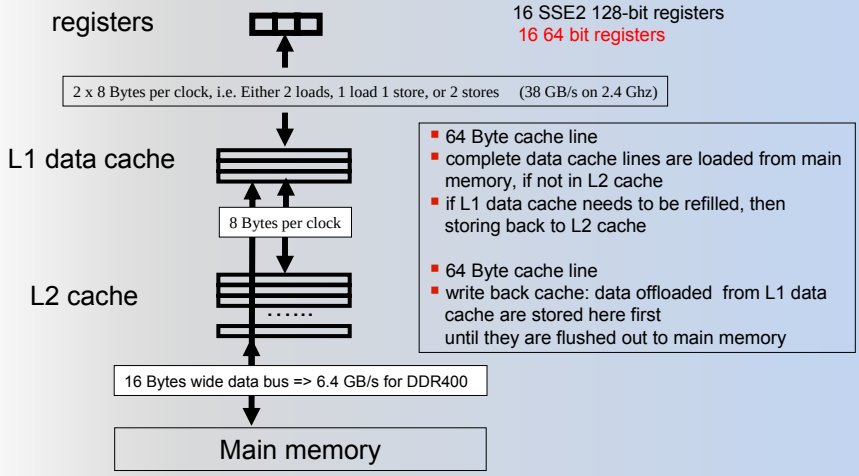
AMD Smarter Choice

- Improve Branch Prediction.
- TLB enhancements.
- More out of order Ld/St capability.
- New Instructions
  - POPCNT / LZCNT
  - EXTRQ / INSERTQ
  - MOVNTSD / MOVNTSS
- Fastpath support for FP to Integer data movement.



6 February 22, 2008

Simplified memory hierachy on the AMD Opteron



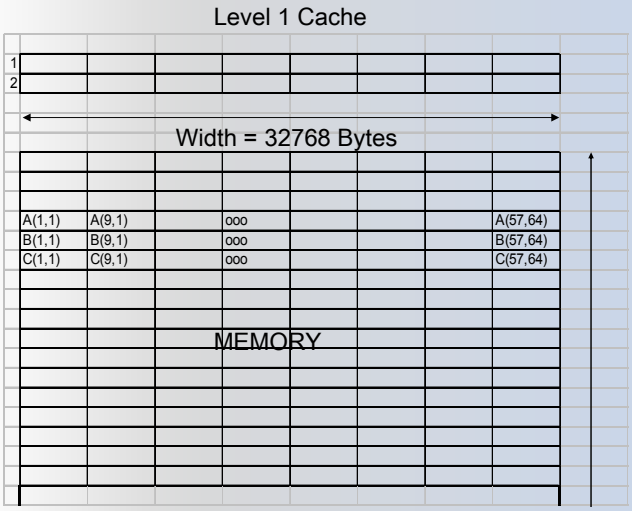
- 64 Byte cache line
- complete data cache lines are loaded from main memory, if not in L2 cache
- if L1 data cache needs to be refilled, then storing back to L2 cache

- 64 Byte cache line
- write back cache: data offloaded from L1 data cache are stored here first until they are flushed out to main memory


```
Real * 8      A(64,64),B(64,64),C(64,64)

DO I = 1,N
      C(I,1) = A(I,1) +B(I,1)
ENDDO
```

Cache Visualization



Level 1 Cache
- 65536 B
- 1024 Lines
- 8192 8B Ws
- 16384 4B Ws
- 2 way Assoc

Associativity Class
- 32768 B
- 512 Lines
- 4096 8B Ws
- 8192 4B Ws

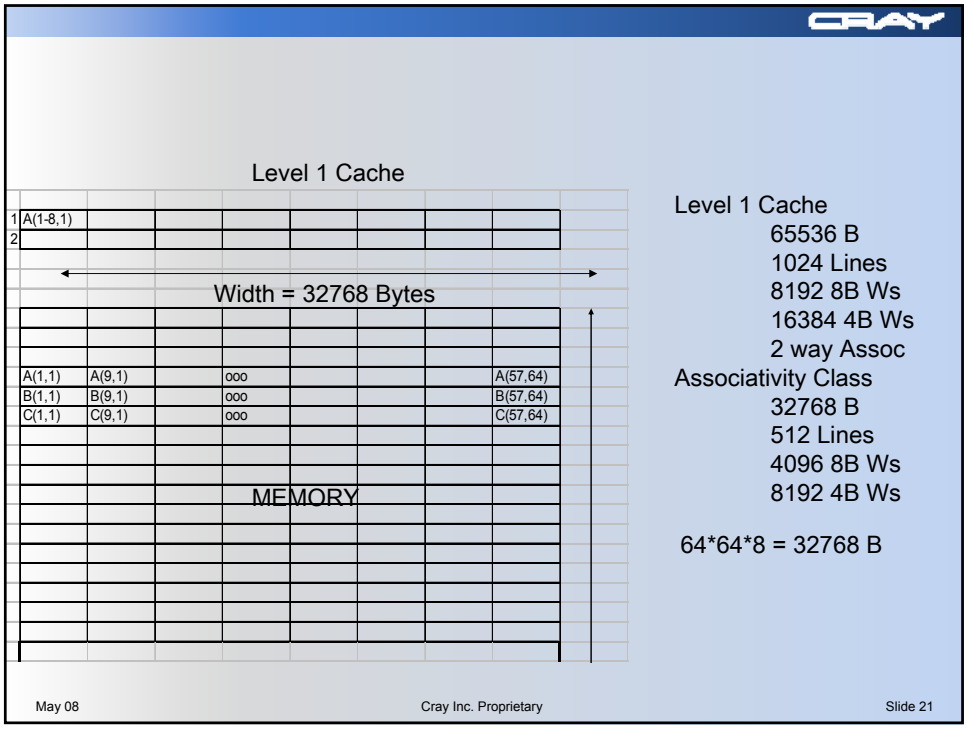
64*64*8 = 32768 B

Consider the following example

```
Real * 8          A(64,64),B(64,64),C(64,64)

DO I = 1,N
      C(I,1) = A(I,1) +B(I,1)
ENDDO

Fetch A(1,1)                Fetch from M Uses 1 Associativity Class
```


Level 1 Cache
1 A(1-8,1)
2
Width = 32768 Bytes
A(1,1) A(9,1) ooo A(57,64)
B(1,1) B(9,1) ooo B(57,64)
C(1,1) C(9,1) ooo C(57,64)
MEMORY
Level 1 Cache
65536 B
1024 Lines
8192 8B Ws
16384 4B Ws
2 way Assoc
Associativity Class
32768 B
512 Lines
4096 8B Ws
8192 4B Ws
64*64*8 = 32768 B
May 08
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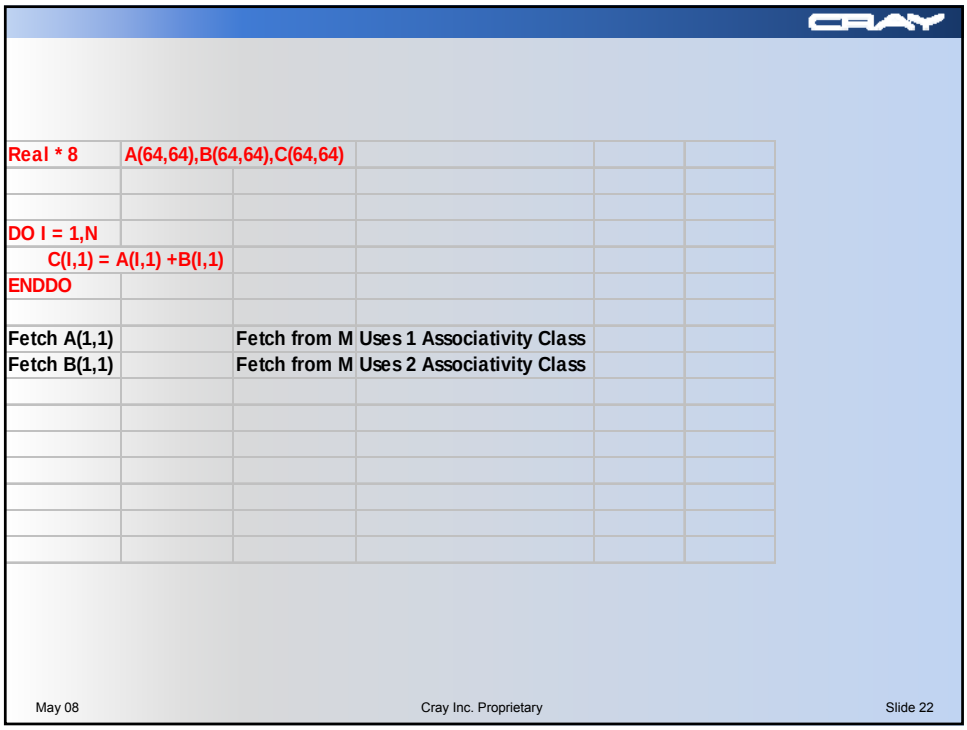
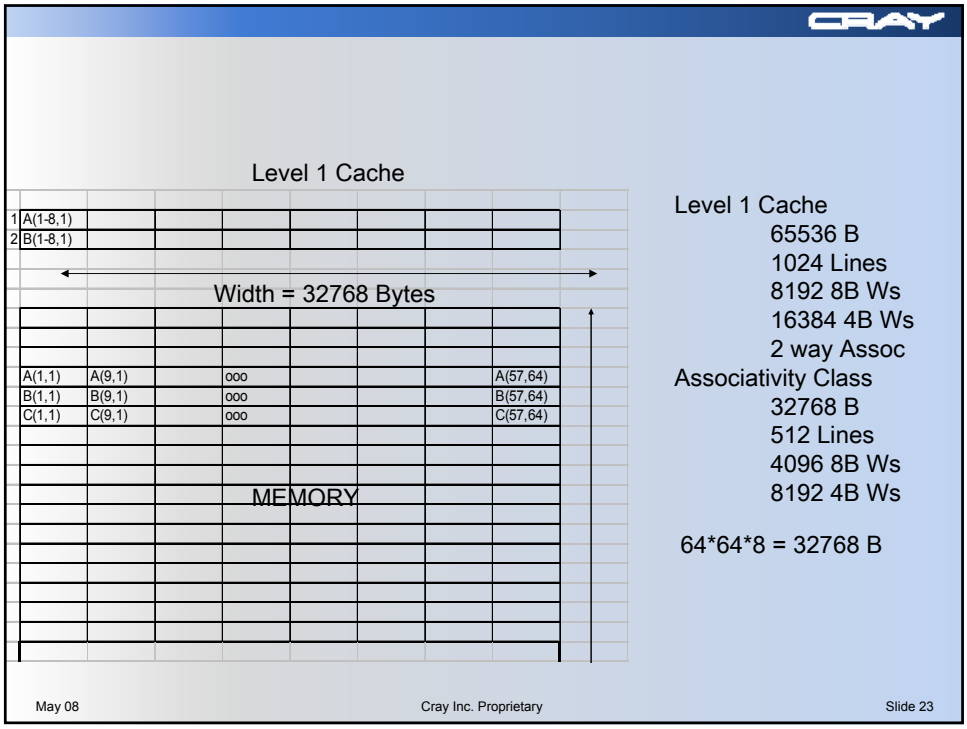
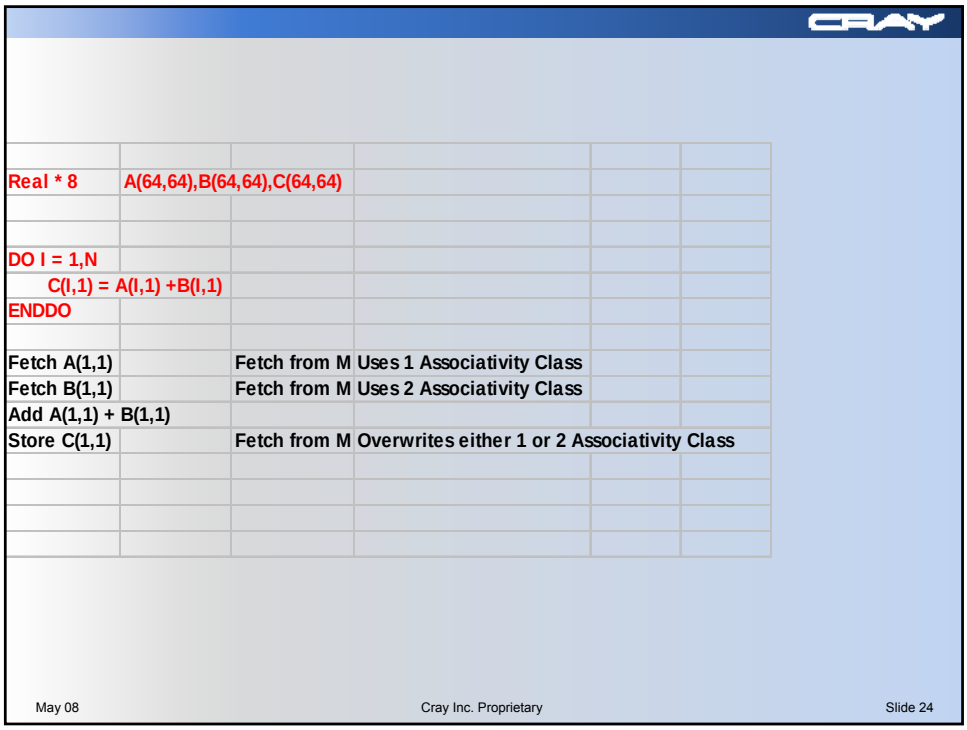
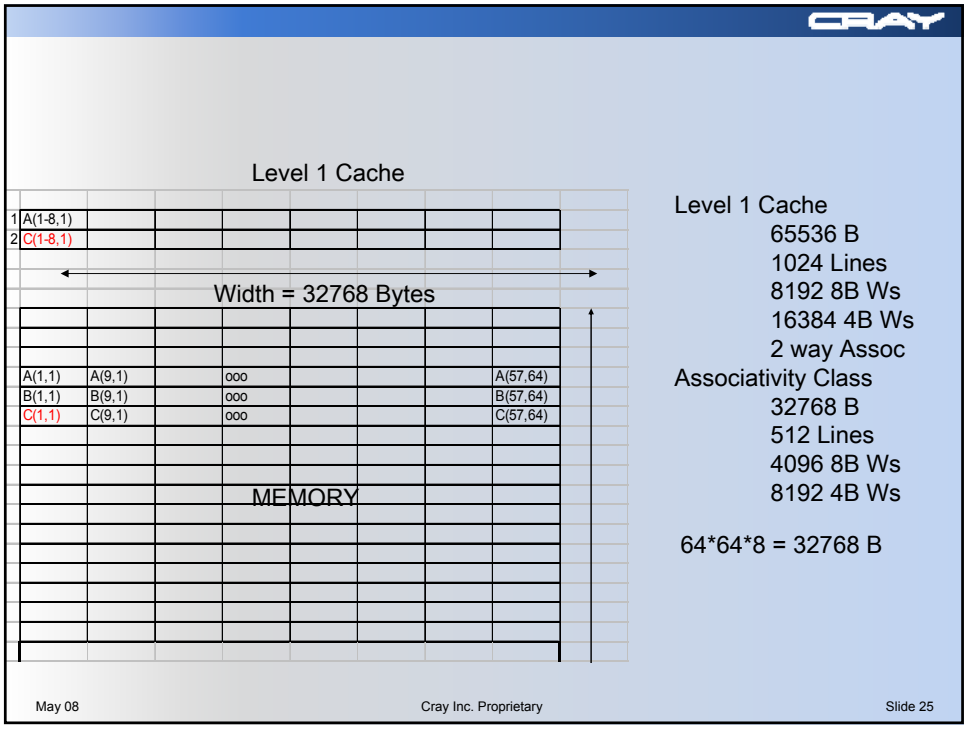
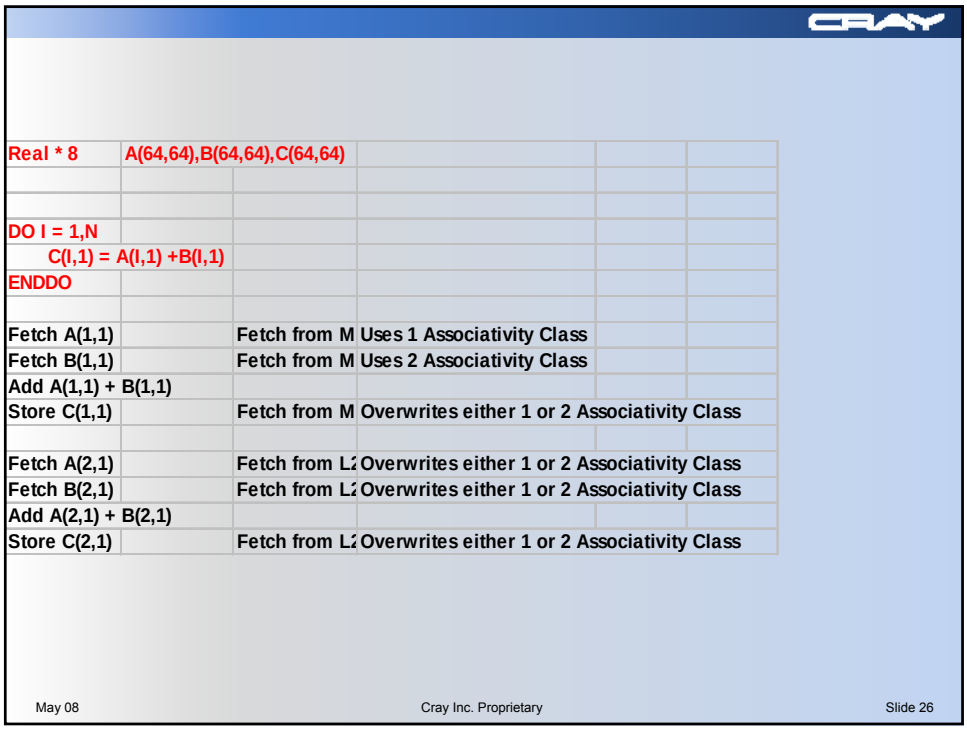
Slide 21


Real * 8 A(64,64),B(64,64),C(64,64)
DO I = 1,N
C(I,1) = A(I,1) +B(I,1)
ENDDO
Fetch A(1,1) Fetch from M Uses 1 Associativity Class
Fetch B(1,1) Fetch from M Uses 2 Associativity Class
May 08
Cray Inc. Proprietary
Slide 22


Level 1 Cache
1 A(1-8,1)
2 B(1-8,1)
Width = 32768 Bytes
A(1,1) A(9,1) ooo A(57,64)
B(1,1) B(9,1) ooo B(57,64)
C(1,1) C(9,1) ooo C(57,64)
MEMORY
Level 1 Cache
65536 B
1024 Lines
8192 8B Ws
16384 4B Ws
2 way Assoc
Associativity Class
32768 B
512 Lines
4096 8B Ws
8192 4B Ws
64*64*8 = 32768 B
May 08
Cray Inc. Proprietary
Slide 23

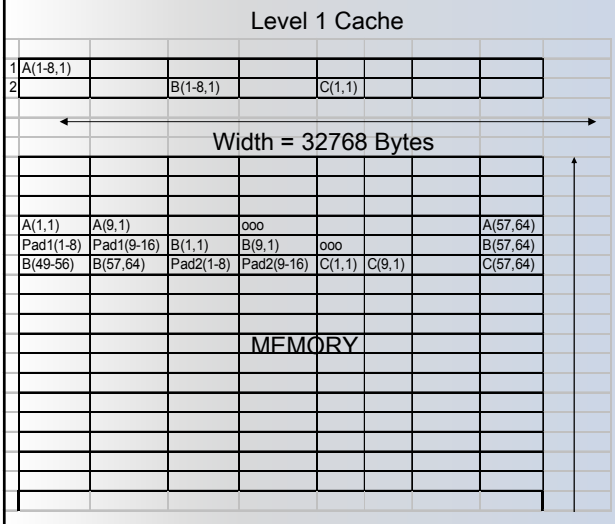

Real * 8 A(64,64),B(64,64),C(64,64)
DO I = 1,N
C(I,1) = A(I,1) +B(I,1)
ENDDO
Fetch A(1,1) Fetch from M Uses 1 Associativity Class
Fetch B(1,1) Fetch from M Uses 2 Associativity Class
Add A(1,1) + B(1,1)
Store C(1,1) Fetch from M Overwrites either 1 or 2 Associativity Class
May 08
Cray Inc. Proprietary
Slide 24


Level 1 Cache
1 A(1-8,1)
2 C(1-8,1)
Width = 32768 Bytes
A(1,1) A(9,1) ooo A(57,64)
B(1,1) B(9,1) ooo B(57,64)
C(1,1) C(9,1) ooo C(57,64)
MEMORY
Level 1 Cache
65536 B
1024 Lines
8192 8B Ws
16384 4B Ws
2 way Assoc
Associativity Class
32768 B
512 Lines
4096 8B Ws
8192 4B Ws
64*64*8 = 32768 B
May 08
Cray Inc. Proprietary
Slide 25


Real * 8 A(64,64),B(64,64),C(64,64)
DO I = 1,N
C(I,1) = A(I,1) +B(I,1)
ENDDO
Fetch A(1,1) Fetch from M Uses 1 Associativity Class
Fetch B(1,1) Fetch from M Uses 2 Associativity Class
Add A(1,1) + B(1,1)
Store C(1,1) Fetch from M Overwrites either 1 or 2 Associativity Class
Fetch A(2,1) Fetch from L Overwrites either 1 or 2 Associativity Class
Fetch B(2,1) Fetch from L Overwrites either 1 or 2 Associativity Class
Add A(2,1) + B(2,1)
Store C(2,1) Fetch from L Overwrites either 1 or 2 Associativity Class
May 08
Cray Inc. Proprietary
Slide 26

Must be a better Way

```
Real * 8    A(64,64),pad1(16),B(64,64),pad2(16),C(64,64)

DO I = 1,N
      C(I,1) = A(I,1) +B(I,1)
ENDDO
```

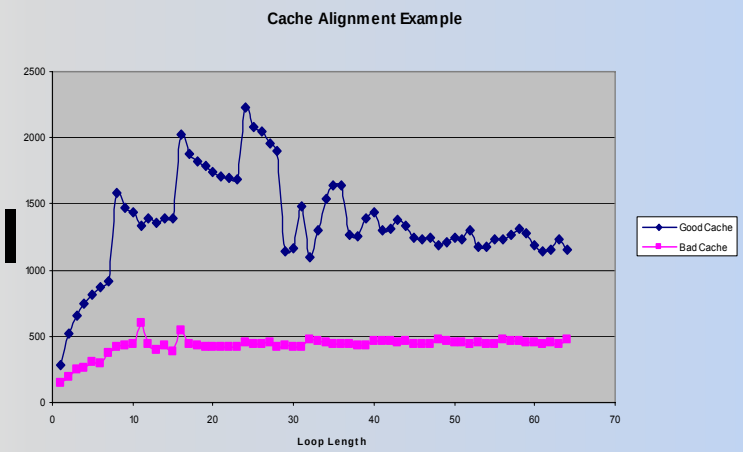



Level 1 Cache
- 65536 B
- 1024 Lines
- 8192 8B Ws
- 16384 4B Ws
- 2 way Assoc

Associativity Class
- 32768 B
- 512 Lines
- 4096 8B Ws
- 8192 4B Ws

64*64*8 = 32768 B

Real * 8	A(64,64),pad1(16),B(64,64),pad2(16),C(64,64)				
DO I = 1,N					
C(I,1) = A(I,1) +B(I,1)					
ENDDO					
Fetch A(1)		Uses 1 Associativity Class			
Fetch B(1)		Uses 2 Associativity Class			
Add A(1) + B(1)					
Store C(1)		Uses 1 Associativity Class			
Fetch A(2)		Gets from L1 Cache			
Fetch B(2)		Gets from L1 Cache			
Add A(2) + B(2)					
Store C(2)		Gets from L1 Cache			

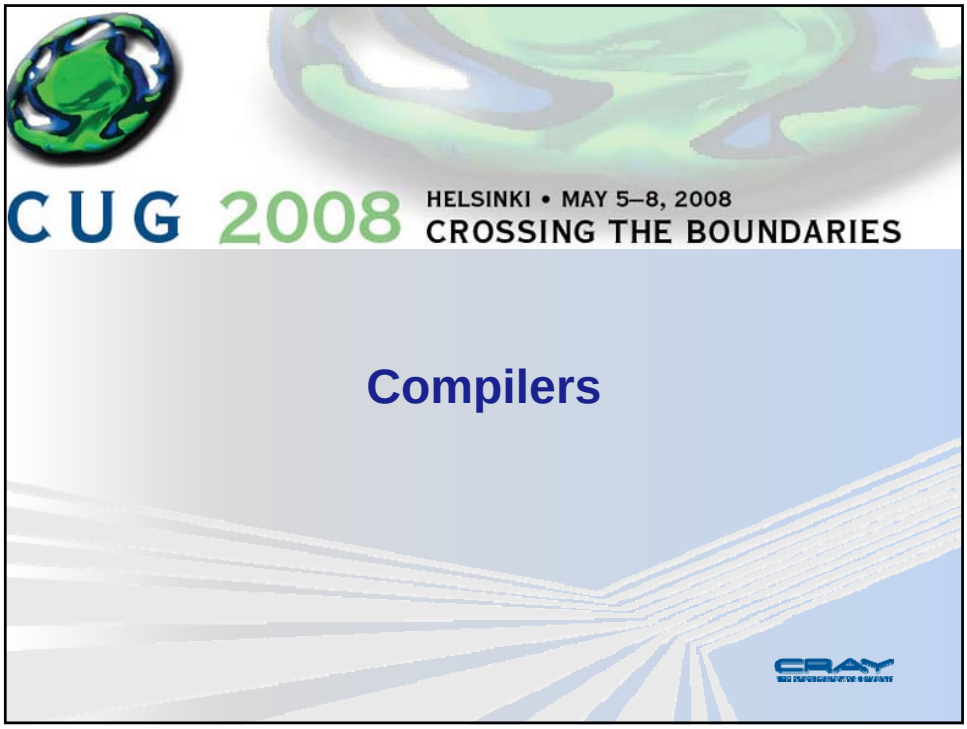


Bad Cache Alignment

Time%		0.2%
Time		0.000003
Calls		1
PAPI_L1_DCA	455.433M/sec	1367 ops
DC_L2_REFILL_MOESI	49.641M/sec	149 ops
DC_SYS_REFILL_MOESI	0.666M/sec	2 ops
BU_L2_REQ_DC	74.628M/sec	224 req
User time	0.000 secs	7804 cycles
Utilization rate		97.9%
L1 Data cache misses	50.308M/sec	151 misses
LD & ST per D1 miss		9.05 ops/miss
D1 cache hit ratio		89.0%
LD & ST per D2 miss		683.50 ops/miss
D2 cache hit ratio		99.1%
L2 cache hit ratio		98.7%
Memory to D1 refill	0.666M/sec	2 lines
Memory to D1 bandwidth	40.669MB/sec	128 bytes
L2 to Dcache bandwidth	3029.859MB/sec	9536 bytes

Good Cache Alignment

Time%		0.1%
Time		0.000002
Calls		1
PAPI_L1_DCA	689.986M/sec	1333 ops
DC_L2_REFILL_MOESI	33.645M/sec	65 ops
DC_SYS_REFILL_MOESI		0 ops
BU_L2_REQ_DC	34.163M/sec	66 req
User time	0.000 secs	5023 cycles
Utilization rate		95.1%
L1 Data cache misses	33.645M/sec	65 misses
LD & ST per D1 miss		20.51 ops/miss
D1 cache hit ratio		95.1%
LD & ST per D2 miss		1333.00 ops/miss
D2 cache hit ratio		100.0%
L2 cache hit ratio		100.0%
Memory to D1 refill		0 lines
Memory to D1 bandwidth		0 bytes
L2 to Dcache bandwidth	2053.542MB/sec	4160 bytes



PGI

- Recommended first compile/run
  - -fastsse –tp barcelona-64
- Get diagnostics
  - -Minfo –Mneginfo
- Inlining
  - **–Mipa=fast,inline**
- Recognize OpenMP directives
  - -mp=nonuma
- **Automatic parallelization**
  - **-Mconcur**

Pathscale

- Recommended first compile/run
  - Ftn –O3 –OPT:Ofast -march=barcelona
- Get Diagnostics
  - -LNO:simd_verbose=ON
- Inlining
  - -ipa
- Recognize OpenMP directives
  - -mp
- **Automatic parallelization**
  - **-apo**

PGI Basic Compiler Usage

- A compiler driver interprets options and invokes pre-processors, compilers, assembler, linker, etc.
- Options precedence: if options conflict, last option on command line takes precedence
- Use -Minfo to see a listing of optimizations and transformations performed by the compiler
- Use -help to list all options or see details on how to use a given option, e.g. pgf90 -Mvect -help
- Use man pages for more details on options, e.g. "man pgf90"
- Use –v to see under the hood

Flags to support language dialects

- Fortran
  - pgf77, pgf90, pgf95, pghpf tools
  - Suffixes .f, .F, .for, .fpp, .f90, .F90, .f95, .F95, .hpf, .HPF
  - -Mextend, -Mfixed, -Mfreeform
  - Type size –i2, -i4, -i8, -r4, -r8, etc.
  - -Mcray, -Mbyteswapio, -Mupcase, -Mnomain, -Mrecursive, etc.
- C/C++
  - pgcc, pgCC, aka pgcpp
  - Suffixes .c, .C, .cc, .cpp, .i
  - -B, -c89, -c9x, -Xa, -Xc, -Xs, -Xt
  - -Msignextend, -Mfcon, -Msingle, -Muchar, -Mgccbugs

Specifying the target architecture

- **Use the “tp” switch. Don’t need for Dual Core**
  - **-tp k8-64 or –tp p7-64 or –tp core2-64 for 64-bit code.**
  - **-tp amd64e for AMD opteron rev E or later**
  - **-tp x64 for unified binary**
  - **-tp k8-32, k7, p7, piv, piii, p6, p5, px for 32 bit code**
  - **-tp barcelona-64**

Flags for debugging aids

- **-g generates symbolic debug information used by a debugger**
- **-gopt generates debug information in the presence of optimization**
- **-Mbounds adds array bounds checking**
- **-v gives verbose output, useful for debugging system or build problems**
- **-Mlist will generate a listing**
- **-Minfo provides feedback on optimizations made by the compiler**
- **-S or –Mkeepasm to see the exact assembly generated**

Basic optimization switches

- **Traditional optimization controlled through -O[<n>], n is 0 to 4.**
- **-fast switch combines common set into one simple switch, is equal to -O2 -Munroll=c:1 -Mnoframe -Mlre**
  - **For -Munroll, c specifies completely unroll loops with this loop count or less**
  - **-Munroll=n:<m> says unroll other loops m times**
- **-Mlre is loop-carried redundancy elimination**

Basic optimization switches, cont.

