Profile-Guided Optimizations

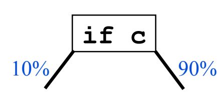
Last time
- Instruction scheduling
  - Register renaming
  - Balanced Load Scheduling
  - Loop unrolling
  - Software pipelining

Today
- More instruction scheduling
  - Profiling
  - Trace scheduling

Motivation for Profiling

Limitations of static analysis
- Compilers can analyze possible paths but must behave conservatively
- Frequency information cannot be obtained through static analysis

How runtime information helps
- Control flow information



Optimize the more frequent path
(perhaps at the expense of the less frequent path)

- Memory conflicts

```
st r1,0(r5)
ld r2,0(r4)
```

If **r5** and **r4** always have different values, we can move the load above the store

Profile-Guided Optimizations

Basic idea

- Instrument and run program on sample inputs to get likely runtime behavior
- Can use this information to improve instruction scheduling
- Many other uses
  - Code placement
  - Inlining
  - Value speculation
  - Branch prediction
  - Class-based optimization (static method lookup)

Profiling Issues

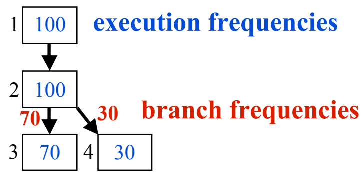
Profile data

- Collected over whole program run
- May not be useful (unbiased branches)
- May not reflect all runs
- May be expensive and inconvenient to gather
  - Continuous profiling [Anderson 97]
- May interfere with program

Control-Flow Profiles

Commonly gather two types of information

- **Execution frequencies** of basic blocks
- **Branch frequencies** of conditional branches
- Represent information in a **weighted flow graph**



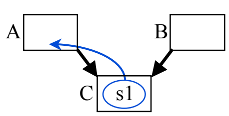
Instrumentation

- Insert instrumentation code at basic block entrances and before each branch
- Take average of values from multiple training runs
- Fairly inexpensive

Code Motion Using Control Flow Profiles

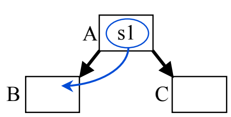
Code motion across basic blocks

- Increased scheduling freedom



move code above a join

- If we want to move s1 to A, we must move s1 to both A and B



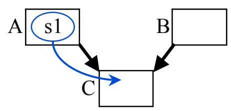
move code below a split

- If we want to move s1 to B, we must move s1 to both B and C

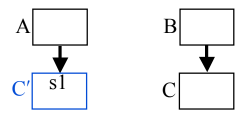
Code Motion Using Control Flow Profiles (cont)

Code motion across basic blocks

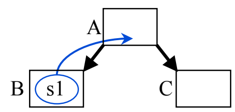
– Increased scheduling freedom



move code below a join



tail duplication prevents B→C from seeing s1



move code above a split

– If we want to move s1 from B to A and if s1 would destroy a value along the A→C path, do renaming (in hardware or software)

– What if s1 might cause an exception?

Memory-Dependence Profiles

Gather information about memory conflicts

– Frequencies of address matches between pairs of loads and stores

– Attempts to answer the question: Are two references independent of one another?

– Concentrate on **ambiguous** reference pairs (those that the compiler cannot figure out)

st1: store r5
ld2: load r4

(st1, ld2, 7) If this number is low, we can speculatively assume that st1 and ld2 do not conflict

Instrumentation

– Much more expensive (in both space and time) to gather than control flow information

– First perform control flow profiling

– Apply only to most frequently executed blocks

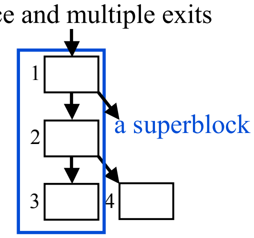
Trace Scheduling [Fisher 81] and [Ellis 85]

Basic idea

– We want large blocks to create large scheduling windows, but basic blocks are small because branches are frequent
– Create **superblocks** to increase scheduling window
– Use profile information to create good superblocks
– Optimize each superblock independently

Superblocks

– A sequence of basic blocks with a single entrance and multiple exits



Goals

– Want large superblocks
– Want to avoid early exits
– Want blocks that match actual execution paths

