Code Generation for Data Processing

Lecture 7: Instruction Selection

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Code Generation – Overview

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  - Map IR to assembly
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- Instruction Scheduling
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  - Keep operations, may increases 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]
```

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- Target offers multiple ways to implement operations
  - `imul x, 2`, `add x, x`, `shl x, 1`, `lea x, [x+x]`

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- 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., no program with better "performance" exists
  - Performance ≈ instructions associated with specific costs

[24] DR Koes and SC Goldstein. "Near-optimal instruction selection on DAGs". In: *CGO*. 2008, pp. 45–54.

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Optimal ISel

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  - I.e., no program with better "performance" exists
  - Performance $\approx$ instructions associated with specific costs
- Problem: optimal code generation is **undecidable**
- Alternative: optimal *tiling* of IR with machine code instructions
  - IR as dataflow graph, instr. tiles to optimally cover graph
  - $\mathcal{NP}$-complete[24]
  - Additional complication: many different ways to express same computation

[24] DR Koes and SC Goldstein. "Near-optimal instruction selection on DAGs". In: *CGO*. 2008, pp. 45–54. 🌐.

Avoiding ISel Altogether

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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

`%5 = add %1, 12345`	$\longrightarrow$	`%5a = movz 12345` `%5 = add %1, %5a`
`%6 = and %2, 7`	$\longrightarrow$	`%6 = and %2, 7`

`%7 = shl %5, %6`	$\longrightarrow$	`%7a = lsl %5, %6`
		`%7b = cmp %6, 64`
		`%7 = csel %7a, xzr, %7b, lo`

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– 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[25]

- Originally: physical window over assembly code
  - Replace with more efficient instructions having same effects
  - Possibly with allocated registers

- Extension: do expansion before register allocation[26]
  - Expand IR into Register Transfer Lists (RTL) with temporary registers
  - While *combining*, ensure that each RTL can be implemented as single instr.

[25] WM McKeeman. "Peephole optimization". In: *CACM* 8.7 (1965), pp. 443–444. 🌐.

[26] 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.
    $\Rightarrow$ Tree-pattern matching

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- Widely used today at different points during compilation

ISel as Graph Covering – High-level Intuition

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- 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)*

ISel as Graph Covering – High-level Intuition

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- 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
