Abstract Expressionism for Parallel Performance

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Abstract

Optimizing Functional Array Language (FAL) compilers for languages such as APL (APEX) and SAC (sac2c), now produce code that outperforms hand-optimized C in both serial and parallel arenas, while retaining the abstract expressionist nature of well-written FAL code.

In this talk, we demonstrate how FAL can now outperform C, in both serial and OpenMP variants, by up to a third, with *no* source code modifications. We also show that modern optimizers can sometimes generate identical loops from substantially different FAL source code.

Talk Layout

- Serial performance: physics relaxation benchmark
- Parallel performance: physics relaxation benchmark
- Wild applause

A Physics Benchmark: Vector Relaxation

- Inputs: temperatures (fixed) at each end of *N*-element rod
- Output: End element temperatures remain unchanged;
  Other element temps are arithmetic mean of neighbors
- Application: image processing, *e.g.*, dust removal (2D)
- Application: temperature distribution in a rod

Dyalog APL/S-64 Version 14.1.25324
8-core AMD FX-8350 (Piledriver) @ 4013MHz, 32GB DRAM
Ubuntu 14.04LTS, sac2c Build #18605, gcc 4.8.2-19ubuntu1
100000 iterations of relaxation kernel
100001-element vector argument, *N*

Three Ways to do Vector Relaxation in Dyalog APL

- Abstract: No tinkering of "memory"
- Expressions: No need for variables (convenience only)
- `TD←{(1↑⍵),(((2↓⍵)+¯2↓⍵)÷2.0),¯1↑⍵}`
- ```
  ROT←{N←⍴⍵
        m←(0=⍳N)∨(N-1)=⍳N
        (m×⍵)+(~m)×((1⌽⍵)+¯1⌽⍵)÷2.0}
  ```
- ```
  SHF←{N←⍴⍵
        m←(0=⍳N)∨(N-1)=⍳N
        (m×⍵)+(~m)×((1 shift ⍵)+¯1 shift ⍵)÷2}
        shift←{((×⍺)×⍴⍵)↑⍺↓⍵}
  ```

Serial Relaxation Timings in Dyalog APL

```
TD←{(1↑ω),(((2↓ω)+¯2↓ω)÷2.0),¯1↑ω}
ROT←{N←ρω
     m←(0=ιN)∨(N−1)=ιN
     (m×ω)+(~m)×((1φω)+¯1φω)÷2.0}
SHF←{N←ρω
     m←(0=ιN)∨(N−1)=ιN
     (m×ω)+(~m)×((1 shift ω)+¯1 shift ω)÷2}
     shift←{((×α)×ρω)↑α↓ω}
```

- Timings:

APL TD	82.6s
APL ROT	203.9s
APL SHF	236.9s

Serial Relaxation in C Using IF/THEN/ELSE

```
for( j=0; j<N; j++) {
    if(0==j) {
      res[j] = v[j];
    } else if((N-1)==j) {
      res[j] = v[j];
    } else {
      res[j] = (v[j-1] + v[j+1])/2.0;
    }
}
```

- Timings:

APL TD	82.6s
APL ROT	203.9s
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Serial Relaxation in C Using IF/THEN/ELSE

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for( j=0; j<N; j++) {
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     res[j] = v[j];
   } else {
     res[j] = (v[j-1] + v[j+1])/2.0;
   }
}
```

- Timings:

APL TD	82.6s
APL ROT	203.9s
APL SHF	236.9s
C IF/THEN/ELSE	16.3s

Serial Relaxation in C Using Conditional Expressions

```
for( j=0; j<N; j++) {
  res[j] = (0==j)       ? v[j] :
           ((N-1)==j) ? v[j] :
             (v[j-1] + v[j+1])/2.0;
}
```

- Timings:

APL TD	82.6s
APL ROT	203.9s
APL SHF	236.9s
C IF/THEN/ELSE	16.3s
C COND	16.4s

Serial Relaxation in SAC Using Conditional Expressions

```
res = with {
      ([0] <= [j] < [N]) :
        (0==j)      ? v[j] :
        ((N-1)==j) ? v[j] :
          (v[j-1] + v[j+1])/2.0;
    } : modarray( v);
```

- Timings:

APL TD	82.6s
APL ROT	203.9s
APL SHF	236.9s
C IF/THEN/ELSE	16.3s
C COND	16.4s
SAC COND	12.0s

Serial Relaxation in SAC, Hand-Optimized

Can SAC do better?

Three data-parallel With-Loop partitions:

