CSc 553

Principles of Compilation

37 : Parallelizing Compilers II

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An Example (a)

```
FOR i := 2 TO 7 DO
   a[i] := a[i]+c; b[i] := a[i-1]*b[i];
```

i	Time	Statement
2	①	a[2]:=a[2]+c
	②	b[2]:=a[1]*b[2]
3	③	a[3]:=a[3]+c
	④	b[3]:=a[2]*b[3]
4	⑤	a[4]:=a[4]+c
	⑥	b[4]:=a[3]*b[4]
5	⑦	a[5]:=a[5]+c
	⑧	b[5]:=a[4]*b[5]
6	⑨	a[6]:=a[6]+c
	Ⓐ	b[6]:=a[5]*b[6]
7	Ⓑ	a[7]:=a[7]+c
	Ⓒ	b[7]:=a[6]*b[7]

An Example (b)

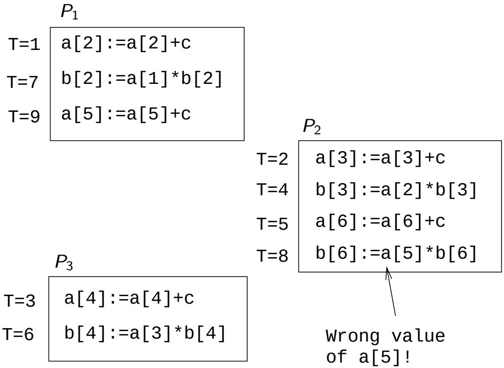
- Schedule the iterations of the following loop onto three CPUs (P_1, P_2, P_3) using cyclic scheduling.

```
FOR i := 2 TO 7 DO
   S1:   a[i] := a[i] + c;
   S2:   b[i] := a[i-1]*b[i];
ENDFOR
```

CPU	i	S_1	S_2
P_1	2	a[2]:=a[2]+c	b[2]:=a[1]*b[2]
	5	a[5]:=a[5]+c	b[5]:=a[4]*b[5]
P_2	3	a[3]:=a[3]+c	b[3]:=a[2]*b[3]
	6	a[6]:=a[6]+c	b[6]:=a[5]*b[6]
P_3	4	a[4]:=a[4]+c	b[4]:=a[3]*b[4]
	7	a[7]:=a[7]+c	b[7]:=a[6]*b[7]

An Example (c)

- The three CPUs run asynchronously at different speeds. So, when P_2 is executing `b[6]:=a[5]*b[6]` at time `T=8`, P_1 has yet to execute `a[5]:=a[5]+c`.
- Hence, P_2 will be using the old (wrong) value of `a[5]`.



An Example (d)

- Statement $\boxed{i/S_1:\ \texttt{a[i]:=a[i]+c}}$ must run before statement $\boxed{i+1/S_2:\ \texttt{b[i]:=a[i-1]*b[i]}}$ in the next iteration.

1	2
$i=2/S_1$: `a[2]:=a[2]+c`	$i=2/S_2$: `b[2]:=a[1]*b[2]`
3	4
$i=3/S_1$: `a[3]:=a[3]+c`	$i=3/S_2$: `b[3]:=a[2]*b[3]`
5	6
$i=4/S_1$: `a[4]:=a[4]+c`	$i=4/S_2$: `b[4]:=a[3]*b[4]`
7	8
$i=5/S_1$: `a[5]:=a[5]+c`	$i=5/S_2$: `b[5]:=a[4]*b[5]`
9	A
$i=6/S_1$: `a[6]:=a[6]+c`	$i=6/S_2$: `b[6]:=a[5]*b[6]`
B	C
$i=7/S_1$: `a[7]:=a[7]+c`	$i=7/S_2$: `b[7]:=a[6]*b[7]`

Parallelizing Options I

- Approaches to fixing the problem:
  1. Give up, and run the loop serially on one CPU.
  2. Rewrite the loop to make it parallelizable.
  3. Insert synchronization primitives.

Give up

- We should notify the programmer why the loop could not be parallelized, so maybe he/she can rewrite it him/herself.

Rewrite the loop

```
FOR i := 2 TO 7 DO
   S1:    a[i] := a[i] + c;
ENDFOR;
FOR i := 2 TO 7 DO
   S2:    b[i] := a[i-1]*b[i];
ENDFOR
```

Parallelizing Options II

Synchronize w/ Event Counters

```
VAR ev :  EventCounter;
FOR i := 2 TO 7 DO
    S1:   a[i] := a[i] + c;
          advance(ev); await(ev, i-1)
    S2:   b[i] := a[i-1]*b[i];
ENDFOR
```

- `await/advance` implements an **ordered critical section**, a region of code that the Workers must enter in some particular order.
- `await/advance` are implemented by means of an **event counter**, an integer protected by a lock.
- `await(ev, i)` sleeps until the event counter reaches `i`.
- `advance(ev)` increments the counter.