  - For non-global ISel: values used outside of block must be generated

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

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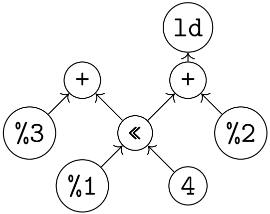
- Data flow graph:



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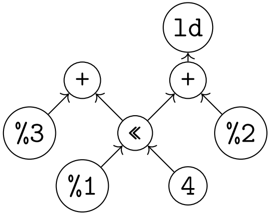
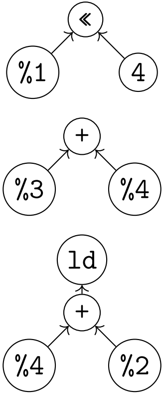


- Method 1:
  Edge Splitting



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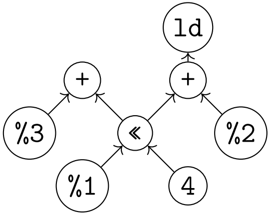

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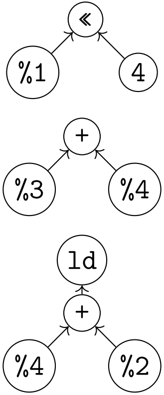
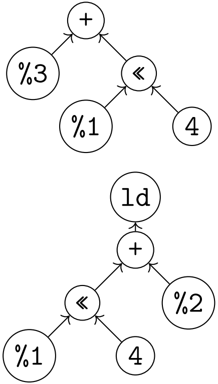


- Method 2:
  Node Duplication



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	$GP_{R1} \rightarrow +(GP_{R2}, \ll(GP_{R3}, K_1))$	2	`add` R_1, R_2, R_3, `lsl` #K_1
P_3	$GP_{R1} \rightarrow +(\ll(GP_{R2}, K_1), GP_{R2})$	2	`add` R_1, R_3, R_2, `lsl` #K_1
P_4	$GP_{R1} \rightarrow \texttt{ld}(GP_{R2})$	2	`ldr` R_1, [R_2]
P_5	$GP_{R1} \rightarrow \texttt{ld}(+(GP_{R2}, GP_{R3}))$	2	`ldr` R_1, [R_2, R_3]
P_6	$GP_{R1} \rightarrow \texttt{ld}(+(GP_{R2}, \ll(GP_{R3}, K_1)))$	3	`ldr` R_1, [R_2, R_3, `lsl` #K_1]
P_7	$GP_{R1} \rightarrow \texttt{ld}(+(\ll(GP_{R2}, K_1), GP_{R3})$	3	`ldr` R_1, [R_3, R_2, `lsl` #K_1]
P_8	$GP_{R1} \rightarrow *(GP_{R2}, GP_{R3})$	3	`madd` R_1, R_2, R_3, `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
⋮	⋮	⋮	⋮

Tree Covering: Greedy/Maximal Munch

- Top-down always take largest pattern
- Repeat for sub-trees, until everything is covered

\+ Easy to implement, fast

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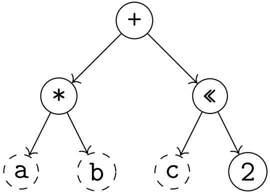
– Result might be non-optimum

Tree Covering: Greedy/Maximal Munch – Example



Matching Patterns:

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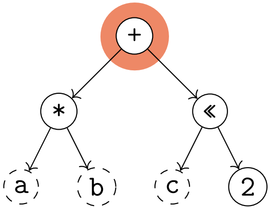

Matching Patterns:

- +: P_1 – cost 1 – covered nodes: 1

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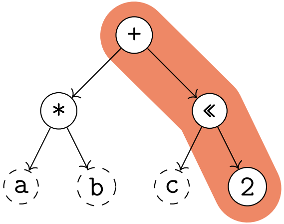

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- +: P_2 – cost 2 – covered nodes: 3

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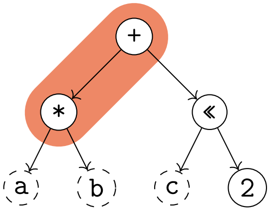

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- +: P_9 – cost 3 – covered nodes: 2

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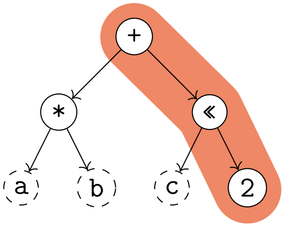

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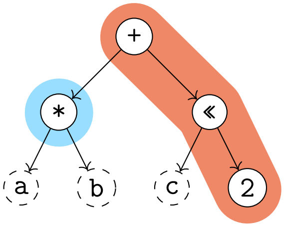

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- ∗: P_8 – cost 3 – covered nodes: 1

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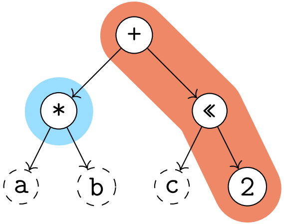

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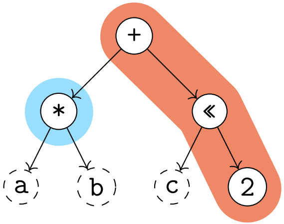

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Total cost: 5

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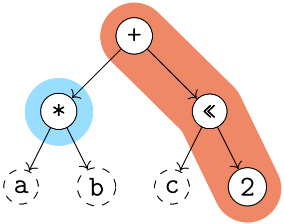

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Total cost: 5

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

Tree Covering: with LR-Parsing?

