Required Readings

This week


- H&H Chapters 7.8 and 7.9

Agenda for Today & Next Few Lectures

- Single-cycle Microarchitectures
- Multi-cycle and Microprogrammed Microarchitectures
- Pipelining
- Issues in Pipelining: Control & Data Dependence Handling, State Maintenance and Recovery, ...
- Out-of-Order Execution
- Other Execution Paradigms
Approaches to (Instruction-Level) Concurrency

- Pipelining
- Out-of-order execution
- Dataflow (at the ISA level)
- Superscalar Execution
- VLIW
- Fine-Grained Multithreading
- SIMD Processing (Vector and array processors, GPUs)
- Decoupled Access Execute
- Systolic Arrays
Control Dependence Handling
Control Dependence

- Question: What should the fetch PC be in the next cycle?
- Answer: The address of the next instruction
  - All instructions are control dependent on previous ones. Why?

- If the fetched instruction is a non-control-flow instruction:
  - Next Fetch PC is the address of the next-sequential instruction
  - Easy to determine if we know the size of the fetched instruction

- If the instruction that is fetched is a control-flow instruction:
  - How do we determine the next Fetch PC?

- In fact, how do we even know whether or not the fetched instruction is a control-flow instruction?
## Branch Types

<table>
<thead>
<tr>
<th>Type</th>
<th>Direction at fetch time</th>
<th>Number of possible next fetch addresses?</th>
<th>When is next fetch address resolved?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conditional</td>
<td>Unknown</td>
<td>2</td>
<td>Execution (register dependent)</td>
</tr>
<tr>
<td>Unconditional</td>
<td>Always taken</td>
<td>1</td>
<td>Decode (PC + offset)</td>
</tr>
<tr>
<td>Call</td>
<td>Always taken</td>
<td>1</td>
<td>Decode (PC + offset)</td>
</tr>
<tr>
<td>Return</td>
<td>Always taken</td>
<td>Many</td>
<td>Execution (register dependent)</td>
</tr>
<tr>
<td>Indirect</td>
<td>Always taken</td>
<td>Many</td>
<td>Execution (register dependent)</td>
</tr>
</tbody>
</table>

Different branch types can be handled differently
How to Handle Control Dependences

- Critical to keep the pipeline full with correct sequence of dynamic instructions.

- Potential solutions if the instruction is a control-flow instruction:
  - Stall the pipeline until we know the next fetch address
  - Guess the next fetch address (branch prediction)
  - Employ delayed branching (branch delay slot)
  - Do something else (fine-grained multithreading)
  - Eliminate control-flow instructions (predicated execution)
  - Fetch from both possible paths (if you know the addresses of both possible paths) (multipath execution)
Stall Fetch Until Next PC is Known: Good Idea?

This is the case with non-control-flow and unconditional br instructions!
The Branch Problem

- Control flow instructions (branches) are frequent
  - 15-25% of all instructions

- Problem: Next fetch address after a control-flow instruction is not determined after N cycles in a pipelined processor
  - N cycles: (minimum) branch resolution latency

- If we are fetching W instructions per cycle (i.e., if the pipeline is W wide)
  - A branch misprediction leads to $N \times W$ wasted instruction slots
Importance of The Branch Problem

- Assume $N = 20$ (20 pipe stages), $W = 5$ (5 wide fetch)
- Assume: 1 out of 5 instructions is a branch
- Assume: Each 5 instruction-block ends with a branch

How long does it take to fetch 500 instructions?

- **100% accuracy**
  - 100 cycles (all instructions fetched on the correct path)
  - No wasted work; IPC = 500/100

- **99% accuracy**
  - 100 (correct path) + 20 * 1 (wrong path) = 120 cycles
  - 20% extra instructions fetched; IPC = 500/120

- **90% accuracy**
  - 100 (correct path) + 20 * 10 (wrong path) = 300 cycles
  - 200% extra instructions fetched; IPC = 500/300

- **60% accuracy**
  - 100 (correct path) + 20 * 40 (wrong path) = 900 cycles
  - 800% extra instructions fetched; IPC = 500/900
Branch Prediction
Branch Prediction: Guess the Next Instruction to Fetch

![Diagram showing branch prediction and instruction execution.]
Misprediction Penalty

LD R0, MEM[R2]
LD R2, MEM[R2]
BR
ZERO
0x0001

LD R1, MEM[R0]
ADD R2, R2, #1
ADD R3, R2, #1
MUL R1, R2, R3
LD R2, MEM[R2]
LD R0, MEM[R2]

Misprediction Penalty

I-$$ RF$$
0x0001
0x0002
0x0003
0x0004
0x0005
0x0006
0x0007

Flush!!

PC$$ DEC$$
D-$$
WB

0x0003
0x0004
0x0005
0x0006
0x0007
Simplest: Always Guess NextPC = PC + 4

- Always predict the next sequential instruction is the next instruction to be executed
- This is a form of next fetch address prediction (and branch prediction)

- How can you make this more effective?

**Idea:** Maximize the chances that the next sequential instruction is the next instruction to be executed

- **Software:** Lay out the control flow graph such that the “likely next instruction” is on the not-taken path of a branch
  - Profile guided code positioning → Pettis & Hansen, PLDI 1990.
- **Hardware:** ??? (how can you do this in hardware...)
  - Cache traces of executed instructions → Trace cache
Guessing $\text{NextPC} = \text{PC} + 4$

- How else can you make this more effective?

- **Idea:** Get rid of control flow instructions (or minimize their occurrence)

- **How?**
  1. Get rid of unnecessary control flow instructions $\rightarrow$ combine predicates (predicate combining)
  2. Convert control dependences into data dependences $\rightarrow$ predicated execution
Branch Prediction: Always PC+4

When a branch resolves:
- branch target (Inst\(_k\)) is fetched.
- all instructions fetched since inst\(_h\) (so called “wrong-path” instructions) must be flushed.
Pipeline Flush on a Misprediction

Inst_h is a branch
Performance Analysis

- correct guess ⇒ no penalty (~86% of the time)
- incorrect guess ⇒ 2 bubbles

Assume

- no data dependency related stalls
- 20% control flow instructions
- 70% of control flow instructions are taken

\[
CPI = [1 + (0.20 \times 0.7) \times 2] = \\
= [1 + 0.14 \times 2] = 1.28
\]

Can we reduce either of the two penalty terms?
Reducing Branch Misprediction Penalty

- Resolve branch condition and target address early

CPI = [ 1 + (0.2*0.7) * 1 ] = 1.14

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Branch Prediction (A Bit More Enhanced)

- **Idea:** Predict the next fetch address (to be used in the next cycle)

- Requires three things to be predicted at fetch stage:
  - Whether the fetched instruction is a branch
  - (Conditional) branch direction
  - Branch target address (if taken)

- **Observation:** Target address remains the same for a conditional direct branch across dynamic instances
  - **Idea:** Store the target address from previous instance and access it with the PC
  - Called Branch Target Buffer (BTB) or Branch Target Address Cache
Fetch Stage with BTB and Direction Prediction

Direction predictor (taken?)

