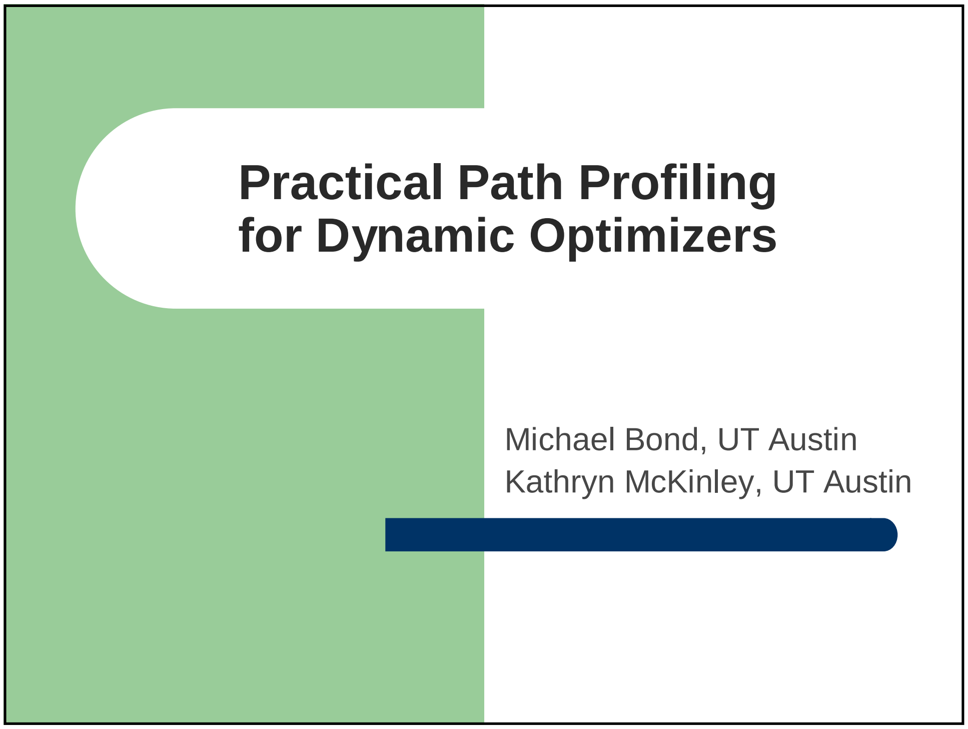
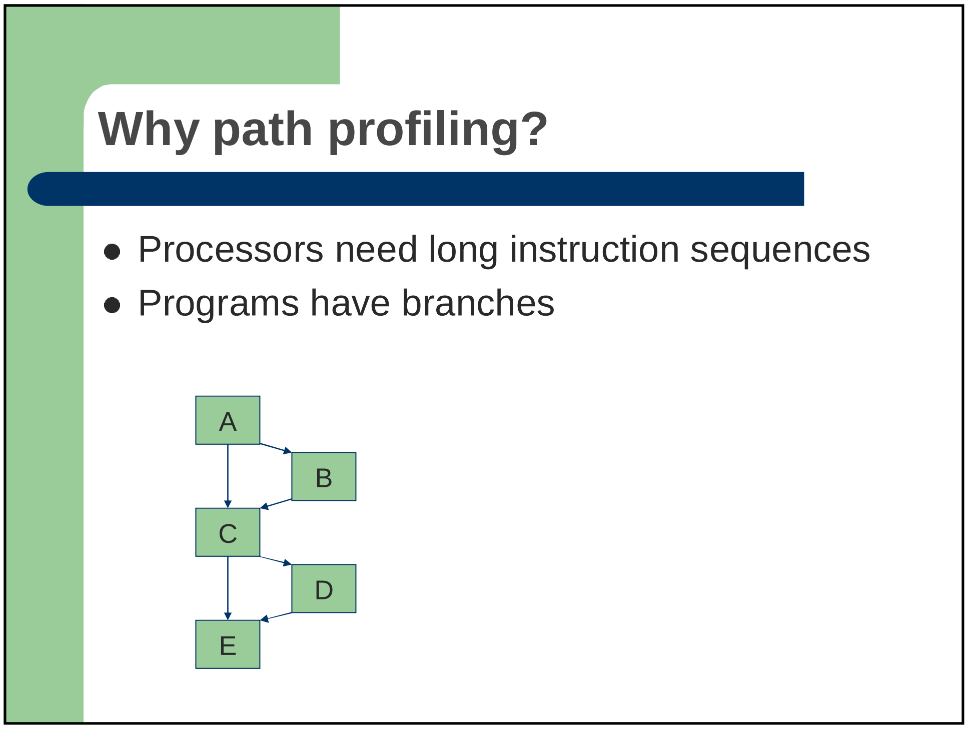


Practical Path Profiling for Dynamic Optimizers

Michael Bond, UT Austin
Kathryn McKinley, UT Austin

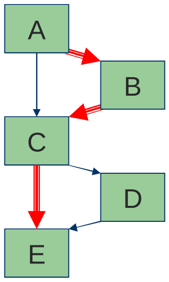


Why path profiling?

- Processors need long instruction sequences
- Programs have branches

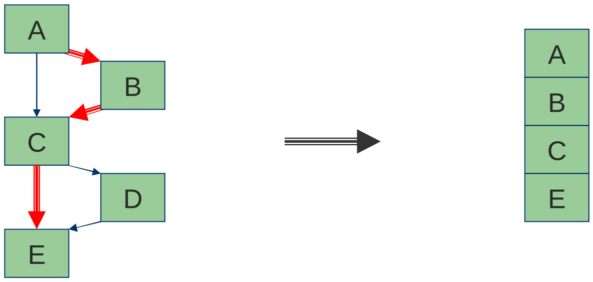
Why path profiling?

- Compiler identifies hot paths across multiple basic blocks



Why path profiling?

- Compiler identifies hot paths across multiple basic blocks
  - Forms and optimizes “traces”



Why path profiling?

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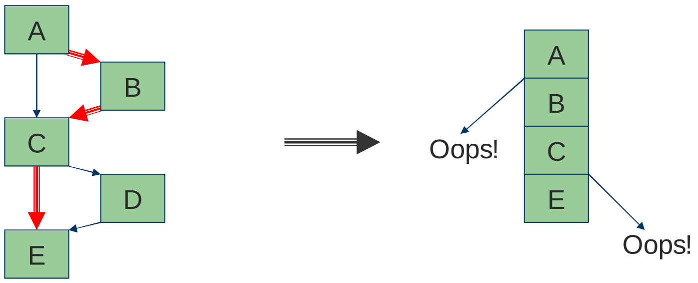

Why path profiling?

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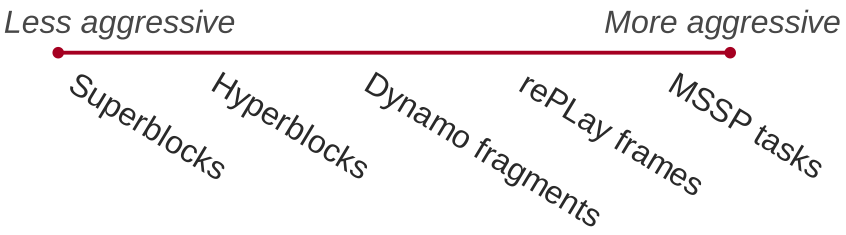
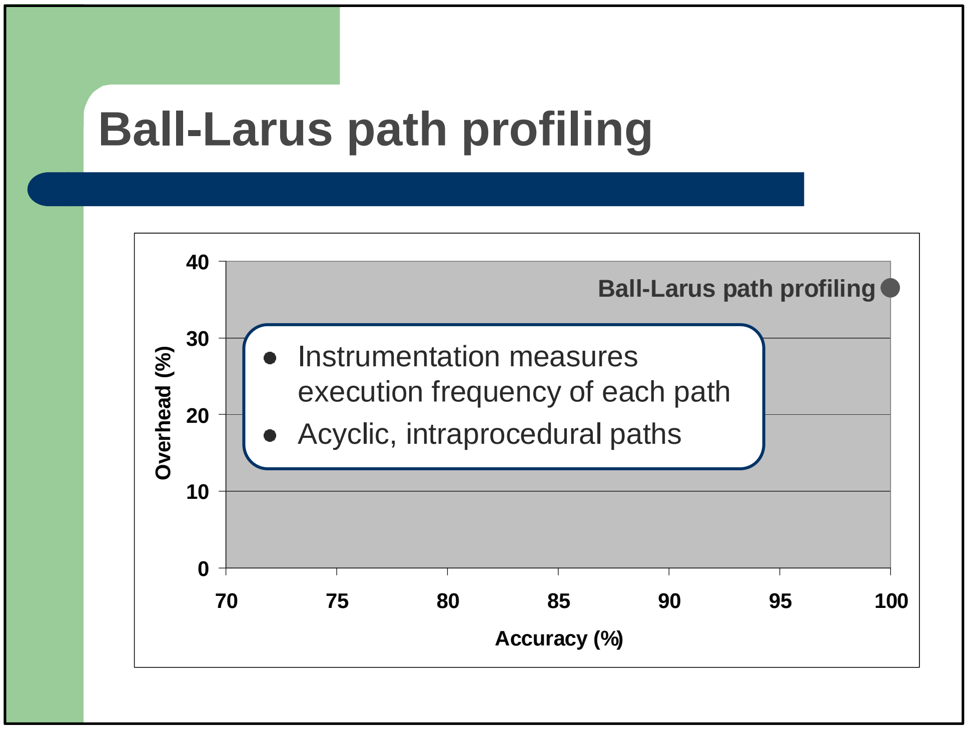


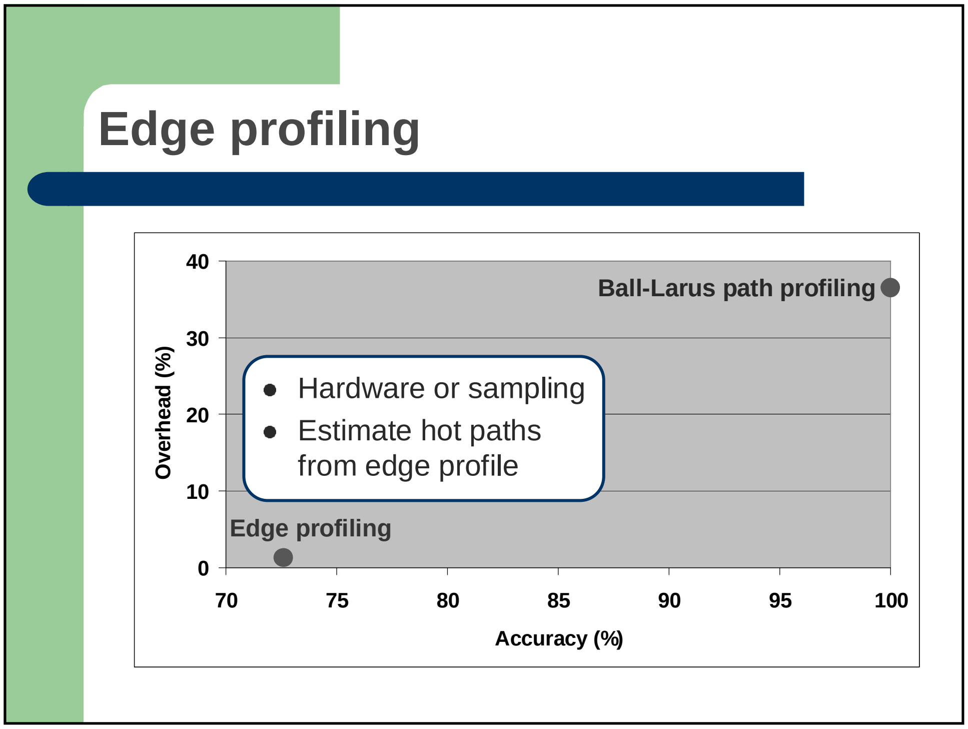
Less aggressive *More aggressive*

Superblocks Hyperblocks Dynamo fragments rePLay frames MSSP tasks



Ball-Larus path profiling

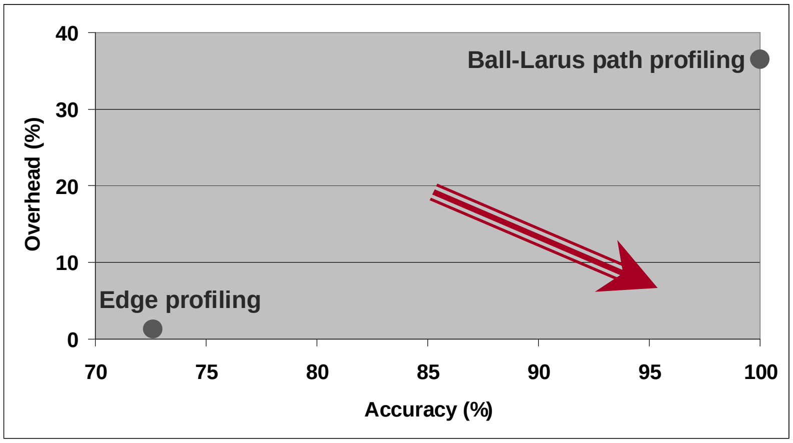
- Instrumentation measures execution frequency of each path
- Acyclic, intraprocedural paths