Parallelizing Options III

Synchronize w/ Vectors

```
VAR ev :  SynchronizationVector;
FOR i := 2 TO 7 DO
   S1:   a[i] := a[i] + c;
         ev[i] := 1;
         IF i > 2 THEN
            wait(ev[i-1])
         ENDIF;
   S2:   b[i] := a[i-1]*b[i];
ENDFOR
```

- ev is a vector of bits, one per iteration. It is protected by a lock and initialized to all 0's.
- `wait(ev[i])` will sleep the process until `ev[i]=1`.
- Initialization of the vector can be expensive.

What does a real compiler do?

pca's Choices I (a)

- Let's see how $\boxed{\texttt{pca}}$ treats this loop.
- `pca -unroll=1 -cmp -lo=cklnps -list=l.l l.c`

C Program in `l.c`

```
int i,n; double a[10000], b[10000];
main () {
   for(i=2; i<=n; i++) {
      a[i] = a[i] + 100.0;
      b[i] = a[i-1]*b[i]; }}
```

Listing in `l.l`

```
for i
    Original loop split into sub-loops
    1. Concurrent
    2. Concurrent
         1 loops concurrentized
```

pca's Choices I (b)

Parallelized program in `l.m`

```
int main( ) {
   int K1, K3;
   K3 = ((n - 1)>(0) ?  (n - 1) :  (0));
#pragma parallel if(n > 51) byvalue(n)
             shared(a, b) local(K1) {
#pragma pfor iterate(K1=2;n-1;1)
      for ( K1 = 2; K1<=n; K1++ )
         a[K1] = a[K1] + 100.e0;
#pragma synchronize
#pragma pfor iterate(K1=2;n-1;1)
      for ( K1 = 2; K1<=n; K1++ )
         b[K1] = a[K1-1] * b[K1];
   }
   i = K3 + 2;
}
```

pca's Choices II (a)

- Let's try a slightly different loop....

C Program in d.c

```
for(i=2; i<=n; i++) {
   a[i] = a[i+1] + 100.0;
   b[i] = a[i-1]*b[i];
}
```

Listing in d.l

```
for i
    Original loop split into sub-loops
    1. Scalar
         Data dependence involving this
         line due to variable "a"
    2. Concurrent
         1 loops concurrentized
```

pca's Choices II (b)

Parallelized program in `d.m`

```
for ( K1 = 2; K1<=n; K1++ )
   a[K1] = a[K1+1] + 100.0;
#pragma parallel if(n > 102) byvalue(n)
         shared(a, b) local(K1)
{
#pragma pfor iterate(K1=2;n-1;1)
   for ( K1 = 2; K1<=n; K1++ )
      b[K1] = a[K1-1] * b[K1];
}
```

- This time pca
  1. split the loop in two subloops (like before),
  2. parallelized the second subloop, and
  3. gave up on the first subloop, executing it serially.

Concurrentization

Concurrentization

- A loop can be concurrentized iff all its data dependence directions are $=$.
- In other words, a loop can be concurrentized iff it has no loop carried data dependences.
- The I-loop below cannot be directly concurrentized. The loop dependences are $S_1\ \delta_{=,<}\ S_1$, $S_1\ \delta_{=,=}\ S_2$, $S_2\ \overline{\delta}_{<,=}\ S_3$. Hence, the I-loop's dependence directions are $(=,=,<)$.

```
FOR I := 1 TO N DO
   FOR J := 2 TO N DO
      S1:   A[I,J] := A[I,J-1] + B[I,J];
      S2:   C[I,J] := A[I,J] + D[I+1,J];
      S3:   D[I,J] := 0.1;
   ENDFOR
ENDFOR
```

Exam I (415.730/96)

```
     FOR i := 1 TO n DO
        FOR j := 1 TO n DO
S1:        A[i,j] := A[i,j-1] + C;
        END;
     END;
```

1. Which of the dependencies are **loop**-carried?
2. Which of the loops can be directly concurrentized (i.e., run in parallel without any loop transformations or extra synchronization)? Motivate your answer!
3. What is the difference between a pre-scheduled and a self-scheduled loop? Under what circumstances should we prefer one over the other?

Readings and References

- Padua & Wolfe, *Advanced Compiler Optimizations for Supercomputers*, CACM, Dec 1996, Vol 29, No 12, pp. 1184–1187.

Summary I

- Dependence analysis is an important part of any parallelizing compiler. In general, it's a very difficult problem, but, fortunately, most programs have very simple index expressions that can be easily analyzed.
- Most compilers will try to do a good job on **common** loops, rather than a half-hearted job on all loops.

Summary II

- When faced with a loop

  ```
  FOR i := From TO To DO
      S1:    A[f(i)] := ···
      S2:    ··· := A[g(i)]
  ENDFOR
  ```

  the compiler will try to determine if there are any index values I, J for which $f(I) = g(J)$. A number of cases can occur:

  1. The compiler decides that $f(i)$ and $g(i)$ are too complicated to analyze. $\Rightarrow$ Run the loop serially.
  2. The compiler decides that $f(i)$ and $g(i)$ are very simple (e.g. `f(i)=i, f(i)=c*i, f(i)=i+c, f(i)=c*i+d`), and does the analysis using some built-in pattern matching rules. $\Rightarrow$ Run the loop in parallel or serially, depending on the outcome.