Disjoint Eager Execution: An Optimal Form of Speculative Execution

or: ILP Speedups in the 10's

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Prologue

“A 21st-century microprocessor may well [issue] up to dozens of instructions [per cycle, peak]...”

David A. Patterson, in:
“Microprocessors in [the year] 2020”,
Scientific American, September 1995.

Contributions of the Work

- New form of speculative execution (DEE)
  - Optimal, low cost, high performance:

    ***Speedup factors of* 26-31 (2,600% - 3,100%)**

- New machine model devised for DEE:

  Levo (target ILP: x 20)

  - On single chip in 4-5 years (by 2000 AD!)

Acknowledgements

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- Other contributors to the work:
  - Sajee Somanathan
  - Sridhar Mahankali

Rest of Talk

- Background
  - ILP limits, Minimal control dependencies, Speculative execution methods
- ***Disjoint Eager Execution* (DEE)**
  - Theory
  - Heuristic
  - Performance evaluation
- The prototype: Levo

Background

- Oracle ILP speedups:
  - Riseman and Foster (1972), harmonic mean speedup $S = 25$;
  - Lam and Wilson (1992): $S = 159$;   & others....
- w/ realistic constraints, only get: $S = 2$ to 3 (to date, using SPECint92's)
- 50-100 million transistors/chip by 2000 AD
- Instruction set compatibility desirable

Minimal Control Dependencies

(Uht85, Ferrante87, Uht91)

- Classic model: *restrictive control dependencies*
- Can be relaxed: w/MCD, `3` & `4` ind. of `1`

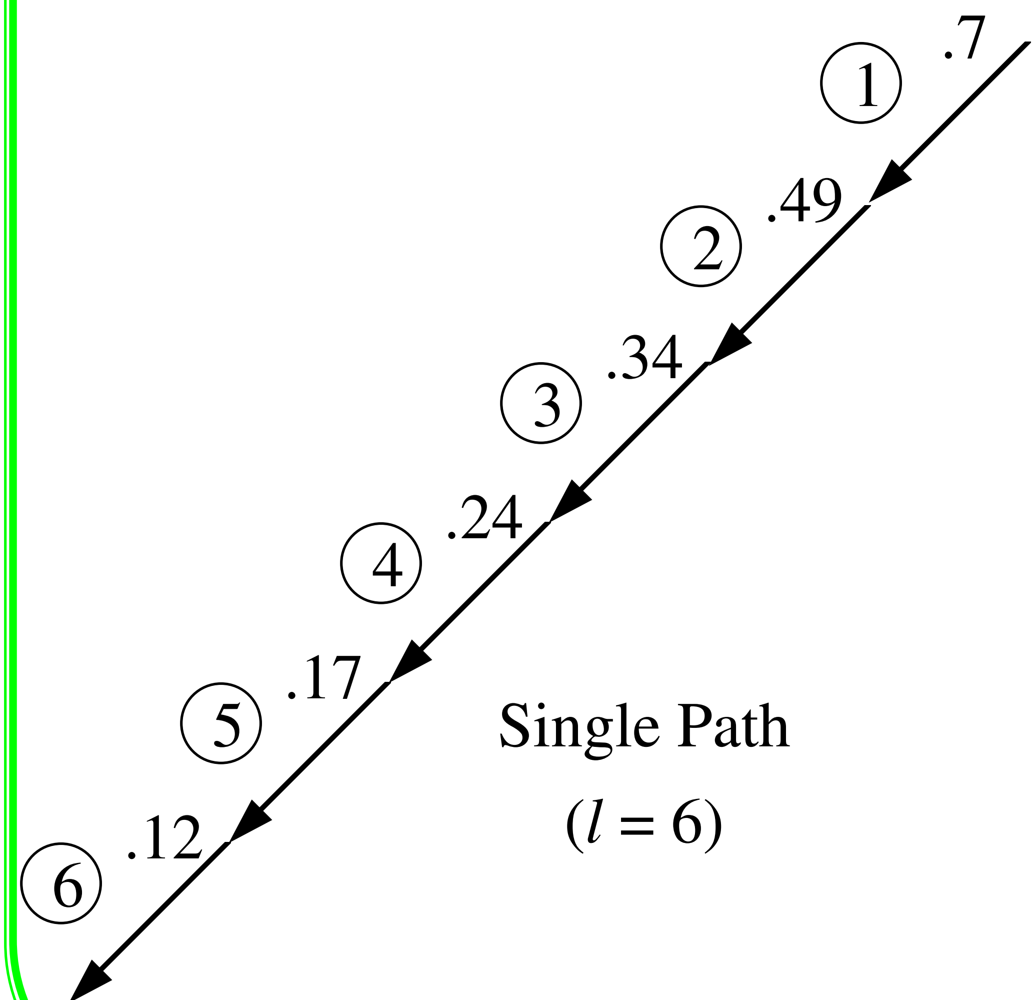
```
1.  if (a<8) {
2.       b=c+d;}
3.  x=y+z;
4.  if (p>5) {...}
```