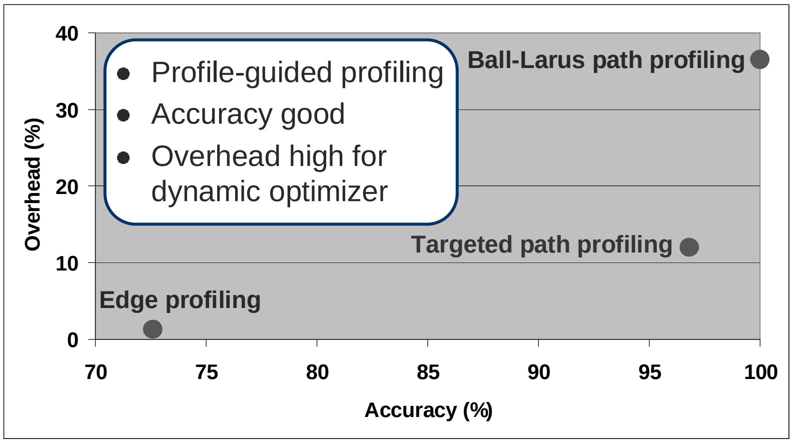
Edge profiling

- Hardware or sampling
- Estimate hot paths from edge profile

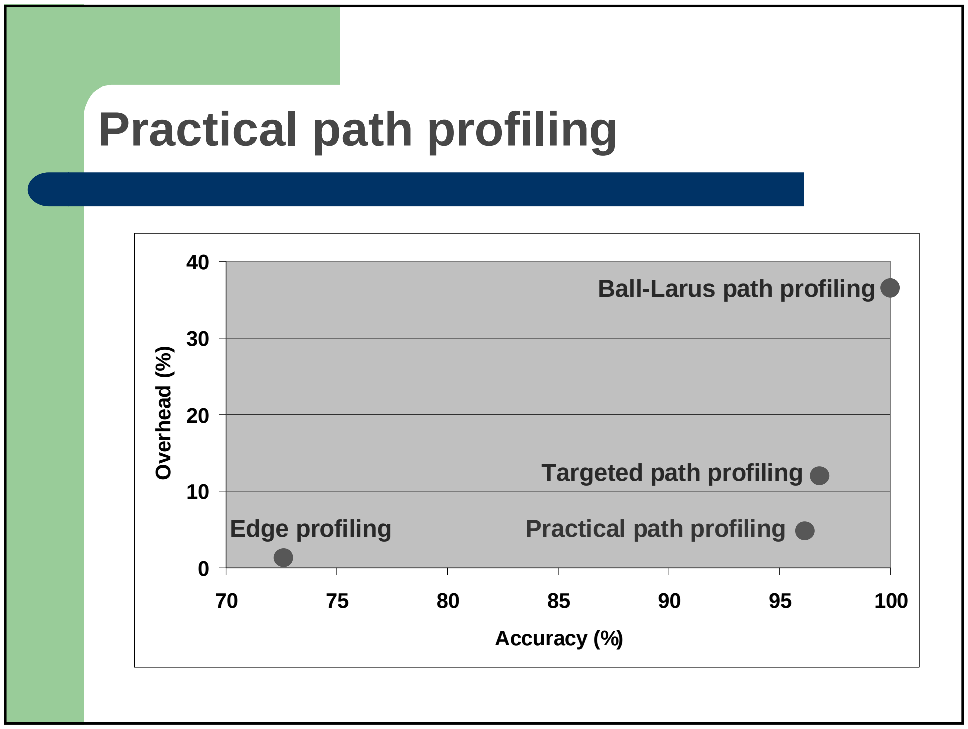
Ideal for dynamic optimizer



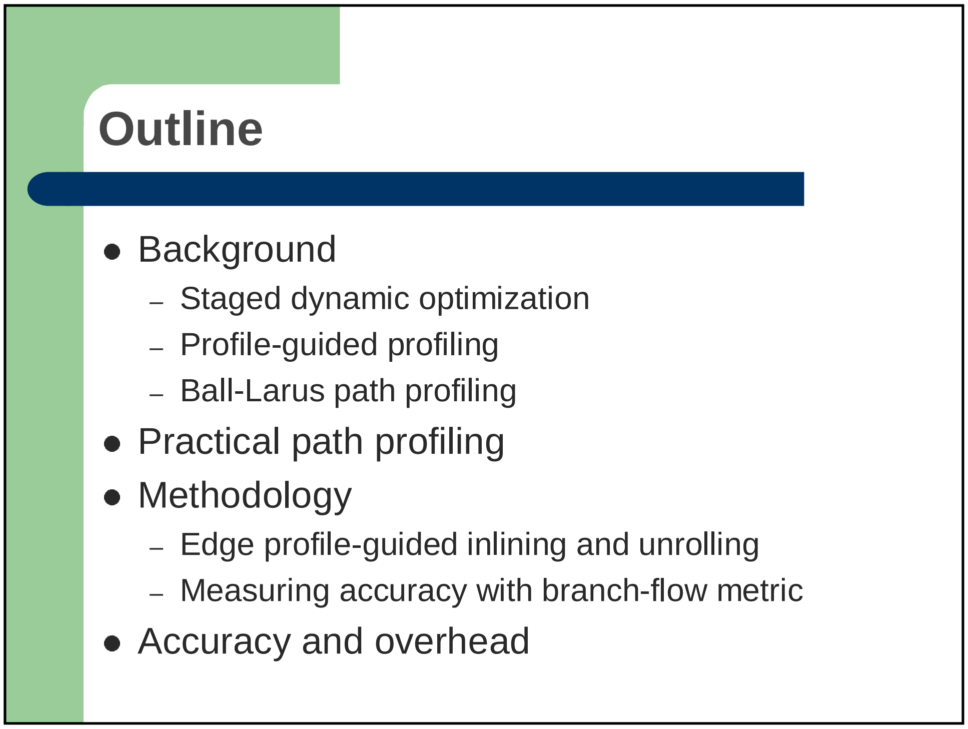
Targeted path profiling [Joshi et al. '04]



- Profile-guided profiling
- Accuracy good
- Overhead high for dynamic optimizer

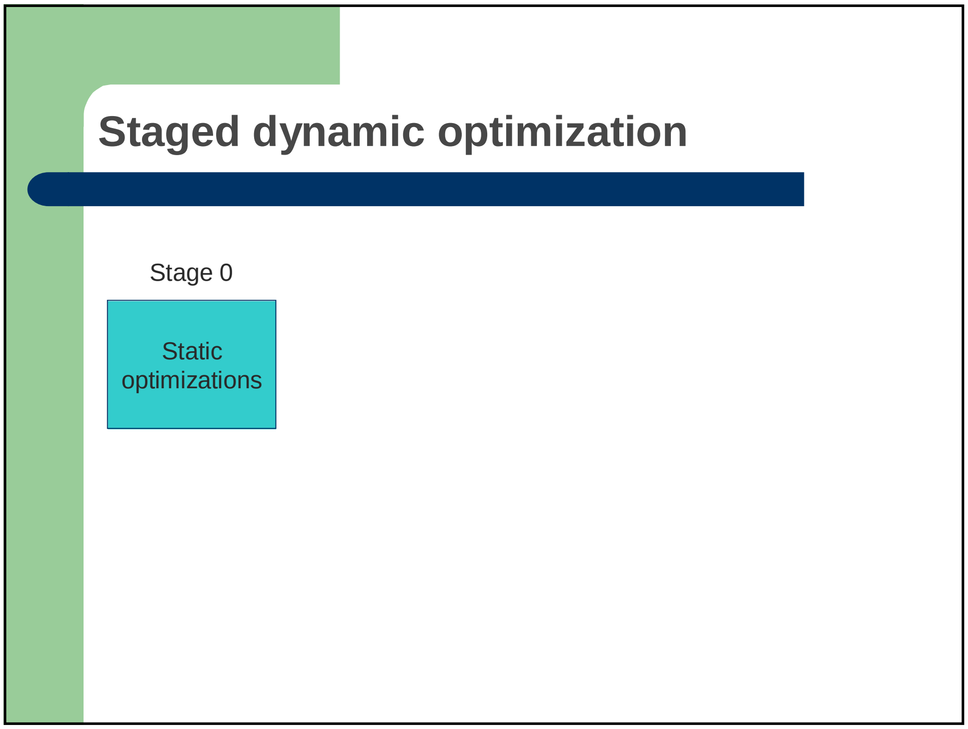


Practical path profiling



Outline

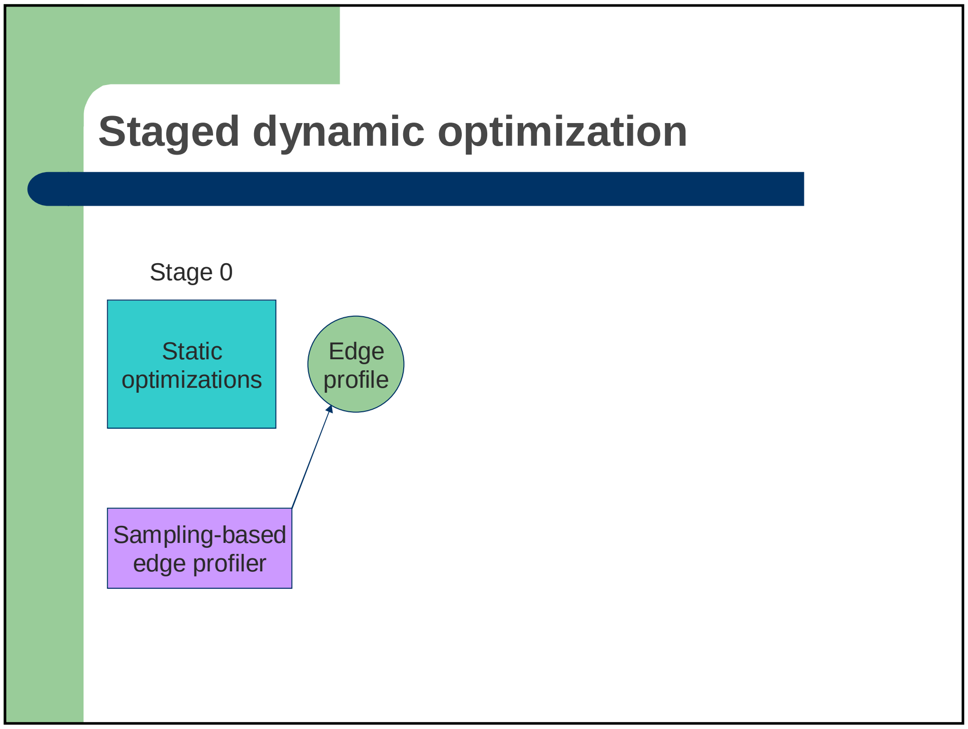
- Background
  - Staged dynamic optimization
  - Profile-guided profiling
  - Ball-Larus path profiling
- Practical path profiling
- Methodology
  - Edge profile-guided inlining and unrolling
  - Measuring accuracy with branch-flow metric
- Accuracy and overhead



