Tiling: A Data Locality Optimizing Algorithm

Previously

- Performance analysis of existing codes
- Data dependence analysis for detecting parallelism
- Specifying transformations using frameworks

Today

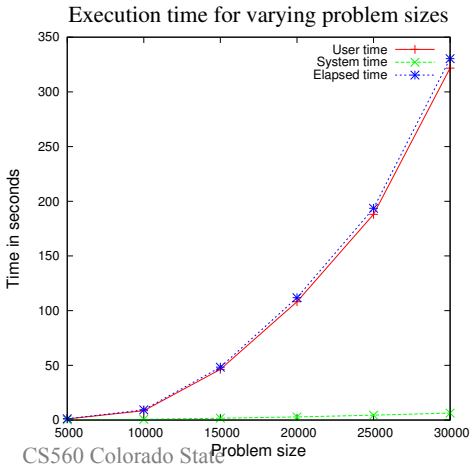
- Usefulness of the polyhedral model
- Using Pluto to automatically transform code
- "Unroll and Jam" and Tiling
- Specifying tiling in the Kelly and Pugh transformation framework
- Status of code generation for tiling

Usefulness of the Polyhedral Model

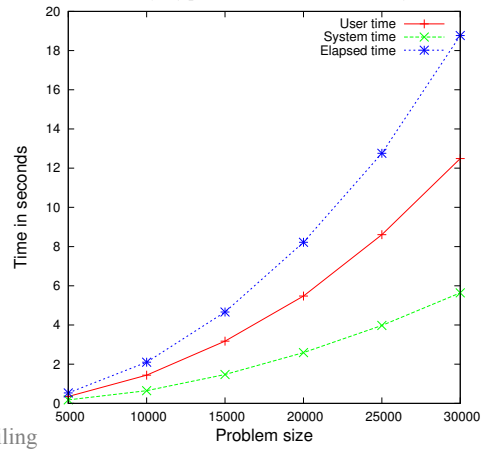
Loop transformations and parallelization can have a significant impact on performance

- Other than new algorithms, data locality and parallelization is necessary for future improvements
- Recall that loop permutation in smithWaterman.c resulted in an order of magnitude execution time difference

Execution time for varying problem sizes



Execution time for varying problem sizes after switching lines 207 and 208



Usefulness of the Polyhedral Model, cont…

Existing tools in industry that use the polyhedral model

- IBM XL/Poly
- Reservoir Labs R-Stream
- Apolent

Polyhedral model in open source and research

- Graphite GCC, au auto parallelization pass
- Pluto and Orio
- PoCC (Clan-Candl-LetSee-Pluto-Cloog-Polylib-PIPLib-ISL-FM)
- AlphaZ, POET, Chill, URUK, Omega, Loopo

Programming language abstractions that are related

- Domains in Chapel
- Regions in X10
- …

Getting Started with Pluto

Pluto has been installed on the CS linux machines

Try out some examples

- git clone git://repo.or.cz/pluto.git will create a directory called pluto
- Test and examples directory contains example input files
- polycc test/seidel.c --tile –parallel

Read some documentation

- more pluto/doc/DOC.txt
- http://pluto-compiler.sourceforge.net/

Using it on your own code

- Put in #pragma scop and #pragma endscop around the code to be transformed
- <show using polycc with the smithWaterman.c example>

Static Control Programs

Static Control Programs Definition

- Symbolic constants are variables that are not modified in the loop
- Loop bounds are affine combinations of loop variables and symbolic constants
- Array accesses are affine combinations of loop variables and symbolic constants
- If conditions are affine functions of loop variables and symbolic constants
- All function calls are pure

References

- Pluto_general_notes.txt (will post with this lecture)
- Pluto/doc/DOC.txt
- Section 2.2 of the Feautrier paper

Control over Pluto transformations (see doc/DOC.txt)

polycc infile.c

--parallel, Parallelize code with OpenMP

--tile, Tile code. Can control tile sizes with an input file in a specific format.

--maxfuse, Do the maximum amount of loop fusion

--unroll, does unroll and jam up to two loops

--prevector, make code amenable to vectorization

--debug, Intermediate files are kept so can see dependences, etc.

