All Paths Pipelining:
An Algorithm for Scheduling Loops with IFs

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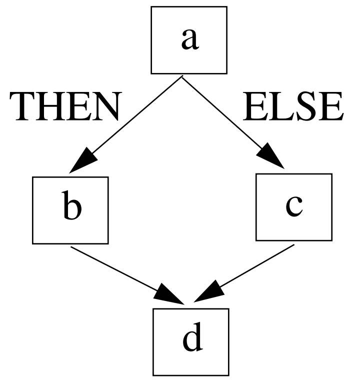
Challenges of Scheduling Loops with IFs

- 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

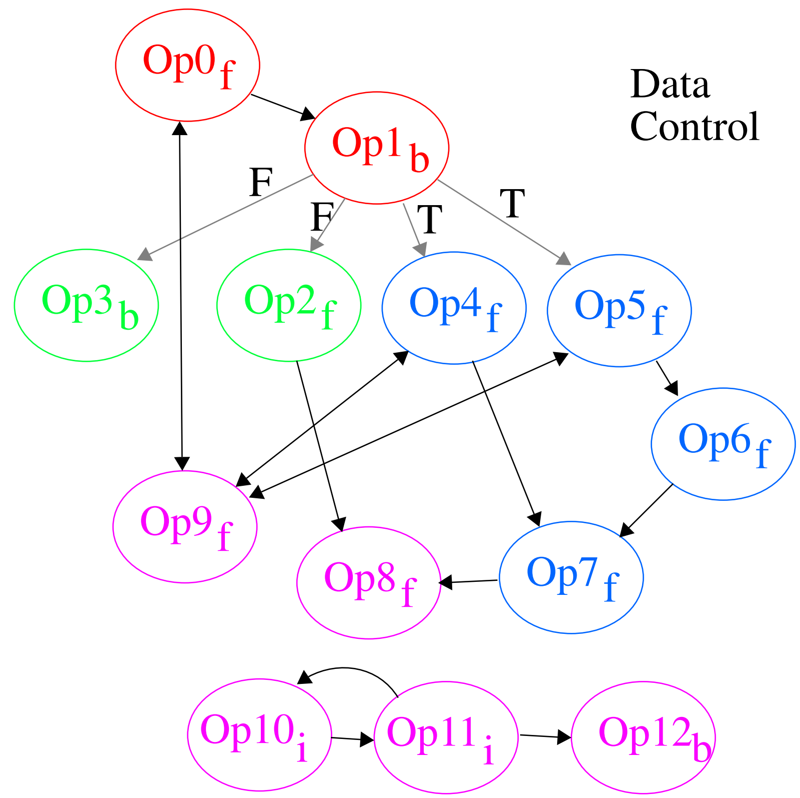
Example C Loop