Program Counter
Address of the current branch

Cache of Target Addresses (BTB: Branch Target Buffer)

PC + inst size

Next Fetch Address

hit?
taken?
taken?
target address
More Sophisticated Branch Direction Prediction

- Global branch history
- Program Counter
- Address of the current branch
- Which direction earlier branches went
- Direction predictor (taken?)
- XOR
- PC + inst size
- hit?
- target address
- Cache of Target Addresses (BTB: Branch Target Buffer)
- Next Fetch Address

Which direction earlier branches went

Address of the current branch

Global branch history

Program Counter

XOR

Direction predictor (taken?)

PC + inst size

hit?

target address

Cache of Target Addresses (BTB: Branch Target Buffer)

Next Fetch Address
Three Things to Be Predicted

- Requires three things to be predicted at fetch stage:
  1. Whether the fetched instruction is a branch
  2. (Conditional) branch direction
  3. Branch target address (if taken)

- Third (3.) can be accomplished using a BTB
  - Remember target address computed last time branch was executed

- First (1.) can be accomplished using a BTB
  - If BTB provides a target address for the program counter, then it must be a branch
  - Or, we can store “branch metadata” bits in instruction cache/memory → partially decoded instruction stored in I-cache

- Second (2.): How do we predict the direction?
Simple Branch Direction Prediction Schemes

- **Compile time (static)**
  - Always not taken
  - Always taken
  - BTFN (Backward taken, forward not taken)
  - Profile based (likely direction)

- **Run time (dynamic)**
  - Last time prediction (single-bit)
More Sophisticated Direction Prediction

- **Compile time (static)**
  - Always not taken
  - Always taken
  - BTFN (Backward taken, forward not taken)
  - Profile based (likely direction)
  - Program analysis based (likely direction)

- **Run time (dynamic)**
  - Last time prediction (single-bit)
  - Two-bit counter based prediction
  - Two-level prediction (global vs. local)
  - Hybrid
  - Advanced algorithms (e.g., using perceptrons)
Static Branch Prediction (I)

- **Always not-taken**
  - Simple to implement: no need for BTB, no direction prediction
  - Low accuracy: ~30-40% (for conditional branches)
  - Remember: Compiler can layout code such that the likely path is the “not-taken” path → more effective prediction

- **Always taken**
  - No direction prediction
  - Better accuracy: ~60-70% (for conditional branches)
    - Backward branches (i.e. loop branches) are usually taken
    - Backward branch: target address lower than branch PC

- **Backward taken, forward not taken (BTFN)**
  - Predict backward (loop) branches as taken, others not-taken
Static Branch Prediction (II)

- Profile-based
  - Idea: Compiler determines likely direction for each branch using a profile run. Encodes that direction as a hint bit in the branch instruction format.

+ Per branch prediction (more accurate than schemes in previous slide) → accurate if profile is representative!

-- Requires hint bits in the branch instruction format

-- Accuracy depends on dynamic branch behavior:
  
  TTTTTTTTTTTNNNNNN→ 50% accuracy
  TNTNTNTNTNTNTNTNTNTNTNT→ 50% accuracy

-- Accuracy depends on the representativeness of profile input set
Static Branch Prediction (III)

- Program-based (or, program analysis based)
  - Idea: Use heuristics based on program analysis to determine statically-predicted direction
  - Example opcode heuristic: Predict BLEZ as NT (negative integers used as error values in many programs)
  - Example loop heuristic: Predict a branch guarding a loop execution as taken (i.e., execute the loop)
  - Pointer and FP comparisons: Predict not equal

+ Does not require profiling

-- Heuristics might be not representative or good
-- Requires compiler analysis and ISA support (ditto for other static methods)

  - 20% misprediction rate
Static Branch Prediction (IV)

- Programmer-based
  - Idea: Programmer provides the statically-predicted direction
  - Via *pragmas* in the programming language that qualify a branch as likely-taken versus likely-not-taken

+ Does not require profiling or program analysis
+ Programmer may know some branches and their program better than other analysis techniques

-- Requires programming language, compiler, ISA support
-- Burdens the programmer?
Pragmas

- **Idea:** Keywords that enable a programmer to convey hints to lower levels of the transformation hierarchy

- if (likely(x)) { ... }
- if (unlikely(error)) { ... }

- Many other hints and optimizations can be enabled with pragmas
  - E.g., whether a loop can be parallelized
  - `#pragma omp parallel`
  - **Description**
    - The omp parallel directive explicitly instructs the compiler to parallelize the chosen segment of code.
Static Branch Prediction

- All previous techniques can be combined
  - Profile based
  - Program based
  - Programmer based

- How would you do that?

- What is the common disadvantage of all three techniques?
  - Cannot adapt to dynamic changes in branch behavior
  - This can be mitigated by a dynamic compiler, but not at a fine granularity (and a dynamic compiler has its overheads...)
  - What is a Dynamic Compiler?
    - A compiler that generates code at runtime
    - Java JIT (just in time) compiler, Microsoft CLR (common lang. runtime)
More Sophisticated Direction Prediction

- **Compile time (static)**
  - Always not taken
  - Always taken
  - BTFN (Backward taken, forward not taken)
  - Profile based (likely direction)
  - Program analysis based (likely direction)

- **Run time (dynamic)**
  - Last time prediction (single-bit)
  - Two-bit counter based prediction
  - Two-level prediction (global vs. local)
  - Hybrid
  - Advanced algorithms (e.g., using perceptrons)
Dynamic Branch Prediction

- **Idea:** Predict branches based on dynamic information (collected at run-time)

- **Advantages**
  + Prediction based on history of the execution of branches
  + It can adapt to dynamic changes in branch behavior
  + No need for static profiling: input set representativeness problem goes away

- **Disadvantages**
  -- More complex (requires additional hardware)
Last Time Predictor

- Last time predictor
  - Single bit per branch (stored in BTB)
  - Indicates which direction branch went last time it executed
    
    TTTTTTTTTTNNNNNNNNNNNNN → 90% accuracy

- Always mispredicts the last iteration and the first iteration of a loop branch
  - Accuracy for a loop with N iterations = (N-2)/N

+ Loop branches for loops with large N (number of iterations)
-- Loop branches for loops will small N (number of iterations)
    
    TNTNTNTNTNTNTNTNTNTNTNTNTN → 0% accuracy
We did not cover the following slides. They are for your preparation for the next lecture.
The 1-bit BHT (Branch History Table) entry is updated with the correct outcome after each execution of a branch.
State Machine for Last-Time Prediction

- State: Predict not taken
  - Transition: Actually not taken
  - Transition: Actually taken

- State: Predict taken
  - Transition: Actually taken
  - Transition: Actually not taken
Improving the Last Time Predictor

- **Problem:** A last-time predictor changes its prediction from T→NT or NT→T too quickly
  - even though the branch may be mostly taken or mostly not taken

- **Solution Idea:** Add hysteresis to the predictor so that prediction does not change on a single different outcome
  - Use two bits to track the history of predictions for a branch instead of a single bit
  - Can have 2 states for T or NT instead of 1 state for each

Two-Bit Counter Based Prediction

- Each branch associated with a two-bit counter
- One more bit provides hysteresis
- A strong prediction does not change with one single different outcome

- Accuracy for a loop with N iterations = \((N-1)/N\)
  TNTNTNTNTNTNTNTNTNTNTN \(\rightarrow\) 50% accuracy
  (assuming counter initialized to weakly taken)

+ Better prediction accuracy
-- More hardware cost (but counter can be part of a BTB entry)
Counter using *saturating arithmetic*
- Arithmetic with maximum and minimum values
Hysteresis Using a 2-bit Counter

Change prediction after 2 consecutive mistakes
Is This Good Enough?

