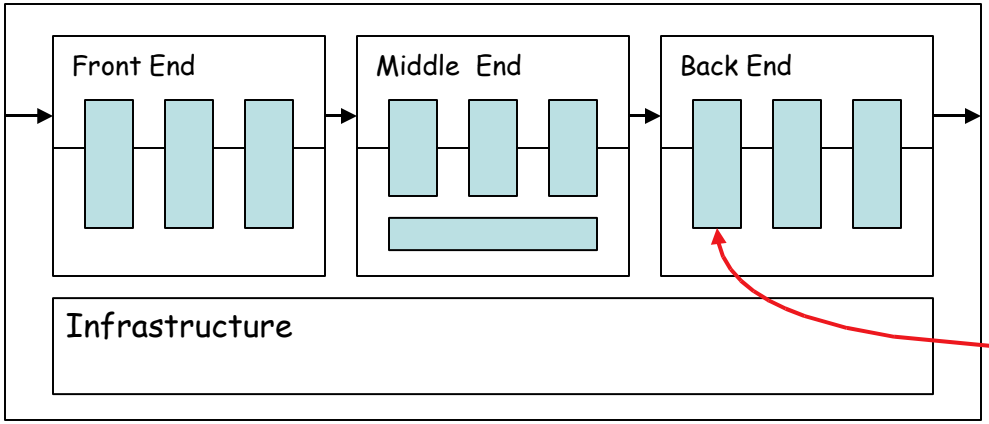
Instruction Selection

The Problem

Writing a compiler is a lot of work

- Would like to reuse components whenever possible
- Would like to automate construction of components



Today's lecture:

Automating Instruction Selection

- Front end construction is largely automated
- Middle is largely hand crafted
- (Parts of) back end can be automated

Definitions

Instruction selection

- Mapping *IR* into assembly code
- Assumes a fixed storage mapping & code shape
- Combining operations, using address modes

Instruction scheduling

- Reordering operations to hide latencies
- Assumes a fixed program *(set of operations)*
- Changes demand for registers

Register allocation

- Deciding which values will reside in registers
- Changes the storage mapping, may add false sharing
- Concerns about placement of data & memory operations

