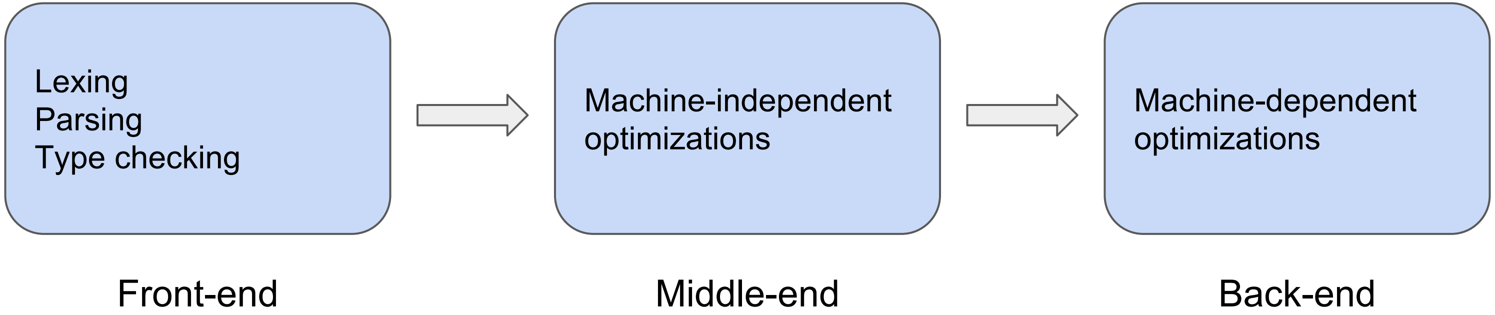
JoeQ Framework

CS243, Winter 2017

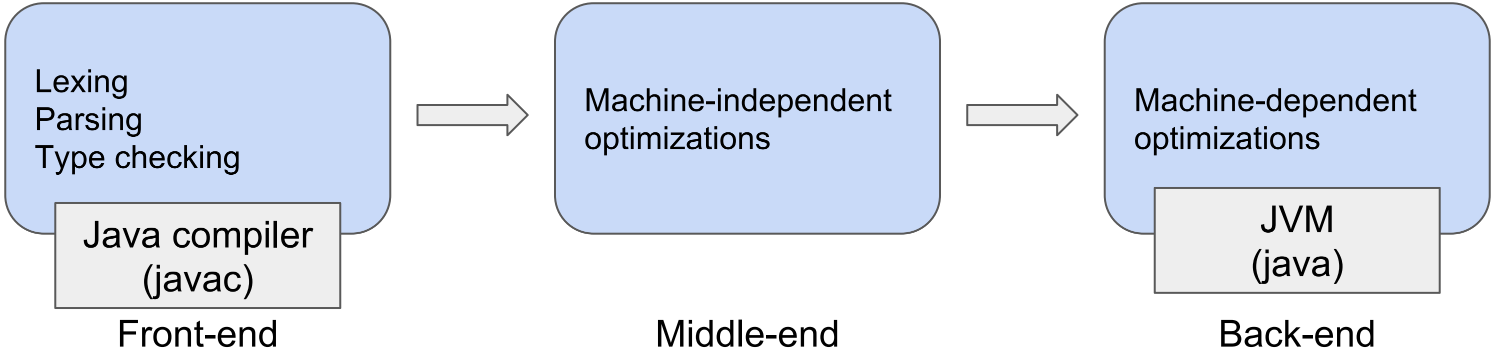
Overview

- Java Compilation and Intermediate Representation
  - Bytecode
- JoeQ Framework
  - Quads: Instruction set used in JoeQ
  - JoeQ constructs
  - Writing analysis in JoeQ
- HW2

Typical Compiler Infrastructure



Java


Lexing
Parsing
Type checking
Java compiler
(javac)
Front-end
Machine-independent
optimizations
Middle-end
Machine-dependent
optimizations
JVM
(java)
Back-end

Java Source Code

- Input to the Java front-end
- A very “rich” representation
  - Human readable and writable
  - Hard to analyze (from the perspective of a computer)
- Many high-level concepts which do not direct hardware counterparts
  - Classes, generics, virtual function calls, exceptions, structured control flow, locks, etc.

