High Bandwidth Instruction Fetching Techniques

- Instruction Bandwidth Issues
  - The Basic Block Fetch Limitation/Cache Line Misalignment
- Requirements For High-Bandwidth Instruction Fetch Units
- Multiple Branch Prediction
- Interleaved Sequential Core Fetch Unit

Enhanced Instruction Caches:
- Collapsing Buffer (CB)
- Branch Address Cache (BAC)

Trace Cache:
- Motivation & Operation
- Components
- Attributes of Trace Segments

Improving Trace Cache Hit Rate/Trace Segment Fill Unit Schemes:
- Rotenberg Fill Scheme
- Alternate (Pelog) Fill Scheme
- The Sliding Window Fill Mechanism with Fill Select Table (SWFM/ FST).

Reducing Number of Conditional Branches within a Trace Cache Segment:
- Branch Promotion
- Combining (SWFM/ FST) with Branch Promotion

Improving Trace Cache Storage Efficiency:
- Block-Based Trace Cache

For Superscalar Processors
Including SMT
Decoupled Fetch/Execute Superscalar Processor Engines

- Superscalar processor micro-architecture is divided into an in-order front-end instruction fetch/decode engine and an out-of-order execution engine.

- The instruction fetch/fill mechanism serves as the producer of fetched and decoded instructions and the execution engine as the consumer.

- Control dependence provide feedback to the fetch mechanism.

- To maintain high-performance the fetch mechanism must provide a high-instruction bandwidth to maintain a sufficient number of instructions in the instruction buffer window to detect ILP.
Instruction Bandwidth Issues

Problem
- In current high performance superscalar processors the instruction fetch bandwidth requirements may exceed what can be provided by conventional instruction cache fetch mechanisms.
- Wider-issue superscalars including those for simultaneously multi-threaded (SMT) cores even have higher instruction-bandwidth needs.
- The fetch mechanism is expected to supply a large number of instructions, but this is hindered because:
  - Long dynamic instruction sequences (traces) are not always in contiguous cache locations.
    - Due to frequency of branches and the resulting small sizes of basic blocks.
    - This leads to cache line misalignment, where multiple cache accesses are needed.
  - Also it is difficult to fetch a taken branch and its target in a single cycle:
    - Current fetch units are limited to one branch prediction per cycle.
    - Thus can only fetch a single basic block per cycle (or I-cache access).
  - All methods proposed to increase instruction fetching bandwidth perform multiple-branch prediction the cycle before instruction fetch, and fall into two general categories:

Possible Solutions
- **Enhanced Instruction Caches**
  - Including: Collapsing Buffer (CB), Branch Address Cache (BAC)
- **Trace Cache**
The Basic Block Fetch Limitation

- Superscalar processors have the potential to improve IPC by a factor of \(w\) (issue width).
- As issue width increases (4 → 8 → Beyond) the fetch bandwidth becomes a major bottleneck.
- Why???

- Average size of basic block = 5 to 7 instructions

- Traditional instruction cache, which stores instructions in static program order pose a limitation by not fetching beyond any taken branch instructions.

- First enhancement: Interleaved I-Cache. 2-Banks
  - Allows limited fetching beyond not-taken branches
  - Requires Multiple Branch Prediction...
Typical Branch & Basic Block Statistics

Sample programs: A number of SPEC92 integer benchmarks

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>taken %</th>
<th>avg basic block size</th>
<th># instr between taken branches</th>
</tr>
</thead>
<tbody>
<tr>
<td>eqntott</td>
<td>86.2%</td>
<td>4.20</td>
<td>4.87</td>
</tr>
<tr>
<td>espresso</td>
<td>63.8%</td>
<td>4.24</td>
<td>6.65</td>
</tr>
<tr>
<td>xlisp</td>
<td>64.7%</td>
<td>4.34</td>
<td>6.70</td>
</tr>
<tr>
<td>gcc</td>
<td>67.6%</td>
<td>4.65</td>
<td>6.88</td>
</tr>
<tr>
<td>sc</td>
<td>70.2%</td>
<td>4.71</td>
<td>6.71</td>
</tr>
<tr>
<td>compress</td>
<td>60.9%</td>
<td>5.39</td>
<td>8.85</td>
</tr>
</tbody>
</table>

Outcome:
Fetching one basic block every cycle may severely limit available instruction bandwidth available to fill instruction buffers/window and execution engine
The Basic Block Fetch Limitation: Example

- A-O = Basic Blocks terminating with conditional branches
- The outcomes of branches determine the basic block dynamic execution sequence or trace

Trace: Dynamic sequence of basic blocks executed

If all three branches are taken, the execution trace ACGO will require four accesses to I-Cache, one access per basic block.

Average Basic Block Size = 5-7 instructions
General Requirements for High-Bandwidth Instruction Fetch Units

• To achieve a high effective instruction-bandwidth a fetch unit must meet the following three requirements:

1. **Multiple branch prediction** in a single cycle to generate addresses of likely basic instruction blocks in the dynamic execution sequence.