Staged dynamic optimization

Stage 0

Static optimizations



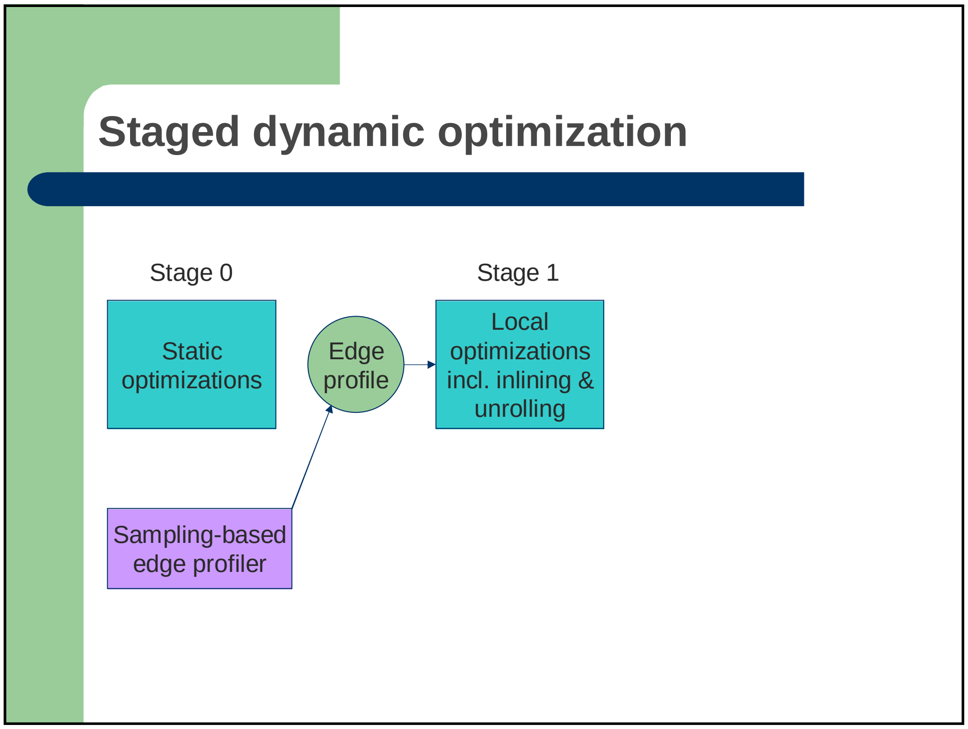
Staged dynamic optimization

Stage 0

Static optimizations

Edge profile

Sampling-based edge profiler



Staged dynamic optimization

Stage 0

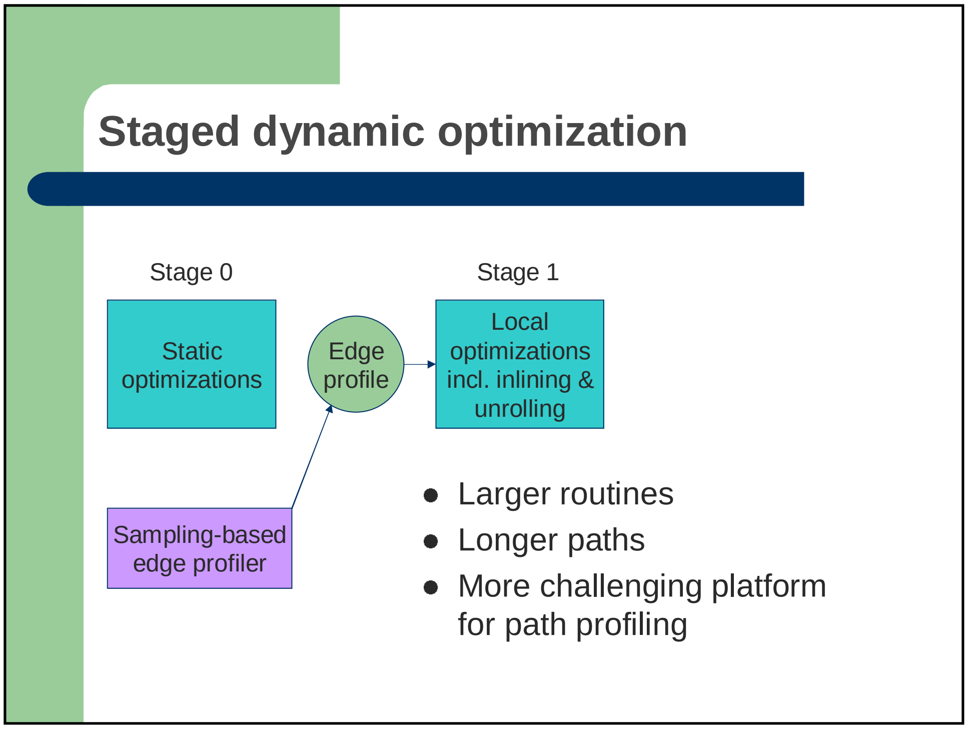
Static optimizations

Sampling-based edge profiler

Edge profile

Stage 1

Local optimizations incl. inlining & unrolling



Staged dynamic optimization

Stage 0

Static optimizations

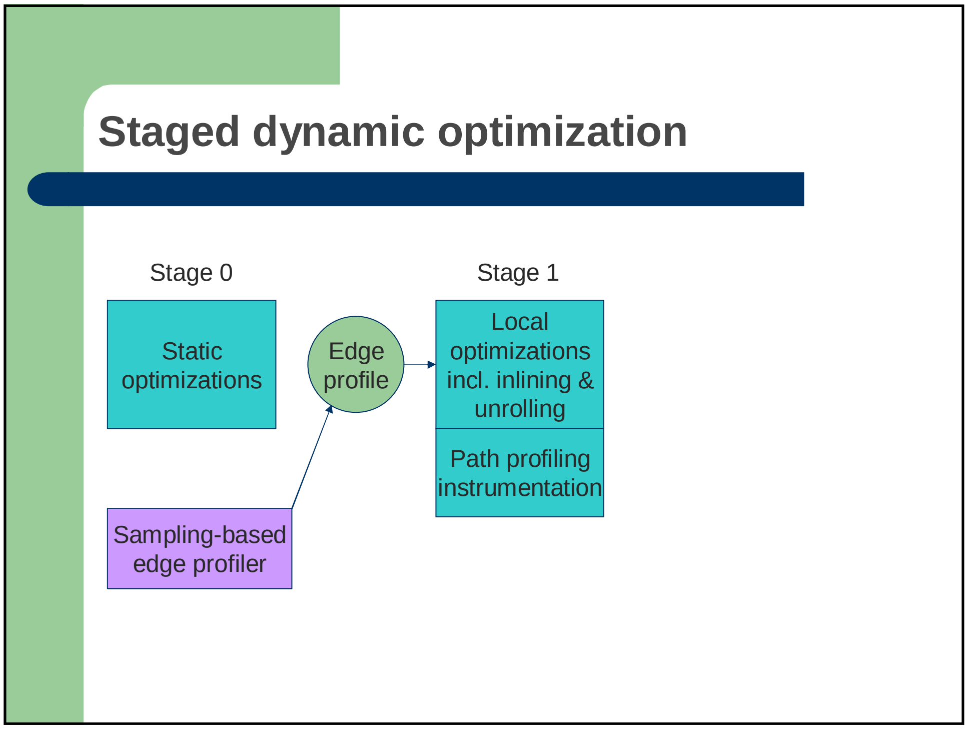
Sampling-based edge profiler

Edge profile

Stage 1

Local optimizations incl. inlining & unrolling

- Larger routines
- Longer paths
- More challenging platform for path profiling



Staged dynamic optimization

Stage 0

Static optimizations

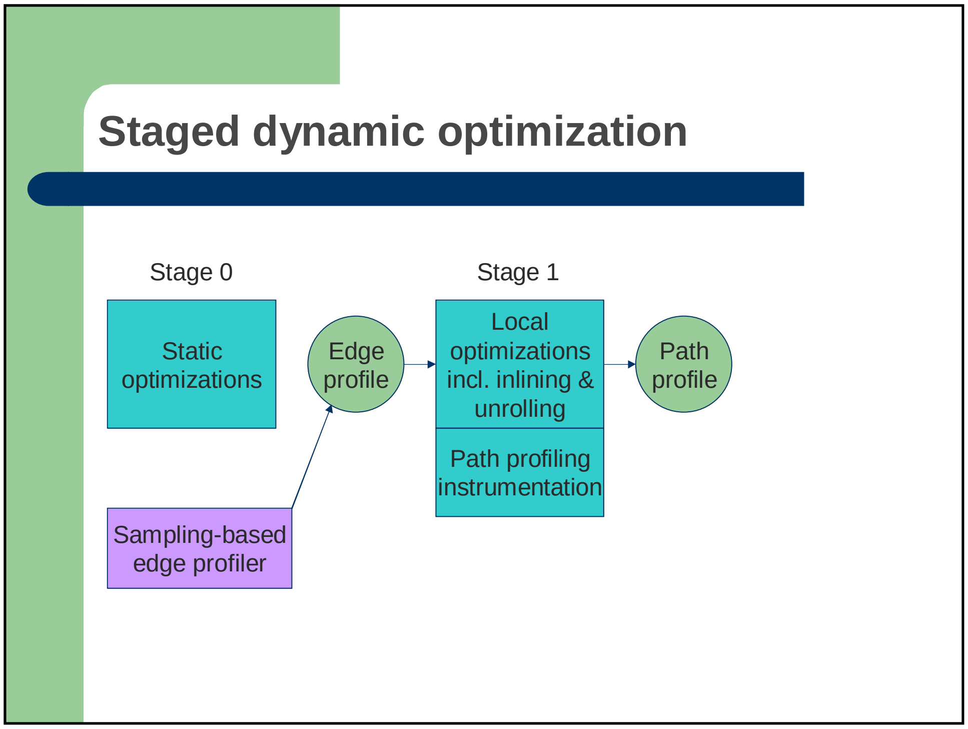
Sampling-based edge profiler

Edge profile

Stage 1

Local optimizations incl. inlining & unrolling

Path profiling instrumentation



Staged dynamic optimization

Stage 0

Static optimizations

Sampling-based edge profiler

Edge profile

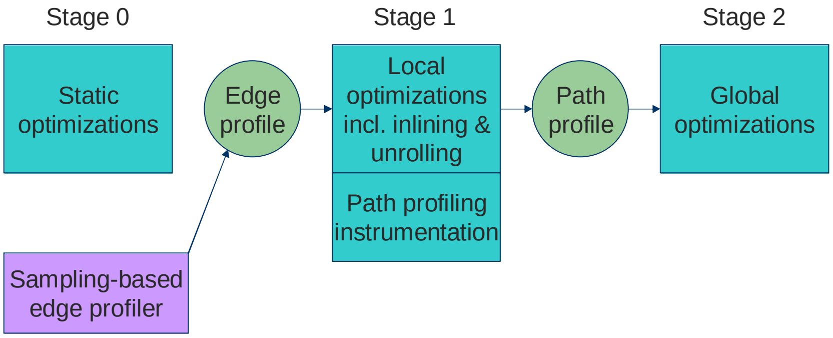
Stage 1

Local optimizations incl. inlining & unrolling

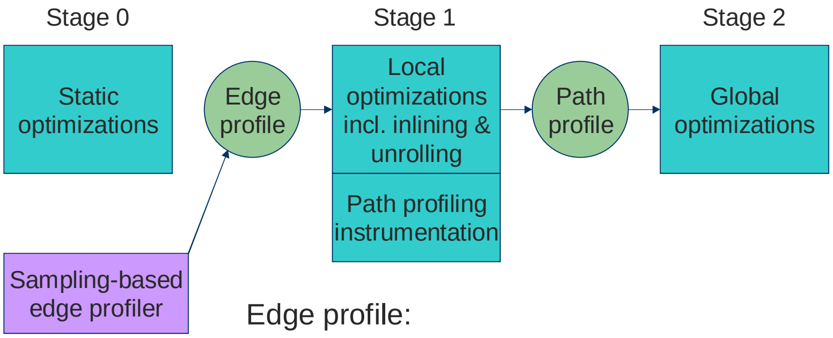
Path profiling instrumentation

Path profile

Staged dynamic optimization


Stage 0
Stage 1
Stage 2
Static optimizations
Edge profile
Local optimizations incl. inlining & unrolling
Path profiling instrumentation
Path profile
Global optimizations
Sampling-based edge profiler

Staged dynamic optimization


Stage 0
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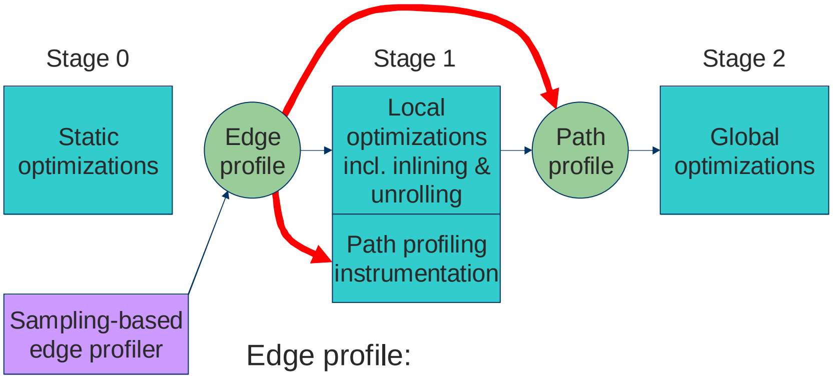
Static optimizations
Edge profile
Local optimizations incl. inlining & unrolling
Path profiling instrumentation
Path profile
Global optimizations
Sampling-based edge profiler

Edge profile:

- Identifies hot and cold edges
- Provides partial path profile

Profile-guided profiling



Stage 0

Static optimizations

Sampling-based edge profiler

Edge profile

Stage 1

Local optimizations incl. inlining & unrolling

Path profiling instrumentation

Path profile

Stage 2

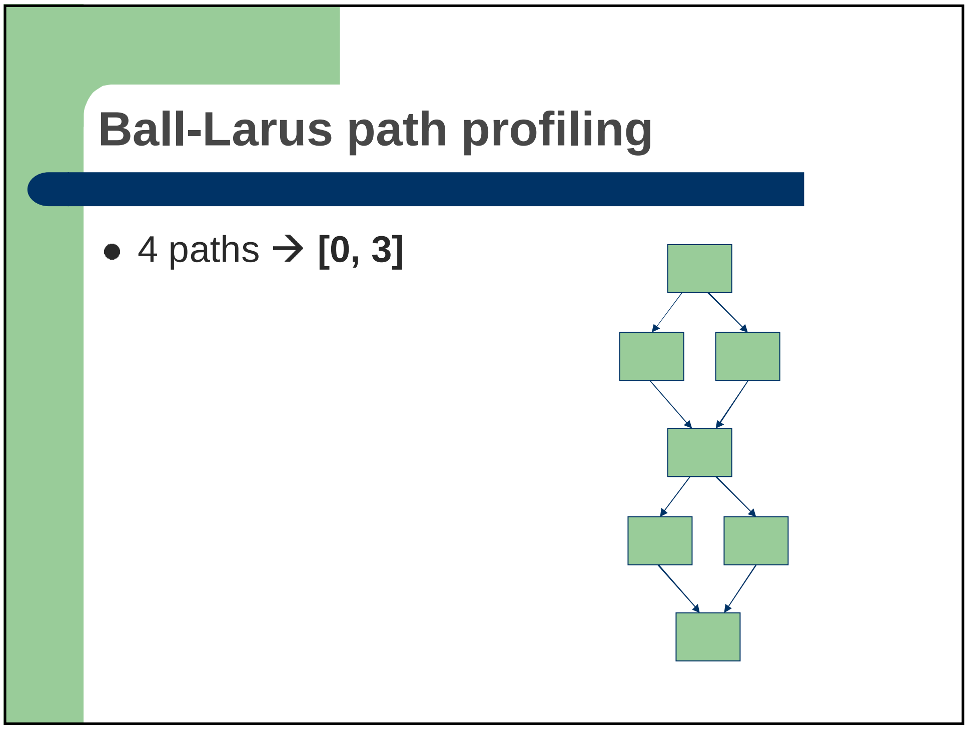
Global optimizations

Edge profile:

