Automatic Generation of OpenMP Directives and Its Application to Computational Fluid Dynamics Codes

WOMPEI
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Outline

- Motivation
- Parallelization Tools
- Generating OpenMP Directives
- Results from CFD Applications
- Future Work

Code Parallelization

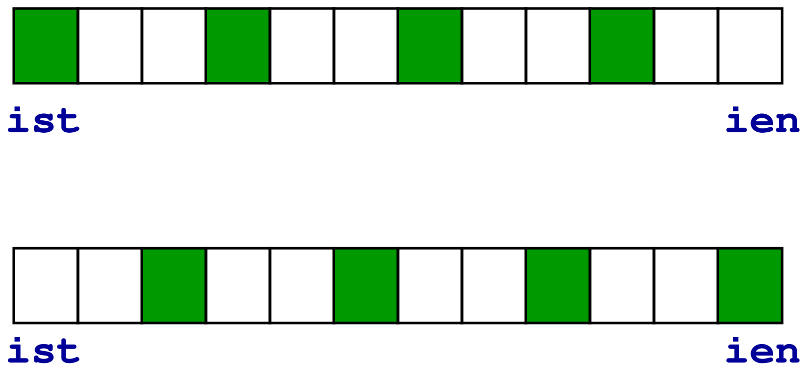
- **By hand**
  - time-consuming
  - error-prone
  - but, better performance
- **Automated compiler**
  - limited depth of analysis (time constraint)
  - limited performance
- **OpenMP directives**
  - less intrusive than message passing to original code
  - easier to insert manually but still error prone!

Nature of the Tools for Parallelization

- **User expectation**
  - fully automatic
  - high parallel efficiency
  - efficient memory usage
- **Reality**
  - interaction essential due to implicit information on input variables
  - user optimization usually needed for high performance
  - constraints on "depth" of analysis acceptable to user
- **Narrowing the gap**
  - automate much of the tedious work
    - accurate data dependence analysis
  - allow user to focus on small part of the problem
    - effective user interface
  - reduce user time and error

Importance of User Knowledge

```
   read*,a,ist,ien,istep
S1 do j=1,nj
      do i=ist,ien,istep
S2      a(i)=...
      enddo
      ...
      do i=ien,ist,-istep
S3       ...=a(i)
      enddo
   enddo
```