- **fastsse switch is commonly used, extends –fast to SSE hardware, and vectorization**
- **-fastsse is equal to -O2 -Munroll=c:1 -Mnoframe -Mlre (-fast) plus -Mvect=sse, -Mscalarsse -Mcache_align, -Mflushz**
- **-Mcache_align aligns top level arrays and objects on cache-line boundaries**
- **-Mflushz flushes SSE denormal numbers to zero**

Node level tuning

- **Vectorization** – packed SSE instructions maximize performance
- **Interprocedural Analysis (IPA)** – use it! motivating examples
- **Function Inlining –** especially important for C and C++
- **Parallelization** – for Cray multi-core processors
- **Miscellaneous Optimizations** – hit or miss, but worth a try

Vectorizable F90 Array Syntax
Data is REAL*4

```
350 !
351 !   Initialize vertex, similarity and coordinate arrays
352 !
353     Do Index = 1, NodeCount
354       IX = MOD (Index - 1, NodesX) + 1
355       IY = ((Index - 1) / NodesX) + 1
356       CoordX (IX, IY) = Position (1) + (IX - 1) * StepX
357       CoordY (IX, IY) = Position (2) + (IY - 1) * StepY
358       JetSim (Index)  = SUM (Graph (:, :, Index) * &
359     &                   GaborTrafo (:, :, CoordX(IX,IY), CoordY(IX,IY)))
360       VertexX (Index) = MOD (Params%Graph%RandomIndex (Index) - 1, NodesX) + 1
361       VertexY (Index) = ((Params%Graph%RandomIndex (Index) - 1) / NodesX) + 1
362     End Do
```

Inner “loop” at line 358 is vectorizable, can used packed SSE instructions

–fastsse to Enable SSE Vectorization
–Minfo to List Optimizations to stderr

```
% pgf95 -fastsse -Mipa=fast -Minfo -S graphRoutines.f90
…
localmove:
  334, Loop unrolled 1 times (completely unrolled)
  343, Loop unrolled 2 times (completely unrolled)
  358, Generated an alternate loop for the inner loop
       Generated vector sse code for inner loop
       Generated 2 prefetch instructions for this loop
       Generated vector sse code for inner loop
       Generated 2 prefetch instructions for this loop
  …
```


Scalar SSE:

```
.LB6_668:
# lineno: 358
      movss   -12(%rax),%xmm2
      movss   -4(%rax),%xmm3
      subl    $1,%edx
      mulss   -12(%rcx),%xmm2
      addss   %xmm0,%xmm2
      mulss   -4(%rcx),%xmm3
      movss   -8(%rax),%xmm0
      mulss   -8(%rcx),%xmm0
      addss   %xmm0,%xmm2
      movss   (%rax),%xmm0
      addq    $16,%rax
      addss   %xmm3,%xmm2
      mulss   (%rcx),%xmm0
      addq    $16,%rcx
      testl   %edx,%edx
      addss   %xmm0,%xmm2
      movaps  %xmm2,%xmm0
      jg      .LB6_625
```

Vector SSE:

```
.LB6_1245:
# lineno: 358
      movlps  (%rdx,%rcx),%xmm2
      subl    $8,%eax
      movlps  16(%rcx,%rdx),%xmm3
      prefetcht0  64(%rcx,%rsi)
      prefetcht0  64(%rcx,%rdx)
      movhps  8(%rcx,%rdx),%xmm2
      mulps   (%rsi,%rcx),%xmm2
      movhps  24(%rcx,%rdx),%xmm3
      addps   %xmm2,%xmm0
      mulps   16(%rcx,%rsi),%xmm3
      addq    $32,%rcx
      testl   %eax,%eax
      addps   %xmm3,%xmm0
      jg      .LB6_1245:
```

Facerec Scalar: 104.2 sec
Facerec Vector: 84.3 sec

Vectorizable C Code Fragment?

```
217   void func4(float *u1, float *u2, float *u3, …
      …
221   for (i = -NE+1, p1 = u2-ny, p2 = n2+ny; i < nx+NE-1; i++)
222       u3[i] += clz * (p1[i] + p2[i]);
223   for (i = -NI+1, i < nx+NE-1; i++) {
224       float vdt = v[i] * dt;
225       u3[i] = 2.*u2[i]-u1[i]+vdt*vdt*u3[i];
226   }
```

```
% pgcc –fastsse –Minfo functions.c
func4:
    221, Loop unrolled 4 times
    221, Loop not vectorized due to data dependency
    223, Loop not vectorized due to data dependency
```

Pointer Arguments Inhibit Vectorization

```
217   void func4(float *u1, float *u2, float *u3, …
      …
221   for (i = -NE+1, p1 = u2-ny, p2 = n2+ny; i < nx+NE-1; i++)
222       u3[i] += clz * (p1[i] + p2[i]);
223   for (i = -NI+1, i < nx+NE-1; i++) {
224       float vdt = v[i] * dt;
225       u3[i] = 2.*u2[i]-u1[i]+vdt*vdt*u3[i];
226   }
```

```
% pgcc –fastsse –Msafeptr –Minfo functions.c
func4:
    221, Generated vector SSE code for inner loop
         Generated 3 prefetch instructions for this loop
    223, Unrolled inner loop 4 times
```

C Constant Inhibits Vectorization

```
217   void func4(float *u1, float *u2, float *u3, …
      …
221   for (i = -NE+1, p1 = u2-ny, p2 = n2+ny; i < nx+NE-1; i++)
222         u3[i] += clz * (p1[i] + p2[i]);
223   for (i = -NI+1, i < nx+NE-1; i++) {
224         float vdt = v[i] * dt;
225         u3[i] = 2.*u2[i]-u1[i]+vdt*vdt*u3[i];
226   }
```

```
% pgcc –fastsse –Msafeptr –Mfcon –Minfo functions.c
func4:
    221, Generated vector SSE code for inner loop
         Generated 3 prefetch instructions for this loop
    223, Generated vector SSE code for inner loop
         Generated 4 prefetch instructions for this loop
```

-Msafeptr Option and Pragma

–M[no]safeptr[=all | arg | auto | dummy | local | static | global]

all	All pointers are safe
arg	Argument pointers are safe
local	local pointers are safe
static	static local pointers are safe
global	global pointers are safe

#pragma [*scope*] [no]safeptr={arg | local | global | static | all},…

Where *scope* is *global*, *routine* or *loop*

Common Barriers to SSE Vectorization

- **Potential Dependencies & C Pointers** – Give compiler more info with –Msafeptr, pragmas, or restrict type qualifer
- **Function Calls** – Try inlining with –Minline or –Mipa=inline
- **Type conversions** – manually convert constants or use flags
- **Large Number of Statements** – Try –Mvect=nosizelimit
- **Too few iterations** – Usually better to unroll the loop
- **Real dependencies** – Must restructure loop, if possible

Barriers to Efficient Execution of Vector SSE Loops

- **Not enough work – vectors are too short**
- **Vectors not aligned to a cache line boundary**
- **Non unity strides**
- **Code bloat if altcode is generated**

What can Interprocedural Analysis and Optimization with –Mipa do for You?

- **Interprocedural constant propagation**
- **Pointer disambiguation**
- **Alignment detection, Alignment propagation**
- **Global variable mod/ref detection**
- **F90 shape propagation**
- **Function inlining**
- **IPA optimization of libraries, including inlining**

Effect of IPA on the WUPWISE Benchmark

PGF95 Compiler Options	Execution Time in Seconds
–fastsse	156.49
–fastsse –Mipa=fast	121.65
–fastsse –Mipa=fast,inline	91.72

- **–Mipa=fast => constant propagation => compiler sees complex matrices are all 4x3 => completely unrolls loops**
- **–Mipa=fast,inline => small matrix multiplies are all inlined**

Using Interprocedural Analysis

- **Must be used at both compile time and link time**
- **Non-disruptive to development process – edit/build/run**
- **Speed-ups of 5% - 10% are common**
- **–Mipa=safe:<*name*> - safe to optimize functions which call or are called from unknown function/library *name***
- **–Mipa=libopt – perform IPA optimizations on libraries**
- **–Mipa=libinline – perform IPA inlining from libraries**

Explicit Function Inlining

–Minline[=[lib:]<inlib> | [name:]<func> | except:<func> | size:<n> | levels:<n>]

[lib:]<inlib>	Inline extracted functions from *inlib*
[name:]<func>	Inline function func
except:<func>	Do not inline function func
size:<n>	Inline only functions smaller than n statements (approximate)
levels:<n>	Inline n levels of functions

For C++ Codes, PGI Recommends IPA-based inlining or –Minline=levels:10!

Other C++ recommendations

- **Encapsulation, Data Hiding -** small functions, inline!
- **Exception Handling –** use –no_exceptions until 7.0
- **Overloaded operators, overloaded functions -** okay
- **Pointer Chasing -** -Msafeptr, restrict qualifer, 32 bits?
- **Templates, Generic Programming –** now okay
- **Inheritance, polymorphism, virtual functions –** runtime lookup or check, no inlining, potential performance penalties

SMP Parallelization

- **–Mconcur for auto-parallelization on multi-core**
  - **Compiler strives for parallel outer loops, vector SSE inner loops**
  - **–Mconcur=innermost forces a vector/parallel innermost loop**
  - **–Mconcur=cncall enables parallelization of loops with calls**
- **–mp to enable OpenMP 2.5 parallel programming model**
  - **See PGI User's Guide or OpenMP 2.5 standard**
  - **OpenMP programs compiled w/out –mp=nonuma**
- **–Mconcur and –mp can be used together!**

EKOPath Basic Optimizations

`-g`	Generate debug (DWARF) information. Changes optimization level to -O0 unless explicitly overridden.
`-O0`	No optimization
`-O1`	Local optimization (straight line code)
`-O2`	Global scalar optimizations (-O2 is default)
`-O3`	Loop level transformations and vectorizations
`-ipa`	Inter-procedural optimizations (whole program). Can be used at any optimization level.
`-OPT:Ofast`	Generally safe but may impact floating point correctness. Maximizes performance. Equivalent to: `-OPT:ro=2:Olimit=0:div_split=ON:alias=typed`
`-Ofast`	Equivalent to `-O3 -ipa -OPT:Ofast -fno-math-errno`

Slide 11

Option Groups

- Options organized into groups by compiler phase or by class of feature
- General syntax:
  `-GROUPNAME:opt[=val]{:opt=[val]}`
- Some GNU-style flags map to these options
  `-march -ffast-math -ffloat-store -fno-inline`
- Group names:

`-LIST:`	User listing
`-OPT:`	Optimizations
`-TARG:`	Target machine
`-TENV:`	Target environment
`-INLINE:`	Back-end inlining
`-IPA:`	Inter-procedural analysis
`-LANG:`	Language features
`-CG:`	Code generation
`-WOPT:`	Global scalar optimization
`-LNO:`	Loop nest optimization

Slide 12

Alias options

Improving performance of generated code by allowing the compiler to make assumptions about aliasing

Mainly for C/C++ programs

-OPT:alias=typed
- Activate ANSI/ISO C standard
- Object not aliased if they have different base types
- Implied by –Ofast

-OPT:alias=restrict
- Regard all pointers as having the 'restrict' attribute

-OPT:alias=disjoint
- No two pointers ever point to the same object
- Many programs will not run correctly with this option

Slide 14

Controlling Floating-point Code

- Lower precision requirements to allow for faster code
- `OPT:roundoff=`
  - Specifies extent of roundoff error the compiler is allowed to introduce
    - `0` = no roundoff error (default at `-O0`, `-O1`, `-O2`)
    - `1` = limited roundoff error (default at `-O3`)
    - `2` = allow roundoff error due to re-associating expressions (default at `-Ofast`)
    - `3` = any roundoff error is allowed
- `OPT:IEEE_arithmetic=`
  - Specifies level of conformance to IEEE 754 floating-point roundoff and overflow behavior
    - 1 = string conformance to IEEE accuracy (default at `-O0`, `-O1`, `-O2`)
    - 2 = allow inexact results not conforming to IEEE 754 (default at `-O3`)
    - 3 = allow any mathematically valid transformations

`-OPT:IEEE_NaN_Inf=(on|off)`
- Controls conformance to IEEE for Not-a-Number and Infinity operands
- Default is `on`

Slide 15

Parallelization

- OpenMP
  - Option to enable directives:
    `-mp`
  - OpenMP 2.5 in Fortran, C, & C++
    - The C++ OpenMP support is limited and does not support OpenMP directives in C++ source that use exceptions, classes or templates. (We have found some codes with very simplistic use of classes may work.)
- Autoparallelization
  - Option to enable: `-apo`

Slide 19

Performance Tuning

`-Ofast` is the most aggressive optimization option
Equivalent to `-O3 -ipa -OPT:Ofast -fno-math-errno`
`-OPT:Ofast` is equivalent to
`-OPT:ro=2:Olimit=0:div_split=ON:alias=typed`

- A large number of other options are related to performance tuning
  - Phase specific options:
    `-CG`
    `-INLINE`
    `-IPA`
    `-WOPT`
    `-LNO`
- PathOpt2 allows automatic search of best flag combinations

Slide 20

Tuning for AMD "Barcelona"

- Tuned Prefetch for smaller L2 cache
  - option LNO: stream_prefetch=1
  - option CG:use_prefetch_nta (non temporal)
- SIMD unaligned loads
  - improves vectorization
- FP instruction tuning
  - aligned packed double (movapd)
    - replaces scalar double (movsd)
    - removes register dependency
  - movsd replaces movlpd (for loads)

Above changes account for >10% performance improvement

Slide 21

Options to Help Expose User Errors

Programs may run incorrectly only at higher optimization levels

- Causes include compiler bugs or bad coding practices

To help diagnose bad coding practices

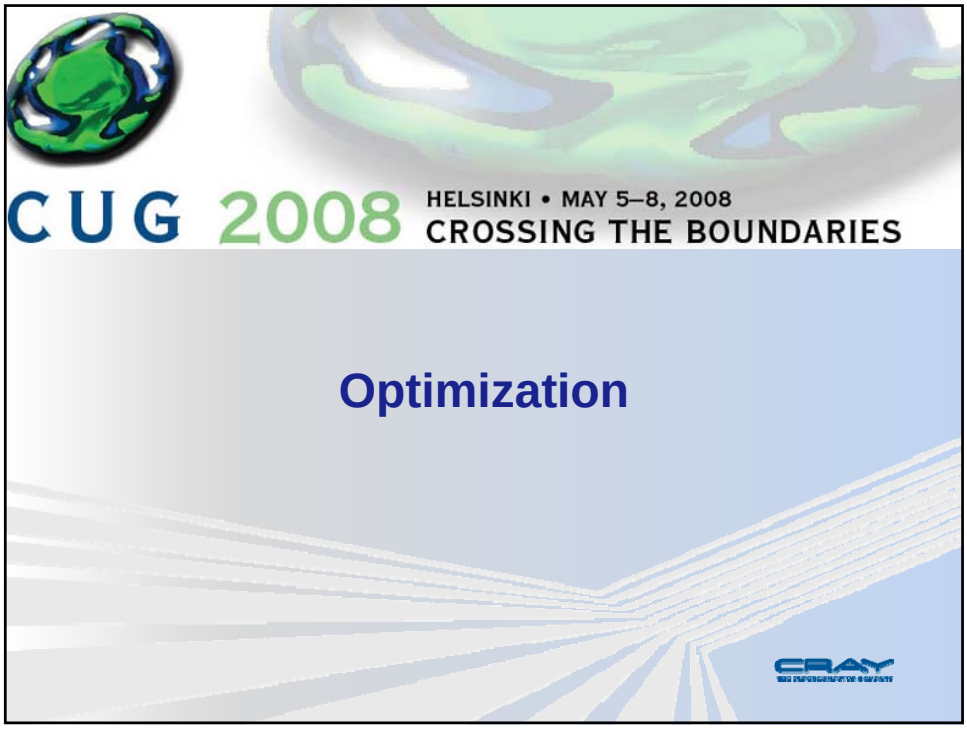
`-OPT:alias=no_parm`
- Fortran compiler does NOT assume Fortran no-alias rule for parameters

`-LANG:rw_const=on`
- For cases where callee modifies constant argument

`-trapuv`
- Initializes variables with NaN. If program uses the uninitialized variable, it will crash instead of generating incorrect results

`-zerouv`
- Initializes variables to 0
- Good for programs that incorrectly assume memory is always initialized to zero.

Slide 23



Getting ready for Quad Core

- Bytes/flops will decrease
  - XT3 – 5 GB/sec/2.6 GHZ* 2Flops/clock
    - 1 Byte/flop
  - XT4 (dual) – 6.25GB/sec/2.6 GHZ* 2Flops/clock/2 processors
    - ½ Byte/flop
  - XT4 (quad) – 8 GB/sec/2.2GHZ*4Flops/clock/4 processors
    - ¼ Byte/flop
- Interconnect Bytes/flop will decrease
  - XT3 – 2 GB/sec/2.6 GHZ* 2Flops/clock
    - 1/3 Bytes/flop
  - XT4 (dual) – 6 GB/sec/2.6 GHZ* 2Flops/clock/2 processors
    - 1/2 Bytes/flop
  - XT4 (quad) – 6 GB/sec/2.2GHZ*4Flops/clock/4 processors
    - 1/7 Byte/flop

What can be done?

- MPI is optimized for intra-node communication; however, messages off the node will contend for bandwidth requirements off the node
  - Number of messages going through the NIC could become a problem
- OpenMP across the cores on the node will help
  - Shared Cache is designed to help OpenMP reduce the applications memory requirements
  - Reduces the message traffic off the node

What about those SSE instructions

- The Quad core is capable of generating 4 flops/clock in 64 bit mode and 8 flops/clock for 32 bit mode
  - Assembler must contain SSE instructions
  - Compilers only generate SSE instructions when they vectorize the DO loops
- Operands should be aligned on 128 bit boundaries
  - Operand alignment can be performed; however, it degrades the performance.
- Watch out for Libraries – are they Quad core enabled?

Caution when timing Kernels

- The worse case timings will be shown in the following examples. None of the operands will be cache resident. This is assured by calling a routine called FLUSH prior to each example.

Flush Routine

```
SUBROUTINE FLUSH
 common/fl/ A(896896),x
 real*8 A,x
 do i=1,896896
 x=x+a(i)
 enddo
 end
```

Notice, we are replacing everything that is in cache with read Data. If we stored into A, the contents of cache would have to Be written to memory before using the cache for other data.

When calling FLUSH

```
      REAL*8 A,X
      common/fl/ A(896896),x
C
        X=0
        A=ranf()
        CALL LP41000
        print *,x
```

These compilers can recognize that x in the COMMON block is not used anywhere, so we print it. Also we initialize A

Compiler Options for Quad Core

- Pathscale
  Ftn –O3 –OPT:Ofast -march=barcelona -LNO:simd_verbose=ON
- PGI
  Ftn –fastsse –r8 –Minfo –Mneginfo –tp barcelona-64

Indirect Addressing

```
(  300) C     FIVE OPERATIONS - TWO OPERANDS     RATIO = 5/2
(  301)
(  302)       DO 41012 I = 1, N
(  303)        Y(IY(I)) =  c0 + X(IX(I)) * (C1 + X(IX(I))
(  304)      *          * (C2 + X(IX(I))                 ))
(  305) 41012 CONTINUE
```

302, Loop unrolled 2 times

Contiguous Addressing

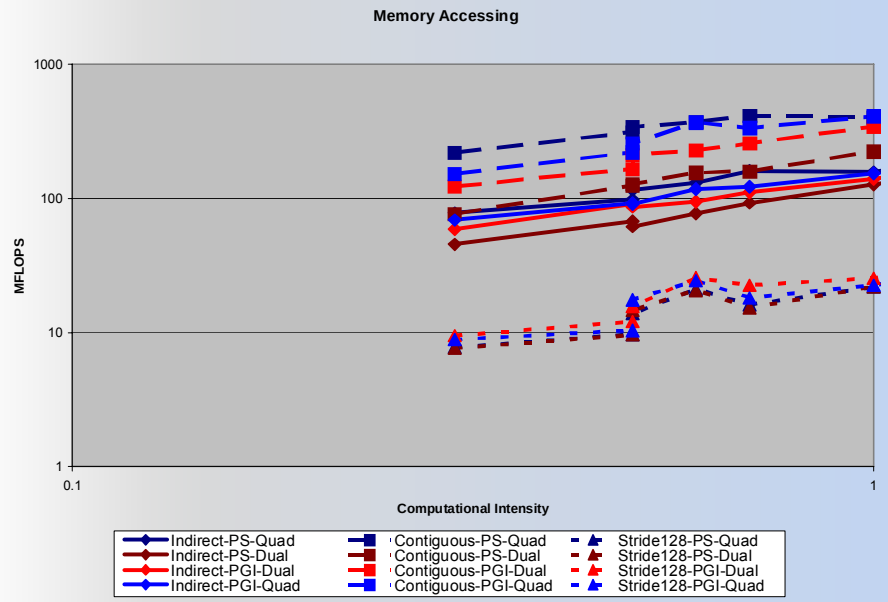
```
(  799)       DO 41033 I = 1, N
(  800)        Y(I) = c0 + X(I) * (C1 + X(I) * (C2 + X(I)
(  801)      *                  * (C3 + X(I)             )))
(  802) 41033 CONTINUE
```

799, Generated an alternate loop for the inner loop
Generated vector sse code for inner loop
Generated 1 prefetch instructions for this loop
Generated vector sse code for inner loop
Generated 1 prefetch instructions for this loop

Bad Stride Addressing

```
( 1239)       II=1
( 1240)
( 1241)       DO 41072 I = 1, N
( 1242)        Y(II) = c0 + X(II) * (C1 + X(II) * (C2 + X(II) ))
( 1243)        II = II + ISTRIDE
( 1244) 41072 CONTINUE
```

1241, Loop unrolled 1 times



Bad Striding

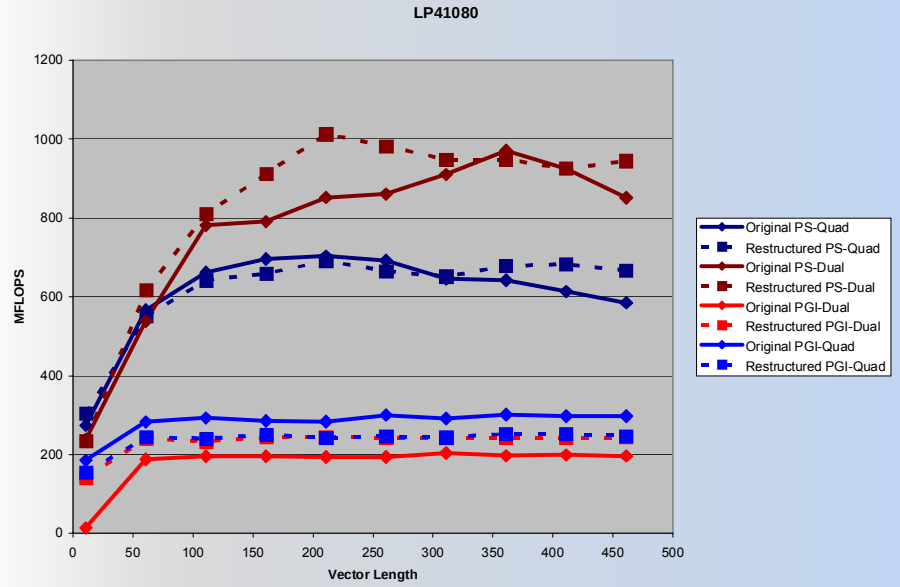
```
(   47) C     DIMENSION A(128,N)
(   48)
(   49)       DO 41080  I = 1,N
(   50)        A( 1,I) = C1*A(13,I) + C2* A(12,I) + C3*A(11,I) +
(   51)      *           C4*A(10,I) + C5* A( 9,I) + C6*A( 8,I) +
(   52)      *           C7*A( 7,I) + C0*(A( 5,I) + A( 6,I) )  + A( 3,I)
(   53) 41080 CONTINUE
```

PGI
49, Generated vector sse code for inner loop
Pathscale
(lp41080.f:49) Non-contiguous array "A(_BLNK__.0.0)" reference exists.
Loop was not vectorized.

Rewrite

```
(   74) C     DIMENSION B(129,N)
(   75)
(   76)       DO 41081 I = 1,N
(   77)        B( 1,I) = C1*B(13,I) + C2* B(12,I) + C3*B(11,I) +
(   78)      *           C4*B(10,I) + C5* B( 9,I) + C6*B( 8,I) +
(   79)      *           C7*B( 7,I) + C0*(B( 5,I) + B( 6,I) )  + B( 3,I)
(   80) 41081 CONTINUE
```

PGI
76, Generated vector sse code for inner loop
Pathscale
(lp41080.f:76) Non-contiguous array "B(_BLNK__.512000.0)" reference exists.
Loop was not vectorized.



Bad Striding

```
(    5)       COMMON A(8,8,IIDIM,8),B(8,8,iidim,8)


(   59)       DO 41090 K = KA, KE, -1
(   60)         DO 41090 J = JA, JE
(   61)           DO 41090 I = IA, IE
(   62)             A(K,L,I,J) = A(K,L,I,J) - B(J,1,i,k)*A(K+1,L,I,1)
(   63)      *    - B(J,2,i,k)*A(K+1,L,I,2) - B(J,3,i,k)*A(K+1,L,I,3)
(   64)      *    - B(J,4,i,k)*A(K+1,L,I,4) - B(J,5,i,k)*A(K+1,L,I,5)
(   65) 41090 CONTINUE
(   66)
```

PGI

59, Loop not vectorized: loop count too small
60, Interchange produces reordered loop nest: 61, 60
Loop unrolled 5 times (completely unrolled)
61, Generated vector sse code for inner loop

Pathscale

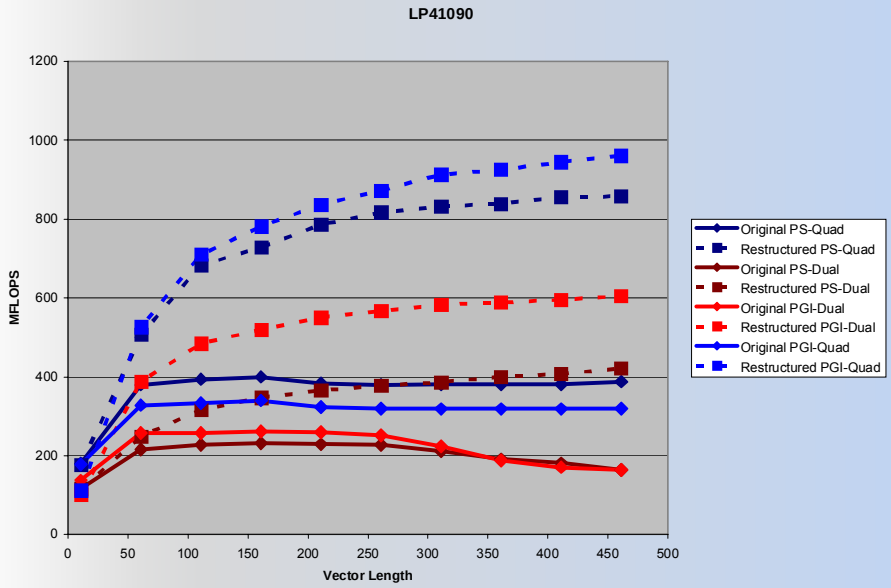
(lp41090.f:62) Non-contiguous array "A(_BLNK__.0.0)" reference exists. Loop was not vectorized.
(lp41090.f:62) Non-contiguous array "A(_BLNK__.0.0)" reference exists. Loop was not vectorized.
(lp41090.f:62) Non-contiguous array "A(_BLNK__.0.0)" reference exists. Loop was not vectorized.
(lp41090.f:62) Non-contiguous array "A(_BLNK__.0.0)" reference exists. Loop was not vectorized.

Rewrite

```
(    6)       COMMON AA(IIDIM,8,8,8),BB(IIDIM,8,8,8)


(   95)       DO 41091 K = KA, KE, -1
(   96)         DO 41091 J = JA, JE
(   97)           DO 41091 I = IA, IE
(   98)             AA(I,K,L,J) = AA(I,K,L,J) - BB(I,J,1,K)*AA(I,K+1,L,1)
(   99)      *    - BB(I,J,2,K)*AA(I,K+1,L,2) - BB(I,J,3,K)*AA(I,K+1,L,3)
(  100)      *    - BB(I,J,4,K)*AA(I,K+1,L,4) - BB(I,J,5,K)*AA(I,K+1,L,5)
(  101) 41091 CONTINUE
```

PGI
95, Loop not vectorized: loop count too small
96, Outer loop unrolled 5 times (completely unrolled)
97, Generated 3 alternate loops for the inner loop
Generated vector sse code for inner loop
Generated 8 prefetch instructions for this loop
Generated vector sse code for inner loop
Generated 8 prefetch instructions for this loop
Generated vector sse code for inner loop
Generated 8 prefetch instructions for this loop
Generated vector sse code for inner loop
Generated 8 prefetch instructions for this loop

Pathscale
(lp41090.f:99) LOOP WAS VECTORIZED.



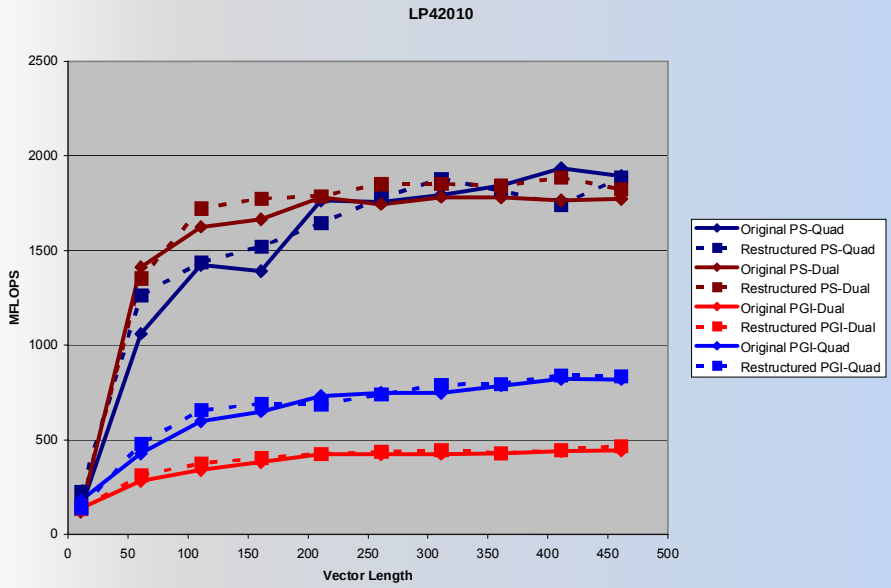
Scalars

```
(   59) C       THE ORIGINAL
(   60)
(   61)       DO 42010 KK = 1, N
(   62)        T000       = A(KK,K000)
(   63)        T001       = A(KK,K001)
(   64)        T010       = A(KK,K010)
(   65)        T011       = A(KK,K011)
(   66)        T100       = A(KK,K100)
(   67)        T101       = A(KK,K101)
(   68)        T110       = A(KK,K110)
(   69)        T111       = A(KK,K111)
(   70)        B1         = B(KK,K000)
(   71)        B2         = B(KK,K001)
(   72)        B3         = B(KK,K010)
(   73)        B4         = B(KK,K011)
(   74)        R1         = T100 * C1 + T110 * C2
(   75)        S1         = T101 * C1 - T111 * C2
(   76)        RS         = T000 + R1
(   77)        SS         = T001 + S1
(   78)        RU         = T010 - R1
(   79)        SU         = T011 - S1
(   80)        B(KK,K000) = B1 + RS
(   81)        B(KK,K001) = B2 + RU
(   82)        B(KK,K010) = B3 + SS
(   83)        B(KK,K011) = B4 - SU
(   84) 42010 CONTINUE
(   85)
```


PGI
61, Generated vector sse code for inner loop
Generated 8 prefetch instructions for this loop
Pathscale
(lp42010.f:61) LOOP WAS VECTORIZED.

```
(  106) C      THE RESTRUCTURED
(  107)
(  108)       DO 42011 KK = 1,N
(  109)         B(KK,K000) = B(KK,K000)       + A(KK,K000)
(  110)      *             + (A(KK,K100) * C1 + A(KK,K110) * C2)
(  111)         B(KK,K001) = B(KK,K001)       + A(KK,K010)
(  112)      *             - (A(KK,K100) * C1 + A(KK,K110) * C2)
(  113)         B(KK,K010) = B(KK,K010)       + A(KK,K001)
(  114)      *             + (A(KK,K101) * C1 - A(KK,K111) * C2)
(  115)         B(KK,K011) = B(KK,K011)       - A(KK,K011)
(  116)      *             + (A(KK,K101) * C1 - A(KK,K111) * C2)
(  117) 42011 CONTINUE
(  118)
```

PGI
108, Generated vector sse code for inner loop
Generated 8 prefetch instructions for this loop
Pathscale
(lp42010.f:108) LOOP WAS VECTORIZED.



VVTVP

```
(   35) C     NON-RECURSIVE DO LOOP FOR TIMING COMPARISON
(   36)
(   37)       DO 43010 I = 2, N
(   38)        A(I) = A(I+1) * B(I) + C(I)
(   39) 43010 CONTINUE
(   40)
```

PGI

37, Generated an alternate loop for the inner loop
Generated vector sse code for inner loop
Generated 3 prefetch instructions for this loop
Generated vector sse code for inner loop
Generated 3 prefetch instructions for this loop

Pathscale

(lp43010.f:37) LOOP WAS VECTORIZED.

FOLR

```
(   52) C       RECURSIVE DO LOOP
(   53)
(   54)       DO 43011 I = 2, N
(   55)        A(I) = A(I-1) * B(I) + C(I)
(   56) 43011 CONTINUE
(   57)
```

PGI

54, Loop not vectorized: data dependency
Loop unrolled 2 times

Pathscale

(lp43010.f:54) Loop has dependencies. Loop was not vectorized.

FOLR - Unrolled

```
(  71) C      UNROLLED TO DEPTH FOUR
(  72)
(  73)       DO 43012 I = 2, N-3, 4
(  74)         A(I)   = A(I-1) * B(I)   + C(I)
(  75)         A(I+1) = A(I)   * B(I+1) + C(I+1)
(  76)         A(I+2) = A(I+1) * B(I+2) + C(I+2)
(  77)         A(I+3) = A(I+2) * B(I+3) + C(I+3)
(  78) 43012 CONTINUE
(  79)
(  80) C      CLEANUP LOOP FOR DEPTH FOUR UNROLLING
(  81)
(  82)       DO 43013 J = I,N
(  83)         A(J) = A(J-1) * B(J) + C(J)
(  84) 43013 CONTINUE
(  85)
```

PGI

73, Loop not vectorized: data dependency

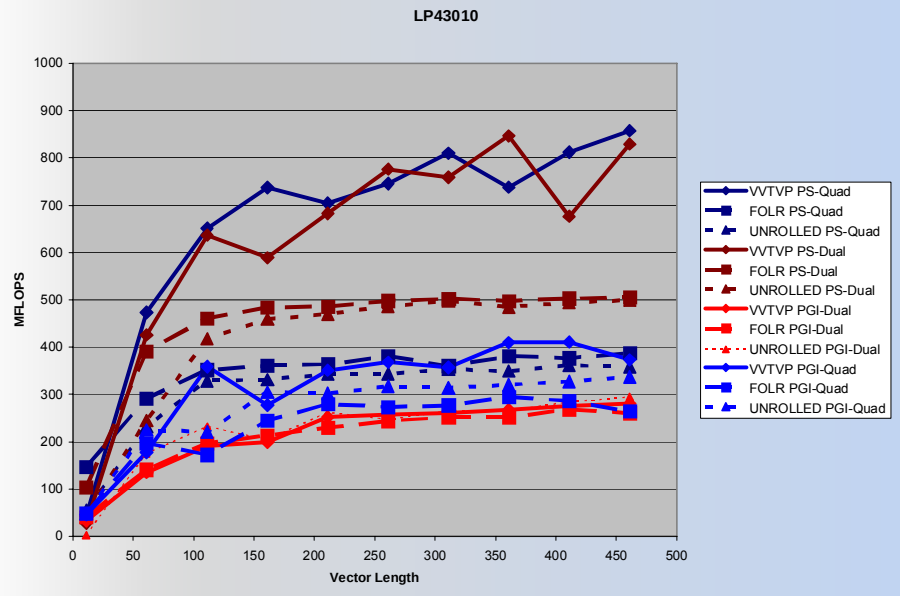
82, Loop not vectorized: data dependency

Loop unrolled 2 times

Pathscale

(lp43010.f:73) Non-contiguous array "C(_BLNK__.8000.0)" reference exists. Loop was not vectorized.

(lp43010.f:82) Loop has dependencies. Loop was not vectorized.



Potential Recursion

```
(   42) C  GAUSS ELIMINATION
(   43)
(   44)       DO 43020 I = 1, MATDIM
(   45)        A(I,I) = 1. / A(I,I)
(   46)        DO 43020 J = I+1, MATDIM
(   47)         A(J,I) = A(J,I) * A(I,I)
(   48)         DO 43020 K = I+1, MATDIM
(   49)          A(J,K) = A(J,K) - A(J,I) * A(I,K)
(   50) 43020 CONTINUE
(   51)
```

Pathscale

(lp43020.f:46) Non-contiguous array "A(_BLNK__.0.0)" reference exists. Loop was not vectorized.
(lp43020.f:48) Non-contiguous array "A(_BLNK__.0.0)" reference exists. Loop was not vectorized.
(lp43020.f:48) Non-contiguous array "A(_BLNK__.0.0)" reference exists. Loop was not vectorized.
(lp43020.f:48) Non-contiguous array "A(_BLNK__.0.0)" reference exists. Loop was not vectorized.