- Identifies hot and cold edges
- Provides partial path profile

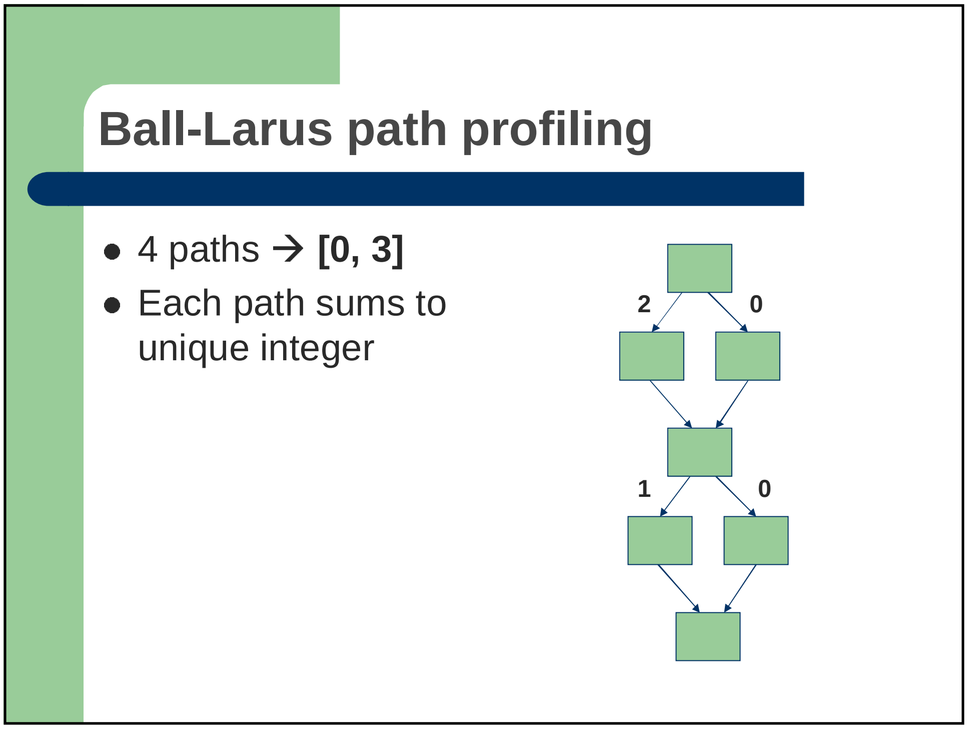
Ball-Larus path profiling

- Acyclic, intraprocedural paths
  - Handles cyclic routines
- Instrumentation maintains execution frequency of each path
  - Each path computes unique integer in **[0, N-1]**



Ball-Larus path profiling

- 4 paths → **[0, 3]**



Ball-Larus path profiling

- 4 paths → **[0, 3]**
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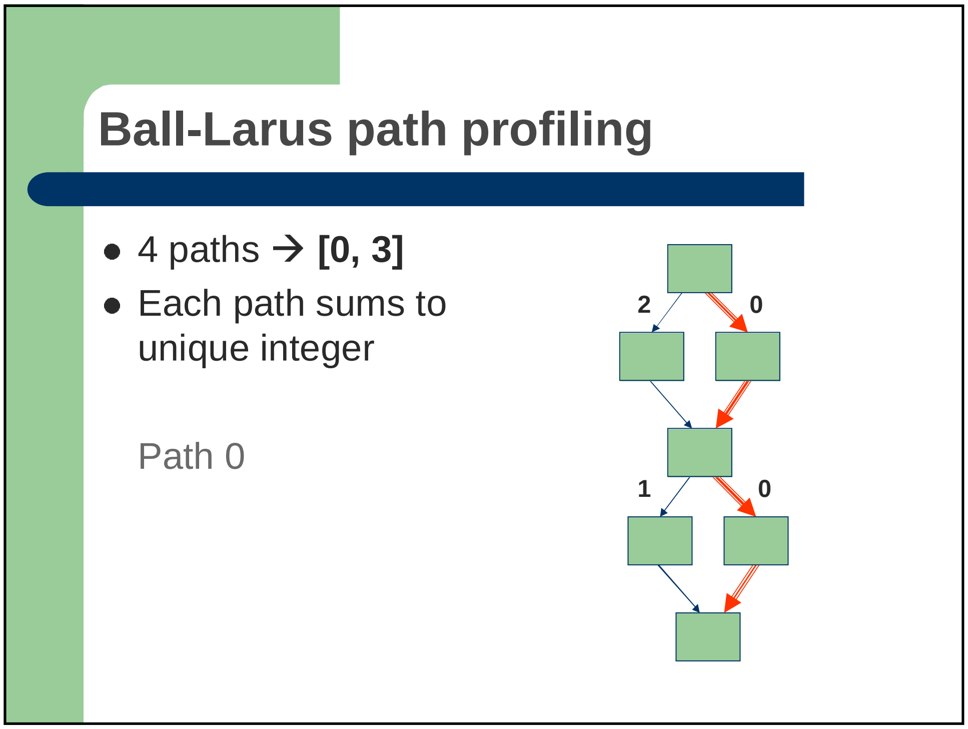

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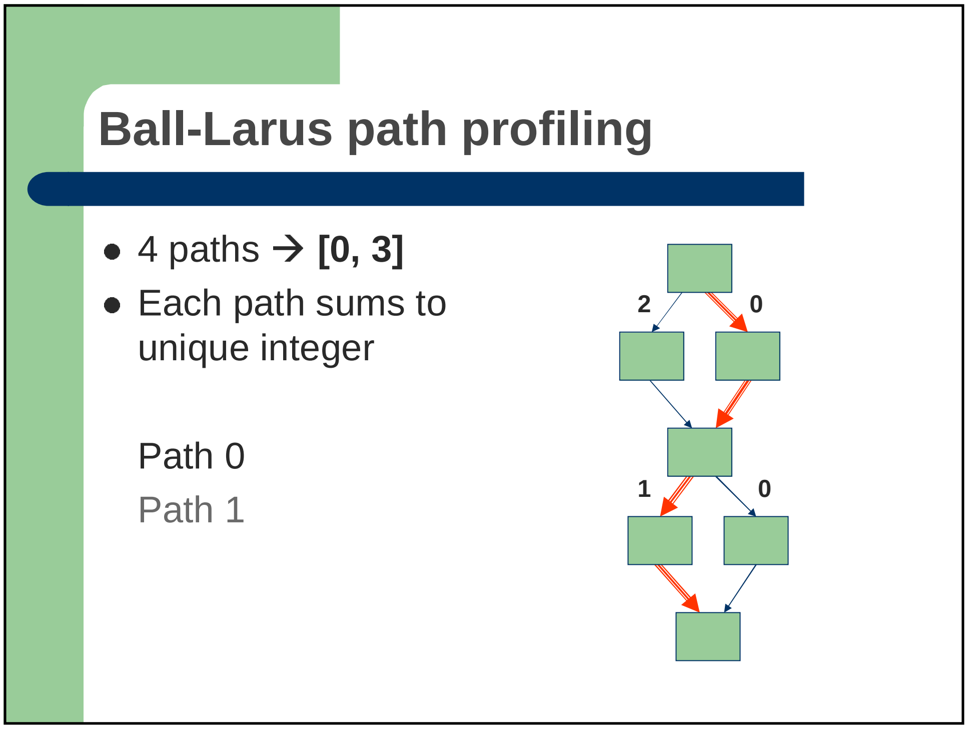

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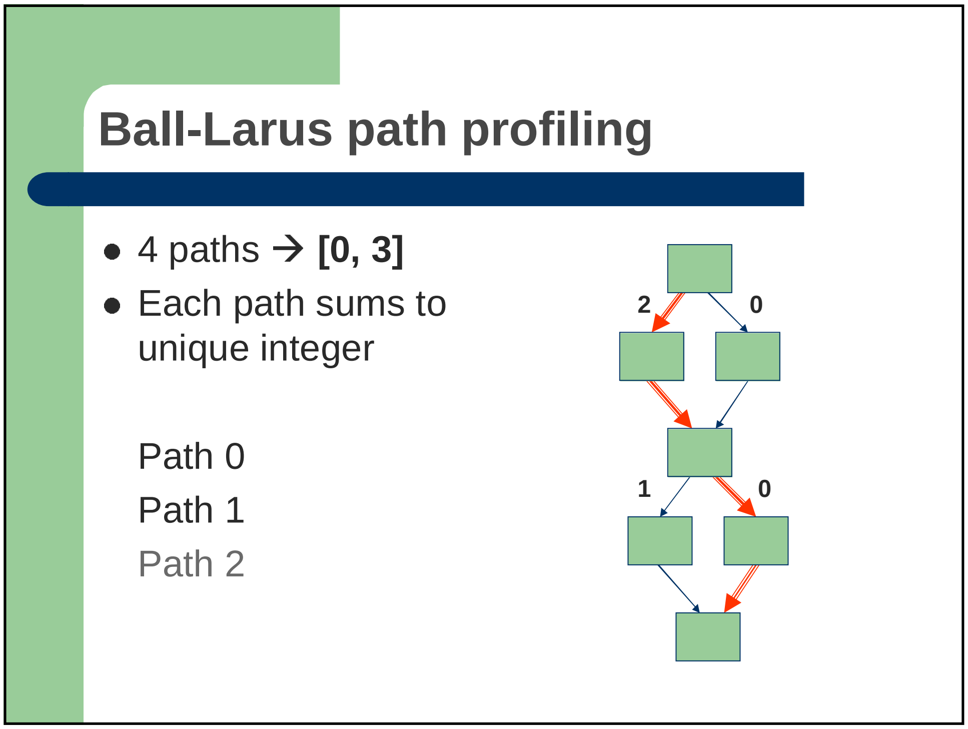

Ball-Larus path profiling

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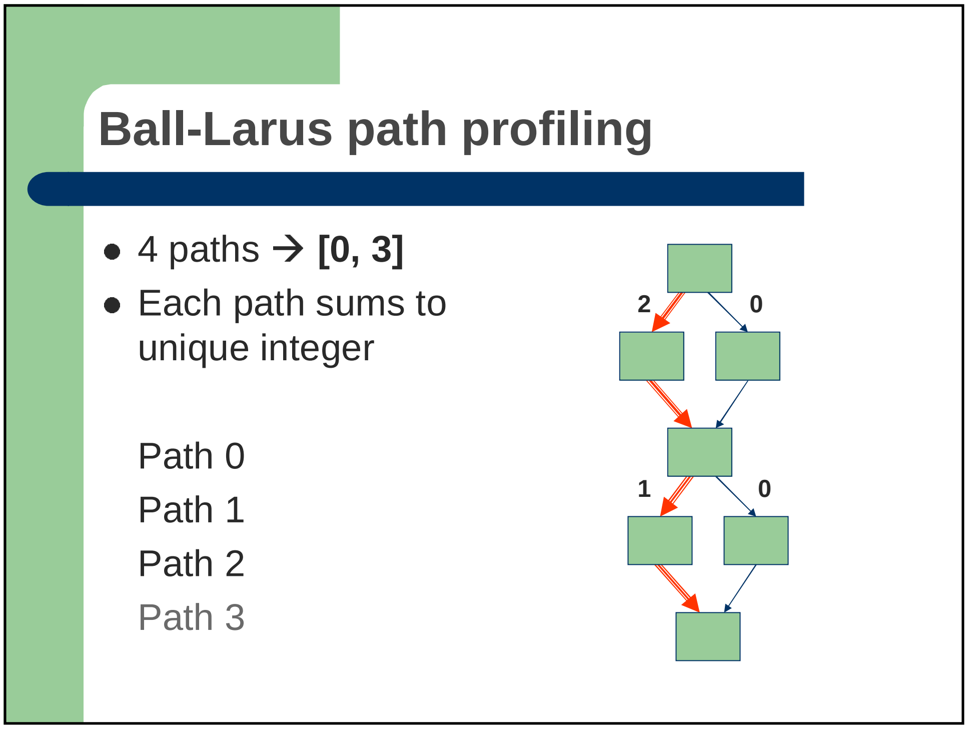
Path 2