Abstract Syntax Tree Representation

- Abstract syntax trees generated by parser that can be analyzed before code generation
    - Attribution (com.sun.tools.javac.comp.Attr)
    - Dataflow (com.sun.tools.javac.comp.Flow)
        - Liveness, exception checks, assignment/unassignment, local variable capture, etc.
    - Desugaring
- Analyses implemented using “visitor” pattern

Java Bytecode

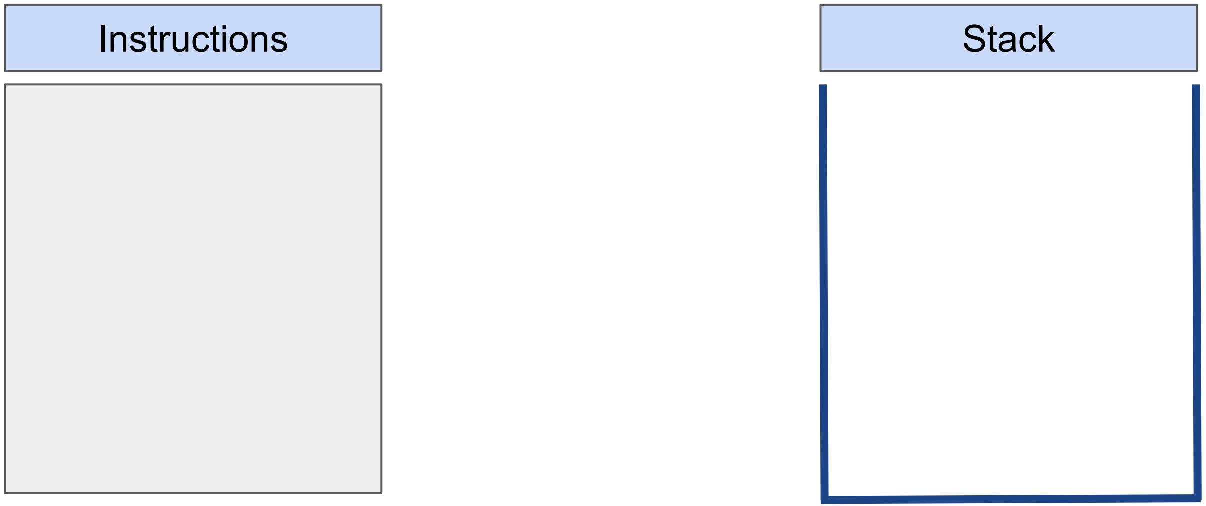
- Machine-independent intermediate representation (.class files)
- Coarse program structure is still maintained
  - One file per class
  - A section per method or field
- Each method has a bytecode sequence for its implementation
- Remains high-level
  - Still have virtual methods, locks, etc.

Bytecode representation

- Each bytecode instruction uses one byte
  - Instructions may have additional operands, stored immediately after the instruction
- Verification
- Stack machine model
  - All intermediate values stored on a stack

What is a stack machine model?

- Each instruction pushes or pops values onto a stack
- Working example: *x = y + 10*



