Compiler Design

Lecture 18:
Instruction Selection via Peephole Matching

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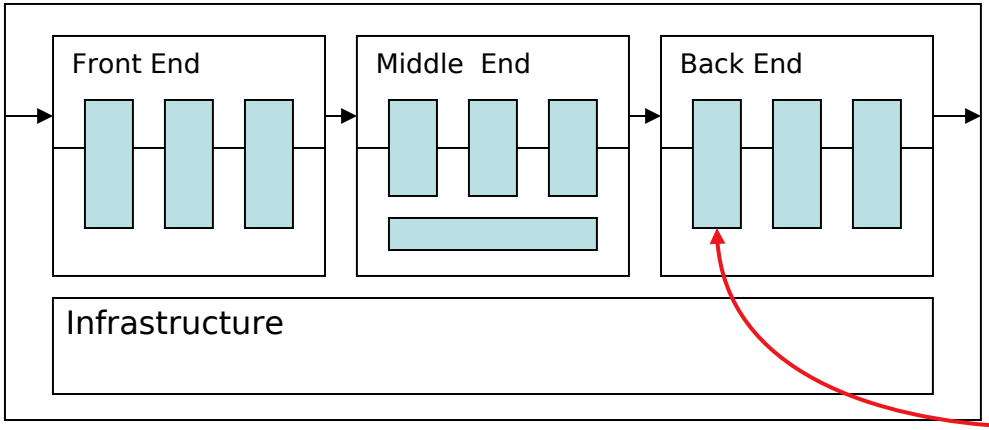
Winter 2023

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

- Process of mapping IR into assembly code
  - → Assumes a fixed storage mapping & code shape
  - → Combining operations, using address modes

Instruction scheduling

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

Register allocation

- Process of 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 have many ways to do anything

Consider register-to-register copy

- Obvious operation is `MOVE` $r_j \leftarrow r_i$
- Many others exist

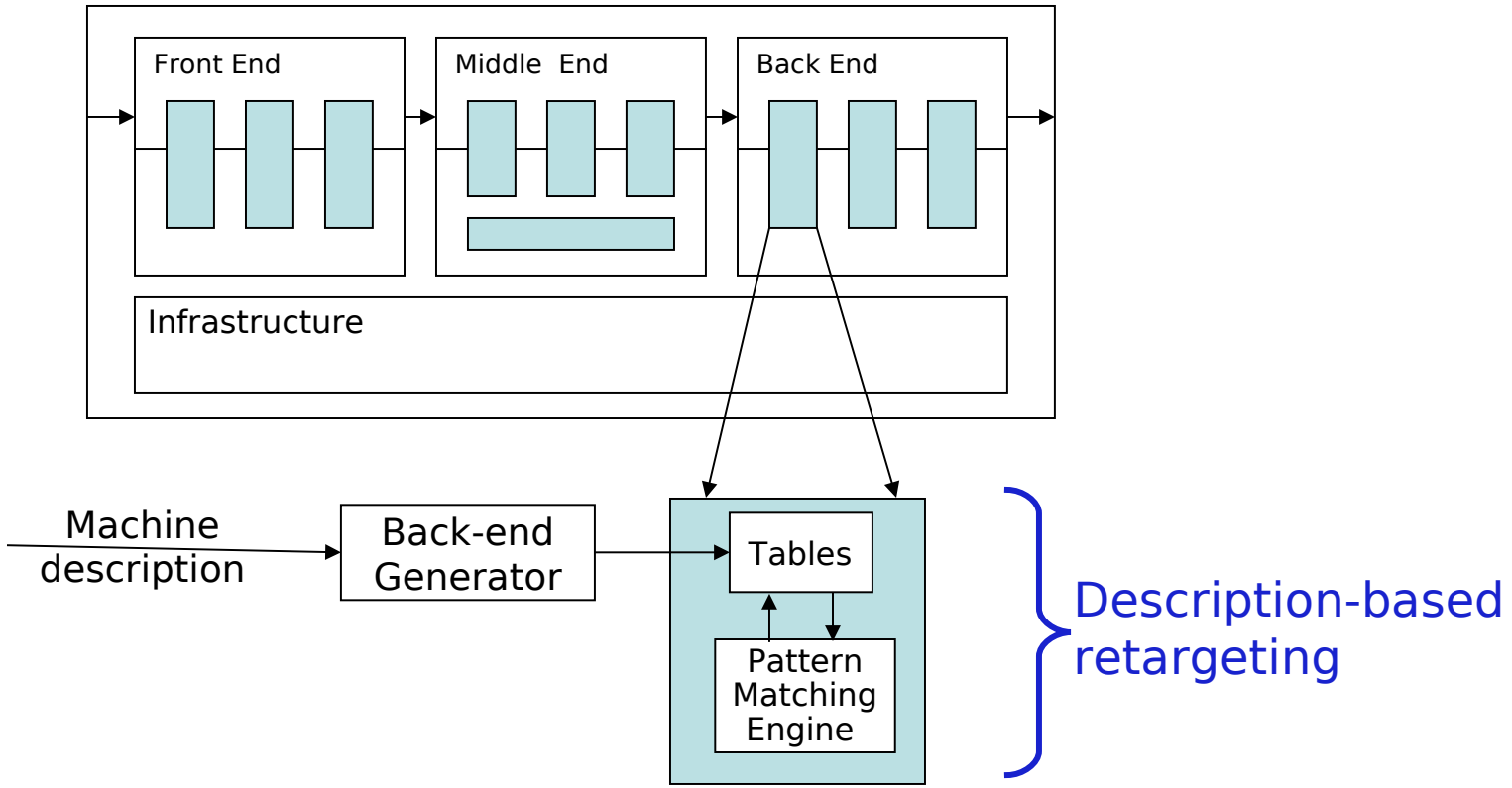
`ADDI` $r_j \leftarrow r_i, 0$	`OR` $r_j \leftarrow r_i, r_0$	`SLL` $r_j \leftarrow r_i, 0$
`ADD` $r_j \leftarrow r_i, r_0$	`MULI` $r_j \leftarrow r_i, 1$	`RSHIFTI` $r_j \leftarrow r_i, 0$
`ORI` $r_j \leftarrow r_i, 0$	`XORI` $r_j \leftarrow r_i, 0$	**… and others …**

