# Performance Tracing & Profiling

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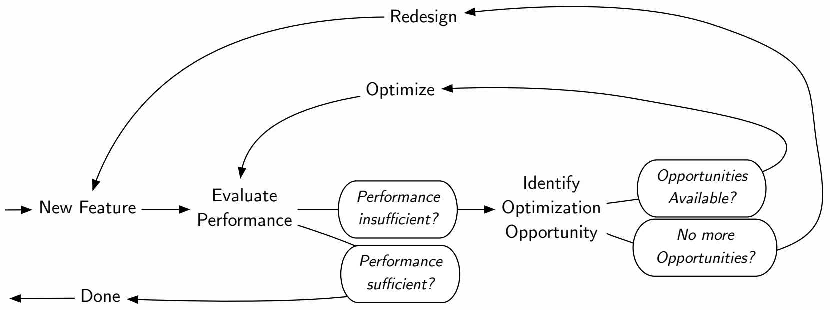
# Motivation

Recall:

# The Optimization Loop



So, how do we identify optimization opportunities?

# How to identify optimization opportunities

- We identify the hot path (the code that takes the most time)
- We identify the bottleneck
  - in terms of CPU, Memory, Network, ...
- Both are functions of the system behavior

So, how do we describe system behavior?

# Events

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- Complex events
  - cache line evicted from L1 to L2 cache, instruction aborted due to misspeculation
- Events have an optional *payload*
- An event has an *accuracy*: the degree to which its value represents reality

# What can you do with events?

## Where they come from

- *Event Sources* are have two components
  - The *generator* observes the changes to the system state
    - Usually online, i.e., part of the runtime environment/system
  - The *consumer* processes the events
    - Can be offline or online

## Where they go

- Tracing
- Profiling

Tracing

# Trace

- Definition: *A complete log of every state the system has ever been in (in the period of interest)*
    - Comprised of events
    - Events are ordered (usually totally ordered)
- Accuracy is "inherited" from the events
- Event collection overhead may be high

Example: Call stack tracing

# Call stack tracing

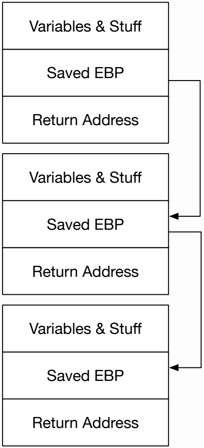
**A typical call stack**

| Address |
| --- |
| 0x231fa90 |
| 0x7828b72 |
| 0x8913ee1 |

- So, what does a stack look like in reality?

# A call stack

## Illustration



# Call stack tracing

## Problems

- Recording the entire call stack is quite expensive
  - The stack needs to be walked, pointers need chasing
  - Call stacks can be deep
  - All frame pointers have to be written to memory
- In particular for small/cheap functions, call stack processing can be way more expensive than the function itself

We call this problem…

Perturbation

# Perturbation

**Definition: Perturbation**

The degree to which the performance of a system changes when it is being analyzed.

- Perturbation negatively affects accuracy if it is non-deterministic
- A bit like quantum theory
  - You influence the state of the system just by looking at it

How do we reduce perturbation?

# How to reduce perturbation

- We reduce *fidelity*
- Fidelity (Oxford Dictionary): *the degree of exactness with which something is copied or reproduced*
- Perfect fidelity, i.e., every event is recorded
- Reduced fidelity, i.e., not every event is recorded

How?

# Sampling

# Sampling

- Idea: do not collect all events to reduce perturbation
- Option 1: Sample in regular intervals
- Option 2: Sample in random intervals

# Example: Call stack sampling

- Idea: Skip some events
  - there is a chance you will not sample a function
  - Fortunately, more expensive functions will be sampled more often
- But:
  - good performance
  - even more important: less perturbation
  - fidelity can be traded against perturbation & performance

What is an interval?

