Lecture 12: Optimization

COS 598C – Advanced Compilers

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Where are we?

- Analysis
  - Control Flow/Predicate
  - Dataflow
  - SSA
- Optimization

Optimization

- Make the code run faster on the target processor
  - My favorite topic !!
  - Anything goes
    - Look at benchmark kernels, what's the bottleneck??
    - Invent your own optimizations (easier and harder than you think)
- Classes of optimization
  - <u>1. Classical</u> (machine independent)
    - Reducing operation count (redundancy elimination)
    - Simplifying operations
    - Generally good for any kind of machine
  - 2. Machine specific
    - Peephole optimizations
    - Take advantage of specialized hardware features
  - 3. ILP enhancing
    - Increasing parallelism
    - Possibly increase instructions

Classical Optimizations

- Operation-level – 1 operation in isolation
  - Constant folding, strength reduction
- Dead code elimination (global, but 1 op at a time)
- Local/Global – Pairs of operations
  - Constant propagation
  - Forward copy propagation
  - Backward copy propagation
  - CSE
  - Constant combining
  - Operation folding
- Loop – Body of a loop
  - Invariant code removal
  - Global variable migration
  - Induction variable strength reduction
  - Induction variable elimination

Caveat

- Traditional compiler class
  - Sophisticated implementations of optimizations, efficient algorithms
  - Spend entire class on 1 optimization
- For this class – Go over concepts of each optimization
  - What it is
  - When can it be applied (set of conditions that must be satisfied)

Static Single Assignment (SSA)

Static Single Assignment Advantages:

- Less space required to represent def-use chains. For each variable, space is proportional to uses * defs.
- Eliminates unnecessary relationships:

```
for i = 1 to N do A[i] = 0
for i = 1 to M do B[i] = 1
```

  – No reason why both loops should be forced to use same register to hold index register.

  – SSA renames second `i` to new register which may lead to better register allocation.

- SSA form make certain optimizations quick and easy → dominance property.

  – Variables have only one definition - no ambiguity.

  – Dominator information is encoded in the assignments.

Dominance Property of SSA

Dominance property of SSA form: definitions dominate uses

- If x is i^{th} argument of ϕ-function in node n, then definition of x dominates i^{th} predecessor of n.
- If x is used in non-ϕ statement in node n, then definition of x dominates n.

Dead Code Elimination

Given d: `t = x op y`

- `t` is live at end of node d if there exists path from end of d to use of `t` that does not go through definition of `t`.
- if program not in SSA form, need to perform liveness analysis to determine if `t` live at end of d.
- if program is in SSA form:

  – cannot be another definition of `t`

  – if there exists use of `t`, then path from end of d to use exists, since definitions dominate uses.

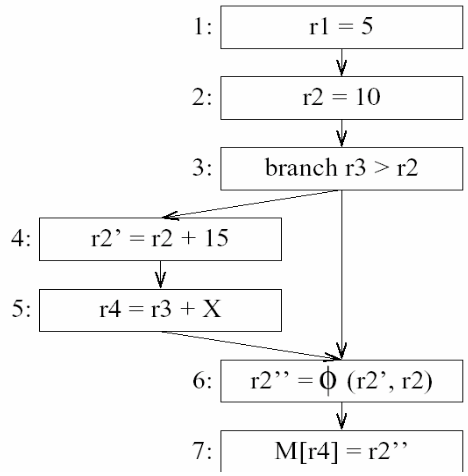
    $*$ every use has a unique definition