PGI

46, Distributed loop; 2 new loops
Interchange produces reordered loop nest: 48, 46
Generated 2 alternate loops for the inner loop
Unrolled inner loop 4 times
Generated 1 prefetch instructions for this loop
Unrolled inner loop 4 times
Generated 2 prefetch instructions for this loop
Unrolled inner loop 4 times
Used combined stores for 1 stores
Generated 1 prefetch instructions for this loop
Unrolled inner loop 4 times
Used combined stores for 1 stores
Generated 1 prefetch instructions for this loop
Unrolled inner loop 4 times
Used combined stores for 1 stores
Generated 2 prefetch instructions for this loop
Unrolled inner loop 4 times
Used combined stores for 1 stores
Generated 2 prefetch instructions for this loop

Rewrite

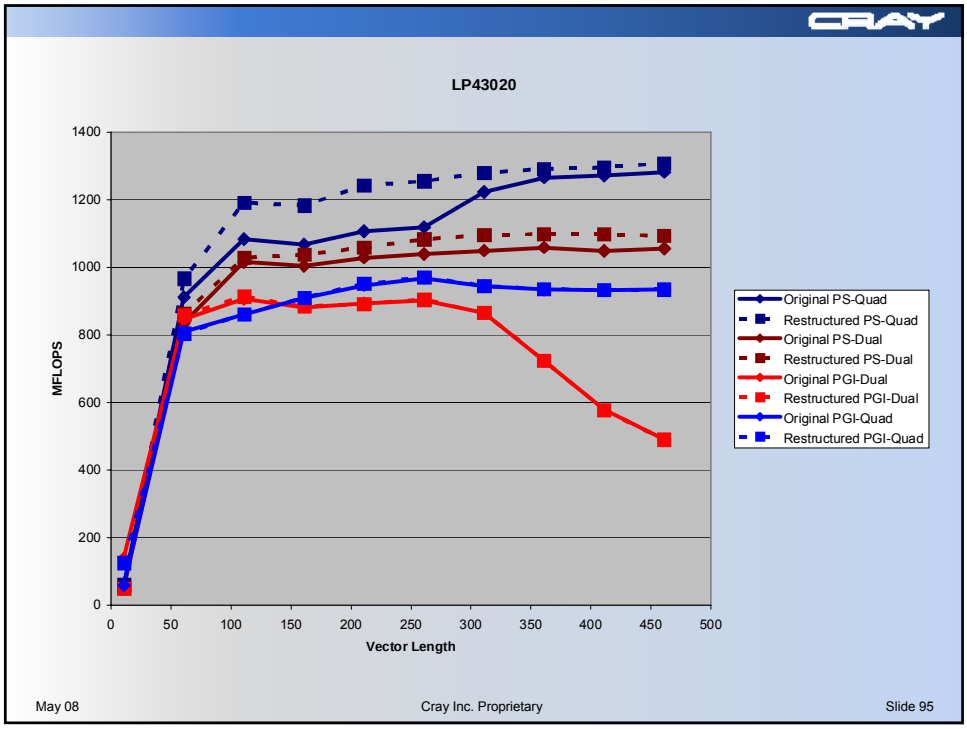
```
(   80) C  GAUSS ELIMINATION
(   81)
(   82)       DO 43021 I = 1, MATDIM
(   83)        A(I,I) = 1. / A(I,I)
(   84)        DO 43021 J = I+1, MATDIM
(   85)         A(J,I) = A(J,I) * A(I,I)
(   86) CVD$ NODEPCHK
(   87) CDIR$ IVDEP
(   88) *VDIR NODEP
(   89)         DO 43021 K = I+1, MATDIM
(   90)          A(J,K) = A(J,K) - A(J,I) * A(I,K)
(   91) 43021 CONTINUE
```

Pathscale

(lp43020.f:84) Non-contiguous array "A(_BLNK__.0.0)" reference exists. Loop was not vectorized.
(lp43020.f:89) Non-contiguous array "A(_BLNK__.0.0)" reference exists. Loop was not vectorized.
(lp43020.f:89) Non-contiguous array "A(_BLNK__.0.0)" reference exists. Loop was not vectorized.
(lp43020.f:89) Non-contiguous array "A(_BLNK__.0.0)" reference exists. Loop was not vectorized.

PGI

84, Distributed loop; 2 new loops
Interchange produces reordered loop nest: 89, 84
Generated 2 alternate loops for the inner loop
Unrolled inner loop 4 times
Generated 1 prefetch instructions for this loop
Unrolled inner loop 4 times
Generated 2 prefetch instructions for this loop
Unrolled inner loop 4 times
Used combined stores for 1 stores
Generated 1 prefetch instructions for this loop
Unrolled inner loop 4 times
Used combined stores for 1 stores
Generated 1 prefetch instructions for this loop
Unrolled inner loop 4 times
Used combined stores for 1 stores
Generated 2 prefetch instructions for this loop
Unrolled inner loop 4 times
Used combined stores for 1 stores



Potential Recursion

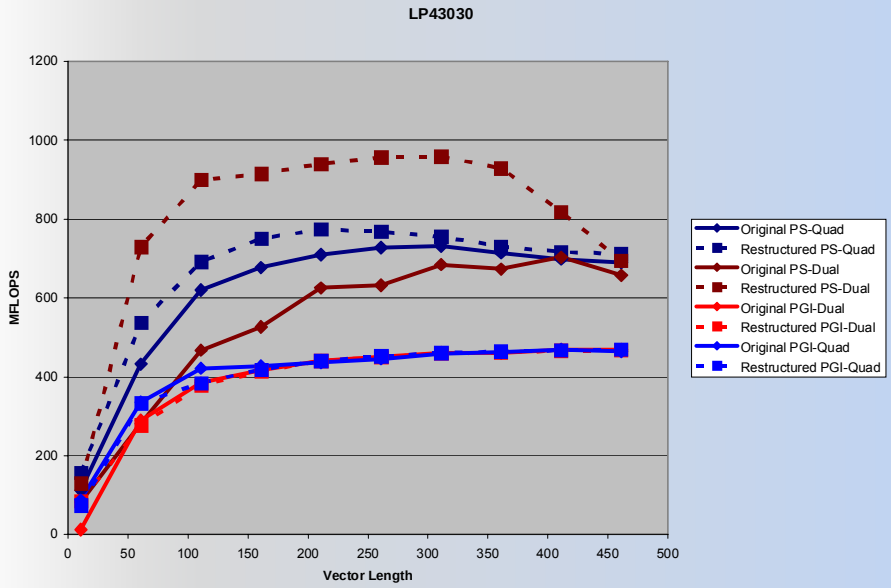
```
(   39) C     THE ORIGINAL
(   40)
(   41)       DO  43030  I = 2, N
(   42)        DO  43030  K = 1, I-1
(   43)         A(I)= A(I)  + B(I,K) * A(I-K)
(   44) 43030 CONTINUE
```

PGI
42, Generated vector sse code for inner loop
Pathscale
(lp43030.f:42) Non-contiguous array "B(_BLNK__.4000.0)" reference exists. Loop was not vectorized.

Rewrite

```
(   67) C      THE RESTRUCTURED
(   68)
(   69)       DO 43031 I = 2, N
(   70) CVD$ NODEPCHK
(   71) CDIR$ IVDEP
(   72) *VDIR NODEP
(   73)        DO 43031 K = 1, I-1
(   74)         A(I) = A(I)  + B(I,K) * A(I-K)
(   75) 43031 CONTINUE
(   76)
```

PGI
73, Generated vector sse code for inner loop
Pathscale
(lp43030.f:73) Non-contiguous array "B(_BLNK__.4000.0)" reference exists.
Loop was not vectorized.



Potential Recursion

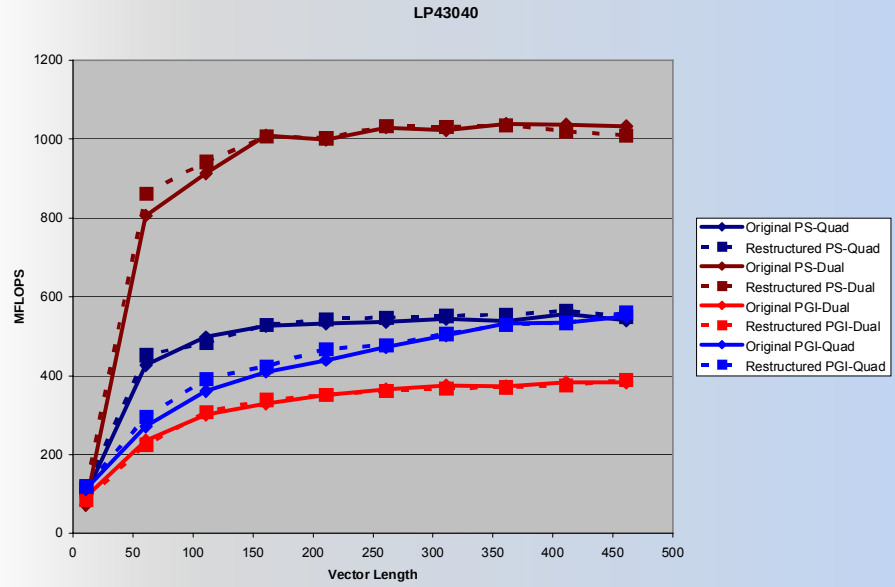
```
(  45)      DO 43040 J = 2, 8
(  46)       N1 = J
(  47)       N2 = J - 1
(  48)       DO 43040 I = 2, N
(  49)        A(I,N1) = A(I-1,N2) * B(I,J) + C(I)
(  50) 43040 CONTINUE
(  51)
```

PGI
48, Loop not vectorized: data dependency
Loop unrolled 2 times
Pathscale
(lp43040.f:48) LOOP WAS VECTORIZED.

Rewrite

```
(   75) C      THE RESTRUCTURED
(   76)
(   77)       DO 43041 J = 2, 8
(   78)        N1 = J
(   79)        N2 = J - 1
(   80) CVD$ NODEPCHK
(   81) CDIR$ IVDEP
(   82) *VDIR NODEP
(   83)        DO 43041 I = 2, N
(   84)         A(I,N1) = A(I-1,N2) * B(I,J) + C(I)
(   85) 43041 CONTINUE
(   86)
```

PGI
83, Loop not vectorized: data dependency
Loop unrolled 2 times
Pathscale
(lp43040.f:83) LOOP WAS VECTORIZED.



Potential Recursion

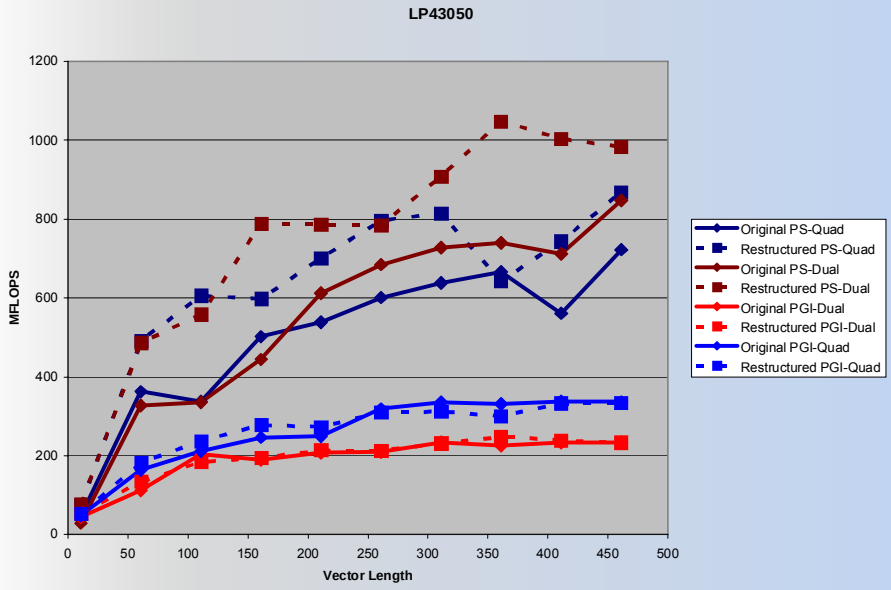
```
(  40) C     THE ORIGINAL
(  41)
(  42)       DO 43050 I = 1, N
(  43)        A(I) = A(I+N2) * A(I+N3) + A(I+N4)
(  44) 43050 CONTINUE
```

PGI
  42, Generated an alternate loop for the inner loop
      Generated vector sse code for inner loop
      Generated 3 prefetch instructions for this loop
      Generated vector sse code for inner loop
      Generated 3 prefetch instructions for this loop
Pathscale
(lp43050.f:42) LOOP WAS VECTORIZED.

Rewrite

```
(   63) C      THE RESTRUCTURED
(   64)
(   65) CVD$ NODEPCHK
(   66) CDIR$ IVDEP
(   67) *VDIR NODEP
(   68)       DO 43051 I = 2, N
(   69)        A(I) = A(I+N2) * A(I+N3) + A(I+N4)
(   70) 43051 CONTINUE
(   71)
```

PGI
68, Generated vector sse code for inner loop
Generated 3 prefetch instructions for this loop
Pathscale
(lp43050.f:68) LOOP WAS VECTORIZED.



Potential Recursion

```
(   72) C      THE ORIGINAL
(   73)
(   74)       DO 43060 KX = 2, 3
(   75)        DO 43060 KY = 2, N
(   76)         D(KY) = A(KX,KY+1,NL12) - A(KX,KY-1,NL12)
(   77)         E(KY) = B(KX,KY+1,NL22) - B(KX,KY-1,NL22)
(   78)         F(KY) = C(KX,KY+1,NL32) - C(KX,KY-1,NL32)
(   79)         A(KX,KY,NL11) = A(KX,KY,NL11)
(   80)      *  + C1*D(KY)           + C2*E(KY)        + C3*F(KY)
(   81)      *  + C0*(A(KX+1,KY,NL1) - 2.*A(KX,KY,NL1) + A(KX-1,KY,NL1))
(   82)         B(KX,KY,NL21) = B(KX,KY,NL21)
(   83)      *  + C4*D(KY)           + C5*E(KY)        + C6*F(KY)
(   84)      *  + C0*(B(KX+1,KY,NL1) - 2.*B(KX,KY,NL1) + B(KX-1,KY,NL1))
(   85)         C(KX,KY,NL31) = C(KX,KY,NL31)
(   86)      *  + C7*D(KY)           + C8*E(KY)        + C9*F(KY)
(   87)      *  + C0*(C(KX+1,KY,NL1) - 2.*C(KX,KY,NL1) + C(KX-1,KY,NL1))
(   88) 43060 CONTINUE
```

PGI

74, Loop not vectorized: loop count too small
Outer loop unrolled 2 times (completely unrolled)
75, Generated vector sse code for inner loop

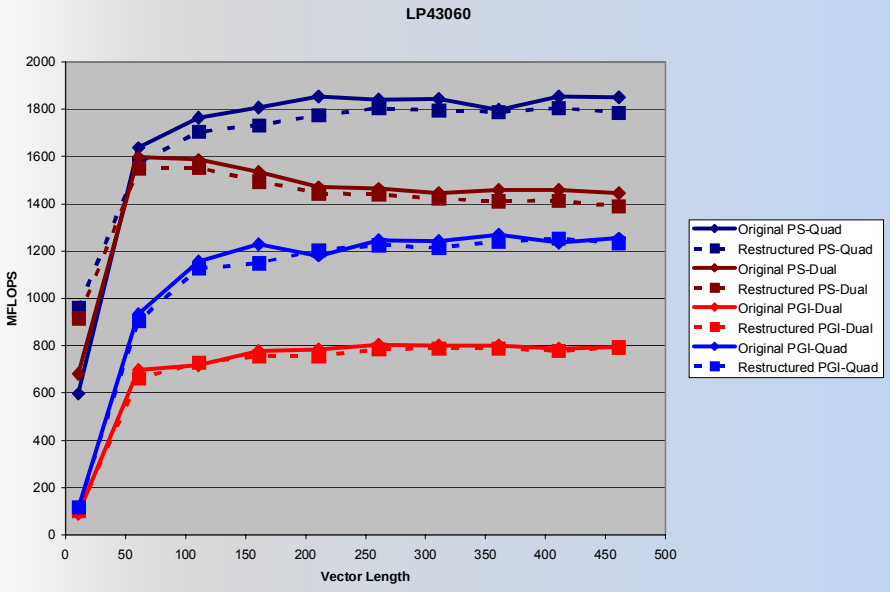
Pathscale

(lp43060.f:75) Non-contiguous array "A(_BLNK__.0.0)" reference exists.
Loop was not vectorized.

Rewrite

```
(  121)       DO  43061 KX = 2, 3
(  122)
(  123) CVD$ NODEPCHK
(  124) CDIR$ IVDEP
(  125) *VDIR NODEP
(  126)
(  127)        DO  43061 KY = 2, N
(  128)         D(KY) = A(KX,KY+1,NL12) - A(KX,KY-1,NL12)
(  129)         E(KY) = B(KX,KY+1,NL22) - B(KX,KY-1,NL22)
(  130)         F(KY) = C(KX,KY+1,NL32) - C(KX,KY-1,NL32)
(  131)         A(KX,KY,NL11) = A(KX,KY,NL11)
(  132)      *  + C1*D(KY)           + C2*E(KY)        + C3*F(KY)
(  133)      *  + C0*(A(KX+1,KY,NL1) - 2.*A(KX,KY,NL1) + A(KX-1,KY,NL1))
(  134)         B(KX,KY,NL21) = B(KX,KY,NL21)
(  135)      *  + C4*D(KY)           + C5*E(KY)        + C6*F(KY)
(  136)      *  + C0*(B(KX+1,KY,NL1) - 2.*B(KX,KY,NL1) + B(KX-1,KY,NL1))
(  137)         C(KX,KY,NL31) = C(KX,KY,NL31)
(  138)      *  + C7*D(KY)           + C8*E(KY)        + C9*F(KY)
(  139)      *  + C0*(C(KX+1,KY,NL1) - 2.*C(KX,KY,NL1) + C(KX-1,KY,NL1))
(  140) 43061 CONTINUE
(  141)
```

PGI
  121, Loop not vectorized: loop count too small
       Outer loop unrolled 2 times (completely unrolled)
  127, Generated vector sse code for inner loop
Pathscale
(lp43060.f:127) Non-contiguous array "A(_BLNK__.0.0)" reference exists.
Loop was not vectorized.



Potential Recursion

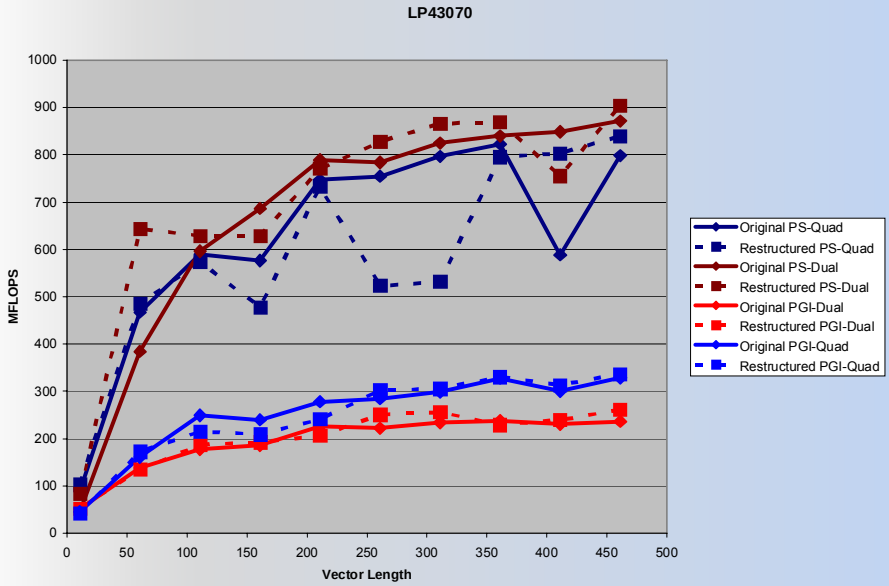
```
(   55) C      THE ORIGINAL
(   56)
(   57)       DO 43070 I = 1, N
(   58)        A(IA(I)) = A(IA(I)) + C0 * B(I)
(   59) 43070 CONTINUE
(   60)
```

PGI
57, Loop not vectorized: data dependency
Loop unrolled 4 times
Pathscale
(lp43070.f:57) Non-contiguous array "A(_BLNK__.0.0)" reference exists.
Loop was not vectorized.

Rewrite

```
(   87) CDIR$ IVDEP
(   88) CVD$ NODEPCHK
(   89) *VDIR NODEP
(   90)       DO 43071 I = 1, N
(   91)        A(IA(I)) = A(IA(I)) + C0 * B(I)
(   92) 43071 CONTINUE
(   93)
```

PGI
90, Loop unrolled 4 times
Pathscale
(lp43070.f:90) Non-contiguous array "A(_BLNK__.0.0)" reference exists.
Loop was not vectorized.



Wrap Around Scalar

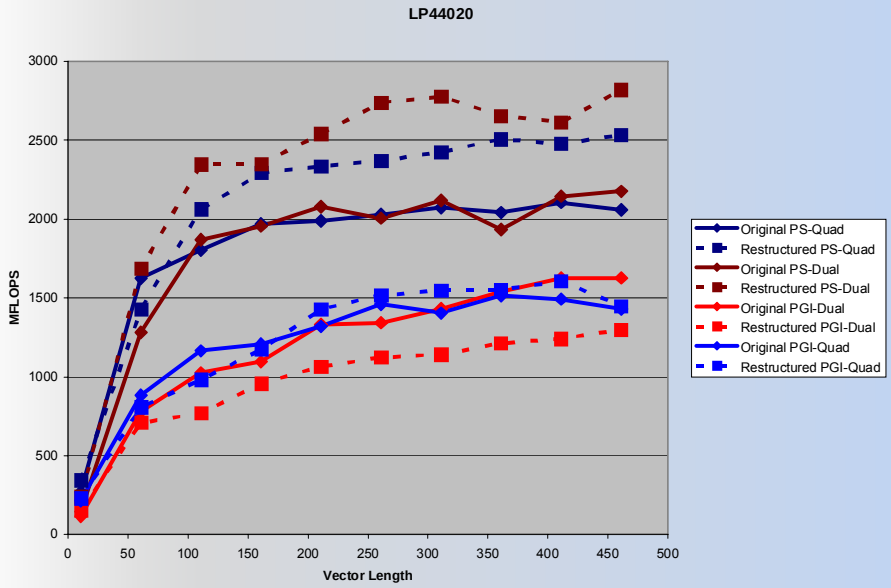
```
(   41)       BR =0.0
(   42)       DO 44020 I = 1, N
(   43)        BL = BR
(   44)        BR = (I-1) * DELB
(   45)        A(I) = (BR - BL) * C(I) + (BR**2 - BL**2) * C(I)**2
(   46) 44020 CONTINUE
```

42, Loop not vectorized: mixed data types
Generated an alternate loop for the inner loop
Loop not vectorized: mixed data types
Unrolled inner loop 4 times
Used combined stores for 1 stores
Generated 1 prefetch instructions for this loop
Loop not vectorized: mixed data types
Unrolled inner loop 4 times
Used combined stores for 1 stores
Generated 1 prefetch instructions for this loop

Rewrite

```
(   67)       BSQ(1) = 0.0
(   68)       A(1)   = 0.0
(   69)       B = 0.0
(   70)       DO 44022 I = 2, N
(   71)       B   = B   + DELB
(   72)       BSQ(I) = B ** 2
(   73)        A(I)   = C(I) * ( DELB + C(I) * (BSQ(I) - BSQ(I-1)))
(   74) 44022 CONTINUE
```

70, Generated 2 alternate loops for the inner loop
Unrolled inner loop 4 times
Generated 2 prefetch instructions for this loop
Unrolled inner loop 4 times
Used combined stores for 1 stores
Generated 2 prefetch instructions for this loop
Unrolled inner loop 4 times
Used combined stores for 1 stores
Generated 2 prefetch instructions for this loop



Maximum within Loop

```
(   61)       DO 44040 I = 2, N
(   62)        RR         = 1. / A(I,1)
(   63)        U          = A(I,2) * RR
(   64)        V          = A(I,3) * RR
(   65)        W          = A(I,4) * RR
(   66)        SNDSP      = SQRT (GD * (A(I,5) * RR + .5* (U*U + V*V + W*W)))
(   67)        SIGA       = ABS (XT + U*B(I) + V*C(I) + W*D(I))
(   68)      *              + SNDSP * SQRT (B(I)**2 + C(I)**2 + D(I)**2)
(   69)        SIGB       = ABS (YT + U*E(I) + V*F(I) + W*G(I))
(   70)      *              + SNDSP * SQRT (E(I)**2 + F(I)**2 + G(I)**2)
(   71)        SIGC       = ABS (ZT + U*H(I) + V*R(I) + W*S(I))
(   72)      *              + SNDSP * SQRT (H(I)**2 + R(I)**2 + S(I)**2)
(   73)        SIGABC     = AMAX1 (SIGA, SIGB, SIGC)
(   74)        IF (SIGABC.GT.SIGMAX) THEN
(   75)        IMAX       = I
(   76)        SIGMAX     = SIGABC
(   77)        ENDIF
(   78) 44040 CONTINUE
```


PGI

61, Generated an alternate loop for the inner loop
Generated vector sse code for inner loop
Generated 8 prefetch instructions for this loop
Generated vector sse code for inner loop
Generated 8 prefetch instructions for this loop

Pathscale

(lp44040.f:62) Expression rooted at op "OPC_IF"(line 63) is not vectorizable. Loop was not vectorized.

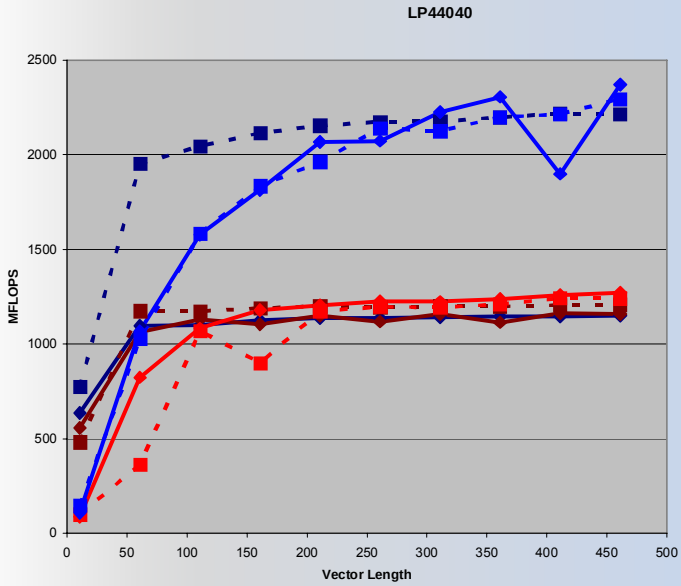
```
(   98)       DO 44041 I = 2, N
(   99)        RR         = 1. / A(I,1)
(  100)        U          = A(I,2) * RR
(  101)        V          = A(I,3) * RR
(  102)        W          = A(I,4) * RR
(  103)        SNDSP      = SQRT (GD * (A(I,5) * RR + .5* (U*U + V*V + W*W)))
(  104)        SIGA       = ABS (XT + U*B(I) + V*C(I) + W*D(I))
(  105)      *              + SNDSP * SQRT (B(I)**2 + C(I)**2 + D(I)**2)
(  106)        SIGB       = ABS (YT + U*E(I) + V*F(I) + W*G(I))
(  107)      *              + SNDSP * SQRT (E(I)**2 + F(I)**2 + G(I)**2)
(  108)        SIGC       = ABS (ZT + U*H(I) + V*R(I) + W*S(I))
(  109)      *              + SNDSP * SQRT (H(I)**2 + R(I)**2 + S(I)**2)
(  110)        VSIGABC(I) = AMAX1 (SIGA, SIGB, SIGC)
(  111) 44041 CONTINUE
(  112)
(  113)       DO 44042 I = 2, N
(  114)        IF (VSIGABC(I) .GT. SIGMAX) THEN
(  115)         IMAX       = I
(  116)         SIGMAX     = VSIGABC(I)
(  117)        ENDIF
(  118) 44042 CONTINUE
(  119)
```


PGI

98, Generated 2 alternate loops for the inner loop
Generated vector sse code for inner loop
Generated 8 prefetch instructions for this loop
Generated vector sse code for inner loop
Generated 8 prefetch instructions for this loop
Generated vector sse code for inner loop
Generated 8 prefetch instructions for this loop
113, Generated an alternate loop for the inner loop
Generated vector sse code for inner loop
Generated 1 prefetch instructions for this loop
Generated vector sse code for inner loop
Generated 1 prefetch instructions for this loop

Pathscale

(lp44040.f:100) LOOP WAS VECTORIZED.
(lp44040.f:115) Expression rooted at op "OPC_IF"(line 116)
is not vectorizable. Loop was not vectorized.



Matrix Multiply

```
(   44) C      THE ORIGINAL
(   45)
(   46)       DO 44050 I = 1, N
(   47)        DO 44050 J = 1, N
(   48)         A(I,J) = 0.0
(   49)         DO 44050 K = 1, N
(   50)          A(I,J) = A(I,J) + B(I,K) * C(K,J)
(   51) 44050 CONTINUE
(   52)
```

PGI

49, Generated 2 alternate loops for the inner loop
Generated vector sse code for inner loop
Generated 1 prefetch instructions for this loop
Generated vector sse code for inner loop
Generated 1 prefetch instructions for this loop
Generated vector sse code for inner loop
Generated 1 prefetch instructions for this loop

Pathscale

(lp44050.f:46) Loop has too many loop invariants. Loop was not vectorized.
(lp44050.f:46) LOOP WAS VECTORIZED.
(lp44050.f:46) LOOP WAS VECTORIZED.
(lp44050.f:46) LOOP WAS VECTORIZED.

Rewritten

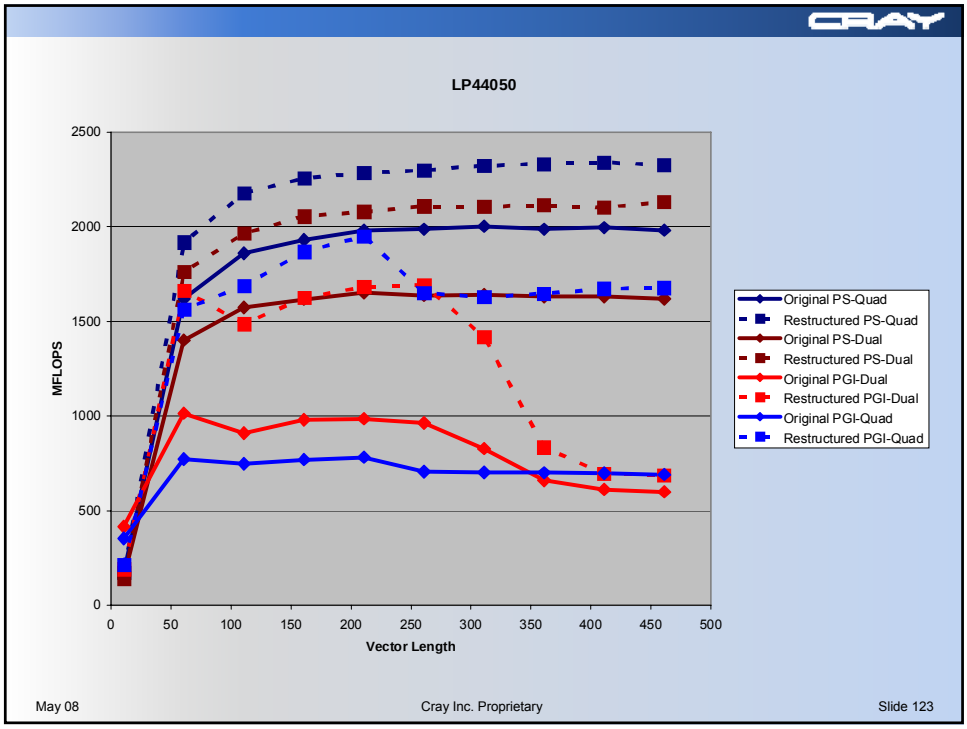
```
(   77) C      THE RESTRUCTURED
(   78)
(   79)       DO 44051 J = 1, N
(   80)        DO 44051 I = 1, N
(   81)         A(I,J) = 0.0
(   82) 44051 CONTINUE
(   83)
(   84)       DO 44052 K = 1, N
(   85)        DO 44052 J = 1, N
(   86)         DO 44052 I = 1, N
(   87)          A(I,J) = A(I,J) + B(I,K) * C(K,J)
(   88) 44052 CONTINUE
(   89) C
```


PGI

79, Loop not vectorized: contains call
80, Memory zero idiom, loop replaced by memzero call
84, Interchange produces reordered loop nest: 85, 84, 86
86, Generated 3 alternate loops for the inner loop
Generated vector sse code for inner loop
Generated 2 prefetch instructions for this loop
Generated vector sse code for inner loop
Generated 2 prefetch instructions for this loop
Generated vector sse code for inner loop
Generated 2 prefetch instructions for this loop
Generated vector sse code for inner loop
Generated 2 prefetch instructions for this loop

Pathscale

(lp44050.f:80) LOOP WAS VECTORIZED.
(lp44050.f:80) LOOP WAS VECTORIZED.
(lp44050.f:86) Loop has too many loop invariants. Loop was not vectorized.
(lp44050.f:86) LOOP WAS VECTORIZED.
(lp44050.f:86) LOOP WAS VECTORIZED.
(lp44050.f:86) LOOP WAS VECTORIZED.