Speculative Execution

- Given: l is depth of greatest speculation
- Single Path (SP) - $O(l)$ cost, but low performance: *cumulative prob.* (cp) --> 0
- Eager Execution (EE) - best performance, w/ infinite resources, but high cost: $O(2^l)$
- Need something better, with good features of <u>both</u> SP and EE:

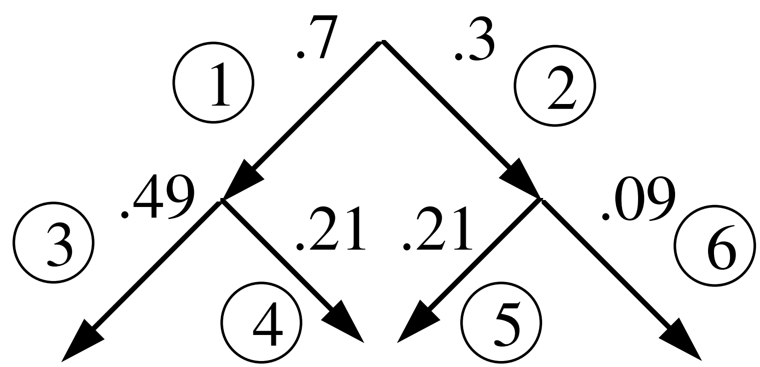
Disjoint Eager Execution **(DEE)**

SP and EE Models



Single Path

($l = 6$)



Eager Execution

($l = 2$)

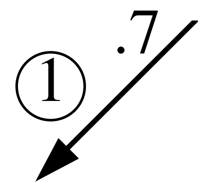
DEE Theory

- *Branch Path* (resources) definition: dynamic code between branches (PE's to execute the code in the path as concurrently as possible)
- Rule of Greatest Marginal Benefit:

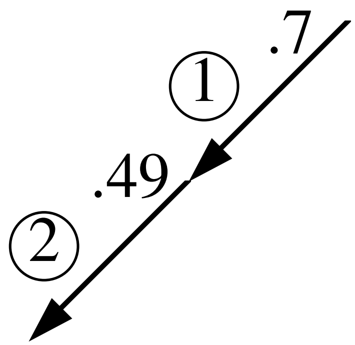
  Assign resources to most likely paths,

  over <u>all</u> pending paths
- Optimal for constrained resources
- Cost: $O(kl^2)$; k<1

