

# Code Generation for Data Processing

## Lecture 7: Instruction Selection

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# Code Generation – Overview

- ▶ Instruction Selection
  - ▶ Map IR to assembly
  - ▶ Keep code shape and storage; change operations
- ▶ Instruction Scheduling
  - ▶ Optimize order to hide latencies
  - ▶ Keep operations, may increase demand for registers
- ▶ Register Allocation
  - ▶ Map virtual to architectural registers and stack
  - ▶ Adds operations (spilling), changes storage

# Instruction Selection (ISel) – Overview

- ▶ Find machine instructions to implement abstract IR
- ▶ Typically separated from scheduling and register allocation
- ▶ Input: IR code with abstract instructions
- ▶ Output: lower-level IR code with target machine instructions

```
i64 %10 = add %8, %9
i8 %11 = trunc %10
i64 %12 = const 24
i64 %13 = add %7, %12
store %11, %13
```

```
i64 %10 = ADD %8, %9
STRB %10, [%7+24]
```

# ISel – Typical Constraints

- ▶ Target offers multiple ways to implement operations
  - ▶ `imul x, 2, add x, x, shl x, 1, lea x, [x+x]`
- ▶ Target operations have more complex semantics
  - ▶ E.g., combine truncation and offset computation into store
  - ▶ Can have multiple outputs, e.g. value+flags, quotient+remainder
- ▶ Target has multiple register sets, e.g. GP and FP/SIMD
  - ▶ Important to consider even before register allocation
- ▶ Target requires specific instruction sequences
  - ▶ E.g., for macro fusion
  - ▶ Often represented as pseudo-instructions until assembly writing

# Optimal ISel

- ▶ Find *most performant* instruction sequence with same semantics (?)
  - ▶ I.e., there no program with better “performance” exists
  - ▶ Performance = instructions associated with specific costs
- ▶ Problem: optimal code generation is **undecidable**
- ▶ Alternative: optimal *tiling* of IR with machine code instrs
  - ▶ IR as dataflow graph, instr. tiles to optimally cover graph
  - ▶  $\mathcal{NP}$ -complete<sup>24</sup>

<sup>24</sup>DR Koes and SC Goldstein. “Near-optimal instruction selection on DAGs”. In: *CGO*. 2008, pp. 45–54. .

# Avoiding ISEL Altogether

Use an interpreter

- + Fast “compilation time”, easy to implement
- Slow execution time
- ▶ Best if code is executed once

# Macro Expansion

- ▶ Expand each IR operation with corresponding machine instrs

<code>%5 = add %1, 12345</code>	→	<code>%5a = movz 12345</code>
		<code>%5 = add %1, %5a</code>
<code>%6 = and %2, 7</code>	→	<code>%6 = and %2, 7</code>
		<code>%7a = lsl %5, %6</code>
<code>%7 = shl %5, %6</code>	→	<code>%7b = cmp %6, 64</code>
		<code>%7 = csel %7a, xzr, %7b, lo</code>


# Macro Expansion


- ▶ Oldest approach, historically also does register allocation
  - ▶ Also possible by walking AST
- + Very fast, linear time, simple to implement, easy to port
- Inefficient and large output code
- ▶ Used by, e.g., LLVM FastISel, Go, GCC



# Peephole Optimization

- ▶ Plain macro expansion leads to suboptimal results
- ▶ Idea: replace inefficient instruction sequences<sup>25</sup>
- ▶ Originally: physical window over assembly code
  - ▶ Replace with more efficient instructions having same effects
  - ▶ Possibly with allocated registers
- ▶ Extension: do expansion before register allocation<sup>26</sup>
  - ▶ Expand IR into Register Transfer Lists (RTL) with temporary registers
  - ▶ While *combining*, ensure that each RTL can be implemented as single instr.

<sup>25</sup>WM McKeeman. "Peephole optimization". In: *CACM* 8.7 (1965), pp. 443–444. 

