

CSE 401 – Compilers

Target Code Generation for MiniJava

Hal Perkins

Winter 2009



Agenda

- Overview of x86 architecture
 - Core 32-bit part only, not old compatibility cruft
- Later
 - Survey of MiniJava's code generator and mapping MiniJava to x86 code
 - More sophisticated back-end algorithms
 - Survey of compiler optimizations



Target Code Generation

- Input: intermediate language (IL)
- Output: target language program
- Target languages include
 - absolute binary (machine) code
 - relocatable binary code
 - assembly code
 - C
- Using the generated intermediate code, convert to instructions and memory characteristics of the target machine
 - Target code generation must bridge the gap



Gap: machine code

IL	Machine Code
global variables	global static memory
unbounded number of interchangeable local variables	fixed number of registers, of various incompatible kinds, plus unbounded number of stack locations
built-in parameter passing & result returning	calling conventions defining where arguments & results are stored and which registers may be overwritten by callee
statements	machine instructions
statements can have arbitrary subexpression trees	instructions have restricted operand addressing
conditional branches based on integers representing Boolean values	conditional branches based on condition codes (maybe)



Tasks of Code Generator

- Register allocation
 - for each IL variable, select register/stack location/global memory location(s) to hold it based on its type and lifetime
- Stack frame layout
- Instruction selection
 - for each IL instruction (sequence), select target language instruction (sequence); must consider operand addressing mode selection



These tasks interact

- Instruction selection depends on where operands are allocated
- Some IL variables may not need a register, depending on the instructions & addressing modes that are selected
- Stack frame layout may depend on instruction set
- ...



Register Allocation

- Intermediate language uses unlimited temporary variables – this intentionally makes ICG easy
- Target machine has fixed resources for representing locals plus other internal things such as stack pointer
 - MIPS, SPARC: 31 registers + 1 always-zero register
 - 68k: 16 registers, divided into data and address
 - x86: 8 word-sized integer registers (with instruction-specific restrictions on use) plus a stack of floating-point data manipulated only indirectly
- Registers are *much* faster than memory
- Must use registers in load/store RISC machines



Consequences

- Should try to keep values in registers if possible
- Must reuse registers, implies free registers after use
- Must handle more variables than registers, implies spill
- Interacts with instruction selection on CISC, implies it's a real pain



Classes of Registers

- Fixed/dedicated registers
 - Stack pointer, frame pointer, return address, ...
 - Claimed by machine architecture, calling convention, or internal convention for special purpose
 - Some registers may be overwritten by called procedures so caller must save them across calls, if allocated
 - caller-saved registers vs. callee-saved registers
- Scratch registers
 - registers kept around for temps (e.g., loading a spilled value from memory to operate on it)
- Free registers
 - remaining registers free for register allocator to use



Classes of Variables

- What variables can the allocator put in registers?
- Temporary variables: easy to allocate
 - Defined and used exactly once, during expression evaluation, implies allocator can free up register when done
 - Usually not too many in use at one time implies less likely to run out of registers
- Local variables: hard, but doable
 - need to determine *last use* of variable to free register
 - can easily run out of registers so must make decision about which variables get register allocation
 - what about assignments to local through pointer?
 - what about debugger?
- Global variables
 - really hard, but doable as a research project



Register Allocation in MiniJava

- Allocate all local variables to stack locations
 - No need for analysis to find last use of local variables
 - Each read of the local variable translated into a load from stack
 - Each assignment to a local translated to a store into its stack location



Register Allocation in MiniJava

- Each IL expression has exactly one use so can allocate result value of IL expression to register
 - Maintain set of allocated registers
 - Allocate an unallocated register for each expression result
 - Free register when done with expression result
 - Not too many IL expressions "active" at a time implies unlikely to run out of registers, even on x86
 - MiniJava compiler dies if it runs out of registers for IL expressions



