Parallelizing Compilers

Scientists/engineers want to speed up old FORTRAN programs by running them on multiprocessors. They don’t want to rewrite the code to make explicit use of the available parallelism.

Instead, they use Parallelizing/Concurrentizing/Vectorizing compilers that convert sequential programs to parallel form.
3 Parallelizing Compilers II

- Concurrentizing compilers convert sequential programs to run on a shared memory multiprocessor. The resulting code uses a Master/Slave paradigm. The Master process executes sequential code (not all code can be parallelized), and starts up slave processors to execute (parts of) loops.

4 Typical Concurrent Execution
5 Concurrentizing Compilers I

Sequential Program | After parallelization
--- | ---
if x < 5 then y := 17 for i := 1 to 100 do A[i] := i*2 end x := 15 | # pragma sequential if x < 5 then y := 17 # pragma parallel for-loop for i := 1 to 100 do A[i] := i*2 end # pragma sequential x := 15

6 Concurrentizing Compilers II

begin CreateSlaves(10); (* Slaves are now idle. *) if x < 5 then y := 17 for i := 1 to 10 do StartSlave(i, ForBody, (i - 1) * 10 + 1, i * 10) end WaitForSlaves(); (* Slaves are idle again. *) x := 15; end

PROCEDURE ForBody(From, To : INTEGER); for i := From to To do A[i] := i*2 end END ForBody;

7 Concurrentizing Compilers III

• While the slaves are working, the Master is idle. This is of course wasteful, so normally the Master would schedule one set of iterations to itself.

• The Master could create a new set of processes before each loop and then kill them off after the loop is finished. On many systems this would be expensive. Instead the Master starts the program by creating a set of processes and then "parks" them (i.e. puts them to sleep). When a parallel region is encountered, the Master wakes up the Slaves and hands them their workload.

• In the example, every Slave manipulates its own sub-array independently of the other processors. There are no cache conflicts. Often not this easy.

8 Prescheduled Loops I

• Here’s a more detailed description of a prescheduled loop. A loop is prescheduled if each Slave is given enough information when it is awakened to execute all of its iterations of the loop.
WorkingSlaves := NoOfSlaves + 1;
(* The Master also works. *)
InitMonitor(Lock);
ContinueAddress := LabelAfterLoop;
FOR i := 1 to NoOfSlaves DO
    From := · · ·; To := · · ·;
    StartSlave(i, ForBody, From, To);
END
ForBody(NoOfSlaves+1, · · ·);
LabelAfterLoop:
(* Master continues here. *)

9 Prescheduled Loops II (a)

PROCEDURE ForBody (From, To : int);
    FOR i := From to To DO
        A[i] := 2 * i;
    END;
EnterMonitor(Lock);
    WorkingSlaves := WorkingSlaves - 1;
    IF WorkingsSlaves > 0 THEN
        ExitMonitor(Lock);
        WAIT;
    END;
EnterMonitor(Lock);
goto ContinueAddress;
END

10 Prescheduled Loops II (b)

• Note: This is pseudo-code. The actual implementation would obviously depend on what kind of support for thread creation & synchronization provided by the particular system.
11 Prescheduled Loops III

<table>
<thead>
<tr>
<th>CPU1 (Master)</th>
<th>CPU2 (Slave 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>if ...</td>
<td>for i:=1 to 10 do</td>
</tr>
<tr>
<td>for i:=1 to 10 do</td>
<td>A[i] := i*2</td>
</tr>
<tr>
<td>StartSlave(i)</td>
<td>end</td>
</tr>
<tr>
<td>wait</td>
<td>end</td>
</tr>
<tr>
<td>x := 1</td>
<td>sleep();</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Memory Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Memory</th>
</tr>
</thead>
<tbody>
<tr>
<td>A[1],A[2],...</td>
</tr>
<tr>
<td>A[99],A[100]</td>
</tr>
</tbody>
</table>

12 Prescheduled Loops IV

- Block-scheduled loops assign the same number of iterations to each processor. This is OK if all iterations perform the same amount of work.

- Consider this loop:

```plaintext
FOR i := 1 TO 1000 DO
    IF i > 500 THEN
        X := X + 1;
    ELSE
        FOR j := 1 to 100000 DO  ...  END;
        END;
    END;
END
```

If this loop was parallelized using block-scheduling, then some processors would be given a lot of work to do, others little. Hence, some processors will finish early, and won’t contribute much to the processing.

13 Prescheduled Loops V

- **cyclic scheduling** is a variant of **block-scheduling** (which is what we’ve done so far).