Ball-Larus path profiling

- 4 paths → **[0, 3]**
- Each path sums to unique integer

Path 0

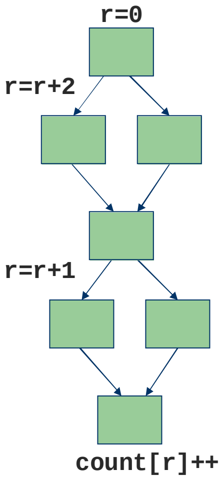
Path 1

Path 2

Path 3

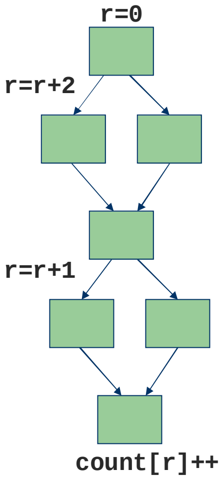
Ball-Larus path profiling

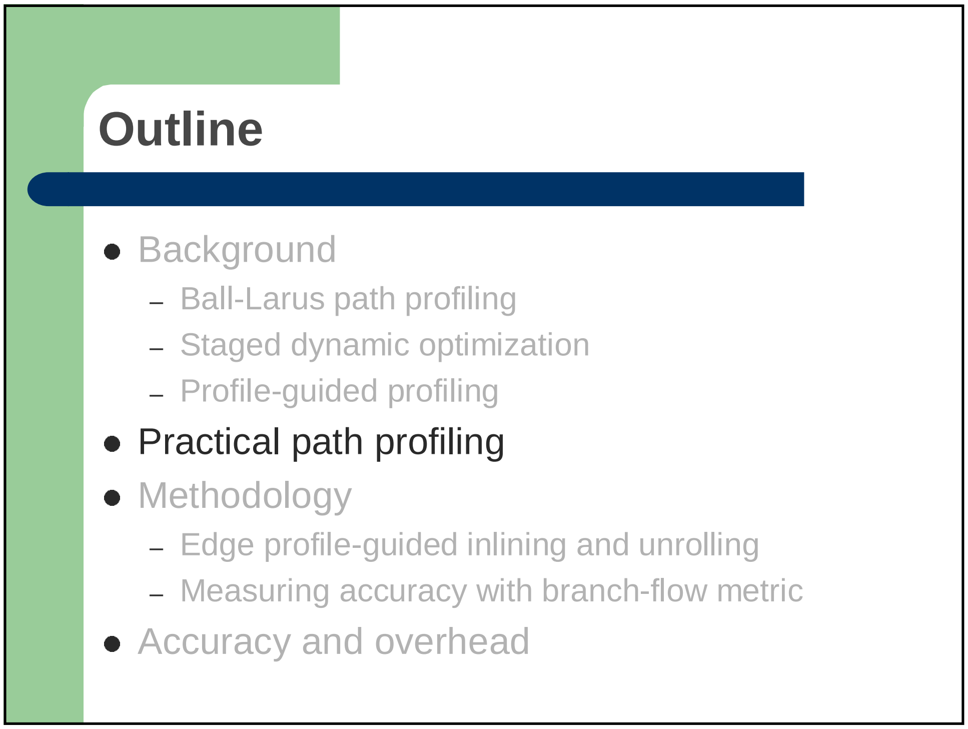
- `r`: path register
  - Computes path number
- `count`:
  - Stores path frequencies



Ball-Larus path profiling

- `r`: path register
  - Computes path number
- `count`:
  - Stores path frequencies
  - Array by default
  - Too many paths?
    - Hash table
    - High overhead





Outline

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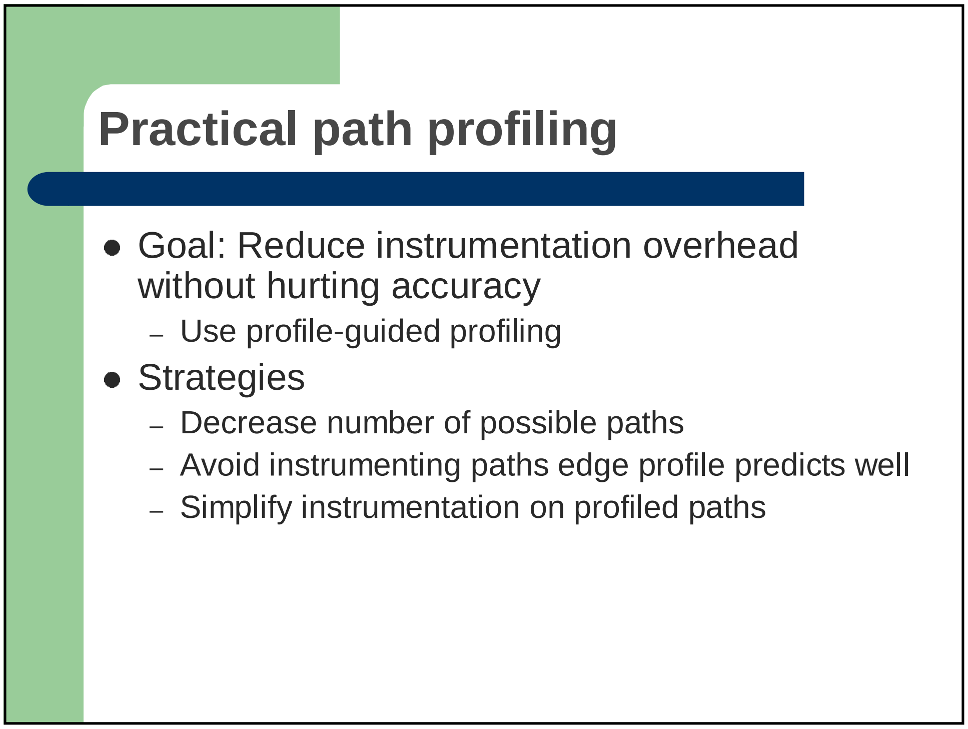


Practical path profiling

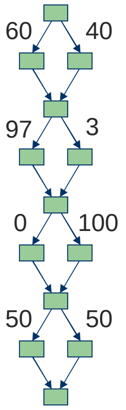
- Goal: Reduce instrumentation overhead without hurting accuracy
  - Use profile-guided profiling
- Strategies
  - Decrease number of possible paths
  - Avoid instrumenting paths edge profile predicts well
  - Simplify instrumentation on profiled paths

Practical path profiling

- Goal: Reduce instrumentation overhead without hurting accuracy
  - Use profile-guided profiling
- Strategies
  - Decrease number of possible paths
  - Avoid instrumenting paths edge profile predicts well
  - Simplify instrumentation on profiled paths
- Techniques from targeted path profiling
  - Improves techniques
  - Adds new techniques

Strategy 1: Fewer possible paths

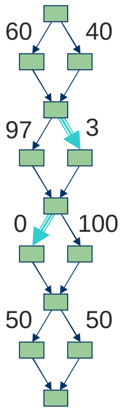
- Goal: Hash table → array
- Want to remove cold paths



Strategy 1: Fewer possible paths

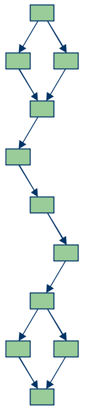
- Goal: Hash table → array
- Want to remove cold paths
- Observation: A path with a cold edge is a cold path
- Remove cold edges
  - Local and global criteria

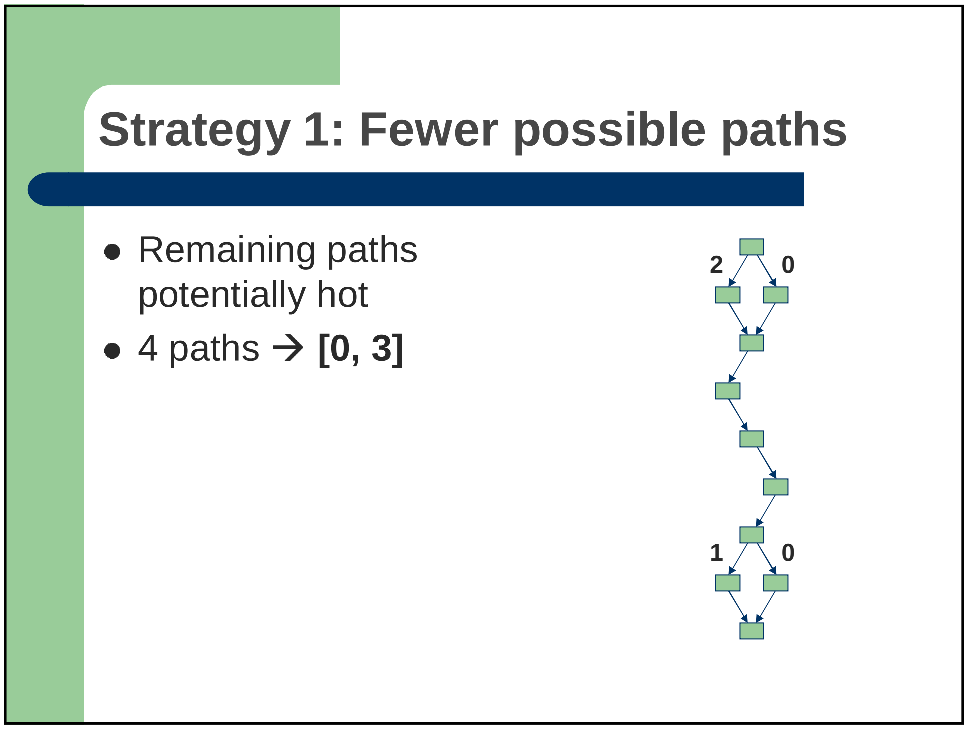
New



Strategy 1: Fewer possible paths

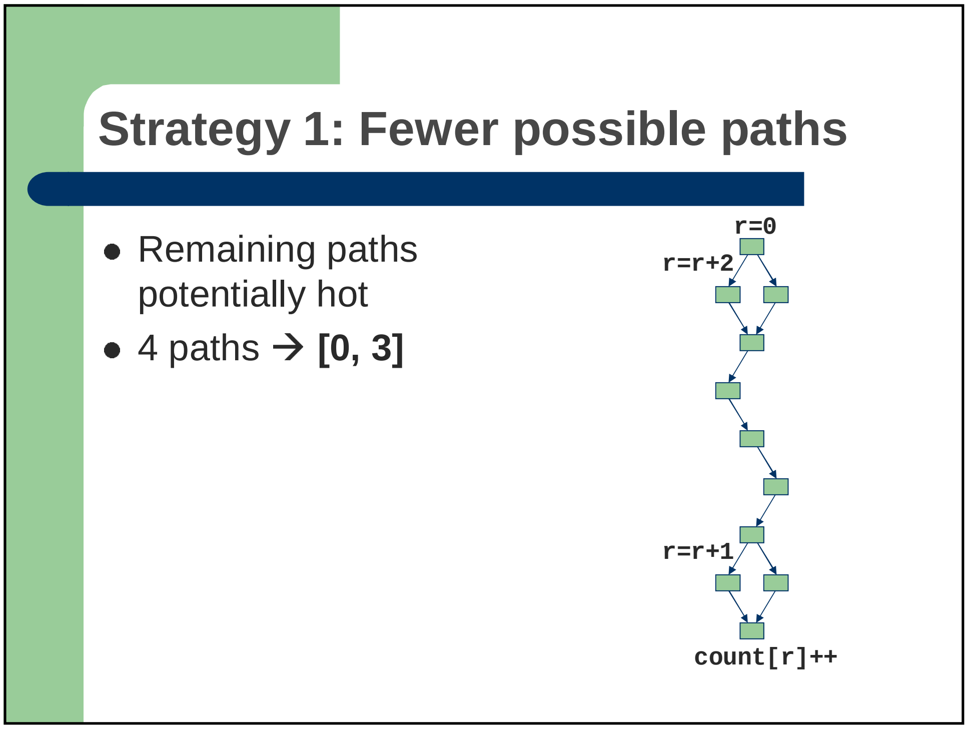
- Goal: Hash table → array
- Want to remove cold paths
- Observation: A path with a cold edge is a cold path
- Remove cold edges
  - Local and global criteria
- Paths: 16 → 4





