Combinatorial Spill Code Optimization and Ultimate Coalescing

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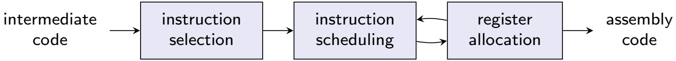
LCTES 2014

Outline

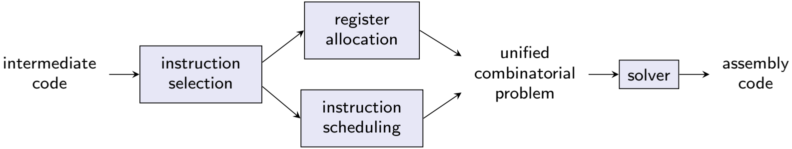
Combinatorial Code Generation

- Traditional approach



  - heuristics, staging: suboptimal, complex

- Combinatorial approach
  - model: variables, constraints, objective
  - solve: integer programming, constraint programming ...



  - optimization, integration: potentially optimal, flexible

Register Allocation

- Global register allocation has many subproblems
- Competitive approaches must capture all of them
- Focus of this presentation:
  - **spill code optimization**
    - remove unnecessary spill instructions
  - **coalescing**
    - remove unnecessary register-to-register moves
    - *basic*: coalesce temps related by moves
    - *ultimate*: even if their live ranges overlap

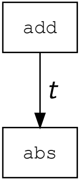
Our Approach

- Alternative temporaries
  - program representation
  - combinatorial structure
- Extends combinatorial reg. allocation and scheduling with
  - spill code optimization
  - ultimate coalescing
- Yields better code than
  - previous combinatorial approaches
  - traditional heuristic approaches
- Scales despite increased solution space

Related Approaches

- Some models include spill code optimization
  - (Chang *et al.*, 1997)
  - (Bashford and Leupers, 1999)
  - (Nagarakatte and Govindarajan, 2007)
  - (Eriksson and Kessler, 2012)
  - typically via a quadratic number of Boolean variables
- Some models include basic coalescing
  - (Wilson *et al.*, 1994)
  - (Bashford and Leupers, 1999)
  - (Castañeda *et al.*, 2012)
- No model includes ultimate coalescing
  - non-trivial when combined with scheduling

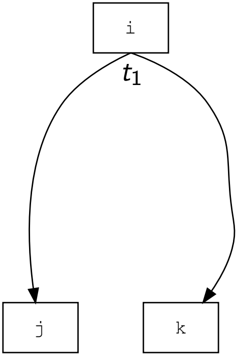
Program Representation



- Dependency graph with processor instructions

Spill Code Optimization

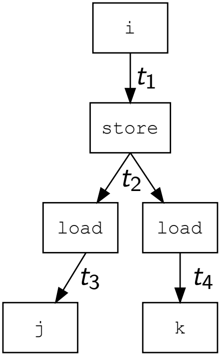
- Remove unnecessary spill load instructions



- Before spilling

Spill Code Optimization

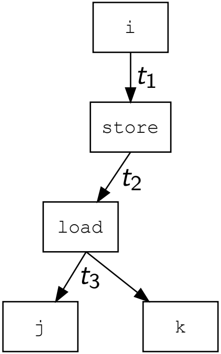
- Remove unnecessary spill load instructions



- Spill everywhere: a `load` before each use

Spill Code Optimization

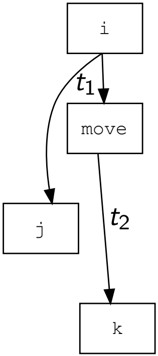
- Remove unnecessary spill load instructions



- Spill code optimization: reuse temp t_3 to remove a `load`

Ultimate Coalescing

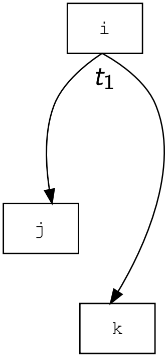
- Remove unnecessary register-to-register moves
  - even if the respective temp live ranges overlap



- Basic: `move`'s temps (t_1,t_2) interfere, cannot coalesce

Ultimate Coalescing

- Remove unnecessary register-to-register moves
  - even if the respective temp live ranges overlap

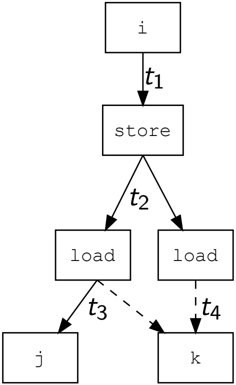


- Ultimate: they hold the same value, can coalesce

Alternative Temporaries

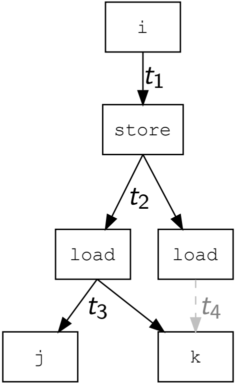
- Program representation and combinatorial structure
- Augments model with
  - spill code optimization
  - ultimate coalescing
- Allows connection of alternative temps to each instruction
  - invariant: alternative temps hold the same value