- Can we use (LR-)parsing for instruction selection?

[27] RS Glanville and SL Graham. "A new method for compiler code generation". In: *POPL*. 1978, pp. 231–254.

Tree Covering: with LR-Parsing

- Can we use (LR-)parsing for instruction selection? Yes![27]
  - Pattern set = grammar; IR (in prefix notation) = input

Advantages

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Advantages

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

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Advantages

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- 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

[27] RS Glanville and SL Graham. "A new method for compiler code generation". In: *POPL*. 1978, pp. 231–254.

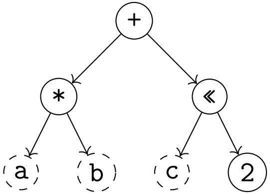
Tree Covering: Dynamic Programming[28]

- Step 1: compute cost matrix, bottom-up for all nodes
  - Matrix: tree node $\times$ register bank
    (different patterns might yield the same result in different register banks)
  - 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, follow rules in matrix

- Time linear w.r.t. tree size

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

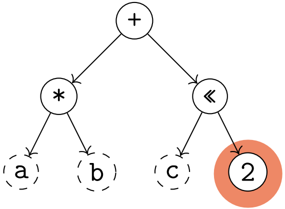
Tree Covering: Dynamic Programming – Example



Node: 2
Pattern:
Pat. Cost:
Cost Sum:

	Node	+	*	«	2
GP	Cost	∞	∞	∞	∞
	Pattern				

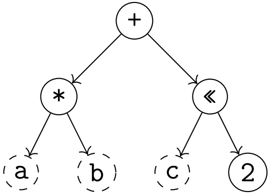
Tree Covering: Dynamic Programming – Example



Node: 2
Pattern: P_{10}: $GP \rightarrow K_1$
Pat. Cost: 1
Cost Sum: 1

		Node	+	*	«	2
GP	Cost		∞	∞	∞	1
	Pattern					P_{10}

Tree Covering: Dynamic Programming – Example



Node: «
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	Node	+	*	«	2
GP	Cost	∞	∞	∞	1
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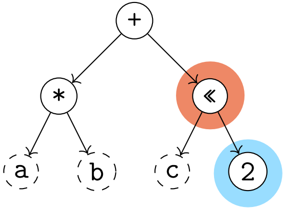

Node:	«
Pattern:	$P_?$: $GP \to «(GP, GP)$
Pat. Cost:	1
Cost Sum:	2

	Node	+	*	«	2
GP	Cost	∞	∞	2	1
	Pattern			$P_?$	P_{10}

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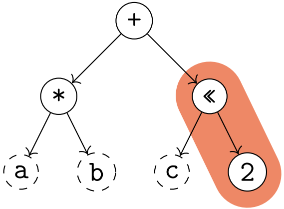

Node: «
Pattern: P_0: $GP \to «(GP, K_1)$
Pat. Cost: 1
Cost Sum: 1

		Node	+	*	«	2
GP	Cost		∞	∞	1	1
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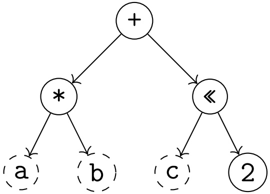

Node: $*$
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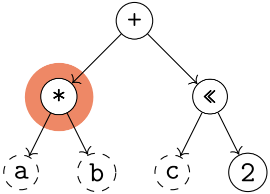
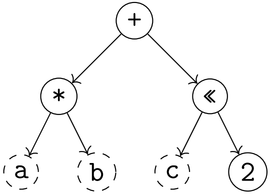


Node: $*$
Pattern: P_8: $GP \to *(GP, GP)$
Pat. Cost: 3
Cost Sum: 3

		Node	+	*	«	2
GP	Cost		∞	3	1	1
	Pattern			P_8	P_0	P_{10}

Tree Covering: Dynamic Programming – Example