- 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 this is an overly-simplified example

The Goal

Want to automate generation of instruction selectors



Machine description should also help with scheduling & allocation

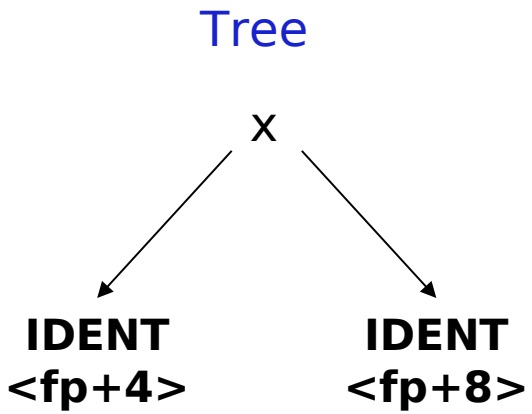
The Big Picture

Need pattern matching techniques

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

Our treewalk (visitor) code generator ran quickly

How good was the code?



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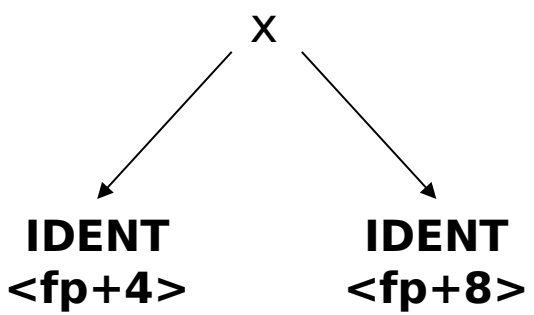

Treewalk Code

```
MOVE  r1 ← 4
ADD   r2 ← r1 , $fp
LW    r3 ← 0(r2)
MOVE  r4 ← 8
ADD   r5 ← r4 , $fp
LW    r6 ← 0(r5)
MUL   r7 ← r3, r6
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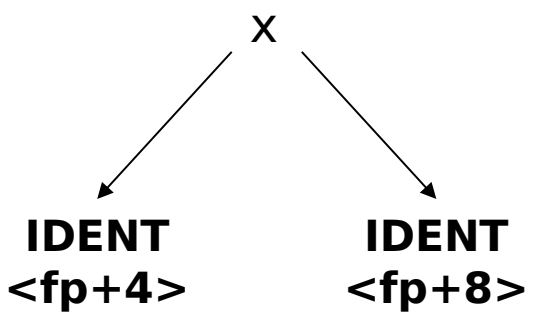

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Desired Code

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LW    r3 ← 4($fp)
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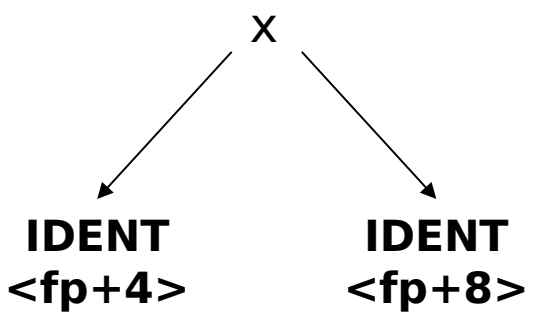

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Desired Code

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LW    r3 ← 4($fp)
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Okay wasn't too hard, could do it in the code generator

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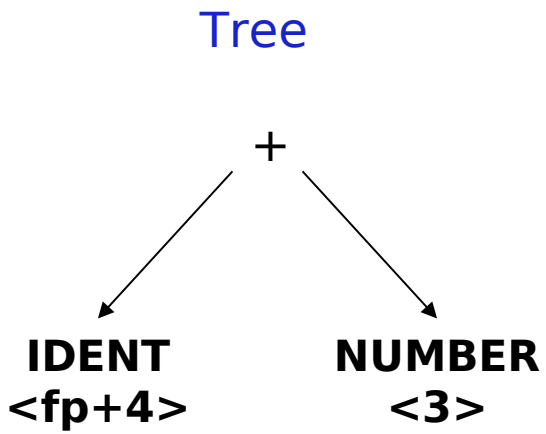

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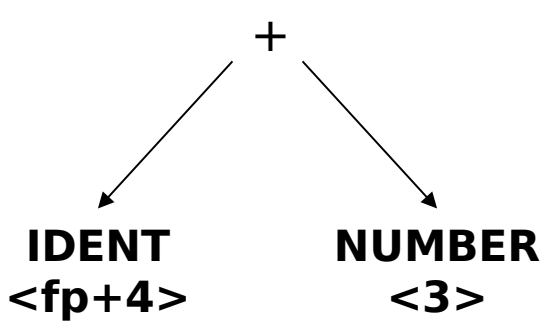

Treewalk Code

