Focusing Processor Policies via Critical-Path Prediction

ISCA 2001

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Presented by

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Executive Summary

Motivation:

- Egalitarian scheduling policies in processors waste resources
- Increasing parallelism and sophistication in processors justify critical path analysis

Key Idea:

- Predict whether an instruction is on the critical path in hardware while keeping cost for graph model as low as possible

Challenges:

- Compile-time optimizations only consider data dependences
- Processor only ever sees fraction of program
  - -> How to optimize for global critical path?

Key Mechanism:

- Token-passing algorithm to estimate criticality of nodes

Results:

- Better scheduling improves CPU performance up to 21%
- Optimized prediction improves CPU performance up to 5%

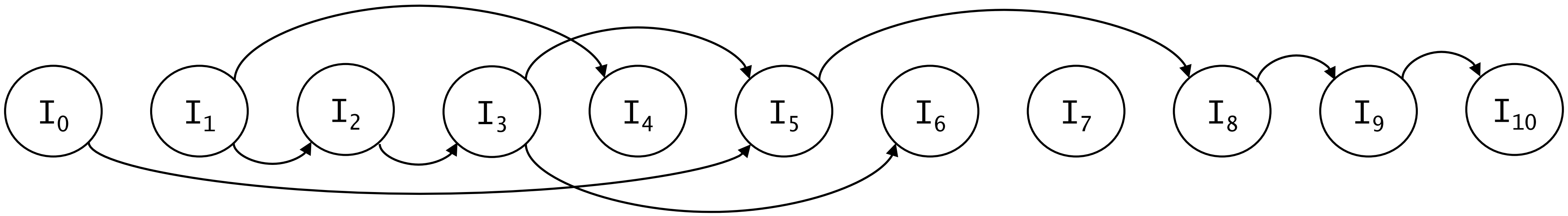
Overview

- The Model of the Critical Path
- Predicting the Critical Path in Hardware
- Applications of the Critical Path Detection
- Conclusion
- Paper Analysis
- Discussion

Compiler Model of Dependences

```
   I0:   r5 = 0
   I1:   r3 = ld[r2]
L1 I2:   r1 = r3*6
   I3:   r6 = ld[r1]
   I4:   r3 = r3+1
   I5:   r5 = r6+r5
   I6:   cmp R6,0
   I7:   br L1
   I8:   r5 = r5+100
   I9:   r0 = r5/3
   I10:  ret r0
```

Compiler optimizes execution by **analysing data dependences**



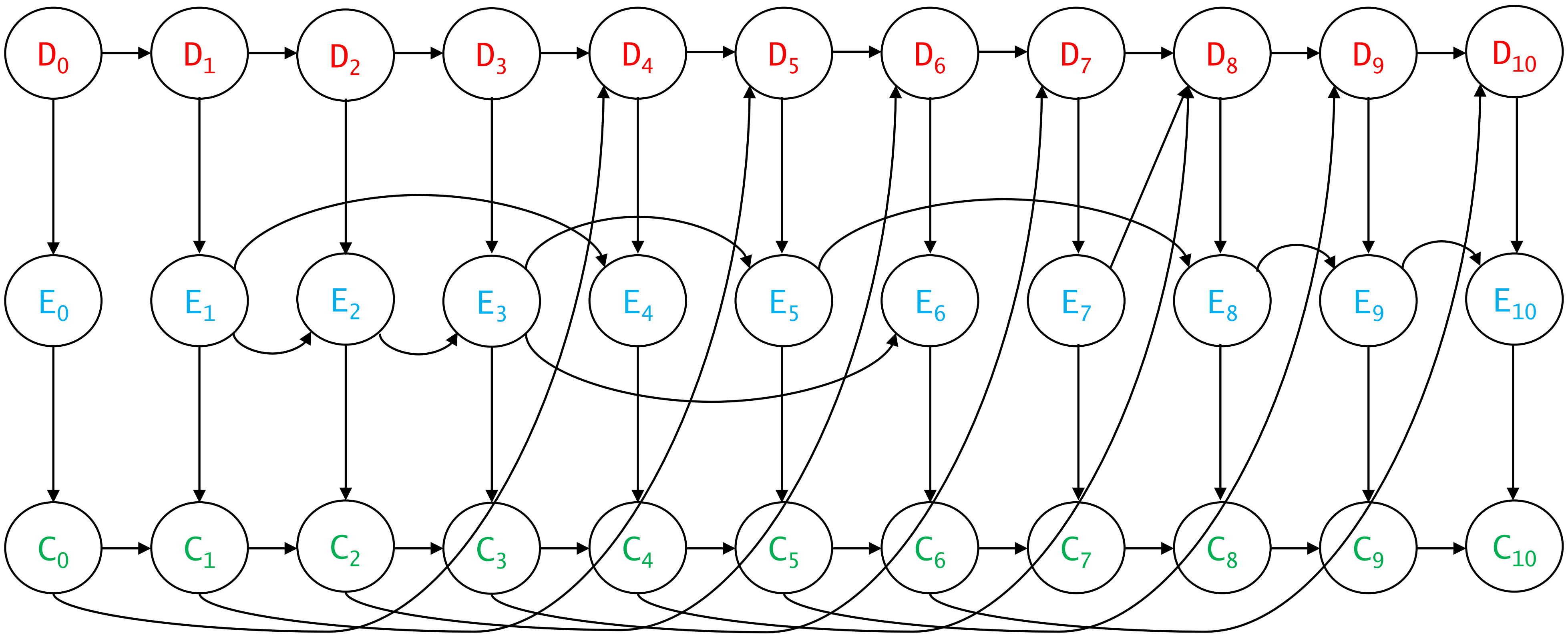
Weaknesses of Compiler Based Approaches

Compiler models critical path solely based on data-dependece

-> Other dependences and hardware constraints are not considered, i.e:

- Control dependences
- In-Order dependences
- Re-order buffer limitations
- ...