<sup>26</sup>JW Davidson and CW Fraser. "Code selection through object code optimization". In: *TOPLAS* 6.4 (1984), pp. 505–526. 

# Peephole Optimization

- ▶ Originally covered only adjacent instructions
- ▶ Can also use logical window of data dependencies
  - ▶ Problem: instructions with multiple uses
  - ▶ Needs more sophisticated matching schemes for data deps.  
⇒ Tree-pattern matching
- + Fast, also allows for target-specific sequences
- Pattern set grows large, limited potential
- ▶ Widely used today at different points during compilation

# ISel as Graph Covering – High-level Intuition

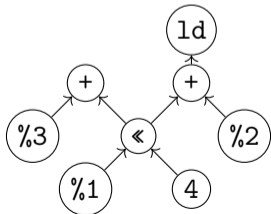
- ▶ Idea: represent program as data flow graph
- ▶ Tree: expression, comb. of single-use SSA instructions *(local ISel)*
- ▶ DAG: data flow in basic block, e.g. SSA block *(local ISel)*
- ▶ Graph: data flow of entire function, e.g. SSA function *(global ISel)*
- ▶ ISA “defines” *pattern set* of trees/DAGs/graphs for instrs.
- ▶ Cover data flow tree/DAG/graph with least-cost combination of patterns
  - ▶ Patterns in data flow graph may overlap

# Tree Covering: Converting SSA into Trees

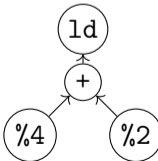
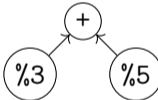
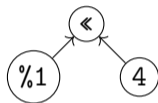
## ▶ SSA form:

```
%4 = shl %1, 4  
%5 = add %2, %4  
%6 = add %3, %4  
%7 = load %5  
live-out: %6, %7
```

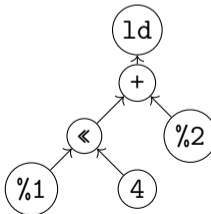
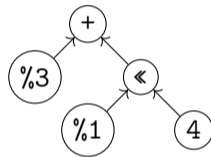
## ▶ Data flow graph:



## ▶ Method 1: Edge Splitting



## ▶ Method 2: Node Duplication



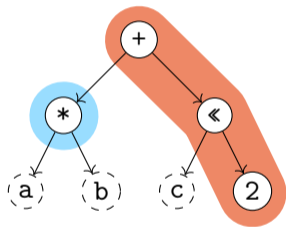
# Tree Covering: Patterns

	Pattern	Cost	Instruction
$P_0$	$GP_{R1} \rightarrow \ll(GP_{R2}, K_1)$	1	lsl $R_1, R_2, \#K_1$
$P_1$	$GP_{R1} \rightarrow +(GP_{R2}, GP_{R3})$	1	add $R_1, R_2, R_3$
$P_2$	$GP_{R1} \rightarrow +(\ll(GP_{R2}, K_1), GP_{R3})$	2	add $R_1, R_2, R_3, \text{lsl } \#K_1$
$P_3$	$GP_{R1} \rightarrow +(\ll(GP_{R2}, K_1), GP_{R2})$	2	add $R_1, R_3, R_2, \text{lsl } \#K_1$
$P_4$	$GP_{R1} \rightarrow \text{ld}(GP_{R2})$	2	ldr $R_1, [R_2]$
$P_5$	$GP_{R1} \rightarrow \text{ld}+(\ll(GP_{R2}, K_1), GP_{R3})$	2	ldr $R_1, [R_2, R_3]$
$P_6$	$GP_{R1} \rightarrow \text{ld}+(\ll(GP_{R2}, K_1), GP_{R2})$	3	ldr $R_1, [R_2, R_3, \text{lsl } \#K_1]$
$P_7$	$GP_{R1} \rightarrow \text{ld}+(\ll(GP_{R2}, K_1), GP_{R3})$	3	ldr $R_1, [R_3, R_2, \text{lsl } \#K_1]$
$P_8$	$GP_{R1} \rightarrow *(GP_{R2}, GP_{R3})$	3	madd $R_1, R_2, R_3, \text{xzr}$
$P_9$	$GP_{R1} \rightarrow +(*(GP_{R2}, GP_{R3}), GP_{R4})$	3	madd $R_1, R_2, R_3, R_4$
$P_{10}$	$GP_{R1} \rightarrow K_1$	1	mov $R_1, K_1$
$\vdots$	$\vdots$	$\vdots$	$\vdots$