Register Allocation in MiniJava

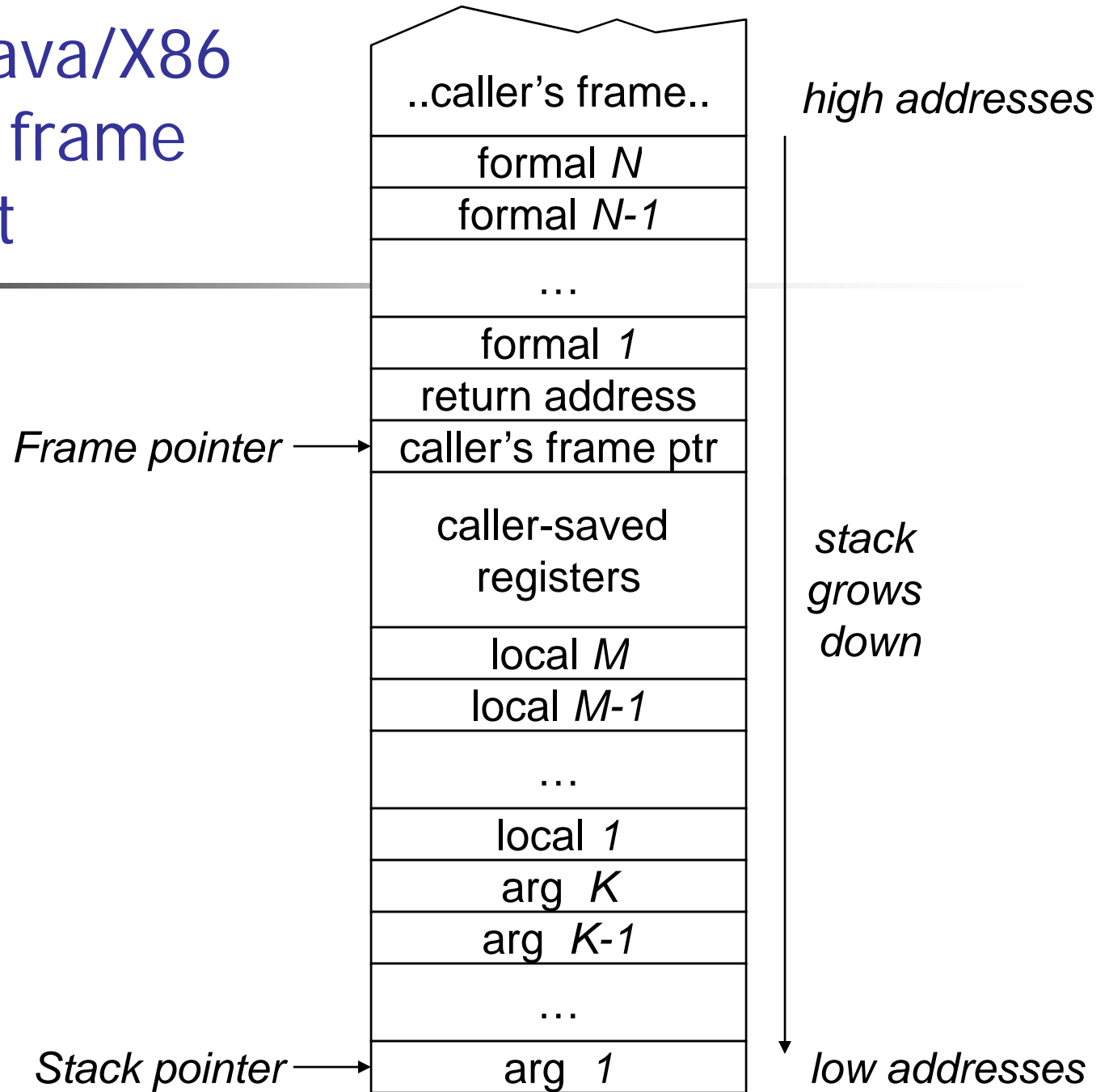
- X86 register allocator
 - `eax`, `ebx`, `ecx`, `edx`: allocatable, caller-save registers
 - `esi`, `edi`: scratch registers
 - `esp`: stack pointer; `ebp`: frame pointer
 - floating-point stack, for `double` values