The Problem

Modern computers (still) have many ways to do anything

Consider register-to-register copy in ILOC

- Obvious operation is `i2i` $r_i \Rightarrow r_j$
- Many others exist

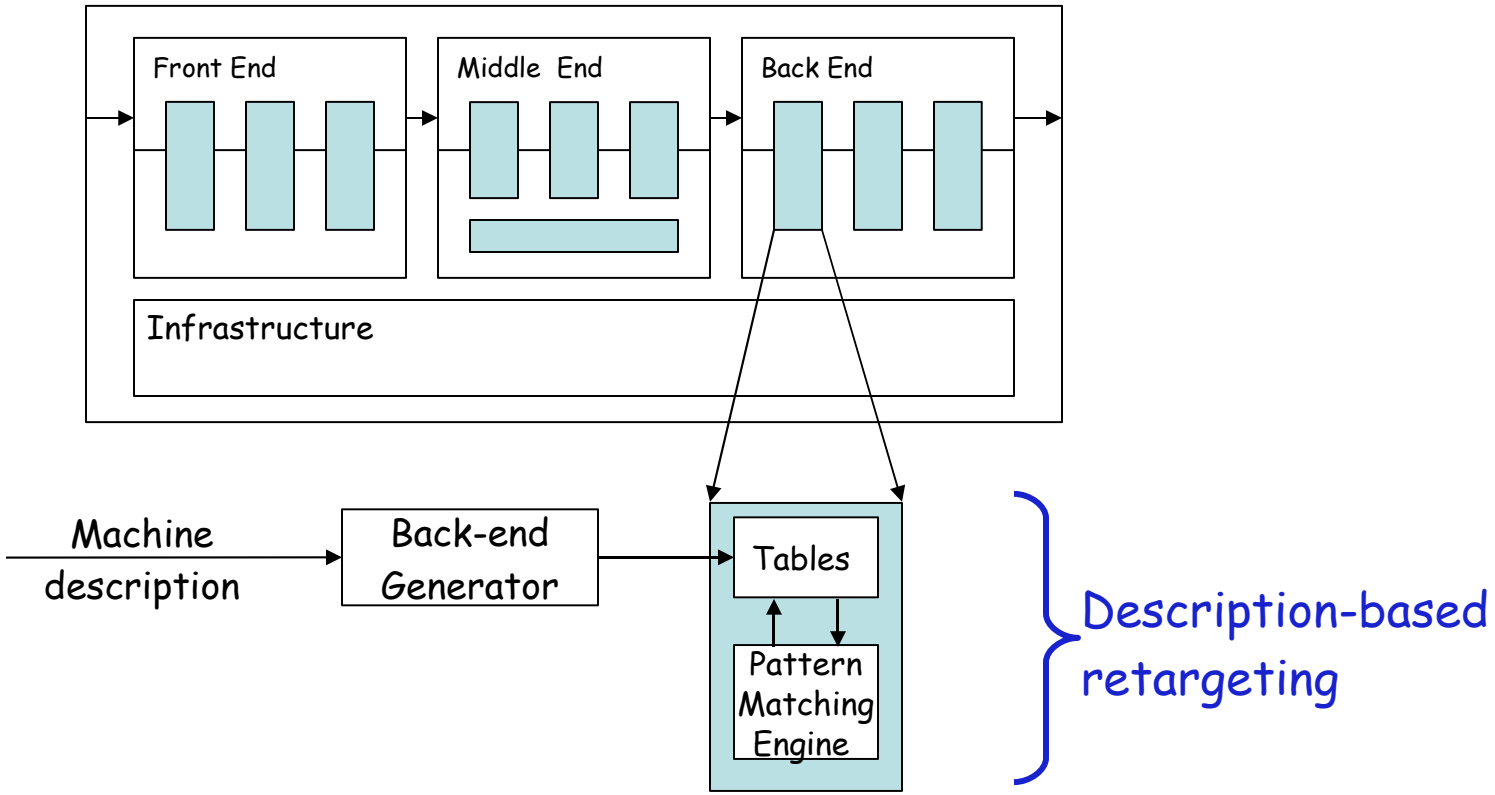
`addI` r_i,0 $\Rightarrow$ r_j	`subI` r_i,0 $\Rightarrow$ r_j	`lshiftI` r_i,0 $\Rightarrow$ r_j
`multI` r_i,1 $\Rightarrow$ r_j	`divI` r_i,1 $\Rightarrow$ r_j	`rshiftI` r_i,0 $\Rightarrow$ r_j
`orI` r_i,0 $\Rightarrow$ r_j	`xorI` r_i,0 $\Rightarrow$ r_j	… and others …

- Human would ignore all of these
- Algorithm must look at all of them & find low-cost encoding
  - → Take context into account (*busy functional unit?*)

And ILOC is an overly-simplified case

The Goal

Want to automate generation of instruction selectors



Machine description should also help with scheduling & allocation

The Big Picture

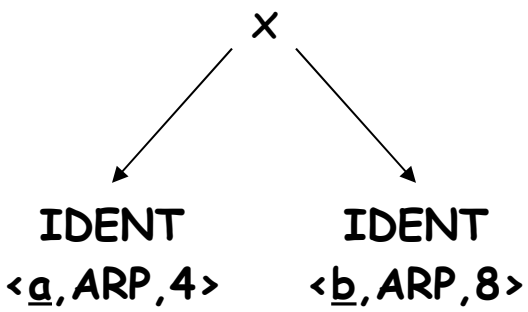
Need pattern matching techniques

- Must produce good code *(some metric for good)*
- Must run quickly

Our treewalk code generator ran quickly

How good was the code?