- ~85-90% accuracy for many programs with 2-bit counter based prediction (also called bimodal prediction)

- Is this good enough?

- How big is the branch problem?
Let’s Do the Exercise Again

- Assume $N = 20$ (20 pipe stages), $W = 5$ (5 wide fetch)
- Assume: 1 out of 5 instructions is a branch
- Assume: Each 5 instruction-block ends with a branch

How long does it take to fetch 500 instructions?

- **100% accuracy**
  - 100 cycles (all instructions fetched on the correct path)
  - No wasted work; IPC = 500/100

- **90% accuracy**
  - 100 (correct path) + 20 * 10 (wrong path) = 300 cycles
  - 200% extra instructions fetched; IPC = 500/300

- **85% accuracy**
  - 100 (correct path) + 20 * 15 (wrong path) = 400 cycles
  - 300% extra instructions fetched; IPC = 500/400

- **80% accuracy**
  - 100 (correct path) + 20 * 20 (wrong path) = 500 cycles
  - 400% extra instructions fetched; IPC = 500/500
Can We Do Better: Two-Level Prediction

- Last-time and 2BC predictors exploit “last-time” predictability

- Realization 1: A branch’s outcome can be correlated with other branches’ outcomes
  - Global branch correlation

- Realization 2: A branch’s outcome can be correlated with past outcomes of the same branch (other than the outcome of the branch “last-time” it was executed)
  - Local branch correlation

Global Branch Correlation (I)

- Recently executed branch outcomes in the execution path are correlated with the outcome of the next branch

```c
if (cond1)
...
if (cond1 AND cond2)
```

- If first branch not taken, second also not taken

```c
branch Y: if (cond1) a = 2;
...
branch X: if (a == 0)
```

- If first branch taken, second definitely not taken
Global Branch Correlation (II)

- branch Y: if (cond1)
- ... 
- branch Z: if (cond2)
- ... 
- branch X: if (cond1 AND cond2)

- If Y and Z both taken, then X also taken
- If Y or Z not taken, then X also not taken
Global Branch Correlation (III)

- Eqntott, SPEC’92: Generates truth table from Boolean expr.

```c
if (aa==2) ;; B1
    aa=0;
if (bb==2) ;; B2
    bb=0;
if (aa!=bb) {
    ;; B3
    ....
}
```

If **B1** is not taken (i.e., aa==0@B3) and **B2** is not taken (i.e. bb=0@B3) then **B3** is certainly taken.
Capturing Global Branch Correlation

- **Idea:** Associate branch outcomes with “global T/NT history” of all branches
- **Make a prediction based on the outcome of the branch the last time the same global branch history was encountered**

**Implementation:**
- Keep track of the “global T/NT history” of all branches in a register → Global History Register (GHR)
- Use GHR to index into a table that recorded the outcome that was seen for each GHR value in the recent past → Pattern History Table (table of 2-bit counters)

- **Global history/branch predictor**
- Uses two levels of history (GHR + history at that GHR)

Two Level Global Branch Prediction

- First level: **Global branch history register** (N bits)
  - The direction of last N branches
- Second level: **Table of saturating counters for each history entry**
  - The direction the branch took the last time the same history was seen

How Does the Global Predictor Work?


This branch tests $i$
Last 4 branches test $j$
History: TTTN
Predict taken for $i$
Next history: TTNT
(shift in last outcome)
Intel Pentium Pro Branch Predictor

- Two level global branch predictor
- 4-bit global history register
- Multiple pattern history tables (of 2 bit counters)
  - Which pattern history table to use is determined by lower order bits of the branch address
Improving Global Predictor Accuracy

- Idea: Add more context information to the global predictor to take into account which branch is being predicted
  - **Gshare predictor**: GHR hashed with the Branch PC
  - + More context information used for prediction
  - + Better utilization of the two-bit counter array
  - -- Increases access latency

Review: One-Level Branch Predictor

Direction predictor (2-bit counters)

Cache of Target Addresses (BTB: Branch Target Buffer)

Program Counter

Address of the current instruction

PC + inst size

Next Fetch Address

taken?

hit?
Two-Level Global History Branch Predictor

- Global branch history
- Program Counter
- Which direction earlier branches went
- Address of the current instruction

Direction predictor (2-bit counters)

Cache of Target Addresses (BTB: Branch Target Buffer)

Input: PC + inst size

Output: Next Fetch Address

- taken?
- hit?
Two-Level Gshare Branch Predictor

Which direction earlier branches went

Global branch history

Program Counter

Address of the current instruction

Direction predictor (2-bit counters)

taken?

PC + inst size

hit?

Next Fetch Address

Next Fetch Address

Cache of Target Addresses (BTB: Branch Target Buffer)

Address of the current instruction

XOR

Target address
Can We Do Better: Two-Level Prediction

- Last-time and 2BC predictors exploit only “last-time” predictability for a given branch

- Realization 1: A branch’s outcome can be correlated with other branches’ outcomes
  - Global branch correlation

- Realization 2: A branch’s outcome can be correlated with past outcomes of the same branch (in addition to the outcome of the branch “last-time” it was executed)
  - Local branch correlation

Local Branch Correlation

for (i=1; i<=4; i++) { }

If the loop test is done at the end of the body, the corresponding branch will execute the pattern \((1110)^n\), where 1 and 0 represent taken and not taken respectively, and \(n\) is the number of times the loop is executed. Clearly, if we knew the direction this branch had gone on the previous three executions, then we could always be able to predict the next branch direction.

More Motivation for Local History

- To predict a loop branch “perfectly”, we want to identify the last iteration of the loop

- By having a separate PHT entry for each local history, we can distinguish different iterations of a loop

- Works for “short” loops
Capturing Local Branch Correlation

- Idea: Have a per-branch history register
  - Associate the predicted outcome of a branch with “T/NT history” of the same branch

- Make a prediction based on the outcome of the branch the last time the same local branch history was encountered

- Called the local history/branch predictor

- Uses two levels of history (Per-branch history register + history at that history register value)
Two Level Local Branch Prediction

- First level: A set of local history registers (N bits each)
  - Select the history register based on the PC of the branch
- Second level: Table of saturating counters for each history entry
  - The direction the branch took the last time the same history was seen

Pattern History Table (PHT)

Local history registers

Two-Level Local History Branch Predictor

Which directions earlier instances of *this branch* went

Direction predictor (2-bit counters)

Cache of Target Addresses (BTB: Branch Target Buffer)

Program Counter

Address of the current instruction

taken?