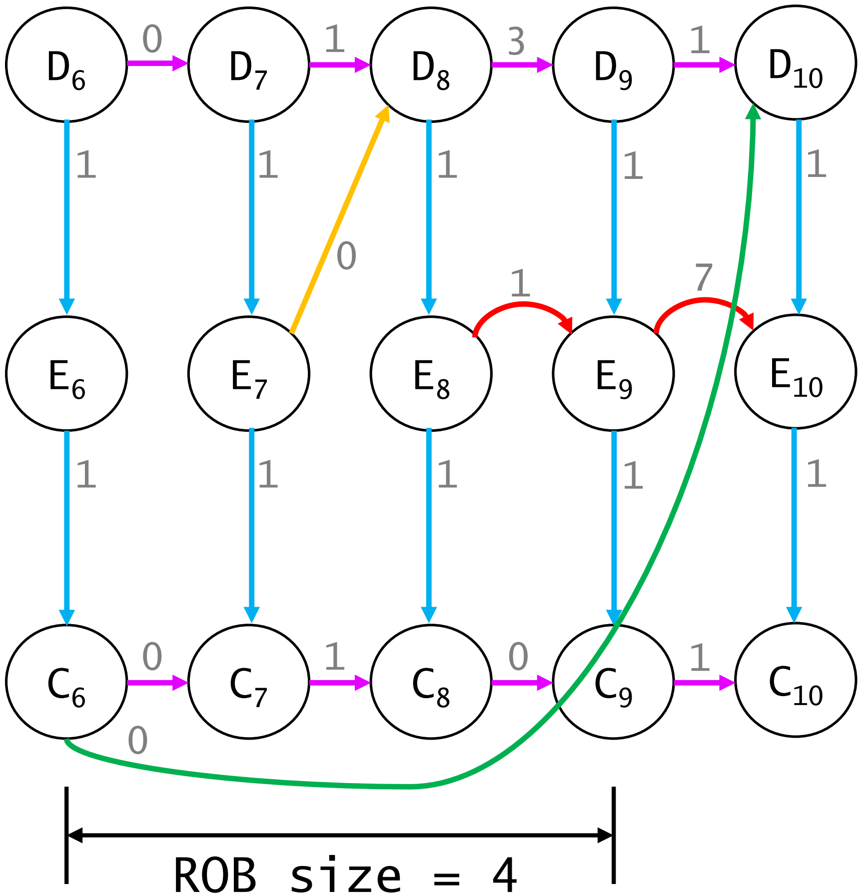
Model of the Critical Path



Idea: Model each dynamic instruction with 3 nodes

Dispatch Node	D_i
Execute Node	E_i
Commit Node	C_i

Classification of Edges



DE: Execution follows dispatch

EC: Commit follows execution

DD: In-order dispatch

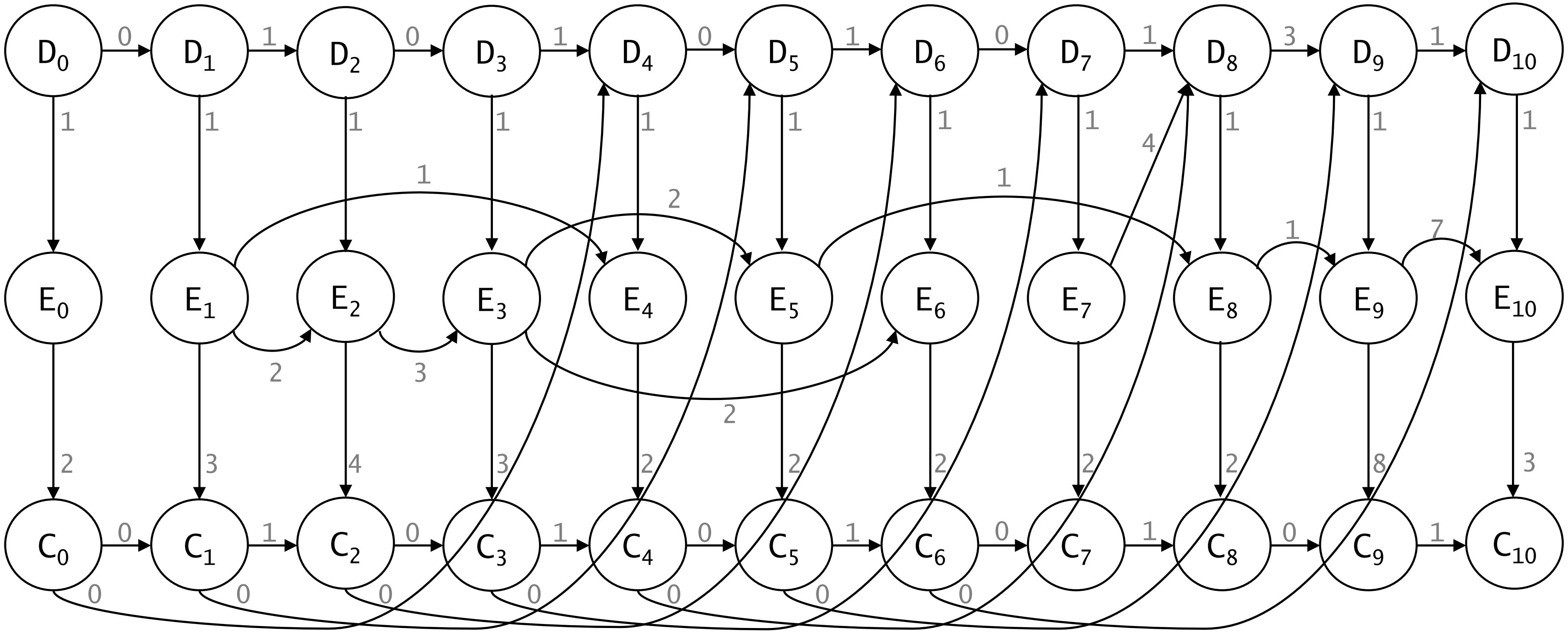
CC: In-order commit

EE: Data dependences

CD: Finite re-order buffer

ED: Control dependence

Critical Instructions



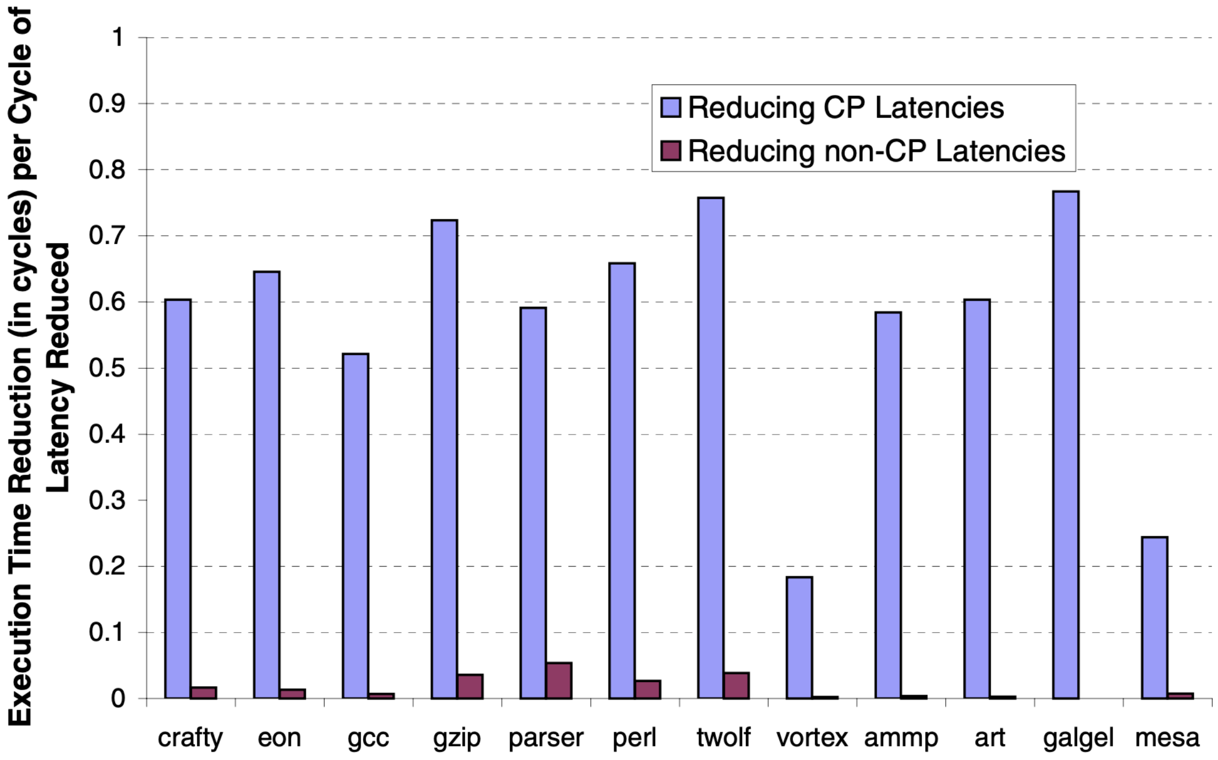
-> Critical Instructions: I_0, I_1, I_2, I_3, I_7, I_8, I_9, I_{10}

