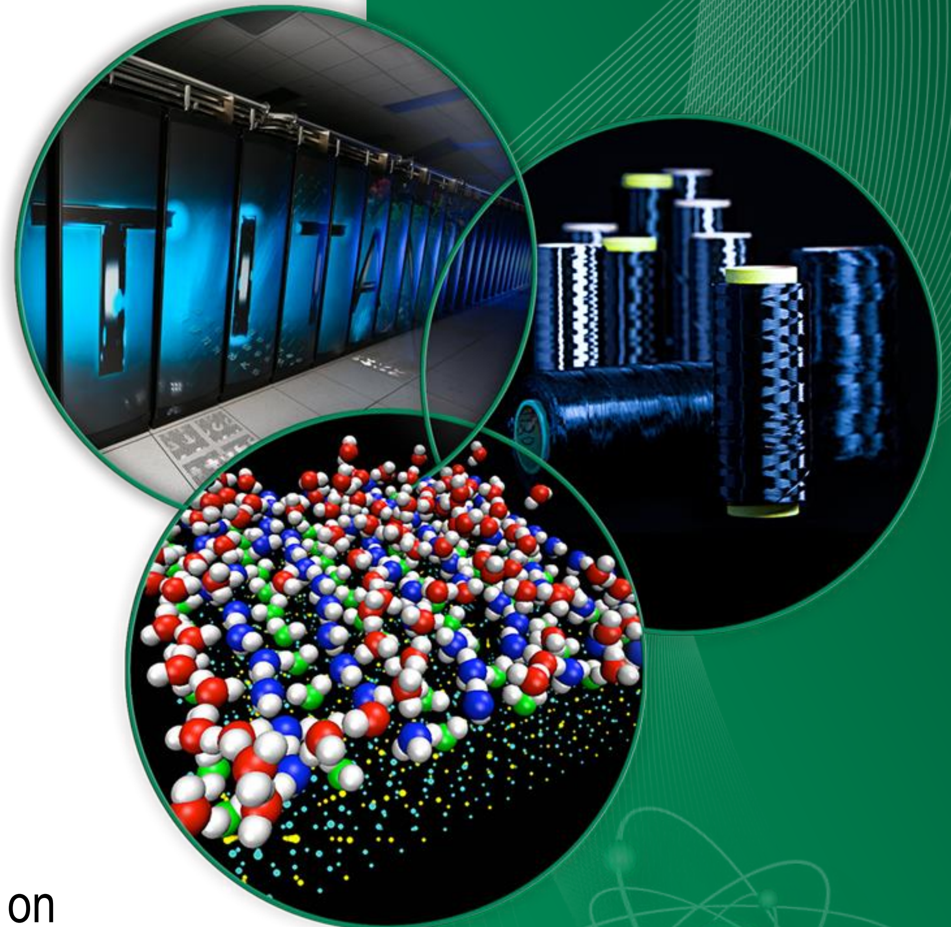
HSLOT: The HERCULES Scriptable Loop Transformations Engine

Christos Kartsaklis (ORNL)

Eunjung Park (UD)

John Cavazos (UD)



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WOLFHPC: Fourth International Workshop on Domain-Specific Languages and High-Level Frameworks for High Performance Computing

In conjunction with SC14: The International Conference for High Performance Computing, Networking, Storage, and Analysis

Introduction

- DoE application challenges in accelerator & exascale era
  - Large production-grade simulation codes need porting
  - Reengineering challenges going beyond parameterization
  - Node design to change again; memory types, etc.
- Different tools researched
  - Language extensions, DSL construction/elevation kits, …
- ORNL HERCULES
  - User-definable/extensible compiler infrastructure
  - Compiler-supported analysis/transformation tools

Directive APIs

- Compiler directives
  - Prescriptive or descriptive (hints) instructions to the compiler
  - `#pragma NAMESPACE` (C) and `!$NAMESPACE` (Fortran)
  - Original code annotated with directives, but unchanged otherwise
- Many directive-based parallelization APIs
  - HPF, OpenMP, OmpSs, OpenACC, hiCUDA, …
  - Often standardized & adopted by many compilers
  - Elegant, annotating:

```
#pragma omp parallel for reduction(+:r)
for (i=0 ; i<n ; i++) { ...; r+=...; }
```

- Compilers offer their own optimization directives:
  - The user may know more than what the compiler can deduce
  - GCC `Loop_Optimize`, Cray Fortran Compiler (`SHORTLOOP`, `FUSION`, etc.), Intel (`ivdep`, `loop_count`, etc.)