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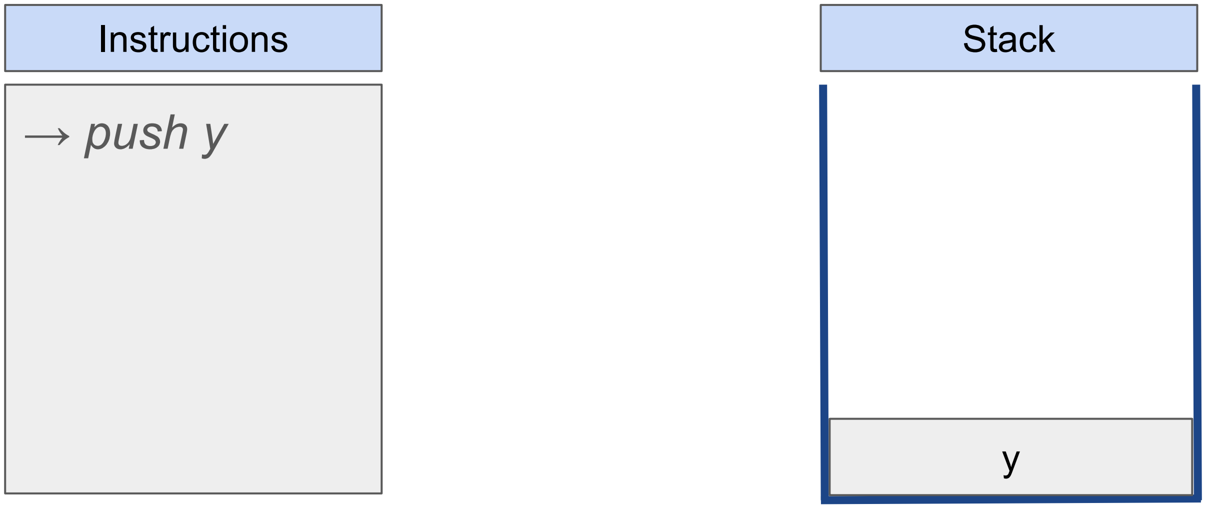

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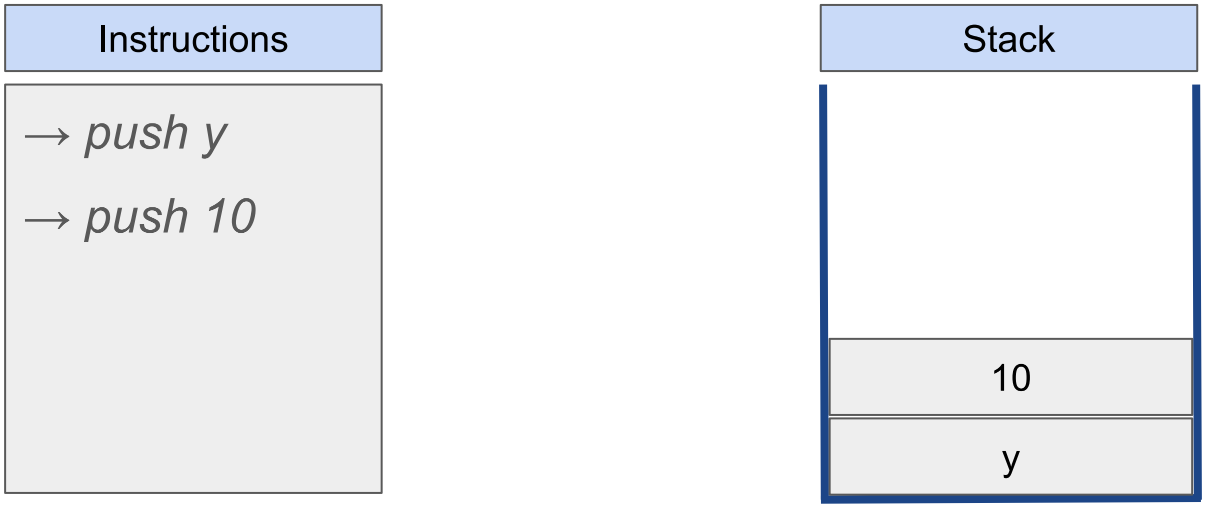