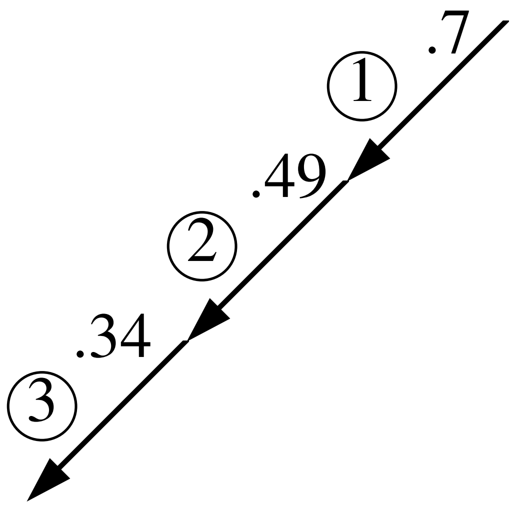
Assigning Resources



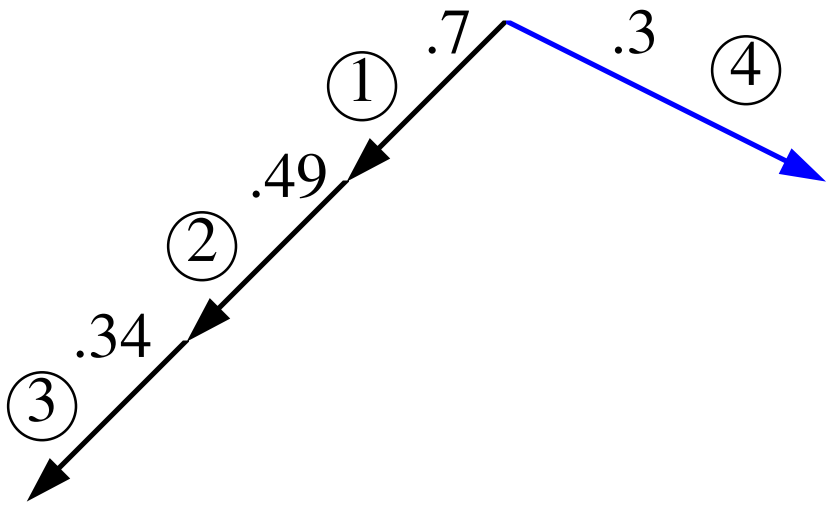
Assigning Resources



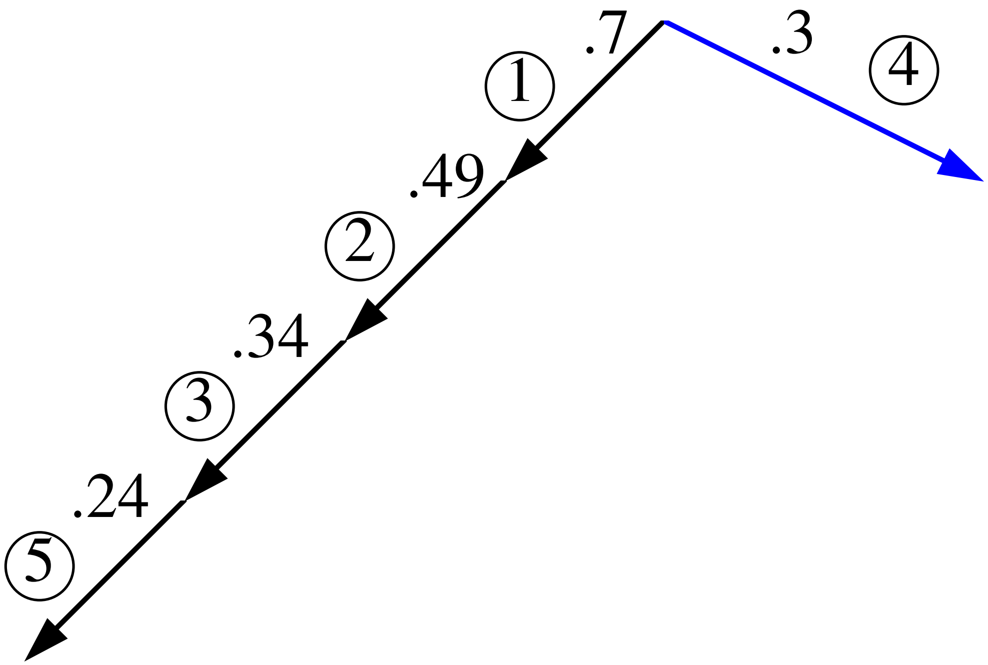
Assigning Resources



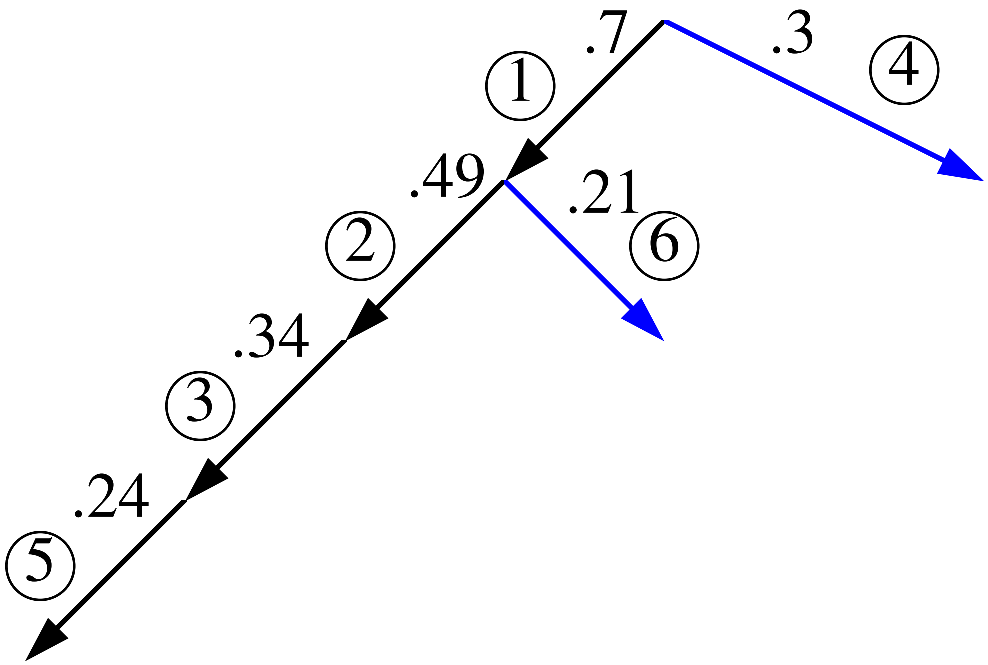
Assigning Resources