```
res = with {
      ([0]   <= [j] < [1]) : v[j];
      ([1]   <= [j] < [N-1]) :
         (v[j-1] + v[j+1])/2.0;
      ([N-1] <= [j] < [N]) : v[j];
    } : modarray( v);
```

- Timings:

APL TD	82.6s
APL ROT	203.9s
APL SHF	236.9s
C IF/THEN/ELSE	16.3
C COND	16.4
SAC COND	12.0s
SAC HAND	5.9s

Serial Relaxation using Abstract Expressionism and APEX

- Take and drop algorithm in APEX
- `TD←{(1↑ω),(((2↓ω)+¯2↓ω)÷2.0),¯1↑ω}`
- Approximate APEX-generated SAC code

```
mid = (drop([2],v)+drop([-2],v))/2.0;
res = take([1],v)++mid++take([-1],v);
```

- Timings:

APL TD	82.6s
SAC HAND	5.9s
APEX TD	5.9s

- *Identical* inner loops for `APEX TD` and `SAC HAND`

Serial Relaxation using Abstract Expressionism and APEX

```
ROT←{N←⍴⍵
     m←(0=⍳N)∨(N−1)=⍳N
     (m×⍵)+(~m)×((1⌽⍵)+¯1⌽⍵)÷2.0}
```

```
m = (0 == iota(N)) | ((N-1) == iota(N));
res = (tod(m) * v) + tod(!m) *
  ((rotate([1], v) + rotate([-1], v)))/2.0;
```

- Rotate algorithm in APEX, generated SAC code
- Timings:

`APL ROT`	82.6s
`SAC HAND`	5.9s
`APEX ROT`	5.9s

- *Identical* inner loops for `APEX ROT` and `SAC HAND`

Serial Relaxation using Abstract Expressionism and APEX

```
SHF←{N←⍴⍵
     m←(0=⍳N)∨(N−1)=⍳N
     (m×⍵)+(~m)×((1 shift ⍵)+¯1 shift ⍵)÷2}
     shift←{((×⍺)×⍴⍵)↑⍺↓⍵}
```

```
m = (0 == iota(N)) | ((N-1) == iota(N));
res = (tod(m) * v) + tod(!m) *
 ((shift([1],v) + shift([-1],v)))/2.0;
```

- Shift algorithm in APEX-generated SAC code
- Timings:

APL TD	82.6s
APL ROT	203.9s
APL SHF	236.9s
SAC HAND	5.9s
APEX TD	5.9s
APEX ROT	5.9s
APEX SHIFT	5.9s

- *ALL* inner loops are identical!

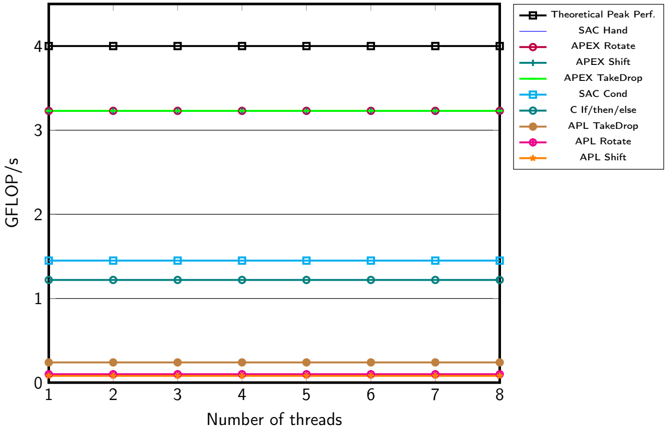
Why are Identical Inner Loops Noteworthy?

- APL source codes differ substantially
- Very different SAC stdlib code for rotate, shift, take/drop
- *E.g.*, number of With-Loops, setup code style
- See paper for stdlib code, here:
  `http://www.snakeisland.com/abstractexpressionism.pdf`

Serial Performance GFLOPS

- Hard to do better? SAC/APEX approach maximum GFLOPS rate
- Let's look at parallel execution

Serial Relaxation Performance (One FPU)



Parallel Relaxation Speedup in C

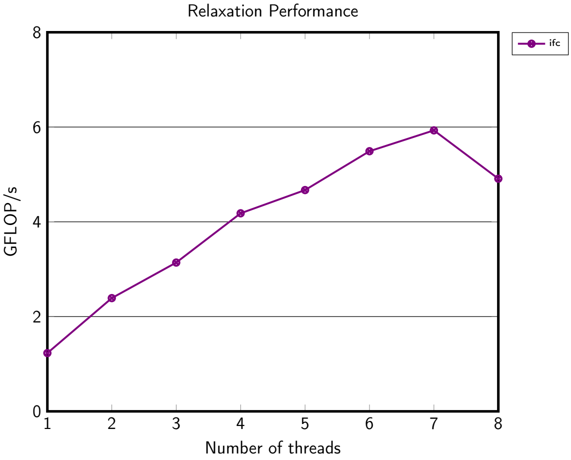
- Open MP
- Basic idea: Introduce ceremonial rubbish into **SOURCE** code
- See paper for ceremonial details
- Basic idea: Introduce pragmas into **SOURCE** code