2. The instruction cache must be able to supply a number of noncontiguous basic blocks in a single cycle. *e.g.* A, C, G, O

3. The multiple instruction blocks must be aligned and collapsed (assembled) into the dynamic instruction execution sequence or stream (into instruction issue queues or buffers) *e.g.* A C G O
Multiple Branch Prediction using a Global Pattern History Table (MGAg)

- Algorithm to make 2 branch predictions from a single branch history register:
  - To predict the secondary branch, the right-most k-1 branch history bits are used to index into the pattern history table.
  - k-1 bits address 2 adjacent entries, in the pattern history table.
  - The primary branch prediction is used to select one of the entries to make the secondary branch prediction.
3-branch Predictions/cycle MGAg

1st Level

BHR

GLOBAL HISTORY REGISTER

\[ \underbrace{b_{12}, b_{11}, b_{10}}_{2^4}\] 2-bit counters
arranged in \((2^4 \times 4)\) array

2nd Level

PATTERN HISTORY TABLE

\[ \underbrace{2^k}_{\text{Entries}}\] 

3rd Branch Prediction

2nd Branch Prediction

1st Branch Prediction

4:1 MUX

\[ b_b, b_0 \]
Interleaved Sequential Core Fetch Unit

- This core fetch unit is implemented using established hardware schemes.
- Fetching up to the first predicted taken branch each cycle can be done using the combination of: 1- an accurate multiple branch predictor, 2- an interleaved branch target buffer (BTB), a return address stack (RAS), and 3- a 2-way interleaved instruction cache.
- The core fetch unit is designed to fetch as many contiguous instructions possible, up to a maximum instruction limit and a maximum branch limit.
  - The instruction constraint is imposed by the width of the datapath, and the branch constraint is imposed by the branch predictor throughput.
- For demonstration, a fetch limit of 16 instructions and 3 branches is used.
- Cache Line Alignment: The cache is interleaved so that 2 consecutive cache lines can be accessed; this allows fetching sequential code that spans a cache line boundary, always guaranteeing a full cache line or up to the first taken branch.
- This scheme requires minimal complexity for aligning instructions:
  1. Logic to swap the order of the two cache lines (interchange switch).
  2. A left-shifter to align the instructions into a 16-wide instruction latch, and
  3. Logic to mask off unused instructions.
- All banks of the BTB are accessed in parallel with the instruction cache. They serve the role of detecting branches in all the instructions currently being fetched and providing their target addresses, in time for the next fetch cycle.
A Current Representative Fetch Unit:

Interleaved Sequential Core Fetch Unit (2-Way Interleaved I-Cache) A

i.e. 2-Banks

Handles:

Cache line misalignment

Allows to fetch contiguous basic blocks from interleaved caches (not taken branches)

i.e up to a taken branch

Paper # 3

EECC722 - Shaaban
Approaches To High-Bandwidth Instruction Fetching

- Alternate instruction fetch mechanisms are needed to provide fetch beyond both Taken and Not-Taken branches.
- All methods proposed to increase instruction fetching bandwidth perform multiple-branch prediction the cycle before instruction fetch, and fall into two general categories:
  1. **Enhanced Instruction Caches**
     - Examples:
       - Collapsing Buffer (CB), T. Conte et al. 1995
       - Branch Address Cache (BAC), T. Yeh et al. 1993
  2. **Trace Cache**
     - Rotenberg et al 1996
Approaches To High-Bandwidth Instruction Fetching:

Enhanced Instruction Caches

- Support fetch of non-contiguous blocks with a multi-ported, multi-banked, or multiple copies of the instruction cache. 

Issue: This leads to multiple fetch groups (blocks of instructions) that must be aligned and collapsed at fetch time, which can increase the fetch latency. 

- Examples:
  - Collapsing Buffer (CB) T. Conte et al. 1995
  - Branch Address Cache (BAC). T. Yeh et al. 1993

Also Paper # 3 has an overview of both techniques

To meet requirement #2

To meet requirement #3

A potential disadvantage of such techniques

Paper # 2

Paper # 1

Paper # 3
Collapsing Buffer (CB)

• This method works on the concept that there are the following elements in the fetch mechanism:
  – A 2-way interleaved (2 banks) I-cache and
  – 16-way interleaved branch target buffer (BTB),
  – A multiple branch predictor,
  – A collapsing buffer.

• The hardware is similar to the core fetch unit (covered earlier) but has two important distinctions.
  – First, the BTB logic is capable of detecting *intrablock taken* branches – short hops within a cache line.
  – Second, a single fetch goes through two BTB accesses.

• The goal of this method is to fetch multiple cache lines from the I-cache and collapse them together in one fetch iteration.

• This method requires the BTB be accessed more than once to predict the successive branches after the first one and the new cache line.

• The successive lines from different cache lines must also reside in different cache banks from each other to prevent cache bank conflicts.

• Therefore, this method not only increases the hardware complexity, and fetch latency, but also is not very scalable.
Collapsing Buffer (CB)

CB Operation Example:
- The fetch address A accesses the interleaved BTB. The BTB indicates that there are two branches in the cache line, target address B, with target address C.
- Based on this, the BTB logic indicates which instructions in the fetched line are valid and produces the next basic block address, C.
- The initial BTB lookup produces (1) a bit vector indicating the predicted valid instructions in the cache line (instructions from basic blocks A and B), and (2) the predicted target address C of basic block B.
- The fetch address A and target address C are then used to fetch two nonconsecutive cache lines from the interleaved instruction cache.
- In parallel with this instruction cache access, the BTB is accessed again, using the target address C. This second, serialized lookup determines which instructions are valid in the second cache line and produces the next fetch address (the predicted successor of basic block C). Used in next access
- When the two cache lines have been read from the cache, they pass through masking and interchange logic and the collapsing buffer (which merges the instructions), all controlled by bit vectors produced by the two passes through the BTB. After this step, the properly ordered and merged instructions are captured in the instruction latches to be fed to the decoders.
Branch Address Cache (BAC)

- This method has four major components:
  - The branch address cache (BAC),
  - A multiple branch predictor.
  - An interleaved instruction cache.
  - An interchange and alignment network.