Strategy 1: Fewer possible paths

- Remaining paths potentially hot
- 4 paths → **[0, 3]**



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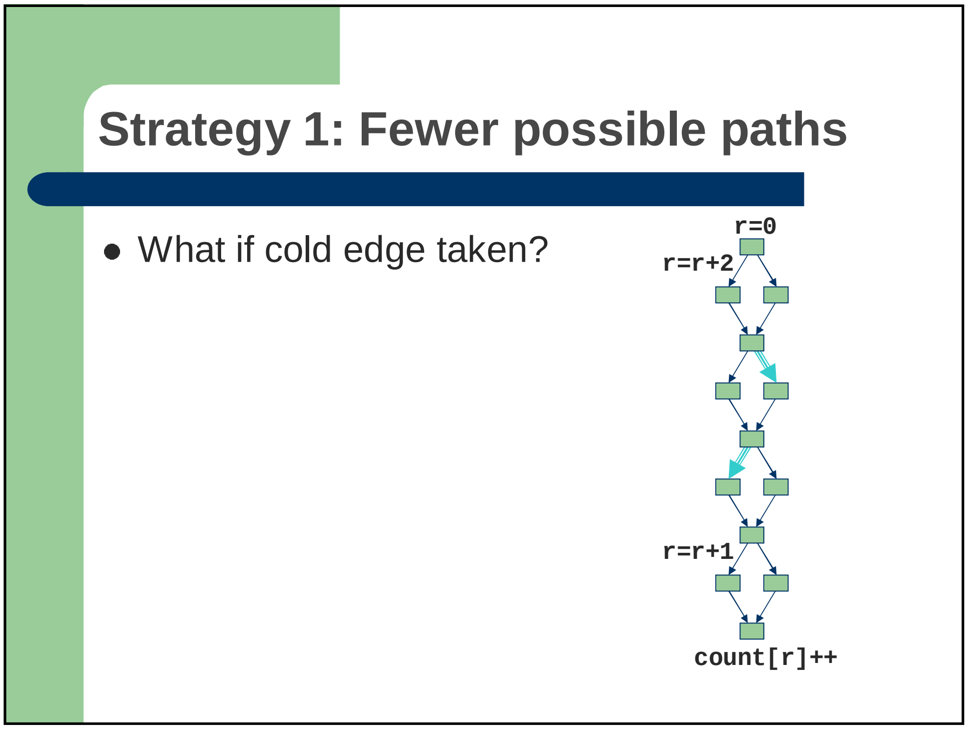
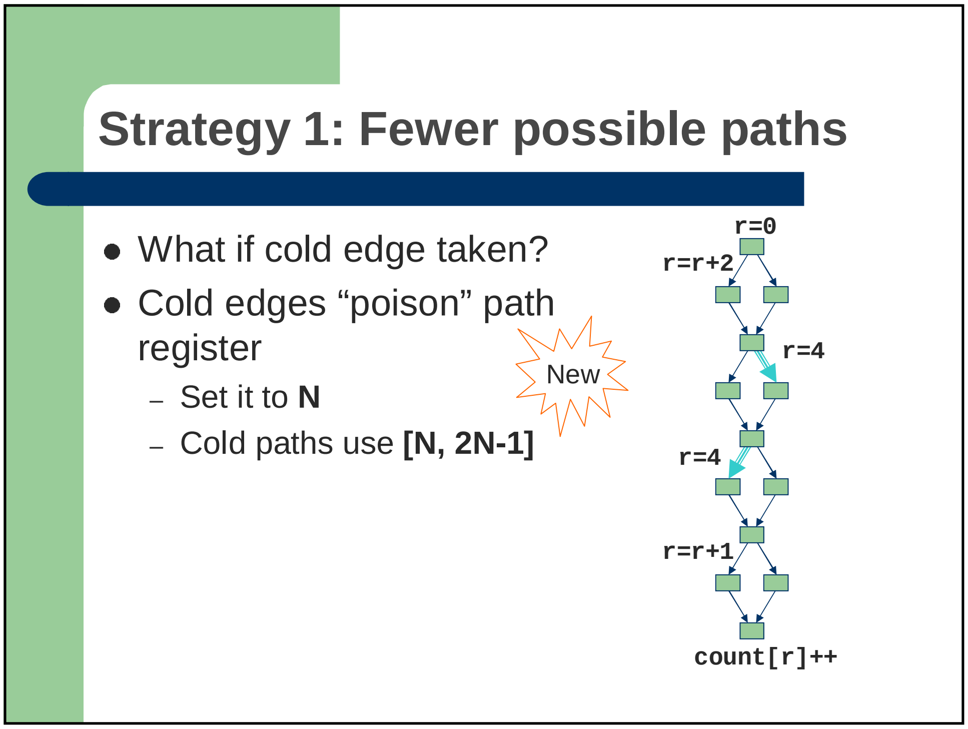


Strategy 1: Fewer possible paths

- What if cold edge taken?



Strategy 1: Fewer possible paths

- What if cold edge taken?
- Cold edges “poison” path register
  - Set it to **N**
  - Cold paths use **[N, 2N-1]**

Strategy 1: Fewer possible paths

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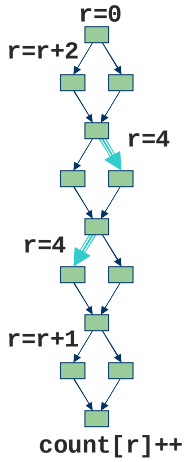
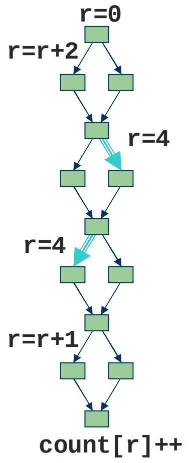
- What if still too many possible paths?



Strategy 1: Fewer possible paths

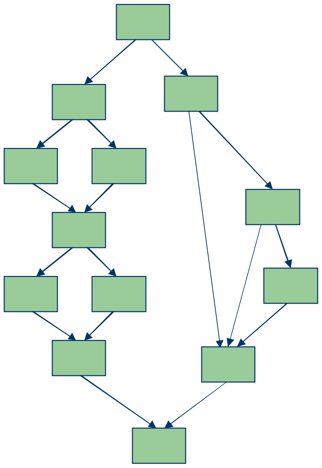
- What if cold edge taken?
- Cold edges “poison” path register
  - Set it to **N**
  - Cold paths use **[N, 2N-1]**
- What if still too many possible paths?
- Adjust cold edge threshold until hashing avoided

New



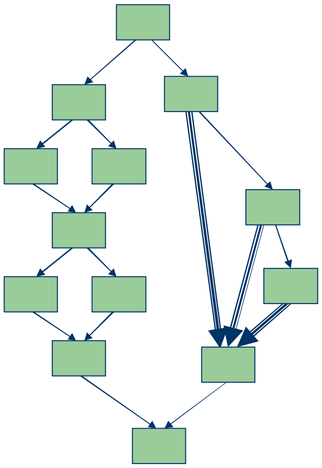
Strategy 2: Avoid instrumenting paths

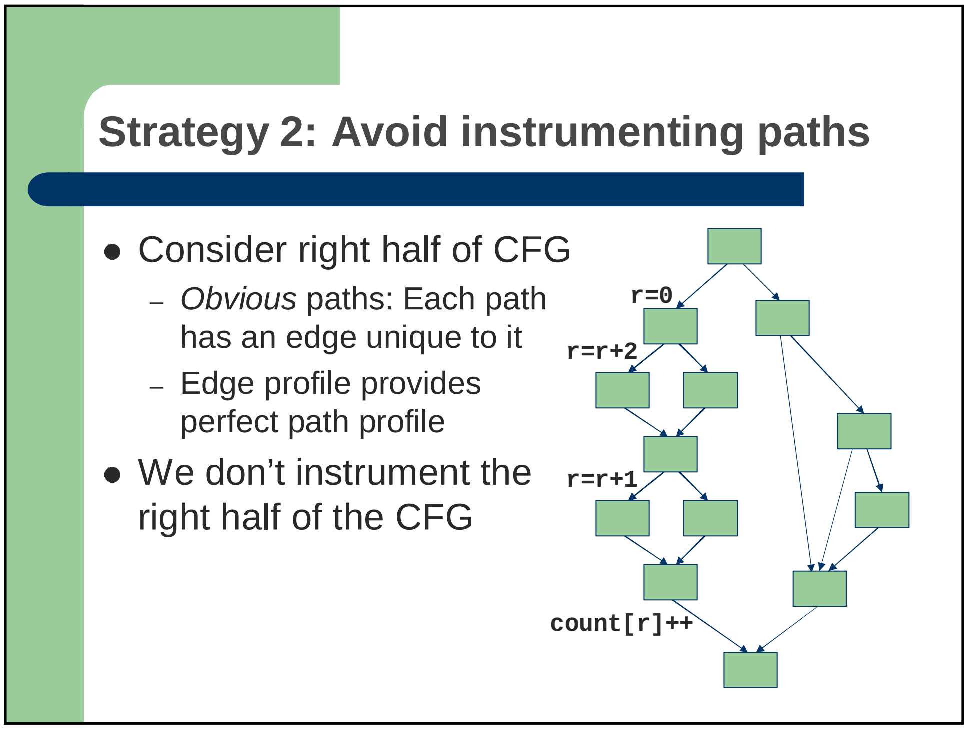
- Consider right half of CFG



Strategy 2: Avoid instrumenting paths

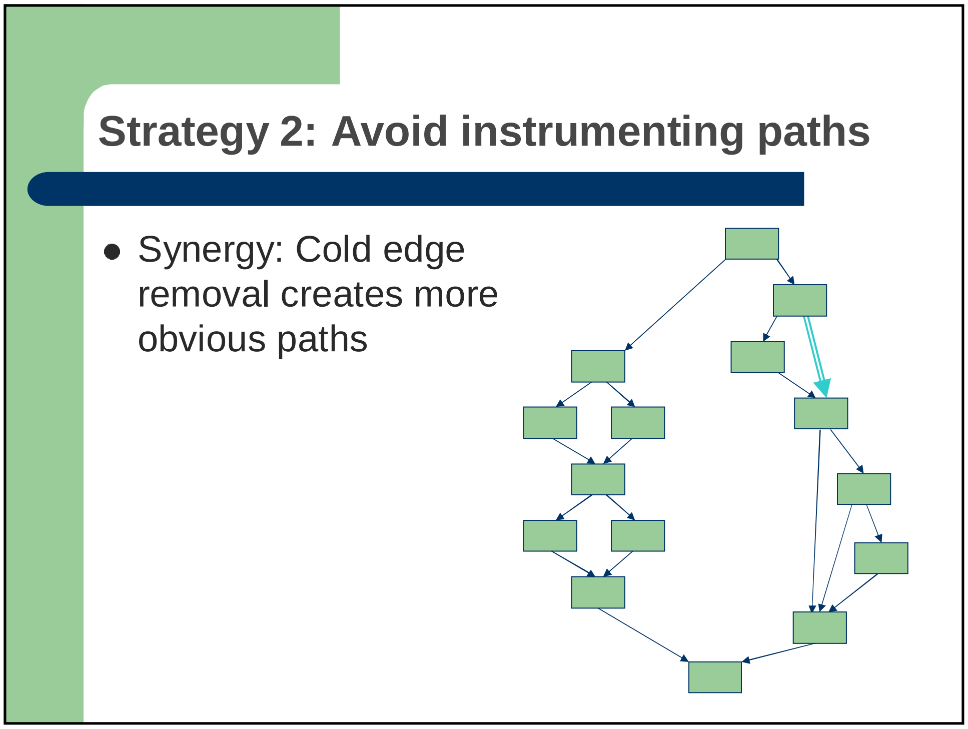
- Consider right half of CFG
  - *Obvious* paths: Each path has an edge unique to it
  - Edge profile provides perfect path profile





Strategy 2: Avoid instrumenting paths

- Consider right half of CFG
  - *Obvious* paths: Each path has an edge unique to it
  - Edge profile provides perfect path profile
- We don’t instrument the right half of the CFG

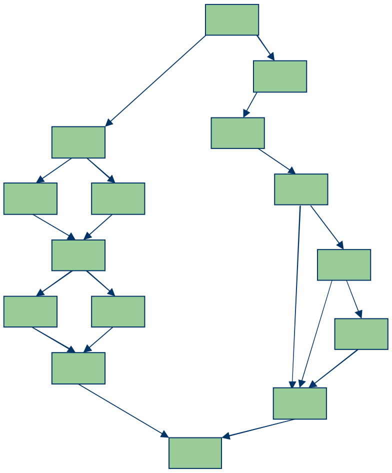


Strategy 2: Avoid instrumenting paths

- Synergy: Cold edge removal creates more obvious paths

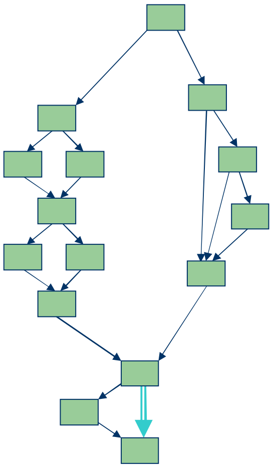
Strategy 2: Avoid instrumenting paths

- Synergy: Cold edge removal creates more obvious paths
  - Right half is obvious



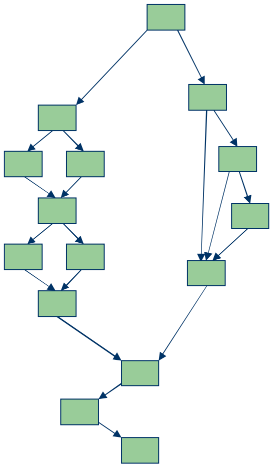
Strategy 2: Avoid instrumenting paths

- What if cold edge is part of obvious and non-obvious paths?