  ```
  #pragma omp parallel for
  ```

  after *SOME* `for` statements.
- Compile with `-fopenmp`

Parallel Relaxation Speedup in C Performance

- Timings: (higher is better)



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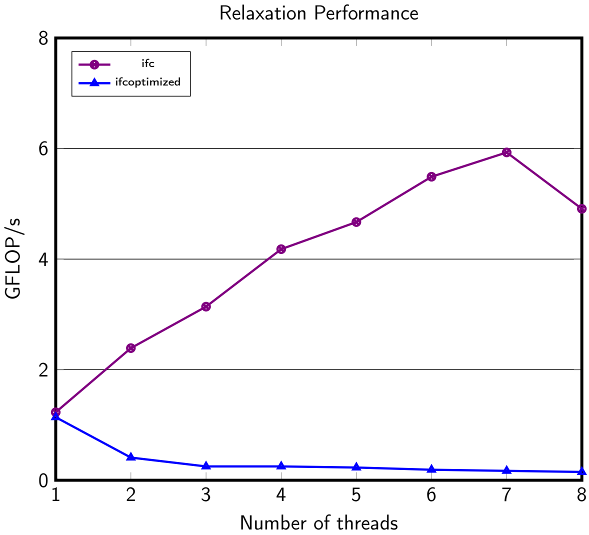
Optimized Parallel Relaxation in C

```
for( j=0; j<N; j++) {
   if(0==j) {
     res[j] = v[j];
   } else if((N-1)==j) {
     res[j] = v[j];
   } else {
     res[j] = (v[j-1] + v[j+1])/2.0;
   }
}
```

- Bright idea: Replace multiple "`res[j] =`" by "`el =`"
- Bright idea: and add "`res[j] = el;`" after IF-statement
- Rationale: Eliminate multiple indexed assigns into "`res`"
- This should improve instruction cache use

Pessimized Parallel Relaxation in C

- Timings: (higher is better)



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Parallel Relaxation Slowdown in C Post-mortem

```
for( j=0; j<N; j++) {
   if(0==j) {
     el = v[j];
   } else if((N-1)==j) {
     el = v[j];
   } else {
     el = (v[j-1] + v[j+1])/2.0;
   }
   res[j] = el;
}
```

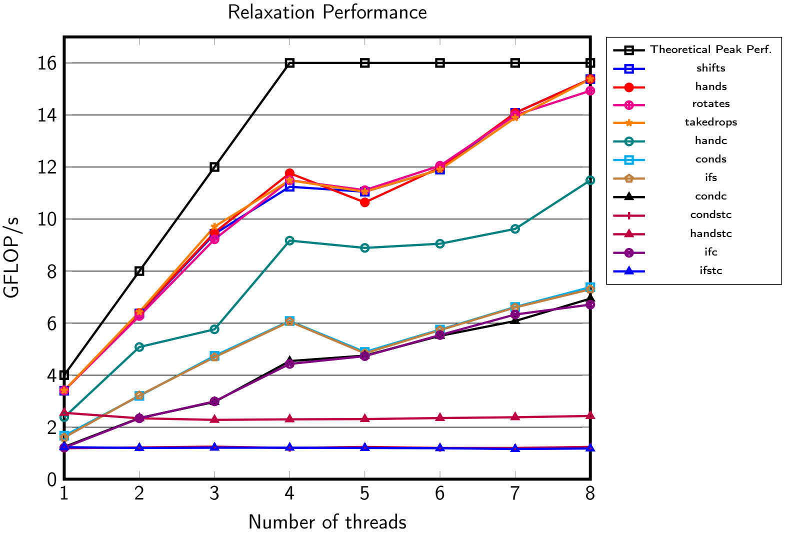
- What went wrong?
- `el` is shared, so it hops among all threads
- Bottom line: Bright idea not so bright (watch system monitor!)
- Bottom line: Writing parallel C code is **NOT** trivial

Serial and Parallel Relaxation Performance

- Abstract expressionist APL matches best SAC code
- SAC and APL beat C by 2.75X in serial environment
- SAC and APL beat Open MP C by 1/3 in parallel environment
- *NO* changes to APL code for parallel execution, unlike C

Serial and Parallel Relaxation Performance

Higher is better



SAC Keys to High-Performance FAL Compilation

- Provide purely functional Intermediate Language (IL)
- Preserve array semantics in IL
- Scalarize small arrays, *e.g.*:
- in Gaussian Elimination pivot, replacing:

```
mat[rowa,rowb;]←mat[rowb,rowa;]
```

by

```
trow←mat[rowa;] ⋄ mat[rowa;]←mat[rowb;] ⋄
mat[rowb;]←trow
```

- …gives 2X speedup!
- Do scalarization in the compiler, *NOT* in app source code.
- Use array-based optimizations, *e.g.*, with-loop folding (WLF)
- and others…
- Stay tuned for the book!

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Thank you! Questions?