Tree



Treewalk Code

```
loadI    4      ⇒ r5
loadAO   r0,r5  ⇒ r6
loadI    8      ⇒ r7
loadAO   r0,r7  ⇒ r8
mult     r6,r8  ⇒ r9
```

Desired Code

```
loadAI   r0,4   ⇒ r5
loadAI   r0,8   ⇒ r6
mult     r5,r6  ⇒ r7
```

The Big Picture

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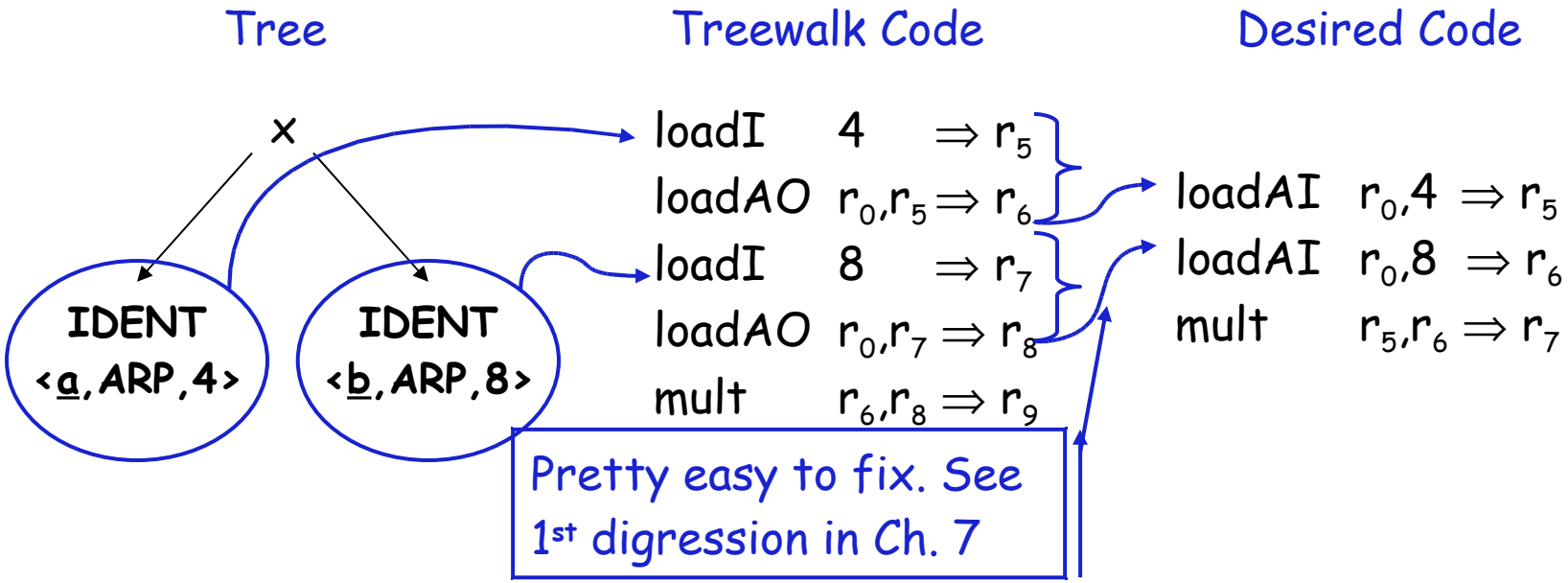
Our treewalk code generator (Lec. 24) ran quickly

How good was the code?



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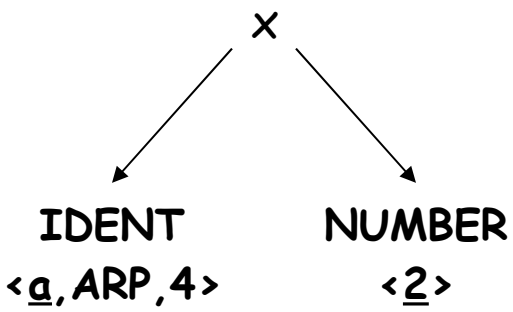

Treewalk Code

```
loadI   4      ⇒ r5
loadAO  r0,r5  ⇒ r6
loadI   2      ⇒ r7
mult    r6,r7  ⇒ r8
```