# Sampling Intervals

# Sampling Intervals

- The distance of two samples being taken
  - Obviously, interval size 1 makes sampling equal to event-tracing
- Two options for specification: time-based and event-based

# Time-based Intervals

- Idea: set a (hardware) recurrant timer and sample whenever it runs out
- We use CPU *reference cycles* as a proxy metric
- Inaccurate, non-deterministic and noisy (computer clocks are poorly defined)
  - Clock rate varies, clocks may not be exactly synchronized among CPUs, etc.
- Easy to interpret (since time is inversely proportional to performance)

# Event-based Intervals

- Generalization of Time-based intervals (since computer time is discrete)
- Define an interval in terms of the occurence of an event
- Example: sample every fifth function call
- Accurate, deterministic semantics and low noise
- Tricky to interpret (in the end, we are interested in time)

# Quantization errors

- Interval resolution is limited (usually to single clock cycles but sometimes more)
- Time is (practically) continuous
- This introduces "quantization errors/biases"
  - E.g., costs being attributed to the wrong state

Here is an interesting instance of event-based intervals:

# Indirect Tracing

# Indirect Tracing

- Idea: Some trace events are "dominated" by others (executed depending on their outcome)
    - Think of it as intervals defined by the execution flow
    - For example, control-flow instructions (`if`, `else`, `for`, `while`) dominate non-control-flow instructions
    - can be used to reduce overhead
    - Fidelity and accuracy usually good (depending on the event and the indirection)

# Wrapup: Tracing

- Tracing collects (subsets of) events
- Perturbation is a problem but can be worked around
- **But:** Analyzing traces is extremely tedious
    - Lots of data, little structure, lots of cognitive overhead

The solution:

# Profiling

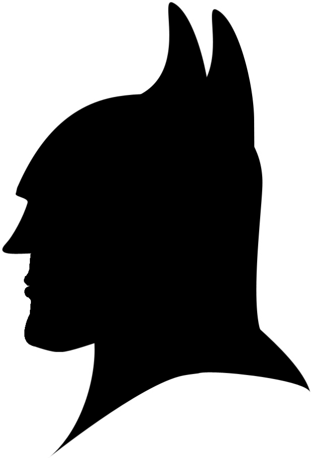
# Profiling

**Definition: Profile**

An outline of something, especially a person's face, as seen from one side.

# Profiling

## A profile



# Profiling

## Definition: Profile

A graphical or other representation of information relating to particular characteristics of something, recorded in quantified form

## In our context

A characterization of a system in terms of the resources it spends in certain states.

# Profile

- An aggregate over the events of a specific metric

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- Why?
  - Post-mortem for ease of interpretation
  - Realtime to reduce perturbation (assuming aggregation is cheaper than dumping)

# Example: Flame Graphs

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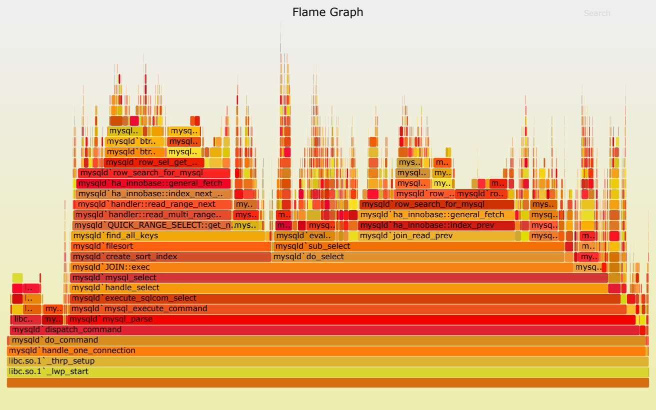


https://queue.acm.org/detail.cfm?id=2927301

# Flame Graphs

- X-axis shows the stack profile population, sorted alphabetically (not by time),
- Y-axis shows stack depth
- Each rectangle represents a stack frame
- Width of a box is proportional to the number of collected samples
- Colors are usually not significant

Okay, now that we know what to do with events...