```
MOVE  r1 ← 4
ADD   r2 ← r1 , $fp
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MOVE  r4 ← 3
ADD   r5 ← r3 , r4
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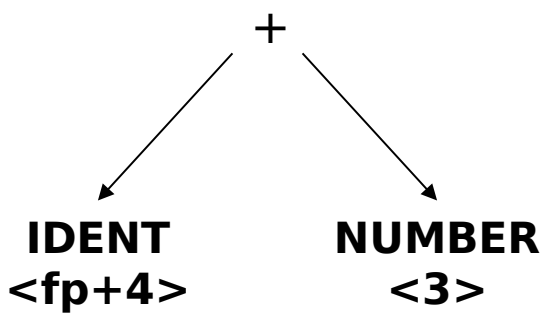

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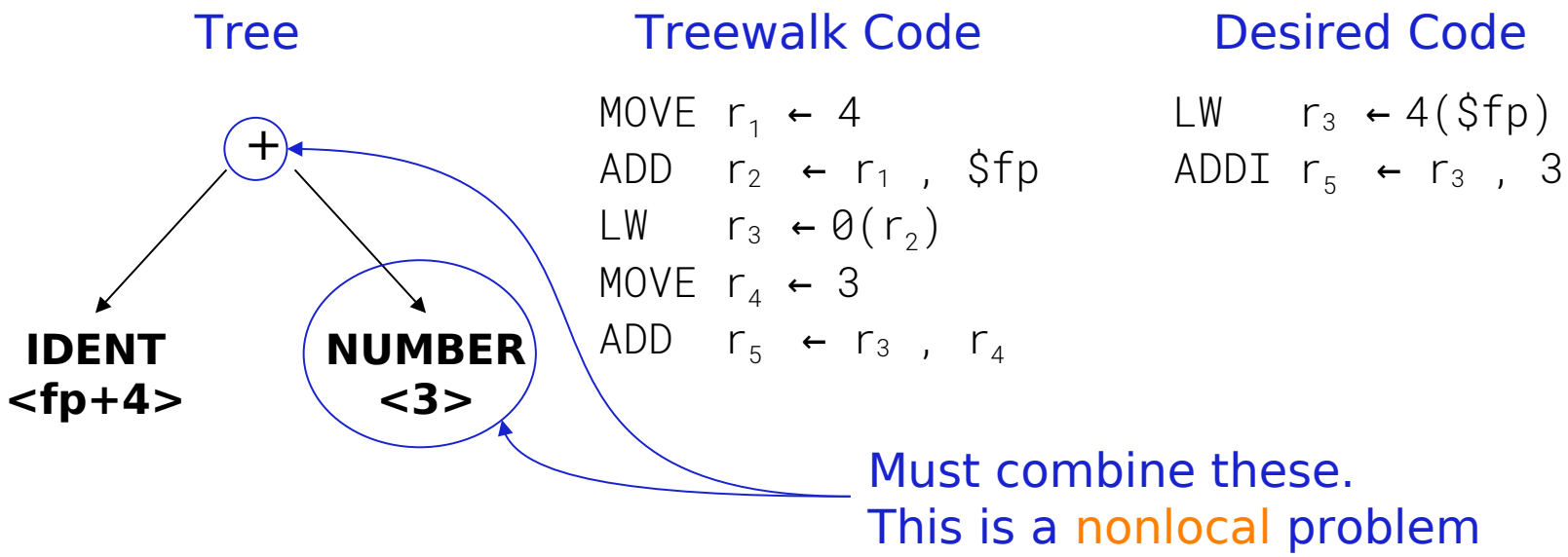

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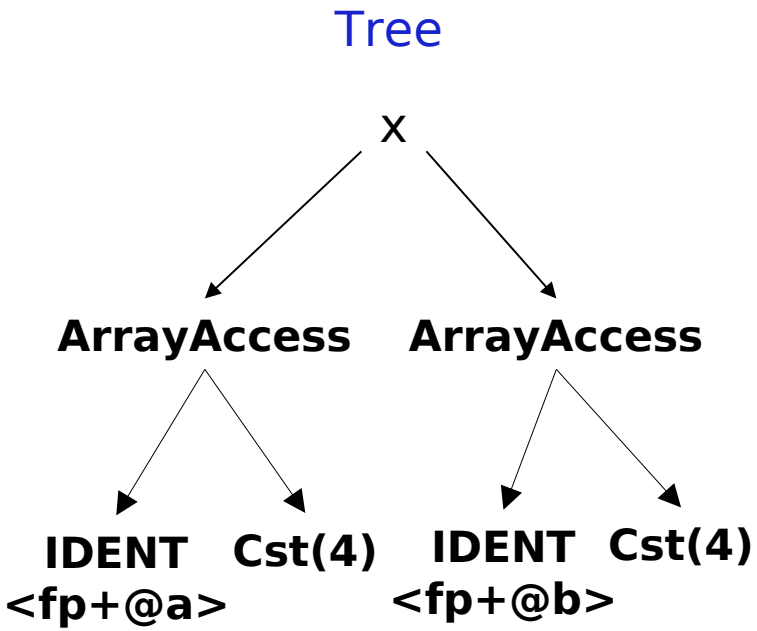