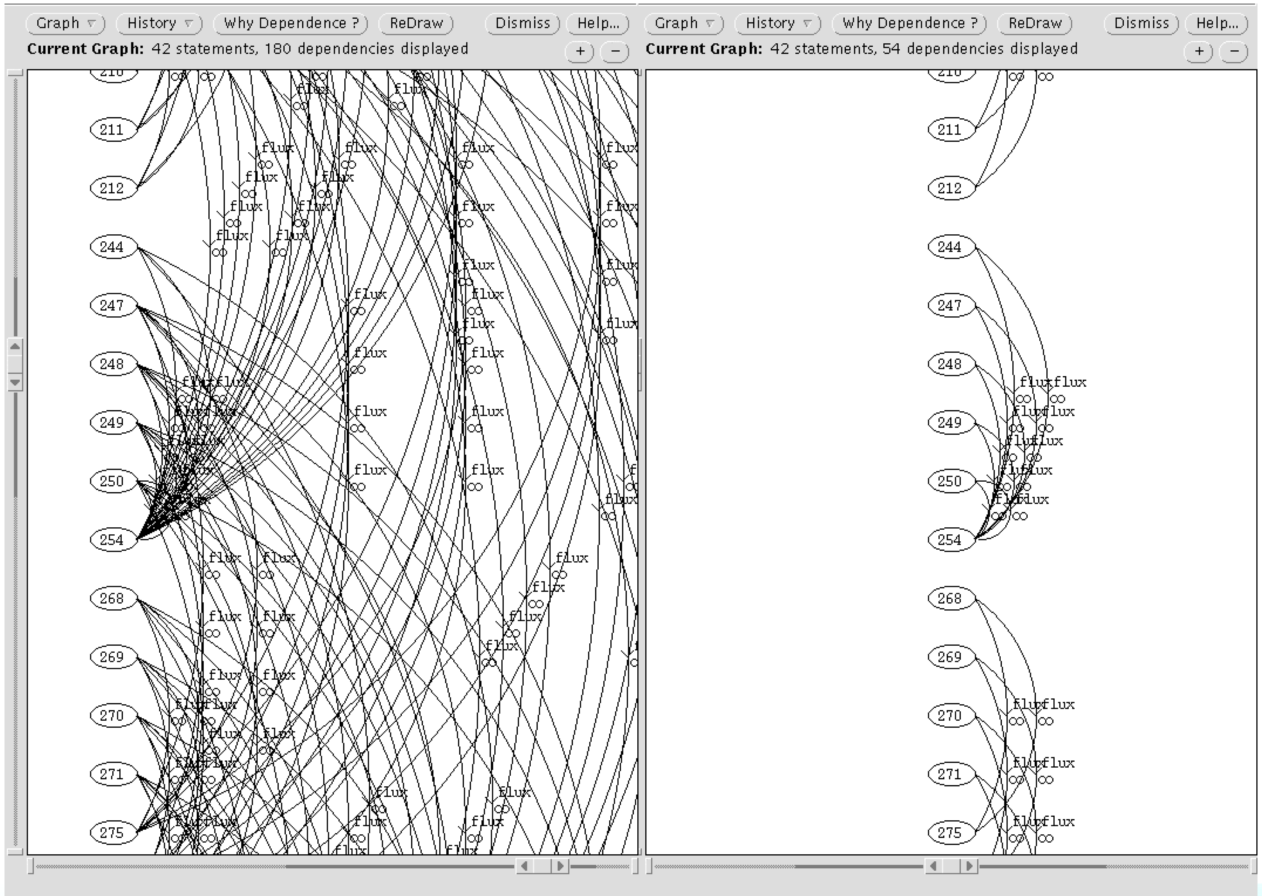
- If it is not CERTAIN that **ien – ist** divisible by **istep** then data used in S_3 may originate from earlier iteration of S_1 or from READ
- Without user knowledge to assist the analysis a dependence is assumed.
- May lead to serialization or communication.