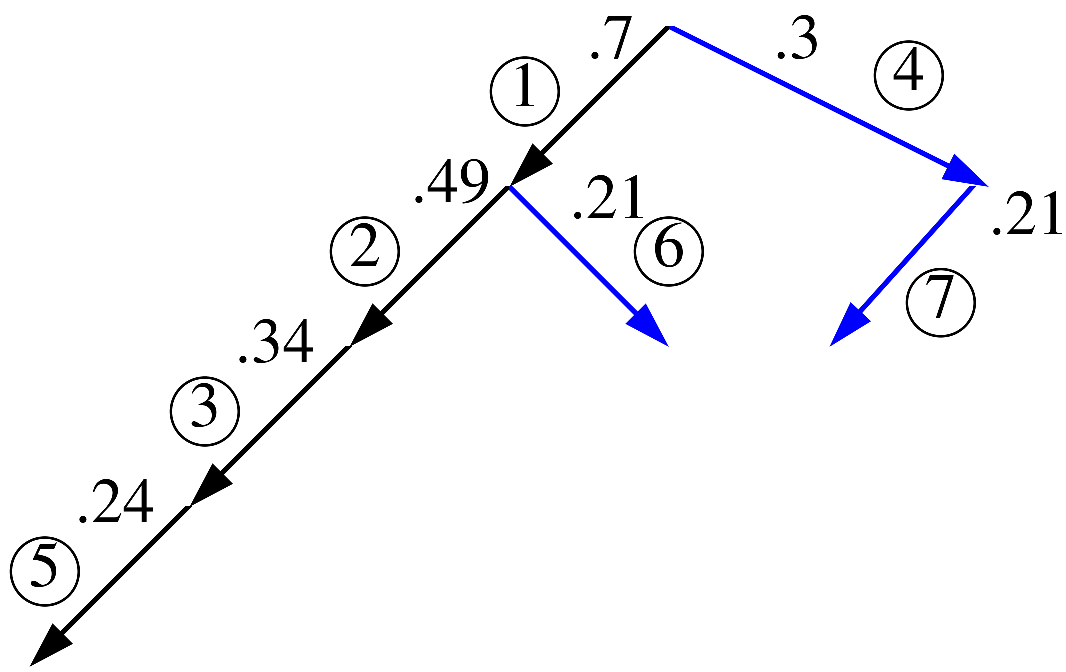
Assigning Resources



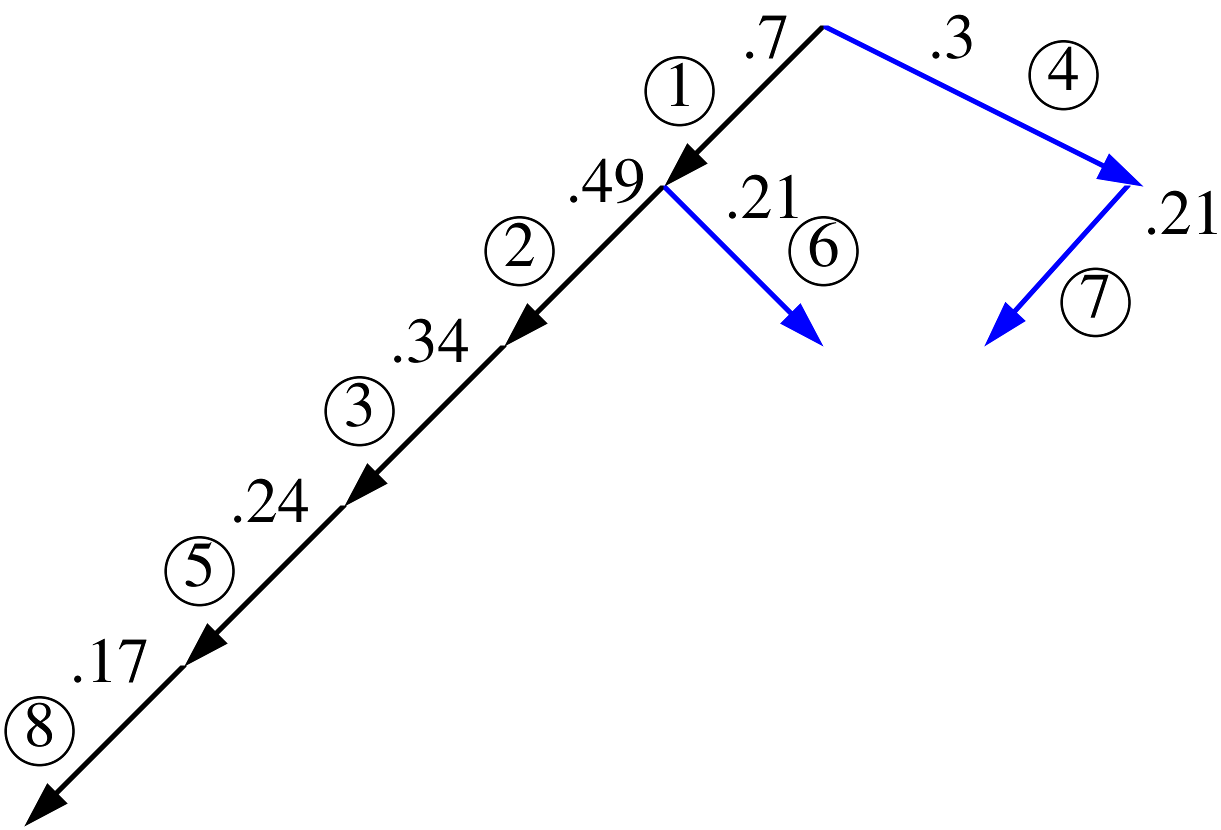
Assigning Resources



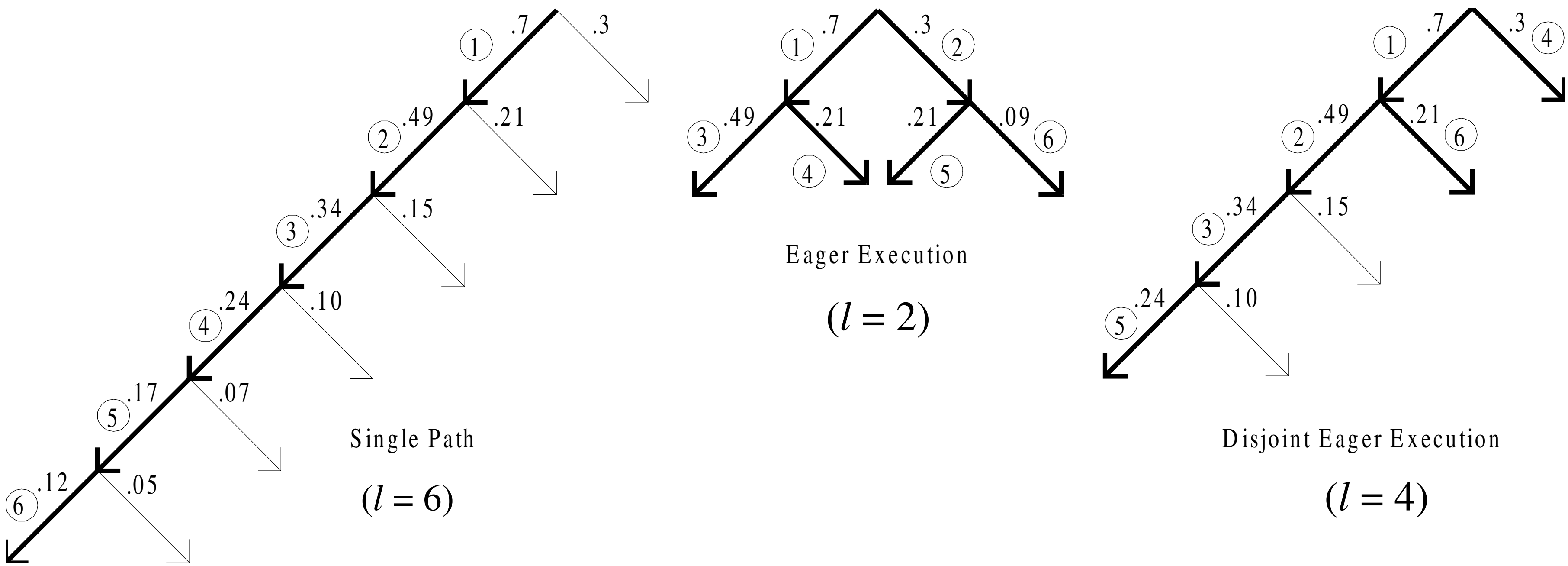
Assigning Resources



Assigning Resources



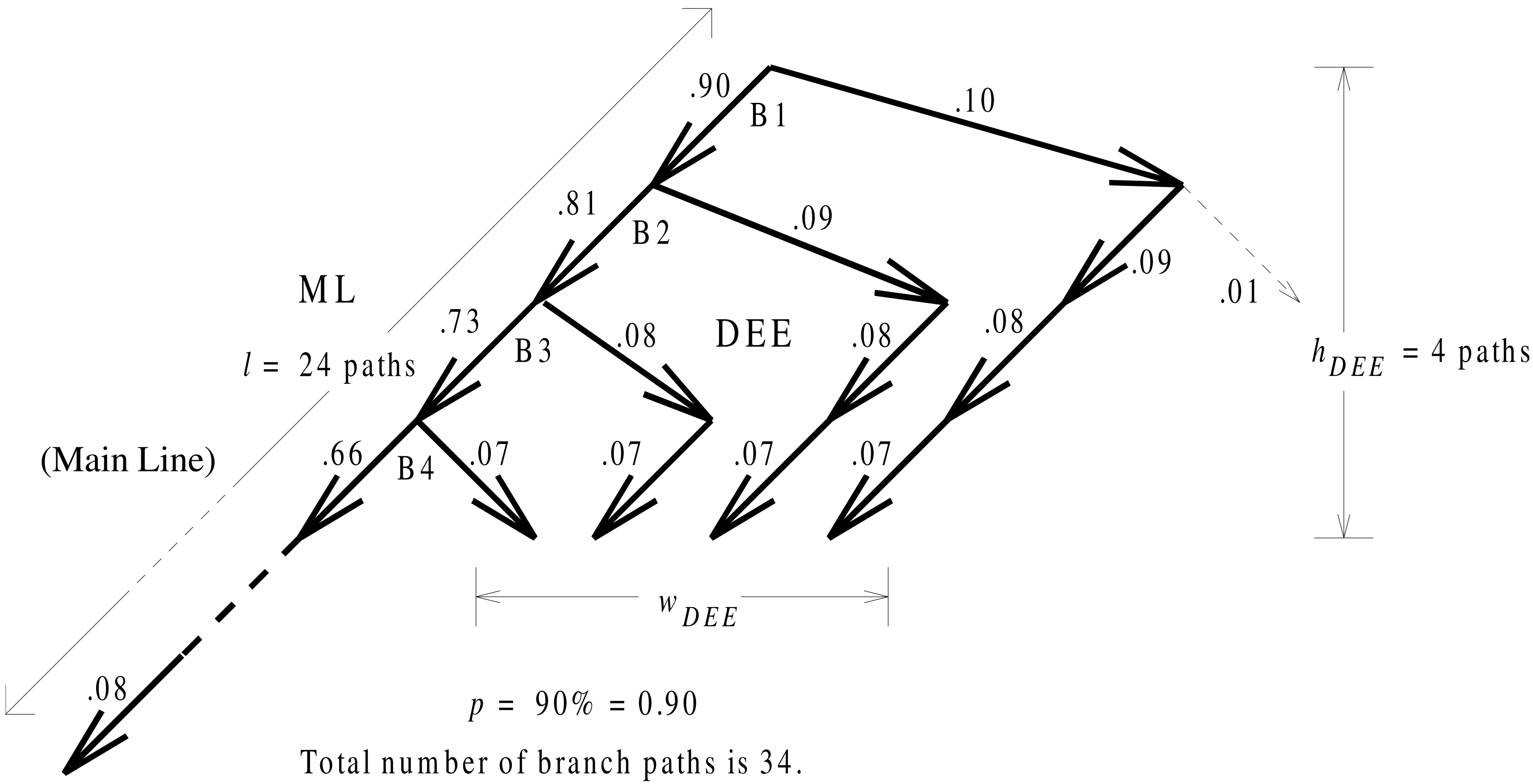
Comparison of SP, EE and DEE