Trace Scheduling (example)

```
b[i] = "old"
a[i] = ...
if (a[i]>0) then
  b[i]="new";
else
  stmt X
  stmt Y
endif
c[i] = ...
```

```
trace:
b[i] = "old"
a[i] = ...
b[i]="new";
c[i] = ...
if (a[i]<=0) then goto repair
continue:
...


repair:
restore old b[i]
stmt X
stmt Y
recalculate c[i]?
goto continue
```

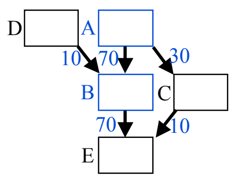
Trace Scheduling (cont)

Three steps

1. Create superblocks
2. Enlarge superblocks
3. Compact (optimize) superblocks

1. Superblock formation

- Create **traces** using **mutual-most-likely** heuristic (two blocks A and B are mutual-most-likely if B is the most likely successor of A, and A is the most likely predecessor of B)

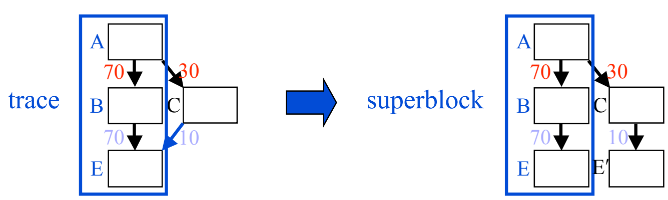


- A **trace** is a maximal sequence of mutual-most-likely blocks that does not contain a back edge
- Each block belongs to exactly one trace

Trace Scheduling (cont)

1. Superblock formation (cont)

- Convert traces into Superblocks
- Use tail duplication to eliminate side entrances



- Tail duplication increases code size

Trace Scheduling (cont)

2. Superblock enlargement

- Enlarge superblocks that are too small
- Code expansion can hurt i-cache performance

Three techniques for enlargement

- **Branch target expansion**
  - If the last branch in a superblock is likely to jump to the start of another superblock, append the contents of the target superblock to the first superblock
- **Loop peeling**
- **Loop unrolling**
  - These last two techniques apply to **superblock loops,** which are superblocks whose last blocks are likely to jump to their first blocks
  - Assume that each loop body has a single dominant path

Trace Scheduling (cont)

3. Optimizations

- Perform list scheduling for each superblock
- Memory-dependence profiles can be used to speculatively assume that load/store pairs do not conflict
  - Insert repair code in case the assumption is incorrect
- Software pipelining

Speculation based on memory-dependence profiles (example)

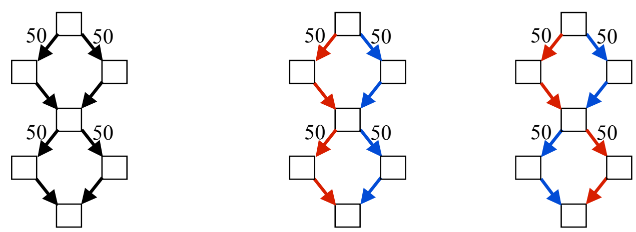
```
b[i] = "old"
a[i] = ...
if (a[i]>0) then
  b[i]="new";
else
  stmt X
  stmt Y
endif
c[i] = a[j]
```

```
trace:
b[i] = "old"
c[i] = a[j]
a[i] = ...
b[i]="new";
if (i==j) then goto deprepair
if (a[i]<=0) then goto repair
continue:
...

deprepair:
c[i] = a[i]
if (a[i]<=0) then goto repair
goto continue

repair:
restore old b[i]
stmt X
stmt Y
goto continue
```


Enhancements to Profile-Guided Code Scheduling

Path profiling [Ball and Larus 96]

– Collect information about entire paths instead of about individual edges



Edge profiles Path profiles Path profiles

– Limit paths to some specified length (can thus handle loops)
– Can also stop paths at back edges
– Disadvantages of path profiling?

Lessons

Larger scope helps

- How can we increase scope? How do we schedule across control dependences?

Static information is limited

- Use profiles
- How else can profiles be used in optimization?
- Can we do these kinds of optimizations at runtime?

Concepts

Instruction scheduling

- Software pipelining
- Trace scheduling
- Both use profile information
- Both look at scopes beyond basic blocks

Miscellany

- Path profiling
- Speculative hedging

Next Time

Reading
- Mahlke'92

Lecture
- Speculation and predication