```
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

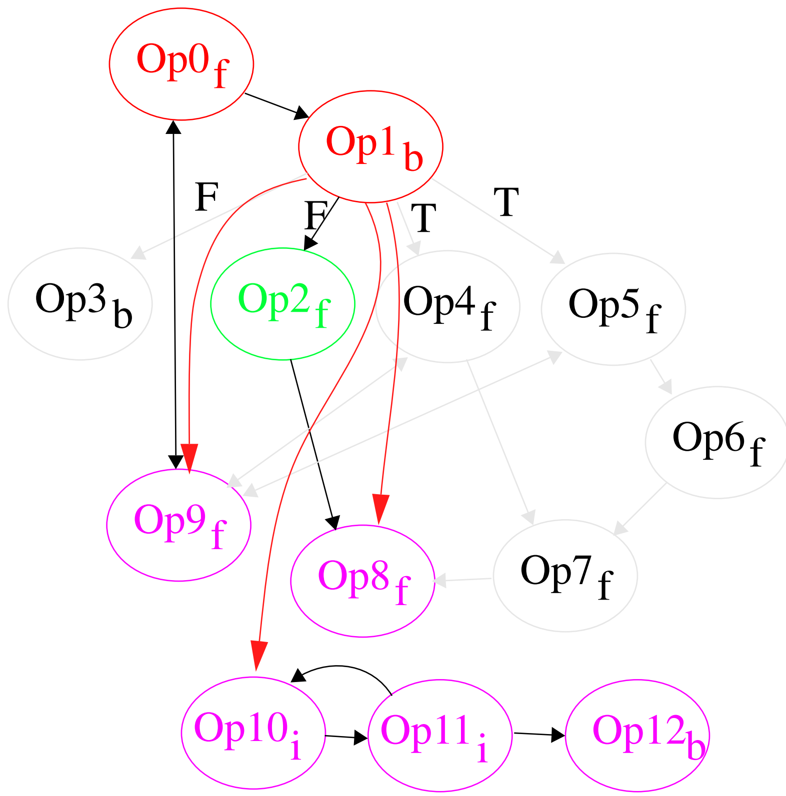
Program Dependence Graph

	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



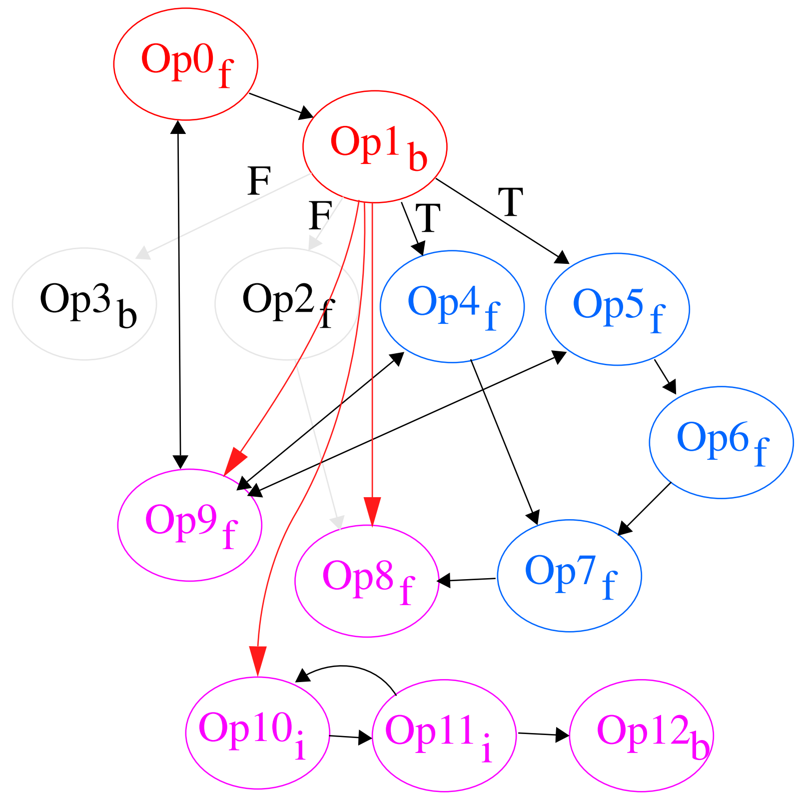
STEP 1: Extract Trace PDGs

THEN (False) Trace



minimum II >= 4 cycles