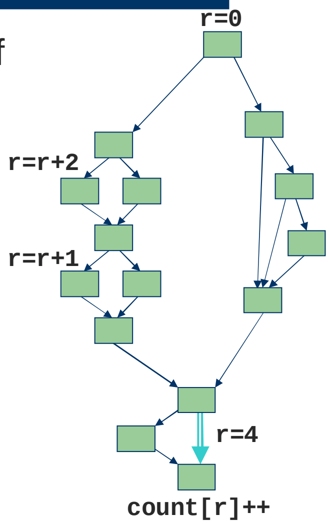
Strategy 2: Avoid instrumenting paths

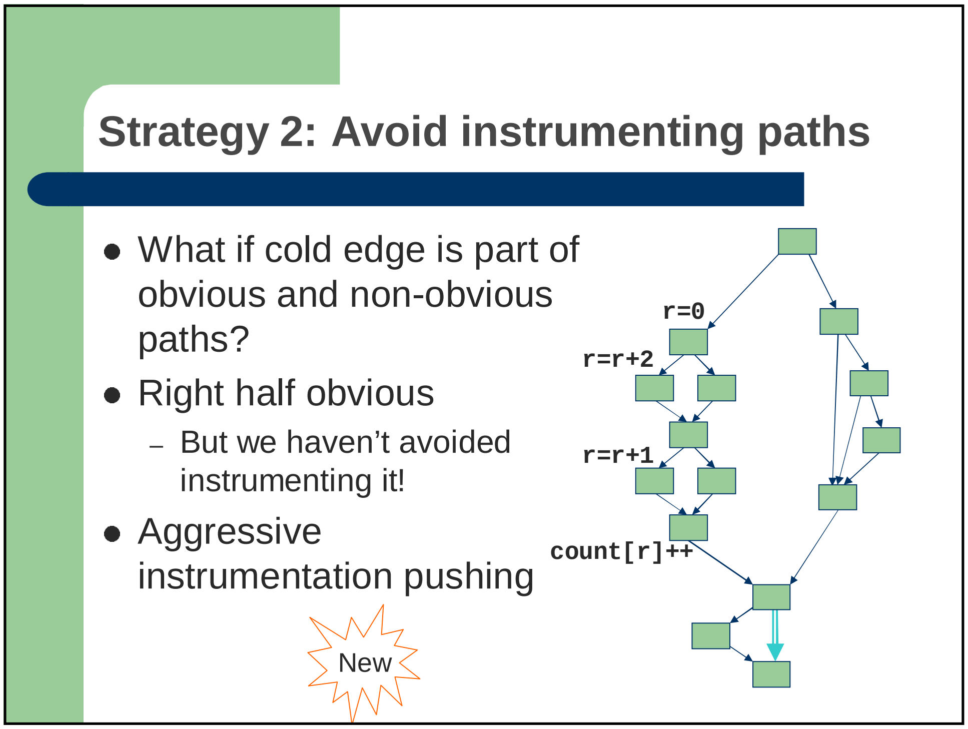
- What if cold edge is part of obvious and non-obvious paths?
- Right half obvious



Strategy 2: Avoid instrumenting paths

- What if cold edge is part of obvious and non-obvious paths?
- Right half obvious
  - But we haven't avoided instrumenting it!

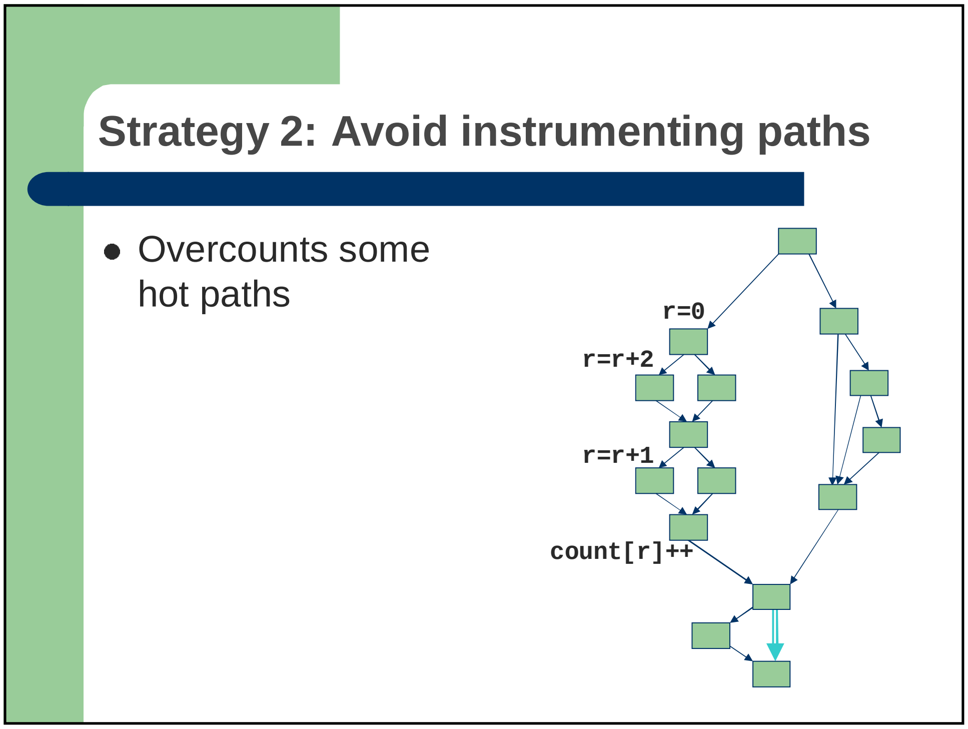




Strategy 2: Avoid instrumenting paths

- What if cold edge is part of obvious and non-obvious paths?
- Right half obvious
  - But we haven't avoided instrumenting it!
- Aggressive instrumentation pushing

New



Strategy 2: Avoid instrumenting paths

- Overcounts some hot paths

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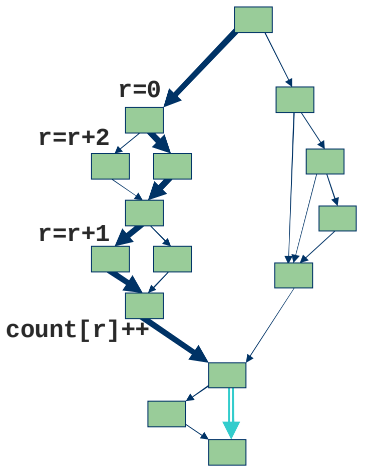
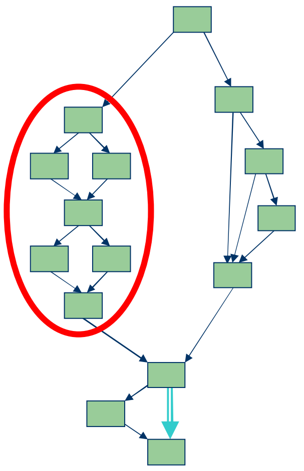
- Overcounts some hot paths
- Example cold path counts hot path number 1
- Overcount tends to be small



Some paths need profiling

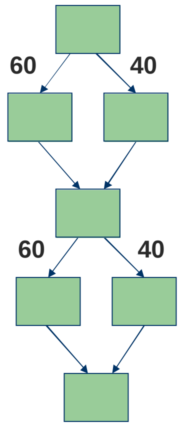
- Correlation between cascading branches



Strategy 3: Simplify instrumentation

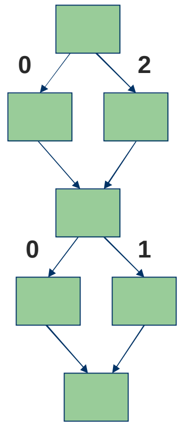
New

- Moderately biased branches



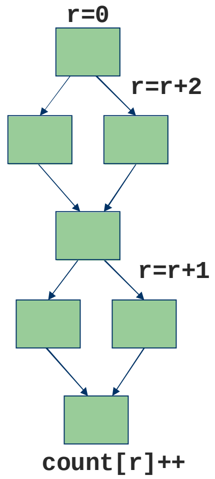
Strategy 3: Simplify instrumentation

- Moderately biased branches
- Put zeros on hotter edges



Strategy 3: Simplify instrumentation

- Moderately biased branches
- Put zeros on hotter edges
  - No instrumentation on hotter edges



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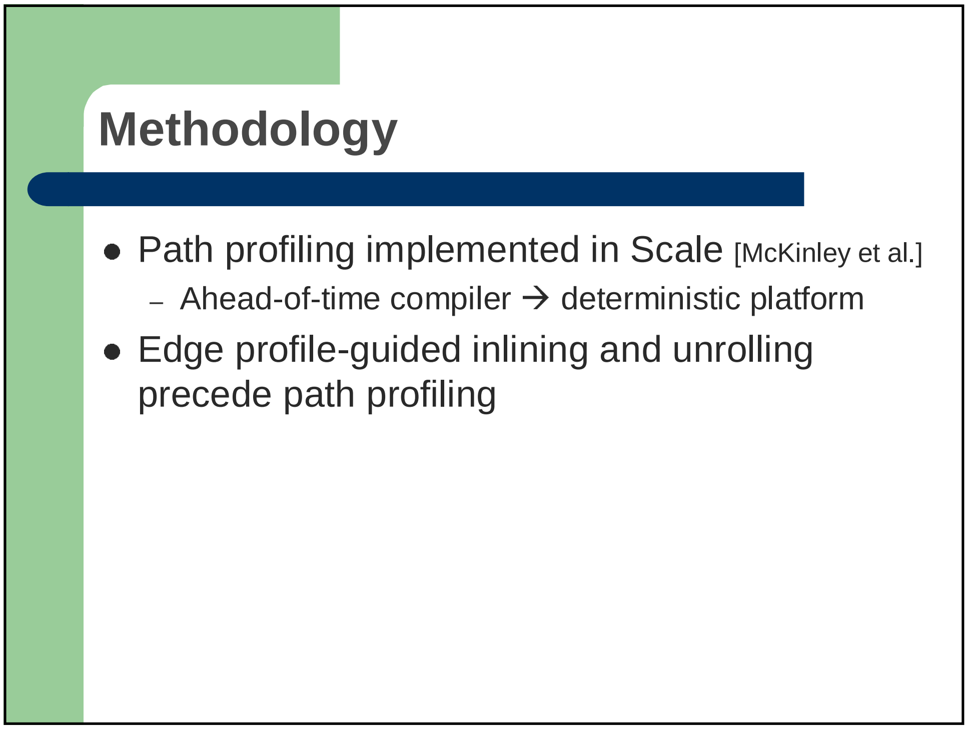
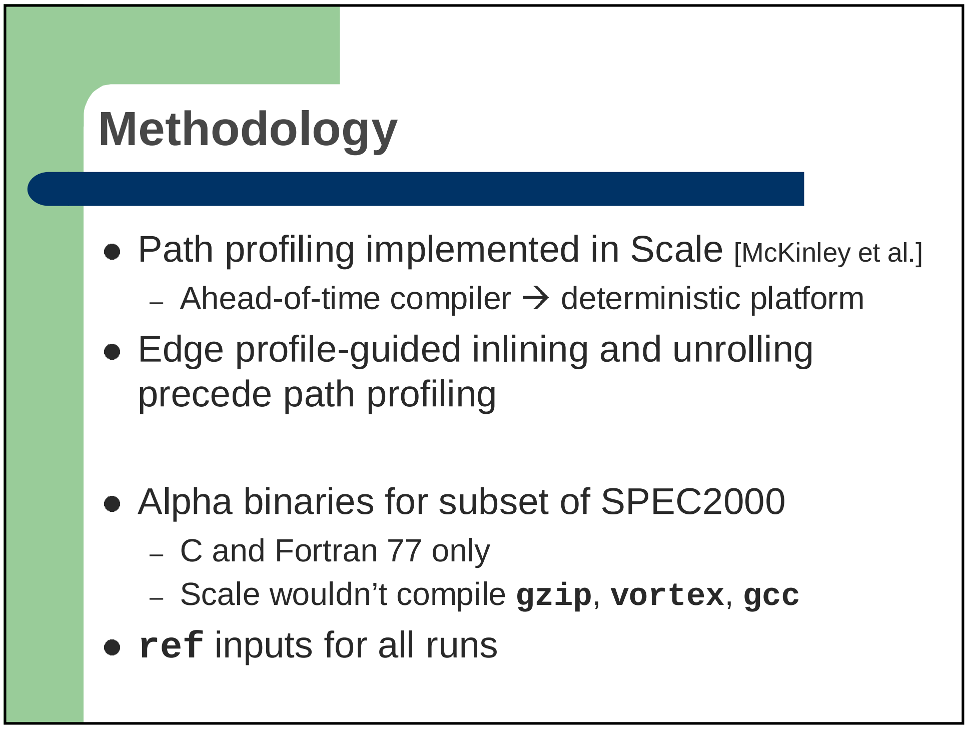
  - Measuring accuracy with branch-flow metric
- Accuracy and overhead



Methodology

- Path profiling implemented in Scale [McKinley et al.]
  - Ahead-of-time compiler → deterministic platform
- Edge profile-guided inlining and unrolling precede path profiling



Methodology

- Path profiling implemented in Scale [McKinley et al.]
  - Ahead-of-time compiler → deterministic platform
- Edge profile-guided inlining and unrolling precede path profiling

- Alpha binaries for subset of SPEC2000
  - C and Fortran 77 only
  - Scale wouldn’t compile **`gzip`**, **`vortex`**, **`gcc`**
- **`ref`** inputs for all runs