Nested Loops

```
(   47)       DO 45020 I = 1, N
(   48)        F(I) = A(I) + .5
(   49)        DO 45020 J = 1, 10
(   50)         D(I,J) = B(J) * F(I)
(   51)         DO 45020 K = 1, 5
(   52)          C(K,I,J) = D(I,J) * E(K)
(   53) 45020 CONTINUE
```

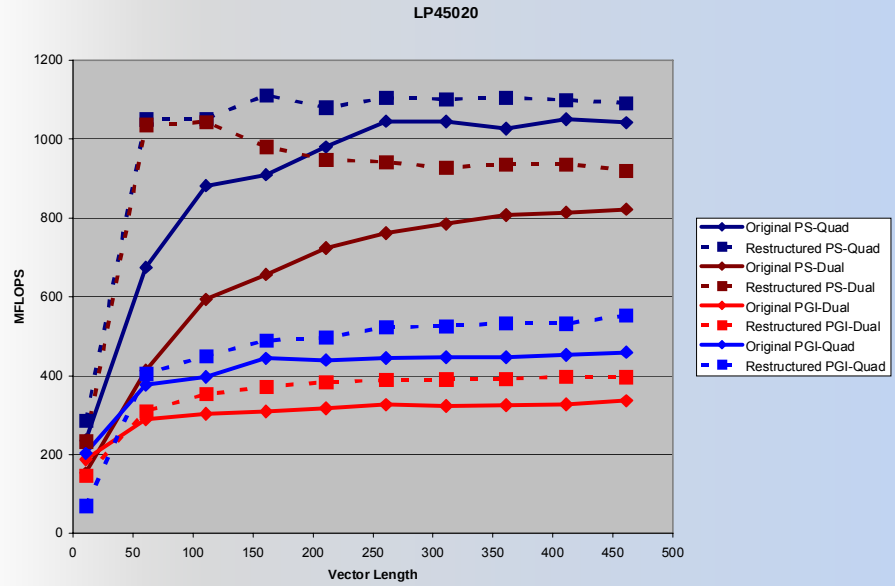
PGI
49, Generated vector sse code for inner loop
Generated 1 prefetch instructions for this loop
Loop unrolled 2 times (completely unrolled)
Pathscale
(lp45020.f:48) LOOP WAS VECTORIZED.
(lp45020.f:48) Non-contiguous array "C(_BLNK__.0.0)" reference exists. Loop was not vectorized.

Rewrite

```
(   71)       DO 45021 I = 1,N
(   72)        F(I) = A(I) + .5
(   73) 45021 CONTINUE
(   74)
(   75)       DO 45022 J = 1, 10
(   76)        DO 45022 I = 1, N
(   77)         D(I,J) = B(J) * F(I)
(   78) 45022 CONTINUE
(   79)
(   80)       DO 45023 K = 1, 5
(   81)        DO 45023 J = 1, 10
(   82)         DO 45023 I = 1, N
(   83)          C(K,I,J) = D(I,J) * E(K)
(   84) 45023 CONTINUE
```



```
PGI
    73, Generated an alternate loop for the inner loop
        Generated vector sse code for inner loop
        Generated 1 prefetch instructions for this loop
        Generated vector sse code for inner loop
        Generated 1 prefetch instructions for this loop
    78, Generated 2 alternate loops for the inner loop
        Generated vector sse code for inner loop
        Generated 1 prefetch instructions for this loop
        Generated vector sse code for inner loop
        Generated 1 prefetch instructions for this loop
        Generated vector sse code for inner loop
        Generated 1 prefetch instructions for this loop
    82, Interchange produces reordered loop nest: 83, 84, 82
        Loop unrolled 5 times (completely unrolled)
    84, Generated vector sse code for inner loop
        Generated 1 prefetch instructions for this loop
Pathscale
(lp45020.f:73) LOOP WAS VECTORIZED.
(lp45020.f:78) LOOP WAS VECTORIZED.
(lp45020.f:78) LOOP WAS VECTORIZED.
(lp45020.f:84) Non-contiguous array "C(_BLNK__.0.0)" reference
exists. Loop was not vectorized.
(lp45020.f:84) Non-contiguous array "C(_BLNK__.0.0)" reference
exists. Loop was not vectorized.
```



Nx4 Matmul

```
(   45)       DO 46020 I = 1,N
(   46)        DO 46020 J = 1,4
(   47)         A(I,J) = 0.
(   48)         DO 46020 K = 1,4
(   49)          A(I,J) = A(I,J) + B(I,K) * C(K,J)
(   50) 46020 CONTINUE
```

PGI

46, Generated an alternate loop for the inner loop
Generated vector sse code for inner loop
Generated 4 prefetch instructions for this loop
Generated vector sse code for inner loop
Generated 4 prefetch instructions for this loop
47, Loop unrolled 4 times (completely unrolled)
49, Loop not vectorized: loop count too small
Loop unrolled 4 times (completely unrolled)

Pathscale

(lp46020.f:46) Loop has too many loop invariants. Loop was not vectorized.

Rewrite

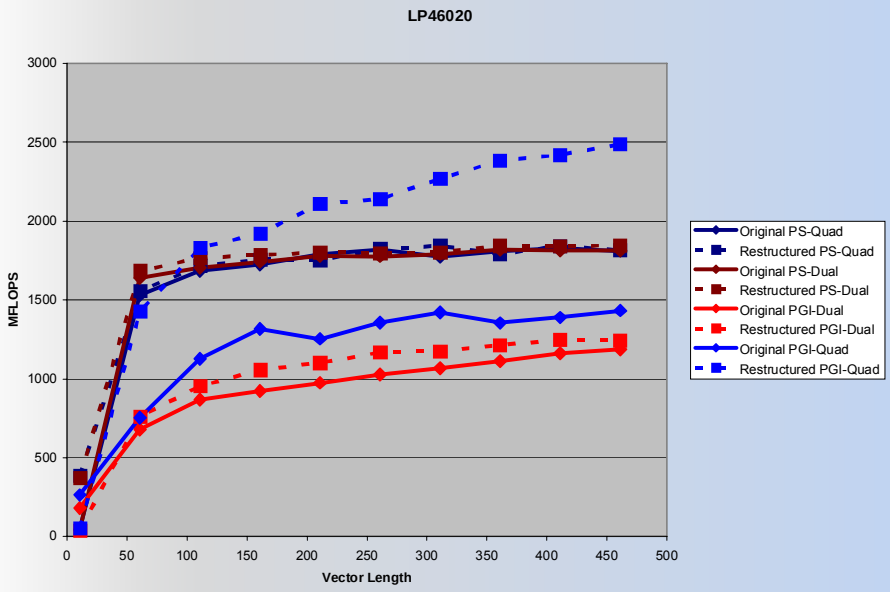
```
(   68) C       THE RESTRUCTURED
(   69)
(   70)       DO 46021 I = 1, N
(   71)         A(I,1) = B(I,1) * C(1,1) + B(I,2) * C(2,1)
(   72)      *         + B(I,3) * C(3,1) + B(I,4) * C(4,1)
(   73)         A(I,2) = B(I,1) * C(1,2) + B(I,2) * C(2,2)
(   74)      *         + B(I,3) * C(3,2) + B(I,4) * C(4,2)
(   75)         A(I,3) = B(I,1) * C(1,3) + B(I,2) * C(2,3)
(   76)      *         + B(I,3) * C(3,3) + B(I,4) * C(4,3)
(   77)         A(I,4) = B(I,1) * C(1,4) + B(I,2) * C(2,4)
(   78)      *         + B(I,3) * C(3,4) + B(I,4) * C(4,4)
(   79) 46021 CONTINUE
(   80)
```

PGI

70, Generated an alternate loop for the inner loop
Generated vector sse code for inner loop
Generated 4 prefetch instructions for this loop
Generated vector sse code for inner loop
Generated 4 prefetch instructions for this loop

Pathscale

(lp46020.f:70) Loop has too many loop invariants. Loop was not vectorized.



Traditional MATMUL

```
(    41) C      THE ORIGINAL
(    42)
(    43)       DO 46030 J  = 1, N
(    44)        DO 46030 I = 1, N
(    45)         A(I,J) = 0.
(    46) 46030 CONTINUE
(    47)
(    48)       DO 46031   K = 1, N
(    49)        DO 46031  J = 1, N
(    50)         DO 46031 I = 1, N
(    51)          A(I,J) = A(I,J) + B(I,K) * C(K,J)
(    52) 46031 CONTINUE
(    53)
```


PGI

```
  43, Loop not vectorized: contains call
   44, Memory zero idiom, loop replaced by memzero call
   48, Interchange produces reordered loop nest: 49, 48, 50
   50, Generated 3 alternate loops for the inner loop
       Generated vector sse code for inner loop
       Generated 2 prefetch instructions for this loop
       Generated vector sse code for inner loop
       Generated 2 prefetch instructions for this loop
       Generated vector sse code for inner loop
       Generated 2 prefetch instructions for this loop
       Generated vector sse code for inner loop
       Generated 2 prefetch instructions for this loop
```

Pathscale

(lp46030.f:44) LOOP WAS VECTORIZED.
(lp46030.f:44) LOOP WAS VECTORIZED.
(lp46030.f:50) Loop has too many loop invariants. Loop was not vectorized.
(lp46030.f:50) LOOP WAS VECTORIZED.
(lp46030.f:50) LOOP WAS VECTORIZED.
(lp46030.f:50) LOOP WAS VECTORIZED.

Rewrite

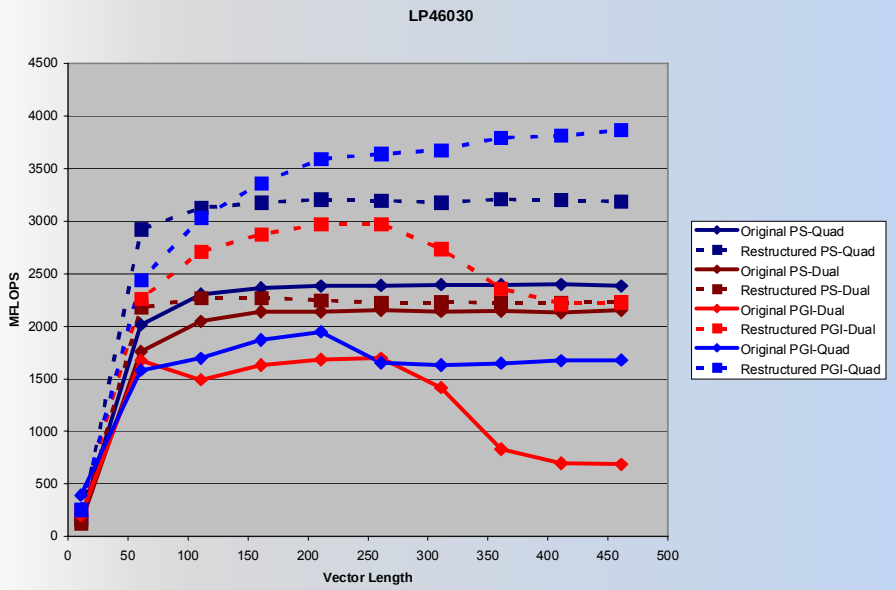
```
(   69) C       THE RESTRUCTURED
(   70)
(   71)       DO 46032  J = 1, N
(   72)        DO 46032 I = 1, N
(   73)         A(I,J)=0.
(   74) 46032 CONTINUE
(   75) C
(   76)       DO 46033   K = 1, N-5, 6
(   77)        DO 46033  J = 1, N
(   78)         DO 46033 I = 1, N
(   79)          A(I,J) = A(I,J) + B(I,K  ) * C(K  ,J)
(   80)      *                   + B(I,K+1) * C(K+1,J)
(   81)      *                   + B(I,K+2) * C(K+2,J)
(   82)      *                   + B(I,K+3) * C(K+3,J)
(   83)      *                   + B(I,K+4) * C(K+4,J)
(   84)      *                   + B(I,K+5) * C(K+5,J)
(   85) 46033 CONTINUE
(   86) C
(   87)       DO 46034  KK = K, N
(   88)        DO 46034  J = 1, N
(   89)         DO 46034 I = 1, N
(   90)          A(I,J) = A(I,J) + B(I,KK) * C(KK ,J)
(   91) 46034 CONTINUE
(   92)
```


Rewrite

PGI
- 71, Loop not vectorized: contains call
- 72, Memory zero idiom, loop replaced by memzero call
- 78, Generated 3 alternate loops for the inner loop
  - Generated vector sse code for inner loop
  - Generated 7 prefetch instructions for this loop
  - Generated vector sse code for inner loop
  - Generated 7 prefetch instructions for this loop
  - Generated vector sse code for inner loop
  - Generated 7 prefetch instructions for this loop
  - Generated vector sse code for inner loop
  - Generated 7 prefetch instructions for this loop
- 87, Interchange produces reordered loop nest: 88, 87, 89
- 89, Generated 3 alternate loops for the inner loop
  - Generated vector sse code for inner loop
  - Generated 2 prefetch instructions for this loop
  - Generated vector sse code for inner loop
  - Generated 2 prefetch instructions for this loop
  - Generated vector sse code for inner loop
  - Generated 2 prefetch instructions for this loop
  - Generated vector sse code for inner loop
  - Generated 2 prefetch instructions for this loop

Rewrite

Pathscale
(lp46030.f:72) LOOP WAS VECTORIZED.
(lp46030.f:72) LOOP WAS VECTORIZED.
(lp46030.f:78) LOOP WAS VECTORIZED.
(lp46030.f:78) LOOP WAS VECTORIZED.
(lp46030.f:89) Loop has too many loop invariants. Loop was not vectorized.
(lp46030.f:89) LOOP WAS VECTORIZED.
(lp46030.f:89) LOOP WAS VECTORIZED.
(lp46030.f:89) LOOP WAS VECTORIZED.



Big Loop

```
(   52) C      THE ORIGINAL
(   53)
(   54)       DO 47020   J = 1, JMAX
(   55)        DO 47020  K = 1, KMAX
(   56)         DO 47020 I = 1, IMAX
(   57)           JP         = J + 1
(   58)           JR         = J - 1
(   59)           KP         = K + 1
(   60)           KR         = K - 1
(   61)           IP         = I + 1
(   62)           IR         = I - 1
(   63)           IF (J .EQ. 1)     GO TO 50
(   64)            IF( J .EQ. JMAX) GO TO 51
(   65)             XJ = ( A(I,JP,K) - A(I,JR,K) ) * DA2
(   66)             YJ = ( B(I,JP,K) - B(I,JR,K) ) * DA2
(   67)             ZJ = ( C(I,JP,K) - C(I,JR,K) ) * DA2
(   68)             GO TO 70
(   69)    50     J1 = J + 1
(   70)           J2 = J + 2
(   71)           XJ = (-3. * A(I,J,K) + 4. * A(I,J1,K) - A(I,J2,K) ) * DA2
(   72)           YJ = (-3. * B(I,J,K) + 4. * B(I,J1,K) - B(I,J2,K) ) * DA2
(   73)           ZJ = (-3. * C(I,J,K) + 4. * C(I,J1,K) - C(I,J2,K) ) * DA2
(   74)           GO TO 70
(   75)    51     J1 = J - 1
(   76)           J2 = J - 2
(   77)           XJ = ( 3. * A(I,J,K) - 4. * A(I,J1,K) + A(I,J2,K) ) * DA2
(   78)           YJ = ( 3. * B(I,J,K) - 4. * B(I,J1,K) + B(I,J2,K) ) * DA2
(   79)           ZJ = ( 3. * C(I,J,K) - 4. * C(I,J1,K) + C(I,J2,K) ) * DA2
(   80)    70     CONTINUE
(   81)           IF (K .EQ. 1)     GO TO 52
(   82)            IF (K .EQ. KMAX) GO TO 53
(   83)             XK = ( A(I,J,KP) - A(I,J,KR) ) * DB2
(   84)             YK = ( B(I,J,KP) - B(I,J,KR) ) * DB2
(   85)             ZK = ( C(I,J,KP) - C(I,J,KR) ) * DB2
(   86)             GO TO 71
```


Big Loop

```
(   87)    52     K1 = K + 1
(   88)           K2 = K + 2
(   89)           XK = (-3. * A(I,J,K) + 4. * A(I,J,K1) - A(I,J,K2) ) * DB2
(   90)           YK = (-3. * B(I,J,K) + 4. * B(I,J,K1) - B(I,J,K2) ) * DB2
(   91)           ZK = (-3. * C(I,J,K) + 4. * C(I,J,K1) - C(I,J,K2) ) * DB2
(   92)           GO TO 71
(   93)    53     K1 = K - 1
(   94)           K2 = K - 2
(   95)           XK = ( 3. * A(I,J,K) - 4. * A(I,J,K1) + A(I,J,K2) ) * DB2
(   96)           YK = ( 3. * B(I,J,K) - 4. * B(I,J,K1) + B(I,J,K2) ) * DB2
(   97)           ZK = ( 3. * C(I,J,K) - 4. * C(I,J,K1) + C(I,J,K2) ) * DB2
(   98)    71     CONTINUE
(   99)           IF (I .EQ. 1)     GO TO 54
(  100)            IF (I .EQ. IMAX) GO TO 55
(  101)             XI = ( A(IP,J,K) - A(IR,J,K) ) * DC2
(  102)             YI = ( B(IP,J,K) - B(IR,J,K) ) * DC2
(  103)             ZI = ( C(IP,J,K) - C(IR,J,K) ) * DC2
(  104)             GO TO 60
(  105)    54     I1 = I + 1
(  106)           I2 = I + 2
(  107)           XI = (-3. * A(I,J,K) + 4. * A(I1,J,K) - A(I2,J,K) ) * DC2
(  108)           YI = (-3. * B(I,J,K) + 4. * B(I1,J,K) - B(I2,J,K) ) * DC2
(  109)           ZI = (-3. * C(I,J,K) + 4. * C(I1,J,K) - C(I2,J,K) ) * DC2
(  110)           GO TO 60
(  111)    55     I1 = I - 1
(  112)           I2 = I - 2
(  113)           XI = ( 3. * A(I,J,K) - 4. * A(I1,J,K) + A(I2,J,K) ) * DC2
(  114)           YI = ( 3. * B(I,J,K) - 4. * B(I1,J,K) + B(I2,J,K) ) * DC2
(  115)           ZI = ( 3. * C(I,J,K) - 4. * C(I1,J,K) + C(I2,J,K) ) * DC2
(  116)    60     CONTINUE
(  117)           DINV     = XJ * YK * ZI  +  YJ * ZK * XI  +  ZJ * XK * YI
(  118)      *               - XJ * ZK * YI  -  YJ * XK * ZI  -  ZJ * YK * XI
(  119)           D(I,J,K) = 1. / (DINV + 1.E-20)
(  120) 47020 CONTINUE
(  121)
```

PGI
55, Invariant if transformation
Loop not vectorized: loop count too small
56, Invariant if transformation
Pathscale
Nothing

Re-Write

```
(  141) C      THE RESTRUCTURED
(  142)
(  143)       DO 47029 J = 1, JMAX
(  144)        DO 47029 K = 1, KMAX
(  145)
(  146)         IF(J.EQ.1)THEN
(  147)
(  148)         J1         = 2
(  149)         J2         = 3
(  150)         DO 47021 I = 1, IMAX
(  151)          VAJ(I) = (-3. * A(I,J,K) + 4. * A(I,J1,K) - A(I,J2,K) ) * DA2
(  152)          VBJ(I) = (-3. * B(I,J,K) + 4. * B(I,J1,K) - B(I,J2,K) ) * DA2
(  153)          VCJ(I) = (-3. * C(I,J,K) + 4. * C(I,J1,K) - C(I,J2,K) ) * DA2
(  154) 47021   CONTINUE
(  155)
(  156)         ELSE IF(J.NE.JMAX) THEN
(  157)
(  158)         JP         = J+1
(  159)         JR         = J-1
(  160)         DO 47022 I = 1, IMAX
(  161)          VAJ(I) = ( A(I,JP,K) - A(I,JR,K) ) * DA2
(  162)          VBJ(I) = ( B(I,JP,K) - B(I,JR,K) ) * DA2
(  163)          VCJ(I) = ( C(I,JP,K) - C(I,JR,K) ) * DA2
(  164) 47022   CONTINUE
(  165)
(  166)         ELSE
(  167)
(  168)         J1         = JMAX-1
(  169)         J2         = JMAX-2
(  170)         DO 47023 I = 1, IMAX
(  171)          VAJ(I) = ( 3. * A(I,J,K) - 4. * A(I,J1,K) + A(I,J2,K) ) * DA2
(  172)          VBJ(I) = ( 3. * B(I,J,K) - 4. * B(I,J1,K) + B(I,J2,K) ) * DA2
(  173)          VCJ(I) = ( 3. * C(I,J,K) - 4. * C(I,J1,K) + C(I,J2,K) ) * DA2
(  174) 47023   CONTINUE
(  175)
(  176)         ENDIF
```

Re-Write

```
(  178)         IF(K.EQ.1) THEN
(  179)
(  180)         K1         = 2
(  181)         K2         = 3
(  182)         DO 47024 I = 1, IMAX
(  183)          VAK(I) = (-3. * A(I,J,K) + 4. * A(I,J,K1) - A(I,J,K2) ) * DB2
(  184)          VBK(I) = (-3. * B(I,J,K) + 4. * B(I,J,K1) - B(I,J,K2) ) * DB2
(  185)          VCK(I) = (-3. * C(I,J,K) + 4. * C(I,J,K1) - C(I,J,K2) ) * DB2
(  186) 47024   CONTINUE
(  187)
(  188)         ELSE IF(K.NE.KMAX)THEN
(  189)
(  190)         KP         = K + 1
(  191)         KR         = K - 1
(  192)         DO 47025 I = 1, IMAX
(  193)          VAK(I) = ( A(I,J,KP) - A(I,J,KR) ) * DB2
(  194)          VBK(I) = ( B(I,J,KP) - B(I,J,KR) ) * DB2
(  195)          VCK(I) = ( C(I,J,KP) - C(I,J,KR) ) * DB2
(  196) 47025   CONTINUE
(  197)
(  198)         ELSE
(  199)
(  200)         K1         = KMAX - 1
(  201)         K2         = KMAX - 2
(  202)         DO 47026 I = 1, IMAX
(  203)          VAK(I) = ( 3. * A(I,J,K) - 4. * A(I,J,K1) + A(I,J,K2) ) * DB2
(  204)          VBK(I) = ( 3. * B(I,J,K) - 4. * B(I,J,K1) + B(I,J,K2) ) * DB2
(  205)          VCK(I) = ( 3. * C(I,J,K) - 4. * C(I,J,K1) + C(I,J,K2) ) * DB2
(  206) 47026   CONTINUE
(  207)         ENDIF
(  208)
```


Re-Write

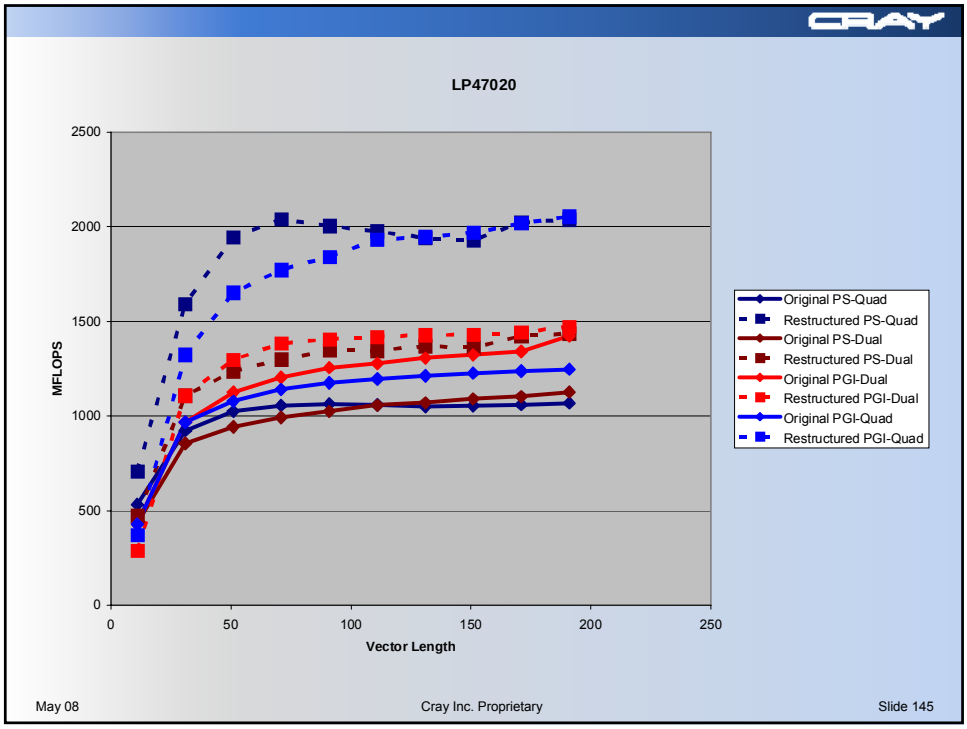
```
(  209)         I = 1
(  210)         I1         = 2
(  211)         I2         = 3
(  212)         VAI(I) = (-3. * A(I,J,K) + 4. * A(I1,J,K) - A(I2,J,K) ) * DC2
(  213)         VBI(I) = (-3. * B(I,J,K) + 4. * B(I1,J,K) - B(I2,J,K) ) * DC2
(  214)         VCI(I) = (-3. * C(I,J,K) + 4. * C(I1,J,K) - C(I2,J,K) ) * DC2
(  215)
(  216)         DO 47027 I = 2, IMAX-1
(  217)          IP         = I + 1
(  218)          IR         = I - 1
(  219)            VAI(I) = ( A(IP,J,K) - A(IR,J,K) ) * DC2
(  220)            VBI(I) = ( B(IP,J,K) - B(IR,J,K) ) * DC2
(  221)            VCI(I) = ( C(IP,J,K) - C(IR,J,K) ) * DC2
(  222) 47027   CONTINUE
(  223)
(  224)           I = IMAX
(  225)           I1         = IMAX - 1
(  226)           I2         = IMAX - 2
(  227)           VAI(I) = ( 3. * A(I,J,K) - 4. * A(I1,J,K) + A(I2,J,K) ) * DC2
(  228)           VBI(I) = ( 3. * B(I,J,K) - 4. * B(I1,J,K) + B(I2,J,K) ) * DC2
(  229)           VCI(I) = ( 3. * C(I,J,K) - 4. * C(I1,J,K) + C(I2,J,K) ) * DC2
(  230)
(  231)           DO 47028 I = 1, IMAX
(  232)            DINV = VAJ(I) * VBK(I) * VCI(I) + VBJ(I) * VCK(I) * VAI(I)
(  233)      1          + VCJ(I) * VAK(I) * VBI(I) - VAJ(I) * VCK(I) * VBI(I)
(  234)      2          - VBJ(I) * VAK(I) * VCI(I) - VCJ(I) * VBK(I) * VAI(I)
(  235)            D(I,J,K) = 1. / (DINV + 1.E-20)
(  236) 47028   CONTINUE
(  237) 47029 CONTINUE

(  238)
```

PGI

```
144, Invariant if transformation
     Loop not vectorized: loop count too small
150, Generated 3 alternate loops for the inner loop
     Generated vector sse code for inner loop
     Generated 8 prefetch instructions for this loop
     Generated vector sse code for inner loop
     Generated 8 prefetch instructions for this loop
     Generated vector sse code for inner loop
     Generated 8 prefetch instructions for this loop
     Generated vector sse code for inner loop
     Generated 8 prefetch instructions for this loop
160, Generated 4 alternate loops for the inner loop
     Generated vector sse code for inner loop
     Generated 6 prefetch instructions for this loop
     Generated vector sse code for inner loop
o o o
```


Pathscale

```
(lp47020.f:132) LOOP WAS VECTORIZED.
(lp47020.f:150) LOOP WAS VECTORIZED.
(lp47020.f:160) LOOP WAS VECTORIZED.
(lp47020.f:170) LOOP WAS VECTORIZED.
(lp47020.f:182) LOOP WAS VECTORIZED.
(lp47020.f:192) LOOP WAS VECTORIZED.
(lp47020.f:202) LOOP WAS VECTORIZED.
(lp47020.f:216) LOOP WAS VECTORIZED.
(lp47020.f:231) LOOP WAS VECTORIZED.
(lp47020.f:248) LOOP WAS VECTORIZED.
```



Original

```
(   48) C      THE ORIGINAL
(   49)
(   50)       DO 47030 I = 1, N
(   51)        A(I) = PROD * B(1,I) * A(I)
(   52)        IF (A(I) .LT. 0.0) A(I) = -A(I)
(   53)        IF (XL .LT. 0.0) A(I) = -A(I)
(   54)        IF (GAMMA) 47030, 47030, 100
(   55) 100     XL = -XL
(   56) 47030 CONTINUE
```

PGI
Nothing
Pathscale
(lp47030.f:50) Non-contiguous array "B(_BLNK__.4000.0)" reference exists.
Loop was not vectorized.

```
(   77) C      THE RESTRUCTURED
(   78)
(   79)       DO 47031 I = 1, N
(   80)        A(I) = PROD * B(1,I) * A(I)
(   81)        A(I) = ABS (A(I))
(   82) 47031 CONTINUE
(   83)
(   84)       IF (GAMMA .LE. 0.) THEN
(   85)
(   86)        IF (XL .LT. 0.0) THEN
(   87)         DO 47032 I = 1, N
(   88)          A(I) = -A(I)
(   89) 47032   CONTINUE
(   90)        ENDIF
(   91)
(   92)       ELSE
(   93)
(   94)        IF (XL .LT. 0.0) THEN
(   95)         DO 47033 I = 1, N, 2
(   96)          A(I) = -A(I)
(   97) 47033   CONTINUE
(   98)        ENDIF
(   99)
(  100)        IF (XL .GT. 0.0) THEN
(  101)         DO 47034 I = 2, N, 2
(  102)          A(I) = -A(I)
(  103) 47034   CONTINUE
(  104)        ENDIF
(  105)
(  106)       ENDIF
(  107)
```

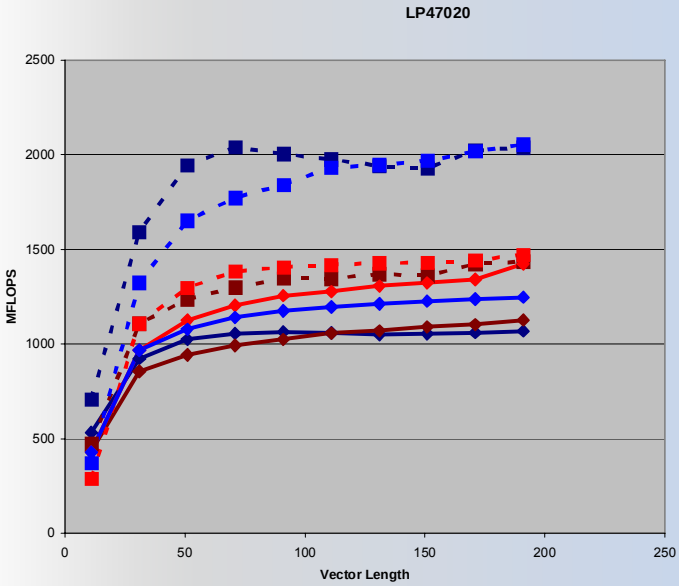

Re-Write

PGI

79, Generated vector sse code for inner loop
Generated 2 prefetch instructions for this loop
95, Generated vector sse code for inner loop
Generated 1 prefetch instructions for this loop

Pathscale

(lp47030.f:79) Non-contiguous array "B(_BLNK__.4000.0)" reference exists. Loop was not vectorized.
(lp47030.f:95) Non-contiguous array "A(_BLNK__.0.0)" reference exists. Loop was not vectorized.



Original

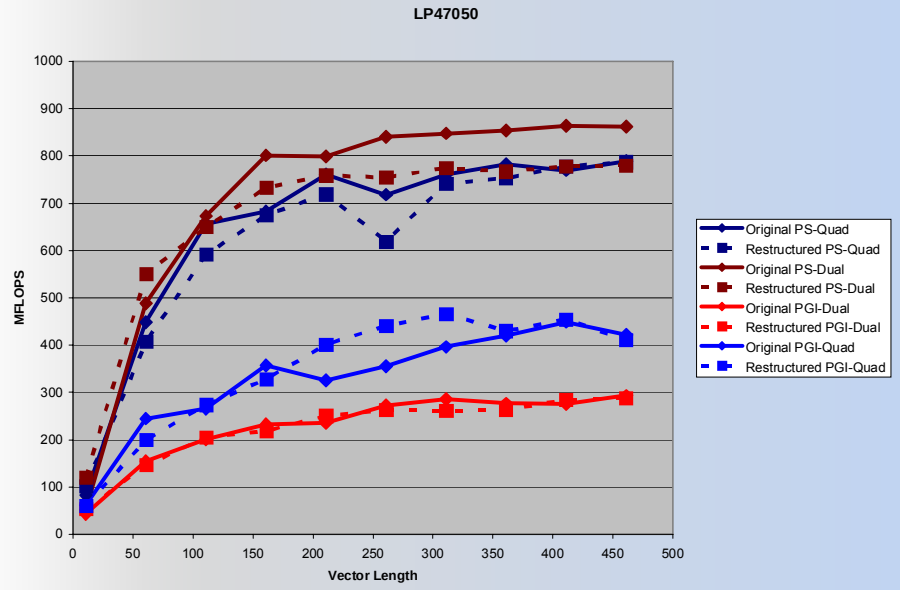
```
(   42) C      THE ORIGINAL
(   43)
(   44)       DO 47050 I = 1, N
(   45)        IIA = IA(I)
(   46)        GO TO (110, 120) IIA
(   47) 110    D(I) = B(I)
(   48)        A(I) = D(I) + 1.7
(   49)        GO TO 47050
(   50) 120    D(I) = C(I)
(   51)        A(I) = D(I) + 1.1
(   52) 47050 CONTINUE
(   53)
```

PGI
Nothing
Pathscale
Nothing

Restructured

```
(   71) C      THE RESTRUCTURED
(   72)
(   73)       DO 47051 I = 1, N
(   74)        IF(IA(I) .NE. 2) THEN
(   75)         D(I) = B(I)
(   76)         A(I) = D(I) + 1.7
(   77)        ELSE
(   78)         D(I) = C(I)
(   79)         A(I) = D(I) + 1.1
(   80)        ENDIF
(   81) 47051 CONTINUE
```

PGI
Nothing
Pathscale
(lp47050.f:73) Expression rooted at op "OPC_IF"(line 74) is not vectorizable.
Loop was not vectorized.



