Array privatization in IBM static compilers

-- technical report

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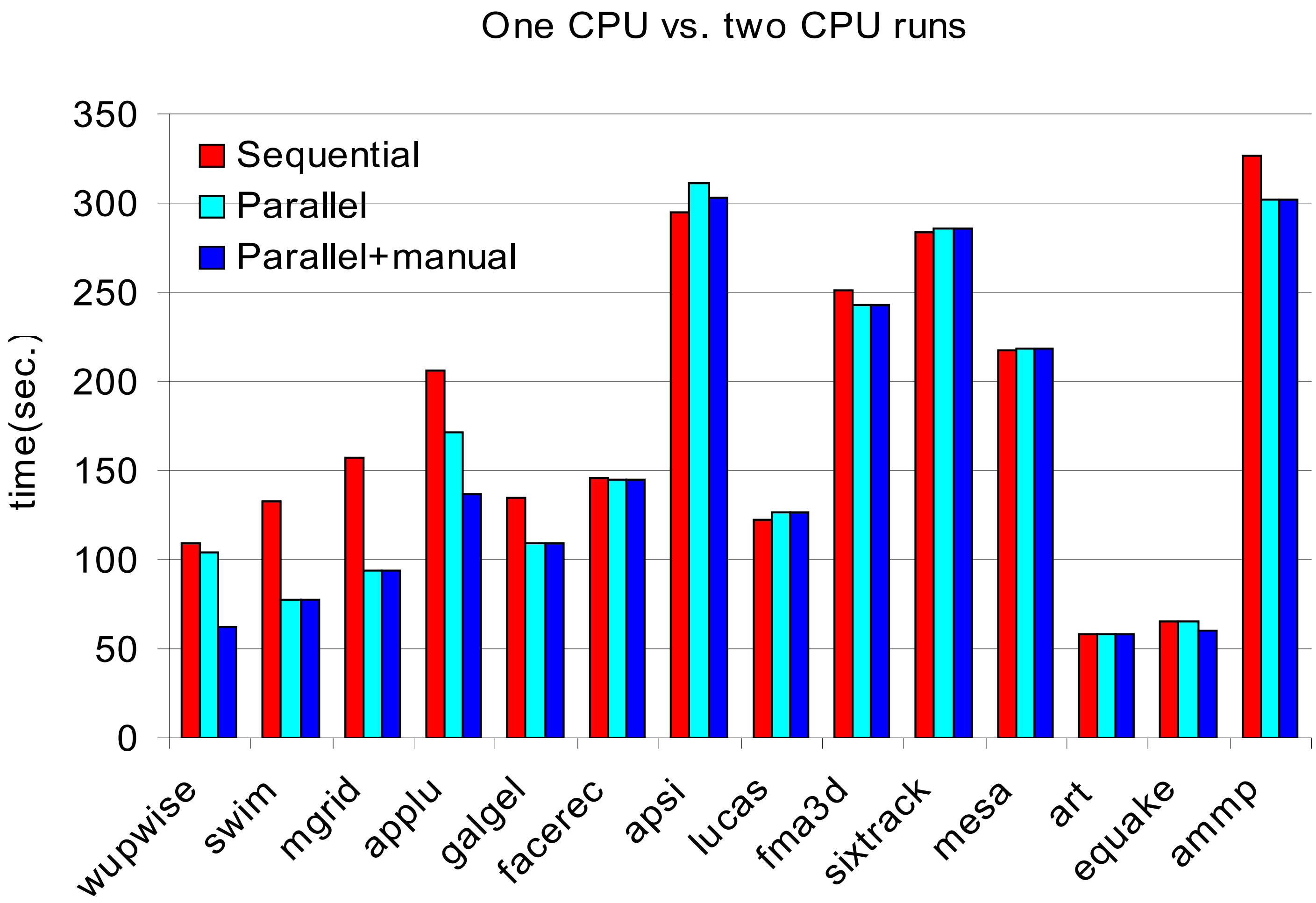
Overview

- Introduction and motivation
- Array data flow analysis
- Array data privatization
- Performance results
- Future work
- Possible usage

Expose limitations

- Compare SPEC2000FP and SPECOMP
- SPECOMP achieves good performance and scalability
  - Compare between explicit and auto-parallelization
- Expose missed opportunities
- 10 common benchmarks
  - Compare on a loop-to-loop basis