HSLOT

- **H**ERCULE**S** **Lo**op **T**ransformations Engine
  - A loop transformations directives API & a supporting compiler
- A new loop transformations directives API
  - About 20 different types of transformation clauses, each with its own configuration options
  - Loop nest/stack & iteration space oriented
  - Simplify codegen mainly, not optimal transformation selection
- HSLF90: An Open64-based directives-implementing compiler
  - Non-validating (trust the user) model
  - Minimal legality checking (VHO D/F & tree constraints)
  - HSLOT happily coexists with –O3 strategies

Programming Model

Original program

```
do i = 1, N
   do j = 1, K
   … ! body 1
   end do
end do
do r = 1, N*K
   … ! body 2
end do
```

Tag Loops

```
!$hslot loop(L1)
do i = 1, N
!$hslot loop(L2)
   do j = 1, K
   … ! body 1
   end do
end do
!$hslot loop(L3)
do r = 1, N*K
   … ! body 2
end do
```

Specify Transformations

```
!$hslot loop(L1)
!$hslot collapse(L1, L2, LC), &
        fuse([LC,L3],same,L3)
do i = 1, N
!$hslot loop(L2)
   do j = 1, K
   … ! body 1
   end do
end do
!$hslot loop(L3)
do r = 1, N*K
   … ! body 2
end do
```

```
L3: do q = 1, N*K
        … ! body 1
        … ! body 2
    end do
```

- Identify loops of interest and tag them with a unique ID
- Provide the list of transformations, passing these and new IDs around
- Transformation directives are always processed in the order that they appear in the text (left to right, top to bottom).

Transformation Steps (1/2)

```
L1: do i = 1, N
L2:   do j = 1, K
        … ! body 1
      end do
    end do
L3: do r = 1, N*K
      … ! body 2
    end do
```

collapse(L1,L2,LC)

```
LC: do q1 = 1, N*K
      … compute i & j
      … ! i-only specifics
      … ! body 1
      … ! i-only specifics
    end do

L3: do r = 1, N*K
      … ! body 2
    end do
```

- Loops L1 & L2 invalidated
- ID LC refers to the collapsed product

Transformation Steps (2/2)

```
LC: do q1 = 1, N*K
      … compute i & j
      … ! i-only specifics
      … ! body 1
      … ! i-only specifics
    end do

L3: do r = 1, N*K
      … ! body 2
    end do
```

```
fuse([LC,L3],same,LC)
```

```
LC: do q2 = 1, N*K
      … compute i & j
      … ! i-only specifics
      … ! body 1
      … ! i-only specifics
      … ! body 2
    end do
```

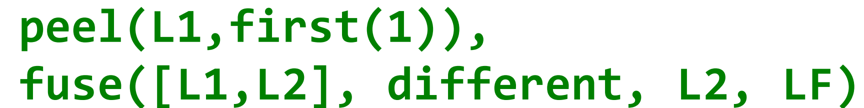
- Loops `LC` & `L3` invalidated
- ID `LC` now refers to the new loop