- The basic operation of the BAC is that of a branch history tree mechanism with the depth of the tree determined by the number of branches to be predicted per cycle.
- The tree determines the path of the code and therefore, the blocks that will be fetched from the I-cache.
- Again, there is a need for a structure to collapse the code into one stream at fetch time and to either access multiple cache banks at once or pipeline the cache reads.
- The BAC method may result in two extra stages to the instruction pipeline.

Thus BAC’s main disadvantage: Increased fetch latency

Also an issue with Collapsing Buffer (CB)
Enhanced Instruction Caches: Branch Address Cache (BAC)

The basic operation of the BAC is that of a branch history tree mechanism with the depth of the tree determined by the number of branches to be predicted per cycle.

Major Disadvantage:

There is a need for a structure to collapse the basic blocks into the dynamic instruction stream at fetch time which increases the fetch latency. This is similar to Collapsing Buffer (CB).
Approaches To High-Bandwidth Instruction Fetching:

Trace Cache

- A trace is a sequence of executed basic blocks representing dynamic instruction execution stream.

- Trace cache stores instruction basic blocks in dynamic execution order upon instruction completion and not at fetch time (unlike CB, BAC) in contiguous locations known as trace segments.

- Major Advantage over previous high fetch-bandwidth methods (i.e CH, BAC):
  - Record retired instructions and branch outcomes upon instruction completion thus not impacting fetch latency.

- Thus the trace cache converts temporal locality of execution traces into spatial locality.
Approaches To High-Bandwidth Instruction Fetching:

Trace Cache

- Trace cache is an instruction cache that captures dynamic instruction sequences (traces) and makes them appear contiguous in trace cache in the form of stored trace segments.
- Each trace cache line of this cache stores a trace segment of the dynamic instruction stream.
- The trace cache line size is n instructions and the maximum branch predictions that can be generated is m. Therefore a stored trace segment can contain at most n instructions and up to m basic blocks.
- A trace segment is defined by the starting address and a sequence of m-1 branch predictions. These m-1 branch predictions define the path followed, by that trace, across m-1 branches.
- The first time a control flow path is executed, instructions are fetched as normal through the instruction cache. This dynamic sequence of instructions is allocated in the trace cache after assembly in the fill unit upon instruction completion not at fetch time as in previous techniques.
- Later, if there is a match for the trace (same starting address and same branch predictions, or trace ID), then the trace is taken from the trace cache and put into the fetch buffer. If not, then the instructions are fetched from the instruction cache.
Trace Cache Operation Example

First time a trace is encountered is generates a trace segment miss. Instructions possibly supplied from conventional I-cache.

\( a \) = starting address of basic block A

### Dynamic Instruction Execution Stream

<table>
<thead>
<tr>
<th>Trace Segment Hit:</th>
<th>Trace Fill Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Access existing trace segment with Trace ID ((a, T, T, T)) using address “a” and predictions (T, T, T)</td>
<td>Fills segment with Trace ID ((a, T, T, T)) from retired instructions stream. i.e store trace (segment) upon instruction completion, not at fetch time</td>
</tr>
</tbody>
</table>

#### Program Control Flow Graph (CFG)

- **1st branch**
- **2nd branch**
- **3rd branch**

**NT** = Branch Not Taken

**T** = Branch Taken

---

**Trace (a, Taken, Taken, Taken)**

- First time a trace is encountered, it generates a trace segment miss. Instructions possibly supplied from conventional I-cache.
- \( a \) = starting address of basic block A

**Trace Fill Unit**

- Fills segment with Trace ID \((a, T, T, T)\) from retired instructions stream.
  - i.e store trace (segment) upon instruction completion, not at fetch time.

**Supplied trace to decoder**

**Execution trace**

ACGO shown
Trace Cache Components

1. Next Trace ID Prediction Logic:
   - Multiple Branch Predictor (m branch predictions/cycle)
   - Branch Target Buffer (BTB)
   - Return Address Stack (RAS)
     - The current fetch address is combined with m-branch predictions to form the predicted Next Trace ID.

2. Trace Segment Storage:
   - Each trace segment (or trace cache line) contains at most \( n \) instructions and at most of \( m \) branches (m basic blocks).
   - A stored trace segment is identified by its Trace ID which is a combination of its starting address and the outcomes of the branches in the trace segment.

3. Trace Segment Hit Logic:
   - Determine if the predicted trace ID matches the trace ID of a stored trace segment resulting in a trace segment hit or miss. On a trace cache miss the conventional I-cache may supply instructions.

4. Trace Segment Fill Unit:
   - The fill unit of the trace cache is responsible for populating the trace cache segment storage by implementing a trace segment fill method.
   - Instructions are buffered in a trace fill buffer as they are retired from the reorder buffer (or similar mechanism).
   - When trace terminating conditions have been met, the contents of the buffer are used to form a new trace segment which is added to the trace cache.

Paper # 3

EECC722 - Shaaban
Trace Cache Components

1. Next Trace ID Prediction Logic
2. Trace Segment Storage
3. Trace Segment Hit Logic
4. Trace Segment Fill Unit

Figure 1 - The conventional trace cache.
Trace Cache: Core Fetch Unit
(i.e. Conventional 2-way Interleaved I-cache, covered earlier)

Interchange, Shift, Mask

Line Size = 16 Instructions

2-Way Interleaved Instruction Cache

not taken branch
taken branch

BTB LOGIC

MULTIPLE BRANCH PREDICTOR

“01x”

valid instructions bit vectors

target address

1st: 0000000000111111
2nd: 1111110000000000

Core Fetch Unit

BRANCH TARGET BUFFER
16-way Interleaved

fetch address

A

RETURN ADDRESS STACK
Trace Cache Components

Block Diagram

2 Trace Segment Storage

3 Trace Segment Hit Logic

<table>
<thead>
<tr>
<th>Trace Segment Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$: Maximum length of Trace Segment in instructions</td>
</tr>
<tr>
<td>$m$: Branch Prediction Bandwidth (maximum number of branches within a trace segment)</td>
</tr>
</tbody>
</table>