. . . let us talk about specific ways to collect events

# Event Sources

# Requirements for event sources

- Detailed
  - As much information as we need
- Accurate
  - The measurements should closely describe the real-world
- Little perturbation

# Where to get events?

- Software
  - Library: Manual Instrumentation/Logging
  - Compiler: Automatic Instrumentation
  - OS: Kernel Counters
- Hardware:
  - Performance counter
- Emulator:
  - a funky hybrid, minimal perturbation but usually not scalable

# Instrumentation

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  - Overhead is high
  - Perturbation is high

# Instrumentation

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- Three approaches
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  - Automatic binary instrumentation
    - Static (compile-time) or
    - Dynamic (runtime)
    - As usual, there are hybrids

# Manual

- basically `printf` logging (or using a logging library)
- Advantages
  - Fine control over instrumentation
  - Needs no support from hardware or compiler
- Disadvantages
  - high overhead for implementation & runtime
  - usually disabled for release build
    - needs recompilation for selective enabling

# Automatic

- Usually compiler-supported
- Source-to-source rewriting is possible
- Disadvantages
  - Less control
  - Need for compiler support
- Advantages
  - Let's discuss this!

# Binary Instrumentation

- Static
  - No magic, simple, portable
  - Instrumentation overhead can be assessed from binary
- Dynamic
  - No recompilation
  - Can be performed on running process
  - Works with JiT-compiled code

Demo time!!!

- http://llvm.org/docs/XRay.html

# LLVM-XRay

```
curl --compressed https://www.gutenberg.org/cache/epub/2229/pg2229.txt |
↪  iconv -c -f UTF8 -t ASCII | tr -d '\r' > faust.txt
for i in {1..1000}; do cat faust.txt >> faust1000.txt; done
clang++ -g -O0 -fxray-instrument -fxray-instruction-threshold=1
↪  ~/pegrep.cpp
XRAY_OPTIONS="patch_premain=true xray_mode=xray-basic verbosity=1"
↪  ./a.out faust1000.txt

llvm-xray convert -f yaml -symbolize -instr_map ./a.out xray-log.a.out.*
↪  | less
llvm-xray account -sort=count -sortorder=dsc -instr_map ./a.out
↪  xray-log.a.out.*
```

# LLVM-XRay

## Explanation

The logging functions by default prune records that are less than 5 microseconds equivalent in walltime deduced from the cycle counter deltas. This allows XRay to retain only records that have a measurable impact in walltime.

We want higher fidelity/lower overhead!

The solution: Hardware Support!

# Performance Counting

# Software Performance Counters (OS)

- Network Packages sent
- Virtual Memory Operations
- ...
- Let's say we want to write code that is efficient at the microarchitectural level

Software is good, Hardware is better!

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- Unfortunately:
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  - Sometimes poorly documented
  - Accuracy can be poor
    - The common ones are usually okay

# Examples

## Try this

```
hlgr@sprite17:~$ perf list pmu | egrep "^  [^ ]" | less | wc
    802    1009   45255
```

# Examples

## And this

```
hlgr@sprite17:~$ perf list pmu | tail +53 | head -n 20
cache:
  l1d.replacement
       [L1D data line replacements]
  l1d_pend_miss.fb_full
       [Number of times a request needed a FB entry but there was no
↪   entry
        available for it. That is the FB unavailability was dominant
↪   reason
        for blocking the request. A request includes
↪   cacheable/uncacheable
        demands that is load, store or SW prefetch]
  l1d_pend_miss.pending
       [L1D miss outstandings duration in cycles]
  l1d_pend_miss.pending_cycles
       [Cycles with L1D load Misses outstanding]
  l1d_pend_miss.pending_cycles_any
       [Cycles with L1D load Misses outstanding from any thread on
↪   physical
        core]
```

# But most importantly

RTFM!

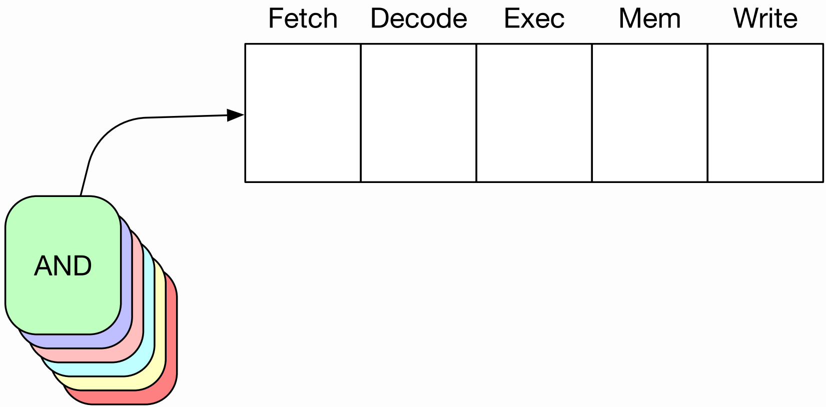
i.e., the "Intel 64 and IA-32 Architectures Optimization Reference Manual"

# Example: Microarchitectural bottleneck analysis

How does a CPU work?