Original

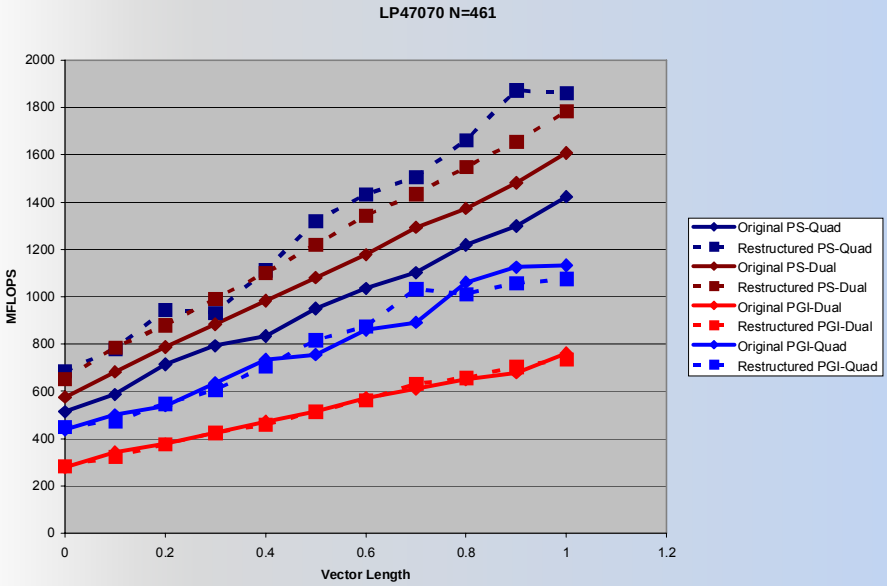
```
(   45)
(   46)       DO 47070 I = 1, N
(   47)        A(I) = B(I) * C(I)
(   48)        IF (A(I) .NE. 0.) GO TO 110
(   49)         C0   = B(I)**2 + C(I)**2
(   50)         A(I) = D(I) * E(I) + C0
(   51)         B(I) = 1.
(   52) 110    CONTINUE
(   53)       F(I) = A(I) + B(I)
(   54) 47070 CONTINUE
(   55)
```

PGI
Nothing
Pathscale
Nothing

Restructured

```
(   74) C      THE RESTRUCTURED
(   75)
(   76)       DO 47071 I = 1, N
(   77)        A(I) = B(I) * C(I)
(   78)        IF (A(I) .EQ. 0.) THEN
(   79)         A(I) = D(I) * E(I) + B(I)**2 + C(I)**2
(   80)         B(I) = 1.
(   81)        ENDIF
(   82)        F(I) = A(I) + B(I)
(   83) 47071 CONTINUE
(   84)
```

PGI
Nothing
Pathscale
(lp47070.f:76) Expression rooted at op "OPC_IF"(line 77) is not vectorizable.
Loop was not vectorized.



Original

```
(   45)
(   46) C      THE ORIGINAL
(   47)
(   48)       DO 47101 I = 1, N
(   49)        U1 = X2(I)
(   50)
(   51)        DO 47100 LT = 1, NTAB
(   52)         IF (U1 .GT. X1(LT)) GO TO 47100
(   53)           IL = LT
(   54)           GO TO 121
(   55) 47100  CONTINUE
(   56)
(   57)        IL = NTAB - 1
(   58) 121    Y2(I) = Y1(IL) + ( Y1(IL+1) - Y1(IL) ) /
(   59)      *                  ( X1(IL+1) - X1(IL) ) *
(   60)      *                     ( X2(I) - X1(IL) )
(   61) 47101 CONTINUE
(   62)
```

PGI

51, Loop not vectorized: multiple exits

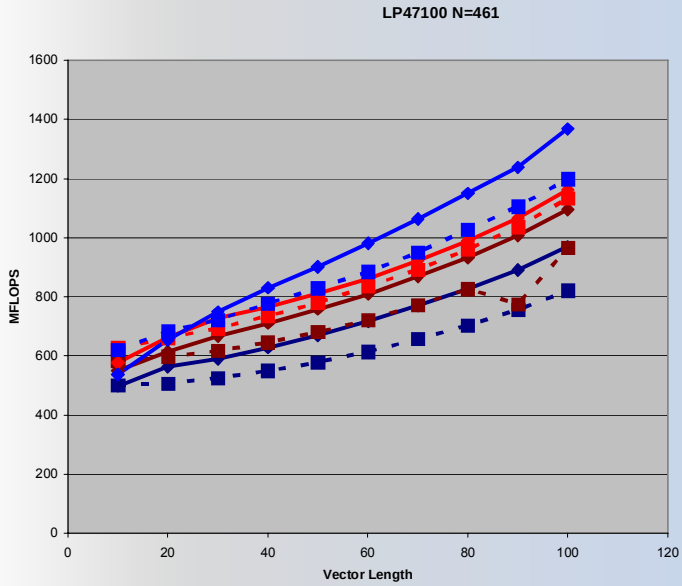
Pathscale

Nothing

Restructured

```
(   80) C      THE RESTRUCTURED
(   81)
(   82)       DO 47103 I = 1, N
(   83)        U1 = X2(I)
(   84)
(   85)        DO 47102 LT = 1, NTAB
(   86)         IF (U1 .GT. X1(LT)) GO TO 47102
(   87)           IV(I) = LT
(   88)           GO TO 47103
(   89) 47102  CONTINUE
(   90)
(   91)        IV(I) = NTAB - 1
(   92) 47103 CONTINUE
(   93)
(   94)       DO 47104 I  =  1, N
(   95)        Y2(I) = Y1(IV(I)) + ( Y1(IV(I)+1) - Y1(IV(I)) ) /
(   96)      *                     ( X1(IV(I)+1) - X1(IV(I)) ) *
(   97)      *                           ( X2(I) - X1(IV(I)) )
(   98) 47104 CONTINUE
(   99)
```


PGI
 85, Loop not vectorized: multiple exits
Pathscale
(lp47100.f:94) Non-contiguous array "Y1(_BLNK__.8808.0)" reference exists.
Loop was not vectorized.



Original

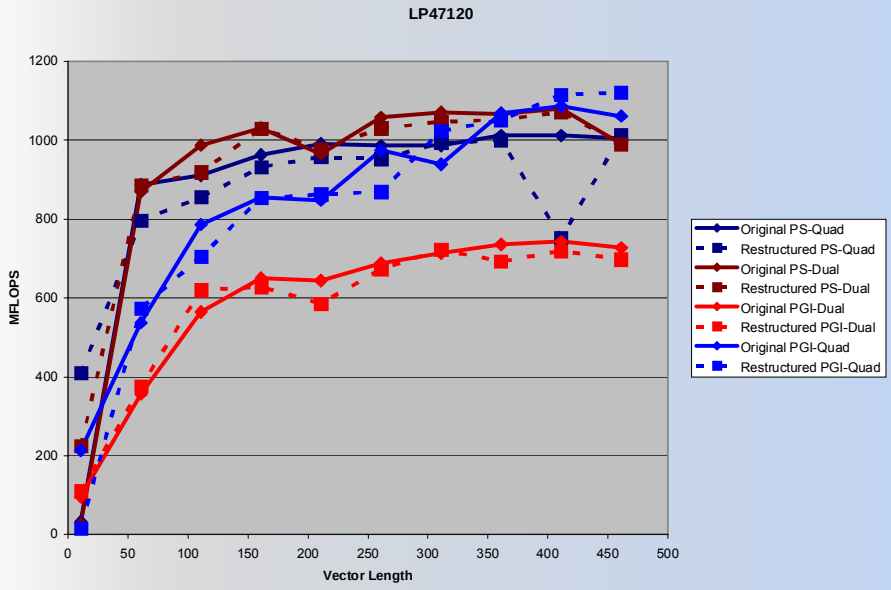
```
(   42) C      THE ORIGINAL
(   43)
(   44)       I = 0
(   45) 47120 CONTINUE
(   46)        I = I + 1
(   47)        A(I) = B(I)**2 + .5 * C(I) * D(I) / E(I)
(   48)       IF (I .LT. N) GO TO 47120
(   49)
```

PGI
Nothing
Pathscale
Nothing

Restructured

```
(   67) C      THE RESTRUCTURED
(   68)
(   69)       DO 47121 I = 1, N
(   70)        A(I) = B(I)**2 + .5 * C(I) * D(I) / E(I)
(   71) 47121 CONTINUE
(   72)
```

PGI
69, Generated an alternate loop for the inner loop
Generated vector sse code for inner loop
Generated 4 prefetch instructions for this loop
Generated vector sse code for inner loop
Generated 4 prefetch instructions for this loop
Pathscale
(lp47120.f:69) Expression rooted at op "OPC_F8RECIP"(line 70) is not vectorizable. Loop was not vectorized.



Original

```
(   39) C      THE ORIGINAL
(   40)
(   41)       DO 48010 I = 1, N
(   42)        A(I) = B(I) * C(I)
(   43)        D(I) = FRED (A(I)**2 + 2.0)
(   44)        E(I) = D(I) / B(I) + A(I)
(   45) 48010 CONTINUE(   49)
```

PGI
41, Loop not vectorized: contains call
Pathscale
Nothing

Restructured

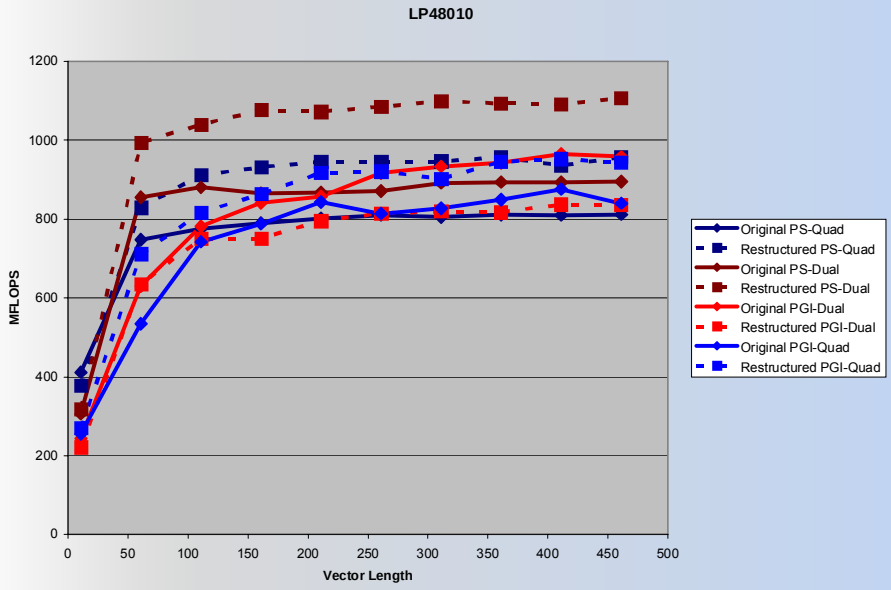
```
(   65) C      THE RESTRUCTURED
(   66)
(   67)       DO 48011 I = 1,N
(   68)        A(I) = B(I) * C(I)
(   69)        D(I) = A(I)**2 + 2.0
(   70) 48011 CONTINUE
(   71)
(   72)       DO 48012 I = 1,N
(   73)        D(I) = FRED (D(I))
(   74) 48012 CONTINUE
(   75)
(   76)       DO 48013 I = 1,N
(   77)        E(I) = D(I) / B(I) + A(I)
(   78) 48013 CONTINUE
(   79)
```

PGI

67, Generated an alternate loop for the inner loop
Generated vector sse code for inner loop
Generated 2 prefetch instructions for this loop
Generated vector sse code for inner loop
Generated 2 prefetch instructions for this loop
72, Loop not vectorized: contains call
76, Generated an alternate loop for the inner loop
Generated vector sse code for inner loop
Generated 3 prefetch instructions for this loop
Generated vector sse code for inner loop
Generated 3 prefetch instructions for this loop

Pathscale

(lp48010.f:67) LOOP WAS VECTORIZED.
(lp48010.f:76) Expression rooted at op "OPC_F8RECIP"(line 77) is not vectorizable. Loop was not vectorized.



Original

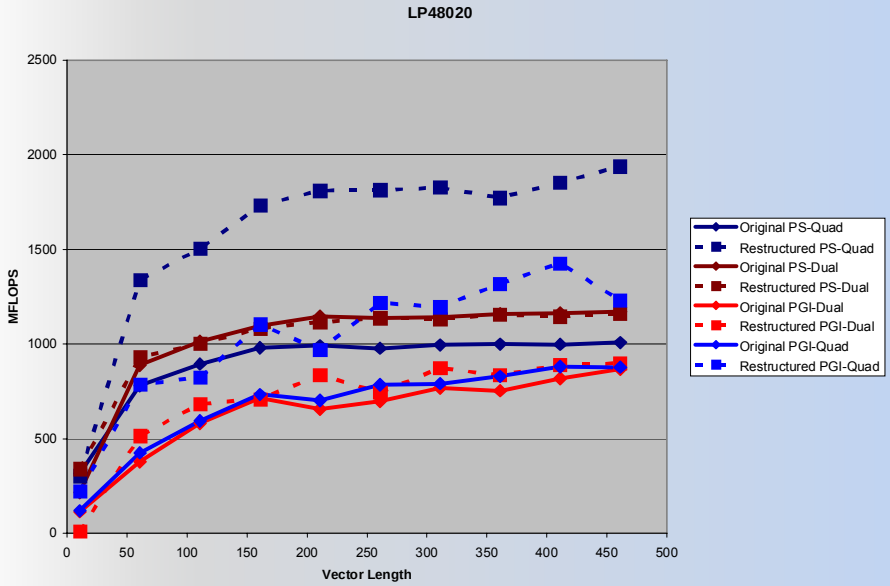
```
(   39) C      THE ORIGINAL
(   40)
(   41)       DO 48020 I = 1, N
(   42)        A(I) = B(I) * FUNC (D(I)) + C(I)
(   43) 48020 CONTINUE
(   44)
```

PGI
41, Loop not vectorized: contains call
Pathscale
Nothing

Restructured

```
(  10)     FUNCX (X) = X**2 + 2.0 / X
(   62)
(   63)       DO 48021 I = 1, N
(   64)        A(I) = B(I) * FUNCX (D(I)) + C(I)
(   65) 48021 CONTINUE
(   66)
```

PGI
63, Generated an alternate loop for the inner loop
Generated vector sse code for inner loop
Generated 3 prefetch instructions for this loop
Generated vector sse code for inner loop
Generated 3 prefetch instructions for this loop
Pathscale
(lp48020.f:63) LOOP WAS VECTORIZED.



Original

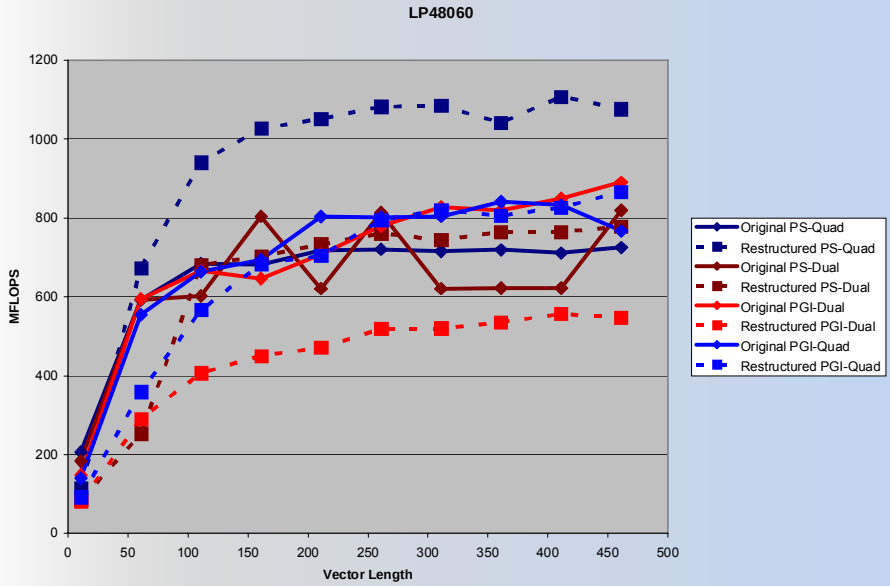
```
(   42) C      THE ORIGINAL
(   43)
(   44)       DO 48060 I = 1, N
(   45)        AOLD = A(I)
(   46)        A(I) = UFUN (AOLD, B(I), SCA)
(   47)        C(I) = (A(I) + AOLD) * .5
(   48) 48060 CONTINUE
(   49)
```

PGI
 41, Loop not vectorized: contains call
Pathscale
Nothing

Restructured

```
(   71) C      THE RESTRUCTURED
(   72)
(   73)       DO 48061 I = 1, N
(   74)        VAOLD(I) = A(I)
(   75) 48061 CONTINUE
(   76)
(   77)       CALL VUFUN (N, VAOLD, B, SCA, A)
(   78)
(   79)       DO 48062 I = 1, N
(   80)        C(I) = (A(I) + VAOLD(I)) * .5
(   81) 48062 CONTINUE
(   82)
```


PGI
  73, Memory copy idiom, loop replaced by memcopy call
    79, Generated an alternate loop for the inner loop
        Generated vector sse code for inner loop
        Generated 2 prefetch instructions for this loop
        Generated vector sse code for inner loop
        Generated 2 prefetch instructions for this loop
    91, Generated vector sse code for inner loop
Pathscale
(lp48060.f:73) LOOP WAS VECTORIZED.
(lp48060.f:79) LOOP WAS VECTORIZED.
(lp48060.f:91) LOOP WAS VECTORIZED.



Original

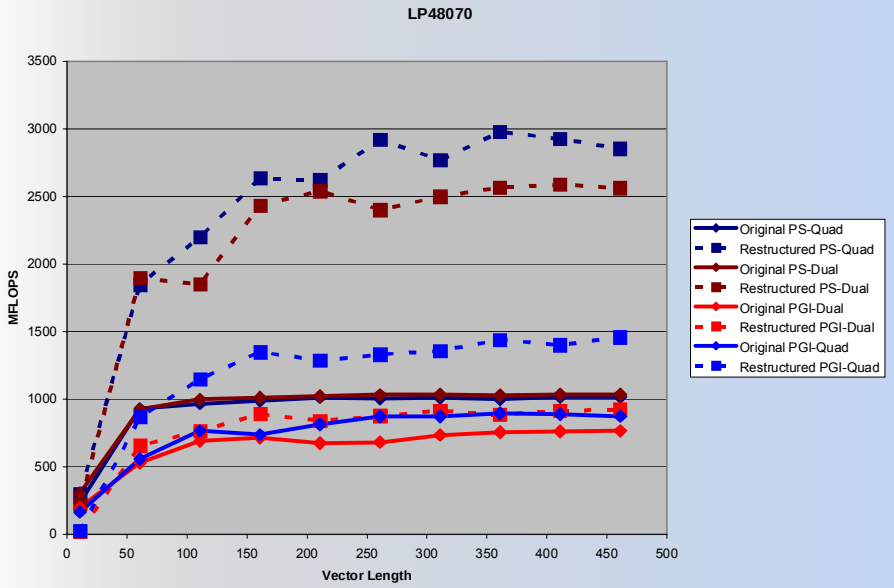
```
(   42) C      THE ORIGINAL
(   43)
(   44)       DO 48070 I = 1, N
(   45)        A(I) =  (B(I)**2 + C(I)**2)
(   46)        CT   = PI * A(I) + (A(I))**2
(   47)        CALL SSUB (A(I), CT, D(I), E(I))
(   48)        F(I) = (ABS (E(I)))
(   49) 48070 CONTINUE
(   50)
```

PGI
  44, Loop not vectorized: contains call
Pathscale
Nothing

Restructured

```
(   69) C      THE RESTRUCTURED
(   70)
(   71)       DO 48071 I = 1, N
(   72)        A(I) = (B(I)**2 + C(I)**2)
(   73)        CT   = PI * A(I) + (A(I))**2
(   74)        E(I) = A(I)**2 + (ABS (A(I) + CT)) * (CT * ABS (A(I) - CT))
(   75)        D(I) = A(I) + CT
(   76)        F(I) = (ABS (E(I)))
(   77) 48071 CONTINUE
(   78)
```

PGI
71, Generated an alternate loop for the inner loop
Unrolled inner loop 4 times
Used combined stores for 2 stores
Generated 2 prefetch instructions for this loop
Unrolled inner loop 4 times
Used combined stores for 2 stores
Generated 2 prefetch instructions for this loop
Pathscale
(lp48070.f:71) LOOP WAS VECTORIZED.



Original

```
(   41) C      THE ORIGINAL
(   42)
(   43)       DO 48080 i = 1 , n
(   44)       a(i)=sqrt(b(i)**2+c(i)**2)
(   45)       sca=a(i)**2+b(i)**2
(   46)       scalr=sca*2
(   47)       CALL sub2(sca)
(   48)       d(i)=sqrt(abs(a(i)+sca))
(   49) 48080 CONTINUE
(   50)
```

PGI

43, Loop not vectorized: contains call

Pathscale

Nothing

Restructured

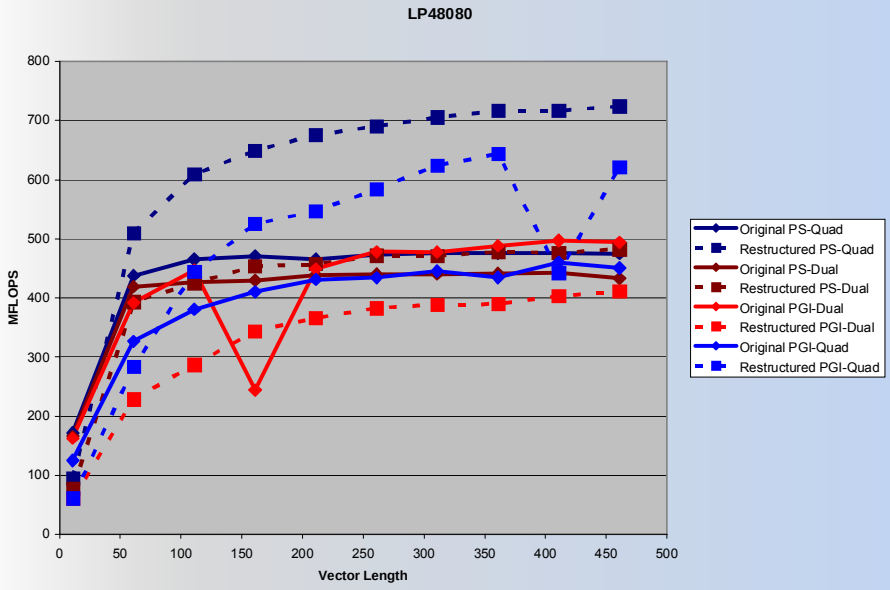
```
(   69) C      THE RESTRUCTURED
(   70)
(   71)       DO 48081 i = 1 , n
(   72)       a(i)=sqrt(b(i)**2+c(i)**2)
(   73) 48081 CONTINUE
(   74)
(   75)       CALL vsub1(n,a,b,vsca,vscalr)
(   76)
(   77)       CALL vsub2(n,vsca,vscalr)
(   78)
(   79)       DO 48082 i = 1 , n
(   80)       d(i)=sqrt(abs(a(i)+vsca(i)))
(   81) 48082 CONTINUE
(   82)
```

PGI

```
 71, Generated an alternate loop for the inner loop
     Generated vector sse code for inner loop
     Generated 2 prefetch instructions for this loop
     Generated vector sse code for inner loop
     Generated 2 prefetch instructions for this loop
 79, Generated an alternate loop for the inner loop
     Generated vector sse code for inner loop
     Generated 2 prefetch instructions for this loop
     Generated vector sse code for inner loop
     Generated 2 prefetch instructions for this loop
```

Pathscale

```
(lp48080.f:71) LOOP WAS VECTORIZED.
(lp48080.f:79) LOOP WAS VECTORIZED.
```

Original

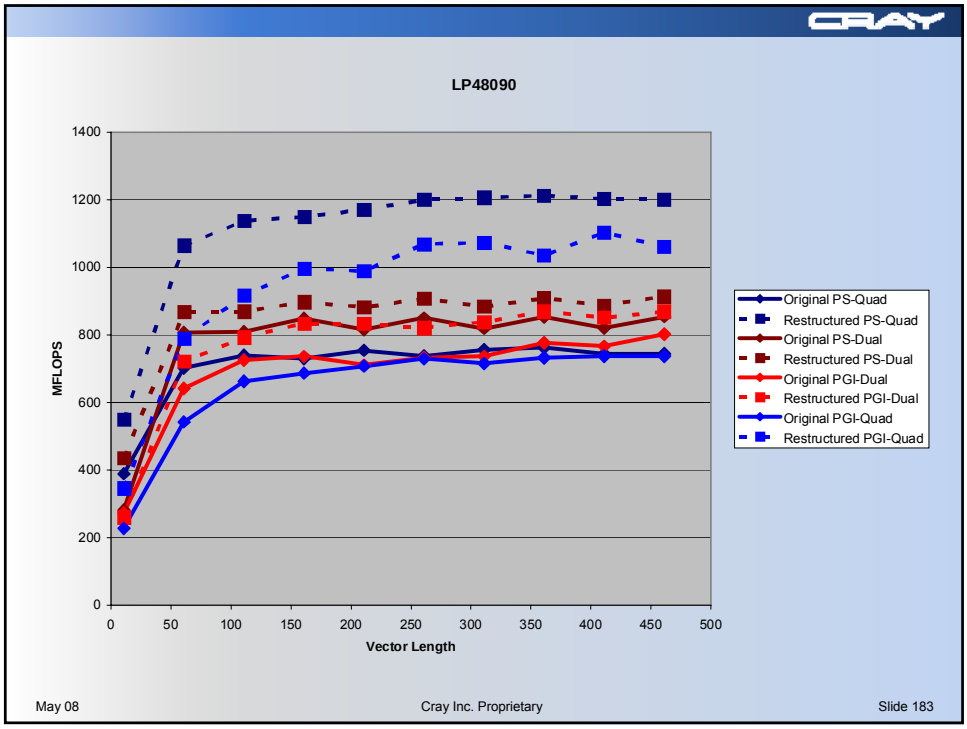
```
(   43) C      THE ORIGINAL
(   44)
(   45)       ET = 0.0
(   46)       DO 48090 I = 1, N
(   47)        B(I) = SQRT (F(I)**2 + E(I)**2) + ET
(   48)        CALL SSSUB (B(I), ET, C(I), D(I), PI)
(   49)        A(I) = SQRT (ABS (D(I) ) )
(   50) 48090 CONTINUE
(   51)
```

PGI
46, Loop not vectorized: contains call
Pathscale
Nothing

Restructured

```
(   70) C      THE RESTRUCTURED
(   71)
(   72)       VET(1)=0.0
(   73)       DO 48091 I = 1, N
(   74)        VET(I+1) = PI * C(I) + C(I)
(   75)        B(I) = SQRT (F(I)**2 + E(I)**2) + VET(I)
(   76)        D(I) = B(I)**2 + C(I)**2 * SQRT (ABS (B(I) + C(I) ) )
(   77)        D(I) = VET(I+1) + D(I)
(   78)        A(I) = SQRT (ABS (D(I) ) )
(   79) 48091 CONTINUE
(   80)
```

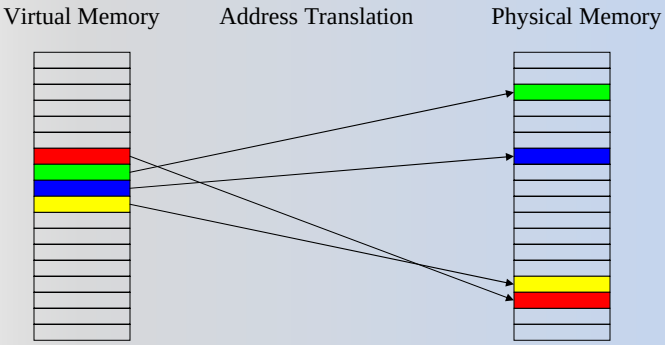
PGI
73, Generated an alternate loop for the inner loop
Generated vector sse code for inner loop
Generated 4 prefetch instructions for this loop
Generated vector sse code for inner loop
Generated 4 prefetch instructions for this loop
Pathscale
(lp48090.f:73) LOOP WAS VECTORIZED.



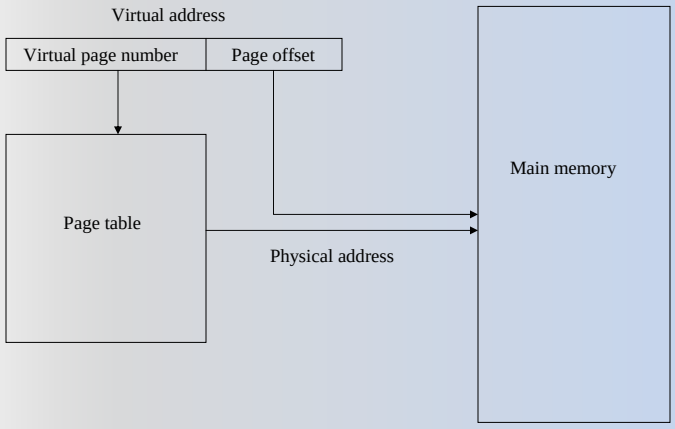
Background: Virtual Memory

- Modern programs operate in “virtual memory”
  - Each program thinks it has all of memory to itself
  - Fixed sized blocks (“pages”) vs variable sized blocks (“segments”)
- Virtual Memory benefits
  - Allow a program that is larger than physical memory to run
    - Programmer does not have to manually create overlays
  - Allow many programs to share limited physical memory
- Virtual Memory problems
  - Each virtual memory reference must be translated into a physical memory reference

Virtual Memory vs Physical Memory



Address Translation



Source: Computer Architecture A Quantitative Approach, by John L. Hennessy and David A. Patterson

Translation Speed

- Translation page table is stored in main memory
  - Each memory access logically takes twice as long – once to find the physical address, once to get the actual data
- Use a hardware cache of least recently used addresses
  - Called a Translation Lookaside Buffer or TLB

Performance Problem: TLB Refills

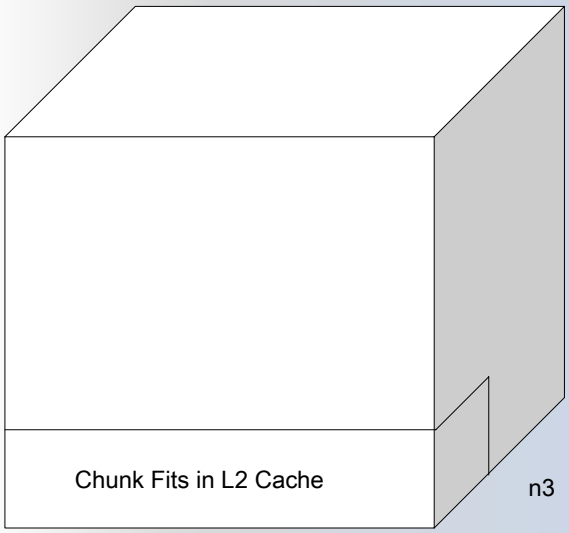
- AMD dual core opteron: 512 data TLB entries
- Covers 2MB of physical memory
  - OK if program fits (unlikely)
  - Large programs accessing data from all over their virtual memory range can trigger excessive TLB misses (“thrash”)
- One solution: huge pages

NPB MG routine RESID

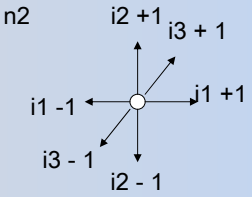
```
do i3=2,n3-1
   do i2=2,n2-1
      do i1=1,n1
         u1(i1) = u(i1,i2-1,i3) + u(i1,i2+1,i3)
     >           + u(i1,i2,i3-1) + u(i1,i2,i3+1)
         u2(i1) = u(i1,i2-1,i3-1) + u(i1,i2+1,i3-1)
     >           + u(i1,i2-1,i3+1) + u(i1,i2+1,i3+1)
      enddo
      do i1=2,n1-1
         r(i1,i2,i3) = v(i1,i2,i3)
     >               - a(0) * u(i1,i2,i3)
     >               - a(2) * ( u2(i1) + u1(i1-1) + u1(i1+1) )
     >               - a(3) * ( u2(i1-1) + u2(i1+1) )
      enddo
   enddo
enddo
```



```
================================================================================
USER / resid_
--------------------------------------------------------------------------------
  Time%                                          42.4%
  Time                                       12.397761
  Imb.Time                                    0.000370
  Imb.Time%                                       0.0%
  Calls                                           340
  PAPI_L1_DCA              2719.188M/sec   33711498004 ops
  DC_L2_REFILL_MOESI         79.644M/sec     987402929 ops
  DC_SYS_REFILL_MOESI         4.059M/sec      50318116 ops
  BU_L2_REQ_DC              129.172M/sec    1601429574 req
  User time                  12.398 secs   32233848320 cycles
  Utilization rate                             100.0%
  L1 Data cache misses       83.703M/sec    1037721045 misses
  LD & ST per D1 miss                           32.49 ops/miss
  D1 cache hit ratio                            96.9%
  LD & ST per D2 miss                          669.97 ops/miss
  D2 cache hit ratio                            96.9%
  L2 cache hit ratio                            95.2%
  Memory to D1 refill         4.059M/sec      50318116 lines
  Memory to D1 bandwidth    247.723MB/sec    3220359424 bytes
  L2 to Dcache bandwidth   4861.112MB/sec   63193787456 bytes
```