Measuring accuracy

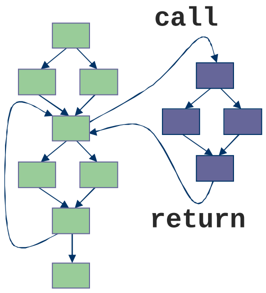
- Compare estimated profile with actual profile
  - Wall weight matching* or profile overlap
- Weight paths by ***flow***: amount of execution
  - Previous work measures flow with unit-flow metric

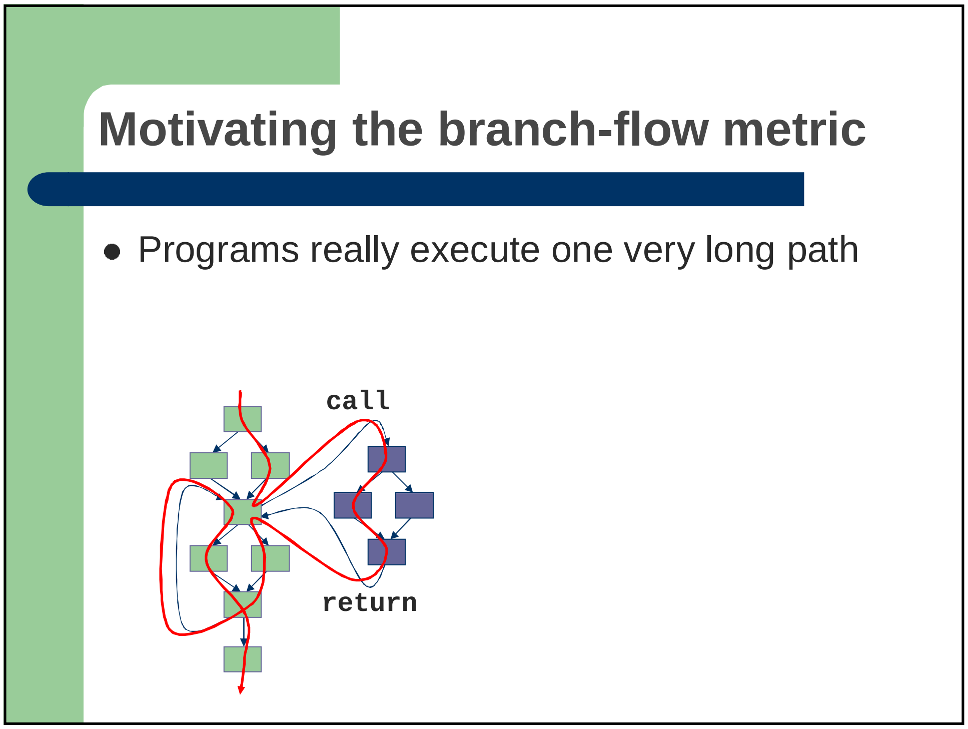
    `Flow(p) = Freq(p)`
  - We introduce ***branch-flow*** metric

    `Flow(p) = Freq(p) x NumBranches(p)`

Motivating the branch-flow metric

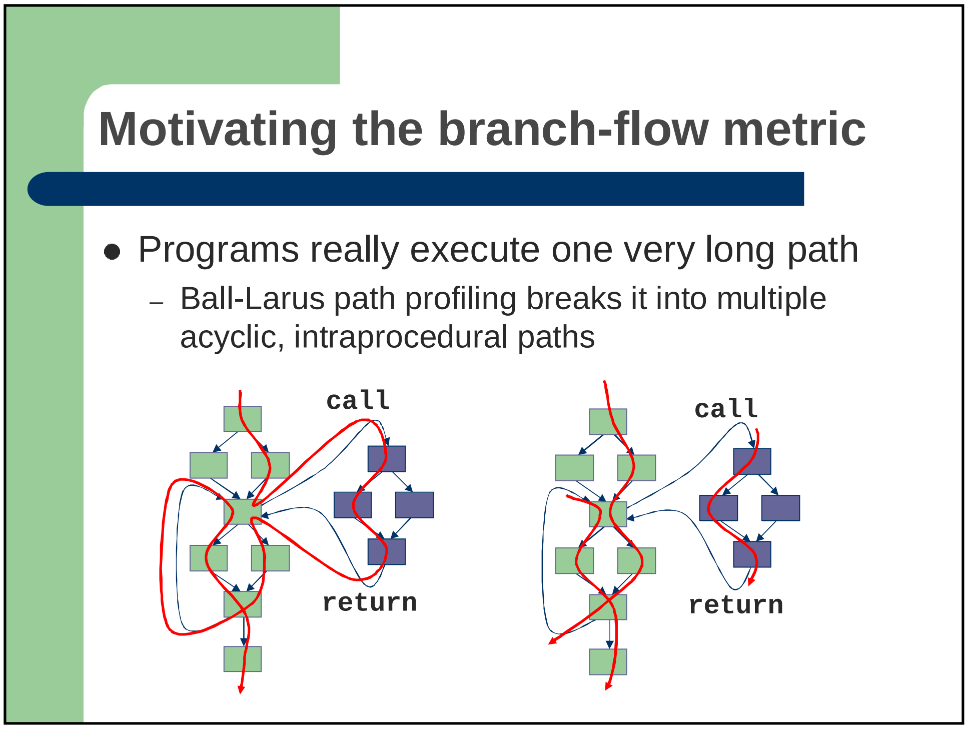
- Programs really execute one very long path





Motivating the branch-flow metric

- Programs really execute one very long path

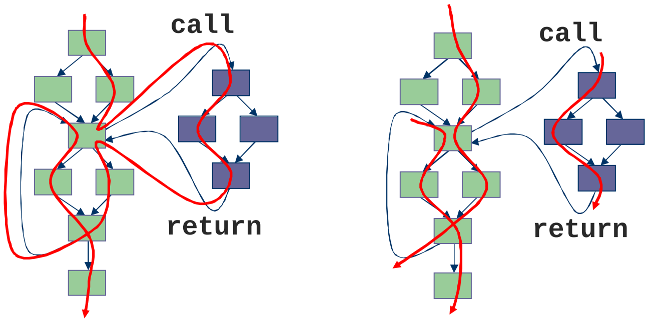


Motivating the branch-flow metric

- Programs really execute one very long path
  - Ball-Larus path profiling breaks it into multiple acyclic, intraprocedural paths

Motivating the branch-flow metric

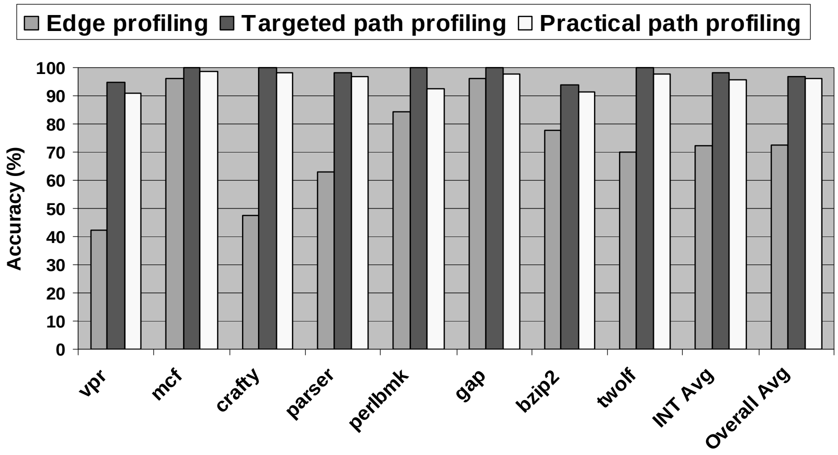
- Some paths longer than others
  - We care more about longer paths
  - Unit-flow metric unfairly rewards edge profiling



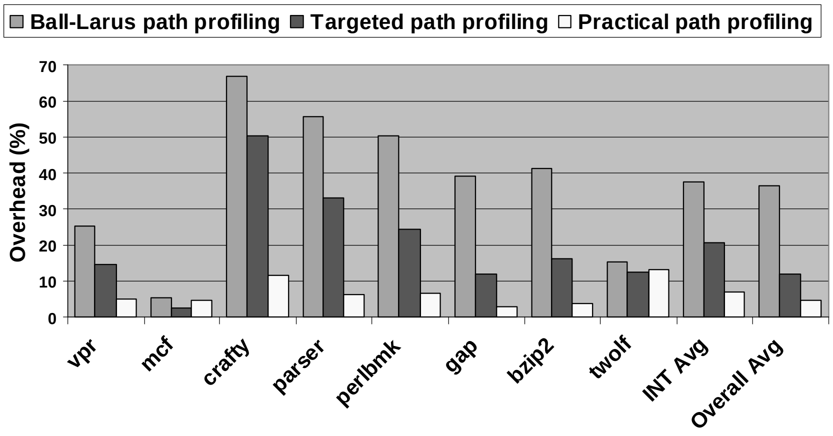
Outline

- Background
  - Staged dynamic optimization
  - Profile-guided profiling
  - Ball-Larus path profiling
- Practical path profiling
- Methodology
  - Edge profile-guided inlining and unrolling
  - Measuring accuracy with branch-flow metric
- Accuracy and overhead

Accuracy



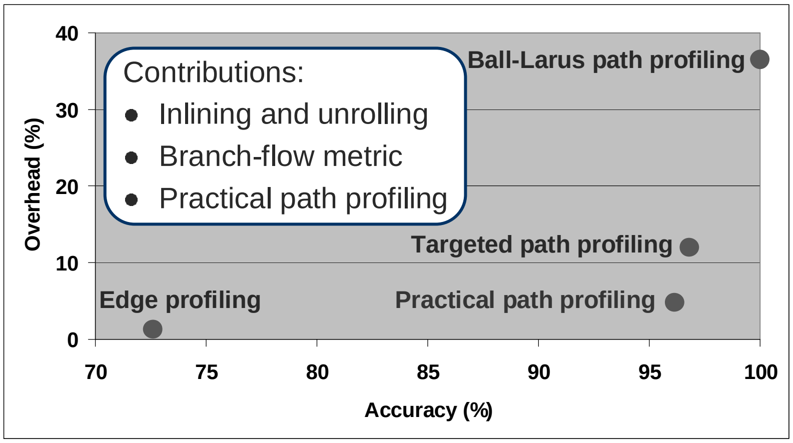
Overhead



Related work

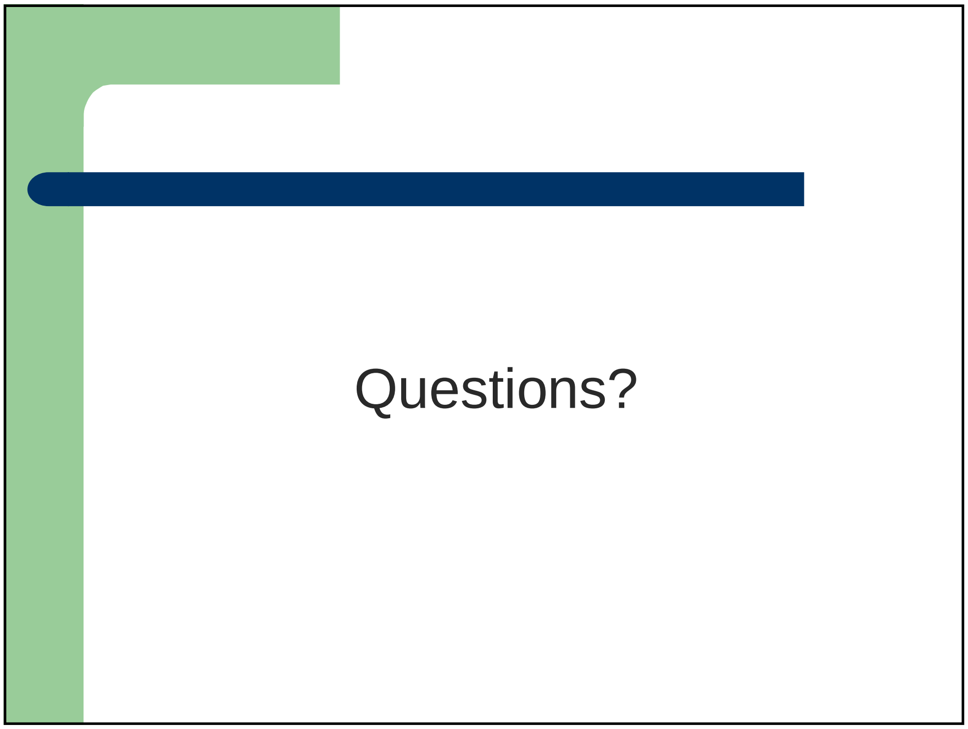
- Dynamo **[Bala et al. ’00]**
  - Successful path-based dynamic optimizer
  - “Bails out” when no dominant path
- Instrumentation sampling & dynamic instrumentation **[Arnold & Ryder ’01, Hirzel & Chilimbi ’04, Yasue et al. ’04]**
  - Lower overhead by extending profiling time
  - Orthogonal to practical path profiling
- Hardware-based path profiling **[Vaswani et al. ’05]**
  - High accuracy when hot path table large enough

Summary



Contributions:

- Inlining and unrolling
- Branch-flow metric
- Practical path profiling



Questions?