DEE in Practice

- Problem: hard to compute "true" cumulative probabilities dynamically
- Solution: DEE *static tree* heuristic:
  - Use average branch prediction accuracy (bpa or *p*) for all branches
  - Static tree shape determined as part of machine design
  - Resources are fixed to the static tree
  - Cost: still $O(kl^2)$; $k<1$

Typical Static Tree



p = 90% = 0.90

Total number of branch paths is 34.

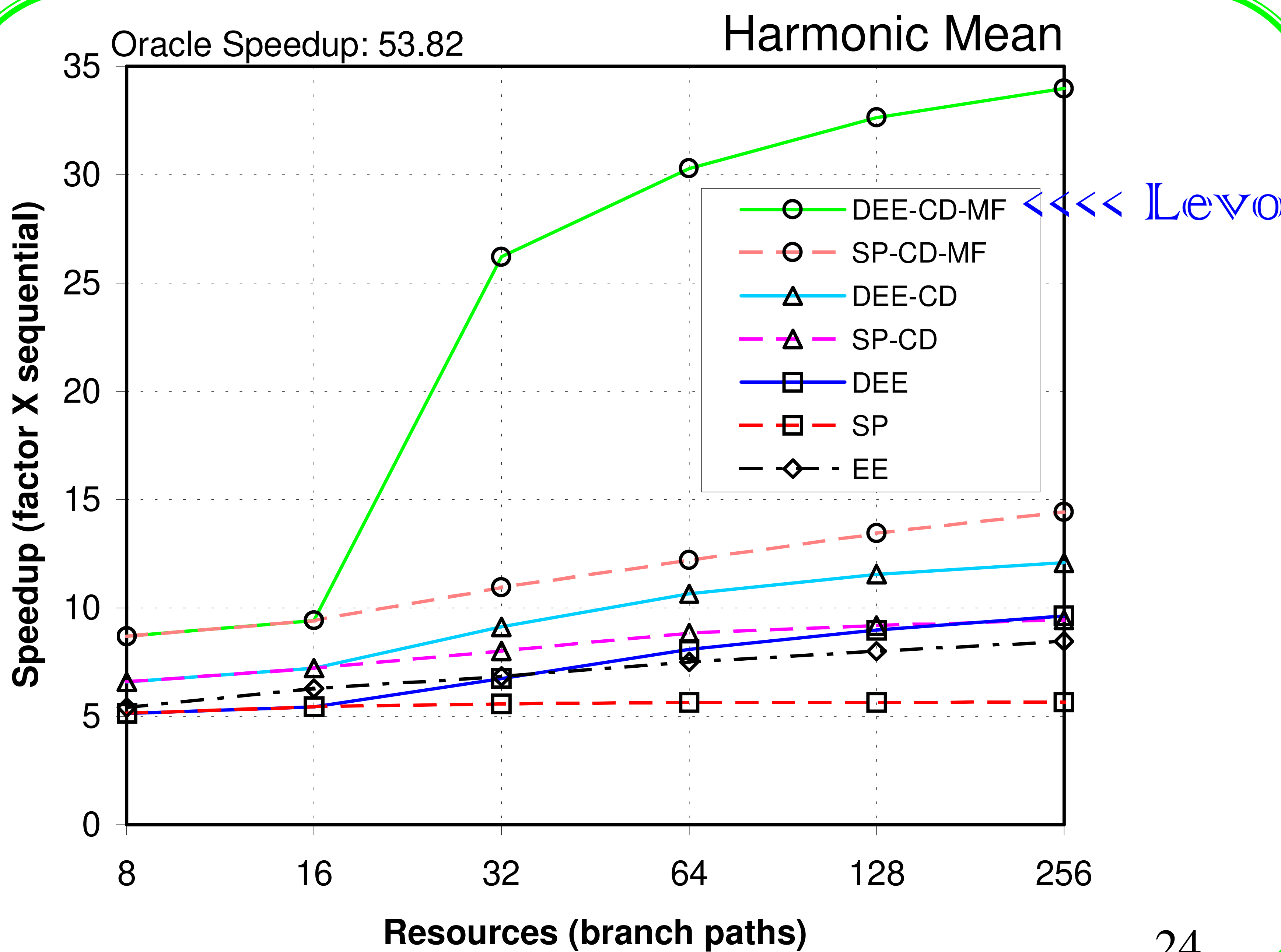
A number on a path is the overall probability of the path being executed.