    $*$ `t` is live at end of node d if `t` is used at least once

Dead Code Elimination

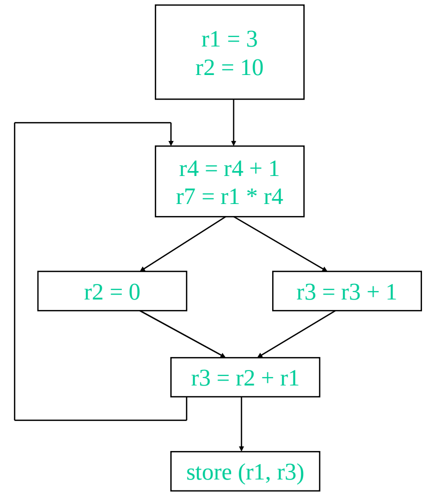
Algorithm:

WHILE (for each temporary t with no uses &&
statement defining t has no other side-effects) DO
delete statement definition t



Dead Code Elimination

- Remove any operation who's result is never consumed
- Rules
  - X can be deleted
    - no stores or branches
  - DU chain empty or dest register not live
- This misses some dead code!!
  - Especially in loops
  - Critical operation
    - store or branch operation
  - Any operation that does not directly or indirectly feed a critical operation is dead
  - Trace UD chains backwards from critical operations
  - Any op not visited is dead



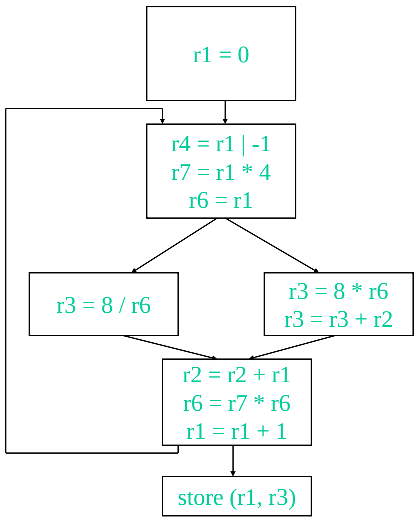
Constant Folding

- Simplify 1 operation based on values of src operands
  - Constant propagation creates opportunities for this
- All constant operands
  - Evaluate the op, replace with a move
    - r1 = 3 * 4 → r1 = 12
    - r1 = 3 / 0 → ??? Don't evaluate excepting ops !, what about floating-point?
  - Evaluate conditional branch, replace with BRU or noop
    - if (1 < 2) goto BB2 → BRU BB2
    - if (1 > 2) goto BB2 → convert to a noop
- Algebraic identities
  - r1 = r2 + 0, r2 – 0, r2 | 0, r2 ^ 0, r2 << 0, r2 >> 0
    - r1 = r2
  - r1 = 0 * r2, 0 / r2, 0 & r2
    - r1 = 0
  - r1 = r2 * 1, r2 / 1
    - r1 = r2

Strength Reduction

- Replace expensive ops with cheaper ones
  - Constant propagation creates opportunities for this
- Power of 2 constants
  - Multiply by power of 2, replace with left shift
    - r1 = r2 * 8 → r1 = r2 << 3
  - Divide by power of 2, replace with right shift
    - r1 = r2 / 4 → r1 = r2 >> 2
  - Remainder by power of 2, replace with logical and
    - r1 = r2 REM 16 → r1 = r2 & 15
- More exotic
  - Replace multiply by constant by sequence of shift and adds/subs
    - r1 = r2 * 6
      - r100 = r2 << 2; r101 = r2 << 1; r1 = r100 + r101
    - r1 = r2 * 7
      - r100 = r2 << 3; r1 = r100 – r2

Class Problem

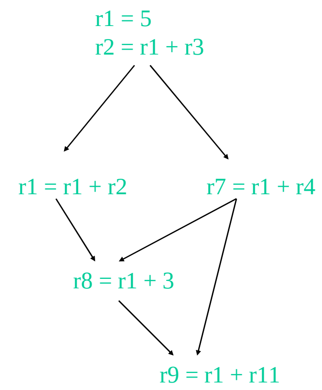


<u>Optimize this applying</u>

1. constant folding
2. strength reduction
3. dead code elimination

Constant Propagation

- Forward propagation of moves of the form
  - rx = L (where L is a literal)
  - Maximally propagate
  - Assume no instruction encoding restrictions
- When is it legal?
  - SRC: Literal is a hard coded constant, so never a problem
  - DEST: Must be available
    - Guaranteed to reach
    - May reach not good enough