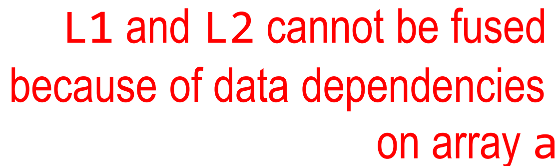
Example1: Merging Non-fusible Loops

- Combining g `peel` and `fuse` to deal with data dependencies

```
$hslot loop(L1)
do i=2,n-1
 S1: b(i) = … * a(i-1) + a(i) + a(i+1)
end do

$hslot loop(L2)
do j=2, n-1
 S2: a(j) = b(j)
end do
```






```
do k=2,n-1
 S1: b(k) = …* a(k-1) +a(k)+ a(k+1)
 S2: a(k) = b(k)
end do
```

```
b(2) = … * a(1) + a(2) + a(3)
a(2) = b(2)
b(3) = … * a(2) + a(3) + a(4)
a(3) = b(3)
```

```
    b(2) = … * a(1) + a(2) + a(3)
LF: do k1=3,n-1
     S1: b(k1) = … * a(k1-1) + a(k1) + a(k+1)
     S2: a(k1-1) = b(k1-1)
    end do ! here k1=(n-1)+1
    do k2=k1, n-1    ! trip count is 0
     S1: b(k2) = …
    end do
L2: do k2=(k1-1), n-1 !
     S2: a(k2) = b(k2)
    end do
```

Example2: Determining the Unroll Factor Dynamically

- Using `fork` for testing trip count at runtime and unrolling accordingly

```
!$hslot loop(L)
do i=1,N
  … ! body
end do
```

```
fork(L,multiple(4),LMOD4,LMOD3),
unroll(LMOD4,4),
fork(LMOD3,multiple(3),LMOD3,L),
unroll(LMOD3,3)
```

```
LMOD4: if (MOD(N,4).eq.0) then
         do i=1,N,4
           … ! body @ iteration i
           … ! body @ iteration i+1
           … ! body @ iteration i+2
           … ! body @ iteration i+3
         end do
       else
LMOD3:   if (MOD(N,3).eq.0) then
           do i=1,N,3
             … ! body @ iteration i
             … ! body @ iteration i+1
             … ! body @ iteration i+2
           end do
         else
L:         do i=1,N
             … ! body
           end do
         endif
       endif
```

Transformations

- Common & unique/customizable set of transformations
  - Emerged by talking to users and by trying to recreate transformed code found in literature.

# of Input Loops Processed	*Transformation Primitives*
Single Loop	`unroll`, `split`, `fork`, `peel`, **`nest`**, `openmp`, **`fission`**, `align`, `gpurr`, `hoistsa`, `ivarep`, `normalize`, `stride`
Double Loops	`collapse`, **`fuse`**, `swpnest`, `interch`
Multiple Loops	**`tile`**, **`specialize`**

Fuse

- Fuses n arbitrary loops together
  - Controlling insertion point (3rd argument)
  - Manage uneven trip counts (2nd argument)

```
!$hslot loop(L1)
do I=1,N1
  DX(I)=DA*DX(I)
end do
call bar();
!$hslot loop(L2)
do J=1,N2
  DY(J)=DY(J)*DX(J)
end do
```

`fuse([L1,L2],same,L2,LF)`

```
     call bar();
     N=N1
LF:  do P=1,N
       I=P
       DX(I)=DA*DX(I)
       J=P
       DY(J)=DY(J)*DX(J)
     end do
```

`fuse([L1,L2],different, L2,LF,[L1R,L2R])`

```
     call bar();
     NMIN=MIN(N1,N2)
LF:  do P=1,NMIN
       I=P
       DX(I)=DA*DX(I)
       J=P
       DY(J)=DY(J)*DX(J)
     end do
L1R: do I=NMIN+1,N1
       DX(I)=DA*DX(I)
     end do
L2R: do J=NMIN+1,N2
       DY(J)=DY(J)*DX(J)
     end do
```

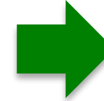
Nest

- Different strategies for creating loop nests

```
!$hslot loop(L), &
 nest(L, simple(J,1,M,2), LNEW)
do I = 1, N
  DX(I) = DA*DX(I)
end do
```

This variable must not exist

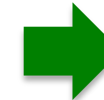
simple



```
do J = 1, M, 2          ! LNEW
  do I = 1, N           ! L
    DX(I) = DA*DX(I)
  end do
end do
```

```
!$hslot loop(L), &
 nest(L, interleave(J,4), LNEW)
do I = 1, N
  DX(I) = DA*DX(I)
end do
```