Parallelization Tools

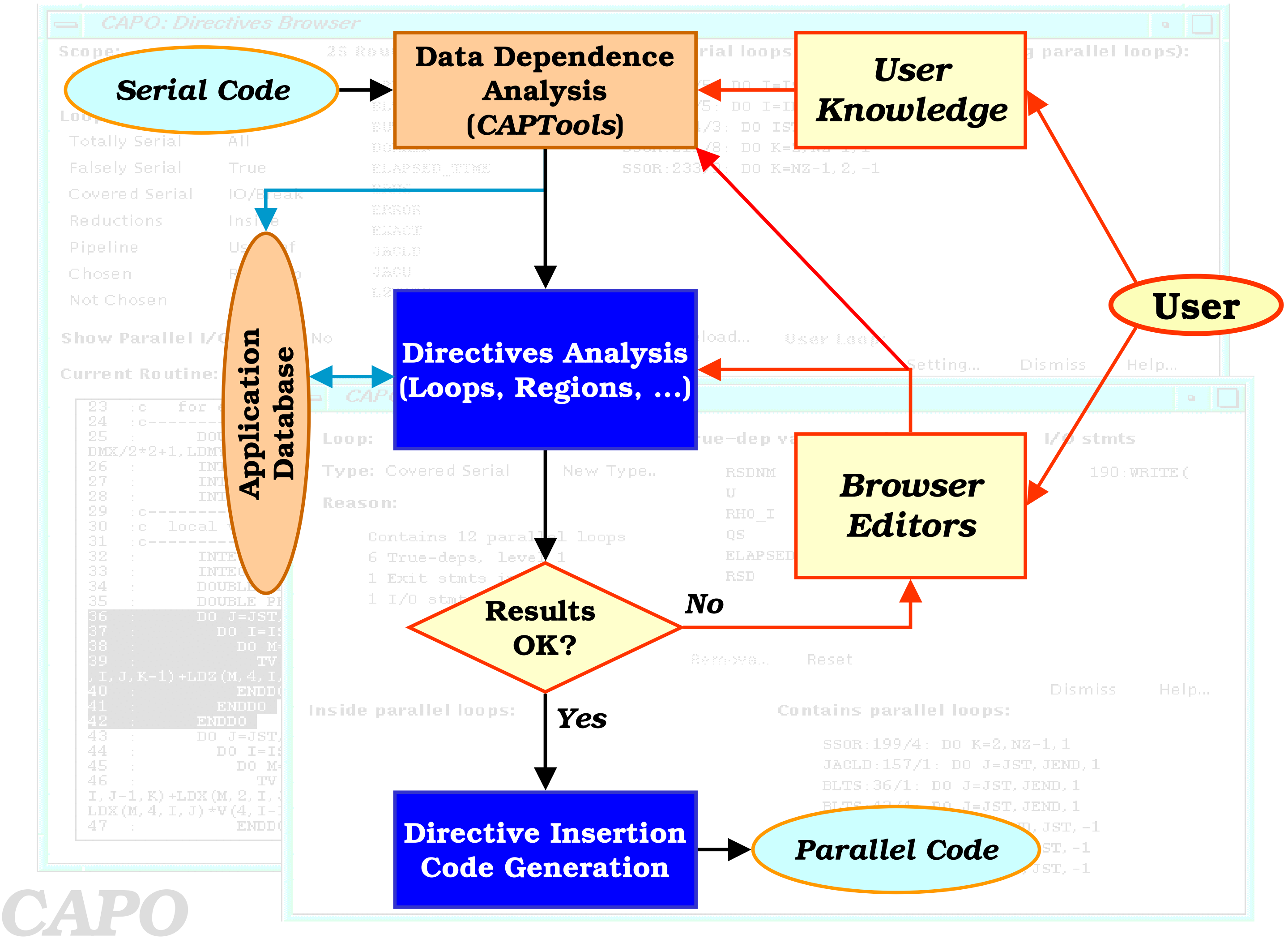
- **CAPTools**
  - interactive semi-automatic toolkit
  - developed at the University of Greenwich
- **CAPTools main feature**
  - accurate and in-depth data dependence analysis
  - domain decomposition strategy for parallelization
  - generic set of message-passing calls, mapped to MPI/PVM
  - a number of browsers for user to interact with the parallelization process
- **CAPO**
  - generating OpenMP directives
  - based on CAPTools (dependence analysis)

Quality Dependence Analysis

- Example for NAS-PAR benchmark code LU
- Standard analysis graph (left) and CAPTools analysis (right)
- Parallelization at best poor with standard graph



Generating OpenMP Parallel Code



Automatic Generation of OpenMP Code

- **Identify parallel loops**
- **Identify and define SHARED and PRIVATE variables**
- **Generate software pipeline constructs using OpenMP where this is necessary e.g. NPB LU code**
- **Identify and define REDUCTION operations**
- **Detect and produce THREADPRIVATE directives for common blocks**

Complexities in OpenMP Code Generation

- Identify and define PARALLEL regions using quality interprocedural dependence analysis to identify parallelism as high as possible
- Merge consecutive parallel regions into a single region to reduce overheads in thread startup and synchronization at end of parallel region
- Detect and produce NOWAIT directives when this is allowed
- Perform automatic routine duplication when a routine usage conflict occurs at different calling points

Private Variables in Common blocks

- **When THREADPRIVATE directive is not possible**
- **Variables are automatically added to argument lists in routines**

Original code

```
   common /csub/b(im),a(im,jm)
   do 10 j=1,ny
     call sub(j,nx)
     do 10 i=1,nx
       a(i,j)=b(i)
10 continue

   subroutine sub(j,nx)
   common /csub/c(im),a(im,jm)
   do 20 i=1,nx
     c(I)=a(i,j)…
20 continue
   end
```