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Pattern:
Pat. Cost:
Cost Sum:

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GP	Cost		∞	3	1	1
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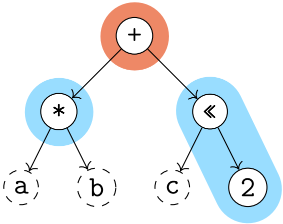
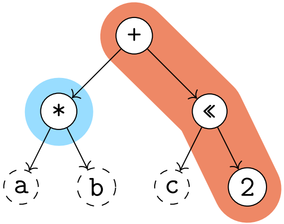


Node: +
Pattern: P_1: $GP \rightarrow +(GP, GP)$
Pat. Cost: 1
Cost Sum: 5

	Node	+	*	«	2
GP	Cost	5	3	1	1
	Pattern	P_1	P_8	P_0	P_{10}

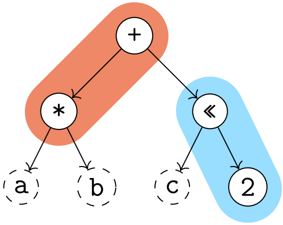
Tree Covering: Dynamic Programming – Example



Node: +
Pattern: P_2: $GP \rightarrow +(GP, \ll(GP, K_1)$
Pat. Cost: 2
Cost Sum: 5

	Node	+	*	«	2
GP	Cost	5	3	1	1
	Pattern	P_1	P_8	P_0	P_{10}

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_0	P_{10}

Tree Covering: Dynamic Programming – Off-line Analysis

- Cost analysis can actually be *precomputed*[29]

- Idea: annotate each node with a state based on child states
- Lookup node label from precomputed table (one per register bank)

- Significantly improves compilation time
- But: Tables can be large, need to cover all possible (sub-)trees

- Variation: dynamically compute and cache state tables[30]

[29] 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.

[30] 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

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+ Efficient: linear time to find local optimum
+ Better code than pure macro expansion
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+ Applicable to many ISAs

– Common sub-expressions cannot be represented
  - Need either edge split (prevents using complex instructions) or node duplication (redundant computation ⇒ 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 ☹

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

DAG Covering

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  - Reminder: an SSA basic block already forms a DAG
- Trivial approach: split into trees ☹
- Least-cost covering is $\mathcal{NP}$-complete[31]

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

DAG Covering: Adapting Dynamic Programming I[32]

- 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/regbank combinations: avoid redundant emit

[32] MA Ertl. "Optimal code selection in DAGs". In: *POPL*. 1999, pp. 242–249.

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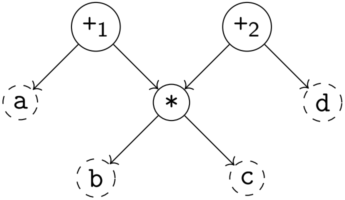
  - Mark visited node/regbank combinations: avoid redundant emit

\+ Linear time

– Generally not optimal, only for specific grammars

[32] MA Ertl. "Optimal code selection in DAGs". In: *POPL*. 1999, pp. 242–249. .