- If we have \( N \) iterations to assign to \( P \) processes, block scheduling would assign \( \lceil \frac{N}{P} \rceil \) consecutive iterations to each processor. I.e., process 1 would get iterations 1·\( \lceil \frac{N}{P} \rceil \) – 1, process 2 iterations \( \lceil \frac{N}{P} \rceil \)·2·\( \lceil \frac{N}{P} \rceil \), etc.

- Cyclic scheduling would instead assign every \( P \)th iteration to each processor.
$P = 4$ processors $P_1 \cdots P_4$, $N = 12$ iterations

<table>
<thead>
<tr>
<th>Block Scheduling</th>
<th>Cyclic Scheduling</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_1$</td>
<td>$P_2$</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
</tr>
</tbody>
</table>

14 Self-Scheduled Loops I

- Prescheduled loops are static, i.e. the scheduling is decided at compile-time.
- Self-scheduled loops are dynamic, they assign workloads to processors at runtime. A dynamic scheduler assigns small amounts of work to each processor. When a processor finishes its task, it goes back to the scheduler and asks for more work.
- Problems:
  - There is overhead in the dynamic scheduler.
  - Should the scheduler hand out big chunks of work ($\Rightarrow$ less scheduling overhead; higher risk of load imbalance) or small chunks, e.g. single iterations ($\Rightarrow$ higher scheduling overhead; better load balance)?

15 Self-Scheduled Loops II

- In this example of a self-scheduled loop, there are $N$ iterations to be scheduled. $\text{CurrentIteration}$ holds the next iteration to be scheduled. Each Slaves tries to get work for itself, until all loops have been executed.

```plaintext
WorkingSlaves := NoOfSlaves + 1;
(* The Master also works. *)
CurrentIteration := 1;
LastIteration := N;
ContinueAddress := LabelAfterLoop;
FOR i := 1 to NoOfSlaves DO
    StartSlave(i, ForBody);
END
ForBody();
LabelAfterLoop:
(* Master continues here. *)
```

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```plaintext
PROCEDURE ForBody()
    LOOP
        EnterMonitor(Lock);
        i := CurrentIteration;
        IF i > LastIteration THEN EXIT;
        CurrentIteration ++;
        ExitMonitor(Lock);
        A[i] := 2 * i;
    ENDLOOP;
```
WorkingSlaves := WorkingSlaves - 1;
IF WorkingsSlave > 0 THEN
    ExitMonitor(Lock);
    WAIT;
END;
ExitMonitor(Lock);
goto ContinueAddress;
END

17 Self-Scheduled Loops IV

• **Chunk Scheduling** removes some overhead of single-iteration scheduling:

```pascal
CurrentIteration:=1; LastIteration:=N; ChunkSize:=10;
(* same as before *)
PROCEDURE ForBody ();
LOOP
    EnterMonitor(Lock);
    i := CurrentIteration;
    IF i > LastIteration THEN EXIT;
    CurrentIteration += ChunkSize;
    ExitMonitor(Lock);
    FOR k := i TO i + ChunkSize DO
        A[k] := 2 * k; ENDFOR;
    ENDLOOP;
(* same as before *)
END
```

18 Self-Scheduled Loops V

• The problem with **chunk scheduling** is that one Slave my wind up with a more expensive chunk than the others.

• **Guided Self-Scheduling** tries to alleviate this through **tapering**: the chunk-sizes get smaller towards the end of the loop. Specifically, the chunk-size is \( \frac{\text{remaining iterations}}{2 \times \# \text{ of processors}} \).

```pascal
RemainingIters := N;
PROCEDURE ForBody ();
LOOP i := CurrentIteration;
    ChunkSize := RemainingIters/(2*WorkingSlaves);
    RemainingIters -= ChunkSize;
    IF i > LastIteration THEN EXIT;
    CurrentIteration += ChunkSize;
    FOR k := i TO i + ChunkSize DO
        A[k] := 2 * k; ENDFOR;
    ENDLOOP;
```

19 Self-Scheduled Loops VI

• One problem with guided self-scheduling is the overhead of the scheduling operations themselves.
- **Factored Scheduling** computes the size of a batch of chunks. Each batch is a fraction $\frac{1}{F}$ of the remaining work. Each chunk is $\frac{1}{\# \text{ of processors}}$ of that batch.

- **Simple Factoring** sets $F = 2$.