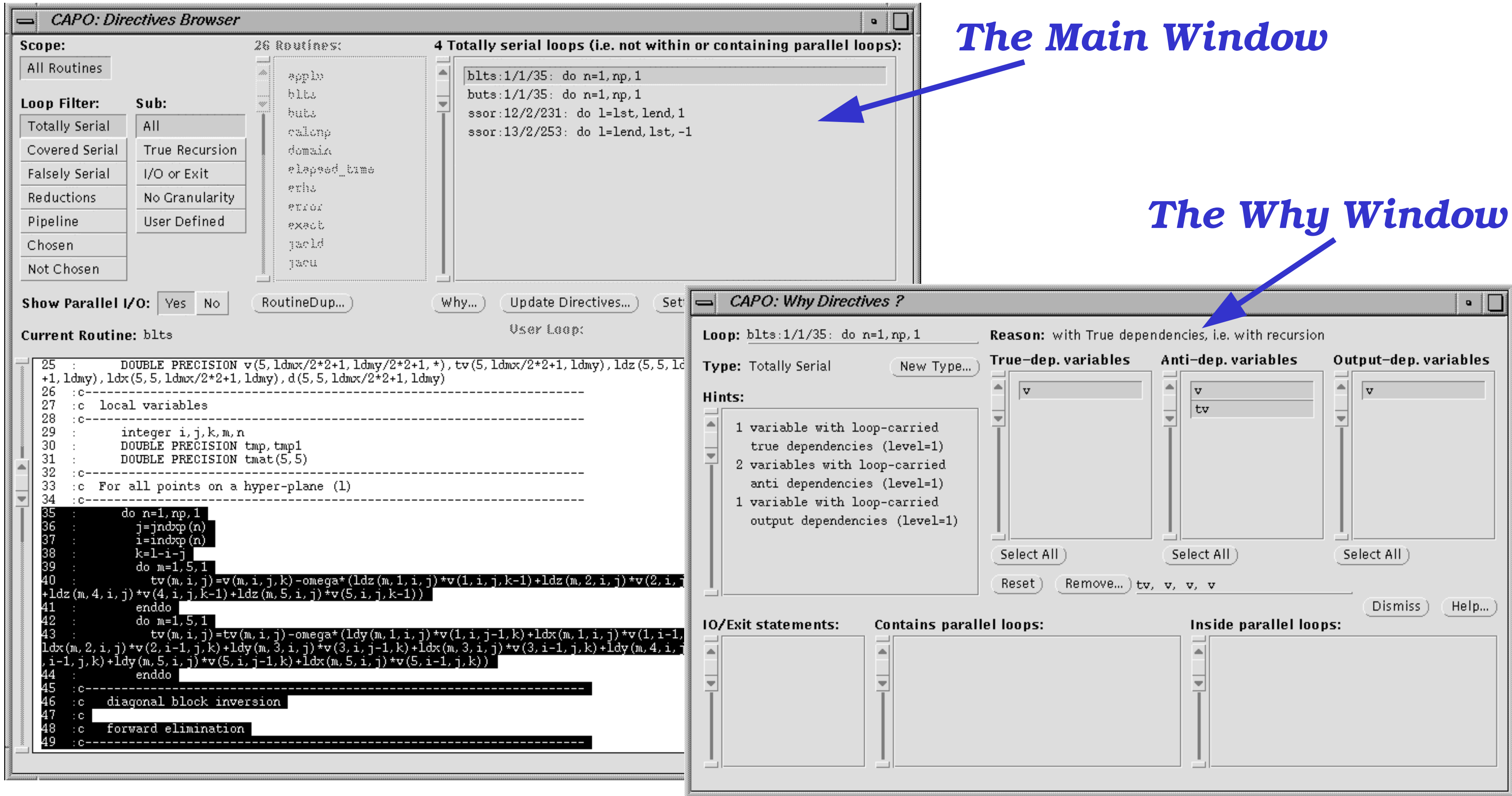
Parallel code

```
   common /csub/b(im),a(im,jm)
!$OMP PARALLEL DO PRIVATE(i,j,B)
   do 10 j=1,ny
     call sub(j,nx,B)
     do 10 i=1,nx
       a(i,j)=b(i)
10 continue
!$OMP END PARALLEL DO

   subroutine sub(j,nx,C)
   common /csub/c_cap(im),a(im,jm)
   dimension C(im)
   do 20 i=1,nx
     c(i)=a(i,j)…
20 continue
   end
```

Presenting Loop Level Information — The Directives Browser

- **Focus on the *problematic* code sections**
- **Understand why a loop is serial or parallel**
- **Prune the analysis (tool follows the conservative path)**