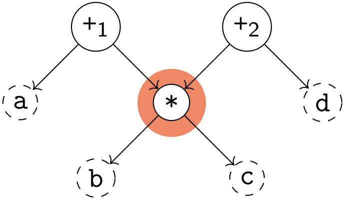
DAG Covering: Adapting Dynamic Programming I – Example



Node: *
Pattern:
Pat. Cost:
Cost Sum:

		Node	$+_2$	$+_1$	*
GP	Cost		∞	∞	∞
	Pattern				

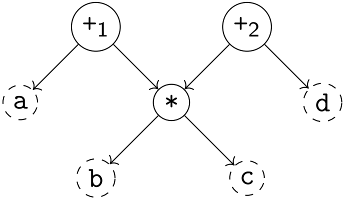
DAG Covering: Adapting Dynamic Programming I – Example



Node: $*$
Pattern: P_8: $GP \rightarrow *(GP,\ GP)$
Pat. Cost: 3
Cost Sum: 3

		Node	$+_2$	$+_1$	$*$
GP	Cost		∞	∞	3
	Pattern				P_8

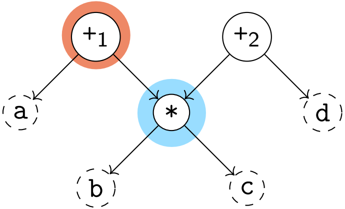
DAG Covering: Adapting Dynamic Programming I – Example



Node: $+_1$
Pattern:
Pat. Cost:
Cost Sum:

		$+_2$	$+_1$	$*$
	Node	$+_2$	$+_1$	$*$
GP	Cost	∞	∞	3
	Pattern			P_8

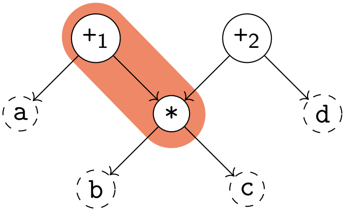
DAG Covering: Adapting Dynamic Programming I – Example



Node: $+_1$
Pattern: P_1: $GP \rightarrow +(GP, GP)$
Pat. Cost: 1
Cost Sum: 4

		Node	$+_2$	$+_1$	$*$
GP	Cost		∞	4	3
	Pattern			P_1	P_8

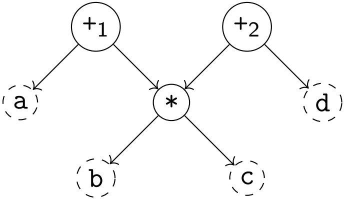
DAG Covering: Adapting Dynamic Programming I – Example



Node: $+_1$
Pattern: P_9: $GP \to +(*(GP, GP), GP)$
Pat. Cost: 3
Cost Sum: 3

		Node	$+_2$	$+_1$	$*$
GP	Cost		∞	3	3
	Pattern			P_9	P_8

DAG Covering: Adapting Dynamic Programming I – Example



Node: $+_2$
Pattern:
Pat. Cost:
Cost Sum:

		Node	$+_2$	$+_1$	$*$
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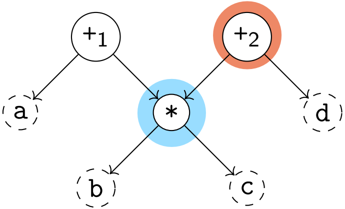

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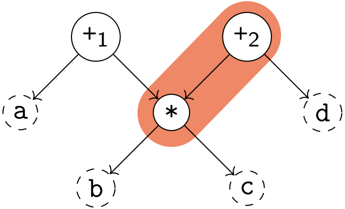

Node: $+_2$
Pattern: P_9: $GP \rightarrow +(*(GP, GP), GP)$
Pat. Cost: 3
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		Node	$+_2$	$+_1$	$*$
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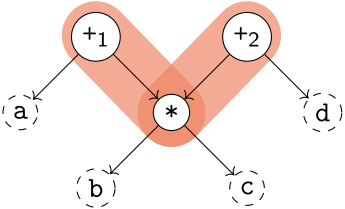

Total cost: 6

```
madd %1, %b, %c, %a
madd %2, %b, %c, %d
```

	Node	$+_2$	$+_1$	$*$
GP	Cost	3	3	3
	Pattern	P_9	P_9	P_8

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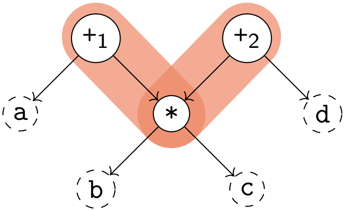

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madd %1, %b, %c, %a
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```

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

	Node	$+_2$	$+_1$	$*$
GP	Cost	3	3	3
	Pattern	P_9	P_9	P_8

DAG Covering: Adapting Dynamic Programming II[33]

- 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

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\+ Probably fast? "Near-optimal"?