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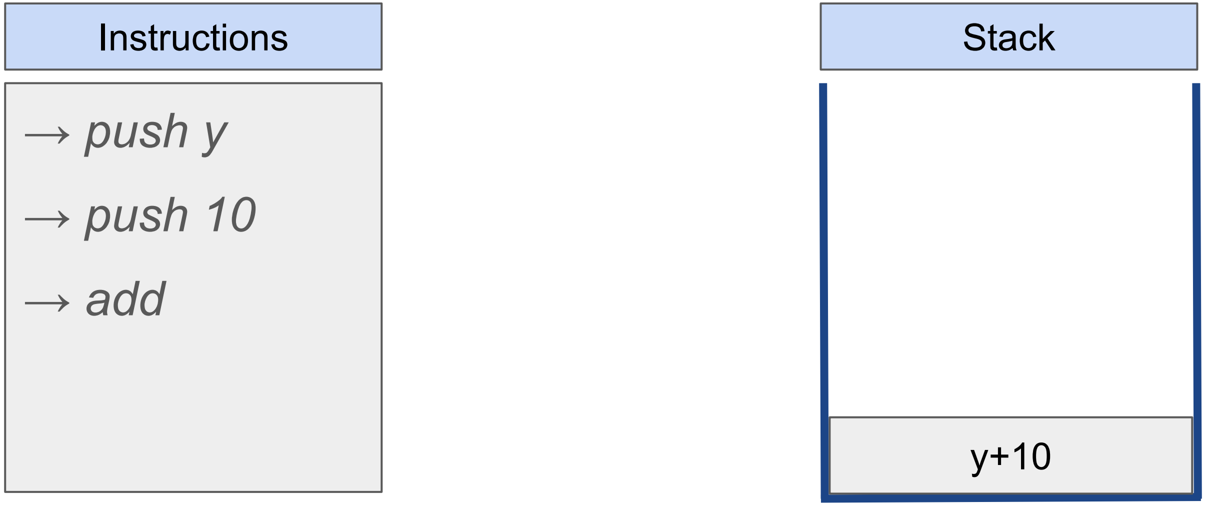


** *add* - implicitly pops the top 2 operands and pushes the result back on the stack

What is a stack machine model?

- Each instruction pushes or pops values onto a stack
- Working example: $x = y + 10$

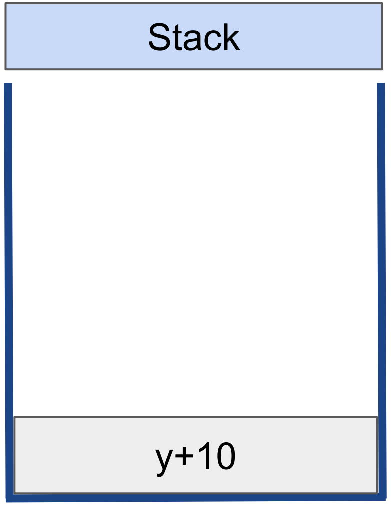
Instructions

→ *push y*

→ *push 10*

→ *add*

→ *pop x*



** *pop* - top of stack is popped and the value assigned to *x*

Bytecode Instructions

- Each instruction is prefixed by the types of operands
- *iload_1*
  - Load the first parameter or local variable and push it on the stack
- *bipush <n>*
  - Push byte constant *n* onto the stack as an integer value
- *iadd*
  - Add the top two values on the stack, and push the result back onto the stack
- *istore_2*
  - Pop the stack and store its value into the second param/local

ExprTest.test(int a)

```
class ExprTest {
    int test (int a) {
        int b, c, d, e, f;
        c = a + 10;
        f = a + c;
        if (f > 2) {
            f = f - c;
        }
        return (f);
    }
}
```

```
> javac ExprTest.java
> javap -c ExprTest

class ExprTest extends java.lang.Object {
    ExprTest();
    int test(int);
}

Method ExprTest():
   0 aload_0
   ...
   4 return

Method int test(int):
   0 iload_1
  ...
  24 ireturn
```

ExprTest.ExprTest()

```
Method ExprTest():

   0 aload_0
     // load address 'this' and push it onto the stack

   1 invokespecial #1 <Method java.lang.Object()>
     // invokes base class methods. #1 is constructor

   4 return
```

ExprTest.test(int a)

```
class ExprTest {
    int test (int a) {
        int b, c, d, e, f;
        c = a + 10;
        f = a + c;
        if (f > 2) {
            f = f - c;
        }
        return (f);
    }
}
```

```
Method int test(int):
   0 iload_1
   1 bipush 10
   3 iadd
   4 istore_3
   5 iload_1
   6 iload_3
   7 iadd
   8 istore_6
  10 iload_6
  12 iconst_2
  13 if_icmple 22
  16 iload_6
  18 iload_3
  19 isub
  20 istore_6
  22 iload_6
  24 ireturn
```

Static vs. Dynamic Optimization

- Static optimization
  - Dataflow analysis
- Adaptive optimization
  - Incorporate information available only at run-time
  - Interpreted bytecode vs. compiled native code
  - Determining hot-spots in code execution to be compiled to native code