Improved auto-parallelization performance



Array privatization example

```
      a = 5

      do 40 j = 1, n

        do 20 i = 2, m
          a(i) = b(i) + c(i)
20      continue

        do 30 i = 2, m
          a(i) = a(i-1) + 4
30      continue

40    continue

      print *, a(2:m)
```

Basic loop parallelizer

```
begin
  for each loop nest in a procedure do
    for each loop in the nest in the depthfirst order (outer first) do
      if the loop is user parallel then
        break
      if the loop is marked sequential, has side-effects etc then
        continue
      if the loop has loop carried dependence then
        try splitting the loop to eliminate dependence
        if dependence not eliminated then
          continue
      if loop cost is known at compile time then
        if  the loop has not enough cost  then
          break
      else
        Insert code for run-time cost estimate
      Mark this loop auto parallel
      break
end
```

Pre-parallelization Phase

- Induction variable identification
- Scalar Privatization --- only scalar !
- Reduction finding
- Loop transformations favoring parallelism

The concept of data privatization

- Data is local to each loop iteration

```
Do I = 1, 10
  Temp = ...

  ... = … Temp …

   ... = … Temp …
Enddo
```

- Purpose: eliminating loop carried dependences.

The concept of data privatization (cont.)

- Array as temp data

```
do J = 1, 10
   do I = 1, 10
      Temp(I) = ...
    end do
    do I = 1, 10
        ... = … Temp (I) …
    enddo
enddo
```

Array data flow and its structure

- Similar to data flow
  - MayDef: array elements that may be written.
  - MustDef: array elements that are definitely written.
  - UpExpUse: array elements that may have an upward exposed use
    - a use not preceded by a definition along a path from the loop header
  - LiveOnExit: array elements that are used after the loop region.
- GARs: *Guarded Array Regions (GARs)*.
  - A GAR is a tuple(G,D),
    - D is a bounded *Regular Section Descriptor (RSD)* for the accessed array section,
    - G is a guard that specifies the condition under which D is accessed
- Notes: many papers discussed the issue

Array privatization algorithm

```
for each array A in the loop do
    for each GAR of A in the MayDef do
        if (GAR in all iterations intersects the UpExpUse of A) then
            Give up privatizing A
        else
            if (GAR intersects the LiveOnExit of A) then
                if (MustDef of A contains MayDef of A in all iterations) then
                    Mark GAR in MayDef as private
                    Mark GAR in MustDef as last private
                else
                    if (MustDef of A contains LiveOnExit of A) then
                        Mark GAR in MayDef as private
                        Mark GAR in LiveOnExit as last private
            else
                Mark GAR in MayDef as private
            if (UpExpUse of A exist) then
                Mark GAR in UpExpUse as first private
```

Loop normalization and array data flow

- Normalized loop

```
    if (gard-expression) goto gard_label
    prelog ...
      init induction variable to lower bound
loop_lable:
    loop body ...
      computation based on induction variable
    latch ...
      increase induction variable
      if (induction variable < upper bound)
         goto loop_lable
     epilog ...
       restore values if needed
gard_lable:
     outside the loop
```

Alias analysis and array data flow

- Ideal situation: no alias at all.
  - Other wise, you can not tell what is the precise intersection of the two array section involved
- Alias coming from:
  - Structural members, e.g. scalar replacement
  - Function parameters,
    - array is a shadow (not mapped data, alias to any global array)
- Procedure summary may help
  - Alias as fall back

Possible parallelization results

```
      a = 5

!$omp parallel do private a
!$omp firstprivate a, lastprivate a

      do 40 j = 1, n

        do 20 i = 2, m
          a(i) = b(i) + c(i)
20      continue

        do 30 i = 2, m
          a(i) = a(i-1) + 4
30      continue

40    continue

      print *, a(2:m)
```

Real case

```
 do i3=2,n3-1   ! This Loop cannot be automatically parallelized.
                ! A dependency is carried by variable "u1".
                ! U1 and U2 are local temporary variables, so that
                ! the loop should be parallelized
    do i2=2,n2-1
       do i1=1,n1       ! Loop is parallelized
          u1(i1) = u(i1,i2-1,i3) + u(i1,i2+1,i3)
>                + u(i1,i2,i3-1) + u(i1,i2,i3+1)
          u2(i1) = u(i1,i2-1,i3-1) + u(i1,i2+1,i3-1)
>                + u(i1,i2-1,i3+1) + u(i1,i2+1,i3+1)
       enddo
       do i1=2,n1-1     ! Loop is parallelized
          r(i1,i2,i3) = v(i1,i2,i3)
>                     - a(0) * u(i1,i2,i3)
>                     - a(2) * ( u2(i1) + u1(i1-1) + u1(i1+1) )
>                     - a(3) * ( u2(i1-1) + u2(i1+1) )
       enddo
    enddo
 enddo
```