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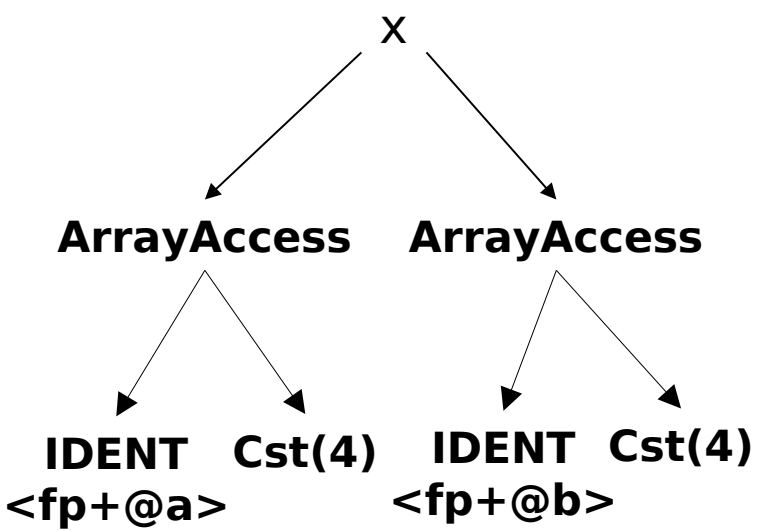

Treewalk Code

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MOVE  r2  ← @a
ADD   r3  ← $fp, r2
MOVE  r4  ← 4
ADD   r5  ← r3, r4
LW    r6  ← 0(r5)
MOVE  r8  ← @b
ADD   r9  ← $fp, r8
MOVE  r10 ← 4
ADD   r11 ← r9, r10
LW    r12 ← 0(r11)
MUL   r13 ← r6, r12
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The Big Picture

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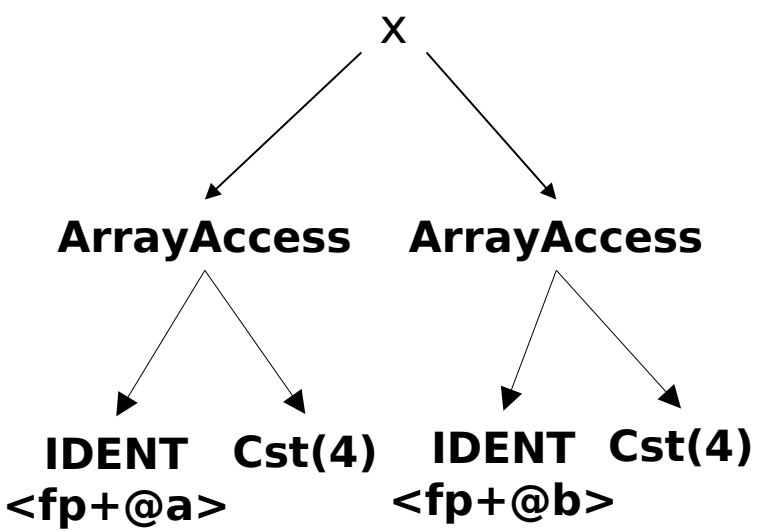

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Desired Code

```
ADDI  r3 ← $fp, 4
LW    r6 ← @a(r3)
LW    r12 ← @b(r3)
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The Big Picture

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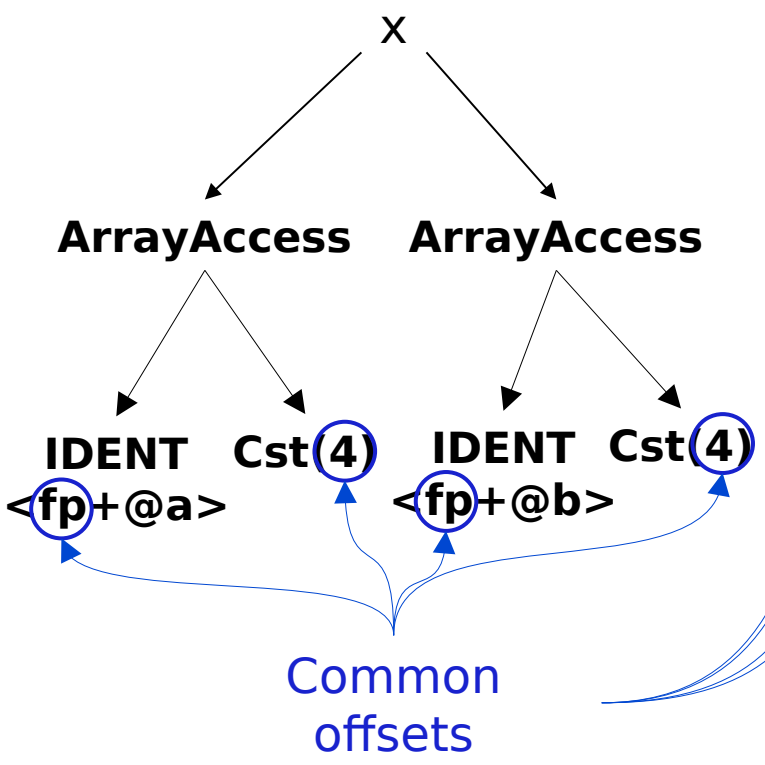

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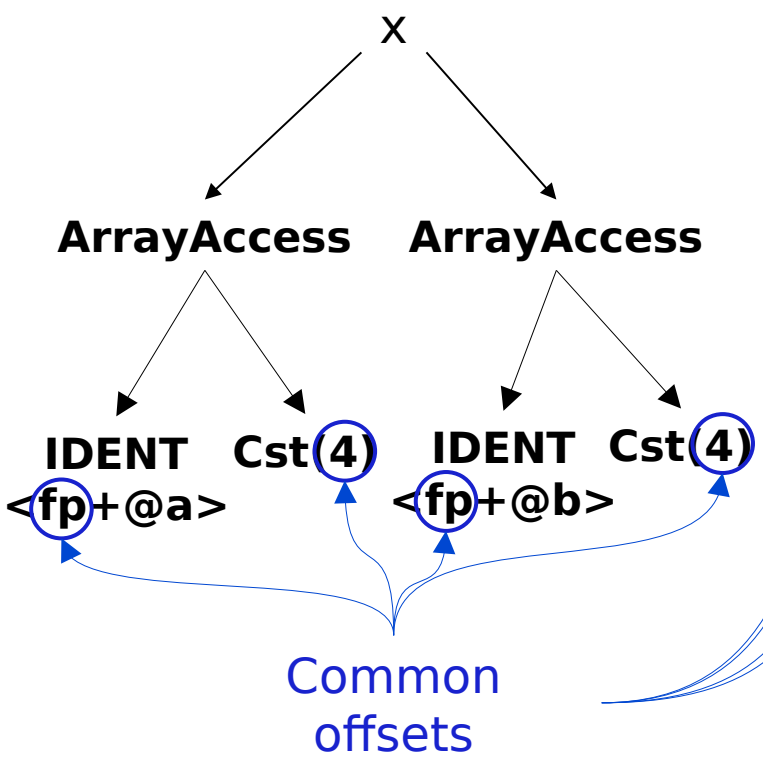

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ADD   r11 ← r9, r10
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```

Desired Code

