RUTGERS
THE STATE UNIVERSITY OF NEW JERSEY

CS 516 Compilers and Programming Languages II

Parallel Computing-2

Review - Task-Centric Concurrency

Goal of parallelization / concurrent execution

Starting point: A sequential application

Goal: Identify "independent pieces of work" that can be executed concurrently without changing the semantics of the application, i.e., do not change application input/output behavior (safety of parallelization).

performance impact → reduction in the length of the critical path

Outcome: A (partially) parallelized application where parts of an application are identified as executable in parallel. Examples: An application may contain parallel regions, parallel loops, fork-join, VLIW, …

Key Challenge: How to decide whether parallel executions of parts of the application are safe? → notion of **data and control dependence**

Review - Dependence Overview

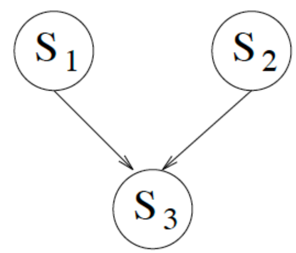
Dependence relation: Describes all program regions (e.g.: statements) execution orderings for a sequential program that must be preserved if the meaning of the program is to remain the same.

There are two sources of dependences, data and control dependencies:

Example:
(statement level)

data dependence

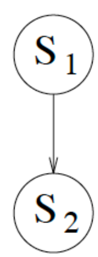
S_1 `pi = 3.14`
S_2 `r = 5.0`
S_3 `area = pi * r**2`



S_3 cannot be executed before S_1 or S_2

control dependence

S_1 `if (t .ne.  0.0) then`
S_2 `    a = a/t`
`endif`



S_2 cannot be executed before S_1

Review - Basic Dependence Theorem

Theorem

Any reordering transformation that preserves every dependence (i.e., visits first the source, and then the sink of the dependence) in a program preserves the meaning of that program.

Note:

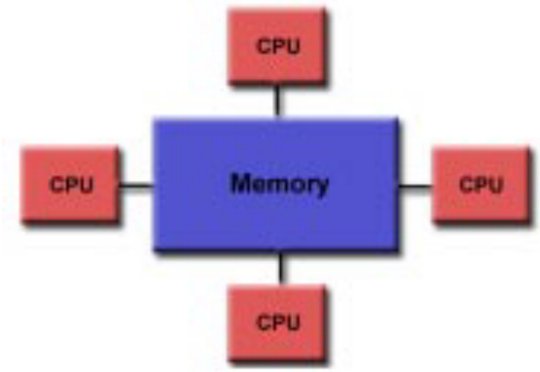
(1) Dependence starts with the notion of a sequential execution, i.e., starts with a sequential program.

(2) Control dependencies can be converted to data dependencies. From now on, we only look at data dependencies,

Loop / Statement-level Dependencies

We will concentrate on compilation issues for compiling scientific codes on shared-memory parallel/vector architectures. Some of the basic ideas can be applied to other application domains as well. Typically, scientific codes

- Use arrays as their main data structures.
- Have loops that contain most of the computation in the program.



As a result, advanced optimizing transformations concentrate on loop level optimizations. Most loop level optimizations are source-to-source, i.e., reshape loops at the source level.

We will talk about

- Dependence analysis
- Automatic vectorization
- Automatic parallelization
- Heterogenous parallel architectures

```
#pragma omp parallel for private(i, hash)
    for (j = 0; j < num_hf; j++) {
        for (i = 0; i < wl_size; i++) {
            hash = hf[j] (get_word(wl, i));
            hash %= bv_size;
            bv[hash] = 1;
        }
    }
```

Review - Statement-level Dependencies

Definition

There is a data dependence from statement S_1 to statement S_2 (S_2 depends on S_1) if:

1. Both statements access the same memory location and at least one of them stores/writes into it, and
2. There is a feasible run-time execution path from S_1 to S_2

Data dependence classification: "S2 depends on S1" — $S_1 \delta S_2$

true (flow) dependence (RAW hazard)

S_1 writes a memory location that S_2 later reads

anti dependence (WAR hazard)

S_1 reads a memory location that S_2 later writes

output dependence (WAW hazard)

S_1 writes a memory location that S_2 later writes

input dependence

S_1 reads a memory location that S_2 later reads.