4 Trace Segment Fill Unit
(Implements trace segment fill policy)

Conventional 2-way Interleaved I-cache

Retired Instructions

MERGE LOGIC

LINE-FILL BUFFER

Trace Segment ID

From 1 Next Trace ID Prediction Logic

Paper # 3
Trace Cache Segment Properties

- **Trace Cache Segment (or line)**

<table>
<thead>
<tr>
<th>A</th>
<th>11</th>
<th>11,1</th>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tag</td>
<td>Branch</td>
<td>Branch</td>
<td>Fall-through</td>
<td>Target</td>
</tr>
<tr>
<td>Flags</td>
<td>Mask</td>
<td>Address</td>
<td>Address</td>
<td>Instructions</td>
</tr>
</tbody>
</table>

  - **Trace ID**: Used to index trace segment (fetch address matched with address tag of first instruction and predicted branch outcomes)
  - **Valid Bit**: Indicates this is a valid trace.
  - **Branch Flags**: Conditional Branch Directions
    - There is a single bit for each branch within the trace to indicate the path followed after the branch (taken/not taken). The m<sup>th</sup> branch of the trace does not need a flag since no instructions follow it, hence there are only m-1 bits instead of m.
  - **Branch Mask**:
    - Number of Branches
    - Is the trace-terminating instruction a conditional branch?
  - **Fall-Through/Target Addresses**
    - Identical if trace-terminating instruction is not a conditional branch

  A trace cache hit requires that requested Trace ID (Fetch Address + branch prediction bits) to match those of a stored trace segment.

  One can identify two Types of Trace Segments:

  - **n-constraint Trace Segment**: the maximum number of instructions n has been reached for this segment
  - **m-constraint Trace Segment**: the maximum number of basic blocks m has been reached for this segment.

  Both important for fill policy
Trace Cache Operation

- The trace cache is accessed in parallel with the instruction cache and BTB using the current fetch address.
- The predictor generates multiple branch predictions while the caches are accessed.
- The fetch address is used together with the multiple branch predictions to determine if the trace read from the trace cache matches the predicted sequence of basic blocks. Specifically a trace cache hit requires that:
  - Fetch address match the tag and the branch predictions match the branch flags.
  - The branch mask ensures that the correct number of prediction bits are used in the comparison.
- On a trace cache hit, an entire trace of instructions is fed into the instruction latch, bypassing the conventional instruction cache.
- On a trace cache miss, fetching proceeds normally from the instruction cache, i.e. contiguous instruction fetching.
- The line-fill buffer logic services trace cache misses: Implementing trace segment fill policy
  - Basic blocks are latched one at a time into the line-fill buffer; the line-fill control logic serves to merge each incoming block of instructions with preceding instructions in the line-fill buffer (after instruction retirement).
  - Filling is complete when either \( n \) instructions have been traced or \( m \) branches have been detected in the new trace.
  - The line-fill buffer are written into the trace cache. The branch flags and branch mask are generated, and the trace target and fall-through addresses are computed at the end of the line-fill. If the trace does not end in a branch, the target address is set equal to the fall-through address.
SEQ.3 = Core fetch unit capable of fetching three contiguous basic blocks
BAC = Branch Address Cache
CB = Collapsing Buffer
TC = Trace Cache
Comparing Trace Cache to Ideal*

* Ideal = Branch outcomes always predicted correctly and instructions hit in instruction cache

TC = Trace Cache

Paper # 3
An Implementation of Trace Cache

- Intel’s P4/Xeon NetBurst microarchitecture is the first and only current implementation of trace cache in a commercial microprocessor.
- In this implementation, trace cache replaces the conventional I-L1 cache.
- The execution trace cache which stores traces of already decoded IA-32 instructions or upos has a capacity 12k upos.
Intel’s P4/Xeon NetBurst Microarchitecture

- Front-End BTB (4K Entries)
- Instruction TLB/Prefetcher
- Instruction Decoder
- Trace Cache BTB (512 Entries)
- Trace Cache (12K μops)
- Allocator / Register Renamer
- Memory uop Queue
- Memory Scheduler
- Integer/Floating Point uop Queue
- Fast
- Slow/General FP Scheduler
- Simple FP
- Integer Register File / Bypass Network
- FP Register / Bypass
- L1 Data Cache (8Kbyte 4-way)
- L2 Cache (256K Byte 8-way)
- Quad Pumped 3.2 GB/s
- Bus Interface Unit

System Bus

Microcode ROM
μop Queue
Possible Trace Cache Improvements

The trace cache presented is the simplest design among many alternatives:

- **Associativity:** The trace cache can be made more associative to reduce trace segment conflict misses.

- **Multiple paths:** It might be advantageous to store multiple paths starting from a given address. This can be thought of as another form of associativity – *path associativity*.

- **Partial matches:** An alternative to providing path associativity is to allow *partial hits*. If the fetch address matches the starting address of a trace and the first few branch predictions match the first few branch flags, provide only a prefix of the trace. The additional cost of this scheme is that intermediate basic block addresses must be stored.

- **Other indexing methods:** The simple trace cache indexes with the fetch address and includes branch predictions in the tag match. Alternatively, the index into the trace cache could be derived by concatenating the fetch address with the branch prediction bits. This effectively achieves path associativity while keeping a direct mapped structure, because different paths starting at the same address now map to consecutive locations in the trace cache.