Validation of Critical Path Model: Methodology

1. Run simulation with benchmark workloads as baseline.
2. Build critical path graph from baseline run.
3. Run two comparison simulations:
   1. All critical path latencies decreased by 1
   2. All non-critical path latencies decreased by 1

-> Idea: If latencies on critical path are reduced, overall execution time must be reduced too

Validation of Critical Path Model: Results

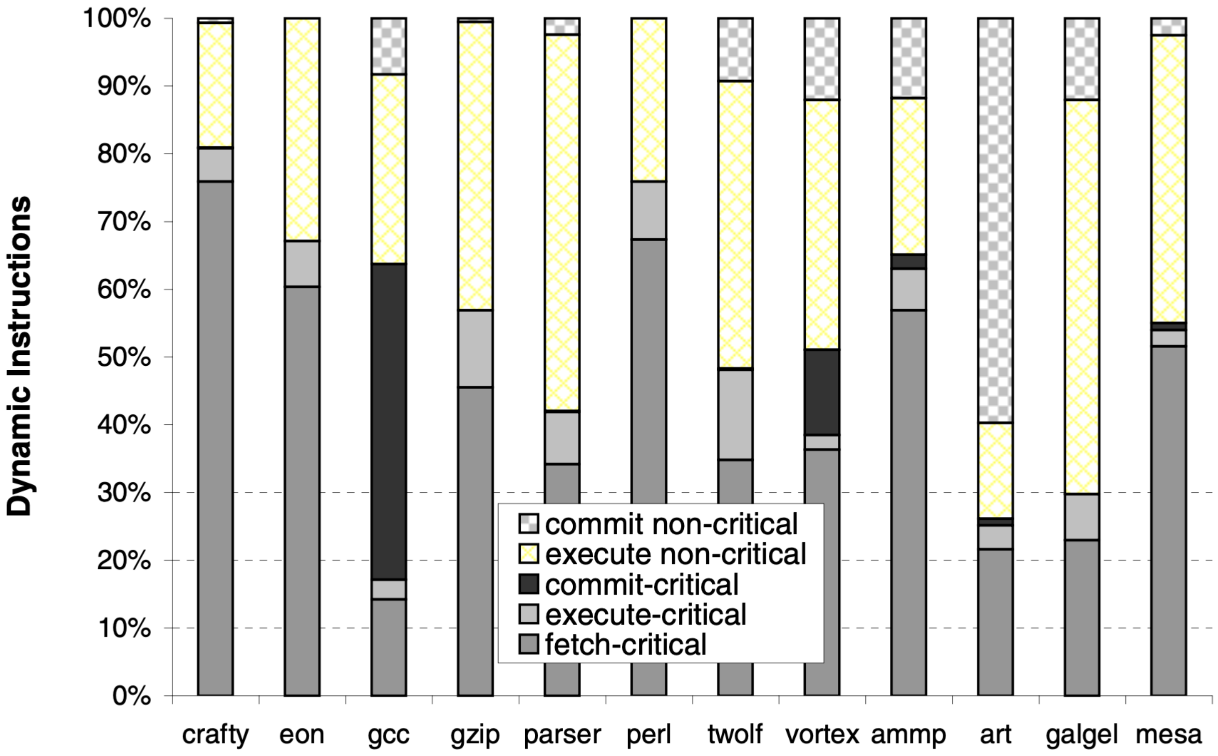


(a) Validation of the critical Path

- Execution time reduction for reduced CP latencies suggests model is good at identifying critical instructions

- Nice insight: Reduction ratio can be used as measure of critical path dominance

Validation of Critical Path Model: Results



(b) Breakdown of the dynamic instruction count

- Only 26-80% of instructions are critical
- More specifically, only 2-13% of instructions are execute critical

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The *Last-Arriving* Rules

Observation: Critical Path can be computed solely by observing the arrival order of instruction operands

-> If a dependence between nodes i and j (i<j) is the last to be resolved for node j, the according edge from i to j is called *last-arriving*

-> Each edge on the critical path is last- arriving edge

-> If an edge is not last-arriving, it is not critical

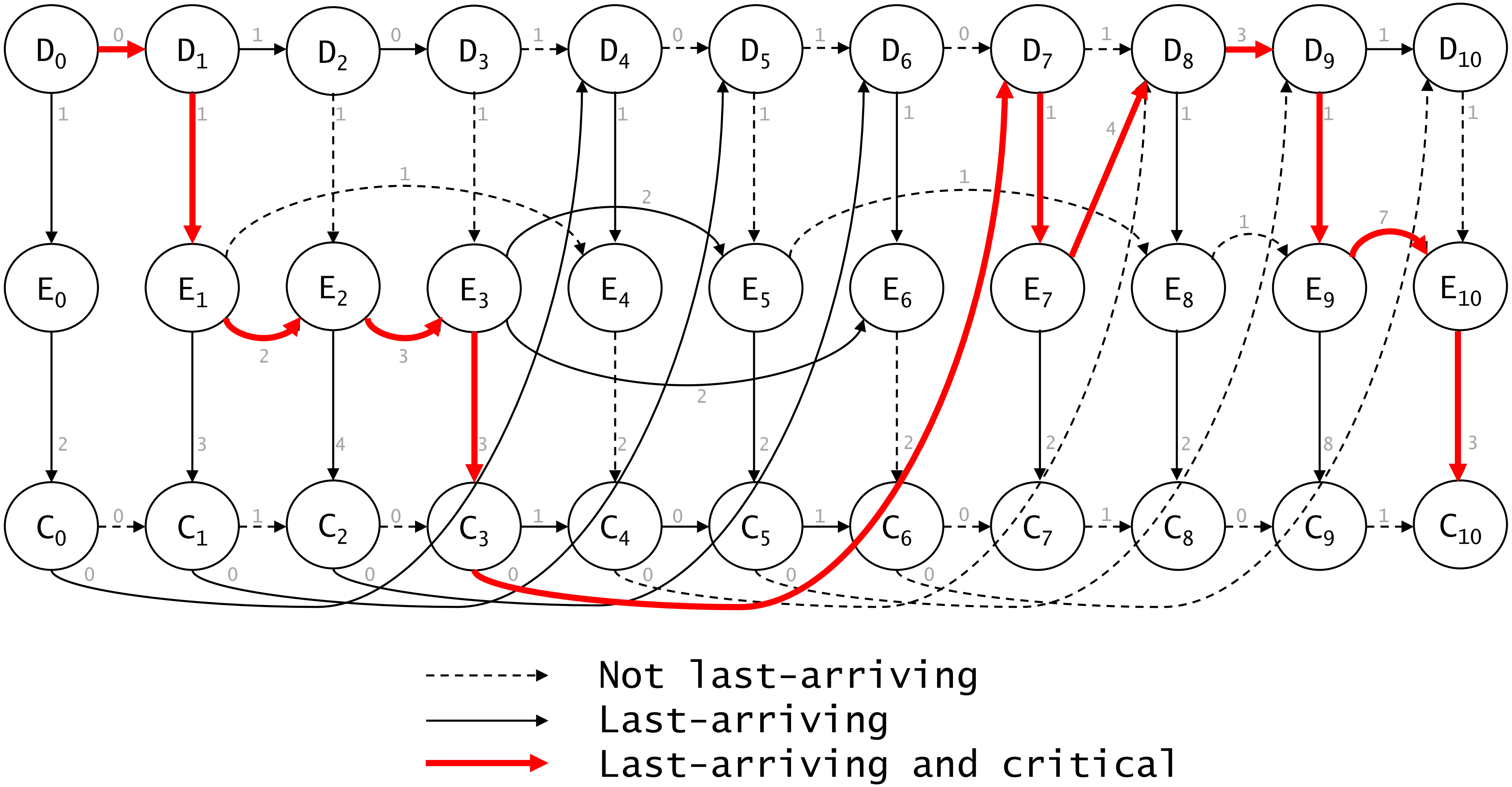
Building the Critical Path (in Simulation)

- Start at commit node of last instruction

- Traverse graph backwards along last-arriving edges

- Done when arrived at dispatch node of first instruction -> Critical path complete!