What is tiling?

- "Unroll and Jam" and Tiling
- Specifying tiling in the Kelly and Pugh transformation framework
- Status of code generation for tiling

Loop Unrolling

Motivation

- Reduces loop overhead
- Improves effectiveness of other transformations
  - Code scheduling
  - CSE

The Transformation

- Make n copies of the loop: n is the **unrolling factor**
- Adjust loop bounds accordingly

Loop Unrolling (cont)

Example

```
do i=1,n
   A(i) = B(i) + C(i)
enddo
```

```
do i=1,n-1 by 2
   A(i)   = B(i) + C(i)
   A(i+1) = B(i+1) + C(i+1)
enddo
 if (i=n)
    A(i) = B(i) + C(i)
```

Details

- When is loop unrolling legal?
- Handle end cases with a cloned copy of the loop
  - Enter this special case if the remaining number of iteration is less than the unrolling factor

Loop Balance

Problem

- We'd like to produce loops with the right balance of memory operations and floating point operations
- The ideal balance is machine-dependent
  - *e.g.* How many load-store units are connected to the L1 cache?
  - *e.g.* How many functional units are provided?

Example

```
do j = 1,2*n
  do i = 1,m
        A(j) = A(j) + B(i)
  enddo
enddo
```

- The inner loop has 1 memory operation per iteration and 1 floating point operation per iteration
- If our target machine can only support 1 memory operation for every two floating point operations, this loop will be memory bound

What can we do?

Unroll and Jam

Idea

- Restructure loops so that loaded values are used many times per iteration

Unroll and Jam

- Unroll the outer loop some number of times
- Fuse (Jam) the resulting inner loops

Example

```
do j = 1,2*n
   do i = 1,m
      A(j) = A(j) + B(i)
   enddo
enddo
```

Unroll the Outer Loop

```
do j = 1,2*n by 2
   do i = 1,m
      A(j)   = A(j)   + B(i)
   enddo
   do i = 1,m
      A(j+1) = A(j+1) + B(i)
   enddo
enddo
```

Unroll and Jam Example (cont)

Unroll the Outer Loop

```
do j = 1,2*n by 2
   do i = 1,m
      A(j)   = A(j)   + B(i)
   enddo
   do i = 1,m
      A(j+1) = A(j+1) + B(i)
   enddo
enddo
```

Jam the inner loops

```
do j = 1,2*n by 2
   do i = 1,m
      A(j)   = A(j)   + B(i)
      A(j+1) = A(j+1) + B(i)
   enddo
enddo
```

- The inner loop has 1 load per iteration and 2 floating point operations per iteration
- We reuse the loaded value of **B(i)**
- The Loop Balance matches the machine balance

Unroll and Jam (cont)

Legality

- When is Unroll and Jam legal?

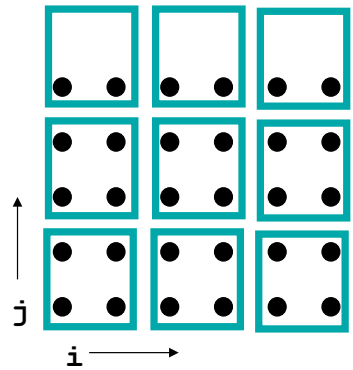
Disadvantages

- What limits the degree of unrolling?

Tiling

A non-unimodular transformation that ...

- groups iteration points into tiles that are executed atomically
- can improve spatial and temporal data locality
- can expose larger granularities of parallelism



Implementing tiling

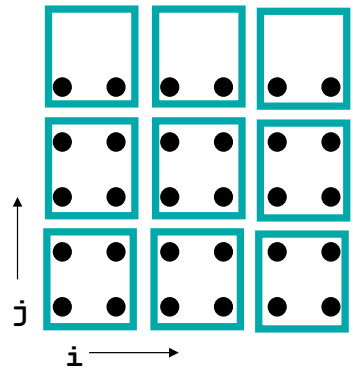
- how can we specify tiling?
- when is tiling legal?
- how do we generate tiled code?

```
do ii = 1,6, by 2
 do jj = 1, 5, by 2
  do i = ii, ii+2-1
   do j = jj, min(jj+2-1,5)
    A(i,j) = ...
```