Desired Code

```
loadAI  r0,4   ⇒ r5
multI   r5,2   ⇒ r7
```

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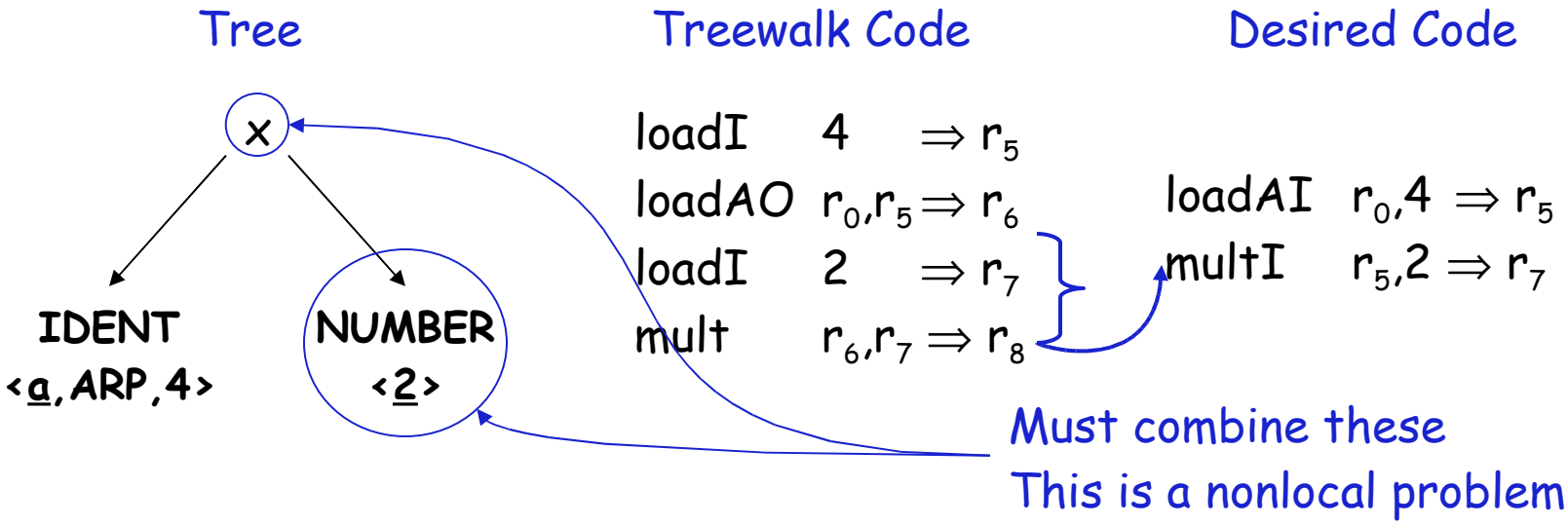

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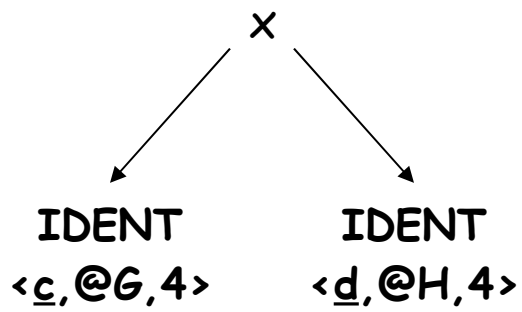


Treewalk Code

```
loadI   @G   ⇒ r5
loadI   4    ⇒ r6
loadAO  r5,r6 ⇒ r7
loadI   @H   ⇒ r7
loadI   4    ⇒ r8
loadAO  r8,r9 ⇒ r10
mult    r7,r10⇒ r11
```

Desired Code

```
loadI   4      ⇒ r5
loadAI  r5,@G  ⇒ r6
loadAI  r5,@H  ⇒ r7
mult    r6,r7  ⇒ r8
```