Entire Cube does not fit in L2 Cache
256*256*256*3 arrays
= 402 MBytes



Take data in chunks that Fit in L2 Cache
256*16*32*3 arrays
= 1 MBytes

Tiling for better Cache utilization

```
do i3block=2,n3-1,BLOCK3
     do i2block=2,n2-1,BLOCK2
     do i3=i3block,min(n3-1,i3block+BLOCK3-1)
        do i2=i2block,min(n2-1,i2block+BLOCK2-1)
           do i1=1, n1
              u1(i1) = u(i1,i2-1,i3) + u(i1,i2+1,i3)
     >               + u(i1,i2,i3-1) + u(i1,i2,i3+1)
              u2(i1) = u(i1,i2-1,i3-1) + u(i1,i2+1,i3-1)
     >               + u(i1,i2-1,i3+1) + u(i1,i2+1,i3+1)
           enddo
           do i1=1, n1
              r(i1,i2,i3) = v(i1,i2,i3)
     >                    - a(0) * u(i1,i2,i3)
     >                    - a(2) * ( u2(i1) + u1(i1-1) + u1(i1+1) )
     >                    - a(3) * ( u2(i1-1) + u2(i1+1) )
           enddo
        enddo
     enddo
     enddo
     enddo
```

```
==========================================================================
USER / resid_
--------------------------------------------------------------------------
  Time%                                      36.3%
  Time                                    8.753226
  Imb.Time                                0.000596
  Imb.Time%                                   0.0%
  Calls                                        340
  PAPI_L1_DCA             3861.533M/sec   33800955933 ops
  DC_L2_REFILL_MOESI       116.399M/sec    1018867620 ops
  DC_SYS_REFILL_MOESI        2.755M/sec      24114222 ops
  BU_L2_REQ_DC             161.490M/sec    1413560527 req
  User time                  8.753 secs   22758444048 cycles
  Utilization rate                           100.0%
  L1 Data cache misses     119.154M/sec    1042981842 misses
  LD & ST per D1 miss                          32.41 ops/miss
  D1 cache hit ratio                           96.9%
  LD & ST per D2 miss                        1401.70 ops/miss
  D2 cache hit ratio                           98.3%
  L2 cache hit ratio                           97.7%
  Memory to D1 refill        2.755M/sec      24114222 lines
  Memory to D1 bandwidth   168.145MB/sec    1543310208 bytes
  L2 to Dcache bandwidth  7104.420MB/sec   65207527680 bytes
```



```
      do i3block=2,n3-1,BLOCK3
      do i2block=2,n2-1,BLOCK2
      do i3=i3block,min(n3-1,i3block+BLOCK3-1)
         do i2=i2block,min(n2-1,i2block+BLOCK2-1)
            do i1=1,n1
               u1(i1) = u(i1,i2-1,i3) + u(i1,i2+1,i3)
     >               + u(i1,i2,i3-1) + u(i1,i2,i3+1)
               u2(i1) = u(i1,i2-1,i3-1) + u(i1,i2+1,i3-1)
     >               + u(i1,i2-1,i3+1) + u(i1,i2+1,i3+1)
            enddo
            do i1=2,n1-1
               r(i1,i2,i3) = v(i1,i2,i3)
     >                     - a(0) * u(i1,i2,i3)
     >                     - a(2) * ( u2(i1) + u1(i1-1) + u1(i1+1) )
     >                     - a(3) * ( u2(i1-1) + u2(i1+1) )
            enddo
         enddo
      enddo
      enddo
      enddo
```

```
      do i3block=2,n3-1,BLOCK3
       do i2block=2,n2-1,BLOCK2
       do i3=i3block,min(n3-1,i3block+BLOCK3-1)
          do i2=i2block,min(n2-1,i2block+BLOCK2-1)
             do i1=2,n1-1
                u21 = u(i1,i2-1,i3-1) + u(i1,i2+1,i3-1)
     >               + u(i1,i2-1,i3+1) + u(i1,i2+1,i3+1)
                u21p1 = u(i1+1,i2-1,i3-1) + u(i1+1,i2+1,i3-1)
     >               + u(i1+1,i2-1,i3+1) + u(i1+1,i2+1,i3+1)
                u21m1 = u(i1-1,i2-1,i3-1) + u(i1-1,i2+1,i3-1)
     >               + u(i1-1,i2-1,i3+1) + u(i1-1,i2+1,i3+1)
                u11p1 = u(i1+1,i2-1,i3) + u(i1+1,i2+1,i3)
     >               + u(i1+1,i2,i3-1) + u(i1+1,i2,i3+1)
                u11m1 = u(i1-1,i2-1,i3) + u(i1-1,i2+1,i3)
     >               + u(i1-1,i2,i3-1) + u(i1-1,i2,i3+1)
                r(i1,i2,i3) = v(i1,i2,i3)
     >                    - a(0) * u(i1,i2,i3)
     >                    - a(2) * ( u21 + u11m1 + u11p1 )
     >                    - a(3) * ( u21m1 + u21p1 )
             enddo
          enddo
       enddo
       enddo
       enddo
```



```
USER / resid_
------------------------------------------------------------------------
------
  Time%                                          37.7%
  Time                                       9.132935
  Imb.Time                                   0.003440
  Imb.Time%                                      0.1%
  Calls                                           340
  PAPI_TLB_DM                0.139M/sec       1270096 misses
  PAPI_L1_DCA              3694.219M/sec   33739238309 ops
  PAPI_FP_OPS              2601.948M/sec   23763548027 ops
  DC_MISS                   111.833M/sec    1021371774 ops
  User time                   9.133 secs   23745753175 cycles
  Utilization rate                             100.0%
  HW FP Ops / Cycles                             1.00 ops/cycle
  HW FP Ops / User time    2601.948M/sec   23763548027 ops
25.0%peak
  HW FP Ops / WCT          2601.948M/sec
  Computation intensity                          0.70 ops/ref
  LD & ST per TLB miss                       26564.32 ops/miss
  LD & ST per D1 miss                           33.03 ops/miss
  D1 cache hit ratio                            97.0%
  % TLB misses / cycle                           0.0%
```

```
USER / resid_
------------------------------------------------------------------------
---
  Time%                                      39.6%
  Time                                     9.752716
  Imb.Time                                 0.002081
  Imb.Time%                                    0.0%
  Calls                                         340
  PAPI_TLB_DM              0.115M/sec       1119418 misses
  PAPI_L1_DCA           2792.319M/sec  27232706384 ops
  PAPI_FP_OPS           3488.881M/sec  34026076279 ops
  DC_MISS                104.718M/sec   1021283533 ops
  User time                 9.753 secs  25357072370 cycles
  Utilization rate                           100.0%
  HW FP Ops / Cycles                           1.34 ops/cycle
  HW FP Ops / User time  3488.881M/sec  34026076279 ops     33.5%peak
  HW FP Ops / WCT        3488.881M/sec
  Computation intensity                        1.25 ops/ref
  LD & ST per TLB miss                     24327.56 ops/miss
  LD & ST per D1 miss                         26.67 ops/miss
  D1 cache hit ratio                          96.2%
  % TLB misses / cycle                         0.0%
```



```
USER / resid_
----------------------------------------------------------------
----------
  Time%                                      38.3%
  Time                                     9.162149
  Imb.Time                                 0.006363
  Imb.Time%                                    0.1%
  Calls                                         340
  PAPI_L1_DCA           3682.405M/sec  33739250204 ops
  DC_L2_REFILL_MOESI     111.475M/sec   1021369289 ops
  DC_SYS_REFILL_MOESI      2.964M/sec     27157915 ops
  BU_L2_REQ_DC           157.164M/sec   1439982850 req
  User time                9.162 secs  23821945786 cycles
  Utilization rate                           100.0%
  L1 Data cache misses   114.439M/sec   1048527204 misses
  LD & ST per D1 miss                          32.18 ops/miss
  D1 cache hit ratio                           96.9%
  LD & ST per D2 miss                        1242.34 ops/miss
  D2 cache hit ratio                           98.1%
  L2 cache hit ratio                           97.4%
  Memory to D1 refill      2.964M/sec     27157915 lines
  Memory to D1 bandwidth 180.914MB/sec   1738106560 bytes
  L2 to Dcache bandwidth 6803.916MB/sec  65367634496 bytes
```

```
USER / resid_
------------------------------------------------------------
----------
  Time%                                             39.4%
  Time                                            9.699533
  Imb.Time                                        0.003564
  Imb.Time%                                           0.1%
  Calls                                                340
  PAPI_L1_DCA              2807.643M/sec    27232738768 ops
  DC_L2_REFILL_MOESI        105.292M/sec     1021281565 ops
  DC_SYS_REFILL_MOESI         2.366M/sec       22945693 ops
  BU_L2_REQ_DC              114.970M/sec     1115152062 req
  User time                   9.700 secs    25218702347 cycles
  Utilization rate                               100.0%
  L1 Data cache misses      107.658M/sec     1044227258 misses
  LD & ST per D1 miss                             26.08 ops/miss
  D1 cache hit ratio                              96.2%
  LD & ST per D2 miss                           1186.83 ops/miss
  D2 cache hit ratio                              97.9%
  L2 cache hit ratio                              97.8%
  Memory to D1 refill         2.366M/sec       22945693 lines
  Memory to D1 bandwidth    144.388MB/sec     1468524352 bytes
  L2 to Dcache bandwidth   6426.524MB/sec    65362020160 bytes
```


Sparse CSR MV

Unroll q loop x times

```
do q = 1, n_rhs

    next_row_begin = row_start (1)

    do i = 1, n_rows                          Should Scream on Granite!

        row_begin      = next_row_begin
        next_row_begin = row_start (i +1)
        ip       = 0.0_wp

        do k = row_begin, next_row_begin - 1
            ip   = ip  +  values (k) * x (col_index (k), q)
        end do

        y (i, q) = ip

    end do
end do
```

Prefetch x cachelines of values and y cachelines of col_index, z iterations ahead

Unroll k loop x times

+ 3 choices of compilers
+ implicit unroll options
+ zero / one based indexing

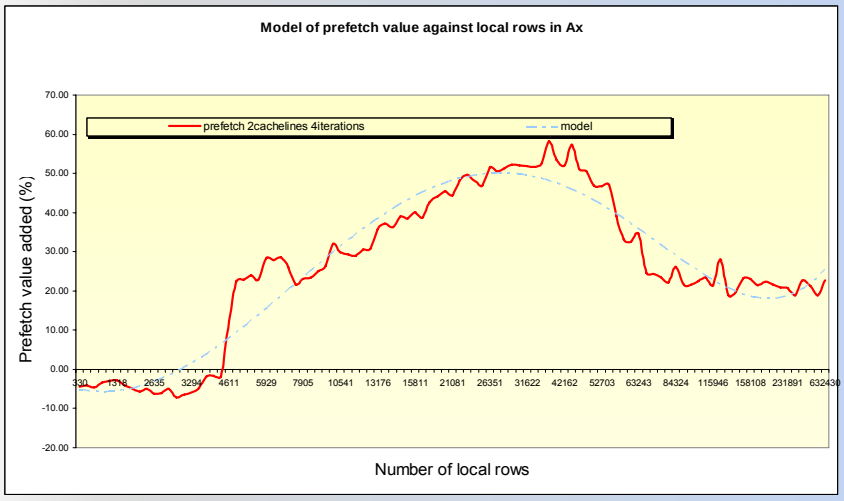
Prefetching example

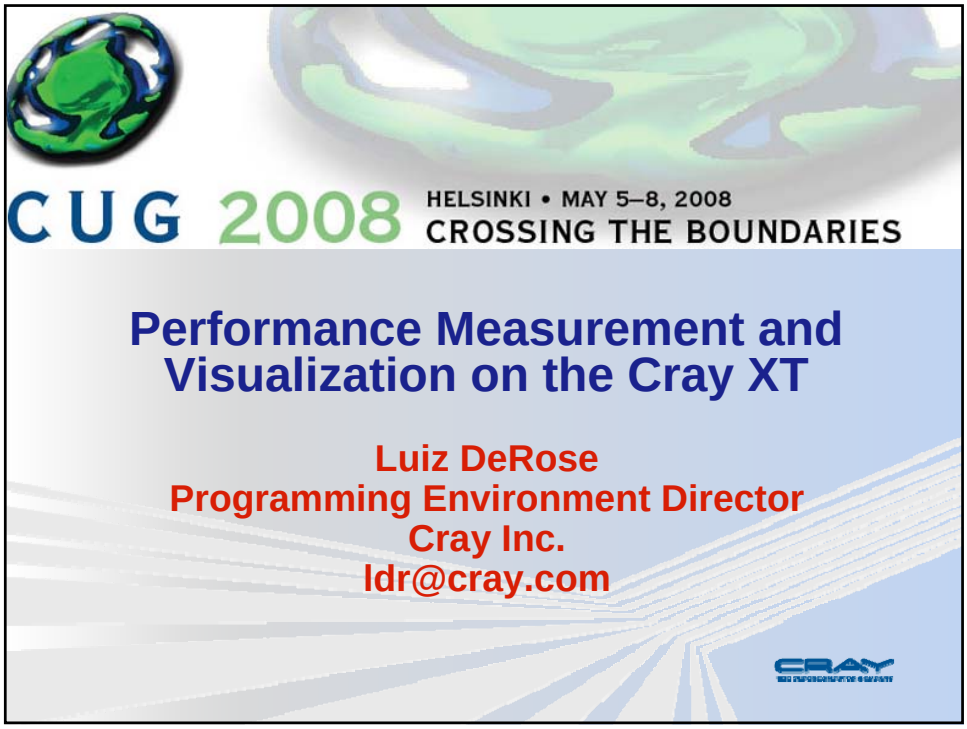
An example using prefetch directives to prefetch data in a matrix multiplication inner loop where a row of one source matrix has been gathered into a contiguous vector might look as follows:

```
real*8 a(m,n), b(n,p), c(m,p), arow(n)
...
do j = 1, p
c$mem prefetch arow(1),b(1,j)
c$mem prefetch arow(5),b(5,j)
c$mem prefetch arow(9),b(9,j)
do k = 1, n, 4
c$mem prefetch arow(k+12),b(k+12,j)
c(i,j) = c(i,j) + arow(k) * b(k,j)
c(i,j) = c(i,j) + arow(k+1) * b(k+1,j)
c(i,j) = c(i,j) + arow(k+2) * b(k+2,j)
c(i,j) = c(i,j) + arow(k+3) * b(k+3,j)
enddo
enddo
```

This pattern of prefetch directives will cause the compiler to emit prefetch instructions whereby elements of arow and b are fetched into the data cache starting 4 iterations prior to first use. By varying the prefetch distance in this way, it is possible in some cases to reduce the effects of main memory latency and improve performance.

e.g. prefetch value





Outline

- The Cray Performance tools Overview
- CrayPat
  - Instrument applications
  - CrayPat runtime library
- Automatic Profiling Analysis
- Pat_report
- Hardware counters collection
- Profile Guided Rank Placement
- OpenMP
- Cray Apprentice2

Cray Performance Analysis Infrastructure

- CrayPat
  - pat_build: Utility for application instrumentation
    - No source code modification required
  - run-time library for measurements
    - transparent to the user
  - pat_report:
    - Performance reports
    - Performance visualization file
  - pat_help
    - Interactive performance tool help utility
- Cray Apprentice^2
  - Graphical performance analysis and visualization tool
  - Can be used off-line on Linux system

Application Instrumentation with pat_build

- No source code or makefile modification required
  - Automatic instrumentation at group (function) level
    - Groups: mpi, io, heap, math SW, …
- Performs link-time instrumentation
  - Requires object files
  - Instruments optimized code
  - Generates stand-alone instrumented program
  - Preserves original binary
  - Supports sample-based and event-based instrumentation
- pat_build [-d dirfile] [-D directive] [-f] [-g tracegroup] [-n] [-O ofile] [-o instr_program] [-t tracefile] [-T tracefunc] [-u] [-V] [-v] [-w] [-z] program [instr_program]

-g tracegroup

biolibs	Cray Bioinformatics library routines
blas	Basic Linear Algebra subprograms
heap	dynamic heap
io	includes stdio and sysio groups
lapack	Linear Algebra Package
math	ANSI math
mpi	MPI
omp	OpenMP API
omp-rtl	OpenMP runtime library (not supported on Catamount)
pthreads	POSIX threads (not supported on Catamount)
shmem	SHMEM
stdio	all library functions that accept or return the FILE* construct
sysio	I/O system calls
system	system calls

CrayPat API - for fine grain instrumentation

- Fortran

```
include “pat_apif.h”
…
call PAT_region_begin(id, “label”, ierr)
do i = 1,n
…
enddo
call PAT_region_end(id, ierr)
```

- C

```
include <pat_api.h>
…
ierr = PAT_region_begin(id, “label”);
< code segment >
ierr = PAT_region_end(id);
```

Performance Data Collection

- Two dimensions
  - When performance collection is triggered
    - Asynchronous
      - Sampling
        - » Timer interrupt
        - » Hardware counters overflow
    - Synchronous
      - Code instrumentation
        - » Event based
        - » Automatic or manual instrumentation
  - How performance data is recorded
    - Profile ::= Summation of events over time
      - run time summarization (functions, call sites, loops, …)
    - Trace file ::= Sequence of events over time

Running the Instrumented Application

- Data collection is transparent to the user
- MUST run on Lustre file system
- Optional runtime environment variables
  - Optional timeline view of program available
    - export PAT_RT_SUMMARY=0
  - Number of files used to store raw data:
    - 1 file created for program with 1 – 256 processes
    - $\sqrt{n}$ files created for program with 257 – *n* processes
    - Ability to customize with PAT_RT_EXPFILE_MAX
  - Request hardware performance counter information:
    - export PAT_RT_HWPC=<HWPC Group>
    - Can specify events or predefined groups

pat_report

- Performs data conversion
  - Combines information from binary with raw performance data
- Generates text report of performance results
- Formats data for input into Cray Apprentice^2
  - pat_report [-V] [-i dir|instrprog] [-o output_file] [-O keyword] [-C 'table_caption'] [-d d-opts] [-b b-opts] [-s key=value] [-H] [-P] [-T] [-z] data_directory | data_file.xf

Automatic Profiling Analysis (APA)

1. Load CrayPat & Cray Apprentice^2 4.2 module files
   - % module load xt-craypat apprentice2
2. Build application
   - % make clean
   - % make
3. Instrument application for automatic profiling analysis
   - % pat_build **–O apa** a.out
     - You should get an instrumented program a.out+pat
4. Run application to get top time consuming routines
   - Remember to modify <script> to run *a.out+pat*
   - Remember to run on Lustre
   - % aprun … *a.out+pat* *(or* qsub <pat script>)
     - You should get a performance file ("<sdatafile>.xf") or multiple files in a directory <sdatadir>
5. Generate .apa file
   - % pat_report –o *my_sampling_report* [<sdatafile>.xf | <sdatadir>]
     - creates a report file & an automatic profile analysis file <apafile>.apa

Pat_report Output

```
CrayPat/X:  Version 4.2 Revision 1579 (xf 1535)  04/03/08 14:26:59
Experiment:  trace
Experiment data file:
  /ufs/home/users/ldr/Apps/sweep3d/sweep3d+apa+1743-12tdt.xf  (RTS)

Current path to data file:
  /home/users/ldr/Apps/sweep3d/sweep3d+apa+1743-12tdt.ap2  (RTS)
  /home/users/ldr/Apps/sweep3d/sweep3d+apa+1743-12tdt.xf   (RTS)

Original program:  /ufs/home/users/ldr/Apps/sweep3d/sweep3d

Instrumented with:
  pat_build -Drtenv=PAT_RT_HWPC=0 -g mpi -w -T sweep_ -o \
        sweep3d+apa /ufs/home/users/ldr/Apps/sweep3d/sweep3d

Instrumented program:  ./sweep3d+apa
Program invocation:  ./sweep3d+apa
Number of PEs:  48
Number of threads per PE:  1
Number of Cores per Processor:  1

Exit Status:  0  PEs:  0-47

Runtime environment variables:
  MPICH_DIR=/opt/mpt/3.0.0.8/xt/mpich2-pgi
  PAT_RT_HWPC=0

Report time environment variables:
  CRAYPAT_ROOT=/opt/xt-tools/craypat/4.2/v22/cpatx

Report command line options:  -o sweep3d48p.txt

System type and speed:   x86_64  2400 MHz

Operating system:
  Linux 2.6.16.54-0.2.5-cnl #1 SMP Thu Apr 3 10:12:46 PDT 2008

Hardware performance counter events:
  PAPI_TOT_INS      Instructions completed
  PAPI_L1_DCA       Level 1 data cache accesses
  PAPI_FP_OPS       Floating point operations
  DATA_CACHE_MISSES  Data Cache Misses
  CYCLES_USER       User cycles (approx, from clock ticks)

Estimated minimum overhead per call of a traced function,
  which was subtracted from the data shown in this report
  (for raw data, use the option:  -s overhead=include):
    PAPI_TOT_INS          2002.994  instr
    PAPI_L1_DCA           1268.744  refs
    PAPI_FP_OPS              0.000  ops
    DATA_CACHE_MISSES        2.553  misses
    CYCLES_USER              0.000  cycles
    Time                     1.741  microseconds

Number of traced functions: 82
  (To see the list, specify:  -s traced_functions=show)
...
```

List of instrumented functions is available when the flag: -s traced_functions=show is set on pat_report.

Sampling Output (Default tables)

```
Notes for table 1:

  Table option:
    -O samp_profile+src
  Options implied by table option:
    -d sa%@0.95,sa,imb_sa,imb_sa% -b gr,fu,so,li,pe=HIDE

  Options for related tables not shown by default:
    -O samp_profile

  The Total value for Samp is the sum of the Group values.
  The Group value for Samp is the sum of the Function values.
  The Function value for Samp is the sum of the Source values.
  The Source value for Samp is the sum of the Line values.
  The Line value for Samp is the avg of the PE values.
    (To specify different aggregations, see:  pat_help report options s1)

  This table shows only lines with Samp% > 0.95.
    (To set thresholds to zero, specify:  -T)

  Percentages at each level are of the Total for the program.
    (For percentages relative to next level up, specify:
      -s percent=r[elative])


)
```

Sampling Output (Default tables)

```
Table 1:  Profile by Group, Function, and Line

 Samp % | Samp |  Imb.  |  Imb.  |Group
        |      |  Samp  | Samp % | Function
        |      |        |        |  Source
        |      |        |        |   Line
        |      |        |        |    PE='HIDE'

 100.0% |  392 |    -- |     -- |Total
|-------------------------------------------------
|  63.8% |  250 |    -- |     -- |USER
||------------------------------------------------
||  62.2% |  244 |    -- |      | sweep
3||      |      |       |      |  ldr/Apps/sweep3d/sweep.f
||------------------------------------------------
4||  13.0% |   51 | 21.00 |  29.9% |line.388
4||  12.0% |   47 | 17.15 |  27.4% |line.478
4||  11.0% |   43 |  9.52 |  18.5% |line.397
4||   9.2% |   36 | 10.88 |  23.6% |line.486
4||   6.1% |   24 | 13.10 |  36.2% |line.416
4||   4.6% |   18 |  8.42 |  33.1% |line.474
||================================================
||   1.3% |    5 |    -- |     -- |source
3||      |      |       |      |  ldr/Apps/sweep3d/source.f
||------------------------------------------------
4||   1.3% |    5 |  1.58 |  23.1% |line.31
|================================================
|  33.9% |  133 |    -- |     -- |MPI
|------------------------------------------------
|  20.2% |   79 | 26.00 |  25.3% |mpi_recv_
|   7.1% |   28 | 29.75 |  52.4% |mpi_barrier_
|   3.3% |   13 | 12.98 |  51.0% |mpi_allreduce_
|   2.6% |   10 | 36.54 |  79.4% |mpi_bcast_
|================================================
|   2.3% |    9 |    -- |     -- |ETC
|------------------------------------------------
|   1.8% |    7 |  6.35 |  49.9% |__c_mcopy8
|================================================
```

Samp % provides absolute percentages

APA File Example

```
#  You can edit this file, if desired, and use it
#  to reinstrument the program for tracing like this:
#
#       pat_build -O ft.ind.B.2+pat+5257-770sdt.apa
#
#  These suggested trace options are based on data from:
#
#      /work/users/luizd/COE_Workshop/run/ft.ind.B.2+pat+5257-
       770sdt.xf

# ----------------------------------------------------------------------

#      HWPC group to collect by default.

 -Drtenv=PAT_RT_HWPC=0  # Summary with instructions metrics.

# ----------------------------------------------------------------------

#      Libraries to trace.

 -g mpi

# ----------------------------------------------------------------------

#      User-defined functions to trace, sorted by % of samples.
#      Limited to top 200. A function is commented out if it has < 1%
#      of samples, or if a cumulative threshold of 90% has been
       reached.

 -w  # Enable tracing of user-defined functions.
     # Note: -u should NOT be specified as an additional option.
```

```
# 37.70%
       -T fftz2_

# 26.23%
       -T cffts2_

#  9.37%
       -T transpose2_local_

#  8.96%
       -T cffts1_

#  7.82%
       -T evolve_

#  Functions below this point account for less than 10% of samples.


#  6.43%
#       -T transpose2_finish_

#  2.72%
#       -T cfftz_

#  0.48%
#       -T vranlc_

#  0.28%
#       -T compute_indexmap_

# ----------------------------------------------------------------------

  -o ft.ind.B.2+apa                 # New instrumented program.

  /work/users/luizd/COE_Workshop/bin/ft.ind.B.2  # Original
       program.
```

APA Performance Data Generation

1. Look at <apafile>.apa file
   - Verify if additional instrumentation is wanted
2. Instrument application for further analysis (a.out+apa)
   - % pat_build **–O <apafile>.apa**
     - You should get an instrumented program a.out+apa
3. Run application
   - Remember to modify <script> to run *a.out+apa*
   - % aprun … *a.out+apa (or* qsub <apa script>)
     - You should get a performance file (“<datafile>.xf”) or multiple files in a directory <datadir>
4. Create text report
   - % pat_report –o *my_text_report* [<datafile>.xf | <datadir>]
     - Will generate a compressed performance file (<datafile>.ap2)
5. View results in text report (my_text_report) and/or with Cray Apprentice^2
   - % app2 <*datafile*>.ap2

Table 1: Flat Profile (Default)

```
Notes for table 1:

  Table option:
    -O profile
  Options implied by table option:
    -d ti%@0.05,ti,imb_ti,imb_ti%,tr -b gr,fu,pe=HIDE

This table shows only lines with Time% > 0.05.
    (To set thresholds to zero, specify:  -T)

  Percentages at each level are relative.
    (For absolute percentages, specify:  -s percent=a)


Table 1:  Profile by Function Group and Function

 Time % |     Time |Imb. Time |   Imb. | Calls |Group
        |          |          | Time % |       | Function
        |          |          |        |       |  PE='HIDE'

 100.0% | 7.193714 |       -- |     -- | 17604 |Total
|-----------------------------------------------------------
|  76.5% | 5.500078 |       -- |     -- |  4752 |USER
||----------------------------------------------------------
||  96.0% | 5.277791 | 0.171848 |   3.3% |    12 |sweep_
||   3.2% | 0.177352 | 0.005482 |   3.1% |    12 |source_
||   0.3% | 0.018588 | 0.000527 |   2.9% |    12 |flux_err_
||   0.2% | 0.010866 | 0.003033 |  22.8% |  2280 |snd_real_
||   0.1% | 0.005032 | 0.000144 |   2.9% |     1 |initialize_
||   0.1% | 0.004933 | 0.000154 |   3.2% |     1 |initxs_
||   0.1% | 0.002819 | 0.001773 |  40.3% |  2280 |rcv_real_
||==========================================================
```

By default, the report will only show functions with at least 0.05% of the time

MPI Sync Time

- Determines if MPI ranks arrive at collectives together
- Separates potential load imbalance from data transfer
- Sync times reported by default if MPI functions traced (-O apa, -g mpi)

Table 1: Flat Profile (Continuation)

```
||=====================================================
|  16.6% | 1.197321 |       -- |     -- |  4603 |MPI
||-----------------------------------------------------
||  93.9% | 1.124227 | 0.277878 |  20.7% |  2280 |mpi_recv_
||   5.9% | 0.070481 | 0.014437 |  17.7% |  2280 |mpi_send_
||   0.2% | 0.002210 | 0.001088 |  34.4% |    32 |mpi_allreduce_
||=====================================================
|   6.3% | 0.453091 |       -- |     -- |    39 |MPI_SYNC
||-----------------------------------------------------
||  61.1% | 0.277012 | 0.215608 |  45.7% |     4 |mpi_bcast_(sync)
||  38.7% | 0.175564 | 0.270049 |  63.2% |    32 |mpi_allreduce_(sync)
||   0.1% | 0.000515 | 0.000265 |  35.5% |     3 |mpi_barrier_(sync)
||=====================================================
|   0.5% | 0.037826 |       -- |     -- |  5992 |IO
||-----------------------------------------------------
||  99.2% | 0.037528 | 0.010681 |  23.1% |  5977 |ioctl
||   0.4% | 0.000159 | 0.000308 |  68.8% |    12 |fwrite
||   0.2% | 0.000069 | 0.001585 | 100.0% |     3 |getc
||   0.2% | 0.000064 | 0.001467 | 100.0% |     0 |fopen
||=====================================================
|   0.1% | 0.005398 |       -- |     -- |  2218 |HEAP
||-----------------------------------------------------
||  52.8% | 0.002850 | 0.002219 |  45.7% |  1109 |malloc
||  47.1% | 0.002545 | 0.002388 |  50.5% |  1108 |free
|=====================================================
|=====================================================
```

Table 2: Load Balance

```
Table 2:  Load Balance with MPI Sent Message Stats

 Time %  |      Time  |  Sent Msg  | Sent Msg  | Avg Sent  |Group
         |            |      Count |     Total |  Msg Size |  PE[mmm]
         |            |            |     Bytes |           |

 100.0% | 7.204620 |  2280 | 34560000 | 15157.89 |Total
|-------------------------------------------------------------
|  76.4% | 5.503022 |    -- |       -- |       -- |USER
|-------------------------------------------------------------
|    4.3% | 5.678452 |    -- |       -- |       -- |pe.20
|    4.2% | 5.505897 |    -- |       -- |       -- |pe.11
|    4.0% | 5.218794 |    -- |       -- |       -- |pe.0
|=============================================================
|  16.7% | 1.200173 |  2280 | 34560000 | 15157.89 |MPI
|-------------------------------------------------------------
|    5.2% | 1.484151 |  2880 | 43545600 | 15120.00 |pe.13
|    4.2% | 1.215197 |  2880 | 42854400 | 14880.00 |pe.10
|    3.4% | 0.968652 |  2160 | 34905600 | 16160.00 |pe.4
|=============================================================
|   6.3% | 0.453115 |    -- |       -- |       -- |MPI_SYNC
|-------------------------------------------------------------
|    7.9% | 0.862266 |    -- |       -- |       -- |pe.1
|    4.4% | 0.473548 |    -- |       -- |       -- |pe.16
|    0.5% | 0.058871 |    -- |       -- |       -- |pe.23
|=============================================================
|   0.6% | 0.041538 |    -- |       -- |       -- |IO
|-------------------------------------------------------------
|    5.4% | 0.053547 |    -- |       -- |       -- |pe.13
|    4.0% | 0.039551 |    -- |       -- |       -- |pe.11
|    2.9% | 0.029267 |    -- |       -- |       -- |pe.20
|=============================================================
|   0.1% | 0.006772 |    -- |       -- |       -- |HEAP
|-------------------------------------------------------------
|    7.7% | 0.012523 |    -- |       -- |       -- |pe.12
|    4.0% | 0.006517 |    -- |       -- |       -- |pe.6
|    2.3% | 0.003699 |    -- |       -- |       -- |pe.17
|=============================================================
```


Table 3: MPI Send Stats by Caller

```
Notes for table 3:
  Table option:
    -O mpi_callers
  Options implied by table option:
    -d sm,sc@,mb1..7 -b fu,ca,pe=[mmm]

  The Total value for each data item is the sum of the Function values.
  The Function value for each data item is the sum of the Caller values.
  The Caller value for each data item is the avg of the PE values.
    (To specify different aggregations, see:  pat_help report options s1)

  This table shows only lines with Sent Msg Count > 0.


Table 3:  MPI Sent Message Stats by Caller

 Sent Msg |  Sent  | 4KB<= |Function
    Total |   Msg  | MsgSz  | Caller
    Bytes | Count  | <64KB  |  PE[mmm]
          |        | Count  |

 34560000 |  2280  |  2280 |Total
|-----------------------------------
|  34560000 |  2280  |  2280 |mpi_send_
|           |        |       |  snd_real_
|3          |        |       |   sweep_
|4          |        |       |    inner_
|5          |        |       |     inner_auto_
|6          |        |       |      MAIN_
|7          |        |       |       main
|||||||-----------------------------
|8||||||  43545600 |  2880  |  2880 |pe.17
|8||||||  34214400 |  2160  |  2160 |pe.11
|8||||||  21427200 |  1440  |  1440 |pe.3
|===================================
```

Table 5: Heap Statistics

```
Notes for table 5:

  Table option:
    -O heap_hiwater
  Options implied by table option:
    -d am@,ub,ta,ua,tf,nf,ac,ab -b pe=[mmm]

  The Total value for each data item is the avg of the PE values.
    (To specify different aggregations, see:  pat_help report options s1)

  This table shows only lines with Tracked Heap HiWater MBytes > 0.


Table 5:  Heap Stats during Main Program

 Tracked |  Total | Total | Tracked | Tracked |PE[mmm]
    Heap | Allocs | Frees | Objects |  MBytes |
 HiWater |        |       |     Not |     Not |
  MBytes |        |       |   Freed |   Freed |

  17.470 |   1109 |  1108 |       1 |   0.010 |Total
|-----------------------------------------------------
|  17.716 |    815 |   814 |       1 |   0.010 |pe.5
|  17.253 |   1053 |  1052 |       1 |   0.010 |pe.10
|  17.236 |    994 |   993 |       1 |   0.010 |pe.19
|=====================================================
```


Table 6: Heap Leaks

```
Notes for table 6:

  Table option:
    -O heap_leaks
  Options implied by table option:
    -d lb%@1,lb@0.0005,lc -b ca,pe=[mmm]

  The Total value for each of Tracked Objects Not Freed, Tracked MBytes Not
    Freed is the sum of the Caller values.
  The Caller value for each of Tracked Objects Not Freed, Tracked MBytes Not
    Freed is the avg of the PE values.
    (To specify different aggregations, see:  pat_help report options s1)

  This table shows only lines with:
    Tracked MBytes Not Freed% > 1
    Tracked MBytes Not Freed > 0.0005    (To set thresholds to zero, specify:  -T)

Table 6:  Heap Leaks during Main Program
 Tracked | Tracked | Tracked |Caller
  MBytes |  MBytes | Objects | PE[mmm]
     Not |     Not |     Not |
 Freed % |   Freed |   Freed |

  100.0% |   0.010 |       1 |Total
|-----------------------------------
|   95.7% |   0.010 |       1 |main
||----------------------------------
||    4.2% |   0.010 |       1 |pe.11
||    4.2% |   0.010 |       1 |pe.6
||    4.2% |   0.010 |       1 |pe.5
|===================================
```