Stack Frame Layout

- Need space for
 - formals
 - local variables
 - return address
 - (maybe) dynamic link (ptr to calling stack frame)
 - (maybe) static link (ptr to lexically-enclosing stack frame)
 - other run-time data (e.g. caller-saved registers)
- Assign dedicated register(s) to support access to stack frames
 - FP: ptr to beginning of stack frame (fixed)
 - SP: ptr to end of stack (can move)
- All data in stack frame is at fixed, statically computed offset from FP
 - Compute all offsets solely from symbol tables

MiniJava/X86 stack frame layout





Calling Conventions

- Need to define responsibilities of caller and callee in setting up, tearing down stack frame
- Only caller can do some things
- Only callee can do other things
- Some things could be done by both
- So, need a protocol – just like in the IL

X86 Calling Sequence

Caller:

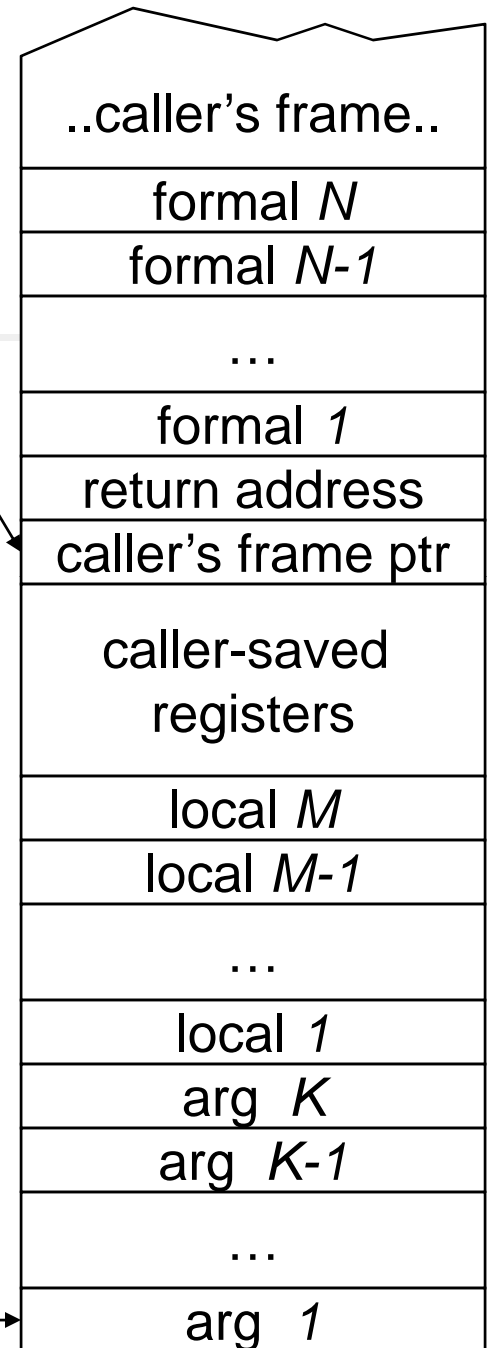
- evaluates actual arguments, pushes them on stack
 - in right-to-left order, to support C varargs
 - alternative: 1st k arguments in registers
- saves caller-save registers in caller's stack
- executes call instruction
 - return address pushed onto the stack by hardware

Callee:

- pushes caller's frame pointer on stack
 - the dynamic link
- sets up callee's frame pointer
- allocates space for locals, caller-saved registers
 - order doesn't matter to calling convention
- starts running callee's code...

