Loop Fusion Amid Complex Control Flow

R Ramshankar
Dibyendu Das
AMD
Loop Fusion

Two loops with proximity in control flow iterating over same large arrays

– Will show poor scalability
– Why? Loops on large arrays stride over memory that is too big to fit in the cache.
– Loops can be fused if dependences can be preserved, but
  – How do we deal with proximity amid complex control flows (and function calls)?
Loop fusion with control dependence

• Build from trivial loop fusion: adjacent loops
  – Loops are typically guarded by an if (i != end) condition
  – Control dependence graph: derive from the CFG
• If two loops have the same or almost identical control dependence
Control dependence

If (x) { A; }

A is control-dependent on the block that contains the conditional branch \( BR \ (x == true) \), A

(i.e., A is control-dependent on the block that decides to bypass A or go to A)

- Formally, a statement \( y \) is said to be control dependent on another statement \( x \) if
  - (1) there exists a non-trivial path from \( x \) to \( y \) such that every statement \( z \neq x \) in the path is post-dominated by \( y \) and
  - (2) \( x \) is not post-dominated by \( y \)

- Added the control dependence construction algorithm from Kennedy/Allen
Generic CFG pattern containing natural loops

int test(int A[], long size...) {
    long i = 0;
    for (i = 0; i < size; i++) {
        A[i] |= (1 << a);
    }
    for (i = 0; i < size; i++) {
        A[i] |= (1 << b);
    }
    // ...
    return 0;
}

• entry leads to the first loop
  – By nature, a control dependence
• Generalize based on this standard pattern
  – Two proximal singly nested loops
    • For ex: proximal in breadth-first order
  – What if instead of the single blocks “entry”/”if.end” we have complex control flow?
Fusing loops despite complex control flow: slicing out paths from the CFG

int test(int A[], long size, int a, int b, int c, int d, int e) {
    long i = 0;
    if (a & b) {
        for (i = 0; i < size; i++) {
            A[i] |= ...;
        }
    }
    if (d & e) {
        for (i = 0; i < size; i++) {
            A[i] |= ...;
        }
    }
    ...
Loop fusion

- To fuse merge entry, if.end blocks
  - Create control flow: no need for C/C++ short-circuiting
  - All conditions are anticipated at entry: collapse conditions with bitwise-and: done here in entrypflLander
- Fuse all the way to the common post-dominator for both loop’s exits: if.end18
  - Preserves the CFG structure; easy recursive application of loop fusion with subsequent loops
Loop fusion – control merging using closures

- We want to allow more control-dependences to be merged:
  - Create closures of the control dependence graph
  - Warshall’s algorithm
  - Ensure that the newly created control flow preserves data dependences
  - Start from the common control prefix of the two loops and attempt to merge or collapse the suffices
  - Control how different the closures are using a heuristic number on the size of suffices (<5 control dependences now)
Head and tail control flow strands

- **for.end** could be more than one block
  - Deal with tail control flows between the two loops
  - Likewise with **if.then**: there can be head control flows leading to the two loops

- The approach used at this time is to enumerate all paths through the head/tail control flow blocks and insert the fused loop in each path
  - Managing this with profile data should be more profitable (TBD)
  - Orthogonal approach would be code-motion (TBD)
Fusing more than two adjacent loops

- Recursive application of fusion using a graph with edges between loop fusion candidates
  - Share a prefix control dependence closure
  - Second loop has a control dependence parent that post-dominates first loop’s exit
  - Breadth-first order of the control flow graph breaks ties
    - Provides a proximity metric
    - Perhaps allows rethinking recursions until fixed point
- Walk over the graph and merge from bottom-up
- Iteratively build loop graphs and fuse, until fixed point (or a specific number of iterations)
  - Intensive optimization
Complex control flow

• Dependences/aliases/phis/opaque-calls will prune the number of collapsed paths

• Adjacent function calls may have loops that can be fused
  – Inlining may allow some loops to be fused
  – Function unswitching (useful approach that looks for the quickly exiting function pattern)

• Inter-procedural mod-ref information provide additional alias information
  – Added metadata to carry over address non-taken global mod-ref info in load/stores for use in scalar transforms or analysis

• Inline functions in a selective manner
  • Walk over call graph SCCs and ascertain if inlining a call may allow loop fusion
Dependence analysis

• First cut approach chooses inner-most loops that are simple (for example, loops that may be favored by the loopvectorizer)

• Need to develop a cache model that verifies to a certain degree of accuracy if loop fusion will be beneficial or not

• Exit/step SCEVs of both loops are checked to be exact matches, check for no LCD with the dependence analyzer

• Used LLVM Dependence Analyzer
  – Dependency Analyzer is said not to be robust, but was able to handle our tests
Results (preliminary)

• Several synthetic cases demonstrate effectiveness
  – for() {} if () { for(){} } else { for () }
  – for() {} if () { for(){} }
  – for() {} for() {}
  – if() {for() {}} if() {for() {} }
  – For large arrays fusion improved performance almost exponentially
• Improves SPECCPU INT 2006
• 462.libquantum rate performance improves close to 2.5X in x86 (AMD/Intel)
  – Non-trivial control flow, inlining, unswitching, global mod-ref
  – more than 100 loop fusion steps
• POC code received favorable response from llvmdev
  – Working to address llvmdev comments
• Need to explore way for use of profile information
Reference


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