– Generally not optimal, superlinear time

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DAG Covering: ILP[34]

- 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

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

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

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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)

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DAG Covering: Greedy/Maximal Munch

- Top-down, start at roots, always take largest pattern
- Repeat for remaining roots until whole graph is covered

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- 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
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  - `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 GlobalISel (all tree-covering)

Flawed Assumptions

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- Cost model is fundamentally flawed

⇒ "Optimal" ISel doesn't really mean anything

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$\Rightarrow$ "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!

Instruction Selection in Practice

- Most compilers use some form of greedy tree/DAG pattern matching
- Later stages use peephole optimizations
  - Basically also tree/DAG matching on machine operations
- Distinction between tree/DAG/graph matching somewhat artificial[35]

[35] My personal opinion.

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Problem in practice: implementing the huge amount of required patterns

- LLVM X86 back-end has 60k lines C++ for lowering + auto-generated patterns
- Needs lots of handling for corner cases, e.g. immediates
- Coming up with the patterns is often non-trivial

[35] My personal opinion.

LLVM Back-end: Overview

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- LLVM-IR $\rightarrow$ Machine IR: instruction selection + scheduling
  - MIR is SSA-representation of target instructions
  - Selectors: SelectionDAG, FastISel, GlobalISel
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- MIR $\rightarrow$ 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 MIR Example