Note: Input dependences do not restrict statement (load/store) order!

Dependence: Identify Concurrent Loops

We restrict our discussion to data dependence for scalar and subscripted variables (no pointers and no control dependence).

Sequential source code

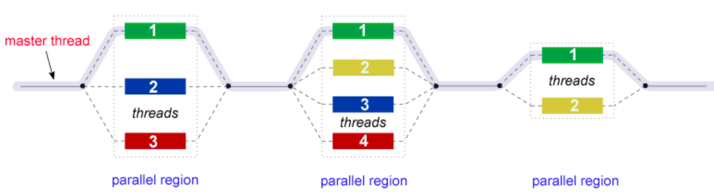
```
do I = 1, 100
  do J = 1, 100
    A(I,J) = A(I,J) + 1
  enddo
enddo
```

```
do I = 1, 99
   do J = 1, 100
      A(I,J) = A(I+1,J) + 1
   enddo
enddo
```

vectorization


```
A(1:100:1,1:100:1) = A(1:100:1,1:100:1) + 1
A(1:99,1:100) = A(2:100,1:100) + 1
```

parallelization




```
doall I = 1, 100
  doall J = 1, 100
    A(I,J) = A(I,J) + 1
  enddo
  implicit barrier sync.
enddo
implicit barrier sync.
```

```
do I = 1, 99
   doall J = 1, 100
      A(I,J) = A(I+1,J) + 1
   enddo
   implicit barrier sync.
enddo
```

Vectorization vs. Parallelization

vectorization - Find parallelism in innermost loops;
fine-grain parallelism

parallelization - Find parallelism in outermost loops;
coarse-grain parallelism

Parallelization is considered more complex than vectorization, since finding coarse-grain parallelism requires more analysis (e.g., interprocedural analysis).

Automatic vectorizers have been very successful

Dependence Analysis

Question

Do two variable references never/maybe/always access the same memory location?

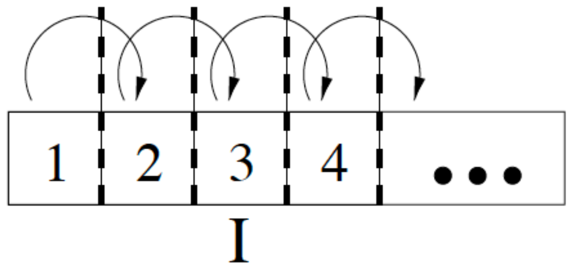
Benefits
- improves alias analysis
- enables loop transformations

Motivation
- classic optimizations
- instruction scheduling
- data locality (register/cache reuse)
- vectorization, parallelization

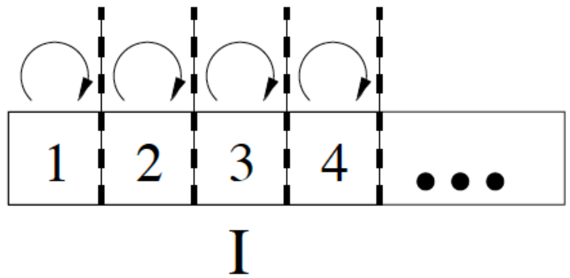
Obstacles
- array references
- pointer references

Dependence Analysis for Arrays

```
do I = 1, 100
   A(I) =
      = A(I-1)
enddo
```




```
do I = 1, 100
   A(I) =
      = A(I)
enddo
```



"I" is the iteration space

A loop-independent dependence exists regardless of the loop structure. The source and sink of the dependence occur on the same loop iteration.

A loop-carried dependence is induced by the iterations of a loop. The source and sink of the dependence occur on different loop iterations.

Loop-carried dependences can inhibit parallelization; together with loop-independent dependencies they can limit possible transformations

Things to Do / Next Class

Homework #2 extension until Tuesday, March 3

Next class

- Iteration space
- Distance and direction vectors
- Valid transformations
- Automatic vectorization