Loop Types Identified with the Browser

- **Totally Serial (Potentially Severe)**
  - Loop carried true dependence present.
  - Not contained in, or containing ANY parallel loops - entirely serial
  - Sequential execution can prevent effective parallel performance.
- **Covered Serial (May be important)**
  - Also a serial loop, but contains or is contained in a parallel loop so some parallelism will be exploited.
  - If containing parallel loops, parallel performance can be enhanced by parallelism at this higher level.
- **Falsely Serial (May be important)**
  - Does not contain loop carried true dependence -should be able to exploit parallelism
  - Serial due to loop carried pseudo (memory re-use) dependence by a non-privatizable variable

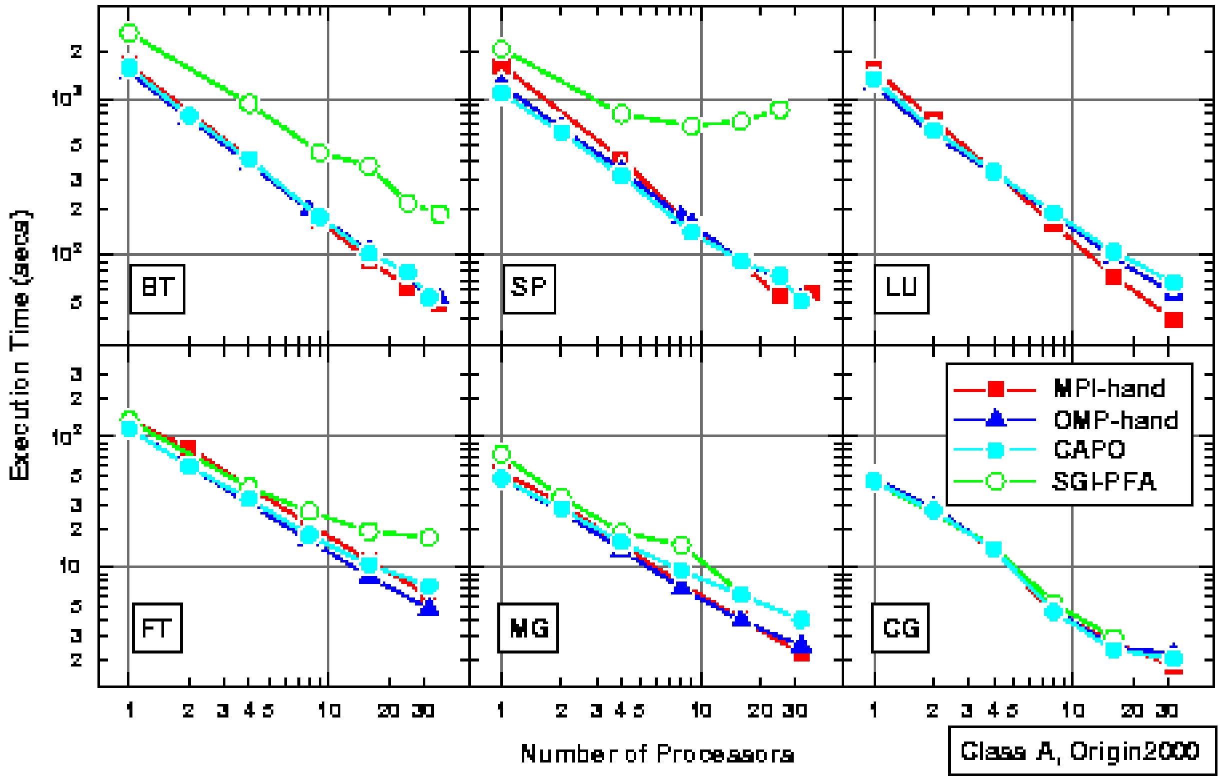
More Loop Types

- **Reduction**
  - Loop contains a recognized reduction operation.
- **Pipeline**
  - Loop identified as a software pipeline.
- **Chosen**
  - Parallel loop that is not nested within other parallel loops.
  - Current Loop level at which parallel DO directive is inserted.
- **Not Chosen**
  - Parallel loop not chosen due to the selection of other parallel loops from the categories above.