DEE Performance Evaluation

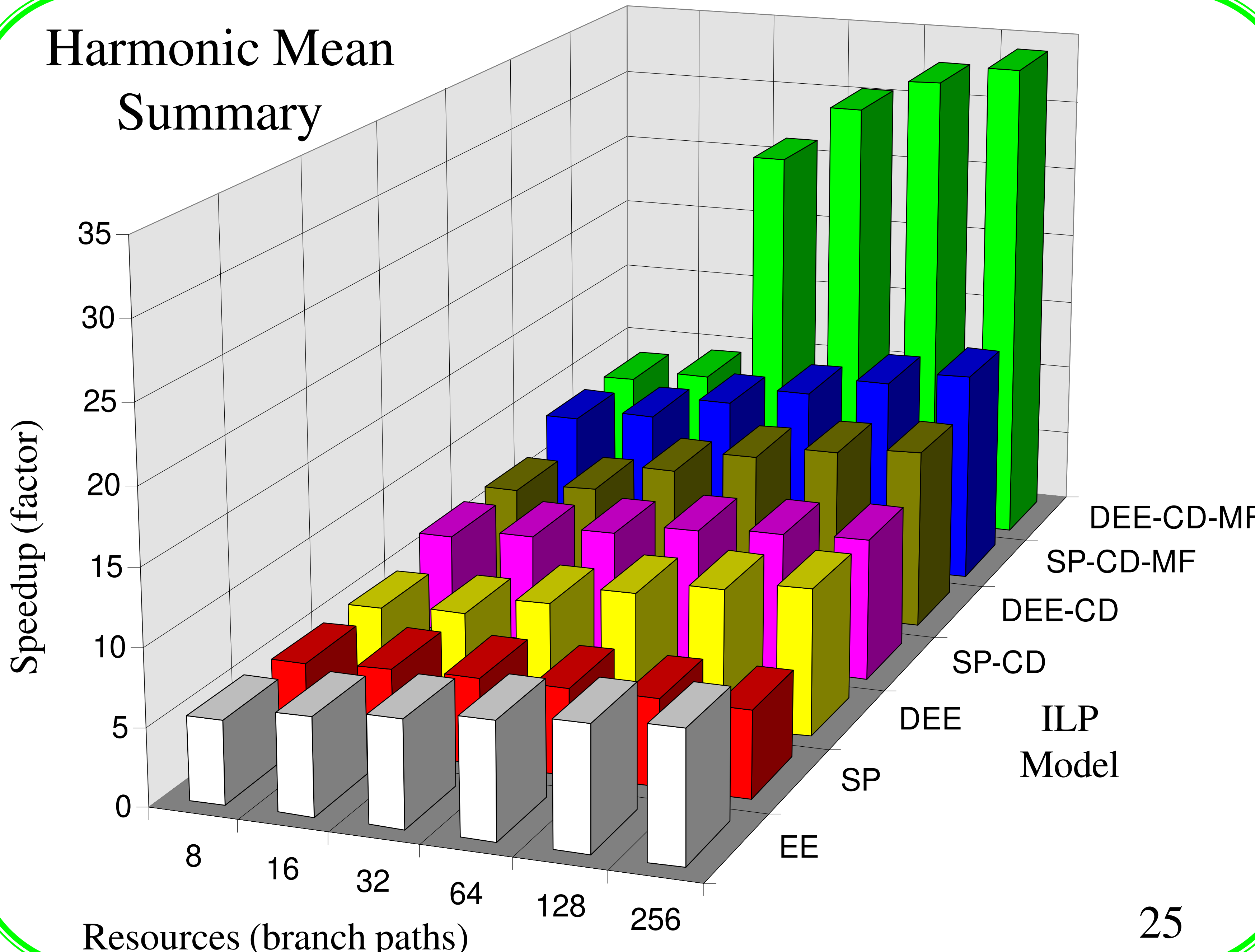
- Method: `pixie` and modified `dsim` used
- Assumptions:
  - Unit latency
  - Dynamic Instruction Stream
  - MIPS R3000 instruction set
  - Practical version (heuristic) of DEE modelled

Harmonic Mean Summary

- 5 of 6 SPECint92 benchmarks used:
  - `cc1`
  - `compress`
  - `eqntott`
  - `espresso`
  - `xlisp`
  - <=100 million instructions each
- 2-bit saturating counter predictor (Smith81)
- "CD-MF" = "Minimal Control Dependencies"
- "DEE-CD-MF" is DEE with MCD; used in Levo


Harmonic Mean
Oracle Speedup: 53.82
35
30
25
20
15
10
5
0
Speedup (factor X sequential)
8
16
32
64
128
256
Resources (branch paths)
DEE-CD-MF
SP-CD-MF
DEE-CD
SP-CD
DEE
SP
EE
<<<< Levo