Specifying Tiling

Rectangular tiling

- tile size vector $(s_1, s_2, \ldots, s_d)$
- tile offset, $(o_1, o_2, \ldots, o_d)$



Possible Transformation Mappings

- creating a tile space

$$\{[i,j] \rightarrow [ti,tj,i,j] \quad | \quad ti = floor((i-o_1)/s_1) \wedge tj = floor((j-o_2)/s_2)\}$$

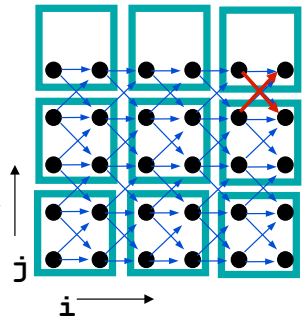
- keeping tile iterators in original iteration space

$$\{[i,j] \rightarrow [ii,jj,i,j] \quad | \quad ii = s_1 floor((i-o_1)/s_1) + o_1 \wedge jj = s_2 floor((j-o_2)/s_2) + o_2\}$$

Legality of Tiling

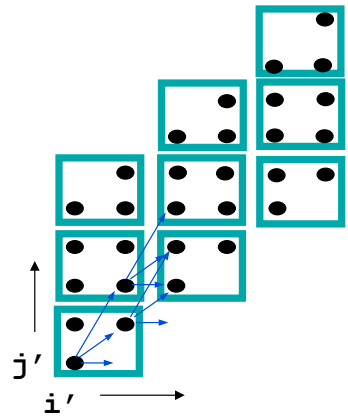
A legal rectangular tiling

- each tile executed atomically
- no dependence cycles between tiles
- Check legality by verifying that transformed data dependences are lexicographically positive



Fully permutable loops

- rectangular tiling is legal on fully permutable loops



Code Generation for Tiling

Fixed-size Tiles

- Omega library
- Cloog
- for rectangular space and tiles, straight-forward

```
do ii = 1,6, by 2
 do jj = 1, 5, by 2
  do i = ii, ii+2-1
   do j = jj, min(jj+2-1,5)
    A(i,j) = ...
```

Parameterized tile sizes

- Parameterized tiled loops for free, PLDI 2007
- HiTLOG - A Tiled Loop Generator that is part of AlphaZ

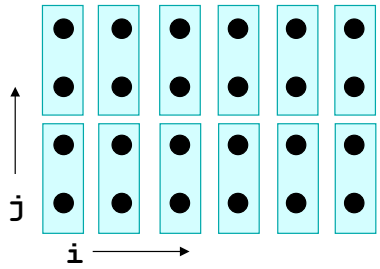
Overview of decoupled approach

- find polyhedron that may contain any loop origins
- generate code that traverses that polyhedron
- post process the code to start a tile origins and step by tile size
- generate loops over points in tile to stay within original iteration space and within tile

Unroll and Jam IS Tiling (followed by inner loop unrolling)

Original Loop

```
do j = 1,2*n
  do i = 1,m
    A(j)= A(j) + B(i)
  enddo
enddo
```



After Tiling

```
do jj = 1,2*n by 2
  do i = 1,m
    do j = jj, jj+2-1
      A(j)= A(j)+B(i)
    enddo
  enddo
enddo
```

After Unroll and Jam

```
do jj = 1,2*n by 2
  do i = 1,m
      A(j)= A(j)+B(i)
      A(j+1)= A(j+1)+B(i)
    enddo
enddo
```


Concepts

Unroll and Jam is the same as Tiling with the inner loop unrolled

Tiling can improve ...

- loop balance
- spatial locality
- data locality
- computation to communication ratio

Implementing tiling

- specification
- checking legality
- code generation

Next Time

Lecture

- Review of transformations covered so far
- Run-time reordering transformations

Schedule

- Project intermediate report due March 28th
- April 3rd will be a lab day during class, Manaf will help people with AlphaZ and Pluto. Distance students can email questions or use the discussion board.
- HW6 and HW7 will BOTH be due April 4th