JoeQ

- Compiler framework for analyzing and optimizing Java bytecode
  - Developed by John Whaley and others
  - Implemented in Java
  - Research project infrastructure: 10+ papers rely on JoeQ
- Also see: http://joeq.sourceforge.net
- Etymology
  - “Jyo-kyu-” like the name “Joe” and the letter “Q”

Java Elements in JoeQ

High level representation: JoeQ has class for various components of Java .class files, in `joeq.Class` package

- `jq_Type`
- `jq_Class`
- `jq_Field`
- `jq_Method`
- . . .

```
> javac ExprTest.java
> javap -c ExprTest

class ExprTest extends java.lang.Object {
    ExprTest();
    int test(int);
}

Method ExprTest():
   0 aload_0
   ...
   4 return

Method int test(int):
   0 iload_1
  ...
  24 ireturn
```

JoeQ Intermediate Representation

- JoeQ uses a lower-level representation called a *Quad*
- JoeQ translates bytecodes into *Quads*
- A *Quad* has one operator and up to four operands: four-address instructions
- Stanford version of TAC (Three address code)
    - Example: `t1 := t2 + t3, t1 = 2 * t3`

ExprTest

```
class ExprTest {
    int test (int a) {
        int b, c, d, e, f;
        c = a + 10;
        f = a + c;
        if (f > 2) {
            f = f - c;
        }
        return (f);
    }
}
```

```
> javac ExprTest.java
> java PrintQuads ExprTest

Class: ExprTest

Control flow graph for ExprTest.<init> ()V:
...

Control flow graph for ExprTest.test (I)I:
...
```

ExprTest.ExprTest()

```
Code:
0: aload_0
// load address 'this' and push it onto the stack
1: invokespecial #1
// invokes base class methods. #1 is constructor
2: return
```

Bytecode

```
B0 (ENTRY)     (in: <none>, out: BB2)

BB2     (in: BB0 (ENTRY), out: BB1 (EXIT))
2   NULL_CHECK              T-1 <g>,                              R0 ExprTest
1   INVOKESPECIAL_V%        java.lang.Object.<init> ()V,         (R0 ExprTest)
3   RETURN_V

BB1 (EXIT)      (in: BB2, out: <none>)
```

Quads

ExprTest.test(int a)

```
Method int test(int):
    0 iload_1
    1 bipush 10
    3 iadd
    4 istore_3
    5 iload_1
    6 iload_3
    7 iadd
    8 istore 6
   10 iload 6
   12 iconst_2
   13 if_icmple 22
   16 iload 6
   18 iload_3
   19 isub
   20 istore 6
   22 iload 6
   24 ireturn
```

Bytecode

```
BB0 (ENTRY)     (in: <none>, out: BB2)

BB2     (in: BB0 (ENTRY), out: BB3, BB4)
1   ADD_I                   T0 int,     R1 int, IConst: 10
2   MOVE_I                  R3 int,     T0 int
3   ADD_I                   T0 int,     R1 int, R3 int
4   MOVE_I                  R6 int,     T0 int
5   IFCMP_I                 R6 int,     IConst: 2,      LE,     BB4

BB3     (in: BB2, out: BB4)
6   SUB_I                   T0 int,     R6 int, R3 int
7   MOVE_I                  R6 int,     T0 int

BB4     (in: BB2, BB3, out: BB1 (EXIT))
8   RETURN_I                R6 int

BB1 (EXIT)      (in: BB4, out: <none>)
```

Quads

Quads (`joeq.Compiler.Quad.Quad`)

Register machine model, not stack machine model

- All temporary data stored in registers
- Closer to RISC machine instructions than a stack model
    - JoeQ is a lower-level IR than Java bytecode
- More conducive to program optimization than the stack architecture

Register Machine Model

- This mode assumes an unbounded number of pseudo-registers
- Pseudo-registers hold local variables of a method and temporary variables
- Data must first be loaded into pseudo registers before operating