Critical Path Model with Last-Arriving Edges



Building the Critical Path

This approach works for simulations, but is too expensive to implement in hardware

- We would have to save almost the entire graph
- Backwards traversal not trivial

Key Mechanism: The Token-Passing Critical Path Predictor

Approximate CP with following intuiton:

> Critical path is chain of last arriving edges through entire graph -> long last-arriving chain is *likely* to be part of critical path

Such a chain can be found with *forward propagation* of tokens

-> Requires no graph building at all!

Token-Passing Algorithm

1. Plant token at node n

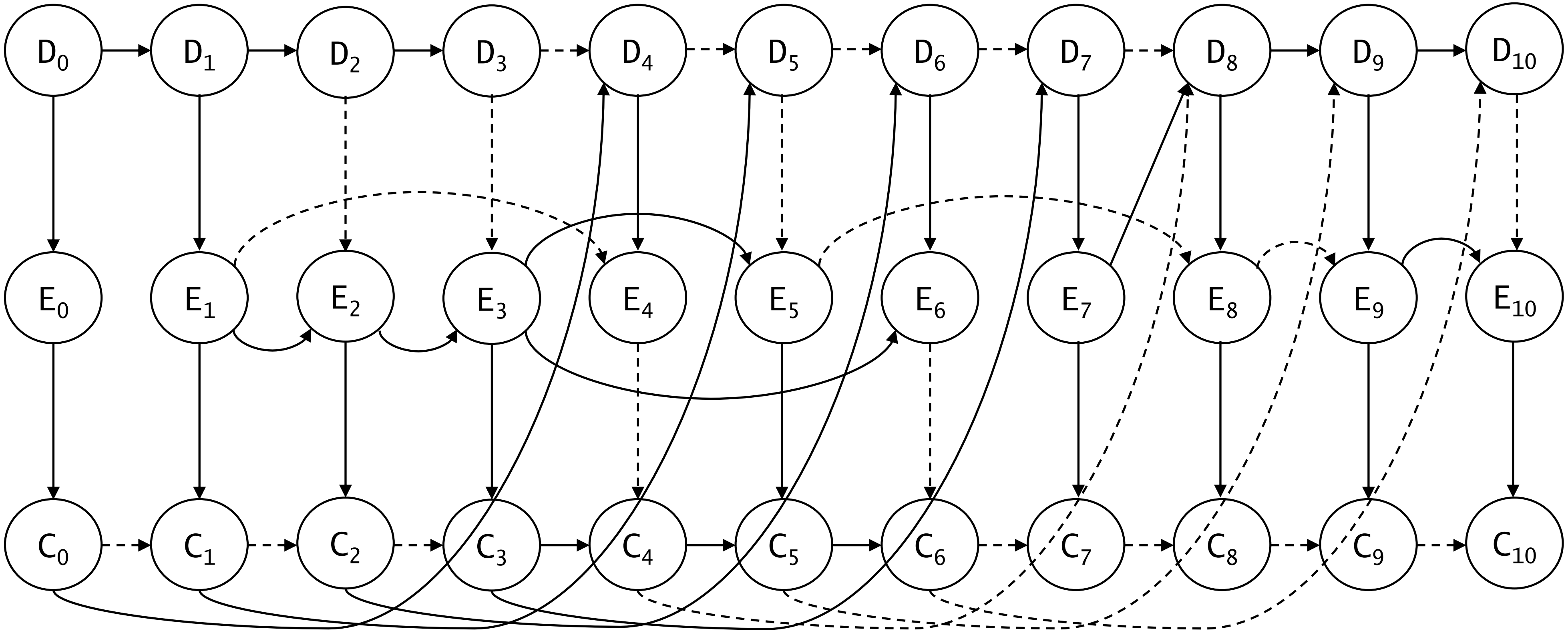
2. Propagate token forward along last-arriving edges.

   -> If a node doesn't have an outgoing last-arriving edge, the token dies.

3. After allowing token to propagate for some time, check if token is still alive

4. If token is alive, train node as critical; otherwise, train n as non-critical

Token-Passing Algorithm: Visualization



Prediction: C_3 is critical

Hardware Implementation: Specs

Critical path table is conventional array indexed by the PC of the instruction

Trainer is implemented as a small token array. It stores information about the [ROB_size] most recent instructions committed

-> No critical path dependence can span more than [ROB_size] entries

Hardware Implementation: Training Parameters

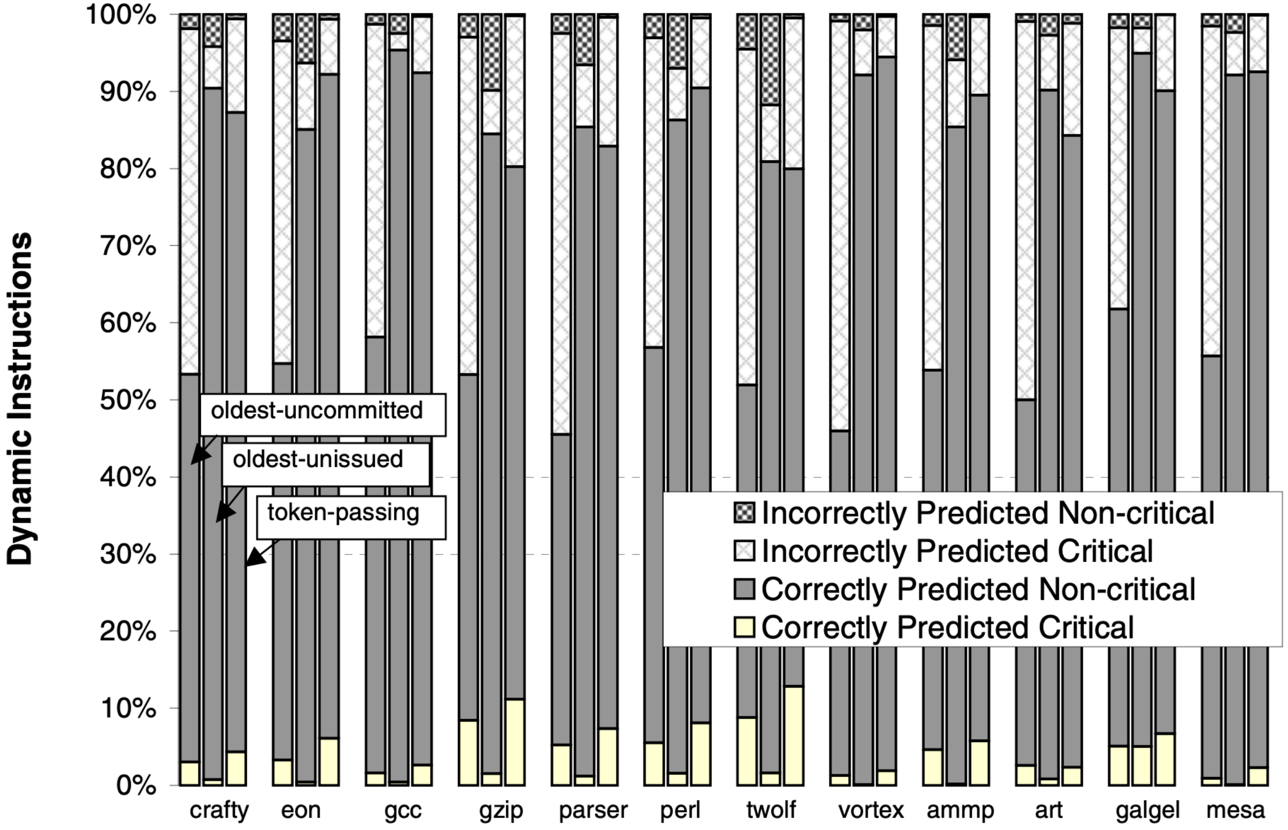
Critical path prediction table:	12 kilobytes (16K entries * 6 bit hysteresis)
Token propagation Distance:	1012 Dynamic instructions (500 + ROB size)
Maximum #tokens in flight:	8
Hysteresis:	Saturate at 63, increment by 8 when training critical, decrement by 1 when training non-critical. Instruction is predicted critical if hysteresis is above 8.
Planting Tokens:	A token is planted randomly in the next 10 instructions after it becomes available