Table 7: I/O (Read) Statistics

```
Notes for table 7:

  Table option:
    -O read_stats
  Options implied by table option:
    -d rt,rb,rR,rd@,rC -b fi,pe=[mmm],fd

  The Total value for each data item is the sum of the File Name values.
  The File Name value for each of Read B/Call, Read Time, Reads is the avg of
    the PE values.
  The File Name value for each of Read Rate MB/sec, Read MB is the sum of the
    PE values.
  The PE value for each data item is the sum of the File Desc values.
    (To specify different aggregations, see:  pat_help report options s1)

  This table shows only lines with Reads > 0.


Table 7:  File Input Stats by Filename

  Read |  Read MB |Read Rate | Reads |   Read |File Name
  Time |          |   MB/sec |       | B/Call | PE[mmm]
       |          |          |       |        |  File Desc

 0.000 | 0.000065 | 0.925430 |     3 |  22.67 |Total
|-----------------------------------------------------
| 0.000 | 0.000065 | 0.925430 |     3 |  22.67 |input
||----------------------------------------------------
|| 0.002 | 0.000065 | 0.038560 |    68 |   1.00 |pe.0
3|       |          |          |       |        |  fd.12
|| 0.000 |       -- |       -- |    -- |     -- |pe.6
|| 0.000 |       -- |       -- |    -- |     -- |pe.5
|=====================================================
```


Table 8: I/O (Write) Statistics

```
Table 8:  File Output Stats by Filename

 Write |  Write MB |  Write Rate |  Writes |   Write |File Name
  Time |           |      MB/sec |         |  B/Call |  PE[mmm]
       |           |             |         |         |   File Desc

 0.000 | 0.002298 |   14.088269 |      12 |  200.83 |Total
|-------------------------------------------------------------
| 0.000 | 0.000298 |    2.070438 |       1 |  312.00 |stderr
||------------------------------------------------------------
|| 0.000 | 0.000012 |    0.026614 |       1 |   13.00 |pe.17
3|       |          |             |         |         |  fd.2
|| 0.000 | 0.000012 |    0.253220 |       1 |   13.00 |pe.7
3|       |          |             |         |         |  fd.2
|| 0.000 | 0.000012 |    2.840267 |       1 |   13.00 |pe.0
3|       |          |             |         |         |  fd.2
||============================================================
| 0.000 | 0.002001 | 102.986588 |      11 |  190.73 |stdout
||------------------------------------------------------------
|| 0.000 | 0.002001 |    4.291078 |     269 |    7.80 |pe.0
3|       |          |             |         |         |  fd.1
|| 0.000 |       -- |          -- |      -- |      -- |pe.6
|| 0.000 |       -- |          -- |      -- |      -- |pe.5
|============================================================
```

Pat_report –O options

New feature:
pat_report –O help

```
% pat_report -O help
pat_report: Help for -O option:
Available option values are in left column, a prefix can be specified:
  ct                      -O calltree
  defaults                Tables that would appear by default.
  heap                    -O heap_program,heap_hiwater,heap_leaks
  io                      -O read_stats,write_stats
  lb                      -O load_balance
  load_balance            -O lb_program,lb_group,lb_function
  mpi                     -O mpi_callers
  ---
  callers                 Profile by Function and Callers
  callers+src             Profile by Function and Callers, with Line Numbers
  calltree                Function Calltree View
  calltree+src            Calltree View with Callsite Line Numbers
  heap_hiwater            Heap Stats during Main Program
  heap_leaks              Heap Leaks during Main Program
  heap_program            Heap Usage at Start and End of Main Program
  hwpc                    HW Performance Counter Data
  load_balance_function   Load Balance across PE's by Function
  load_balance_group      Load Balance across PE's by FunctionGroup
  load_balance_program    Load Balance across PE's
  load_balance_sm         Load Balance with MPI Sent Message Stats
  loops                   Loop Stats from -hprofile_generate
  mpi_callers             MPI Sent Message Stats by Caller
  mpi_dest_bytes          MPI Sent Message Stats by Destination PE
  mpi_dest_counts         MPI Sent Message Stats by Destination PE
  mpi_rank_order          Suggested MPI Rank Order
  mpi_sm_rank_order       Sent Message Stats and Suggested MPI Rank Order
  pgo_details             Loop Stats detail from -hprofile_generate
  profile                 Profile by Function Group and Function
  profile+src             Profile by Group, Function, and Line
  profile_pe.th           Profile by Function Group and Function
  profile_pe_th           Profile by Function Group and Function
  profile_th_pe           Profile by Function Group and Function
  program_time            Program Wall Clock Time
  read_stats              File Input Stats by Filename
  samp_profile            Profile by Function
  samp_profile+src        Profile by Group, Function, and Line
  thread_times            Program Wall Clock Time
  write_stats             File Output Stats by Filename
```


Call Tree Profile (Top Down)

```
Notes for table 1:

  High level option:  -O calltree
  Low level options:  -d ti%@0.05,cum_ti%,ti,tr -b exp,ct,pe=HIDE

  This table shows only lines with Time% > 0.05.

  Percentages at each level are relative
    (for absolute percentages, specify:  -s percent=a).


Table 1:  Function Calltree View

 Time % |   Cum.   |      Time |     Calls |Experiment=1
        | Time %   |           |           |Calltree
        |          |           |           | PE='HIDE'

 100.0% | 100.0% | 90.217759 | 637231917 |Total
|-----------------------------------------------------
| 100.0% | 100.0% | 90.175202 | 637205576 |MAIN_
||----------------------------------------------------
||  99.7% |  99.7% | 89.922750 | 637194666 |runhyd_
|||---------------------------------------------------
|||  15.4% |  15.4% | 13.864217 | 106169040 |zysweep_
||||--------------------------------------------------
||||  87.3% |  87.3% | 12.097038 | 106168320 |sppm2_
|||||-------------------------------------------------
|||||  49.4% |  49.4% |  5.980766 |  11796480 |sppm2_(exclusive)
|||||  24.1% |  73.6% |  2.920440 |  11796480 |difuze_
|||||  19.0% |  92.6% |  2.296747 |  58982400 |interf_
|||||   7.4% | 100.0% |  0.899084 |  23592960 |dintrf_
||||==================================================
||||  12.7% | 100.0% |  1.767180 |       720 |zysweep_(exclusive)
|||==================================================
|||  15.4% |  30.8% | 13.854807 | 106169040 |xysweep_
||||--------------------------------------------------
||||  87.0% |  87.0% | 12.049373 | 106168320 |sppm2_
|||||-------------------------------------------------
|||||  49.5% |  49.5% |  5.970403 |  11796480 |sppm2_(exclusive)
|||||  24.0% |  73.6% |  2.894189 |  11796480 |difuze_
```

Callers Profile (Bottom Up)

```
 Notes for table 1:

  High level option:  -O callers
  Low level options:  -d ti%@0.05,cum_ti%,ti,tr -b exp,gr,fu,ca,pe=HIDE

  This table shows only lines with Time% > 0.05.

Table 1:  Profile by Function and Callers

 Time % |    Cum.  |      Time |     Calls |Experiment=1
        |  Time %  |           |           |Group
        |          |           |           | Function
        |          |           |           |  Caller
        |          |           |           |   PE='HIDE'

 100.0% | 100.0% | 90.217759 | 637231917 |Total
|-------------------------------------------------------
|  92.3% |  92.3% | 83.265853 | 637033288 |USER
||------------------------------------------------------
||  43.1% |  43.1% | 35.864107 |  70778880 |sppm2_
|||-----------------------------------------------------
|||  16.7% |  16.7% |  5.986173 |  11796480 |yxsweep_
|||       |        |           |           | runhyd_
|||       |        |           |           |  MAIN_
|||  16.7% |  33.4% |  5.980851 |  11796480 |yzsweep_
|||       |        |           |           | runhyd_
|||       |        |           |           |  MAIN_
|||  16.7% |  50.0% |  5.980766 |  11796480 |zysweep_
|||       |        |           |           | runhyd_
|||       |        |           |           |  MAIN_
|||  16.7% |  66.7% |  5.973496 |  11796480 |zzsweep_
|||       |        |           |           | runhyd_
|||       |        |           |           |  MAIN_
|||  16.7% |  83.4% |  5.972417 |  11796480 |xxsweep_
|||       |        |           |           | runhyd_
|||       |        |           |           |  MAIN_
|||  16.6% | 100.0% |  5.970403 |  11796480 |xysweep_
|||       |        |           |           | runhyd_
|||       |        |           |           |  MAIN_
||=======================================================
||  21.0% |  64.0% | 17.447719 |  70778880 |difuze_
||       |        |           |           | sppm2_
```


Callers Profile – MPI (Cont.)

```
||=======================================================
|  7.7% |  99.9% |  6.906194 |    106344 |MPI
||------------------------------------------------------
||  70.2% |  70.2% |  4.851312 |     51840 |mpi_wait_
|||-----------------------------------------------------
|||  41.2% |  41.2% |  1.997854 |     17280 |zbdrys_
||||----------------------------------------------------
||||       |        |           |           |runhyd_
|||||---------------------------------------------------
|||||      |        |           |           |MAIN_
||=======================================================
|||  34.3% |  75.5% |  1.664276 |     17280 |ybdrys_
|||       |        |           |           | runhyd_
|||       |        |           |           |  MAIN_
|||  24.5% | 100.0% |  1.189183 |     17280 |xbdrys_
|||       |        |           |           | runhyd_
|||       |        |           |           |  MAIN_
||=======================================================
||  29.7% |  99.9% |  2.048254 |      2232 |mpi_allreduce_
|||-----------------------------------------------------
|||  96.6% |  96.6% |  1.978537 |       720 |glblmax_
|||       |        |           |           | runhyd_
|||       |        |           |           |  MAIN_
|||   3.4% | 100.0% |  0.069717 |      1512 |glbldsum_
||||----------------------------------------------------
||||  98.5% |  98.5% |  0.068700 |       792 |trace_
||||       |        |           |           | MAIN_
||||   1.5% | 100.0% |  0.001017 |       720 |runhyd_
||||       |        |           |           | MAIN_
||=======================================================
|   0.1% | 100.0% |  0.004263 |     25920 |mpi_isend_
||------------------------------------------------------
|||  33.7% |  33.7% |  0.001436 |      8640 |xbdrys_
|||       |        |           |           | runhyd_
|||       |        |           |           |  MAIN_
|||  33.2% |  66.9% |  0.001416 |      8640 |zbdrys_
|||       |        |           |           | runhyd_
|||       |        |           |           |  MAIN_
|||  33.1% | 100.0% |  0.001410 |      8640 |ybdrys_
|||       |        |           |           | runhyd_
|||       |        |           |           |  MAIN_
|=======================================================
```

Callers Profile with Line Numbers

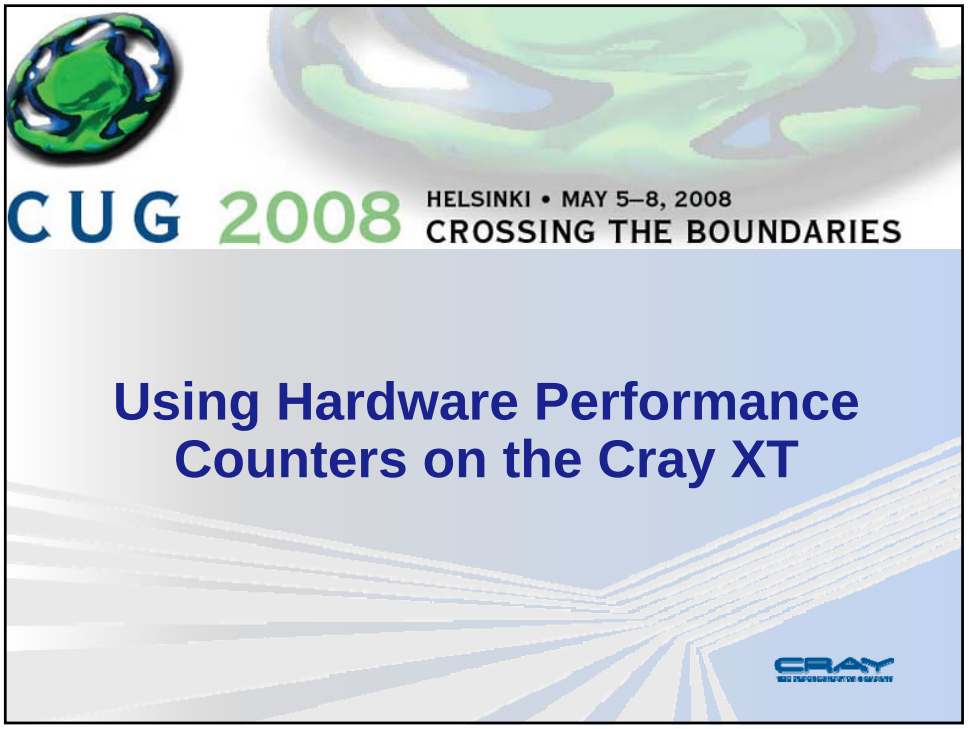
```
Notes for table 1:

  High level option:  -O callers+src
  Low level options:  -d ti%@0.05,cum_ti%,ti,tr \
    -b exp,gr,fu,ca,pe=HIDE -s show_ca='fu,so,li' \
    -s source_limit='1'

  This table shows only lines with Time% > 0.05.

  Percentages at each level are relative
    (for absolute percentages, specify:  -s percent=a).

Table 1:  Profile by Function and Callers, with Line Numbers

 Time % |   Cum.   |      Time |     Calls |Experiment=1
        | Time %   |           |           |Group
        |          |           |           | Function
        |          |           |           |  Caller
        |          |           |           |   PE='HIDE'

 100.0% | 100.0% | 90.217759 | 637231917 |Total
|-------------------------------------------------------
  92.3% |  92.3% | 83.265853 | 637033288 |USER
|------------------------------------------------------
  43.1% |  43.1% | 35.864107 |  70778880 |sppm2_
|-----------------------------------------------------
  16.7% |  16.7% |  5.986173 |  11796480 |yxsweep_:sweeps.F:line.1400
        |        |           |           |  runhyd_:main.F:line.1080
        |        |           |           |   MAIN_:main.F:line.226
  16.7% |  33.4% |  5.980851 |  11796480 |yzsweep_:sweeps.F:line.518
        |        |           |           |  runhyd_:main.F:line.1056
        |        |           |           |   MAIN_:main.F:line.226
  16.7% |  50.0% |  5.980766 |  11796480 |zysweep_:sweeps.F:line.1106
        |        |           |           |  runhyd_:main.F:line.1072
        |        |           |           |   MAIN_:main.F:line.226
  16.7% |  66.7% |  5.973496 |  11796480 |zzsweep_:sweeps.F:line.812
        |        |           |           |  runhyd_:main.F:line.1064
        |        |           |           |   MAIN_:main.F:line.226
  16.7% |  83.4% |  5.972417 |  11796480 |xxsweep_:sweeps.F:line.1694
        |        |           |           |  runhyd_:main.F:line.1088
        |        |           |           |   MAIN_:main.F:line.226
  16.6% | 100.0% |  5.970403 |  11796480 |xysweep_:sweeps.F:line.219
        |        |           |           |  runhyd_:main.F:line.1048
        |        |           |           |   MAIN_:main.F:line.226
|=====================================================
  21.0% |  64.0% | 17.447719 |  70778880 |difuze_
        |        |           |           |  sppm2_:sppm.F:line.630
. . .
```


Documentation

- The pat_help utility is an interactive viewer used to access information about and examples of using CrayPat
  - pat_help [topic [subtopic...]]
- See also man pages:
  - intro_craypat
  - pat_build
  - pat_report
  - pat_help
  - pat_hwpc
  - hwpc
  - papi_counters
  - app2

pat_help Example

```
% pat_help

    The top level CrayPat/X help topics are listed below.
    A good place to start is:

        overview

    If a topic has subtopics, they are displayed under the heading
    "Additional topics", as below.  To view a subtopic, you need
    only enter as many initial letters as required to distinguish
    it from other items in the list.  To see a table of contents
    including subtopics of those subtopics, etc., enter:

        toc

    To produce the full text corresponding to the table of contents,
    specify "all", but preferably in a non-interactive invocation:

        pat_help all . > all_pat_help
        pat_help report all . > all_report_help

  Additional topics:

    API                     execute
    balance                 experiment
    build                   first_example
    counters                overview
    demos                   report
    environment             run

pat_help (.=quit ,=back ^=up /=top ~=search)
=>
```

Hardware Performance Counters

- AMD Opteron Hardware Performance Counters
  - Four 48-bit performance counters.
    - Each counter can monitor a single event
      - Count specific processor events
        - » the processor increments the counter when it detects an occurrence of the event
        - » (e.g., cache misses)
      - Duration of events
        - » the processor counts the number of processor clocks it takes to complete an event
        - » (e.g., the number of clocks it takes to return data from memory after a cache miss)
  - Time Stamp Counters (TSC)
    - Cycles (user time)

PAPI Predefined Events

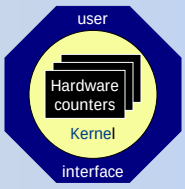
- Common set of events deemed relevant and useful for application performance tuning
  - Accesses to the memory hierarchy, cycle and instruction counts, functional units, pipeline status, etc.
  - The “papi_avail” utility shows which predefined events are available on the system – execute on compute node
- PAPI also provides access to native events
  - The “papi_native_avail” utility lists all AMD native events available on the system – execute on compute node
- Information on PAPI and AMD native events
  - pat_help counters
  - man papi_counters
  - For more information on AMD counters:
    - http://www.amd.com/us-en/assets/content_type/white_papers_and_tech_docs/26049.PDF

Hardware Counters Selection

- PAT_RT_HWPC <set number> | <event list>
  - Specifies hardware counter events to be monitored
    - A set number can be used to select a group of predefined hardware counters events (recommended)
      - 10 groups on Dual Core systems
      - Additional groups specific to Quad Core systems
    - Alternatively a list of hardware performance counter event names can be used
      - Maximum of 4 events
    - Both formats can be specified at the same time, with later definitions overriding previous definitions
    - Hardware counter events are not collected by default
    - Hardware counters collection is not supported with sampling on systems running Catamount on the compute nodes

Accuracy Issues

- Granularity of the measured code
  - If not sufficiently large enough, overhead of the counter interfaces may dominate
- Pay attention to what is not measured:
  - Out-of-order processors
  - Speculation
  - Lack of standard on what is counted
    - Microbenchmarks can help determine accuracy of the hardware counters
- For more information on AMD counters:
  - architecture manuals:
    - http://www.amd.com/us-en/assets/content_type/white_papers_and_tech_docs/26049.PDF



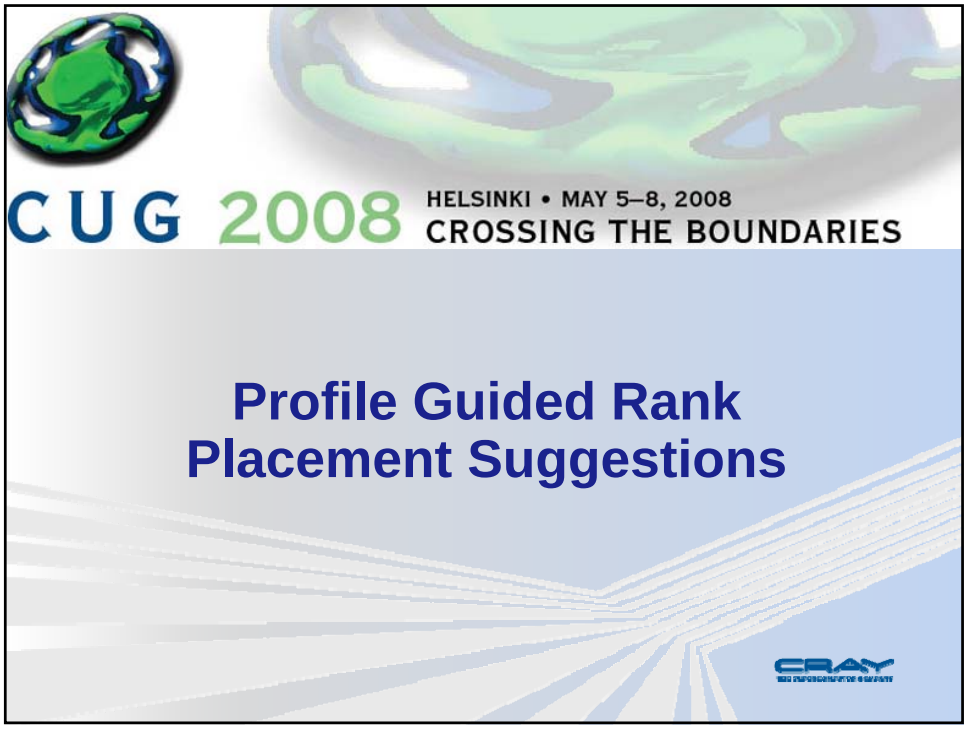
Hardware Performance Counters

```
Hardware performance counter events:
  PAPI_TOT_INS       Instructions completed
  PAPI_L1_DCA        Level 1 data cache accesses
  PAPI_FP_OPS        Floating point operations
  DATA_CACHE_MISSES  Data Cache Misses
  CYCLES_USER        User Cycles (approx, from clock ticks)

Estimated minimum overhead per call of a traced function,
  which was subtracted from the data shown in this report
  (for raw data, use the option:  -s overhead=include):
    PAPI_TOT_INS        2021.905  instr
    PAPI_L1_DCA         1275.739  refs
    PAPI_FP_OPS            0.000  ops
    DATA_CACHE_MISSES      7.702  misses
    CYCLES_USER            0.000  cycles
    Time                   2.054  microseconds
```


Hardware Performance Counters

```
================================================================
USER / sweep_
----------------------------------------------------------------
  Time%                                        97.1%
  Time                                     3.205429
  Imb.Time                                 0.055034
  Imb.Time%                                   1.7%
  Calls                                         12
  DATA_CACHE_MISSES          25.967M/sec    82965477 misses
  PAPI_TOT_INS             2018.073M/sec  6447742786 instr
  PAPI_L1_DCA               783.213M/sec  2502366829 refs
  PAPI_FP_OPS               590.020M/sec  1885113173 ops
  User time (approx)          3.195 secs  7029000000 cycles
  Cycles                      3.195 secs  7029000000 cycles
  User time (approx)          3.195 secs  7029000000 cycles
  Utilization rate                            99.7%
  Instr per cycle                              0.92 inst/cycle
  HW FP Ops / Cycles                           0.27 ops/cycle
  HW FP Ops / User time     590.020M/sec  1885113173 ops         13.4%peak
  HW FP Ops / WCT           588.100M/sec
  HW FP Ops / Inst                            29.2%
  Computation intensity                        0.75 ops/ref
  MIPS                    96867.50M/sec
  MFLOPS                  28320.95M/sec
  Instructions per LD ST                       2.58 inst/ref
  LD & ST per D1 miss                         30.16 refs/miss
  D1 cache hit ratio                          96.7%
  LD ST per Instructions                      38.8%
```

PAT_RT_HWPC=0
Flat profile data
Hard counts
Derived metrics



Rank Reorder Example - hycom

```
pat_report -O load_balance

Table 2:  Load Balance across PE's by FunctionGroup

  Time % |    Cum. |       Time |      Calls |Group
         | Time % |            |            | PE[mmm]

  100.0% | 100.0% | 482.705844 | 7446623155 |Total
|-------------------------------------------------
|  57.7% |  57.7% | 278.657370 | 7329740077 |USER
||------------------------------------------------
||   0.5% |   0.5% | 361.310805 |   33130409 |pe.201
||   0.4% |  58.2% | 311.898417 |   34020074 |pe.45
||   0.0% | 100.0% |  23.780267 |     320096 |pe.184
||================================================
|  42.3% | 100.0% | 204.048383 |  116783478 |MPI
||------------------------------------------------
||   0.9% |   0.9% | 476.662251 |     399087 |pe.184
||   0.3% |  61.9% | 167.921814 |     422197 |pe.37
||   0.2% | 100.0% | 119.123503 |     514637 |pe.201
|================================================
```

Rank Reorder Example - hycom

```
pat_report -O load_balance -s pe=ALL

Table 2:  Load Balance across PE's by FunctionGroup

  Time % |   Cum. |       Time |      Calls |Group
         | Time % |            |            | PE

  100.0% | 100.0% | 482.705844 | 7446623155 |Total
|-------------------------------------------------
|  57.7% |  57.7% | 278.657370 | 7329740077 |USER
||------------------------------------------------
||   0.5% |   0.5% | 361.310805 |   33130409 |pe.201
||   0.5% |   1.0% | 349.849557 |   30460022 |pe.182
||   0.5% |   1.5% | 346.919713 |   33685730 |pe.200
||   0.5% |   2.0% | 342.844256 |   34879988 |pe.188
||   0.5% |   2.5% | 342.308415 |   34913960 |pe.172
. . .
||   0.1% |  99.8% |  45.464691 |    3000260 |pe.248
||   0.1% |  99.9% |  35.970972 |     399401 |pe.213
||   0.0% |  99.9% |  27.431543 |     340673 |pe.232
||   0.0% | 100.0% |  25.142167 |     117620 |pe.240
||   0.0% | 100.0% |  23.780267 |     320096 |pe.184
||================================================
```


Rank Reorder Example - hycom

```
After custom placement:

Table 2:  Load Balance with MPI Sent Message Stats

  Time % |       Time | Sent Msg |     Sent Msg | Avg Sent |Group
         |            |    Count |  Total Bytes | Msg Size | PE[mmm]

  100.0% | 437.418783 | 17161829 | 289328285840 | 16858.83 |Total
|-----------------------------------------------------------------
|  60.2% | 263.211966 |       -- |           -- |       -- |USER
||----------------------------------------------------------------
||   0.5% | 322.019049 |       -- |           -- |       -- |pe.158
||   0.4% | 286.179471 |       -- |           -- |       -- |pe.126
||   0.0% |  23.318648 |       -- |           -- |       -- |pe.184
||================================================================
|  39.8% | 174.206510 | 17161829 | 289328285840 | 16858.83 |MPI
||----------------------------------------------------------------
||   1.0% | 414.091071 |    62224 |    635942368 | 10220.21 |pe.184
||   0.3% | 151.242560 |    68002 |   1039329136 | 15283.80 |pe.126
||   0.3% | 115.396258 |    68002 |   1039329136 | 15283.80 |pe.158
|================================================================
```

MPI Rank Reorder

- MPI rank placement with environment variable

  - Distributed placement
  - SMP style placement
  - Folded rank placement
  - User provided rank file

MPI Rank Order Suggestions

- When to use?
  - Point-to-point communication consumes significant fraction of program time and load imbalance detected
- Available if MPI functions traced (-g mpi)
  - pat_build –O my_program.apa
- Information in resulting report
- Custom placement files automatically generated
- pat_report -O mpi_sm_rank_order (sent message)
- pat_report -O mpi_rank_order (user time)
- Add –s rank_grid_dim=N (N=leading grid dimension)

Profile Guided Rank Placement Suggestions

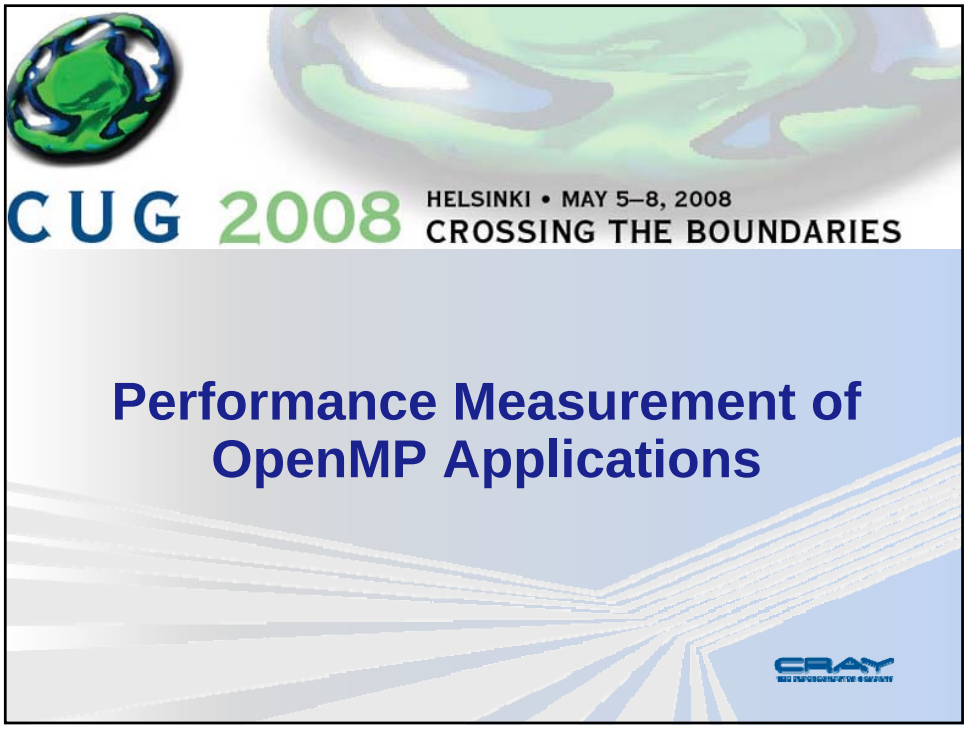
- From the APA profile:
  - If point to point MPI functions use a significant fraction of the program time and if they have a significant imbalance, then:
    - pat_report -O mpi_sm_rank_order ...
      - "sm" stands for "sent message“
  - If, there seems to be a load imbalance of another type, then you can get a report and suggested rank order file based on user time:
    - pat_report -O mpi_rank_order ...
  - If you have a different metric than user time that you want to balance, then:
    - pat_report -O mpi_rank_order -s mro_metric=DATA_CACHE_MISSES ...
      - "mro" stands for mpi_rank_order

Example: -O mpi_sm_rank_order (sweep3d)

```
Notes for table 1:

    To maximize the locality of point to point communication, choose
    and specify a Rank Order with small Max and Avg Sent Msg Total Bytes
    per node for the target number of cores per node.

    To specify a Rank Order with a numerical value, set the environment
    variable MPICH_RANK_REORDER_METHOD to the given value.

    To specify a Rank Order with a letter value 'x', set the environment
    variable MPICH_RANK_REORDER_METHOD to 3, and copy or link the file
    MPICH_RANK_ORDER.x to MPICH_RANK_ORDER.
```

Example: -O mpi_sm_rank_order (sweep3d)

```
Table 1:  Sent Message Stats and Suggested MPI Rank Order


                  Sent Msg Total Bytes per MPI rank

              Max           Avg           Min  Max   Min
      Total Bytes   Total Bytes   Total Bytes  Rank  Rank

         60825600      51840000      29721600  7     42

-------------------------------------------------------------

       Dual core:  Sent Msg Total Bytes per node

 Rank          Max           Avg           Min  Max Node  Min Node
Order   Total Bytes   Total Bytes   Total Bytes  Ranks     Ranks

    d     108518400     103680000      90547200  7,23      34,42
    u     108518400     103680000      90547200  7,23      34,42
    0     121651200     103680000      77414400  7,31      18,42
    1     121651200     103680000      71884800  8,9       42,43
    2     121651200     103680000      60134400  25,22     42,5

-------------------------------------------------------------

       Quad core:  Sent Msg Total Bytes per node

 Rank          Max           Avg           Min  Max Node      Min Node
Order   Total Bytes   Total Bytes   Total Bytes  Ranks         Ranks

    d     211507200     207360000     199065600  37,35,22,1    13,11,34,42
    u     211507200     207360000     199065600  37,35,22,1    13,11,34,42
    1     230169600     207360000     156211200  8,9,10,11     44,45,46,47
    0     243302400     207360000     180403200  8,32,9,33     18,42,19,43
    2     243302400     207360000     145843200  26,21,27,20   42,5,43,4
```

OpenMP Performance Metrics Availability

- Available in craypat/Apprentice2 4.2 and later
- Craypat supports OpenMP from the following compilers
  - PGI, Pathscale
  - GNU support will be available in craypat 4.2.1
- Use of HW counters and OpenMP available in CNL 2.1

How to Collect OpenMP Performance Data

- Performance data collected by default for sampling
- Event traces
  - pat_build –g omp
  - pat_build –g omp_rtl
- User level API available to instrument OpenMP constructs
  - PGI 7.2 will automatically insert calls to trace points
    - Similar to Cray compiler on X2 systems
  - Craypat 4.2.1 will recognize the trace points

OpenMP Performance Metrics

- Per-thread timings
- Overhead incurred at enter/exit of
  - parallel regions
  - worksharing constructs within parallel regions
- Load balance information across threads
- Sampling performance data without API
- Separate metrics for OpenMP runtime and OpenMP API calls