PC + inst size

hit?

target address

Next Fetch Address

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Can We Do Even Better?

- Predictability of branches varies

- Some branches are more predictable using local history
- Some using global
- For others, a simple two-bit counter is enough
- Yet for others, a single bit is enough

Observation: There is heterogeneity in predictability behavior of branches
- No one-size fits all branch prediction algorithm for all branches

Idea: Exploit that heterogeneity by designing heterogeneous branch predictors
Hybrid Branch Predictors

- **Idea:** Use more than one type of predictor (i.e., multiple algorithms) and select the “best” prediction
  - E.g., hybrid of 2-bit counters and global predictor

- **Advantages:**
  - Better accuracy: different predictors are better for different branches
  - Reduced *warmup* time (faster-warmup predictor used until the slower-warmup predictor warms up)

- **Disadvantages:**
  - Need “meta-predictor” or “selector”
  - Longer access latency

Alpha 21264 Tournament Predictor

- Minimum branch penalty: 7 cycles
- Typical branch penalty: 11+ cycles
- 48K bits of target addresses stored in I-cache
- Predictor tables are reset on a context switch

Are We Done w/ Branch Prediction?

- Hybrid branch predictors work well
  - E.g., 90-97% prediction accuracy on average

- Some “difficult” workloads still suffer, though!
  - E.g., gcc
  - Max IPC with tournament prediction: 9
  - Max IPC with perfect prediction: 35
Some Other Branch Predictor Types

- **Loop branch detector and predictor**
  - Loop iteration count detector/predictor
  - Works well for loops with small number of iterations, where iteration count is predictable
  - Used in Intel Pentium M

- **Perceptron branch predictor**
  - Learns the *direction correlations* between individual branches
  - Assigns weights to correlations

- **Hybrid history length based predictor**
  - Uses different tables with different history lengths
The advanced branch prediction in the Pentium M processor is based on the Intel Pentium® 4 processor’s [6] branch predictor. On top of that, two additional predictors to capture special program flows, were added: a Loop Detector and an Indirect Branch Predictor.

A perceptron is a simplified model of a biological neuron
It is also a simple **binary classifier**

A perceptron maps an input vector \( X \) to a 0 or 1
- **Input** = Vector \( X \)
- Perceptron learns the linear function (if one exists) of how each element of the vector affects the output (stored in an internal Weight vector)
- **Output** = Weight.\( X \) + Bias > 0

In the branch prediction context
- Vector \( X \): Branch history register bits
- Output: Prediction for the current branch
Perceptron Branch Predictor (I)

- **Idea:** Use a perceptron to learn the correlations between branch history register bits and branch outcome
- **A perceptron learns a target Boolean function of N inputs**
  
  Each branch associated with a perceptron
  
  A perceptron contains a set of weights $w_i$
  
  - Each weight corresponds to a bit in the GHR
  
  - How much the bit is correlated with the direction of the branch
  
  - Positive correlation: large $+ w_i$
  
  - Negative correlation: large $- w_i$

  **Prediction:**
  
  - Express GHR bits as 1 (T) and -1 (NT)
  
  - Take dot product of GHR and weights
  
  - If output $> 0$, predict taken

Perceptron Branch Predictor (II)

Prediction function:

\[ y = w_0 + \sum_{i=1}^{n} x_i w_i. \]

Output compared to 0

Bias weight (bias of branch, independent of the history)

Training function:

\[
\text{if } \text{sign}(y_{out}) \neq t \text{ or } |y_{out}| \leq \theta \text{ then}
\]
\[
\text{for } i := 0 \text{ to } n \text{ do}
\]
\[
    w_i := w_i + tx_i
\]
\[
\text{end for}
\]
\[
\text{end if}
\]
Perceptron Branch Predictor (III)

- **Advantages**
  - + More sophisticated learning mechanism $\Rightarrow$ better accuracy

- **Disadvantages**
  - -- Hard to implement (adder tree to compute perceptron output)
  - -- Can learn only linearly-separable functions
    - e.g., cannot learn XOR type of correlation between 2 history bits and branch outcome
Observation: Different branches require different history lengths for better prediction accuracy

Idea: Have multiple PHTs indexed with GHRs with different history lengths and intelligently allocate PHT entries to different branches

State of the Art in Branch Prediction

- See the Branch Prediction Championship
  - https://www.jilp.org/cbp2016/program.html


Figure 1. The TAGE-SC-L predictor: a TAGE predictor backed with a Statistical Corrector predictor and a loop predictor.
Branch Confidence Estimation

- **Idea:** Estimate if the prediction is likely to be correct
  - i.e., estimate how “confident” you are in the prediction

- **Why?**
  - Could be very useful in deciding how to speculate:
    - What predictor/PHT to choose/use
    - Whether to keep fetching on this path
    - Whether to switch to some other way of handling the branch, e.g. dual-path execution (eager execution) or dynamic predication
    - ...

Other Ways of Handling Branches
How to Handle Control Dependences

- Critical to keep the pipeline full with correct sequence of dynamic instructions.

- Potential solutions if the instruction is a control-flow instruction:
  - **Stall** the pipeline until we know the next fetch address
  - Guess the next fetch address (**branch prediction**)
  - Employ delayed branching (**branch delay slot**)
  - Do something else (**fine-grained multithreading**)
  - Eliminate control-flow instructions (**predicated execution**)
  - Fetch from both possible paths (if you know the addresses of both possible paths) (**multipath execution**)

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Delayed Branching (I)

- Change the semantics of a branch instruction
  - Branch after N instructions
  - Branch after N cycles

- Idea: Delay the execution of a branch. N instructions (delay slots) that come after the branch are always executed regardless of branch direction.

- Problem: How do you find instructions to fill the delay slots?
  - Branch must be independent of delay slot instructions

- Unconditional branch: Easier to find instructions to fill the delay slot
- Conditional branch: Condition computation should not depend on instructions in delay slots → difficult to fill the delay slot
Delayed Branching (II)

Normal code:

A
B
C
BC X
D
E
F
G  

X:

Timeline:

if  ex

A
B  A
C  B
BC  C
--  BC
G  --

6 cycles

Delayed branch code:

A
C
BC X
B
D
E
F
G  

X:

if  ex

A
C  A
BC  C
B  BC
G  B

5 cycles
Fancy Delayed Branching (III)

- Delayed branch with squashing
  - In SPARC
  - Semantics: If the branch falls through (i.e., it is not taken), the delay slot instruction is not executed
  - Why could this help?