Evaluating the CP Predictor: Methodology

We want to evaluate the accuracy of the proposed predictor

- Compare predictions to ”ideal” critical path model
- Comparison of latency reduction against two heuristics:
  - oldest-unissued instruction is critical
  - oldest-uncommitted instruction is critical

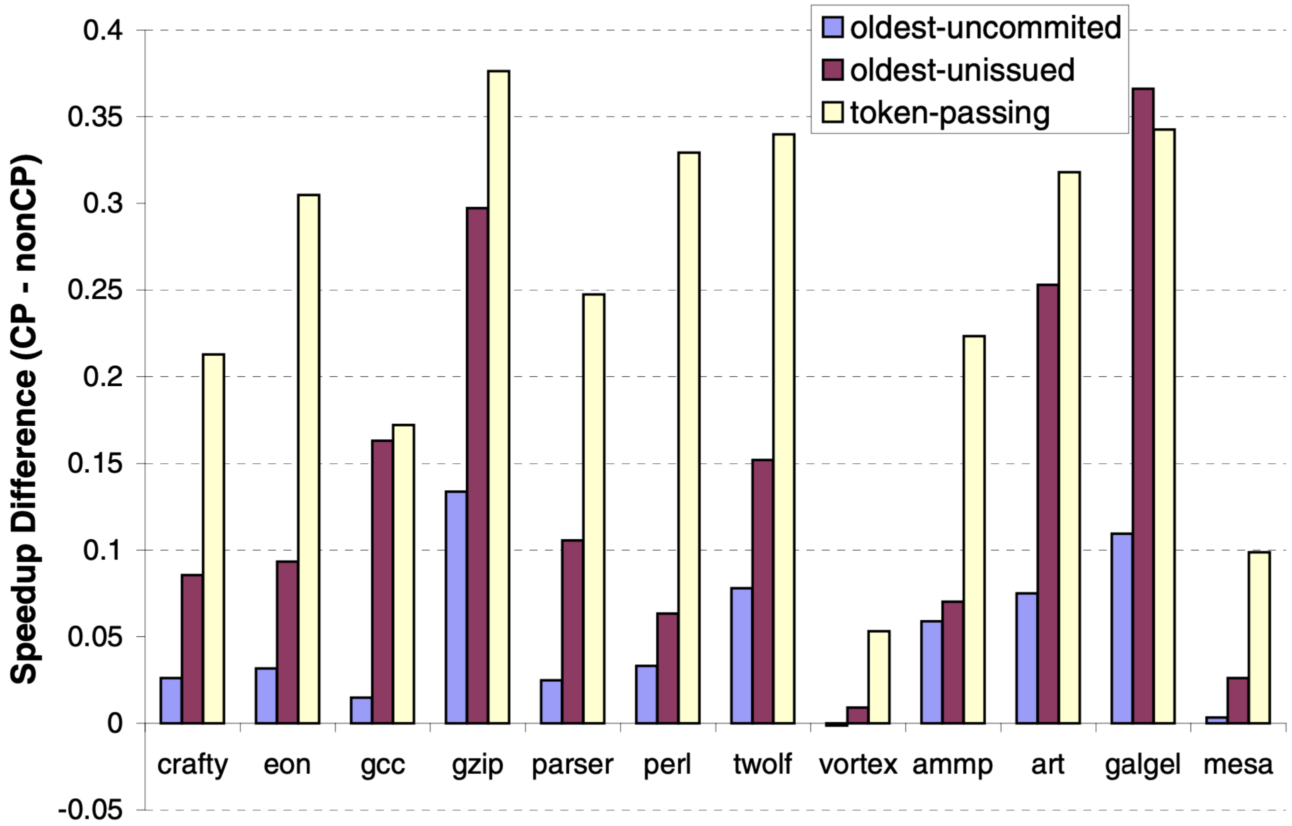
Evaluating the CP Predictor: Results



(a) Comparison against ideal CP trace

- Up to 88% accuracy (avg. 80%)
- Especially good at correctly predicting critical instructions

Evaluating the CP Predictor: Results



(b) Comparison via latency reduction

- Comparison against heuristics for evaluation independent of critical path model
- Heuristics work nicely for some workloads
- But CP Predictor is most robust across different workloads

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Applications of the Critical Path

The following applications are examined in the paper:

- Focused cluster instruction scheduling and steering
- Focused value prediction

Focused Cluster Instruction Scheduling and Steering

Complexity of increasingly large instruction windows has prompted proposals of clustering (partitioning) instruction windows and functional units. This introduced new challenges:

-> Latency to bypass results increased -> Instruction steering

-> Functional unit contention increased due to smaller issue width -> Instruction scheduling

-> Steering policies have conflicting goals: Good load balancing might increase inter-cluster bypass latency

Decreasing Inter-Cluster Bypass Latency

Baseline policy: Register-dependence steering

Assign instruction to cluster that procuces one of its operands.

If there is more than one producing cluster (tie), choose cluster with fewest instructions.

Decreasing Inter-Cluster Bypass Latency

Modified policy: Focused instruction steering

- Assign instruction to cluster that produces one of its operands.
- If there is more than one producing cluster (tie) and instruction is critical, it is placed into the cluster of its critical predecessor.