```
ADDI  r3  ← $fp, 4
LW    r6  ← @a(r3)
LW    r12 ← @b(r3)
MUL   r13 ← r6, r12
```

($fp+@a)+4=($fp+4)+@a
($fp+@b)+4=($fp+4)+@b

Again, a nonlocal problem

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. Today we will look at matchers on Linear IR.

Peephole Matching

- Basic idea: Compiler can discover local improvements
  - → Look at a small set of adjacent operations
  - → Move a “peephole” over code & search for improvement

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  - → Look at a small set of adjacent operations
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- Classic examples:
  - → store followed by load

Original code	Improved code
SW $r_1 \rightarrow 0(r_2)$	SW $r_1 \rightarrow 0(r_2)$
LW $r_{15} \leftarrow 0(r_2)$	MOVE $r_{15} \leftarrow r_1$

Peephole Matching

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  - → Look at a small set of adjacent operations
  - → Move a “peephole” over code & search for improvement
- Classic examples:
  - → store followed by load
  - → simple algebraic identities

Original code	Improved code
ADDI $r_7 \leftarrow r_2, 0$ MUL $r_{10} \leftarrow r_4, r_7$	MUL $r_{10} \leftarrow r_4, r_2$

Peephole Matching

- Basic idea: Compiler can discover local improvements
  - → Look at a small set of adjacent operations
  - → Move a “peephole” over code & search for improvement
- Classic examples:
  - → store followed by load
  - → simple algebraic identities
  - → jump to a jump

Original code	Improved code
Jump L_{10} L_{10}: Jump L_{11}	L_{10}: Jump L_{11}

Peephole Matching

Implementing it

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

Modern peephole instruction selectors

- 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
- Significant, albeit constant, expansion of size

*RTL = Register Transfer Language

Peephole Matching

Simplifier

- Looks at LLIR through window and rewrites it
- Uses forward substitution, algebraic simplification, local constant propagation, 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

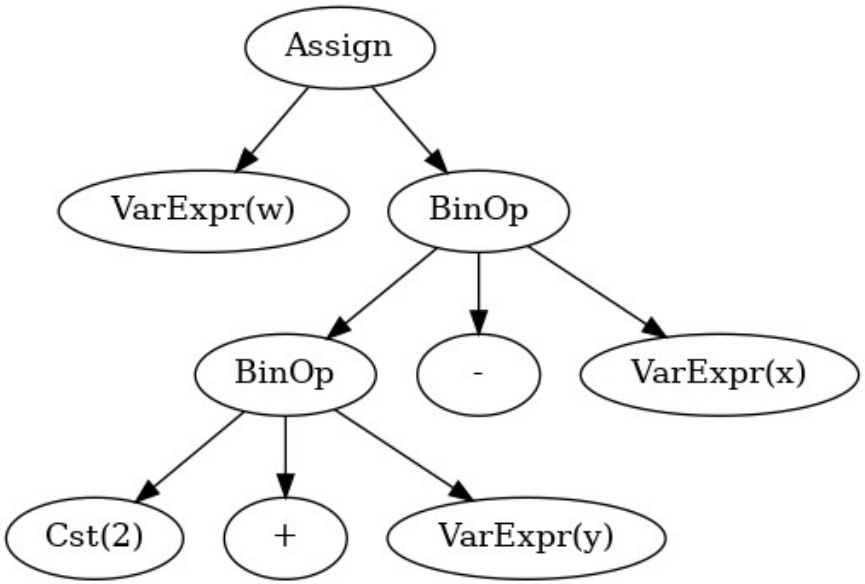
Peephole Matching

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 condition code*)
- Generates the assembly code output

Example

Original IR



Expand

LLIR Code

$r_{10} \leftarrow 2$
$r_{11} \leftarrow @y$
$r_{12} \leftarrow fp + r_{11}$
$r_{13} \leftarrow \text{MEM}(r_{12})$
$r_{14} \leftarrow r_{10} + r_{13}$
$r_{15} \leftarrow @x$
$r_{16} \leftarrow fp + r_{15}$
$r_{17} \leftarrow \text{MEM}(r_{16})$