Simple Constant Propagation

Given d: `t = c`, c is constant Given u: `x = t op b`

- if program not in SSA form:
  - need to perform reaching definition analysis
  - use of `t` in u may be replaced by `c` if d reaches u and no other definition of `t` reaches u
- if program is in SSA form:
  - d reaches u, since definitions dominate uses, and no other definition of `t` exists on path from d to u
  - d is only definition of `t` that reaches u, since it is the only definition of `t`.
    - ∗ any use of `t` can be replaced by `c`
    - ∗ any ϕ-function of form `v` $= \phi(c_1, c_2, ..., c_n)$, where $c_i = c$, can be replaced by `v = c`

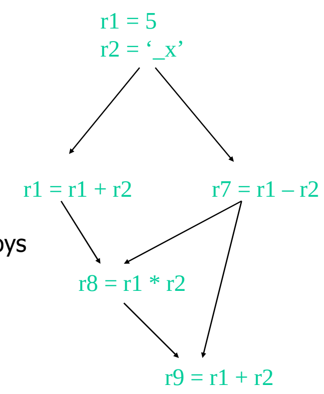
Local Constant Propagation

- Consider 2 ops, X and Y in a BB, X is before Y
  - 1. X is a move
  - 2. src1(X) is a literal
  - 3. Y consumes dest(X)
  - 4. There is no definition of dest(X) between X and Y
  - 5. No danger betw X and Y
    - When dest(X) is a Macro reg, BRL destroys the value

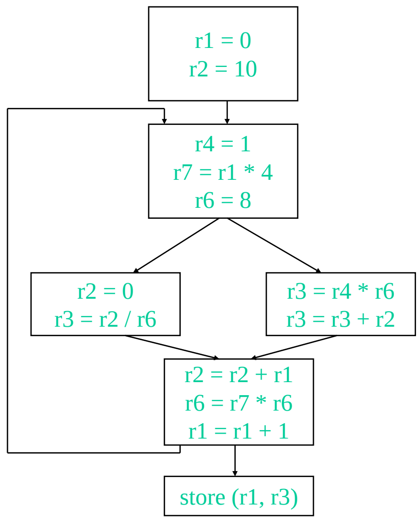
r1 = 5
r2 = ‘_x’
r3 = 7
r4 = r4 + r1
r1 = r1 + r2
r1 = r1 + 1
r3 = 12
r8 = r1 - r2
r9 = r3 + r5
r3 = r2 + 1
r10 = r3 – r1

Global Constant Propagation

- Consider 2 ops, X and Y in different BBs
  - 1. X is a move
  - 2. src1(X) is a literal
  - 3. Y consumes dest(X)
  - 4. X is in a_in(BB(Y))
  - 5. Dest(x) is not modified between the top of BB(Y) and Y
  - 6. No danger betw X and Y
    - When dest(X) is a Macro reg, BRL destroys the value



Class Problem

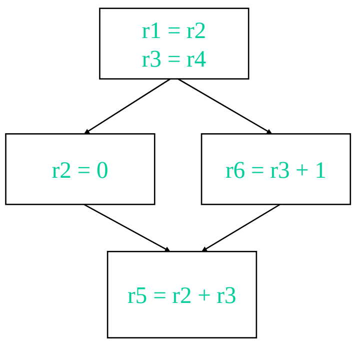


<u>Optimize this applying</u>

1. constant propagation
2. constant folding
3. strength reduction
4. dead code elimination

Forward Copy Propagation

- Forward propagation of the RHS of moves
  - r1 = r2
  - …
  - r4 = r1 + 1 → r4 = r2 + 1
- Benefits
  - Reduce chain of dependences
  - Eliminate the move
- Rules (ops X and Y)
  - X is a move
  - src1(X) is a register
  - Y consumes dest(X)
  - X.dest is an available def at Y
  - X.src1 is an available expr at Y