Parallelization of CFD Applications

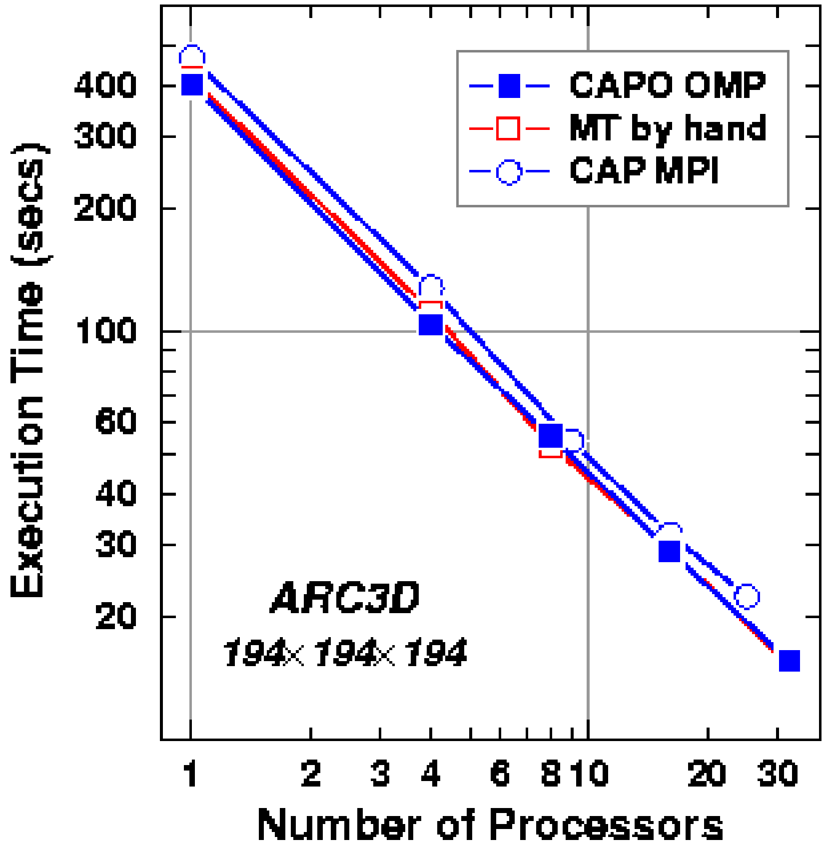
- **NAS Parallel Benchmarks**
  - six serial versions (BT, SP, LU, FT, CG, MG)
- **Three CFD codes**
  - ARC3D, OVERFLOW, INS3D
- **Parallelization**
  - strategy: outer-most loops for large granularity
  - straightforward for NPBs and ARC3D
  - some user interaction for OVERFLOW and INS3D
- **Testing Platform**
  - SGI Origin2000, MIPSpro Fortran 77 compiler