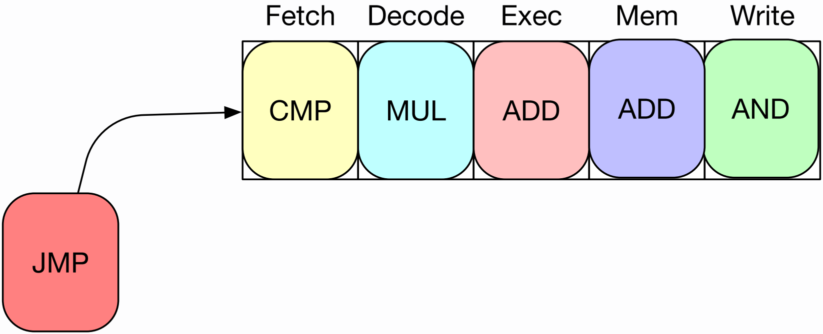
# How does pipelined execution work?

## An Empty CPU Pipeline



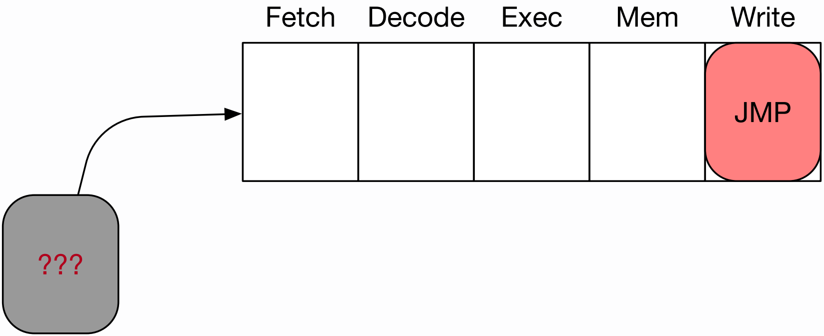
# How does pipelined execution work?

## A Filled CPU Pipeline



# How does pipelined execution work?

## A control hazard/pipeline bubble



How does Branch Prediction work?

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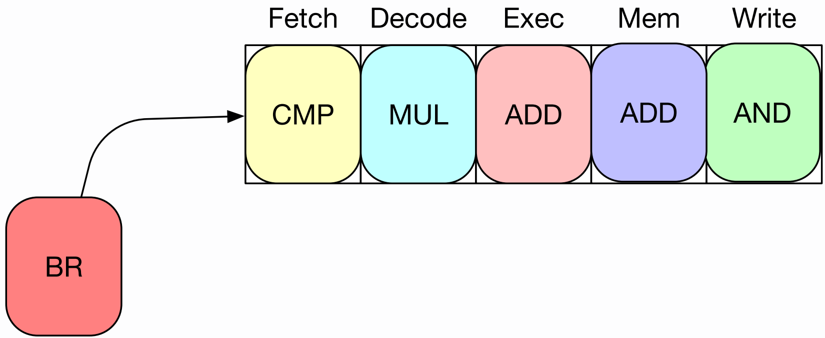
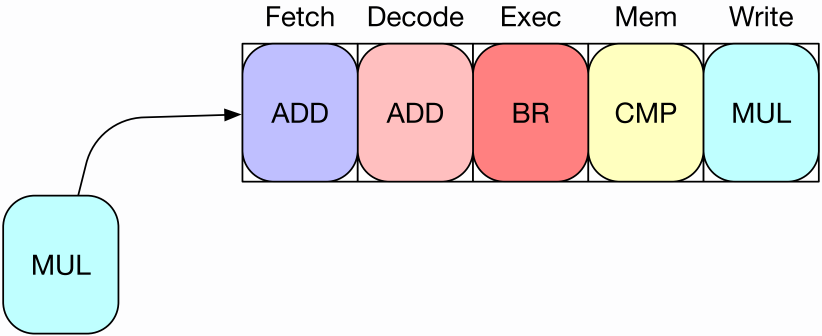
## A branch to be predicted (a.k.a., speculated upon)