Normal code:  
Delayed branch code:  
Delayed branch w/ squashing:

X: A
   B
   C
   BC X
   D
   E

X: A
   B
   C
   BC X
   NOP
   D
   E

X: A
   B
   C
   BC X
   A
   D
   E
Delayed Branching (IV)

- **Advantages:**
  
  + Keeps the pipeline full with useful instructions in a simple way assuming
    
    1. Number of delay slots == number of instructions to keep the pipeline full before the branch resolves
    2. All delay slots can be filled with useful instructions

- **Disadvantages:**
  
  -- Not easy to fill the delay slots (even with a 2-stage pipeline)
    
    1. Number of delay slots increases with pipeline depth, superscalar execution width
    2. Number of delay slots should be variable with variable latency operations. Why?
  
  -- Ties ISA semantics to hardware implementation
    
    -- SPARC, MIPS, HP-PA: 1 delay slot
    -- What if pipeline implementation changes with the next design?
An Aside: Filling the Delay Slot

reordering data independent (RAW, WAW, WAR) instructions does not change program semantics

within same basic block

For correctness: add a new instruction to the not-taken path?

For correctness: add a new instruction to the taken path?

Safe?
How to Handle Control Dependences

- Critical to keep the pipeline full with correct sequence of dynamic instructions.

- Potential solutions if the instruction is a control-flow instruction:
  - Stall the pipeline until we know the next fetch address
  - Guess the next fetch address (branch prediction)
  - Employ delayed branching (branch delay slot)
  - Do something else (fine-grained multithreading)
  - Eliminate control-flow instructions (predicated execution)
  - Fetch from both possible paths (if you know the addresses of both possible paths) (multipath execution)
Predicate Combining (not Predicated Execution)

- Complex predicates are converted into multiple branches
  - if ((a == b) && (c < d) && (a > 5000)) { ... }
    - 3 conditional branches

- Problem: This increases the number of control dependencies

- Idea: Combine predicate operations to feed a single branch instruction instead of having one branch for each
  - Predicates stored and operated on using condition registers
  - A single branch checks the value of the combined predicate

  + Fewer branches in code → fewer mipredictions/stalls

  -- Possibly unnecessary work
    -- If the first predicate is false, no need to compute other predicates

- Condition registers exist in IBM RS6000 and the POWER architecture
Predication (Predicated Execution)

- **Idea:** Convert control dependence to data dependence

- **Simple example:** Suppose we had a Conditional Move instruction...
  - CMOV condition, R1 ← R2
  - R1 = (condition == true) ? R2 : R1
  - Employed in most modern ISAs (x86, Alpha)

- **Code example with branches vs. CMOVs**
  ```
  if (a == 5) {b = 4;} else {b = 3;}
  ```
  ```
  CMPEQ condition, a, 5;
  CMOV condition, b ← 4;
  CMOV !condition, b ← 3;
  ```
Predication (Predicated Execution)

- **Idea:** Compiler converts control dependence into data dependence $\rightarrow$ branch is eliminated
  - Each instruction has a predicate bit set based on the predicate computation
  - Only instructions with TRUE predicates are committed (others turned into NOPs)

(normal branch code)           (predicated code)

```plaintext
if (cond) {
    b = 0;
} else {
    b = 1;
}
```

```
if (cond) {
    p1 = (cond);
    branch p1, TARGET
}
```

```
mov b, 1
jmp JOIN
```

```
TARGET:
    mov b, 0
    add x, b, 1
```

```
p1 = (cond)
```

```
(!p1)
```

```
(p1)
```

```
mov b, 1
```

```
add x, b, 1
```
Predicated Execution References


Conditional Move Operations

- Very limited form of predicated execution

- CMOV R1 ← R2
  - R1 = (ConditionCode == true) ? R2 : R1
  - Employed in most modern ISAs (x86, Alpha)
Predicated Execution (II)

- Predicated execution can be high performance and energy-efficient

```
A

C  B

D

E

F
```

**Predicated Execution**
- Fetch
- Decode
- Rename
- Schedule
- RegisterRead
- Execute

```
F  E  D  C  B  A
```

**Branch Prediction**
- Fetch
- Decode
- Rename
- Schedule
- RegisterRead
- Execute

```
F  E  D  B  A
```

Pipeline flush!!
Predicated Execution

- Eliminates branches → enables straight line code (i.e., larger basic blocks in code)

Advantages
- Eliminates hard-to-predict branches
- Always-not-taken prediction works better (no branches)
- Compiler has more freedom to optimize code (no branches)
  - control flow does not hinder inst. reordering optimizations
  - code optimizations hindered only by data dependencies

Disadvantages
- Useless work: some instructions fetched/executed but discarded (especially bad for easy-to-predict branches)
- Requires additional ISA (and hardware) support
- Can we eliminate all branches this way?
Predicated Execution vs. Branch Prediction

+ Eliminates mispredictions for hard-to-predict branches
  + No need for branch prediction for some branches
  + Good if misprediction cost > useless work due to predication

-- Causes useless work for branches that are easy to predict
  -- Reduces performance if misprediction cost < useless work
  -- **Adaptivity**: Static predication is not adaptive to run-time branch behavior. Branch behavior changes based on input set, program phase, control-flow path.
Predicated Execution in Intel Itanium

- Each instruction can be separately predicated
- 64 one-bit predicate registers
  - Each instruction carries a 6-bit predicate field
- An instruction is effectively a NOP if its predicate is false
Conditional Execution in the ARM ISA

- Almost all ARM instructions can include an optional condition code.
  - Prior to ARM v8

- An instruction with a condition code is executed only if the condition code flags in the CPSR meet the specified condition.
## Conditional Execution in ARM ISA

### Instruction type
- **Data processing / PSR Transfer**
- **Multiply**
- **Long Multiply** *(v3M / v4 only)*
- **Swap**
- **Load/Store Byte/Word**
- **Load/Store Multiple**
- **Halfword transfer : Immediate offset (v4 only)**
- **Halfword transfer: Register offset (v4 only)**
- **Branch**
- **Branch Exchange** *(v4T only)*
- **Coprocessor data transfer**
- **Coprocessor data operation**
- **Coprocessor register transfer**
- **Software interrupt**