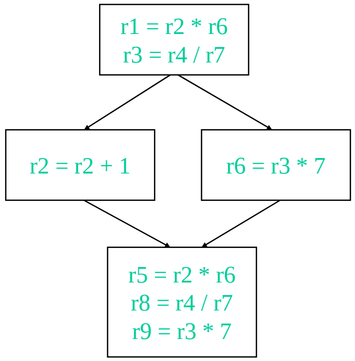
Backward Copy Propagation

- Backward propagation of the LHS of moves
  - r1 = r2 + r3 → r4 = r2 + r3
  - …
  - r5 = r1 + r6 → r5 = r4 + r6
  - …
  - r4 = r1 → noop
- Rules (ops X and Y in same BB)
  - dest(X) is a register
  - dest(X) not live out of BB(X)
  - Y is a move
  - dest(Y) is a register
  - Y consumes dest(X)
  - dest(Y) not consumed in (X…Y)
  - dest(Y) not defined in (X…Y)
  - There are no uses of dest(X) after the first redefinition of dest(Y)

```
r1 = r8 + r9
r2 = r9 + r1
r4 = r2
r6 = r2 + 1
r9 = r1
r10 = r6
r5 = r6 + 1
r4 = 0
r8 = r2 + r7
```

CSE – Common Subexpression Elimination

- Eliminate recomputation of an expression by reusing the previous result
  - r1 = r2 * r3
  - → r100 = r1
  - …
  - r4 = r2 * r3 → r4 = r100
- Benefits
  - Reduce work
  - Moves can get copy propagated
- Rules (ops X and Y)
  - X and Y have the same opcode
  - src(X) = src(Y), for all srcs
  - expr(X) is available at Y
  - if X is a load, then there is no store that may write to address(X) along any path between X and Y



if op is a load, call it redundant load elimination rather than CSE

Class Problem

```
r1 = 9
r4 = 4
r5 = 0
r6 = 16
r2 = r3 * r4
r8 = r2 + r5
r9 = r3
r7 = load(r2)
r5 = r9 * r4
r3 = load(r2)
r10 = r3 / r6
store (r8, r7)
r11 = r2
r12 = load(r11)
store(r12, r3)
```

Optimize this applying

1. constant propagation
2. constant folding
3. strength reduction
4. dead code elimination
5. forward copy propagation
6. backward copy propagation
7. CSE

Constant Combining

- Combine 2 dependent ops into 1 by combining the literals
  - r1 = r2 + 4
  - …
  - r5 = r1 - 9 → r5 = r2 – 5
- First op often becomes dead
- Rules (ops X and Y in same BB)
  - X is of the form rx +- K
  - dest(X) != src1(X)
  - Y is of the form ry +- K (comparison also ok)
  - Y consumes dest(X)
  - src1(X) not modified in (X…Y)

```
r1 = r2 + 4
r3 = r1 < 0
r2 = r3 + 6
r7 = r1 – 3
r8 = r7 + 5
```


Operation Folding

- Combine 2 dependent ops into 1 complex op
  - Classic example is MPYADD
  - r1 = r2 * r3
  - …
  - r5 = r1 + r4 → r5 = r2 * r3 + r4
- First op often becomes dead
- Borders on machine dependent opti (often it is !!)
- Rules (ops X and Y in same BB)
  - X is an arithmetic operation
  - dest(X) != any src(X)
  - Y is an arithmetic operation
  - Y consumes dest(X)
  - X and Y can be merged
  - src(X) not modified in (X…Y)

```
r1 = r2 & 4
r3 = r1 ^ -1
r2 = r3 < 6
r4 = r2 == 0
r5 = r6 << 1
r7 = r5 + r8
```