Register Machine Model

```
class ExprTest {
    int test (int a) {
        int b, c, d, e, f;
        c = a + 10;
        f = a + c;
        if (f > 2) {
            f = f - c;
        }
        return (f);
    }
}
```

```
BB0 (ENTRY)     (in: <none>, out: BB2)

BB2     (in: BB0 (ENTRY), out: BB3, BB4)
1   ADD_I                  T0 int,     R1 int, IConst: 10
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3   ADD_I                  T0 int,     R1 int, R3 int
4   MOVE_I                 R6 int,     T0 int
5   IFCMP_I                R6 int,     IConst: 2,      LE,     BB4

BB3     (in: BB2, out: BB4)
6   SUB_I                  T0 int,     R6 int, R3 int
7   MOVE_I                 R6 int,     T0 int

BB4     (in: BB2, BB3, out: BB1 (EXIT))
8   RETURN_I               R6 int

BB1 (EXIT)      (in: BB4, out: <none>)
```

Quad Operators and Operands

```
BB2     (in: BB0 (ENTRY), out: BB3, BB4)
1   ADD_I                   T0 int,     R1 int, IConst: 10
2   MOVE_I                  R3 int,     T0 int
3   ADD_I                   T0 int,     R1 int, R3 int
4   MOVE_I                  R6 int,     T0 int
5   IFCMP_I                 R6 int,     IConst: 2,      LE,     BB4
```

- `quad.getOperator()` gives operator for quad
- `getAllOperands() ...` gives a list of all operands for a quad
- More meaningful methods such as `getDest()` to get destination register for a `move` instruction
  - Hierarchically ordered operators
  - Different operand types

JoeQ Operators (*joeq.Compiler.Quad.Operators*)

- `Operator.Move`
- `Operator.Unary, Operator.Binary`
- `Operator.Invoke`
- `Operator.Branch, Operator.GetField, Operation.PutField, Operator.New`
- Have suffixes indicating return type
  - For example, `ADD_I` adds two `ints`
  - Suffixes `I,L,F,D,A,V` refer to `int, long,float,double,reference, void`

```
BB0 (ENTRY)     (in: <none>, out: BB2)

BB2     (in: BB0 (ENTRY), out: BB3, BB4)
1   ADD_I              T0 int,     R1 int, IConst: 10
2   MOVE_I             R3 int,     T0 int
3   ADD_I              T0 int,     R1 int, R3 int
4   MOVE_I             R6 int,     T0 int
5   IFCMP_I            R6 int,     IConst: 2,  LE,BB4

BB3     (in: BB2, out: BB4)
6   SUB_I              T0 int,     R6 int, R3 int
7   MOVE_I             R6 int,     T0 int

BB4     (in: BB2, BB3, out: BB1 (EXIT))
8   RETURN_I           R6 int

BB1 (EXIT)      (in: BB4, out: <none>)
```

JoeQ Runtime Check Operators

```
Code:
0: aload_0
1: invokespecial #1
2: return
```

```
BB2     (in: BB0 (ENTRY), out: BB1 (EXIT))
2   NULL_CHECK          T-1 <g>,                          R0 ExprTest
1   INVOKESPECIAL_V%    java.lang.Object.<init> ()V,     (R0 ExprTest)
3   RETURN_V
```

- Runtime checks are explicit quads
  - Not implicit as in bytecodes
  - JoeQ is a lower-level IR than Java bytecode
- `Operator.NullCheck`
- `Operator.BoundsCheck`
- `Operator.CheckCast`, `Operator.StoreCheck`, etc.

JoeQ Operands (*`joeq.Compiler.Quad.Operand`*)

- `RegisterOperand`
  - Abstract registers representing parameters, local variables, and temporal variables
- `ConstOperand`
  - `int,float,long,double` constants
- `TargetOperand`
  - Basic block target of a branch instruction
- `MethodOperand, ParamListOperand`
  - Target and arguments to a method call
- `FieldOperand, TypeOperand,` etc.