### Instruction Format

<table>
<thead>
<tr>
<th>Cond</th>
<th>Opcode</th>
<th>S</th>
<th>Rn</th>
<th>Rd</th>
<th>Operand2</th>
</tr>
</thead>
<tbody>
<tr>
<td>001</td>
<td>0</td>
<td>0</td>
<td>Rn</td>
<td>Rd</td>
<td>Rs</td>
</tr>
<tr>
<td>000</td>
<td>1</td>
<td>0</td>
<td>RdHi</td>
<td>RdLo</td>
<td>Rs</td>
</tr>
<tr>
<td>001</td>
<td>0</td>
<td>1</td>
<td>Rn</td>
<td>Rd</td>
<td>000 1001</td>
</tr>
<tr>
<td>011</td>
<td>1</td>
<td>0</td>
<td>Rn</td>
<td>Rd</td>
<td>Offset</td>
</tr>
<tr>
<td>100</td>
<td>0</td>
<td>0</td>
<td>Rn</td>
<td>Rd</td>
<td>Offset1</td>
</tr>
<tr>
<td>000</td>
<td>1</td>
<td>0</td>
<td>Rn</td>
<td>Rd</td>
<td>Offset2</td>
</tr>
<tr>
<td>101</td>
<td>1</td>
<td></td>
<td>Rn</td>
<td></td>
<td>Offset</td>
</tr>
<tr>
<td>000</td>
<td>1</td>
<td>0</td>
<td>Rn</td>
<td></td>
<td></td>
</tr>
<tr>
<td>110</td>
<td>0</td>
<td>0</td>
<td>Rn</td>
<td></td>
<td>Offset</td>
</tr>
<tr>
<td>111</td>
<td>0</td>
<td></td>
<td>Rn</td>
<td></td>
<td>Op1</td>
</tr>
<tr>
<td>111</td>
<td>0</td>
<td></td>
<td>Rn</td>
<td></td>
<td>Op1</td>
</tr>
<tr>
<td>111</td>
<td>1</td>
<td></td>
<td>Rn</td>
<td></td>
<td>SWI Number</td>
</tr>
</tbody>
</table>

### Register List

<table>
<thead>
<tr>
<th>Cond</th>
<th>Opcode</th>
<th>S</th>
<th>Rn</th>
<th>Rd</th>
<th>Offset1</th>
<th>Rm</th>
</tr>
</thead>
<tbody>
<tr>
<td>000</td>
<td>1</td>
<td>0</td>
<td>Rn</td>
<td>Rd</td>
<td>1 1 S H 1</td>
<td>Rm</td>
</tr>
<tr>
<td>000</td>
<td>1</td>
<td>0</td>
<td>Rn</td>
<td>Rd</td>
<td>0 0 0 0 1</td>
<td>Rm</td>
</tr>
<tr>
<td>110</td>
<td>0</td>
<td>0</td>
<td>Rn</td>
<td></td>
<td>CRd</td>
<td></td>
</tr>
<tr>
<td>111</td>
<td>0</td>
<td></td>
<td>Rn</td>
<td></td>
<td>CRn</td>
<td></td>
</tr>
<tr>
<td>111</td>
<td>0</td>
<td></td>
<td>Rn</td>
<td></td>
<td>CRd</td>
<td></td>
</tr>
<tr>
<td>111</td>
<td>1</td>
<td></td>
<td>Rn</td>
<td></td>
<td>CRn</td>
<td></td>
</tr>
</tbody>
</table>

### Example Instructions

- **Load/Store Multiple**
- **Branch Exchange**
- **Coprocessor data transfer**
- **Coprocessor data operation**
- **Coprocessor register transfer**
- **Software interrupt**
Conditional Execution in ARM ISA

<table>
<thead>
<tr>
<th>Condition Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000</td>
<td>EQ - Z set (equal)</td>
</tr>
<tr>
<td>0001</td>
<td>NE - Z clear (not equal)</td>
</tr>
<tr>
<td>0010</td>
<td>HS / CS - C set (unsigned higher or same)</td>
</tr>
<tr>
<td>0011</td>
<td>LO / CC - C clear (unsigned lower)</td>
</tr>
<tr>
<td>0100</td>
<td>MI -N set (negative)</td>
</tr>
<tr>
<td>0101</td>
<td>PL - N clear (positive or zero)</td>
</tr>
<tr>
<td>0110</td>
<td>VS - V set (overflow)</td>
</tr>
<tr>
<td>0111</td>
<td>VC - V clear (no overflow)</td>
</tr>
<tr>
<td>1000</td>
<td>HI - C set and Z clear (unsigned higher)</td>
</tr>
<tr>
<td>1001</td>
<td>LS - C clear or Z (set unsigned lower or same)</td>
</tr>
<tr>
<td>1010</td>
<td>GE - N set and V set, or N clear and V clear (&gt;= or =)</td>
</tr>
<tr>
<td>1011</td>
<td>LT - N set and V clear, or N clear and V set (&gt;</td>
</tr>
<tr>
<td>1100</td>
<td>GT - Z clear, and either N set and V set, or N clear and V set (&gt;)</td>
</tr>
<tr>
<td>1101</td>
<td>LE - Z set, or N set and V clear, or N clear and V set (&lt;, or =)</td>
</tr>
<tr>
<td>1110</td>
<td>AL - always</td>
</tr>
<tr>
<td>1111</td>
<td>NV - reserved.</td>
</tr>
</tbody>
</table>
Conditional Execution in ARM ISA

* To execute an instruction conditionally, simply postfix it with the appropriate condition:
  - For example an add instruction takes the form:
    - ADD r0,r1,r2 ; r0 = r1 + r2 (ADDA)
  - To execute this only if the zero flag is set:
    - ADDEQ r0,r1,r2 ; If zero flag set then...
      ; ... r0 = r1 + r2

* By default, data processing operations do not affect the condition flags (apart from the comparisons where this is the only effect). To cause the condition flags to be updated, the S bit of the instruction needs to be set by postfixing the instruction (and any condition code) with an “S”.
  - For example to add two numbers and set the condition flags:
    - ADDS r0,r1,r2 ; r0 = r1 + r2
      ; ... and set flags
Conditional Execution in ARM ISA

1) “Normal” assembler, where only branches can be conditional.
2) ARM assembler, where all instructions are conditional, thus improving code density.

* The only instructions you need are CMP, B and SUB.
Conditional Execution in ARM ISA

“Normal” Assembler

gcd  cmp  r0, r1 ;reached the end?
beq  stop
blt  less   ;if r0 > r1
sub  r0, r0, r1 ;subtract r1 from r0
bal  gcd

less sub  r1, r1, r0 ;subtract r0 from r1
bal  gcd

stop

ARM Conditional Assembler

gcd  cmp  r0, r1 ;if r0 > r1
subgt r0, r0, r1 ;subtract r1 from r0
sublt r1, r1, r0 ;else subtract r0 from r1
bne  gcd     ;reached the end?
How to Handle Control Dependences

- Critical to keep the pipeline full with correct sequence of dynamic instructions.
- Potential solutions if the instruction is a control-flow instruction:
  - Stall the pipeline until we know the next fetch address
  - Guess the next fetch address (branch prediction)
  - Employ delayed branching (branch delay slot)
  - Do something else (fine-grained multithreading)
  - Eliminate control-flow instructions (predicated execution)
  - Fetch from both possible paths (if you know the addresses of both possible paths) (multipath execution)
Multi-Path Execution

**Idea:** Execute both paths after a conditional branch

- For a hard-to-predict branch: Use dynamic confidence estimation

**Advantages:**

+ Improves performance if misprediction cost > useless work
+ No ISA change needed

