Topic 8:

Optimization for Parallel Computation
Reading List

- Slides: Topic 8x
- Other readings as assigned in class or homework
Outline

- Basic Concepts
  - Parallelism
  - Locality
- Loop Nest Optimization
- Summary
Parallelism

- What is Parallelism?
- Parallelism in Computer Architecture
  - Instruction-Level Parallelism (ILP)
  - Thread-Level Parallelism (TLP)
- Parallelism in Programs/Applications
  - Statement Level Parallelism
  - Loop Level Parallelism
  - Task Level Parallelism
Good IPO
Good LNO
Good global optimization
Good integration of IPO/LNO/OPT
Smooth information passing between FE and CG
Complete and flexible support of inner-loop scheduling (SWP), instruction scheduling and register allocation
A Multiprocessor Architecture

- A generic modern multiprocessor

Node: processor(s), memory system, plus communication assist
- Network interface and communication controller

• Scalable network

Network
Locality

- **Temporal Locality**
  the same data is used several times within a short time period

- **Spatial Locality**
  when different data elements that are located near to each other are used within a short period of time
Loop Nest Transformation and Optimization

- Simple Loop Transformation
- Unimodular Loop Transformations
- Beyond Unimodular Transformations
- Combining Loop Transformation
- Summary
Simple Loop Transformation

- Loop unrolling
- Loop peeling
- ...

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Unimodular Loop Transformation

- Loop interchange
- Loop reversal
- Loop skewing
Loop Interchange

\[
\begin{align*}
& do \ j = 1, N \\
& \quad do \ i = 1, N \\
& \quad \quad X[i, j] = X[i - 1, j] + B[i] \\
& \quad \quad end \ do \\
& \quad end \ do \\
& \end{align*}
\]

\[
\begin{align*}
& do \ i = 1, N \\
& \quad do \ j = 1, N \\
& \quad \quad X[i, j] = X[i - 1, j] + B[i] \\
& \quad \quad end \ do \\
& \quad end \ do \\
& \end{align*}
\]

Why we wish to perform loop interchange?
Safety of Loop Interchange

\[
\begin{align*}
  &DO \ J = 1, M \\
  &\quad DO \ I = 1, N \\
  &\quad \quad A(I, J+1) = A(I+1, J) + B \\
  &\quad \quad ENDDO \\
  &ENDDO \\
\end{align*}
\]

Is it legal to do interchange of I, J?
Legality of Loop Interchange

\[ A(I, J+1) = A(I+1, J) + B \]

Note: Interchange here is Illegal!
Loop Reversal – An Example

\[
\begin{align*}
&DO\ I = 1,\ N \\
&\quad DO\ J = 1,\ M \\
&\quad\quad A(I+1, J) = A(I, J+1) + B \\
&\quad ENDDO \\
&ENDDO
\end{align*}
\]

\[
\begin{align*}
&DO\ I = 1,\ N \\
&\quad DO\ J = M,\ 1,\ -1 \\
&\quad\quad A(I+1, J) = A(I, J+1) + B \\
&\quad ENDDO \\
&ENDDO
\end{align*}
\]
Loop Reversal – An Example (Cont’d)

Interchange

\[
\begin{align*}
DO & \ J = M, \ 1, \ -1 \\
DO & \ I \\
& A(I+1, \ J) = A(I, \ J+1)) + B \\
ENDDO \\
ENDDO
\end{align*}
\]

A(I, J+1)) + B

DO J = M, 1, -1
A(2:N+1, J) = A(1:N, J) + B

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**Skewing - An Example**

\[ \text{DO } I = 1, N \]
\[ \text{DO } J = 1, N \]
\[ + A[I, J-1] \]

\[ j = J + I \]

\[ \text{DO } I = 1, N \]
\[ \text{DO } j = I + 1, I + N \]

\[ (=, <) \]
\[ (<, <) \]
Skewing - An Example

(Cont’d)

```
DO j = 2, N+N
  DO I = max(1, j-n), min(N, j-1)
  END
END
```

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Disadvantage of Loop Skewing

- Recompute loop bounds
- Loop bounds changes
- Average vector length changes.
Unimodular Transformations

Motivation

- Easy to represent “compound” transformations
- Elegant formulation of objective functions under compound loop transformations
Beyond Unimodular Loop Transformation

- Loop Strip-Mining
- Loop Tiling
- Loop Fusion
- Loop Fission
- ...

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Advanced Topics:
Toward A Framework of Combining Loop Transformations
An Example

Subroutine nest (a, b, c)
Real*8 a(1000)
Real*8 b(1000, 1000), c(1000)
Do j = 1, 1000
   DO i = 1, 1000
      a(j) = a(j) + b(j, i) * c(j)
   END DO
END DO
end

Assume: a multi-issue architecture with resource constraints to be considered
(1) caches,
(2) registers,
(3) instruction scheduling

Question: What loop transformations to apply and in what order?
- Unimodular (e.g. permutation?)
- Loop unrolling?
- Both?
- Others?

Objective: performance? code size? energy?
Motivating Example

Motivating Example

Subroutine nest (a, b, c)
Real*8 a(1000)
Real*8 b(1000, 1000), c(1000)
Do j = 1, 1000
  DO i = 1, 1000
    a(j) = a(j) + b(j, i) * c(j)
  END DO
END DO
end

Do i = 1, 1000, 4
  DO j = 1, 1000
    a(j) = a(j) + b(j, i) * c(j)
  END DO
END DO
end

Question: Is the above a good combination?:

   Loop interchange + Outer loop unrolling +
   Inner loop fusion

Why do this? (cache effect? # of loads/stores? Reg. Alloc?)
What We Need?

- A good cost model
- A way to enumerate the space of possible loop transformation
- An intelligent way to search through the space
- Modularity of each individual transformation so to facilitate their combination
It is still a problem for open research