# Tree Covering: Greedy/Maximal Munch

- ▶ Top-down always take largest pattern
  - ▶ Repeat for sub-trees, until everything is covered
- 
- + Easy to implement, fast
  - Result might be non-optimum

# Tree Covering: Greedy/Maximal Munch – Example



Matching Patterns:

- ▶  $+$ :  $P_1$  – cost 1 – covered nodes: 1
- ▶  $+$ :  $P_2$  – cost 2 – covered nodes: 3 – best
- ▶  $+$ :  $P_9$  – cost 3 – covered nodes: 2
- ▶  $*$ :  $P_8$  – cost 3 – covered nodes: 1 – best

Total cost: 5

```
madd %1, %a, %b, xzr
add %2, %1, %c, ls1 #2
```

# Tree Covering: with LR-Parsing

- ▶ Can we use (LR-)parsing for instruction selection? Yes!<sup>27</sup>
  - ▶ Pattern set = grammar; IR (in prefix notation) = input

## Advantages

- ▶ Possible in linear time
- ▶ Can be formally verified
- ▶ Implementation can be generated automatically


## Disadvantages

- ▶ Constraints must map to non-terminals
  - ▶ Constant ranges, reg types, ...
- ▶ CISC: handle all operand combinations
  - ▶ Large grammar (impractical)
  - ▶ Refactoring into non-terminals
- ▶ Ambiguity hard to handle optimally

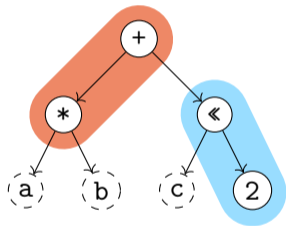


# Tree Covering: Dynamic Programming<sup>28</sup>

- ▶ Step 1: compute cost matrix, bottom-up for all nodes
  - ▶ Matrix: tree node  $\times$  non-terminal  
(different patterns might yield different non-terminals)
  - ▶ Cost is sum of pattern and sum of children costs
  - ▶ Always store cheapest rule and cost
- ▶ Step 2: walk tree top-down using rules in matrix
  - ▶ Start with goal non-terminal, follow rules in matrix
- ▶ Time linear w.r.t. tree size

<sup>28</sup>AV Aho, M Ganapathi, and SWK Tjiang. "Code generation using tree matching and dynamic programming". In: *TOPLAS* 11.4 (1989), pp. 491–516. .

# Tree Covering: Dynamic Programming – Example



Node: +  
Pattern:  $P_9: GP \rightarrow +(* (GP, GP), GP)$   
Pat. Cost: 3  
Cost Sum: 4

		Node	+	*	<<	2
GP	Cost		4	3	1	1
	Pattern		$P_9$	$P_8$	$P_1$	$P_{10}$

# Tree Covering: Dynamic Programming – Off-line Analysis

- ▶ Cost analysis can actually be *precomputed*<sup>29</sup>
- ▶ Idea: annotate each node with a state based on child states
- ▶ Lookup node label from precomputed table (one per non-terminal)
- ▶ Significantly improves compilation time
- ▶ But: Tables can be large, need to cover all possible (sub-)trees
- ▶ Variation: dynamically compute and cache state tables<sup>30</sup>

<sup>29</sup>A Balachandran, DM Dhamdhere, and S Biswas. "Efficient retargetable code generation using bottom-up tree pattern matching". In: *Computer Languages* 15.3 (1990), pp. 127–140.