**Disadvantages:**

-- What happens when the machine encounters another hard-to-predict branch? Execute both paths again?
  -- Paths followed quickly become exponential
-- Each followed path requires its own context (registers, PC, GHR)
-- Wasted work (and reduced performance) if paths merge
Dual-Path Execution versus Predication

Hard to predict

Dual-path
path 1
C
D
E
F

Predicated Execution
path 1
C
D
E
F
CFMerge

path 2
B
D
E
F
CFMerge

path 2
B
D
E
F
Handling Other Types of Branches
### Remember: Branch Types

<table>
<thead>
<tr>
<th>Type</th>
<th>Direction at fetch time</th>
<th>Number of possible next fetch addresses?</th>
<th>When is next fetch address resolved?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conditional</td>
<td>Unknown</td>
<td>2</td>
<td>Execution (register dependent)</td>
</tr>
<tr>
<td>Unconditional</td>
<td>Always taken</td>
<td>1</td>
<td>Decode (PC + offset)</td>
</tr>
<tr>
<td>Call</td>
<td>Always taken</td>
<td>1</td>
<td>Decode (PC + offset)</td>
</tr>
<tr>
<td>Return</td>
<td>Always taken</td>
<td>Many</td>
<td>Execution (register dependent)</td>
</tr>
<tr>
<td>Indirect</td>
<td>Always taken</td>
<td>Many</td>
<td>Execution (register dependent)</td>
</tr>
</tbody>
</table>

*How can we predict an indirect branch with many target addresses?*
Call and Return Prediction

- **Direct calls are easy to predict**
  - Always taken, single target
  - Call marked in BTB, target predicted by BTB

- **Returns are indirect branches**
  - A function can be called from many points in code
  - A return instruction can have many target addresses
    - Next instruction after each call point for the same function
  - **Observation:** Usually a return matches a call
  - **Idea:** Use a stack to predict return addresses (Return Address Stack)
    - A fetched call: pushes the return (next instruction) address on the stack
    - A fetched return: pops the stack and uses the address as its predicted target
    - **Accurate most of the time:** 8-entry stack $\rightarrow > 95\%$ accuracy
Indirect Branch Prediction (I)

- Register-indirect branches have multiple targets
  
  ![Diagram]
  
  TARG | A+1
  
  Conditional (Direct) Branch
  
  - Used to implement
    - Switch-case statements
    - Virtual function calls
    - Jump tables (of function pointers)
    - Interface calls
  
  ![Diagram]
  
  R1 = MEM[R2]
  
  branch R1
  
  Indirect Jump
Indirect Branch Prediction (II)

- No direction prediction needed
- Idea 1: Predict the last resolved target as the next fetch address
  + Simple: Use the BTB to store the target address
  -- Inaccurate: 50% accuracy (empirical). Many indirect branches switch between different targets

- Idea 2: Use history based target prediction
  - E.g., Index the BTB with GHR XORed with Indirect Branch PC
  + More accurate
  -- An indirect branch maps to (too) many entries in BTB
    -- Conflict misses with other branches (direct or indirect)
    -- Inefficient use of space if branch has few target addresses
The advanced branch prediction in the Pentium M processor is based on the Intel Pentium® 4 processor’s [6] branch predictor. On top of that, two additional predictors to capture special program flows, were added: a Loop Detector and an Indirect Branch Predictor.

Issues in Branch Prediction (I)

- Need to identify a branch before it is fetched

- How do we do this?
  - BTB hit → indicates that the fetched instruction is a branch
  - BTB entry contains the “type” of the branch
  - Pre-decoded “branch type” information stored in the instruction cache identifies type of branch

- What if no BTB?
  - Bubble in the pipeline until target address is computed
  - E.g., IBM POWER4
Latency of Branch Prediction

- **Latency**: Prediction is latency critical
  - Need to generate next fetch address for the next cycle
  - Bigger, more complex predictors are more accurate but slower
Approaches to (Instruction-Level) Concurrency

- Pipelining
- Out-of-order execution
- Dataflow (at the ISA level)
- Superscalar Execution
- VLIW
- Fine-Grained Multithreading
- SIMD Processing (Vector and array processors, GPUs)
- Decoupled Access Execute
- Systolic Arrays
VLIW
VLIW Concept

- **Superscalar**
  - **Hardware** fetches multiple instructions and checks dependencies between them

- **VLIW (Very Long Instruction Word)**
  - Software (compiler) packs independent instructions in a larger “instruction bundle” to be fetched and executed concurrently
  - Hardware fetches and executes the instructions in the bundle concurrently

- No need for hardware dependency checking between concurrently-fetched instructions in the VLIW model

- ELI: Enormously longword instructions (512 bits)
VLIW (Very Long Instruction Word)

- A very long instruction word consists of multiple independent instructions packed together by the compiler
  - Packed instructions can be logically unrelated (contrast with SIMD/vector processors, which we will see soon)

- Idea: Compiler finds independent instructions and statically schedules (i.e. packs/bundles) them into a single VLIW instruction

- Traditional Characteristics
  - Multiple functional units
  - All instructions in a bundle are executed in lock step
  - Instructions in a bundle statically aligned to be directly fed into the functional units
VLIW Performance Example (2-wide bundles)

```assembly
lw $t0, 40($s0)
add $t1, $s1, $s2
sub $t2, $s1, $s3
and $t3, $s3, $s4
or $t4, $s1, $s5
sw $s5, 80($s0)
```

*Ideal IPC = 2*

*Actual IPC = 2* (6 instructions issued in 3 cycles)
VLIW Lock-Step Execution

- Lock-step (all or none) execution: If any operation in a VLIW instruction stalls, all instructions stall

- In a truly VLIW machine, the compiler handles all dependency-related stalls, hardware does not perform dependency checking
  - What about variable latency operations?
VLIW Philosophy

- Philosophy similar to RISC (simple instructions and hardware)
  - Except multiple instructions in parallel

- RISC (John Cocke, 1970s, IBM 801 minicomputer)
  - Compiler does the hard work to translate high-level language code to simple instructions (John Cocke: control signals)
    - And, to reorder simple instructions for high performance
  - Hardware does little translation/decoding → very simple

- VLIW (Josh Fisher, ISCA 1983)
  - Compiler does the hard work to find instruction level parallelism
  - Hardware stays as simple and streamlined as possible
    - Executes each instruction in a bundle in lock step
    - Simple → higher frequency, easier to design
Commercial VLIW Machines

- Multiflow TRACE, Josh Fisher (7-wide, 28-wide)
- Cydrome Cydra 5, Bob Rau
- Transmeta Crusoe: x86 binary-translated into internal VLIW
- TI C6000, Trimedia, STMicro (DSP & embedded processors)
  - Most successful commercially

- Intel IA-64
  - Not fully VLIW, but based on VLIW principles
  - EPIC (Explicitly Parallel Instruction Computing)
  - Instruction bundles can have dependent instructions
  - A few bits in the instruction format specify explicitly which instructions in the bundle are dependent on which other ones
VLIW Tradeoffs