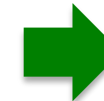
interleave



```
do J = 1, 4             ! LNEW
  do I = 1+J, N, 4      ! L
    DX(I) = DA*DX(I)
  end do
end do
```

```
!$hslot loop(L), &
 nest(L, pick([L1,L2]), LNEW)
do I = 1, N
  … ! block
end do
!$hslot loop(L1)
do J = 1, K
  …
end do
!$hslot loop(L2)
do Q = 1, M
  …
end do
```

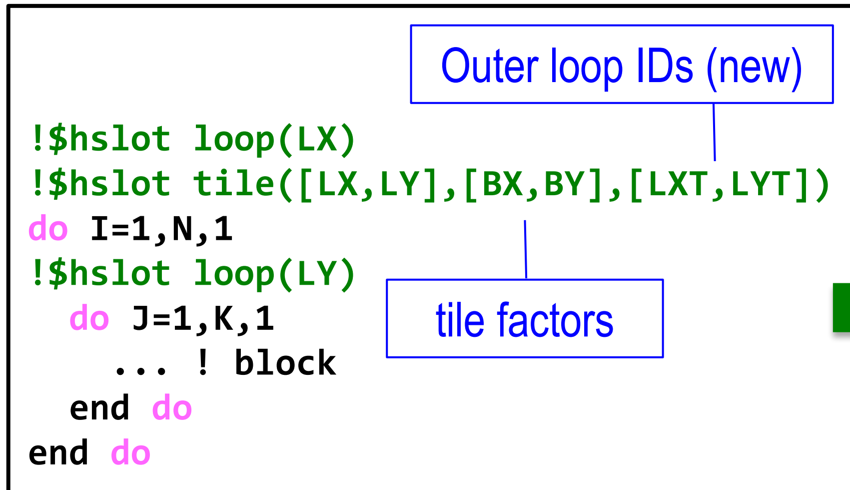
pick



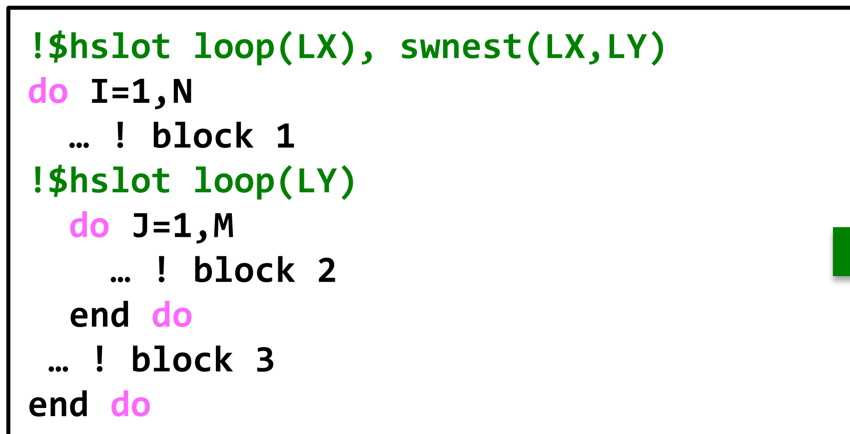
```
do J = 1, K             ! LNEW
  do Q = 1, M
    do I = 1, N         ! L
      … ! block
    end do
  end do
end do
do J = 1, K             ! L1
  …
end do
do Q = 1, M             ! L2
  …
end do
```

Tile & swnest (1/2)

- `tile` - blocking for a multi-level memory hierarchy, simple loop nest expected
- `swnest` – helper tool for swapping nests




```
LXT: do I0=1,N,BX
LYT:   do J0=1,K,BY
LX:      do I=I0,min(I0+BX-1,N),1
LY:        do J=J0,min(J0+BY-1,K),1
             ... ! block
           end do
         end do
       end do
     end do
```




```
LY: do J=1,M
LX:   do I=1,N
        … ! block 1
        … ! block 2
        … ! block 3
      end do
    end do
```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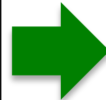
Tile & swnest (2/2)