Decreasing Functional Unit Contention

Baseline policy: Prioritize long latency instructions

Modified policy: Schedule critical instructions before non-critical ones

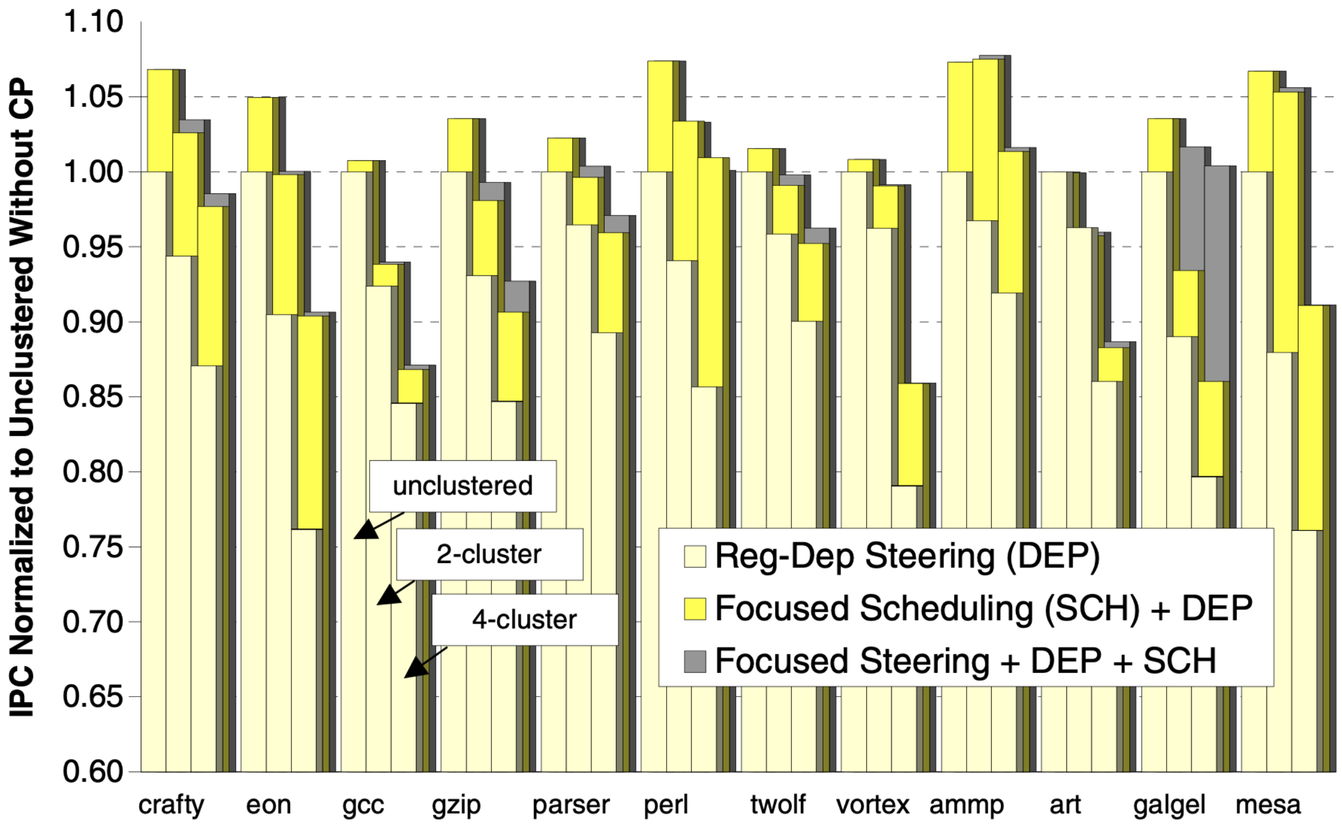
-> Goal: Add contention only to non-critical instructions

Evaluating Proposed Policies – Methodology

- Same workloads as before
- Observing performance degradation of
  - 2-clustered 4-way issue architecture
  - 4-clustered 2-way issue architecture

  compared to unclustered architecture
- Further comparison against heuristics seen before

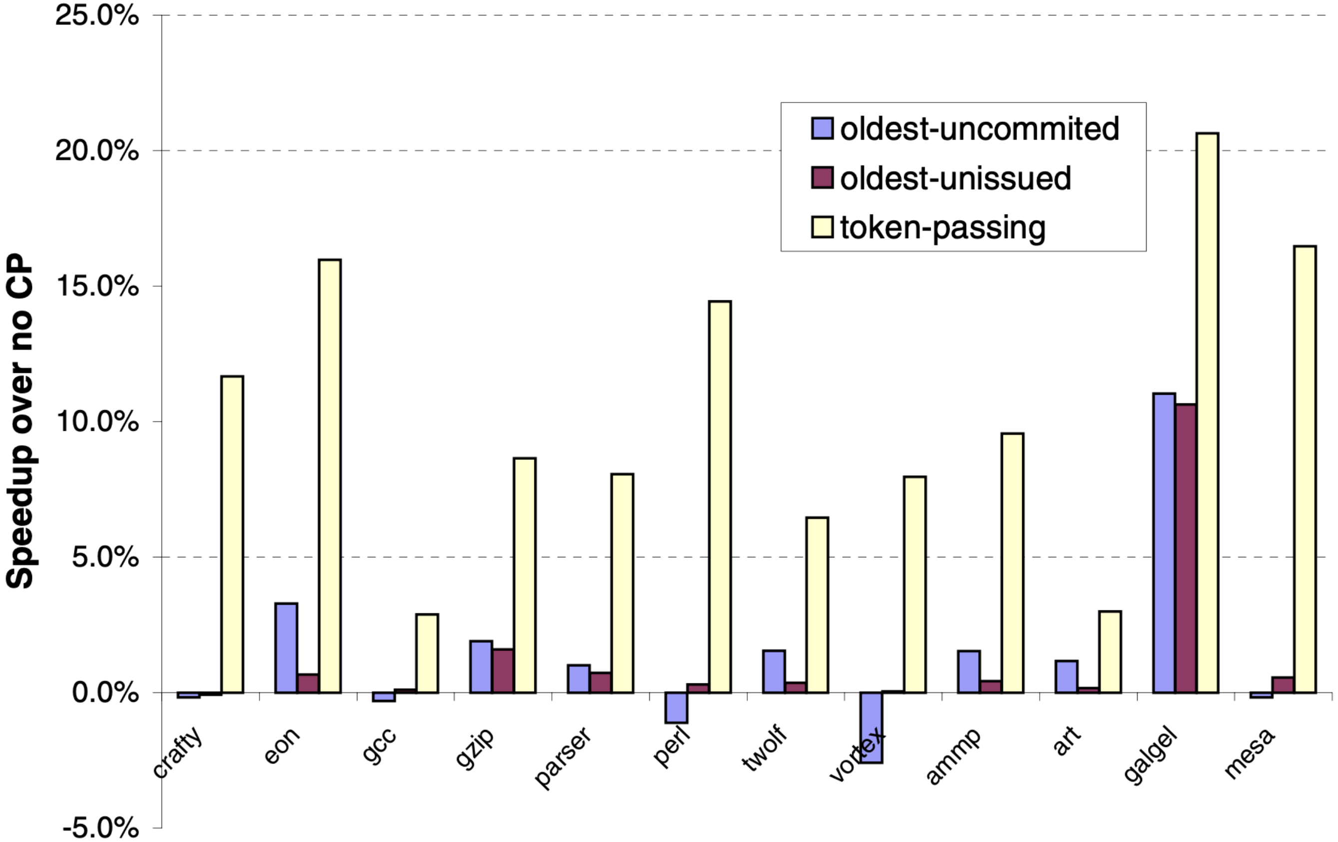
Evaluating Proposed Policies – Results



(a) Scheduling in clustered architectures

- Unclustered: Speedup of up to 7% (Average 3.5%)
- 2-cluster: Average slowdown from 7% improved to slight speedup of 1%
- 4-cluster: Degradation improved from 19% to 6%

Evaluating Proposed Policies – Results



(b) Comparison to heuristics based predictors

- Token-passign algorithm clearly more effective

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Questions about the paper?

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Paper Strengths

- Fundamentally novel approach with global critical path prediction at little hardware cost

- Many possible applications for critical path

- Nice insight from validation approach

  i.e. dominance of critical path

Paper Weaknesses

- Validation method not really sound. Increasing all edge weights by one can have unwanted consequences.
  -> Solid proof not possible?
- Hardware implementation ambiguous
- No sensitivity analysis for training parameters

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Expanding the Critical Path Model

- How could the critical path model be expanded to capture more dependences and increase precision?
  - Cache-line-sharing and other memory dependences are not captured by model
  - What are other dependences you can think of that are not captured?