**Advantages**
- No need for dynamic scheduling hardware → simple hardware
- No need for dependency checking within a VLIW instruction → simple hardware for multiple instruction issue + no renaming
- No need for instruction alignment/distribution after fetch to different functional units → simple hardware

**Disadvantages**
- Compiler needs to find N independent operations per cycle
  - If it cannot, inserts NOPs in a VLIW instruction
  - Parallelism loss AND code size increase
- Recompilation required when execution width (N), instruction latencies, functional units change (Unlike superscalar processing)
- Lockstep execution causes independent operations to stall
  - No instruction can progress until the longest-latency instruction completes
VLIW Summary

- VLIW simplifies hardware, but requires complex compiler techniques
- Solely-compiler approach of VLIW has several downsides that reduce performance
  -- Too many NOPs (not enough parallelism discovered)
  -- Static schedule intimately tied to microarchitecture
    -- Code optimized for one generation performs poorly for next
  -- No tolerance for variable or long-latency operations (lock step)

++ Most compiler optimizations developed for VLIW employed in optimizing compilers (for superscalar compilation)
  - Enable code optimizations
++ VLIW successful when parallelism is easier to find by the compiler (traditionally embedded markets, DSPs)
An Example Work: Superblock

The Superblock: An Effective Technique for VLIW and Superscalar Compilation

Wen-mei W. Hwu    Scott A. Mahlke    William Y. Chen    Pohua P. Chang
Nancy J. Warter    Roger A. Bringmann    Roland G. Ouellette    Richard E. Hank
Tokuzo Kiyohara    Grant E. Haab    John G. Holm    Daniel M. Lavery *


Lecture Video on Static Instruction Scheduling

- https://www.youtube.com/watch?v=isBEVkJgGA
Another Example Work: IMPACT

**IMPACT**: An Architectural Framework for Multiple-Instruction-Issue Processors

Pohua P. Chang, Scott A. Mahlke, William Y. Chen, Nancy J. Warter, Wen-mei W. Hwu

Center for Reliable and High-Performance Computing
University of Illinois
Urbana, IL 61801

The performance of multiple-instruction-issue processors can be severely limited by the compiler’s ability to generate efficient code for concurrent hardware. In the IMPACT project, we have developed IMPACT-I, a highly optimizing C compiler to exploit instruction level concurrency. The optimization capabilities of the IMPACT-I C compiler are summarized in this paper. Using the IMPACT-I C compiler, we ran experiments to analyze the performance of multiple-instruction-issue processors executing some important non-numerical programs. The multiple-instruction-issue processors achieve solid speedup over high-performance single-instruction-issue processors.

Approaches to (Instruction-Level) Concurrency

- Pipelining
- Out-of-order execution
- Dataflow (at the ISA level)
- Superscalar Execution
- VLIW
- Fine-Grained Multithreading
- SIMD Processing (Vector and array processors, GPUs)
- Decoupled Access Execute
- Systolic Arrays
Recall: How to Handle Data Dependences

- Anti and output dependences are easier to handle
  - write to the destination in one stage and in program order

- Flow dependences are more interesting

- Five fundamental ways of handling flow dependences
  - Detect and wait until value is available in register file
  - Detect and forward/bypass data to dependent instruction
  - Detect and eliminate the dependence at the software level
    - No need for the hardware to detect dependence
  - Predict the needed value(s), execute “speculatively”, and verify
  - Do something else (fine-grained multithreading)
    - No need to detect
How to Handle Control Dependences

- Critical to keep the pipeline full with correct sequence of dynamic instructions.

- **Potential solutions if the instruction is a control-flow instruction:**
  - **Stall** the pipeline until we know the next fetch address
  - Guess the next fetch address (branch prediction)
  - Employ delayed branching (branch delay slot)
  - Do something else (fine-grained multithreading)
  - Eliminate control-flow instructions (predicated execution)
  - Fetch from both possible paths (if you know the addresses of both possible paths) (multipath execution)
Fine-Grained Multithreading
Fine-Grained Multithreading

- Idea: Hardware has multiple thread contexts (PC+registers). Each cycle, fetch engine fetches from a different thread.
  - By the time the fetched branch/instruction resolves, no instruction is fetched from the same thread
  - Branch/instruction resolution latency overlapped with execution of other threads’ instructions

+ No logic needed for handling control and data dependences within a thread
-- Single thread performance suffers
-- Extra logic for keeping thread contexts
-- Does not overlap latency if not enough threads to cover the whole pipeline
Fine-Grained Multithreading (II)

- **Idea:** Switch to another thread every cycle such that no two instructions from a thread are in the pipeline concurrently.

- Tolerates the control and data dependency latencies by overlapping the latency with useful work from other threads.

- Improves pipeline utilization by taking advantage of multiple threads.


Fine-Grained Multithreading: History

- CDC 6600’s peripheral processing unit is fine-grained multithreaded
  - Processor executes a different I/O thread every cycle
  - An operation from the same thread is executed every 10 cycles

- Denelcor HEP (Heterogeneous Element Processor)
  - 120 threads/processor
  - available queue vs. unavailable (waiting) queue for threads
  - each thread can have only 1 instruction in the processor pipeline; each thread independent
  - to each thread, processor looks like a non-pipelined machine
  - system throughput vs. single thread performance tradeoff
Fine-Grained Multithreading in HEP

- Cycle time: 100ns
- 8 stages → 800 ns to complete an instruction
  - assuming no memory access
- No control and data dependency checking

Burton Smith (1941-2018)
Multithreaded Pipeline Example
Fine-grained Multithreading

**Advantages**
- No need for dependency checking between instructions (only one instruction in pipeline from a single thread)
- No need for branch prediction logic
- Otherwise-bubble cycles used for executing useful instructions from different threads
- Improved system throughput, latency tolerance, utilization

**Disadvantages**
- Extra hardware complexity: multiple hardware contexts (PCs, register files, ...), thread selection logic
- Reduced single thread performance (one instruction fetched every N cycles from the same thread)
- Resource contention between threads in caches and memory
- Some dependency checking logic *between* threads remains (load/store)
Modern GPUs are FGMT Machines
NVIDIA GeForce GTX 285 “core”

- 136 = instruction stream decode
- 64 KB of storage for thread contexts (registers)
- ... = execution context storage

= data-parallel (SIMD) func. unit, control shared across 8 units
- yellow = multiply-add
- blue = multiply

Slide credit: Kayvon Fatahalian
**NVIDIA GeForce GTX 285 “core”**

- Groups of 32 threads share instruction stream (each group is a Warp): they execute the same instruction on different data
- Up to 32 warps are interleaved in an FGMT manner
- Up to 1024 thread contexts can be stored

Slide credit: Kayvon Fatahalian
NVIDIA GeForce GTX 285

30 cores on the GTX 285: 30,720 threads

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End of
Fine-Grained Multithreading