<sup>30</sup>MA Ertl, K Casey, and D Gregg. "Fast and flexible instruction selection with on-demand tree-parsing automata". In: *PLDI* 41.6 (2006), pp. 52–60.

# Tree Covering

- + Efficient: linear time to find local optimum
- + Better code than pure macro expansion
- + Applicable to many ISAs
- Common sub-expressions cannot be represented
  - ▶ Need either edge split (prevents using complex instructions) or node duplication (redundant computation  $\Rightarrow$  inefficient code)
- Cannot make use of multi-output instructions (e.g., `divmod`)

# DAG Covering

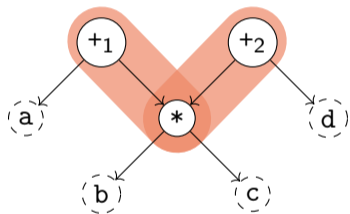
- ▶ Idea: lift restriction of trees, operate on data flow DAG
  - ▶ Reminder: an SSA basic block already forms a DAG
- ▶ Trivial approach: split into trees ☹
- ▶ Least-cost covering is  $\mathcal{NP}$ -complete<sup>31</sup>

<sup>31</sup>DR Koes and SC Goldstein. "Near-optimal instruction selection on DAGs". In: *CGO*. 2008, pp. 45–54. .

# DAG Covering: Adapting Dynamic Programming I<sup>32</sup>

- ▶ Step 1: compute cost matrix, bottom-up for all nodes
    - ▶ As before; make sure to visit each node once
  - ▶ Step 2: iterate over DAG top-down
    - ▶ Respect that multiple roots exist: start from all roots
    - ▶ Mark visited node/non-terminal combinations: avoid redundant emit
- + Linear time
- Generally not optimal, only for specific grammars

# DAG Covering: Adapting Dynamic Programming I – Example



Total cost: 6

madd %1, %b, %c, %a

madd %2, %b, %c, %d

Optimal cost: 5  $\rightsquigarrow$  non-optimal result

		Node	+ <sub>2</sub>	+ <sub>1</sub>	*
GP	Cost		3	3	3
	Pattern		$P_9$	$P_9$	$P_8$

## DAG Covering: Adapting Dynamic Programming II<sup>33</sup>

- ▶ Step 1: compute cost matrix, bottom-up (as before)
  - ▶ Step 2: iterate over DAG top-down (as before)
  - ▶ Step 3: identify overlaps and check whether split is beneficial
    - ▶ Mark nodes which should not be duplicated as *fixed*
  - ▶ Step 4: as step 1, but skip patterns that *include* fixed nodes
  - ▶ Step 5: as step 2
- + Probably fast? “Near-optimal”?
- Generally not optimal, superlinear time



## DAG Covering: ILP<sup>34</sup>

- ▶ Idea: model ISel as integer linear programming (ILP) problem
- ▶  $P$  is set of patterns with cost and edges,  $V$  are DAG nodes
- ▶ Variables:  $M_{p,v}$  is 1 iff a pattern  $p$  is rooted at  $v$

$$\begin{aligned} & \text{minimize} && \sum_{p,v} p.\text{cost} \cdot M_{p,v} \\ & \text{subject to} && \forall r \in \text{roots}. \sum_p M_{p,r} \geq 1 \\ & && \forall p, v, e \in p.\text{edges}(v). M_{p,v} - \sum_{p'} M_{p',e} \leq 0 \\ & && M_{p,v} \in \{0, 1\} \end{aligned}$$

Minimize cost for all matched patterns s.t. every root has a match and every input of a match has a match.