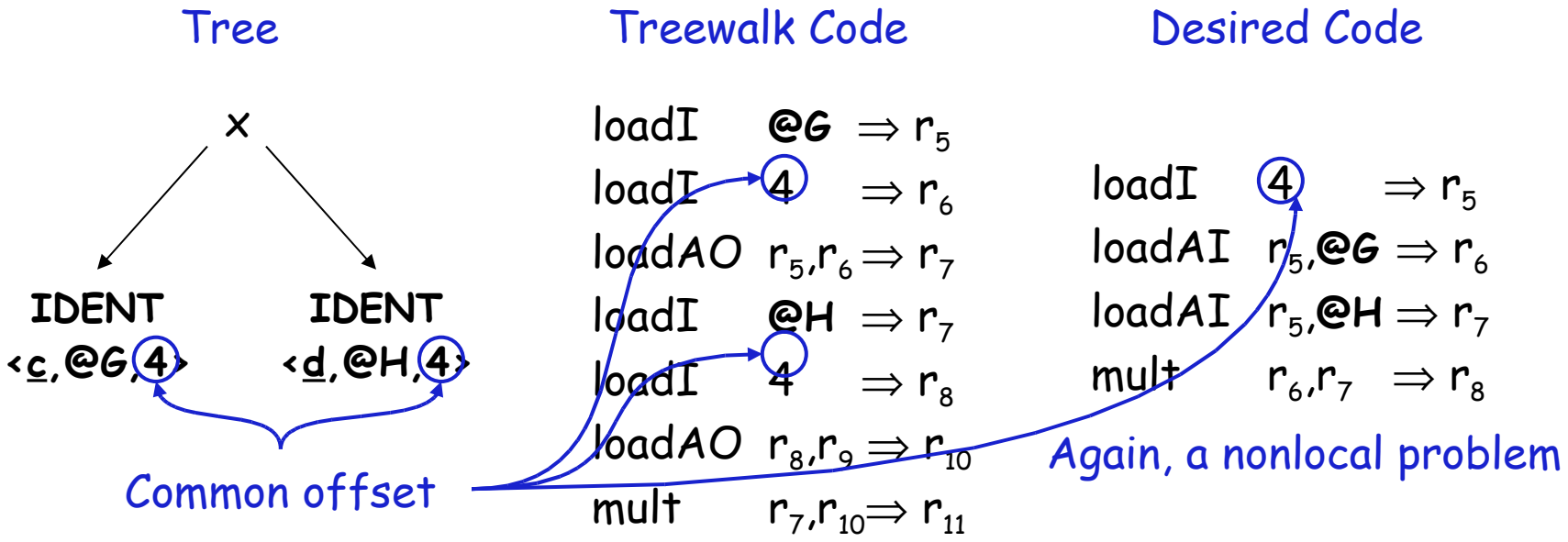
The Big Picture

Need pattern matching techniques

- Must produce good code *(some metric for good)*
- Must run quickly

Our treewalk code generator met the second criteria

How did it do on the first ?



How do we perform this kind of matching ?

Tree-oriented IR suggests pattern matching on trees

- Tree-patterns as input, matcher as output
- Each pattern maps to a target-machine instruction sequence
- Use dynamic programming or bottom-up rewrite systems

Linear IR suggests using some sort of string matching

- Strings as input, matcher as output
- Each string maps to a target-machine instruction sequence
- Use text matching (Aho-Corasick) or peephole matching

In practice, both work well; matchers are quite different

Peephole Matching

- Basic idea
- Compiler can discover local improvements locally
  - → Look at a small set of adjacent operations
  - → Move a "peephole" over code & search for improvement
- Classic example was store followed by load

Original code	Improved code
storeAI r_1 ⇒ r_0,8	storeAI r_1 ⇒ r_0,8
loadAI r_0,8 ⇒ r_{15}	i2i r_1 ⇒ r_{15}

Peephole Matching

- Basic idea
- Compiler can discover local improvements locally
  - → Look at a small set of adjacent operations
  - → Move a "peephole" over code & search for improvement
- Classic example was store followed by load
- Simple algebraic identities

Original code		Improved code	
addI	r_2,0 ⇒ r_7		
mult	r_4,r_7 ⇒ r_{10}	mult	r_4,r_2 ⇒ r_{10}

