# All Paths Pipelining: An Algorithm for Scheduling Loops with IFs

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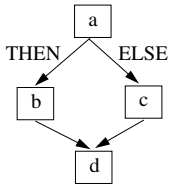
## Challenges of Scheduling Loops with IFs

- a loop that iterates $N$ times has $2^N$ possible execution paths




one iteration path, T=abd
another iteration path, E=acd

possible execution paths:

T E T E T E T E T E T E T E . . . . .
T T T T T E E E E T T T T E . . . . .
E E E T T T T T T T E E E T . . . . .

- optimal execution time for runs of T's can be different from optimal execution time for runs of E's





## Scheduling Loops with IFs

- ideal goal: find near-optimal schedule for all possible execution paths
- previous attempts:
  - Enhanced Percolation Scheduling [Ebcioglu, 1987]
  - Hierarchical Reduction [Lam, 1989]
  - Predicated Operations [Park & Schlansker, 1991]
  - Enhanced Modulo Scheduling [Warter, Bockhaus, *et al.*, 1992]

  all execution paths are sub-optimal or
  one execution path is near-optimal and all others are sub-optimal





## Using All Paths Pipelining to Schedule Loops with IFs

- observation: many execution paths have runs of T's and E's
  ➥make long runs of T's or E's execute quickly
- execution paths with long runs of T's or E's are near-optimal and all others are possibly sub-optimal
- rather than paying a penalty for executing the "wrong" path, instead possibly pay a penalty for switching iteration paths
- algorithm extends to loops with multiple IFs

✔ no special hardware requirements
✔ does not rely on profiling information

## Overview of All Paths Pipelining Algorithm

STEP 1: Create a trace for each iteration path in the loop. Add dependence edges to prevent global and speculative code motion.

STEP 2: Software pipeline each trace in isolation, possibly achieving different initiation intervals for each trace.

STEP 3: Merge the traces into one schedule by adding introductory and intermediate instructions that allow any execution path to be executed.





## Example Loop with a Conditional Statement

**Example C Loop**

```
for (i=0; i<N; i++) {
  if (x < threshold)
     z = threshold;
  else
     z = (x+1.0)*(x/2+3.0);
  sum += z;
  x = x*x;
}
```

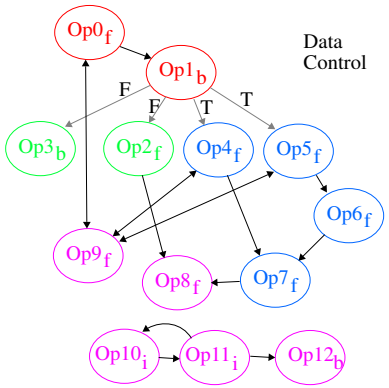
| | Assembly Code | Op Name |
|---|---|---|
| TEST | L7: fslt.s x,threshold,f1 | Op0 |
| | beqz.s f1,L5 | Op1 |
| THEN | fmov.s threshold,f10 | Op2 |
| | jmp L6 | Op3 |
| ELSE | L5: fadd.s x,f9,f2 | Op4 |
| | fdiv.s x,f8,f3 | Op5 |
| | fadd.s f3,f7,f11 | Op6 |
| | fmult.s f2,f11,f10 | Op7 |
| | L6: fadd.s sum,f10,sum | Op8 |
| | fmult.s x,x,x | Op9 |
| LOOP CONTROL | add.d i,d4,i | Op10 |
| | slt.d i,N,d1 | Op11 |
| | bnez.d d1,L7 | Op12 |





## Program Dependence Graph

| | Assembly Code | Op Name |
|---|---|---|
| BB0 | L7: fslt.s x,threshold,f1 | Op0 |
| | beqz.s f1,L5 | Op1 |
| BB1 | fmov.s threshold,f10 | Op2 |
| | jmp L6 | Op3 |
| BB2 | L5: fadd.s x,f9,f2 | Op4 |
| | fdiv.s x,f8,f3 | Op5 |
| | fadd.s f3,f7,f11 | Op6 |
| | fmult.s f2,f11,f10 | Op7 |
| BB3 | L6: fadd.s sum,f10,sum | Op8 |
| | fmult.s x,x,x | Op9 |
| | add.d i,d4,i | Op10 |
| | slt.d i,N,d1 | Op11 |
| | bnez.d d1,L7 | Op12 |