Training parameters

-> How could we tweak the training parameters to increase performance / adapt to usecase?

-> Interesting parameters:

- Token propagation distance
- Maximum number of tokens in flight
- Hysteresis
- Token-planting heuristic

Applications

-> What other applications can you imagine for critical path analysis?

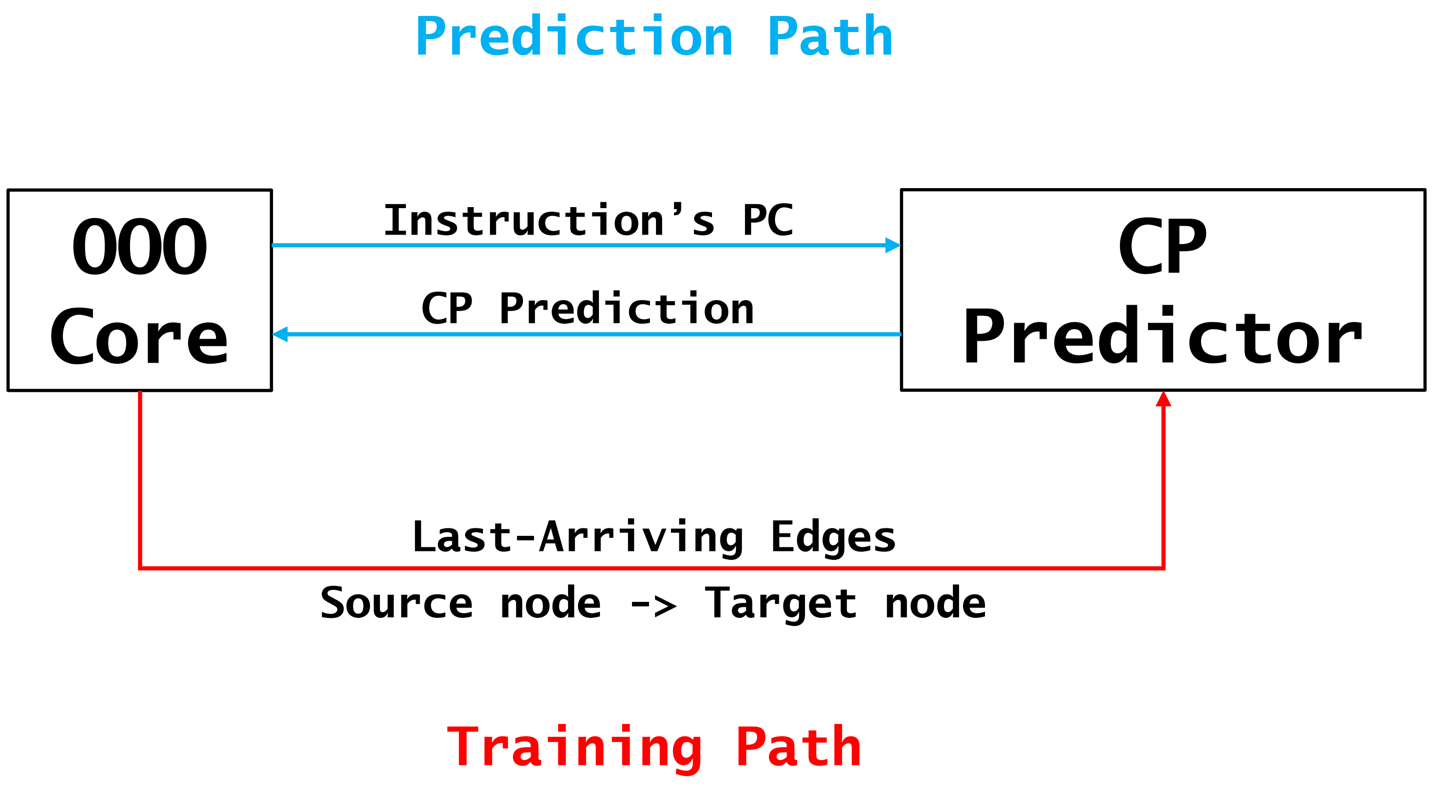
-> Some ideas:

- Scheduling memory accesses in GPUs by criticality (Adwait Jog, et al. SIGMETRICS 2016)
- Optimizing cache prefetching (Anant Vithal Nori, et al. ISCA 2018)
- Focused Value Prediction (Summet Bandishte, et al. ISCA 2020)

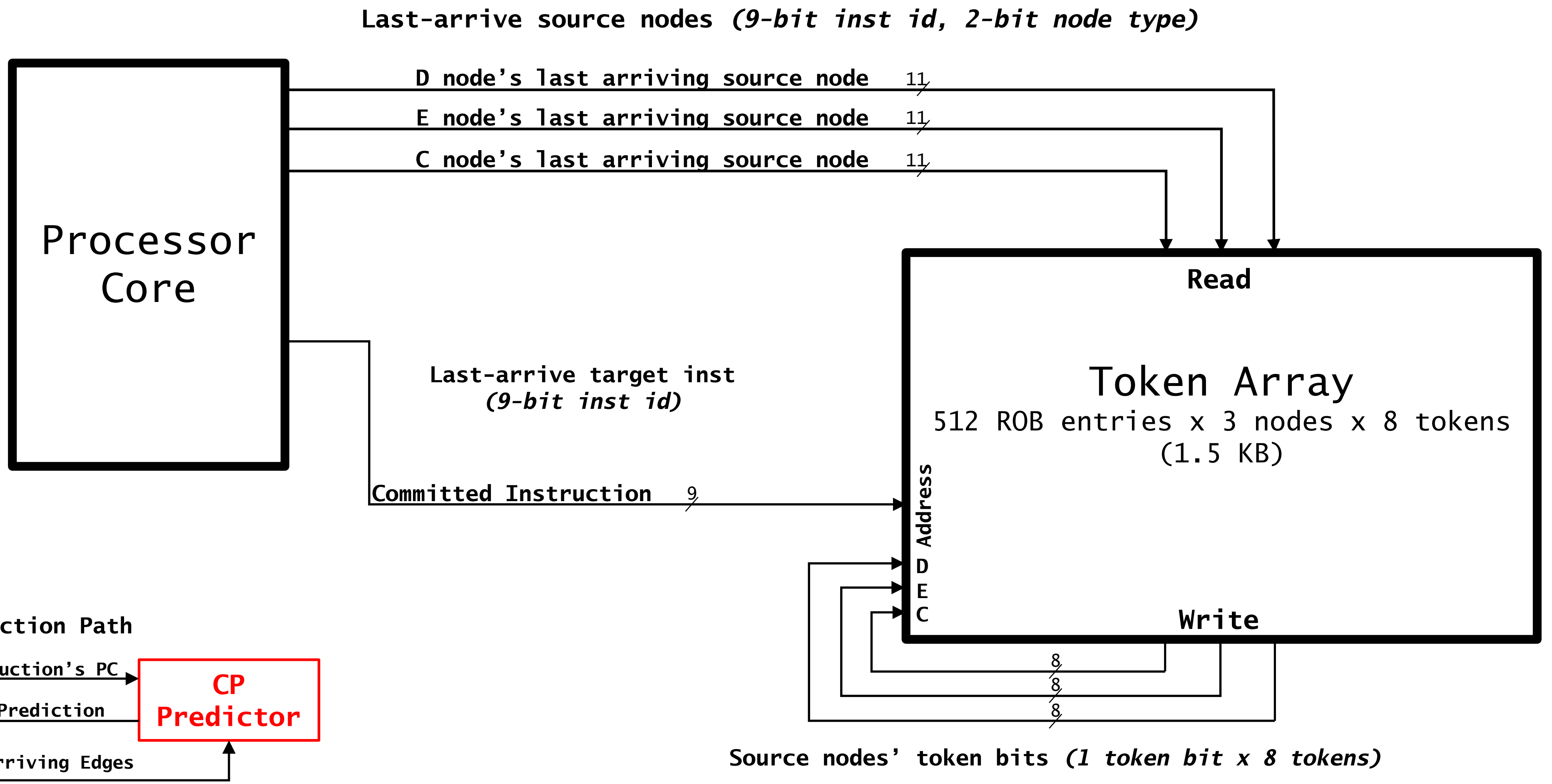
Thank you for your attention!