$r_{18} \leftarrow r_{14} - r_{17}$
$r_{19} \leftarrow @w$
$r_{20} \leftarrow fp + r_{19}$
$\text{MEM}(r_{20}) \leftarrow r_{18}$

assumes x,y,w stack allocated

Each register is single use

@x, @y, @w = offsets from fp

Example

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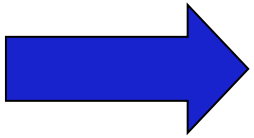
Simplify



LLIR Code

$r_{13} \leftarrow \text{MEM}(fp+ @y)$
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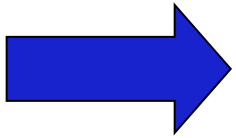
Match



MIPS Code

LW	r_{13} , @y($fp)
ADDI	r_{14} , r_{13} , 2
LW	r_{17} , @x($fp)
SUB	r_{18} , r_{14} , r_{17}
SW	r_{18} , @w($fp)

- Turned out pretty good code

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

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$r_{15} \leftarrow @x$

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

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

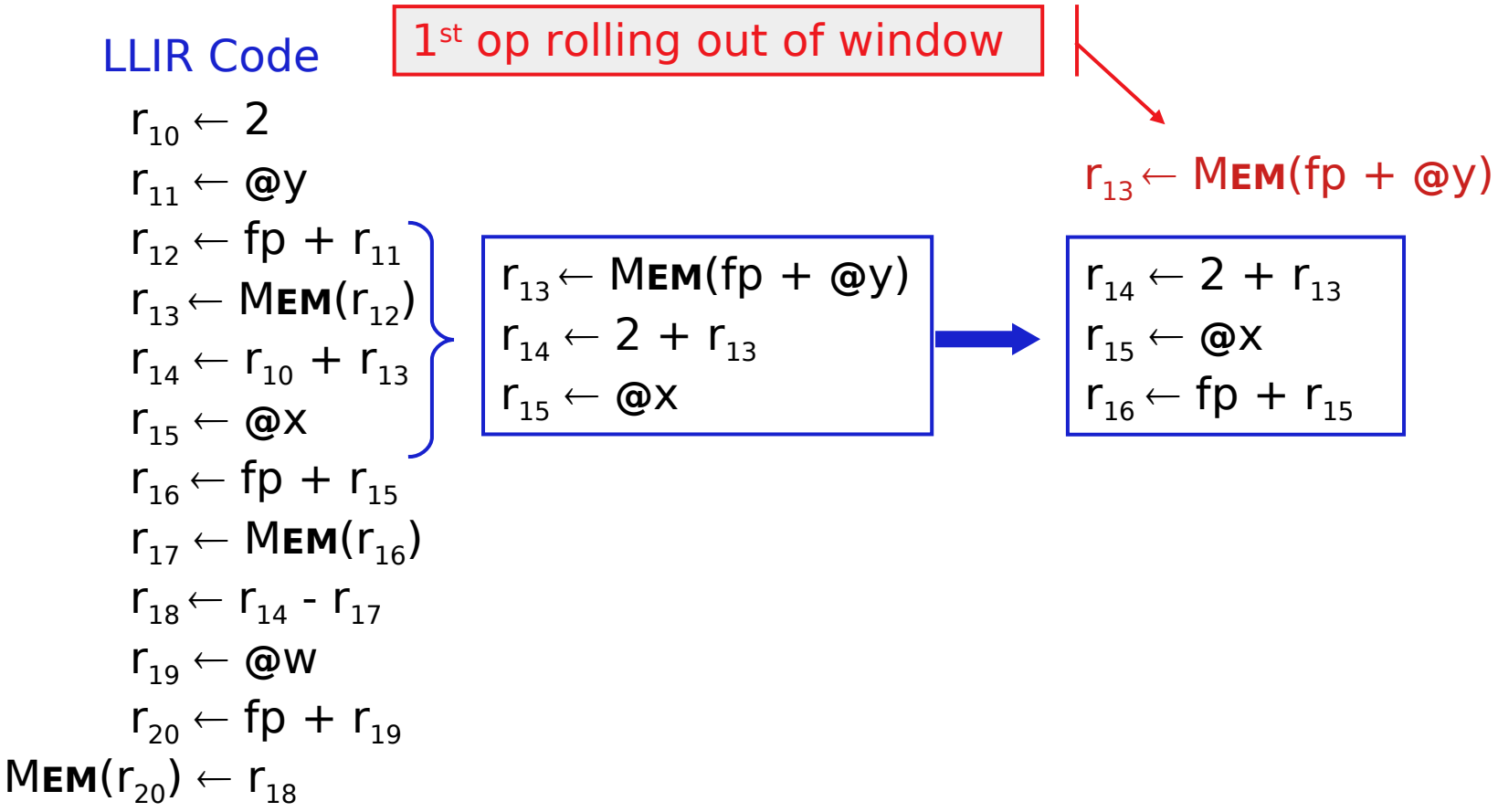
LLIR Code

$r_{10} \leftarrow 2$
$r_{11} \leftarrow @y$
$r_{12} \leftarrow fp + r_{11}$
$r_{13} \leftarrow \text{MEM}(r_{12})$
$r_{14} \leftarrow r_{10} + r_{13}$
$r_{15} \leftarrow @x$
$r_{16} \leftarrow fp + r_{15}$
$r_{17} \leftarrow \text{MEM}(r_{16})$
$r_{18} \leftarrow r_{14} - r_{17}$
$r_{19} \leftarrow @w$
$r_{20} \leftarrow fp + r_{19}$
$\text{MEM}(r_{20}) \leftarrow r_{18}$

$r_{10} \leftarrow 2$
$r_{13} \leftarrow \text{MEM}(fp + @y)$
$r_{14} \leftarrow r_{10} + r_{13}$

$r_{13} \leftarrow \text{MEM}(fp + @y)$
$r_{14} \leftarrow 2 + r_{13}$
$r_{15} \leftarrow @x$

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



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

LLIR Code

$r_{10} \leftarrow 2$
$r_{11} \leftarrow @y$
$r_{12} \leftarrow fp + r_{11}$
$r_{13} \leftarrow \text{MEM}(r_{12})$
$r_{14} \leftarrow r_{10} + r_{13}$
$r_{15} \leftarrow @x$
$r_{16} \leftarrow fp + r_{15}$
$r_{17} \leftarrow \text{MEM}(r_{16})$
$r_{18} \leftarrow r_{14} - r_{17}$
$r_{19} \leftarrow @w$
$r_{20} \leftarrow fp + r_{19}$
$\text{MEM}(r_{20}) \leftarrow r_{18}$

$r_{14} \leftarrow 2 + r_{13}$
$r_{15} \leftarrow @x$
$r_{16} \leftarrow fp + r_{15}$

$r_{14} \leftarrow 2 + r_{13}$
$r_{15} \leftarrow @x$
$r_{16} \leftarrow fp + @x$

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

LLIR Code

$r_{10} \leftarrow 2$
$r_{11} \leftarrow @y$
$r_{12} \leftarrow fp + r_{11}$
$r_{13} \leftarrow \text{MEM}(r_{12})$
$r_{14} \leftarrow r_{10} + r_{13}$
$r_{15} \leftarrow @x$
$r_{16} \leftarrow fp + r_{15}$
$r_{17} \leftarrow \text{MEM}(r_{16})$