Harmonic Mean Summary



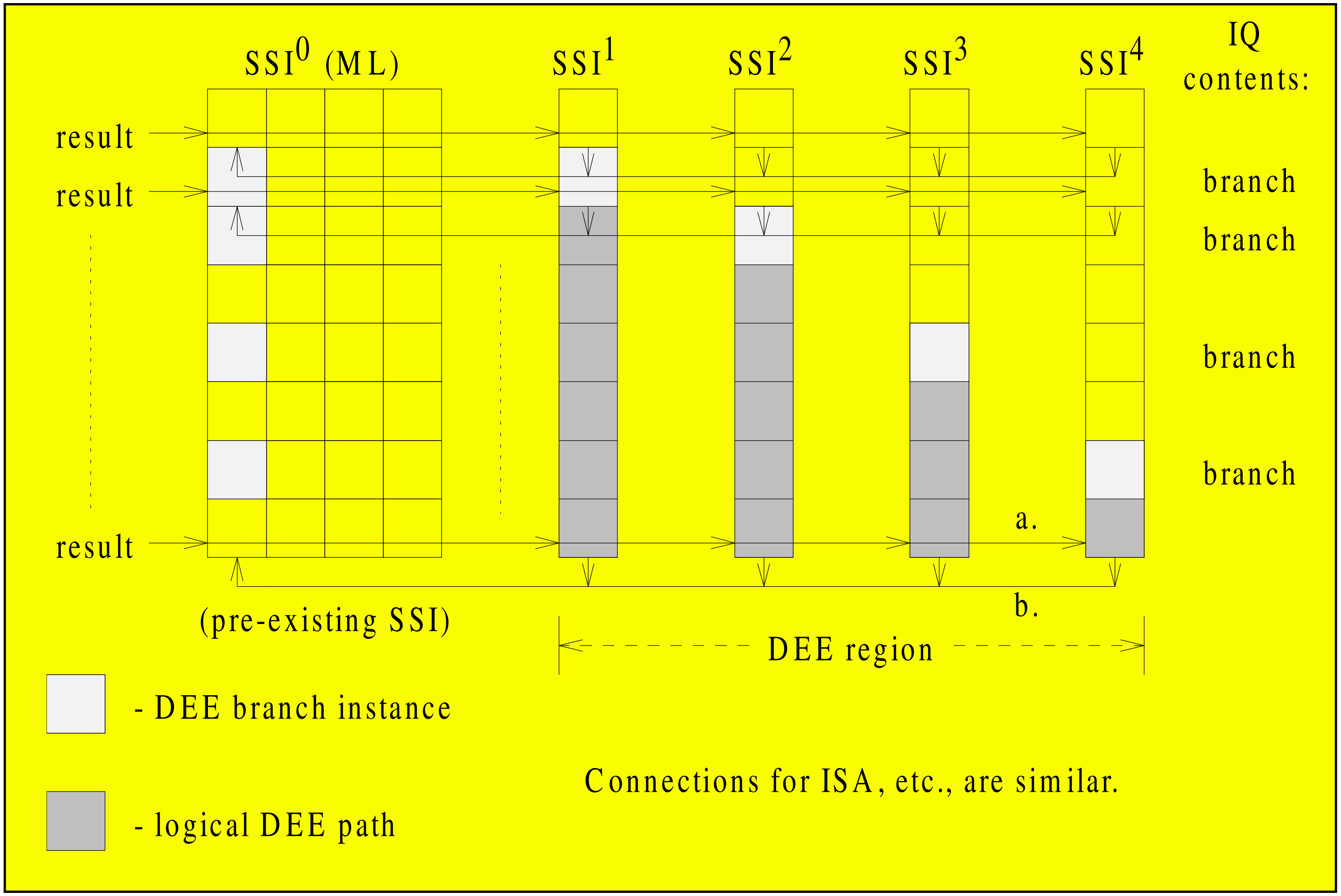
Comments on Results

- Speedup factors of 26-31 demonstrated with limited resources and DEE-CD-MF
- Combination of DEE and minimal control dependencies is necessary
- Speedup of 20 potentially achievable with

Levo

Levo

- Revised CONDEL-2 (Uht85, Uht92) + DEE
  - From CONDEL-2:
    - IQ: Instruction Queue: static instruction window
    - SSI: register and memory renaming registers
    - ISA: storage addresses, one per SSI
- Implements: DEE-CD-MF
- 1-to-1 correspondence with ML and DEE paths of static tree



a. - Broadcast bus for copying of ML state to DEE paths.

b. - Update bus for copying a DEE path state to ML path,
upon a DEE branch resolving as mispredicted.

Levo

Note: a. and b. can be combined into a single bidirectional bus.

Summary

- Disjoint Eager Execution (DEE):
  - Optimal speculative execution
  - Realizes high ILP's even with hard-to-predict-branch-intensive general-purpose code
  - Achieves 59% of oracle performance
  - Ideas useful elsewhere:
    - Multiprocessors
    - VLIW / software-based ILP machines