Alternative Temporaries: Spill Code Optimization



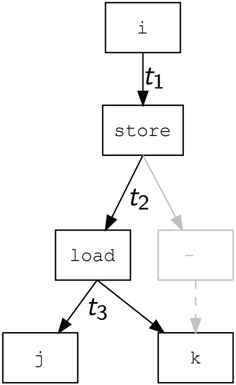
- Instruction `k` *can be connected* (dashed) to t_3 or t_4

Alternative Temporaries: Spill Code Optimization



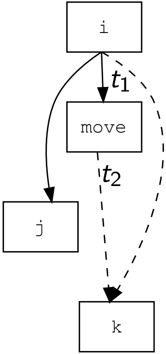
- If k is connected to t_3, t_4 is not used

Alternative Temporaries: Spill Code Optimization



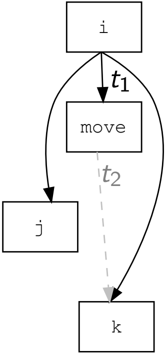
- If t_4 is not used, its definer `load` becomes inactive

Alternative Temporaries: Ultimate Coalescing



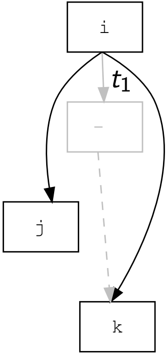
- Instruction `k` can be connected to t_1 or t_2

Alternative Temporaries: Ultimate Coalescing



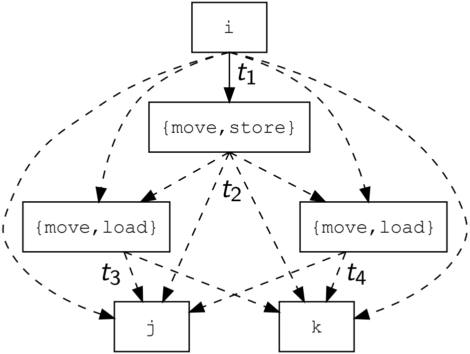
- If `k` is connected to t_1, t_2 is not used

Alternative Temporaries: Ultimate Coalescing



- If t_2 is not used, its definer `move` becomes inactive

Alternative Temporaries: Construction



1. Extend program with optional copies
   - after definition: reg-to-reg `move` or memory `store`
   - before use: reg-to-reg `move` or memory `load`
2. Replace each temporary use with alternatives
   - $\{t_1, t_2, t_3, t_4\}$ all hold the same value
   - due to copy semantics of `move`, `store`, and `load`

Combinatorial Model

$$
\begin{aligned}
&\text{minimize} \quad \sum_{b \in B} \text{weight}(b) \times \text{cost}(b) \quad \text{subject to} \\
l_t &\iff \exists p \in P : \left(\text{use}(p) \land y_p = t\right) && \forall t \in T \\
a_{\text{definer}(t)} &\iff l_t && \forall t \in T \\
a_o &\iff y_p \neq \bot && \forall o \in O,\ \forall p \in \text{operands}(o) \\
a_o &\iff i_o \neq \bot && \forall o \in O \\
r_{y_p} &\in \text{class}(i_o, p) && \forall o \in O,\ \forall p \in \text{operands}(o) \\
&\text{disjoint2}(\{\langle r_t, r_t + \text{width}(t) \times l_t, ls_t, le_t \rangle : t \in \text{T}(b)\}) && \forall b \in B \\
r_{y_p} &= \mathtt{r} && \forall p \in P : p \rhd \mathtt{r} \\
r_{y_p} &= r_{y_q} && \forall p, q \in P : p \equiv q \\
l_t &\implies ls_t = c_{\text{definer}(t)} && \forall t \in T \\
l_t &\implies le_t = \max_{o \in \text{users}(t)} c_o && \forall t \in T \\
a_o &\implies c_o \geq c_{\text{definer}(y_p)} + \text{lat}(i_{\text{definer}(y_p)}) && \forall o \in O,\ \forall p \in \text{operands}(o) : \text{use}(p) \\
&\text{cumulative}(\{\langle\langle c_o, \text{con}(i_o, \mathtt{r}), \text{dur}(i_o, \mathtt{r}) \rangle\rangle : o \in \text{O}(b)\}, \text{cap}(\mathtt{r})) && \forall b \in B,\ \forall \mathtt{r} \in R
\end{aligned}
$$