- **Victim trace cache:** It may keep valuable traces from being permanently displaced by useless traces.

- **Fill issues:** While the line-fill buffer is collecting a new trace, the trace cache continues to be accessed by the fetch unit. This means a miss could occur in the midst of handling a previous miss.

- **Reducing trace storage requirements** using block-based trace cache  

  Covered later
# Trace Cache
## Limitations and Possible Solutions

<table>
<thead>
<tr>
<th>Limitation</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum number of conditional branches ( m ) within a Trace Cache line.</td>
<td>• Path-Based Prediction</td>
</tr>
<tr>
<td></td>
<td>• <strong>Branch Promotion</strong>/Trace Packing</td>
</tr>
<tr>
<td>Trace Cache indexed by address of the first instruction; No multiple paths.</td>
<td>• Fetch address renaming</td>
</tr>
<tr>
<td>Trace Cache Miss Rate</td>
<td>• Partial Matching /Inactive Issue</td>
</tr>
<tr>
<td></td>
<td>• <strong>Fill unit Optimizations</strong></td>
</tr>
<tr>
<td></td>
<td>• Trace Preconstruction</td>
</tr>
<tr>
<td>Storage/Resource Inefficiency</td>
<td>• Block-based schemes</td>
</tr>
<tr>
<td></td>
<td>• Cost-regulated trace packing</td>
</tr>
<tr>
<td></td>
<td>• Selective trace storage</td>
</tr>
<tr>
<td></td>
<td>• <strong>Fill unit Optimizations</strong></td>
</tr>
<tr>
<td></td>
<td>• Pre-processing</td>
</tr>
</tbody>
</table>

*Paper #4*  
*Paper #6*  
*Paper #7*
Improving Trace Cache Hit Rate:

Important Attributes of Trace Segments

• **Trace Continuity**
  - An n-constrained trace is succeeded by a trace which starts at the next sequential fetch address.
  - If so, *trace continuity* is maintained

• **Probable Entry Points**
  - Fetch addresses that start regions of code that will be encountered later in the course of normal execution.
  - *Probable entry points* usually start on basic block boundaries

Let’s examine the two common trace segment fill schemes with respect to these attributes …
Two Common Trace Segment Fill Unit Schemes:

1. **Rotenberg Fill Scheme**

   - When Rotenberg proposed the trace cache in 1996 he proposed a fill unit scheme to populate the trace cache segment storage.
     - Thus a trace cache that utilizes the Rotenberg fill scheme is referred to as a Rotenberg Trace Cache.
   - The Rotenberg fill scheme entails flushing the trace segment fill buffer to trace cache segment storage, possibly storing a new trace segment, once the maximum number of instructions (n) or basic blocks (m) has been reached.
   - The next instruction to retire will be added to the empty fill buffer as the first instruction of a future trace segment thus maintaining trace continuity (for \( n \)-constraint trace segments).
   - While The Rotenberg Fill Method maintains trace continuity, it has the potential to miss some probable entry points (start of basic blocks).
Prior to the initial Rotenberg et al 1996 paper introducing trace cache, a US patent was granted describing a mechanism that closely approximates the concept of the trace cache.


The alternate fill scheme introduced differs from the Rotenberg fill scheme:

– Similar to Rotenberg a new trace segment is stored when n or m has been reached.
– Then, unlike Rotenberg, the fill buffer is not entirely flushed instead the front most (oldest) basic block is discarded from the fill buffer and the remaining instructions are shifted to free room for newly retired instructions. → New trace segment
– The original second oldest basic block now forms the start of a potential trace segment.
– In effect, every new basic block encountered in the dynamic instruction stream possibly causes a new trace segment to be added to trace cache segment storage.

While The Alternate Fill Method is deficient at maintaining trace continuity (for n-constraint trace segments), yet it will always begin traces at probable entry points (start of basic blocks)
Rotenberg Vs. Alternate (Pelog) Fill Scheme

Assuming a maximum of two basic blocks fit completely in a trace segment, i.e., size of two basic blocks $\leq n$ instructions

**Fill Unit Operation:**

Resulting Trace Segments:

<table>
<thead>
<tr>
<th>Rotenberg Fill Policy</th>
<th>Alternate Fill Policy</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-B-C1</td>
<td>A-B-C1</td>
</tr>
<tr>
<td>C2-D-E1</td>
<td>B-C-D1</td>
</tr>
<tr>
<td></td>
<td>C-D-E1</td>
</tr>
<tr>
<td></td>
<td>D-E</td>
</tr>
</tbody>
</table>

Example

<table>
<thead>
<tr>
<th>m = 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A B</td>
</tr>
<tr>
<td>A B</td>
</tr>
<tr>
<td>A B C1</td>
</tr>
<tr>
<td>C2 D</td>
</tr>
<tr>
<td>C2 D E1</td>
</tr>
<tr>
<td>Trace Cache</td>
</tr>
</tbody>
</table>

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<tbody>
<tr>
<td>A B C1</td>
</tr>
<tr>
<td>B C D1</td>
</tr>
<tr>
<td>C D E1</td>
</tr>
<tr>
<td>Trace Cache</td>
</tr>
</tbody>
</table>

Rotenberg Fill Scheme

Alternate (Pelog) Fill Scheme
Rotenberg Vs. Alternate (Pelog) Fill Scheme
Trace Cache Hit Rate

Trace Cache Hit Rate for Rotenberg and Alternate Fill Schemes

- roots
- solve
- integ
- lag
- matrix
- gzip
- djpeg
- cjpeg
- fft
- inv_fft

Rotenberg Fill
Alternate Fill
The Alternate (Pelog) Fill Scheme adds a trace for virtually every basic block encountered, generating twice as many unique traces than Rotenberg’s fill scheme.
Rotenberg Vs. Alternate (Pelog) Fill Scheme

Speedup

Alternative (Pelog) fill scheme’s performance is mostly equivalent to that of Rotenberg’s Trace Fill Scheme

Speedup Comparison
(Rotenberg vs Alternate Fill Mechanisms)

The chart shows a comparison of speedup for various tasks between Rotenberg Fill and Alternate Fill. The performance is mostly equivalent across different tasks such as roots, solve, integ, lag, matrix, gzip, djpeg, cjpeg, fft, and inv_fft.
Trace Fill Scheme Tradeoffs...