$r_{18} \leftarrow r_{14} - r_{17}$
$r_{19} \leftarrow @w$
$r_{20} \leftarrow fp + r_{19}$
$\text{MEM}(r_{20}) \leftarrow r_{18}$

$r_{14} \leftarrow 2 + r_{13}$
$r_{15} \leftarrow @x$
$r_{16} \leftarrow fp + r_{15}$

$r_{14} \leftarrow 2 + r_{13}$
$r_{16} \leftarrow fp + @x$
$r_{17} \leftarrow \text{MEM}(r_{16})$

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

LLIR Code

$r_{10} \leftarrow 2$
$r_{11} \leftarrow @y$
$r_{12} \leftarrow fp + r_{11}$
$r_{13} \leftarrow \text{MEM}(r_{12})$
$r_{14} \leftarrow r_{10} + r_{13}$
$r_{15} \leftarrow @x$
$r_{16} \leftarrow fp + r_{15}$
$r_{17} \leftarrow \text{MEM}(r_{16})$
$r_{18} \leftarrow r_{14} - r_{17}$
$r_{19} \leftarrow @w$
$r_{20} \leftarrow fp + r_{19}$
$\text{MEM}(r_{20}) \leftarrow r_{18}$

$r_{14} \leftarrow 2 + r_{13}$
$r_{16} \leftarrow fp + @x$
$r_{17} \leftarrow \text{MEM}(r_{16})$

$r_{14} \leftarrow 2 + r_{13}$
$r_{17} \leftarrow \text{MEM}(fp+@x)$
$r_{18} \leftarrow r_{14} - r_{17}$

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

LLIR Code

$r_{10} \leftarrow 2$
$r_{11} \leftarrow @y$
$r_{12} \leftarrow fp + r_{11}$
$r_{13} \leftarrow \text{MEM}(r_{12})$
$r_{14} \leftarrow r_{10} + r_{13}$
$r_{15} \leftarrow @x$
$r_{16} \leftarrow fp + r_{15}$
$r_{17} \leftarrow \text{MEM}(r_{16})$
$r_{18} \leftarrow r_{14} - r_{17}$
$r_{19} \leftarrow @w$
$r_{20} \leftarrow fp + r_{19}$
$\text{MEM}(r_{20}) \leftarrow r_{18}$

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

$r_{14} \leftarrow 2 + r_{13}$
$r_{17} \leftarrow \text{MEM}(fp+@x)$
$r_{18} \leftarrow r_{14} - r_{17}$

$r_{17} \leftarrow \text{MEM}(fp+@x)$
$r_{18} \leftarrow r_{14} - r_{17}$
$r_{19} \leftarrow @w$

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

LLIR Code

$r_{10} \leftarrow 2$
$r_{11} \leftarrow @y$
$r_{12} \leftarrow fp + r_{11}$
$r_{13} \leftarrow \text{MEM}(r_{12})$
$r_{14} \leftarrow r_{10} + r_{13}$
$r_{15} \leftarrow @x$
$r_{16} \leftarrow fp + r_{15}$
$r_{17} \leftarrow \text{MEM}(r_{16})$
$r_{18} \leftarrow r_{14} - r_{17}$
$r_{19} \leftarrow @w$
$r_{20} \leftarrow fp + r_{19}$
$\text{MEM}(r_{20}) \leftarrow r_{18}$

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

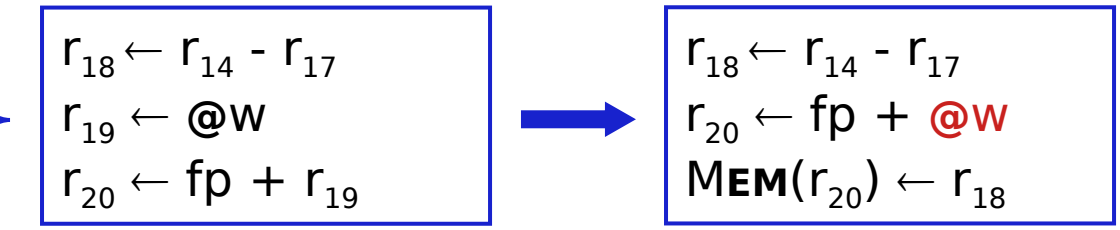
$r_{17} \leftarrow \text{MEM}(fp+@x)$
$r_{18} \leftarrow r_{14} - r_{17}$
$r_{19} \leftarrow @w$

$r_{18} \leftarrow r_{14} - r_{17}$
$r_{19} \leftarrow @w$
$r_{20} \leftarrow fp + r_{19}$

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

LLIR Code

$r_{10} \leftarrow 2$
$r_{11} \leftarrow @y$