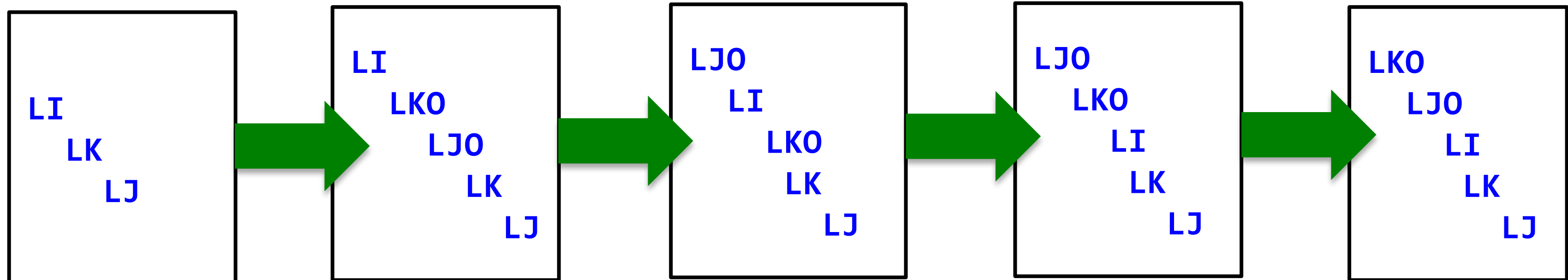
```
tile([LK,LJ],[KBF,JBF],[LKO,LJO]),
swnest(LI,LJO), swnest(LI,LKO), swnest(LJO,LKO)
```

```
!$hslot loop(LI)
do I=1,N
!$hslot loop(LK)
  do K=1,N
    Z = B(K,I)
!$hslot loop(LJ)
    do J=1,N
      C(J,I) = C(J,I) + Z*A(J,K)
    end do
  end do
end do
```



```
LKO: do K0=1,N,KBF
LJO:   do J0=1,N,JBF
LI:      do I=1,N
LK:        do K=K0,MIN(K0+KBF-1,N)
             Z = B(K,I)
LJ:          do J=J0,MIN(J0+JBF-1,N)
               C(J,I) = C(J,I) + Z*A(J,K)
             end do
           end do
         end do
       end do
     end do
```

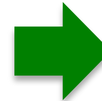
- Transforming a naive matrix multiplier by tiling for reuse (factors as variables – target knowledge necessary).



Specialize

- Performs a conditional or unconditional constant propagation
- User specifies variable names & constants

```
!$hslot specialize([L1,L2], true,          &
                   [BETA,ALPHA],[1.0,0.0])
do J=1,N
!$hslot loop(L1)
  do I=1,M
    C(I,J)=BETA*C(I,J)
  end do
  do L=1,K
    TEMP=ALPHA*B(L,J)
!$hslot loop(L2)
    do I=1,M
      C(I,J)=C(I,J)+TEMP*A(I,L)
    end do
  end do
end do
```



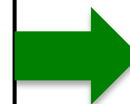
```
do J=1,N
  if ( (BETA  .eq. 1.0) .and. &
       (ALPHA .eq. 0.0)) then
    do I=1,M
      C(I,J)=1.0*C(I,J)
    end do
    do L=1,K
      TEMP=0.0*B(L,J)
      do I=1,M
        C(I,J)=C(I,J)+TEMP*A(I,L)
      end do
    end do
  else
    … ! Original body
  end if
end do
```

Can be simplified and/or eliminated

Fission

- Loop fission using a nested loop statements bookmark approach
- Loop body dissected around these bookmarks, hints control which new nest instance statements end up in
- For every body statement, if bookmark encountered: before (dump queue, add), after (add, dump queue), both (dump queue, add, dump), none (add)