NAS Parallel Benchmarks



on SGI Origin2000, 195MHz

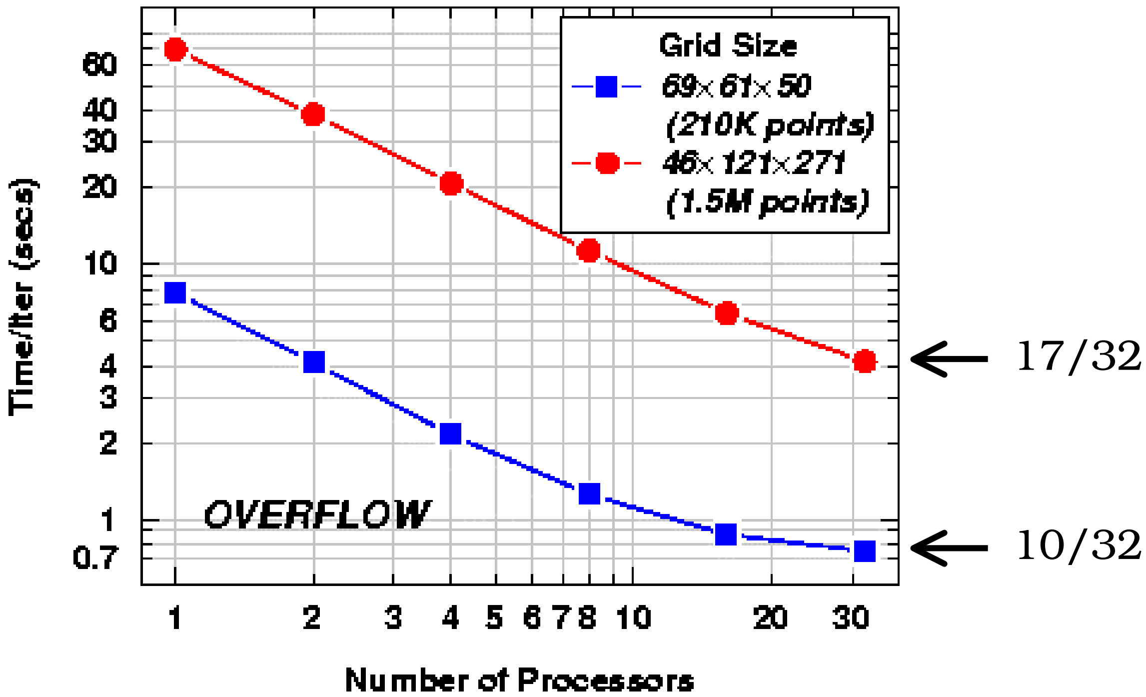
ARC3D



on SGI Origin2000, 195MHz

OVERFLOW Performance

- Two test cases: 210K and 1.5M points
- Single zone



on SGI Origin2000, 195MHz

User Interaction (OVERFLOW)

- **Removing *false* dependences**
  - example of *false* dependence

```
      NTMP2 = JD*KD*31
      DO 100 L=LS,LE
        CALL GETARX(NTMP2,TMP2,ITMP2)
        CALL WORK(L,TMP2(ITMP2,1),TMP2(ITMP2,7),...)
        CALL FREARX(NTMP2,TMP2,ITMP2)
100   CONTINUE
```

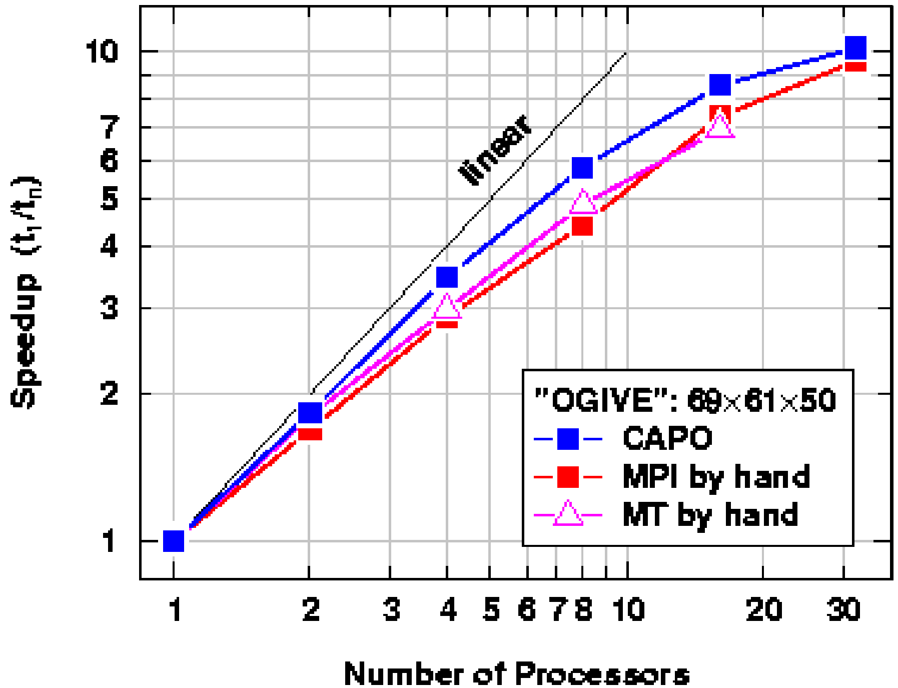
Allocate TMP2

Free TMP2

  - **GETARX** and **FREARX** calls for dynamic memory allocation
  - loop-carried dependences caused by **TMP2** were removed

Performance Comparison

- Three versions of OVERFLOW
  - ⇒ OpenMP directives from CAPO
  - ⇒ MPI by hand
  - ⇒ Multi-Tasking directives by hand