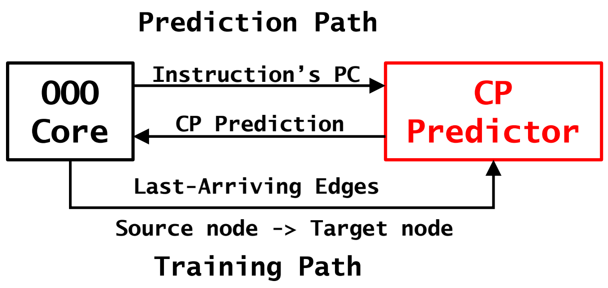
Back-Up Slides

Hardware Implementation



Hardware Implementation: The Critical Path Predictor





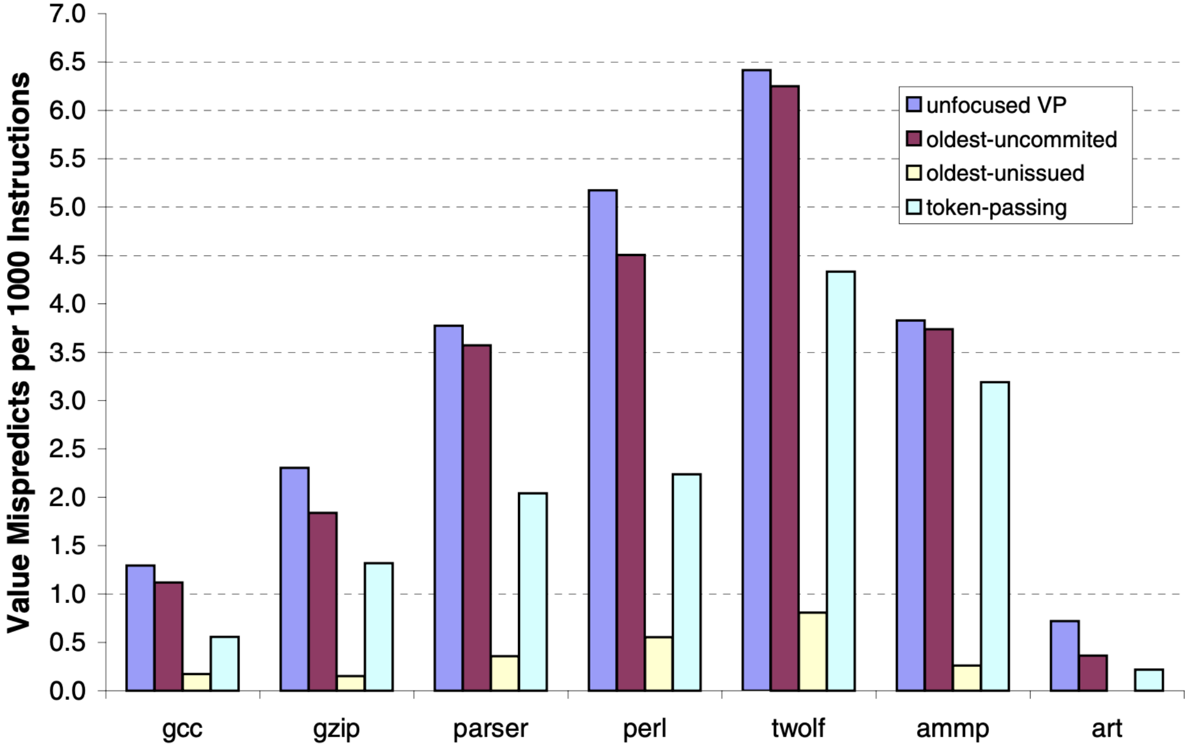
Focused Value Prediction

Idea: Try to predict result of calculation to break data-flow dependences

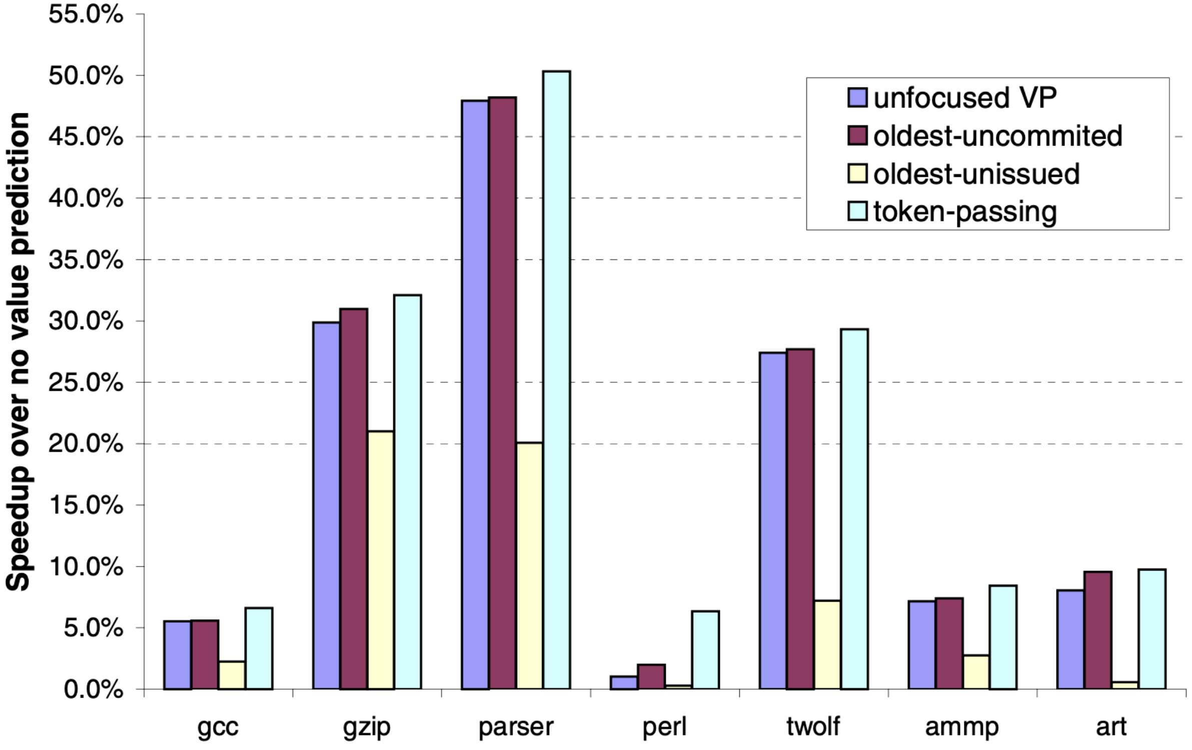
Problem: If non-critical instructions are mispredicted, it might severely degrade performance. If correct, nothing gained.

-> Only make predictions for critical instructions

Focused Value Prediction: Evaluation



(a) Value misspeculations



(b) Speedup of focused value prediction