High-level software-pipelining in LLVM

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Rationale

Software pipelining (often Modulo Scheduling)

- Interleave operations from multiple loop iterations
- Improved loop ILP
- Currently missing from LLVM
- Loop scheduling technique
  - Requires both loop dependency and resource availability information
  - Usually done at a target specific level as part of scheduling
- But it would be very good if we could re-use this implementation for different targets
Example: resource constrained

```java
for (int i = 0; i < N; i++) {
}
```

(a) Original  (b) Single memory  (c) Two memories
Example: data dependencies

B[0] = A[0];
for (int i = 1; i < N; i++) {
    B[i] = B[i-1] + A[i];
}

dependency
Example: data dependencies

```
B[0] = A[0];
for (int i = 1; i < N; i++) {
    B[i] = B[i-1] + A[i];
}
```

```
register int r = A[0];
B[0] = r;
for (int i = 1; i < N; i++) {
    r = r + A[i];
    B[i] = r;
}
```
Source Level Modulo Scheduling (SLMS)

SLMS: Source-to-source translation at statement level

\[
\begin{align*}
\text{for}(i = 0; i < n; i++) \\
\{ \\
S1_i : & \quad t = A[i] \times B[i]; \\
S2_i : & \quad s = s + t;
\}
\]

\[
\begin{align*}
S1_0 : & \quad t = A[0] \times B[0]; \\
\text{for}(i = 0; i < n - 1; i++) \\
\{ \\
S2_i : & \quad s = s + t;
\}
S1_{i+1} : & \quad t = A[i + 1] \times B[i + 1]; \\
\}
S2_{n-1} : & \quad s = s + t;
\end{align*}
\]

Towards a Source Level Compiler: Source Level Modulo Scheduling
– Ben-Asher & Meisler (2007)
SLMS results

Livermore and Linpack Kernels on Itanium II
Compiled with gcc, with and without -O3
SLMS features and limitations

- Improves performance in many cases
- No resource constraints considered
- Works with complete statements
- When no valid II is found statements may be split (decomposed)
This work

Finding the middle ground:

What would happen if we do this at LLVM’s IR level
This work

Finding the middle ground:

What would happen if we do this at LLVM’s IR level

- More fine grained statements (close to operations)
- Coarse resource constraints through target hooks
- Schedule loop pipelining pass late in the optimization sequence (just before final cleanup)
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IR data dependencies

- Memory dependencies

```
<table>
<thead>
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```

dependency
IR data dependencies

- Memory dependencies

- Phi nodes
Revisiting our example: memory dependencies

define void @foo(i8* nocapture %in, i32 %width) #0 {
  entry:
    %cmp = icmp ugt i32 %width, 1
    br i1 %cmp, label %for.body, label %for.end

  for.body: ; preds = %entry, %for.body
    %i.012 = phi i32 [ %inc, %for.body ], [ 1, %entry ]
    %sub = add i32 %i.012, -1
    %arrayidx = getelementptr inbounds i8* %in, i32 %sub
    %0 = load i8* %arrayidx, align 1, !tbaa !0
    %arrayidx1 = getelementptr inbounds i8* %in, i32 %i.012
    %1 = load i8* %arrayidx1, align 1, !tbaa !0
    %add = add i8 %1, %0
    store i8 %add, i8* %arrayidx1, align 1, !tbaa !0
    %inc = add i32 %i.012, 1
    %exitcond = icmp eq i32 %inc, %width
    br i1 %exitcond, label %for.end, label %for.body

  for.end: ; preds = %for.body, %entry
    ret void
}
Revisiting our example: using a phi-node

```assembly
define void @foo(i8* nocapture %in, i32 %width) #0 {
  entry:
    %arrayidx = getelementptr inbounds i8* %in, i32 0
    %prefetch = load i8* %arrayidx, align 1, !tbaa !0
    %cmp = icmp ugt i32 %width, 1
    br i1 %cmp, label %for.body, label %for.end

  for.body: ; preds = %entry, %for.body
    %i.012 = phi i32 [ %inc, %for.body ], [ 1, %entry ]
    %0 = phi i32 [ %add, %for.body ], [ %prefetch, %entry ]
    %arrayidx1 = getelementptr inbounds i8* %in, i32 %i.012
    %1 = load i8* %arrayidx1, align 1, !tbaa !0
    %add = add i8 %1, %0
    store i8 %add, i8* %arrayidx1, align 1, !tbaa !0
    %inc = add i32 %i.012, 1
    %exitcond = icmp eq i32 %inc, %width
    br i1 %exitcond, label %for.end, label %for.body

  for.end: ; preds = %for.body, %entry
    ret void
}
```
Target hooks

- Communicate available resources from target specific layer
- Candidate resource constraints
  - Number of scalar function units
  - Number of vector function units
  - ...
- IR instruction cost
  - Obtained from CostModelAnalysis
  - Currently only a debug pass and re-implemented by each user (e.g. vectorization)
The scheduling algorithm

- Swing Modulo Scheduling
  - Fast heuristic algorithm
  - Also used by GCC (and in the past LLVM)
- Scheduling in five steps
  - Find cyclic (loop carried) dependencies and their length
  - Find resource pressure
  - Compute minimal initiation interval (II)
  - Order nodes according to 'criticality'
  - Schedule nodes in order

*Swing Modulo Scheduling: A Lifetime-Sensitive Approach*
– Llosa et al. (1996)
Construct new loop structure (prologue, kernel, epilogue)
Branch into new loop when sufficient iterations are available
Clean-up through constant propagation, CSE, and CFG simplification
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Target platform

- Initial implementation for Movidius’ SHAVE architecture
- 8 issue VLIW processor
- With DSP and SIMD extensions
- But implemented in the IR layer so mostly target independent

*Always-on vision processing unit for mobile applications*
– B. Barry et al., IEEE Micro 35(2), 2015
Results

- **Good points:**
  - It works
  - Up to 1.5x speedup observed in TSVC tests
  - Even higher ILP improvements
Results

- **Good points:**
  - It works
  - Up to 1.5x speedup observed in TSVC tests
  - Even higher ILP improvements

- **Weak spots**
  - Still many big regressions (up to 4x slowdown)
  - Some serious problems still need to be fixed
    - Instruction patterns are split over multiple loop iterations
    - My bookkeeping of live variables needs improvement
    - Currently blocking some of the more viable candidate loops
    - Slowly getting fixed!
Possible improvements

- User control
  - Selective application to loops (e.g. through #pragma)
- Predictability
  - Modeling of instruction patterns in IR
  - Improved resource model
  - Better profitability analysis
  - Superblock instruction selection to find complex operations crossing BB bounds?
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- It works, somewhat...
- IR instruction patterns are difficult to keep intact
- Still lots of room for improvement
  - Upgrade from LLVM 3.5 to trunk
  - Fix bugs (bookkeeping of live values, ...)
  - Re-check performance!
  - Fix regressions
  - Test with other targets!
Thank you

https://github.com/rjordans/llvm