ELSE (True) Trace



minimum II >= 7 cycles

STEP 2: Software Pipeline Each Trace

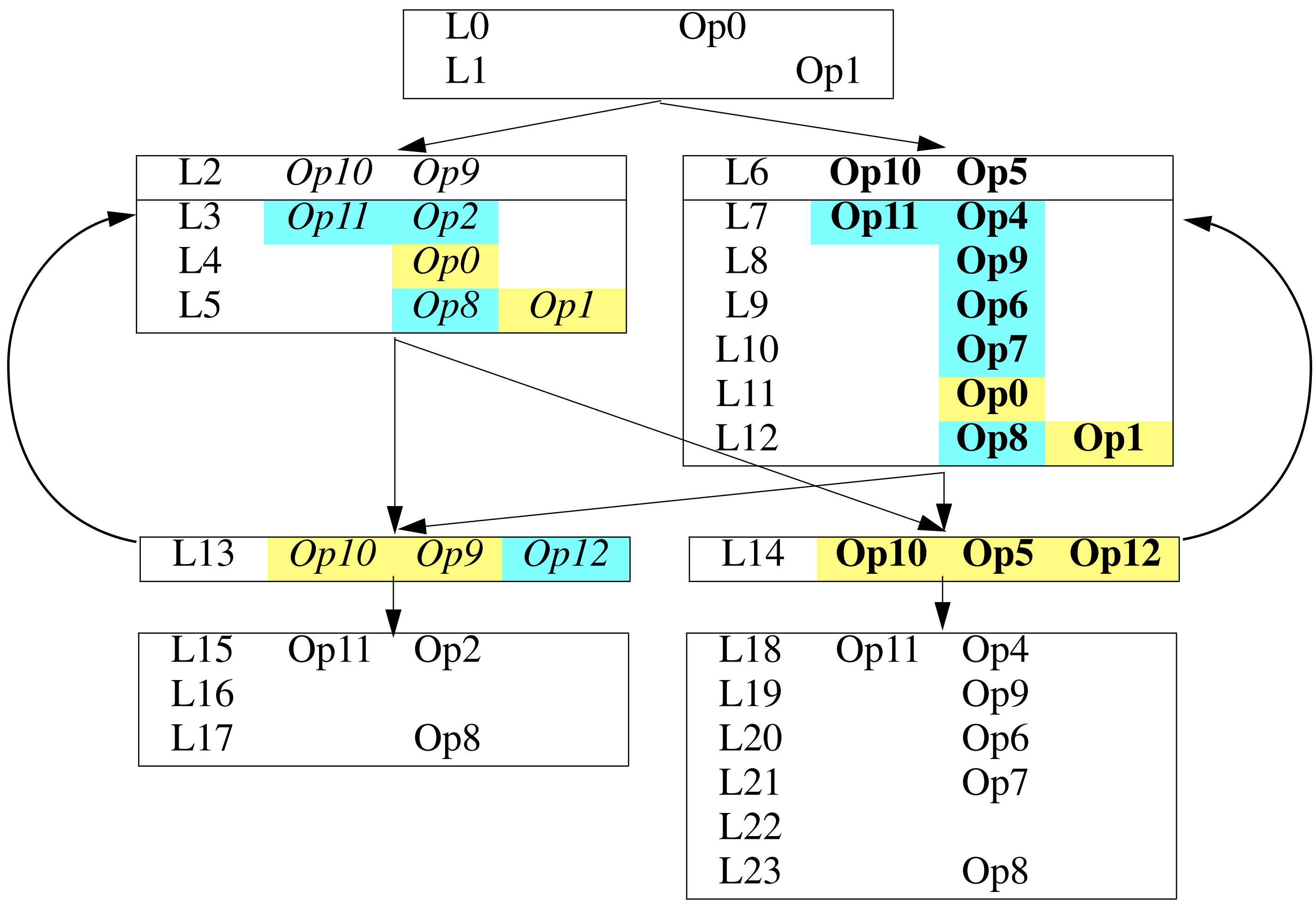
label	int	FP	branch
L3	*Op11*	*Op2*	
L4		*Op0*	
L5		*Op8*	*Op1*

L13	*Op10*	*Op9*	*Op12*

label	int	FP	branch
L7	**Op11**	**Op4**	
L8		**Op9**	
L9		**Op6**	
L10		**Op7**	
L11		**Op0**	