Frame pointer

Stack pointer



X86 return sequence

Callee:

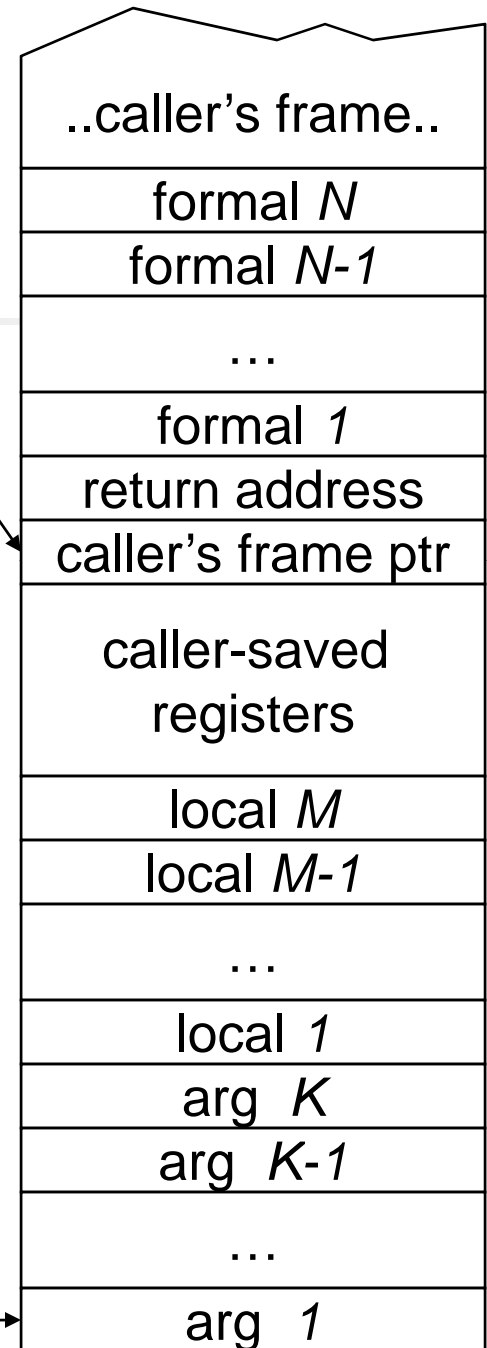
- puts returned value in right place (eax or floating-point stack)
- deallocates space for locals, caller-saved regs
- pops caller's frame pointer from stack
- pops return address from stack and jumps to it

Caller:

- deallocates space for args
- restores caller-saved registers from caller's stack
- continues execution in caller after call...

Frame pointer

Stack pointer





Instruction Selection

- Given one or more IL instructions, pick “best” sequence of target machine instructions with same semantics
- “best” = fastest, shortest, lowest power, ...
- Correctness a big issue, particularly if codegen is complex



Codegen difficulty depends on target

- RISC: easy
 - usually only one way to do something
 - closely resembles IL instructions
- CISC: hard to do well
 - lots of alternative instructions with similar semantics
 - lots of possible operand addressing modes
 - lots of tradeoffs among speed, size
 - simple RISC-like translation may not be very efficient
- C: easy, as long as C appropriate for desired semantics
 - can leave optimizations to C compiler