- + Optimal result
- Practicability beyond small programs questionable (at best)

<sup>34</sup>DR Koes and SC Goldstein. "Near-optimal instruction selection on DAGs". In: CGO. 2008, pp. 45–54. 

# DAG Covering: Greedy/Maximal Munch

- ▶ Top-down, start at roots, always take largest pattern
  - ▶ Repeat for remaining roots until whole graph is covered
- + Easy to implement, reasonably fast
- Result often non-optimal
- ▶ Used by: LLVM SelectionDAG

# Graph Covering

- ▶ Idea: lift limitation of DAGs, cover entire function graphs
- ▶ Better handling of predication and VLIW bundling
  - ▶ E.g., hoisting instructions from a conditional block
- ▶ Allows to handle instructions that expand to multiple blocks
  - ▶ `switch`, `select`, etc.
- ▶ May need new IR to model control flow in addition to data flow
- ▶ In practice: only used by adapting methods showed for DAGs
- ▶ Used by: Java HotSpot Server, LLVM GlobalSel (all tree-covering)

# Flawed Assumptions

- ▶ Cost model is fundamentally flawed
- ⇒ “Optimal” ISel doesn’t really mean anything
- ▶ Out-of-order execution: costs are not linear
  - ▶ Instructions executed in parallel, might execute for free
  - ▶ Possible contention of functional units
- ▶ Register allocator will modify instructions
- ▶ “Bad” instructions boundaries increase register requirements
  - ▶ More stack spilling  $\rightsquigarrow$  much slower code!

# LLVM Back-end: Overview

- ▶ LLVM-IR → Machine IR: instruction selection + scheduling
  - ▶ MIR is SSA-representation of target instructions
  - ▶ Selectors: SelectionDAG, FastISel, GlobalISel
  - ▶ Also selects register bank (GP/FP/...) – required for instruction
  - ▶ Annotates registers: calling convention, encoding restrictions, etc.
- ▶ MIR: minor (peephole) optimizations
- ▶ MIR: register allocation
- ▶ MIR: prolog/epilog insertion (stack frame, callee-saved regs, etc.)
- ▶ MIR → MC: translation to machine code

# LLVM MIR Example

```
define i64 @fn(i64 %a,i64 %b,i64 %c) {  
  %shl = shl i64 %c, 2  
  %mul = mul i64 %a, %b  
  %add = add i64 %mul, %shl  
  ret i64 %add  
}
```

```
# YAML with name, registers, frame info  
body: |  
  bb.0 (%ir-block.0):  
    liveins: $x0, $x1, $x2  
  
    %2:gpr64 = COPY $x2  
    %1:gpr64 = COPY $x1  
    %0:gpr64 = COPY $x0  
    %3:gpr64 = MADDXrrr %0, %1, $xzr  
    %4:gpr64 = ADDXrs killed %3, %2, 2  
    $x0 = COPY %4  
    RET_ReallyLR implicit $x0
```

```
llc -march=aarch64 -stop-after=finalize-isel
```

# LLVM: Instruction Selectors

## FastISel

- ▶ Uses macro expansion
- ▶ Low compile-time
- ▶ Code quality poor
  
- ▶ Only common cases
- ▶ Otherwise: fallback to SelectionDAG
  
- ▶ Default for -O0

## SelectionDAG

- ▶ Converts each block into separate DAGs
- ▶ Greedy tree matching
- ▶ Slow, but good code
  
- ▶ Handles all cases
- ▶ No cross-block opt. (done in DAG building)
  