• The Alternate (Pelog) Fill Method is deficient at maintaining trace continuity, yet will always begin traces at probable entry points (start of basic blocks).

• The Rotenberg Fill Method maintains trace continuity, yet has the potential to miss entry points.

Can one combine the benefits of both??
A New Proposed Trace Fill Unit Scheme

- To supply an intelligent set of trace segments, the Fill Unit should:
  1. Maintain trace continuity when faced with a series of one or more n-constrained segments.
  2. Identify probable entry points and generate traces based on these fetch addresses.

Proposed Solution

The Sliding Window Fill Mechanism (SWFM) with Fill Select Table (FST)

- “Improving Trace Cache Hit Rates Using the Sliding Window Fill Mechanism and Fill Select Table”, M. Shaaban and E. Mulrane, ACM SIGPLAN Workshop on Memory System Performance (MSP-2004), 2004.

Paper # 7
The proposed Sliding Window Fill Mechanism paired with the Fill Select Table (FST) is an extension of the alternate (Pelog) fill scheme examined earlier.

The difference is that in that following \( n \)-constraint traces:
- Instead of discarding the entire oldest basic block in the trace fill buffer from consideration, single instructions are evaluated as probable entry points one at a time.

Probable entry points accounted for by this scheme are:
1. Fetch addresses that resulted in a trace cache miss.
2. Fetch addresses following allocated \( n \)-constraint trace segments.

The count of how many times a probable entry point has been encountered as a fetch address is maintained in the Fill Select Table (FST), a tag-matched table that serves as probable trace segment entry point filtering mechanism:
- Each FST entry is associated with a probable entry point and consists of an address tag, a valid bit and a counter.

A trace segment is added to the trace cache when the FST entry count associated with its starting address is equal or higher than a defined threshold value \( T \).
The SWFM Components

Trace Fill Buffer

• The SWFM trace fill buffer is implemented as a circular buffer, as shown next.

• Pointers are used to mark:
  – The current start of a potential trace segment (trace_head)
  – The final instruction of a potential trace segment (trace_tail)
  – The point at which retired instructions are added to the fill buffer (next_instruction).

• When a retired instruction is added to the fill buffer the next_instruction pointer is incremented.

• At the same time, the potential trace segment bounded by the trace_head and trace_tail pointers is considered for addition to the trace cache.
  – When the count of FST entry associated with the current start of a potential trace segment (trace_head) meets threshold requirements, the segment is added to trace cache and trace_head is incremented to examine the next instruction as a possible start of trace segment again consulting the FST.
The SWFM Components

Trace Fill Buffer

Trace Head Pointer:
Current start of a potential trace segment

Trace Tail Pointer:
Final instruction of a potential trace segment

Fill Direction

FST  > T?

Compare with Fill Select Table (FST) entries

Next Instruction Pointer:
Where retired instructions are added to the fill buffer
The SWFM Components
Trace Fill Buffer Update

- Initially when the circular fill buffer is empty trace_head = trace_tail = next_instruction

- As retired instructions are added to the fill buffer, the next_instruction pointer is incremented accordingly.
  - The trace_tail is incremented until the potential trace segment bounded by the trace_head and trace_tail pointers is either:
    1. The segment is n-constraint or
    2. The segment m-constraint
    3. or trace_tail reaches next_instruction whichever happens first.

- After the potential trace segment starting at trace_head has been considered for addition to the trace cache by performing an FST lookup, trace_head is incremented.
  - For n-constraint potential trace segments the tail is incremented until one of the three conditions above occur.
  - For m-constraint potential trace segments the tail is not incremented until trace_head is incremented discarding one or more branch instructions. When this occurs the trace_tail is incremented until one the three conditions above are met.
The SWFM Components
The Fill Select Table (FST)

• A Tag-matched Table that serves as probable trace segment entry point filtering mechanism:
  – Each FST entry consists of an address tag, a valid bit and a counter.

• The fill unit will allocate or increment the count of an existing FST entry if its associated fetch address is a potential trace segment entry point:
  – Resulted in a trace cache miss and was serviced by the core fetch unit (conventional I-cache).
  – Followed an $n$-constraint trace segment (for trace continuity).

• Thus, an address in the fill buffer with an FST entry with a count higher than a set threshold, $T$ is identified as a probable trace segment entry points and the segment is added to trace cache.