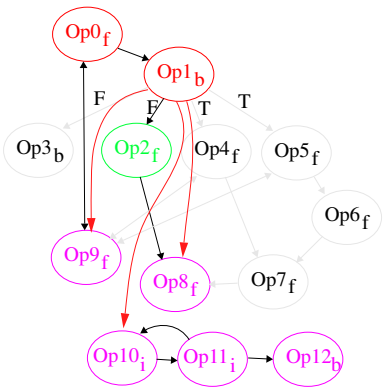






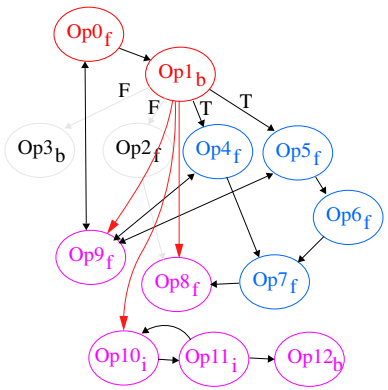

## STEP 1: Extract Trace PDGs

THEN (False) Trace



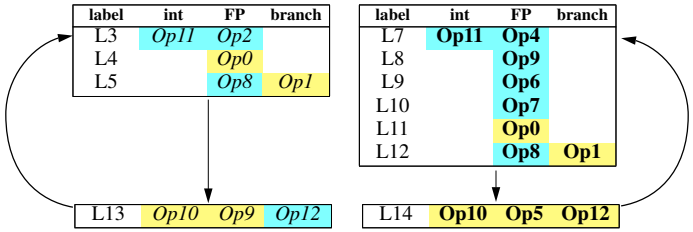

**minimum II >= 4 cycles**

ELSE (True) Trace




**minimum II >= 7 cycles**

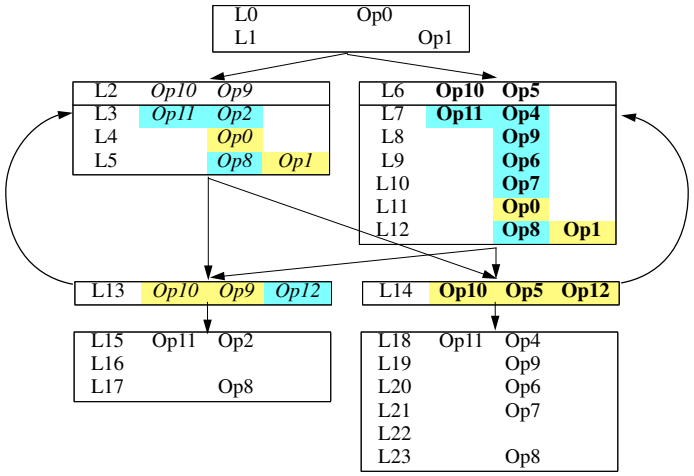
## STEP 2: Software Pipeline Each Trace








## STEP 3: Combine Traces








## Execution Time of APP-Scheduled Loop

- execution time depends on $p_{THEN}$ = probability THEN path is executed
- number of cycles to execute 1 iteration:

$$T_I = 4p_{THEN} + (1 - p_{THEN})\,7 = 7 - 3p_{THEN} \text{ cycles}$$

NOTE: no additional cycles needed to switch iteration paths!

- range of execution times:

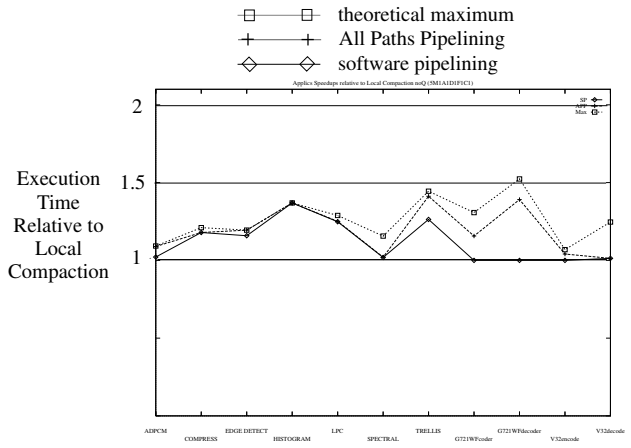
$$4 \text{ cycles} \le T_I \le 7 \text{ cycles}$$

- ideal goal achieved for this loop
  BUT not possible in general



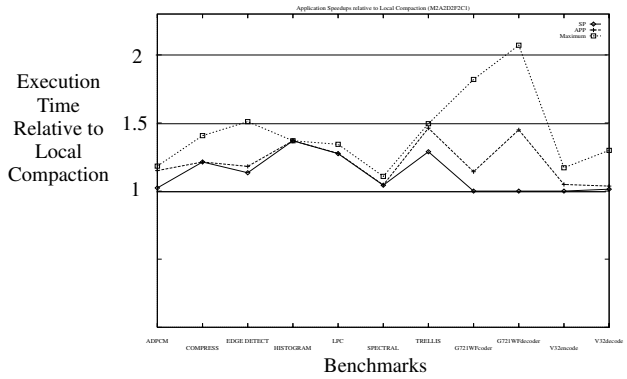


## Performance Results for 5 Functional Units



## Performance Results for 9 Functional Units

theoretical maximum
All Paths Pipelining
software pipelining




Execution Time Relative to Local Compaction

Benchmarks