L12		**Op8**	**Op1**

L14	**Op10**	**Op5**	**Op12**

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:

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

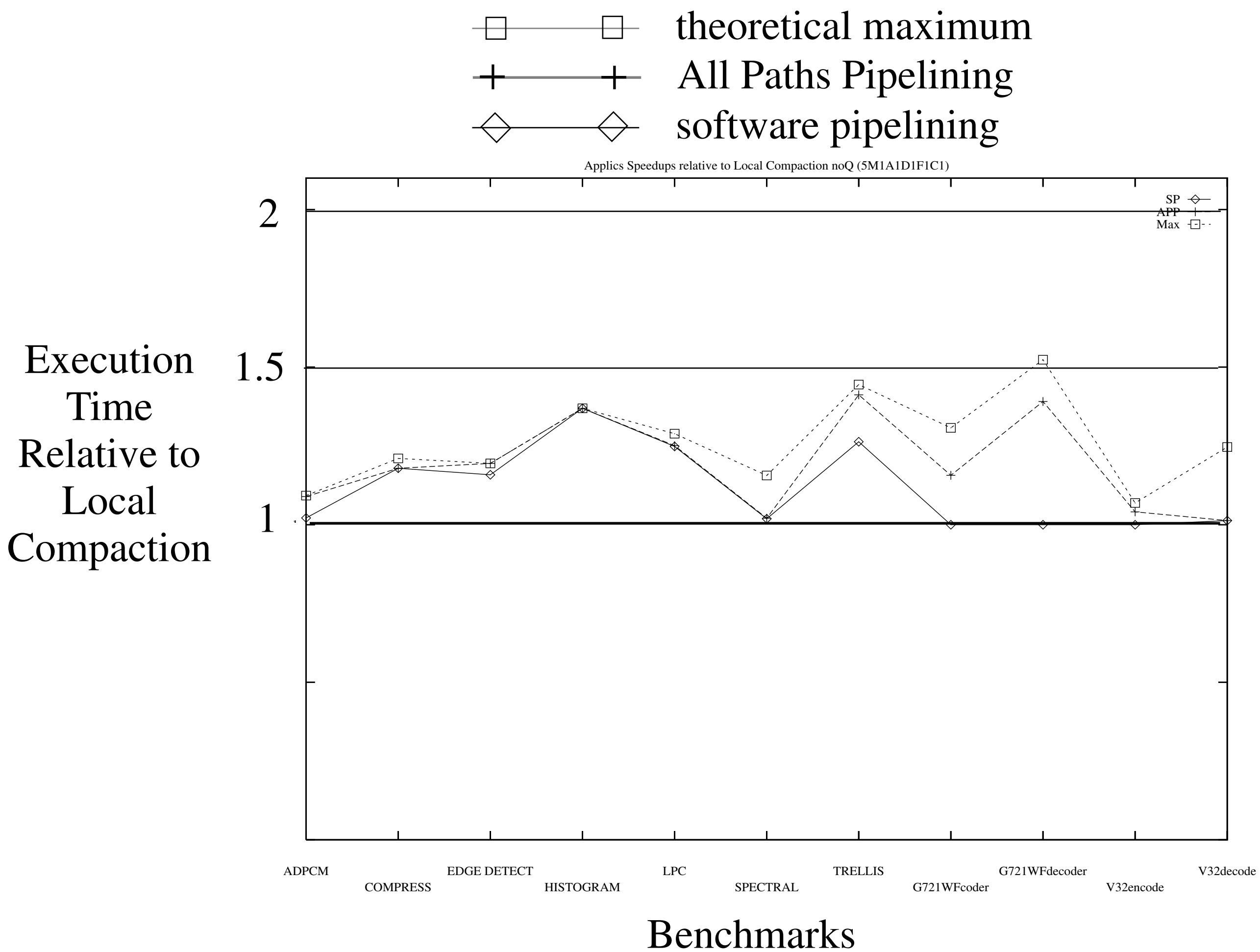
NOTE: no additional cycles needed to switch iteration paths!

- 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