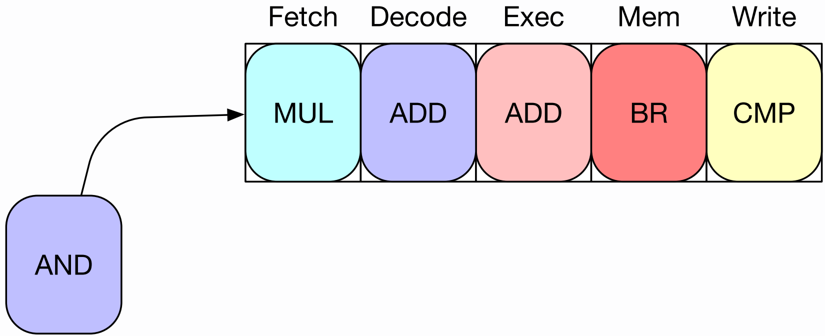
# How does Branch Prediction work?

## A speculatively executed branch



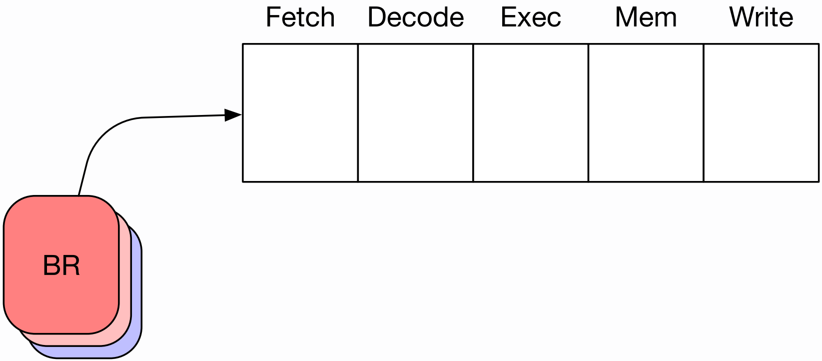
# How does Branch Prediction work?