$r_{12} \leftarrow fp + r_{11}$
$r_{13} \leftarrow \text{MEM}(r_{12})$
$r_{14} \leftarrow r_{10} + r_{13}$
$r_{15} \leftarrow @x$
$r_{16} \leftarrow fp + r_{15}$
$r_{17} \leftarrow \text{MEM}(r_{16})$
$r_{18} \leftarrow r_{14} - r_{17}$
$r_{19} \leftarrow @w$
$r_{20} \leftarrow fp + r_{19}$
$\text{MEM}(r_{20}) \leftarrow r_{18}$



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

LLIR Code

$r_{10} \leftarrow 2$
$r_{11} \leftarrow @y$
$r_{12} \leftarrow fp + r_{11}$
$r_{13} \leftarrow \text{MEM}(r_{12})$
$r_{14} \leftarrow r_{10} + r_{13}$
$r_{15} \leftarrow @x$
$r_{16} \leftarrow fp + r_{15}$
$r_{17} \leftarrow \text{MEM}(r_{16})$
$r_{18} \leftarrow r_{14} - r_{17}$
$r_{19} \leftarrow @w$
$r_{20} \leftarrow fp + r_{19}$
$\text{MEM}(r_{20}) \leftarrow r_{18}$

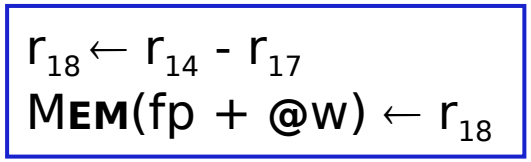
$r_{18} \leftarrow r_{14} - r_{17}$
$r_{20} \leftarrow fp + @w$
$\text{MEM}(r_{20}) \leftarrow r_{18}$

$r_{18} \leftarrow r_{14} - r_{17}$
$\text{MEM}(fp + @w) \leftarrow r_{18}$

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

LLIR Code

$r_{10} \leftarrow 2$
$r_{11} \leftarrow @y$
$r_{12} \leftarrow fp + r_{11}$
$r_{13} \leftarrow \text{MEM}(r_{12})$
$r_{14} \leftarrow r_{10} + r_{13}$
$r_{15} \leftarrow @x$
$r_{16} \leftarrow fp + r_{15}$
$r_{17} \leftarrow \text{MEM}(r_{16})$
$r_{18} \leftarrow r_{14} - r_{17}$
$r_{19} \leftarrow @w$
$r_{20} \leftarrow fp + r_{19}$
$\text{MEM}(r_{20}) \leftarrow r_{18}$



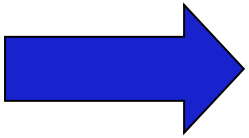
$r_{18} \leftarrow r_{14} - r_{17}$
$\text{MEM}(fp + @w) \leftarrow r_{18}$

Example

LLIR Code

$r_{10} \leftarrow 2$
$r_{11} \leftarrow @y$
$r_{12} \leftarrow fp + r_{11}$
$r_{13} \leftarrow \text{MEM}(r_{12})$
$r_{14} \leftarrow r_{10} + r_{13}$
$r_{15} \leftarrow @x$
$r_{16} \leftarrow fp + r_{15}$
$r_{17} \leftarrow \text{MEM}(r_{16})$
$r_{18} \leftarrow r_{14} - r_{17}$
$r_{19} \leftarrow @w$
$r_{20} \leftarrow fp + r_{19}$
$\text{MEM}(r_{20}) \leftarrow r_{18}$

Simplify



LLIR Code

$r_{13} \leftarrow \text{MEM}(fp + @y)$
$r_{14} \leftarrow 2 + r_{13}$
$r_{17} \leftarrow \text{MEM}(fp + @x)$
$r_{18} \leftarrow r_{14} - r_{17}$
$\text{MEM}(fp + @w) \leftarrow r_{18}$

Making It All Work

Details

- LLIR is largely machine independent (RTL)
- Target machine described as LLIR → ASM pattern
- Actual pattern matching
  - → Use a hand-coded pattern matcher (GCC)
  - → 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

Next lecture

Instruction selection

- Tree-based pattern matching (LLVM)