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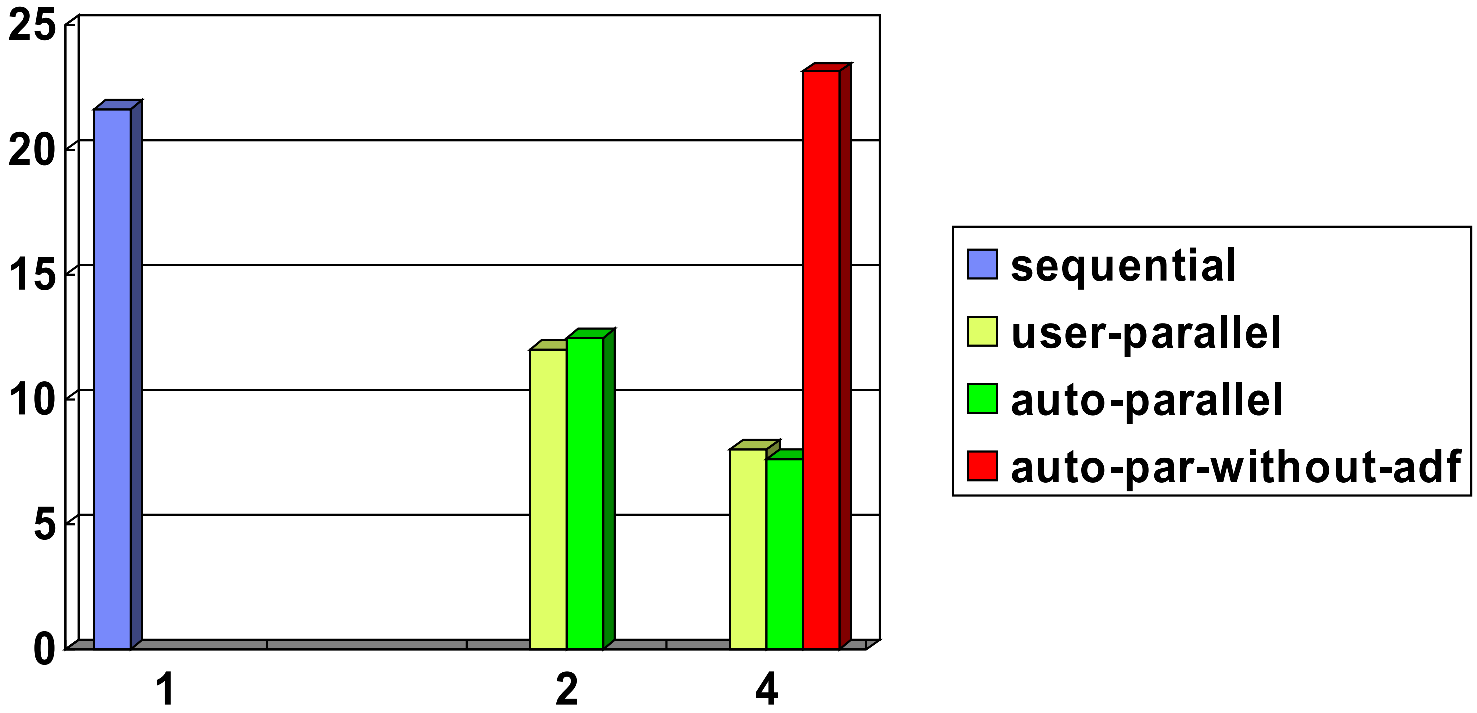

Summary

- Challenges
  - Compilation time
    - Work with other optimizations
      - Loop unroll
    - Graph complexity
      - Number of branches
    - Array section caculation accuracy
  - Memory usage
    - Managing and reusing

Summary (cont.)

- Further improvement:
  - Inter-procedural array data flow
    - Procedure summary
    - More accurate section information instead of using alias
  - Symbolic range analysis
    - Expression simplifier: lot of room to be improved
  - Compilation efficiency
- Possible usage
  - Auto parallelization
  - Array contraction
  - Array coalescing