- ▶ Default

## GlobalISel

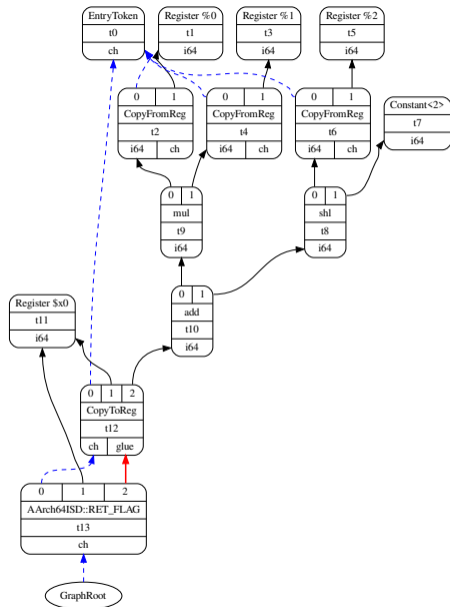
- ▶ Conv. to generic-MIR then legalize to MIR
- ▶ Reuses SD patterns
- ▶ Faster than SelDAG
  
- ▶ Few architectures
- ▶ Handles many cases, SelDAG-fallback

# LLVM SelectionDAG: IR to ISelDAG

- ▶ Construct DAG for basic block
  - ▶ EntryToken as ordering chain
- ▶ Legalize data types
  - ▶ Integers: promote or expand into multiple
  - ▶ Vectors: widen or split (or scalarize)
- ▶ Legalize operations
  - ▶ E.g., conditional move, etc.
- ▶ Optimize DAG, e.g. some pattern matching, removing unneeded sign/zero extensions

`llc -march=aarch64 -view-isel-dags`

Note: needs LLVM debug build



isel input for fn:

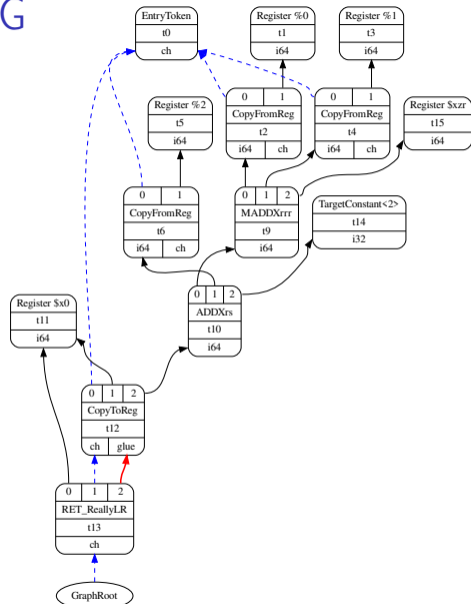


# LLVM SelectionDAG: ISelDAG to DAG

- ▶ Mainly pattern matching
- ▶ Simple patterns specified in TableGen
  - ▶ Matching/selection compiled into bytecode
  - ▶ SelectionDAGISel::SelectCodeCommon()
- ▶ Complex selections done in C++
- ▶ Scheduling: linearization of graph

llc -march=aarch64 -view-sched-dags

Note: needs LLVM debug build



scheduler input for fn:

# Instruction Selection – Summary

- ▶ Instruction Selection: transform generic into arch-specific instructions
- ▶ Often focus on optimizing tiling costs
- ▶ Target instructions often more complex, e.g., multi-result
  
- ▶ Macro Expansion: simple, fast, but inefficient code
- ▶ Peephole optimization on sequences/trees to optimize
- ▶ Tree Covering: allows for better tiling of instructions
- ▶ DAG Covering: support for multi-res instrs., but  $\mathcal{NP}$ -complete
- ▶ Graph Covering: mightiest, but also most complex, rarely used

## Instruction Selection – Questions

- ▶ What is the (nowadays typical) input and output IR for ISel?
- ▶ Why is good instruction selection important for performance?
- ▶ Why is peephole optimization beneficial for nearly all ISel approaches?
- ▶ How can peephole opt. be done more effectively than on neighboring instrs.?
- ▶ What are options to transform an SSA-IR into data flow trees?
- ▶ Why is a greedy strategy not optimal for tree pattern matching?
- ▶ When is DAG covering beneficial over tree covering?
- ▶ Which ISel strategies does LLVM implement? Why?