```plaintext
RemainingIters := N;
...
ChunkSize := RemainingIters/(WorkingSlaves * F);
RemainingIters := RemainingIters -
    WorkingSlaves * ChunkSize;
```

20 **Self-Scheduled Loops VII**

- Compare block scheduling, chunk self-scheduling, guided self-scheduling, and factoring when scheduling 100 iterations on 4 processors. Use chunk-size=10 and $F = 2$.

<table>
<thead>
<tr>
<th>block</th>
<th>25 25 25 25</th>
</tr>
</thead>
<tbody>
<tr>
<td>chunk</td>
<td>10 10 10 10</td>
</tr>
<tr>
<td>guided</td>
<td>13 11 10 10</td>
</tr>
<tr>
<td>factor</td>
<td>13 13 13 13</td>
</tr>
</tbody>
</table>

- Note that guided self-scheduling has 23 scheduling operations, factoring only 5 (since it schedules 4 chunks at a time).

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A Parallelizing Compiler

22 **A Parallelizing Compiler I**

- SGI’s IRIX Power C parallelizing compiler consists of two programs. pca inserts parallel directives into the sequential C program. mpc converts this program into parallel form. cc compiles the resulting program.
24 A Parallelizing Compiler II

- `#/usr/lib/cpp mm.c > mm1.c; /usr/lib/pca -unroll=1 -cmp -list mm1.c`

```c
#define N 600
double A[N][N], B[N][N], C[N][N];
main () {
    long i, j, k;
    for(i=1; i<=N; i++) {
        for(j=1; j<=N; j++) {
            A[i][j] = 0.0;
            for(k=1; k<=N; k++)
        }
    }
}
```

```c
double A[600][600], B[600][600], C[600][600];
main () {
    long i, j, k;
    #pragma parallel shared(A, B, C)
    local(i, j, _Kdd1, k)
    {
        #pragma pfor iterate(i=1;600;1)
        for (i = 1; i <= 600; i++)
            for (j = 1; j <= 600; j++)
                A[i][j] = 0.0;
        #pragma synchronize
        #pragma pfor iterate(i=1;600;1)
        for (i = 1; i <= 600; i++)
```
for ( k = 1; k<=600; k++ ) {
    Kdd1 = B[i][k];
    for ( j = 1; j<=600; j++ )
}
}

26 A Parallelizing Compiler IV

- pca analyzes the C-code and inserts #pragmas which are then used by mpc.
- #pragma parallel starts a parallel region. #pragma pFor starts a parallel for loop. #pragma synchronize is a classic barrier construct.
- The next slide shows the explanation produced by the compiler.

27 A Parallelizing Compiler IV

for i
    Line:8 Unrolling of this loop was not done because size is ok as is.
    Original loop split into sub-loops
    1. Concurrent
    2. Concurrent
for j
    Original loop split into sub-loops
    1. Scalar Already in a parallel loop.
    2. Scalar Already in a parallel loop.
for k
    1. Scalar Already in a parallel loop.
Optimization Summary
    1 loops concurrentized
    2 preferred scalar mode

28 Summary

29 Summary I

- Read:
- A concurrentizing compiler should
  1. find loops that can be parallelized,
  2. reorganize remaining loops so that they can also be parallelized,
3. devise the best scheduling policy for each loop. We’ve seen

**static (pre) scheduling:** block, cyclic

**dynamic (self) scheduling:** single iteration, chunk, guided, factoring,

4. explain to the user why some loops could not be parallelized.

### 30 Summary II

- Static scheduling works well when the cost of each iteration can be determined at compile time. This is true of most scientific codes since these typically perform simple arithmetic on each element of an array.

- Dynamic scheduling handles loops where the cost of each iteration can’t be determined at compile time. Usually this is because the loop contains an IF-statement or a function call.

- Most concurrentizing compilers only parallelize *outermost* loops.

### 31 Summary III

- Compilers for parallel vector machines (such as the Cray J916) will concurrentize outer loops and vectorize inner loops. In the loop-nest below, for example, the $j$ loop would be converted to vector operations, and the $i$ loop would be scheduled over the available processors:

```
FOR i := 1 TO 1000 DO
  FOR j := 1 TO 64 DO
```

### 32 Homework

### 33 Homework I

- Compare block scheduling, chunk self-scheduling, guided self-scheduling, and factoring when scheduling 120 iterations on 6 processors. Use chunk-size=12 and $F = 2$.

<table>
<thead>
<tr>
<th>Schedule Type</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>block</td>
<td></td>
</tr>
<tr>
<td>chunk</td>
<td></td>
</tr>
<tr>
<td>guided</td>
<td></td>
</tr>
<tr>
<td>factor</td>
<td></td>
</tr>
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</table>