Analyze the Machine IR of the following code. (Also consult the reference[37].)

- What is the difference between physical and virtual registers?
- What do `killed` and `implicit-def` mean?
- How do branches differ from branches in LLVM-IR?

```
// clang --target=aarch64 -c -mllvm -stop-after=finalize-isel -O1 -o -
int foo(int n) {
  int r = 1;
  while (n) { r *= n << n; n--; }
  return r;
}
```

Also try `-O0`, `-O2`, `-g`, and `-target=x86_64`.

[37] https://llvm.org/docs/MIRLangRef.html

LLVM: Instruction Selectors

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FastISel

- Uses macro expansion
- Low compile-time
- Code quality poor

- Only common cases
- Otherwise: fallback to SelectionDAG

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- Converts each block into separate DAGs
- Greedy tree matching
- Slow, but good code

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GlobalISel

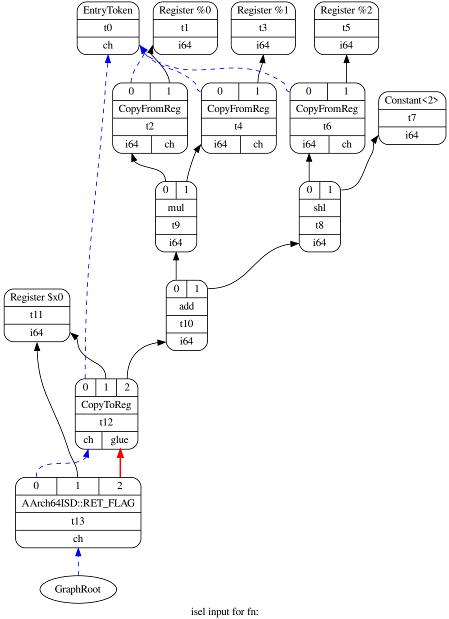
- Conv. to generic-MIR then legalize to MIR
- Reuses SD patterns
- Faster than SelDAG

- Few architectures
- Handles many cases, SelDAG-fallback

- Default AArch64 -O0

LLVM SelectionDAG: IR to ISelDAG

- Construct DAG for basic block
  - EntryToken as ordering chain



LLVM SelectionDAG: IR to ISelDAG

- Construct DAG for basic block
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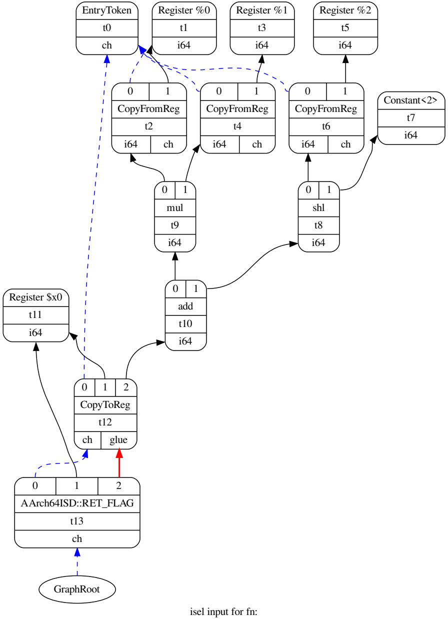
- Legalize data types
  - Integers: promote or expand into multiple
  - Vectors: widen or split (or scalarize)



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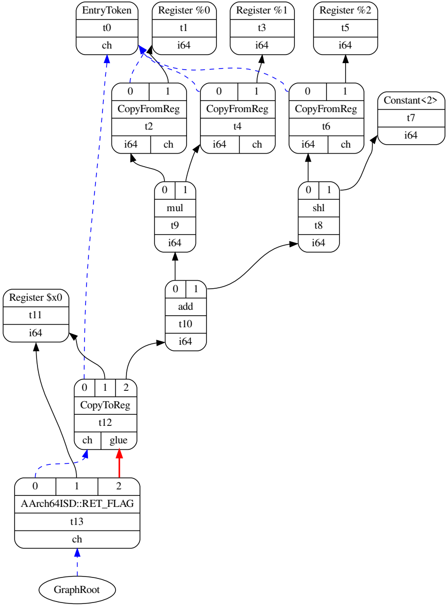

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- Construct DAG for basic block
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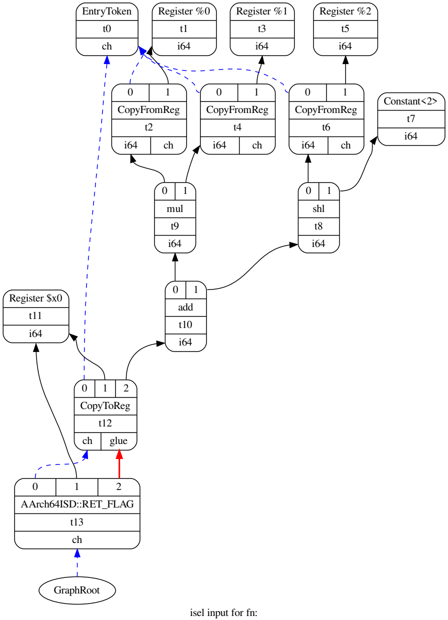
- Legalize data types
  - Integers: promote or expand into multiple
  - Vectors: widen or split (or scalarize)
- Legalize operations
  - E.g., conditional move, etc.
- Optimize DAG, e.g. some pattern matching,
  removing unneeded sign/zero extensions

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

Note: needs LLVM debug build

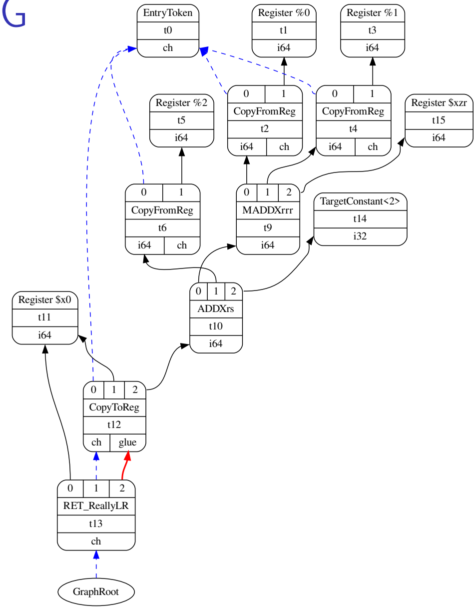


LLVM SelectionDAG: ISelDAG to DAG

- 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?