Summary of CAPO on CFD Applications

Application	*BT,SP,LU*	*FT,CG,MG*	*ARC3D*	*OVERFLOW*	*INS3D*
Code Size	~3000 lines benchmark	~2000 lines benchmark	~4000 lines	851 routines 100K lines	256 routines 41K lines
Dependence Analysis	30 mins to 1 hour	10 mins to 30 mins	40 mins	25 hours	42 hours
Code Generation	< 5 mins	< 5 mins	< 5 mins	1 day	2 days
Testing	1 day	1 day	1 day	3 days	3 days
Performance Compared to Hand-coded Version	within 5-10%	within 10% for CG 30-36% for FT,MG	within 6%	slightly better	no hand-coded paral-lel version

- **Dependence Analysis**:
  on Indy R5K (NPBs and ARC3D) and Sun E10K (OVERFLOW and INS3D)
- **Code Generation:**
  including user interaction with the tool and code restructure
- **Testing:**
  debugging and running the parallel codes

Future Work

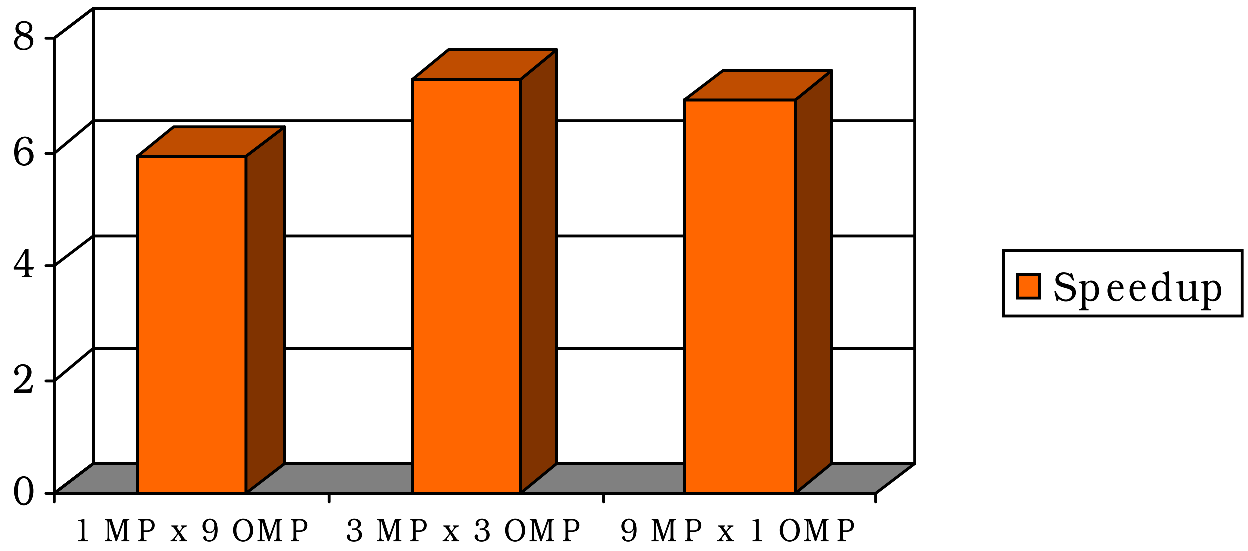
- **Enhance performance**
  - automated code transformation for cache performance
  - automated data placement
- **Combine MP and OMP for multi-level parallelism**
  - CAPTools/CAPO
    - message passing parallel code based on an SPMD paradigm
    - OpenMP parallel code based on a loop distribution approach
  - why not combine the two strategies:

```
do k=1,nk           Parallel loop exploited with MPI
  do j=1,nj         Parallel loop exploited with OpenMP
    do i=1,ni
      ...
    end do
  end do
end do
```

  - first pass: message passing, second pass: OpenMP

The Hybrid Approach

- Tested on BT benchmark
- CAPTools generated message passing code followed by
- CAPO generated OpenMP code
- Test on 195 MHz Origin2000, 1 vs 9 CPUs



Contact Information

- **CAPO**
  `mailto:capo@nas.nasa.gov`
  `http://www.nas.nasa.gov/Tools/CAPO/`

- **CAPTools**
  `http://captools.gre.ac.uk/`