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2. Code Generation
Overview

Front-end
- Lexer
- Parser
- AST builder
- Semantic Analyser

Middle-end
- Optimizations (Compiler Optimisations course)
Translate IR into target machine code
Choose instructions to implement each IR operation
Decide which value to keep in registers
Ensure conformance with system interfaces
Automation has been less successful in the back end
Mapping the IR into assembly code (in our case AST to MIPS assembly)
- Assumes a fixed storage mapping & code shape
- Combining operations, using address modes
Register Allocation

- Deciding which value reside in a register
- Minimise amount of spilling
Instruction Scheduling

- Avoid hardware stalls and interlocks
- Reordering operations to hide latencies
- Use all functional units productively

Instruction scheduling is an optimisation
Improves quality of the code. Not strictly required.
The Big Picture

How hard are these problems?

- Instruction selection
  - Can make locally optimal choices, with automated tool
  - Global optimality is NP-Complete
- Instruction scheduling
  - Single basic block $\Rightarrow$ heuristic work quickly
  - General problem, with control flow $\Rightarrow$ NP-Complete
- Register allocation
  - Single basic block, no spilling, 1 register size $\Rightarrow$ linear time
  - Whole procedure is NP-Complete (graph colouring algorithm)

These three problems are tightly coupled!

However, conventional wisdom says we lose little by solving these problems independently.
How to solve these problems?

- **Instruction selection**
  - Use some form of pattern matching
  - Assume enough registers or target “important” values

- **Instruction scheduling**
  - Within a block, list scheduling is “close” to optimal
  - Across blocks, build framework to apply list scheduling

- **Register allocation**
  - Start from virtual registers & map “enough” into $k$
  - With targeting, focus on “good” priority heuristic

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**Approximate solutions**

Will be important to define good metrics for “close”, “good”, “enough”, ....
The key code quality issue is holding values in registers

- when can a value be safely allocated to a register?
  - When only 1 name can reference its value
  - Pointers, parameters, aggregate & arrays all cause trouble
- when should a value be allocated to a register?
  - when it is both safe & profitable

Encoding this knowledge into the IR

- assign a virtual register to anything that go into one
- load or store the others at each reference

Register allocation is key

All this relies on a strong register allocator.
Most real physical machine are register-based
Instruction operates on registers.
The number of architecture register available to the compiler can vary from processor to processors.
The first phase of code generation usually assumes an unlimited numbers of registers (virtual registers).
Later phases (register allocator) converts these virtual register to the finite set of available physical architectural registers (more on this in lecture on register allocation).
Generating Code for Register-Based Machine

Example: \( x + y \)

- load \( @x \) \( \rightarrow \) \( r1 \) // load the address of \( x \) into \( r1 \)
- loadA \( r1 \) \( \rightarrow \) \( r2 \) // now value of \( x \) is in \( r2 \)
- load \( @y \) \( \rightarrow \) \( r3 \) // load the address of \( y \) into \( r3 \)
- loadA \( r3 \) \( \rightarrow \) \( r4 \) // now value of \( y \) is in \( r4 \)
- add \( r2, r4 \) \( \rightarrow \) \( r5 \) // \( r5 \) contains \( x + y \)
Exercise
Write down the list of assembly instructions for \( x + (y \times 3) \)

Exercise
Assuming you have an instruction muli (\texttt{multiply immediate}), rewrite the previous example.

This illustrate the instruction selection problem (more on this in following lectures).
Visitor Implementation for binary operators

Binary operators

```c
Register visitBinOp(BinOp bo) {
    Register lhsReg = bo.lhs.accept(this);
    Register rhsReg = bo.rhs.accept(this);
    Register result = nextRegister();
    switch (bo.op) {
        case ADD:
            emit(add lhsReg.id rhsReg.id → result.id);
            break;
        case MUL:
            emit(mul lhsReg.id rhsReg.id → result.id);
            break;
        ...
    }
    freeRegister(lhsReg);
    freeRegister(rhsReg);
    return result;
}
```
Visitor Implementation for variables

```
x
loadl @x → r1 // load the address of x into r1
loadA r1 → r2 // now value of x is in r2
```
Visitor Implementation for integer literals

3

\texttt{loadl 3 \rightarrow r1}

\textbf{IntLiteral}

\begin{verbatim}
Register visitIntLiteral(IntLiteral it) {
    Register result = nextRegister();
    emit(\texttt{loadl it.value \rightarrow result.id});
    return result;
}
\end{verbatim}
Next lecture

Code Shape
- Conditions
- Function calls
- Loops
- If statement

Memory management
- Static/stack/heap allocation
- Data structure memory layout
- Register spilling