Example

IL code:

```
t3 = t1 + t2;
```

Target code (MIPS):

```
add $3,$1,$2
```

Target code (SPARC):

```
add %1,%2,%3
```

Target code (68k):

```
mov.l d1,d3
```

```
add.l d2,d3
```

Target code (x86):

```
movl %eax,%ecx
```

```
addl %ebx,%ecx
```

One IL instruction may expand to several target instructions



Another Example

IL code:

```
t1 = t1 + 1;
```

Target code (MIPS):

```
add $1,$1,1
```

Target code (SPARC):

```
add %1,1,%1
```

Target code (68k):

```
add.l #1,d1 ...or...
```

```
inc.l d1
```

Target code (x86):

```
addl $1,%eax ...or...
```

```
incl %eax
```

Can have choices: requires making decisions



Yet another example

IL code:

```
// push x onto stack
sp = sp - 4;
*sp = t1;
```

Target code (MIPS):

```
sub $sp,$sp,4
sw $1,0($sp)
```

Target code (SPARC):

```
sub %sp,4,%sp
st %1,[%sp+0]
```

Target code (68k):

```
mov.l d1,-(sp)
```

Target code (x86):

```
pushl %eax
```

Several IL instructions can combine to one target instruction



Instruction Selection in MiniJava

- Expand each IL statement into some number of target machine instructions
 - don't attempt to combine IL statements together
- In Target subdirectory: abstract classes `Target` and `Location`
 - define abstract methods for emitting machine code for statements and data access: `emitVarAssign`, `emitFieldAssign`, `emitBranchTrue`, `emitVarRead`, `emitFieldRead`, `emitIntMul`, ...
 - return `Location` representing where result is allocated
- IL statement and expression classes invoke these operations to generate their machine code
 - each IL statement and expression has a corresponding emit operation on the `Target` class
- Details of target machines are hidden from IL and the rest of the compiler behind the `Target` and `Location` interfaces



Implementing Target and Location

- A particular target machine provides a concrete subclass of `Target`, plus concrete subclasses of `Location` as needed
- For example, in `Target/X86` subdirectory:
 - class `X86Target` extends `Target`
 - class `X86Register` extends `Location`
 - for expressions whose results are in (integer) registers
 - class `X86FloatingPointStack` extends `Location`
 - for expressions whose results are pushed on the floating-point stack
 - class `X86ComparisonResult` extends `Location`
 - for boolean expressions whose results are in condition codes
- Could define `Target/MIPS`, `Target/C`, etc.



An Example X86 emit method

```
Location emitIntConstant(int value) {  
    Location result_location =  
        allocateReg(ILType.intILType());  
    emitOp("movl",  
        intOperand(value),  
        regOperand(result_location));  
    return result_location;  
}
```

Location allocateReg(ILType):

allocate a new register to hold a value of the given type

void emitOp(String opname, String arg1, ...):

emit assembly code

String intOperand(int):

return the asm syntax for an int constant operand

String regOperand(Location):

return the asm syntax for a reference to a register



An Example X86 Target emit method

- What x86 code to generate for **arg1 +.int arg2?**
- x86 int add instruction:
addl %arg, %dest
 - semantics: **%dest = %dest + %arg;**
- emit **arg1** into **register%arg1**
- emit **arg2** into **register%arg2**
- then?



An Example X86 Target emit method

```
Location emit IntAdd(ILExprarg1, ILExprarg2) {
    Location arg1_location=arg1.codegen(this);
    Location arg2_location=arg2.codegen(this);
    emitOp("addl",
           regOperand(arg2_location),
           regOperand(arg1_location));
    deallocateReg(arg2_location);
    return arg1_location;
}
```

```
void deallocateReg(Location):
```

*deallocate register,
make available for use by later instructions*



An Example X86 Target emit method

- What x86 code to generate for var read or assignment?
- Need to access var's home stack location
- x86 stack reference operand:
`%ebp(offset)`
 - semantics: **`*(%ebp + offset);`**
 - **`%ebp = frame pointer`**

An Example X86 Target emit method



```
Location emitVarRead(ILVarDecl var) {
    int var_offset = var.getByteOffset(this);
    ILType var_type = var.getType();
    Location result_location =
        allocateReg(var_type);
    emitOp("movl",
           ptrOffsetOperand(FP, var_offset),
           regOperand(result_location));
    return result_location;
}
```



Continued

```
void emitVarAssign(ILVarDecl var,  
                  Location rhs_location) {  
    int var_offset = var.getByteOffset(this);  
    emitOp("movl",  
          regOperand(rhs_location),  
          ptrOffsetOperand(FP, var_offset));  
}
```

String ptrOffsetOperand(Location, int):

return the asm syntax for a reference to a "ptr + offset" memory location

An Example X86 Target emit method



```
void emitAssign(ILAssignableExpr lhs,
                ILExpr rhs) {
    Location rhs_location =
        rhs.codegen(this);
    lhs.codegenAssign(rhs_location, this);
    deallocateReg(rhs_location);
}
```

Each `ILAssignableExpr` implements `codegenAssign`

- invokes appropriate `emitAssign` operation,
e.g. `emitVarAssign`



Generation for Comparisons

- What code to generate for `arg1 <.int arg2`
- MIPS: use an `slt` instruction to compute boolean-valued int result into a register
- x86 (and most other machines): no direct instruction
- Have comparison instructions, which set condition codes
 - e.g. `cmpl %arg2, %arg1`
- Later conditional branch instructions can test condition codes
 - e.g. `j1, jle, jge, jg, je, jne label`
- What instructions to generate?