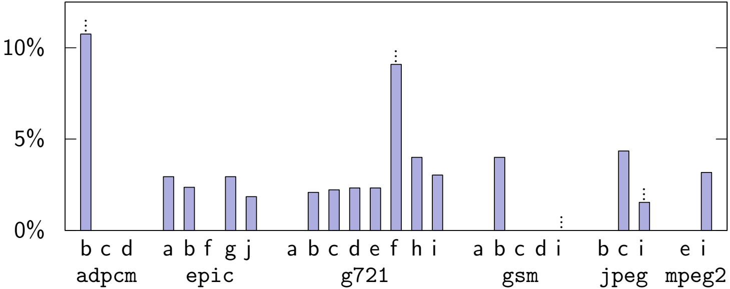
- Generic objective function: speed, code size, . . .
- See the paper for details

Experiment Setup

- 10 functions from each DSP application in MediaBench
  - medium size: 10 to 1000 instructions
  - sampled by clustering (size, register pressure)
- Selected Hexagon V4 instructions with LLVM 3.3
  - VLIW DSP in Qualcomm's *Snapdragon* system-on-chip
- Constraint-based code generator
  - uses Gecode 4.2.1 as the underlying constraint solver
  - iterative scheme: finds better solutions every iteration
  - fixed to 10 iterations (point of convergence)
- LLVM as a traditional code generator
  - register allocation by priority-based coloring
  - instruction scheduling by list scheduling

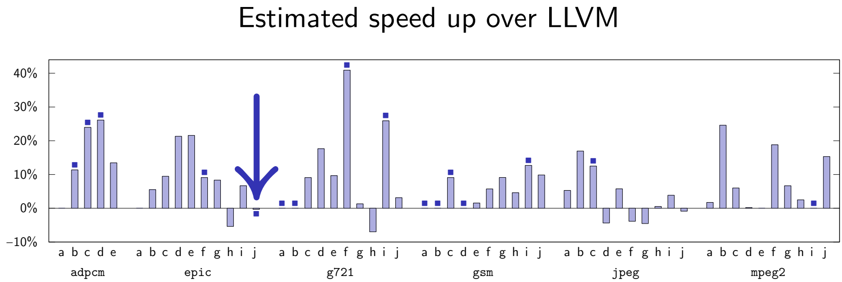
Impact of Alternative Temporaries

Optimal solution improvement due to alternative temps
(compared to model by Castañeda *et al.*, 2012)



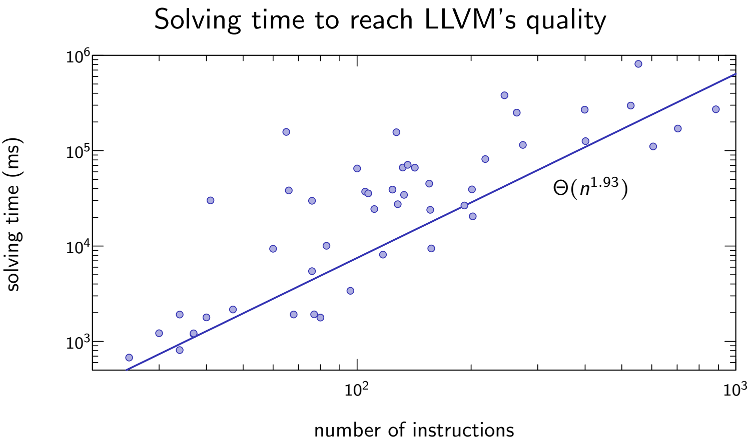
- 62% of the functions are faster
- None is slower – as expected
- 2% geometric mean improvement

Code Quality Compared to Traditional Approaches



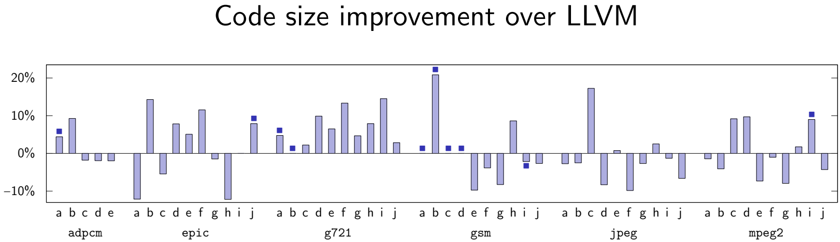
- 7% geometric mean improvement
- Provably optimal code (■) for 29% of the functions
- Model limitation: no rematerialization

Scalability



- Quadratic average complexity up to 1000 instructions
- Comparable to approach **without** alternative temps

Different Optimization Criteria



- 1% geometric mean improvement
- Low development effort to adapt the code generator

Conclusion

- Alternative temporaries completes combinatorial code generation with
  - spill code optimization
  - ultimate coalescing
- Yields a code generator that
  - delivers faster code than traditional ones
  - is robust and scales to medium-size functions
  - adapts easily to different optimization criteria
- Lots of future work
  - rematerialization
  - global instruction scheduling
  - handle unknown instruction latencies
  - improve runtime with different solving techniques