Peephole Matching

- Basic idea
- Compiler can discover local improvements locally
  - → Look at a small set of adjacent operations
  - → Move a "peephole" over code & search for improvement
- Classic example was store followed by load
- Simple algebraic identities
- Jump to a jump

Original code	Improved code
jumpI → L_{10} L_{10}: jumpI → L_{11}	L_{10}: jumpI → L_{11}

Peephole Matching

Implementing it

- Early systems used limited set of hand-coded patterns
- Window size ensured quick processing

Modern peephole instruction selectors (*Davidson*)

- Break problem into three tasks

- Apply symbolic interpretation & simplification systematically

Peephole Matching

Expander

- Turns IR code into a low-level IR (LLIR) such as RTL
- Operation-by-operation, template-driven rewriting
- LLIR form includes all direct effects (*e.g., setting cc*)
- Significant, albeit constant, expansion of size

Peephole Matching

Simplifier

- Looks at LLIR through window and rewrites is
- Uses forward substitution, algebraic simplification, local constant propagation, and dead-effect elimination
- Performs local optimization within window

- This is the heart of the peephole system
  - → Benefit of peephole optimization shows up in this step

Peephole Matching

Matcher

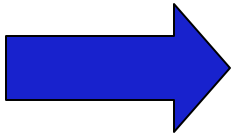
- Compares simplified LLIR against a library of patterns
- Picks low-cost pattern that captures effects
- Must preserve LLIR effects, may add new ones *(e.g., set cc)*
- Generates the assembly code output

Example

Original IR Code

OP	Arg_1	Arg_2	Result
mult	2	y	t_1
sub	x	t_1	w

Expand



LLIR Code

$r_{10} \leftarrow 2$

$r_{11} \leftarrow @y$

$r_{12} \leftarrow r_0 + r_{11}$

$r_{13} \leftarrow MEM(r_{12})$

$r_{14} \leftarrow r_{10} \times r_{13}$

$r_{15} \leftarrow @x$

$r_{16} \leftarrow r_0 + r_{15}$

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Example

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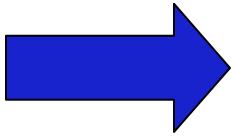
Simplify



LLIR Code

$r_{13} \leftarrow MEM(r_0 + @y)$

$r_{14} \leftarrow 2 \times r_{13}$

$r_{17} \leftarrow MEM(r_0 + @x)$

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Example

LLIR Code

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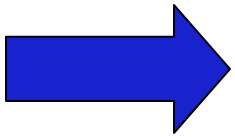
Match



ILOC Code

loadAI r_0,@y $\Rightarrow r_{13}$

multI $2 \times r_{13} \Rightarrow r_{14}$

loadAI r_0,@x $\Rightarrow r_{17}$

sub $r_{17} - r_{14} \Rightarrow r_{18}$

storeAI $r_{18} \Rightarrow r_0$,@w

- Introduced all memory operations & temporary names
- Turned out pretty good code

Steps of the Simplifier (*3-operation window*)

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1st op it has rolled out of window

$r_{13} \leftarrow MEM(r_0 + @y)$

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Example

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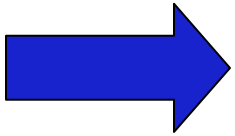
Simplify



LLIR Code

$r_{13} \leftarrow MEM(r_0 + @y)$

$r_{14} \leftarrow 2 \times r_{13}$

$r_{17} \leftarrow MEM(r_0 + @x)$

$r_{18} \leftarrow r_{17} - r_{14}$

$MEM(r_0 + @w) \leftarrow r_{18}$

Making It All Work

Details

- LLIR is largely machine independent (RTL)
- Target machine described as LLIR $\rightarrow$ ASM pattern
- Actual pattern matching
  - $\rightarrow$ Use a hand-coded pattern matcher (gcc)
  - $\rightarrow$ Turn patterns into grammar & use LR parser (VPO)
- Several important compilers use this technology
- It seems to produce good portable instruction selectors

Key strength appears to be late low-level optimization