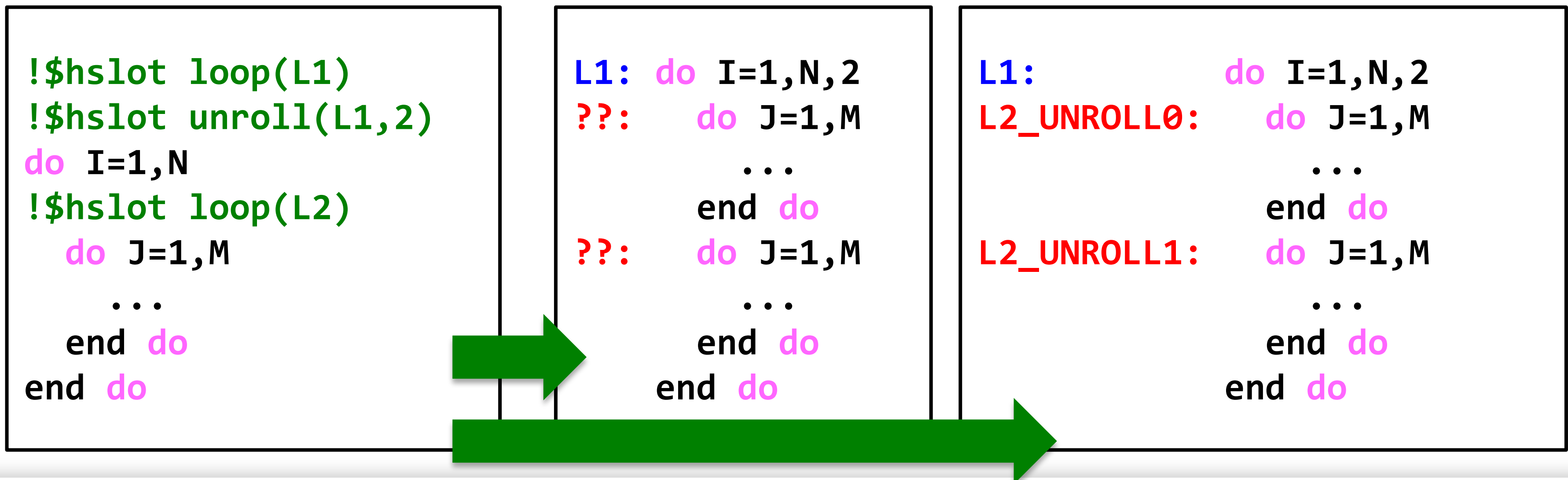
```
!$hslot loop(L)
!$hslot fission(L, [L1,L2], [both,none],
                   [LI1,LI2])
do I=1,N
  DX(I)=DA*DX(I)
!$hslot loop(L1)
  do J=1,K
    … ! block 1
  end do
!$hslot loop(L2)
  do M=1,K
    … ! block 2
  end do
  … ! block 3
end do
```



```
      do I=1,N
        DX(I)=DA*DX(I)
      end do
L1I:  do I=1,N
L1:     do J=1,K
          … ! block 1
        end do
      end do
L2I:  do I=1,N
L2:     do M=1,K
          … ! block 2
        end do
        … ! block 3
      end do
```

Programming Model - ROC

- Problem: what happens to tagged loops' IDs during duplication?
- Re-Tag on Copy (ROC): automatically assign new identifiers during copying of loops – predefined patterns:
  - Unroll: `_UNROLLx`, where x is the body copy (0-based).
  - Fork: `_ELSE` for the "else" branch
  - Peel: `_PREx` and `_PSTx` for the first/last iter peeled (0-based)
  - Specialize: `_SPEC` for the specialized part