• An FST lookup with the fetch address at trace_head every time a trace segment bounded by the trace_head and trace_tail pointers is considered for addition to the trace cache as described next ...
The SWFM: Trace Segment Filtering Using the FST

- Before filling a segment to the trace cache, FST lookup is performed using the potential trace segment starting address (trace_head).
- If a matching FST entry is found, its count is compared with a defined threshold value T:
  - FST Entry Count ≥ Threshold (T) → Segment is Added to the Trace Cache, → FST entry used is cleared & → Fill Buffer is updated
  - FST Entry Count < Threshold (T) → Fill Buffer is updated, → No segment is added to the Trace Cache
The SWFM/FST
Number of Unique Traces Added

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>T=1</th>
<th>T=2</th>
<th>T=3</th>
<th>T=4</th>
<th>T=8</th>
<th>T=16</th>
</tr>
</thead>
<tbody>
<tr>
<td>roots</td>
<td>25,725</td>
<td>4,828</td>
<td>2,121</td>
<td>1,828</td>
<td>837</td>
<td>327</td>
</tr>
<tr>
<td>solve</td>
<td>19,308</td>
<td>2,856</td>
<td>1,579</td>
<td>1,058</td>
<td>444</td>
<td>237</td>
</tr>
<tr>
<td>integ</td>
<td>11,480</td>
<td>1,968</td>
<td>1,013</td>
<td>708</td>
<td>303</td>
<td>144</td>
</tr>
<tr>
<td>lag</td>
<td>16,269</td>
<td>2,609</td>
<td>1,149</td>
<td>800</td>
<td>360</td>
<td>172</td>
</tr>
<tr>
<td>matrix</td>
<td>6,829</td>
<td>1,622</td>
<td>803</td>
<td>567</td>
<td>326</td>
<td>238</td>
</tr>
<tr>
<td>gzip</td>
<td>56,020</td>
<td>16,274</td>
<td>11,214</td>
<td>7,784</td>
<td>4,728</td>
<td>2,496</td>
</tr>
<tr>
<td>djpeg</td>
<td>327,289</td>
<td>25,265</td>
<td>15,770</td>
<td>11,488</td>
<td>5,297</td>
<td>2,344</td>
</tr>
<tr>
<td>cjpeg</td>
<td>303,101</td>
<td>39,720</td>
<td>24,436</td>
<td>18,703</td>
<td>8,666</td>
<td>4,500</td>
</tr>
<tr>
<td>fft</td>
<td>334,094</td>
<td>48,395</td>
<td>23,438</td>
<td>17,495</td>
<td>6,313</td>
<td>2,228</td>
</tr>
<tr>
<td>inv_fft</td>
<td>653,229</td>
<td>82,096</td>
<td>37590</td>
<td>26,158</td>
<td>10,167</td>
<td>3,068</td>
</tr>
</tbody>
</table>

For FST threshold (T) larger than 1, the number of unique traces added is substantially lower than either Rotenberg or Alternative fill Schemes.
On the average, an FST Threshold $T = 2$ provided the highest hit rates and thus was chosen for further simulations of SWFM.
On Average, Trace Cache Hit Rates Improved by 7% over the Rotenberg Fill Method when utilizing the Sliding Window Fill Mechanism.
The SWFM/FST: Speedup Comparison

On Average, speedup Improved by 4% over the Rotenberg Fill Method when utilizing the Sliding Window Fill Mechanism

Speedup Comparisons Among Fill Schemes

- Roots solve integ lag matrix gzip djpeg cjpeg fft inv_fft
- Speedup

Legend:
- Rotenberg Trace Cache
- Alternate Fill Scheme
- SWFM/ FST

Paper # 7
Reducing Number of Conditional Branches within a Trace Cache Segment:

Branch Promotion

- Proposed by Patel, Evers, Patt (1998)

- **Observation:**
  - Over half of conditional branches are strongly biased. *e.g. loops*
  - Identification of these allows for treatment as static predictions.

- **Bias Table:**
  - Tag checked associative table
  - Stores the number of times a branch has evaluated to the same result consecutively
  - Bias Threshold is the number of times a branch must consistently evaluate taken or not-taken before it is promoted.

- **Promoted Branches:**
  - Fill unit references branch instructions with Bias Table, if count is greater than threshold, branch is *Promoted.*
  - Promoted branches are marked with a single bit flag, and associated with Taken or Not-Taken path
  - Not included in Branch Mask/Flags field, alleviating the multiple branch predictor

- **Potential Benefit**
  - Increases trace cache utilization by decreasing the number of m-constrained traces
Rotenberg TC Vs. TC With Branch Promotion
Speedup Comparison

Branch Promotion Bias Threshold used = 32
Average Speedup over Rotenberg = 14%

Speedup Comparison
(Rotenberg Trace Cache vs. Trace Cache with Branch Promotion)

Paper # 7
Combined Scheme: SWFM/SFT & Branch Promotion

Trace Fill Policy

• Independently, Branch Promotion and the SWFM with FST improve trace cache, hit rate, fetch bandwidth and performance independently:
  
  – **Branch promotion** reduces the number of m-constraint trace segments. This increases trace segment utilization resulting in better trace cache performance.
  
  – **SWFM with FST** excels at generating relevant traces that start at probable entry points while providing trace continuity for n-constraint trace segments.

• Intuitively, these schemes seem to compliment each other and combining them has the potential of further performance improvement.

*We next examine the preliminary results of the combined scheme ...*
Combined Scheme: SWFM/SFT & Branch Promotion

Hit Rate Comparison

Combined with Branch Promotion, the SWFM improved Trace Cache Hit Rates over the Rotenberg Scheme by 17% on average.
Combined with Branch Promotion, the SWFM improved Fetch Bandwidth over the Rotenberg Scheme by 19% on average.
Combined Scheme: SWFM/SFT & Branch Promotion

Speedup Comparison

Combined scheme showed no speedup improvement over Rotenberg scheme with branch promotion

Why?

Speedup Results for Branch Promotion and Alternate Fill Combination
Combined Scheme: SWFM/SFT & Branch Promotion
Prediction Accuracy Comparison

The decrease in multiple branch prediction accuracy limits performance improvement for the combined scheme.