Generation for Compares

```
Location emitIntLessThanValue(ILExpr arg1,ILExpr arg2) {
    Location arg1_location=arg1.codegen(this);
    Location arg2_location=arg2.codegen(this);
    emitOp("cmpl",regOperand(arg2_location),...);
    deallocateReg(arg1_location);...
    Location result_location = allocateReg(ILType.intILType());
    String true_label = getNewLabel();
    emitOp("jl", true_label);
    emitOp("movl", intOperand(0),regOperand(result_location));
    String done_label = getNewLabel();
    emitOp("jmp", done_label);
    emitLabel(true_label);
    emitOp("movl", intOperand(1),regOperand(result_location));
    emitLabel(done_label);
    return result_location;
}
```



Generation for Branch

- What code to generate for
`iftrue test goto label ?`

```
void emitConditionalBranchTrue(ILExpr
    test,ILLabeltarget){
    Location test_location=test.codegen(this);
        emitOp("cmpl", intOperand(0),
                regOperand(test_location));
        emitOp("jne", target.getName());
    }
```



Generation for Branch

- What is generated for
`iftrue arg1 <.int arg2 goto label`
 `<emit arg1 into %arg1>`
 `<emit arg2 into %arg2>`
 `cmpl %arg2, %arg1`
 `j1 true_label`
 `movl $0, %res`
 `jmp done_label`
`true_label:`
 `movl $1, %res`
`done_label:`
 `cmpl $0, %res`
 `jne label`
- Can we do better?



Optimized Branches

- Idea: boolean-valued IL expressions can be generated two ways, depending on their consuming context
 - for their value or for their condition code
- Existing code gen operation on IL expression produces its value
- New **codegenTest** operation on IL expression produces its condition code
 - **X86ComparisonResultLocation** represents this result
- Now conditional branches can evaluate their test expression in the "for condition code" style



Optimized Branches

```
void emitConditionalBranchTrue(ILExpr test,
                               ILLabeltarget){
    Location test_location=test.codegen(this);
    X86ComparisonResultLoc cc =
        (X86ComparisonResultLoc) test_location;
    emitOp("j" + cc.branchTrueOp(),
           target.getName());
}
```

IL codegenTest Default Behavior

```
class ILEExpr extends ILEExpr {  
    ...  
    Location codegenTest(Target target) {  
        return target.emitTest(this);  
    }  
}
```

In X86Target class:

```
Location emitTest(ILEExpr arg) {  
    Location arg_location = arg.codegen(this);  
    emitOp("cmpl", intOperand(0),  
          regOperand(arg_location));  
    deallocateReg(arg_location);  
    return new X86ComparisonResultLoc("ne");  
}
```



IL codegenTest Specialized Behavior

```
class ILIntLessThanExpr extends ILEExpr {
    ...
    Location codegenTest(Target target) {
        return target.emitIntLessThanTest(arg1, arg2);
    }
}
```

In X86Target class:

```
Location emitIntLessThanTest(ILEExpr arg1, ILEExpr arg2) {
    Location arg1_location=arg1.codegen(this);
    Location arg2_location=arg2.codegen(this);
    emitOp("cmpl", regOperand(arg2_location), ...);
    deallocateReg(arg1_location);
    ...
    return new X86ComparisonResultLoc("l");
}
```




What Next?

- Look at more general back-end algorithms
 - Instruction Selection and Scheduling
 - Register allocation (graph coloring)
- Then overview of optimization and dataflow analysis