## Time of prediction resolution



# How does Branch Prediction work?

## Rollback upon misprediction

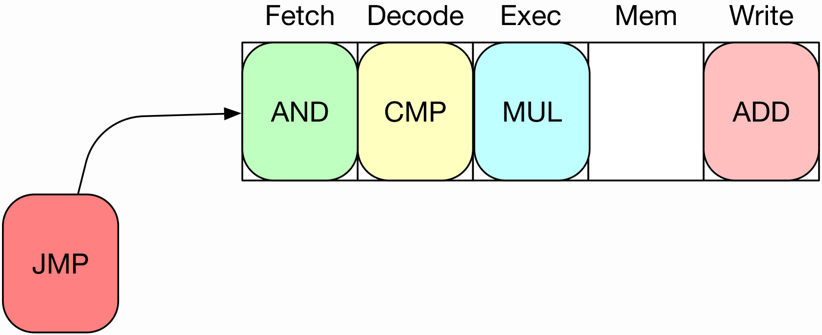


# How does pipelined execution work?

- Bottom line:
  - CPUs can stall on control dependencies

# Resource Stalls

## An ALU Stall

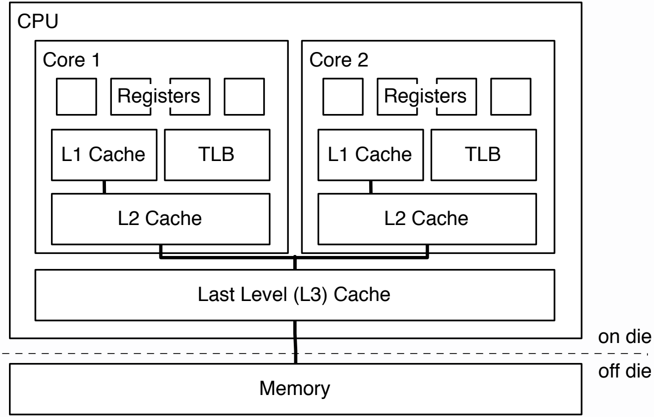


# Resource Stalls

- Bottom line:
  - CPUs can stall due to lack of compute resources

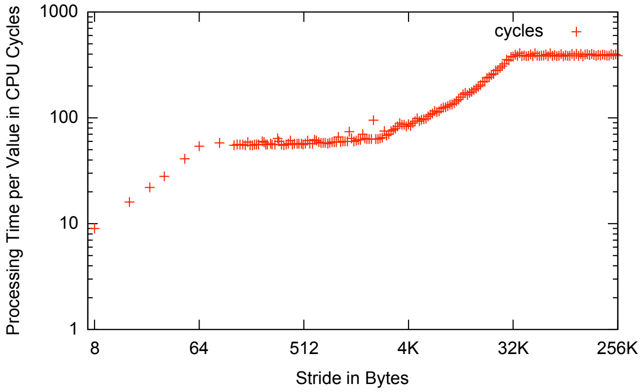
# How does the memory subsystem work?

## A CPU



# How does the memory subsystem work?

## Memory Access Latencies (depending on locality)



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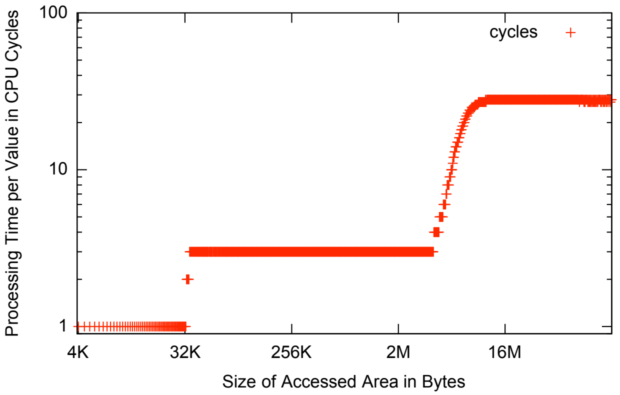
## Memory Access Latencies (depending on data size)



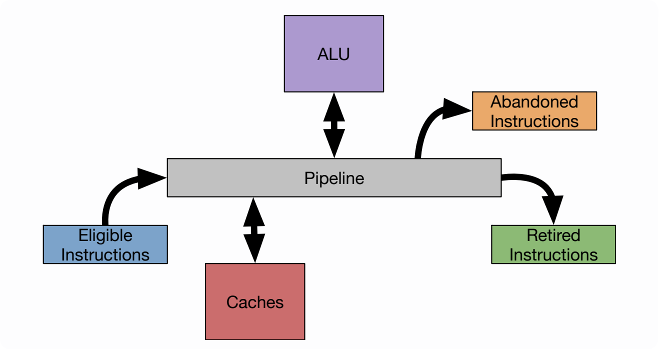
# How does the memory subsystem work?

- Bottom line:
  - CPUs can stall on data access

# Bottleneck analysis

- Let's find some microarchitectural bottlenecks
  - Data Stalls
  - ALU Stalls
  - Branch Mispredictions
  - Control-flow dependencies

# Bottleneck analysis



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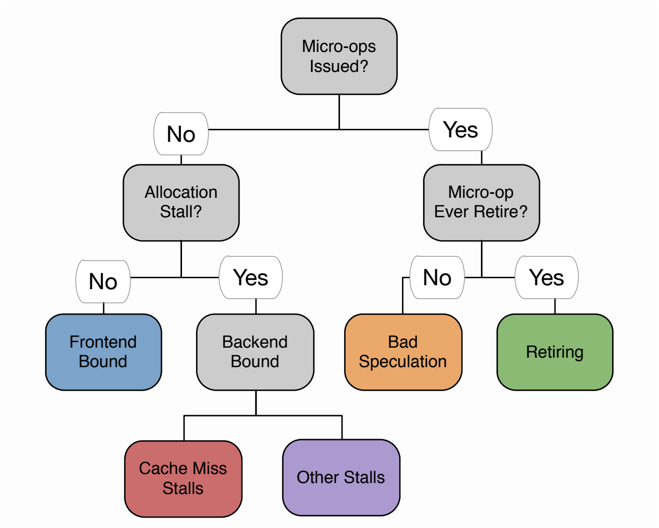

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