HSLF90 Tag Tracking / Debugging

- HSLF90 tracks tag lifetime
- What the user has declared
  - Report on attempts to use undeclared tags
- What was once a valid tag, then destroyed
  - Report on outdated tag uses

```
hslf90 -c fork-unroll-test.f90
... // transformed source dump
slot: (V) finished with 'fork(L,multiple(4),LMOD4,L)'.
slot: (W) ignoring unnecessary normalization of 'LMOD4'
slot: (V) finished with 'normalize(LMOD4,LMOD4)'.
... // transformed source dump
slot: (V) finished with 'unroll(LMOD4,4)'.
slot: (E) reason: alias 'LX' not bound to a loop
slot: (E) transformations stack trace:
slot: (E)   fork(LX,multiple(3),LMOD3,L)
```

Early Results (1/2)

- 11 programs from Polybench Fortran V2.1
  - Manually optimized with HSLOT (EunJung, UD)
- Dual Xeon E5-2650 system (8/16; 20MB LLC)
- HSLF90 is modified Open64 Fortran 4.2.4 (openf90)
- Comparing baseline (–O3) to HSLOT directives + –O3
  - HSLOT is VHO, so no interference with LNO but interesting to see effects of heavily/radically modified loops & LNO
- Serial & threaded versions (8, 16 & 32 counts)

Early Results (2/2)

Kernel	Config	Serial	8 Thr.	16 Thr.	32 Thr.	Transformation Choice/Count
2mm	NI,NJ,NK,NL=1024	1.21x	2.18x	1.76x	4.03x	peel(2), fuse(3), openmp
3mm	NI,NJ,NK,NL,NM= 1024	1.15x	1.29x	1.43x	2.05x	peel(2), fuse(3), openmp
correlation	N,M=512	0.62x	-	-	-	fission(2), unroll(1), peel(2), fuse(2)
doitgen	NQ,NR,NP=128	1.04x	8.24x	8.29x	16.5x	unroll, openmp
dynprog	LEN=50, TSTEPS=10000	1.17x	1.74x	1.39x	1.23x	unroll(2), fuse, openmp
fdtd-2D	NX,NY=1000	1.08x	-	-	-	peel(3), fuse(2)
gemm	NI,NJ=1024	1.05x	6.65x	7.58x	14.56x	unroll, fuse(2), openmp
jacobi-1D	N=10000, TSTEPS=100	1.14x	-	-	-	peel(2), fuse, unroll
jacobi-2D	N=9000, TSTEPS=10	1.32x	3.36x	3.41x	2.23x	unroll(2), fuse(4), peel(2), openmp
mvt	N=4000	2.48x	4.38x	4.48x	8.29x	unroll(2), openmp(2)
seidel-2D	N=3200, TSTEPS=4	1.06x	7.41x	13.52x	26.96x	unroll, fuse, openmp
GMEAN		1.15x	2.47x	2.57x	3.47x	

Thank you!

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Split

- Different strategies for splitting the iteration space

```
$hslot loop(L1)
$hslot split(L, ???, L1, L2)
do I=1,N
  DX(I) = DA*DX(I)
end do
```

```
L1: do I0=1,MOD(N,4)
      DX(I0) = DA*DX(I0)
    end do
L2: do I=MOD(N,4)+1,N
      DX(I) = DA*DX(I)
    end do
```

```
L1: do I=1,N,2
      DX(I) = DA*DX(I)
    end do
L2: do I=2,N
      DX(I) = DA*DX(I)
    end do
```

```
L1: do I=1,N/2
      DX(I) = DA*DX(I)
    end do
L2: do I=(N/2)+1,N
      DX(I) = DA*DX(I)
end do
```

Peel & openmp

```
peel(L, first(2), last(1))
```

```
$hslot loop(L)
do I=1,N
  C(I) = BETA*C(I)
end do
```

```
C(1)=BETA*C(1)
C(2)=BETA*C(2)
do I=3,N-1
  C(I) = BETA*C(I)
end do
C(N)=BETA*C(N)
I=N
```

```
openmp(for,L)
```

The loop index variable will be `lastprivate`, arrays become `shared` and everything else is set to `firstprivate`.

```
!$omp parallel do lastlocal(I), &
      shared(C), firstprivate(BETA,N)
do I=1,N
  C(I) = BETA*C(I)
end do
```