Branch Prediction Accuracy Among Trace Cache Schemes

Prediction Accuracy

- Branch Promotion
- SWFM/FST
- Combined
The Sliding Window Fill Mechanism (SWFM) with Fill Select Table (FST) Summary

- The Proposed Sliding Window Fill Mechanism tightly coupled with the Fill Select Table exploits trace continuity and identifies probable trace segment start regions to improve trace cache hit rate.

- For the selected benchmarks, simulation results show a 7% average hit rate increase over the Rotenberg fill mechanism.

- When combined with branch promotion, trace cache hit rates experienced a 19% average increase along with a 17% average improvement in fetch bandwidth.
  - However, the decrease in multiple branch prediction accuracy limited performance improvement for the combined scheme.

- Possible Future Enhancements:
  - Further evaluation of SWFM/FST performance using more comprehensive benchmarks (SPEC).
  - Investigate combining SWFM/FST with other trace cache optimizations including partial trace matching ….
  - Further investigation of the nature of the inverse relationship between trace cache hit rate/fetch bandwidth and multiple prediction accuracy.
  - Incorporate better multiple branch prediction schemes with SWFM/FST & Branch Promotion.

i.e other than MGAg
Improving Trace Cache Storage Efficiency: Block-Based Trace Cache

- Block-Based Trace Cache improves on conventional trace cache by instead of explicitly storing instructions of a trace, pointers to basic blocks constituting a trace are stored in a much smaller trace table.

  Why?
  - This reduces trace storage requirements for traces that share the same basic blocks.

- The block-based trace cache renames fetch addresses at the basic block level using block IDs and stores aligned blocks in a block cache.

- Traces are constructed by accessing the replicated block cache using block pointers from the trace table.

- Four major components:
  1. The trace table,
  2. The block cache,
  3. The rename table
  4. The fill unit.
Block-Based Trace Cache

Construction of dynamic execution traces from stored basic blocks done at fetch time, potentially increasing fetch latency over conventional trace cache.

Potential Disadvantage:

Provides Block IDs of Completed Basic Blocks

Storing trace blocks by fill unit done at completion time (similar to normal trace cache)
Block-Based Trace Cache: Trace Table

- The Trace Table is the mechanism that stores the renamed pointers (block ids) to the basic blocks for trace construction.
- Each entry in the Trace Table holds a shorthand version of the trace. Each trace table entry consists of 1- a valid bit, 2- a tag, and 3- the block ids of the trace.
- These block ids of a trace are used in the fetch cycle to tell which blocks are to be fetched and how the blocks are to be collapsed using the final collapse MUX to form the trace.
- The next trace segment is also predicted using the Trace Table. This is done using a hashing function, which is based either on the last block id and global branch history (gshare prediction) or a combination of the branch history and previous block ids.
- The filling of the Trace Table with a new trace is done in the completion stage. The block ids and block steering bits are created in the completion stage based on the blocks that were executed and just completed.
Trace Table

Or Fetch Address

\[
\begin{array}{cccc}
 b_{id0} & b_{id1} & b_{id2} & b_{id3} \\
\end{array}
\]

Trace ID

Hash Function

Next trace_id

[Diagram of Trace Table]

- Hash Function
- Trace ID
- b_id0, b_id1, b_id2, b_id3
- branch history
- block_ids
- Trace Table
- Hit
- w pred. block_ids to the block cache
Block-Based Trace Cache: Block Cache

- The Block Cache is the storage mechanism for the basic instruction blocks to execute.
- The Block Cache consists of replicated storage to allow for simultaneous accesses to the cache in the fetch stage.
- The number of copies of the Block Cache will therefore govern the number of blocks allowed per trace.
- At fetch time, the Trace Table provides the block ids to fetch and the steering bits. The blocks needed are then collapsed into the predicted trace using the final collapse MUX. From here, the instructions in the trace can be executed as normal on the Superscalar core.

Disadvantage: Potentially longer instruction fetch latency than conventional trace cache which does not require constructing a trace from its basic blocks (similar to CB, BAC).
Block Cache With Final Collapse MUX

From Trace Table

N = \(2^n\) word lines

block_id (n-bit)

decoder

Instructions from the block fill unit

FA i1 i2 ... ib

direct mapped cache

Trace Fetch Phase

b inst

copy-2

copy-3

copy-4

4-6 copies

Final Collapse

Done at fetch time potentially increasing fetch time

Fetch Buffer

Paper # 6
Example Implementation of The Rename Table

Block fetch address

<table>
<thead>
<tr>
<th>Tag</th>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(8 entries, 2-way set associative).

<table>
<thead>
<tr>
<th>v</th>
<th>tag</th>
<th>block_id</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
</tr>
</tbody>
</table>

Optimal rename table associativity = 4 or 8 way

N=8 entries

Block fetch address renamed to a block_id
Block-Based Trace Cache: The Fill Unit

- The Fill Unit is an integral part of the Block-based Trace Cache. It is used to update the Trace Table, Block Cache, and Rename Table at completion time.

- The Fill Unit constructs a trace of the executed blocks after their completion. From this trace, it updates the Trace Table with the trace prediction, the Block Cache with Physical Blocks from the executed instructions, and the Rename Table with the fetch addresses of the first instruction of the execution blocks (to generate blocks IDs).

- It also controls the overwriting of Block Cache and Rename Table elements that already exist. In the case where the entry already exists, the Fill Unit will not write the data, so that bandwidth is not wasted.
Performance Comparison:
Block vs. Conventional Trace Cache

~ 4 IPC with only 4k Block Trace Cache

vs. ~ 4 IPC with over 64k conventional Trace Cache