Trace Point API for OpenMP Constructs

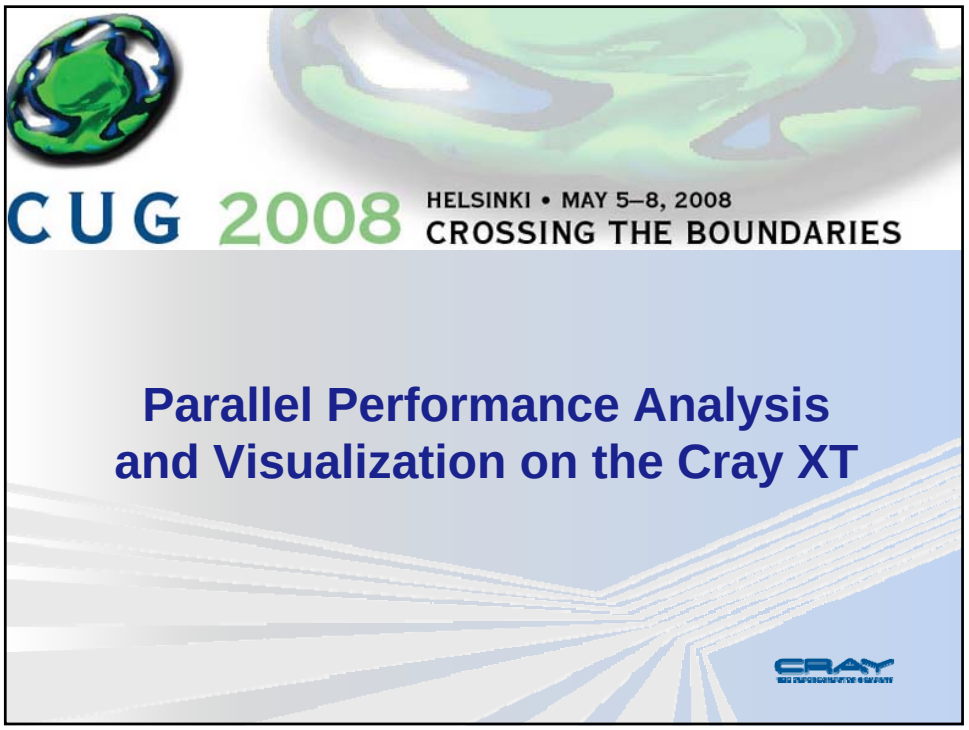
- C functions

```
extern void PAT_omp_parallel_enter (void);
extern void PAT_omp_parallel_exit (void);
extern void PAT_omp_parallel_begin (void);
extern void PAT_omp_parallel_end (void);
extern void PAT_omp_loop_enter (void);
extern void PAT_omp_loop_exit (void);
extern void PAT_omp_sections_enter (void);
extern void PAT_omp_sections_exit (void);
extern void PAT_omp_section_begin (void);
extern void PAT_omp_section_end (void);
```

- Fortran subroutines have same names

OpenMP Data from pat_report

- Default view (no options needed to pat_report)
  - focus on where program is spending its time
  - shows imbalance across all threads
  - assumes all requested resources should be used
  - Highlights non-uniform imbalance across threads
  - Top threads got most of the work
  - Bottom threads got least of the work

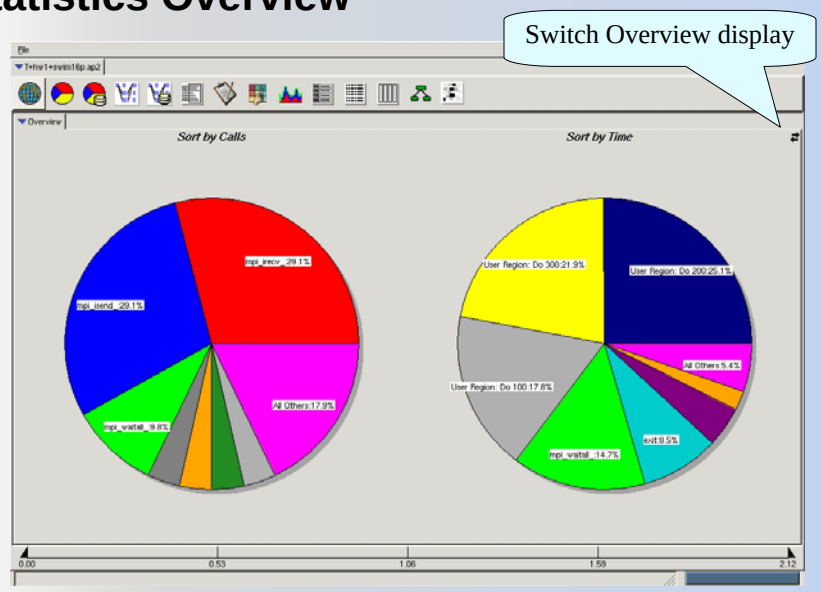


Cray Apprentice^2

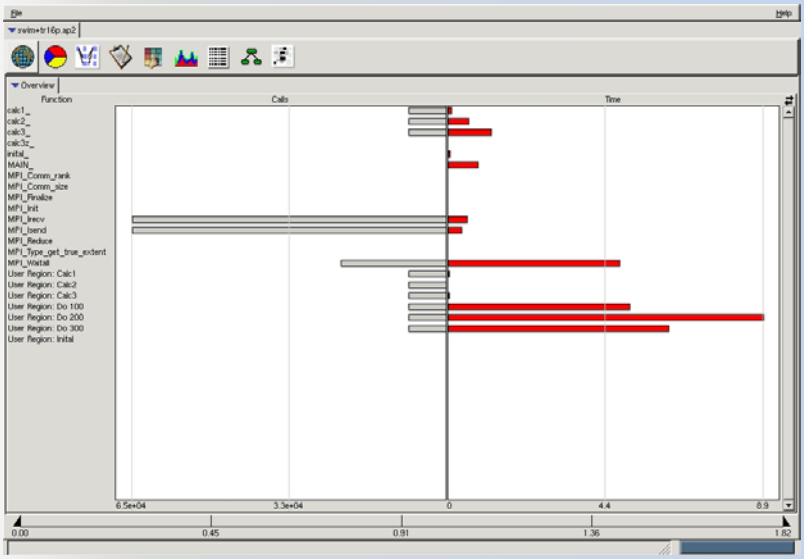
- Call graph profile
- Communication statistics
- Time-line view
  - Communication
  - I/O
- Activity view
- Pair-wise communication statistics
- Text reports
- Source code mapping

- Cray Apprentice^2
- is target to help and correct:
  - Load imbalance
  - Excessive communication
  - Network contention
  - Excessive serialization
  - I/O Problems

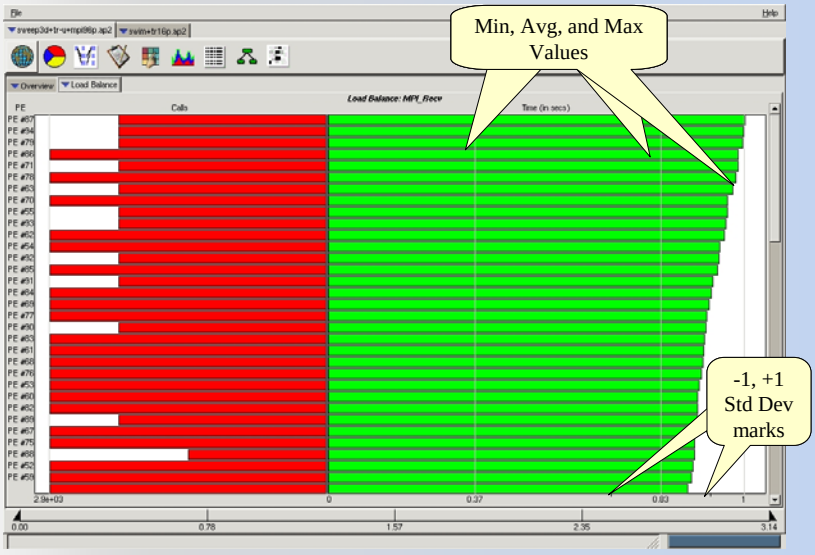
Statistics Overview



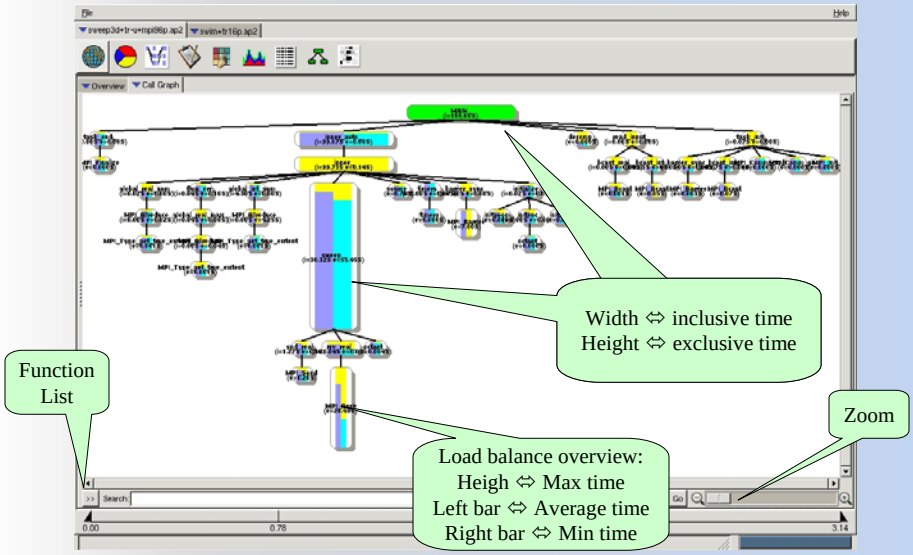
Function Profile



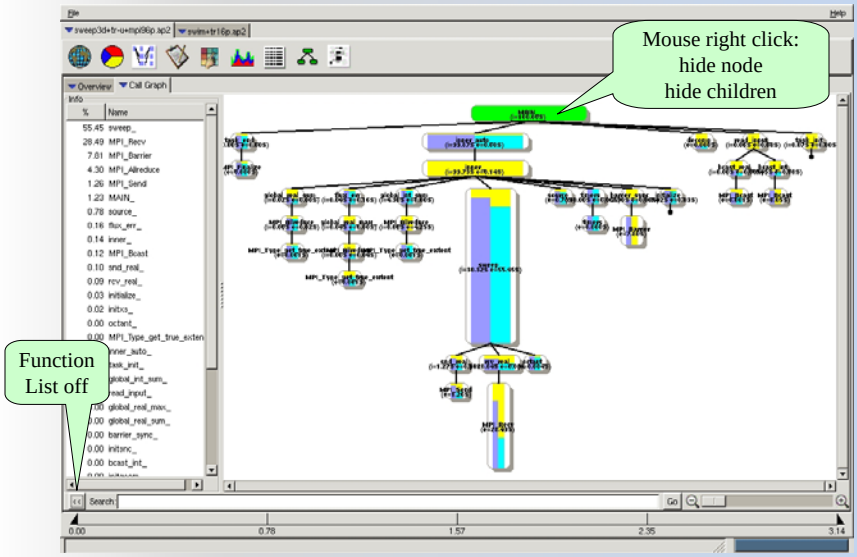
Load Balance View (Aggregated)



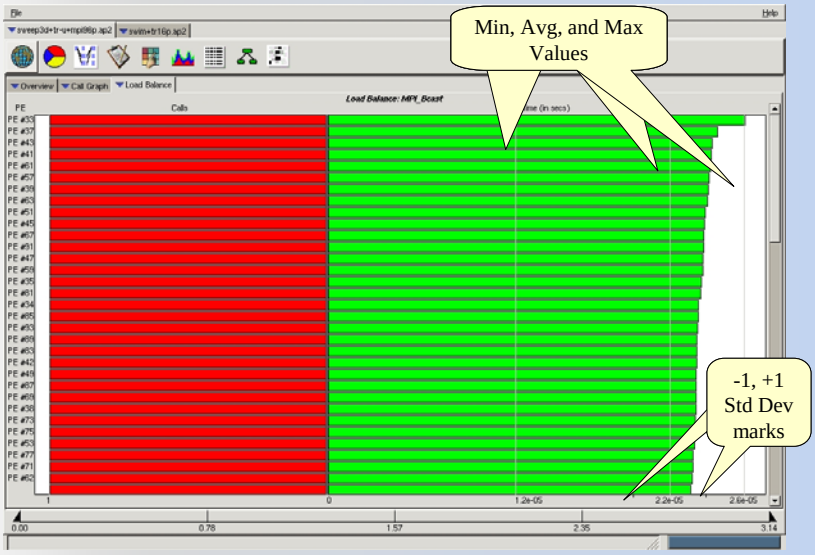
Call Graph View - Zoom



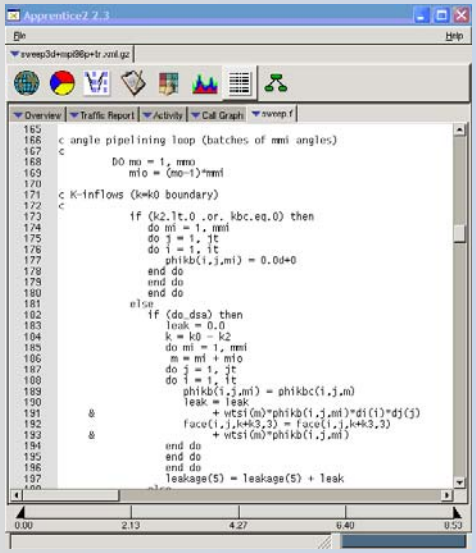
Call Graph View – Function List



Load Balance View (from Call Graph)

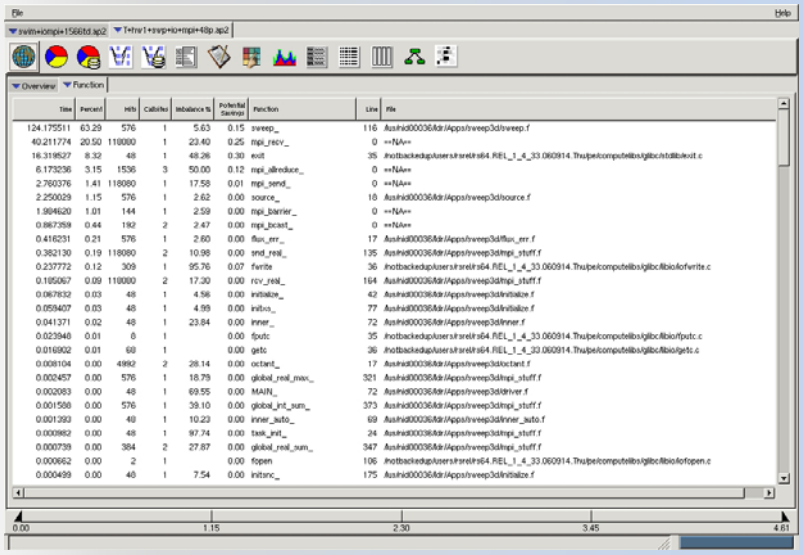


Source Mapping from Call Graph

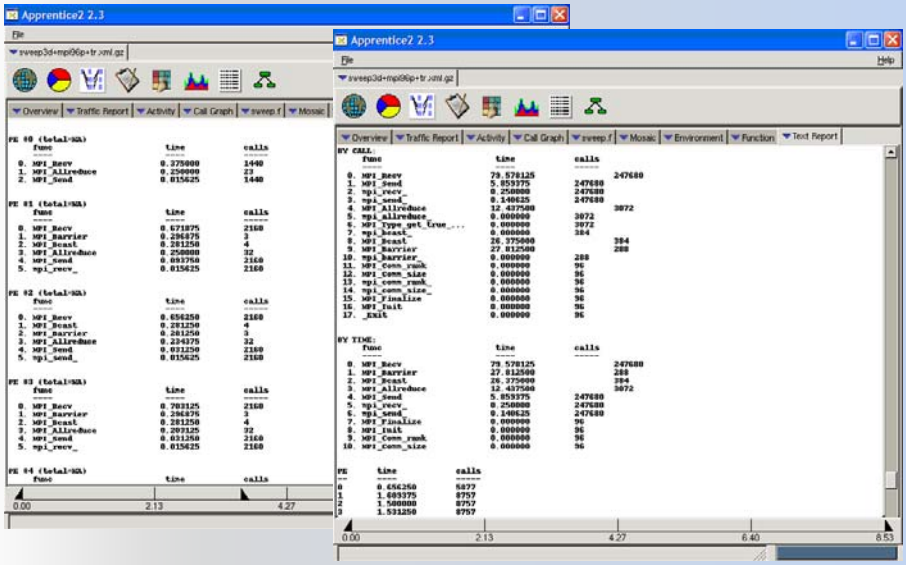


```
c angle pipelining loop (batches of mmi angles)
c
      DO mo = 1, mmo
         mio = (mo-1)*mmi

c K-inflows (k=k0 boundary)
c
         if (k2.lt.0 .or. kbc.eq.0) then
            do mi = 1, mmi
            do j = 1, jt
            do i = 1, it
               phikb(i,j,mi) = 0.0d+0
            end do
            end do
            end do
         else
            if (do_dsa) then
               leak = 0.0
               k = k0 - k2
               do mi = 1, mmi
                m = mi + mio
               do j = 1, jt
               do i = 1, it
                  phikb(i,j,mi) = phikbc(i,j,m)
                  leak = leak
     &                 + wtsi(m)*phikb(i,j,mi)*di(i)*dj(j)
                  face(i,j,k+k3,3) = face(i,j,k+k3,3)
     &                 + wtsi(m)*phikb(i,j,mi)
               end do
               end do
               end do
               leakage(5) = leakage(5) + leak
```

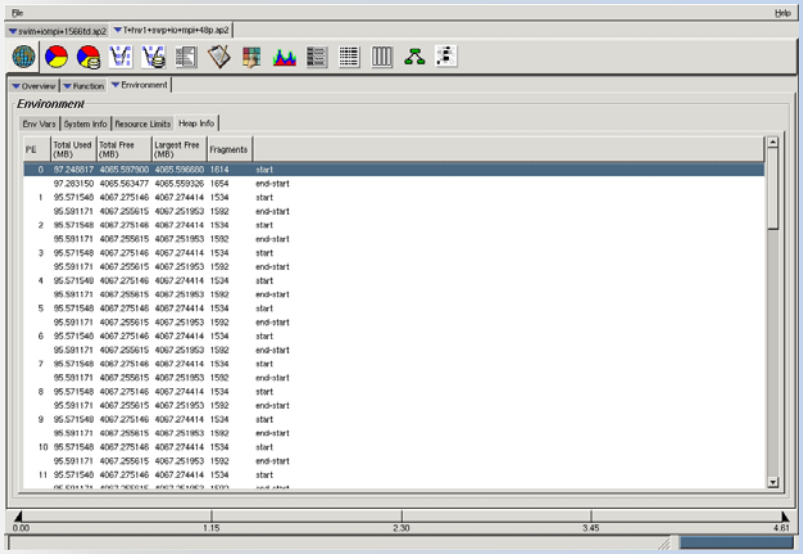
Function Profile



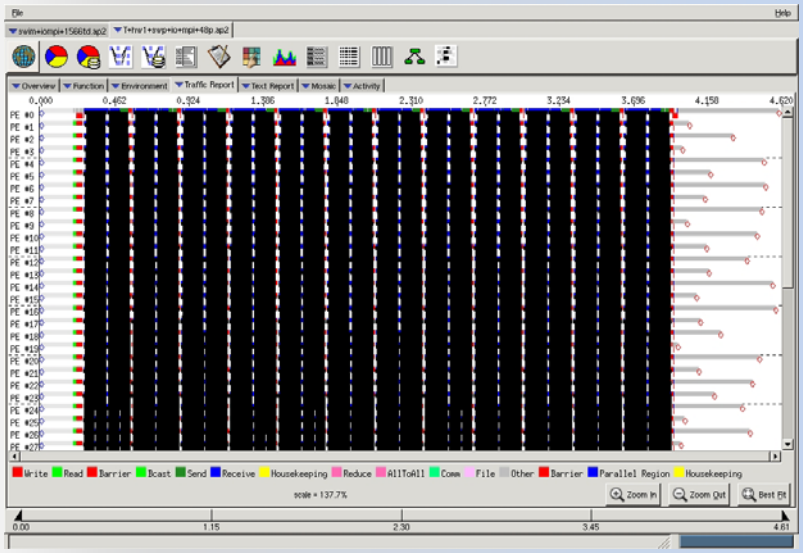
Distribution by PE, by Call, & by Time



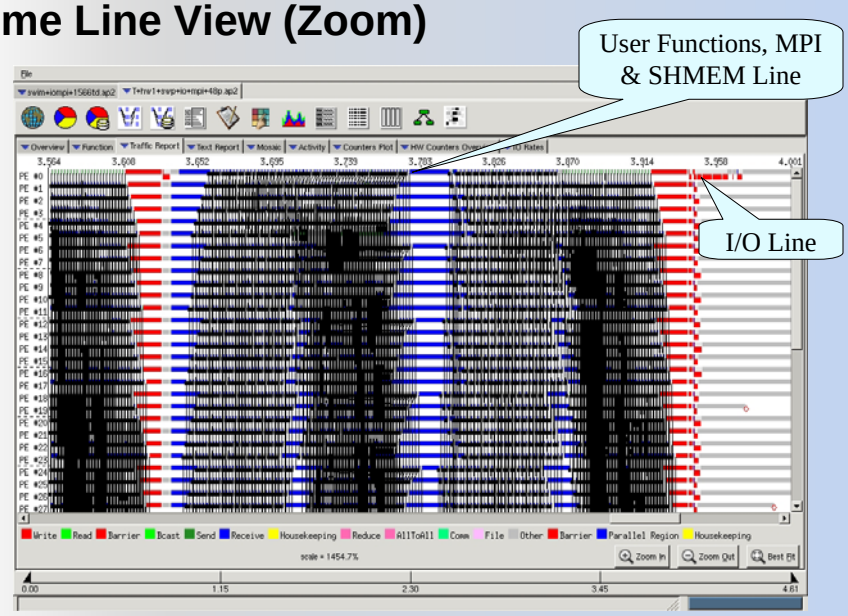
Environment & Execution Details



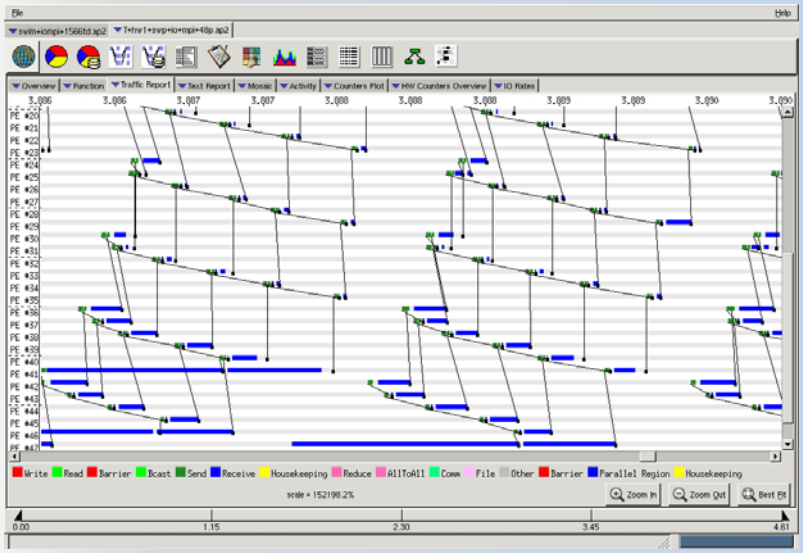
Time Line View (Sweep3D)



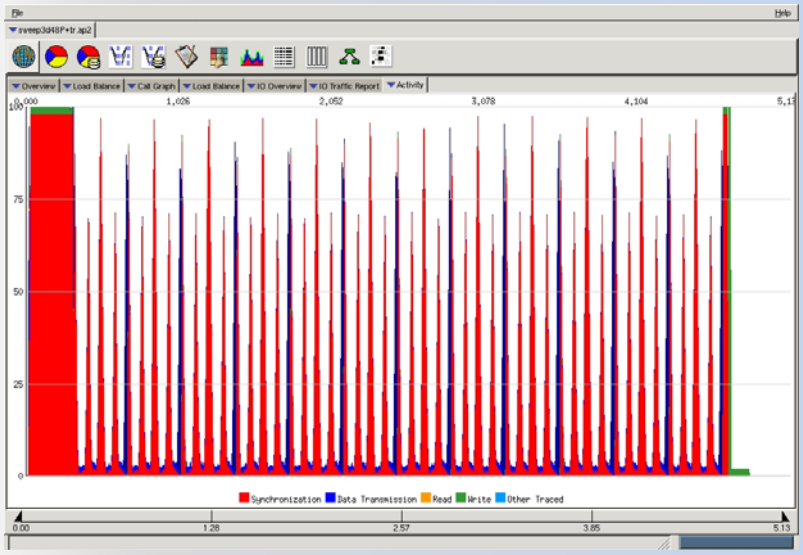
Time Line View (Zoom)



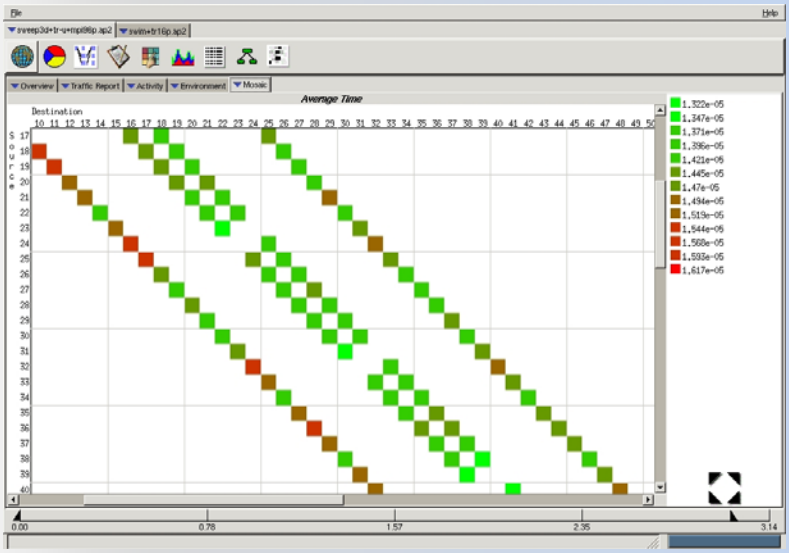
Time Line View (Fine Grain Zoom)



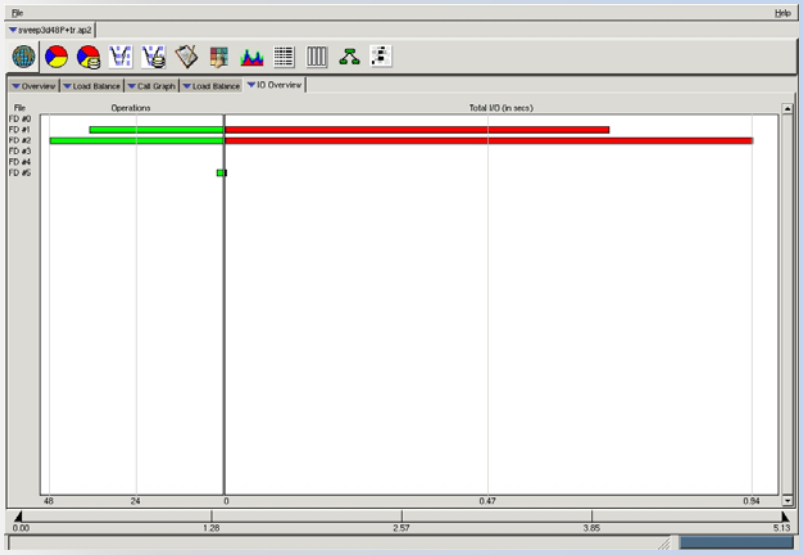
Activity View



Pair-wise Communication



I/O Overview



I/O Rates

File Help

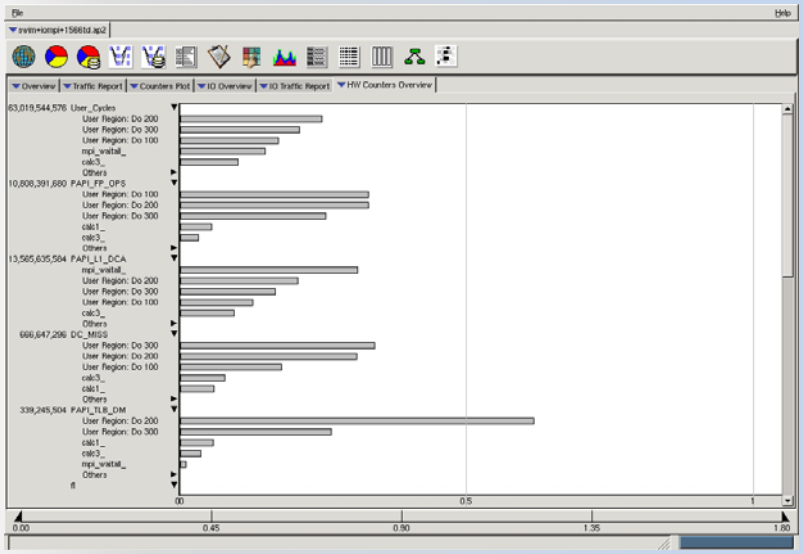
sweep3d48P+tr.ap2

Overview | IO Overview | IO Traffic Report | IO Rates

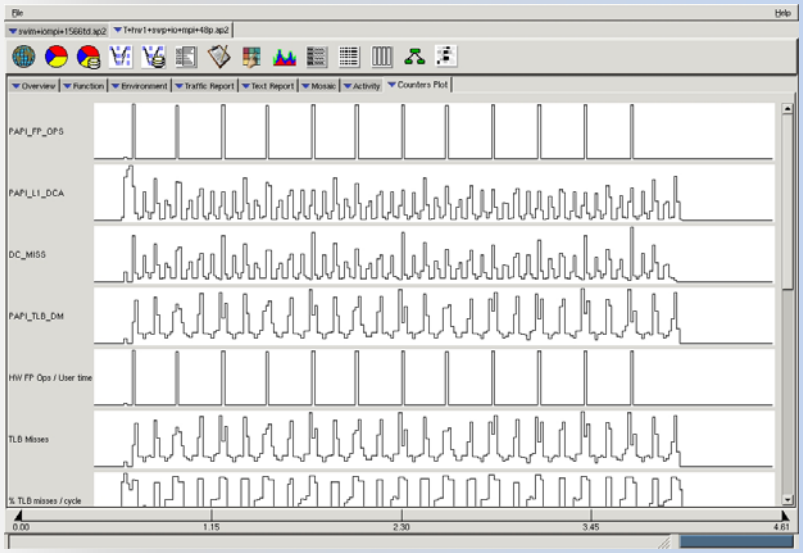
FD	Write Calls	Write Tot (MB)	Write Min (MB/s)	Write Avg (MB/s)	Write Max (MB/s)	Read Calls	Read Tot (MB)	Read Min (MB/s)	Read Avg (MB/s)	Read Max (MB/s)
1	37	0.002	0.001	0.039	0.869	0	0.000	0.000	0.000	0.000
2	48	0.001	0.001	0.003	0.136	0	0.000	0.000	0.000	0.000
5	0	0.000	0.000	0.000	0.000	2	0.000	0.039	0.045	0.051

0.00 1.34 2.67 4.01 5.34

Hardware Counters Overview



Hardware Counters Time Line

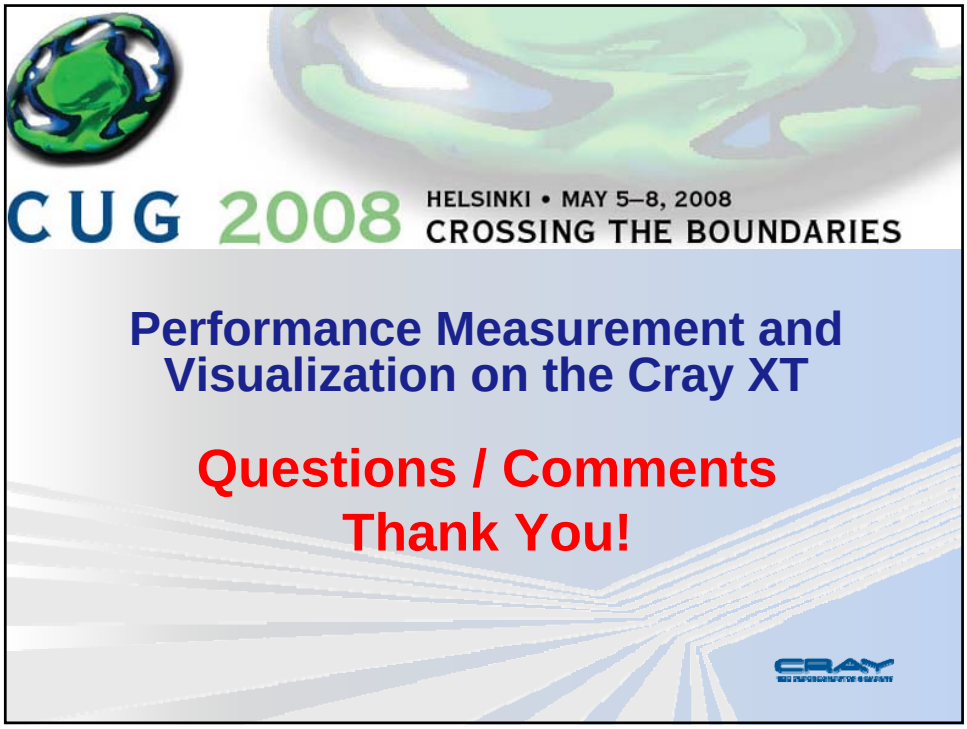


Controlling Trace File Size

- Several environment variables are available to limit trace files to a reasonable size:
  - PAT_RT_CALLSTACK
    - Limit the depth to trace the call stack
  - PAT_RT_HWPC
    - Avoid collecting hardware counters (unset)
  - PAT_RT_RECORD_PE
    - Collect trace for a subset of the PEs
  - PAT_RT_TRACE_FUNCTION_ARGS
    - Limit the number of function arguments to be traced
  - PAT_RT_TRACE_FUNCTION_LIMITS
    - Avoid tracing indicated functions
  - PAT_RT_TRACE_FUNCTION_MAX
    - Limit the maximum number of traces generated for all functions for a single process
- Use CrayPat API to toggle trace state (on / off) or to select functions to trace
  - int PAT_tracing_state (int state)
  - int PAT_trace_function (const void *addr, int state)
- Use the limit built-in command for ksh(1) or csh(1) to control how much disk space the trace file can consume

Additional API Functions

- int PAT_profiling_state (int state)
- int PAT_record (int state)
- int PAT_sampling_state (int state)
- int PAT_tracing_state (int state)
- int PAT_trace_function (const void *addr, int state)
- State can have one of the following:
  - PAT_STATE_ON
  - PAT_STATE_OFF
  - PAT_STATE_QUERY
- int PAT_flush_buffer (void)


CUG 2008
HELSINKI • MAY 5–8, 2008
CROSSING THE BOUNDARIES
Performance Measurement and Visualization on the Cray XT
Questions / Comments
Thank You!
CRAY