JoeQ Quads

- Many useful methods, to get named registers, defined and used registers, etc
- See the assignment and JoeQ javadoc for more details

JoeQ CFGs (`joeq.Compiler.Quad.ControlFlowGraph`)

- Quads are organized into basic blocks
- Basic blocks are single-entry and also single-exit (barring exceptions)
- CFG, a control flow graph, is a graph of basic blocks with entry and exit
    - Entry and exit basic blocks always exist and are empty
    - Basic blocks are numbered with unique integer identifiers
    - Entry has identifier 0, exit has identifier 1

ExprTest.test(int a)

```
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    int test (int a) {
        int b, c, d, e, f;
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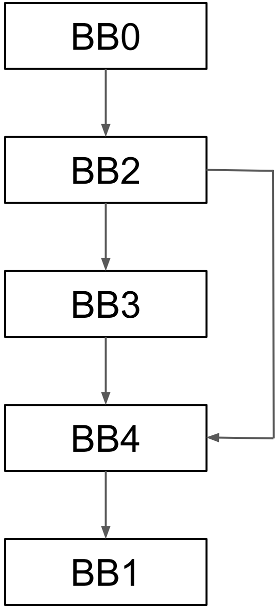
        f = a + c;
        if (f > 2) {
            f = f - c;
        }
        return (f);
    }
}
```




```
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BB2      (in: BB0 (ENTRY), out: BB3, BB4)
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4    MOVE_I             R6 int,      T0 int
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BB3      (in: BB2, out: BB4)
6    SUB_I              T0 int,      R6 int, R3 int
7    MOVE_I             R6 int,      T0 int

BB4      (in: BB2, BB3, out: BB1 (EXIT))
8    RETURN_I           R6 int

BB1  (EXIT)       (in: BB4, out: <none>)
```

JoeQ Basic Blocks (`joeQ.Compiler.Quad.BasicBlock`)

- List of quads
- Provide access to successors and predecessors
- Exception control flow is not explicit in JoeQ basic blocks
  - An exception can jump out of the middle of a basic block
  - You do not need to consider exceptions in this class

Writing Analysis with JoeQ

Often can be written with *visitors*, that traverse all loaded CFGs, or all basic blocks or quads in those CFGs

- `ControlFlowGraphVisitor`: interface for an analysis that makes a pass over CFGs
- `BasicBlockVisitor`: interface for an analysis that makes a pass over all basic blocks
- `QuadVisitor`: interface for an analysis that makes a pass over quads

Visitor Design Pattern

- A clean interface to the complexities of JoeQ (Façade design pattern)
- Add an operation to existing objects without modifying the structure of objects
  - Operations: variable, Objects: fixed
- Control flow graph analysis 1, analysis 2, etc.
  - Add methods analysis1, analysis2, etc. to ControlFlowGraph class *vs.*
  - Visitor pattern: Analysis1CfgVisitor, Analysis2CfgVisitor, etc.
- In compiler, representation is (almost) fixed
- Adding analysis/transformation should be flexible

QuadCounter

```
public class QuadCounter extends QuadVisitor.EmptyVisitor {
    public int count = 0;
    public void visitQuad(Quad q) { count++; }
}
```

QuadCounter

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}
```

- Some interfaces specify many methods
  - `visitQuad` will visit all `quads`
  - `visitX will visit only specific quads`
    - `visitStore` will visit only quads with `Store` operand
    - `visitLoad` will visit only quads with `Load` operand
- `EmptyVisitor` implements each method with a no-op
- Can override only the necessary methods

`LoadStoreCounter`

What if we only wanted to count the loads and stores?

LoadStoreCounter

```
public class QuadCounter extends QuadVisitor.EmptyVisitor {
    public int count = 0;
    public void visitQuad(Quad q) {
        count++;
    }
}

public class LoadStoreCounter extends QuadVisitor.EmptyVisitor {
    public int loadCount = 0, storeCount = 0;
    public void visitLoad(Quad q)  { loadCount++; }
    public void visitStore(Quad q) { storeCount++; }
}
```

`JoeQ.Main.Helper` Example: `QuadCounter`

```
class CountQuads {
     public static void main(String[] args) {
          jq_Class[] classes = new jq_Class[args.length];
          for (String className : args) {
               jq_Class c = (jq_Class)Helper.load(className);
               System.out.println("Class:" + className);
               QuadCounter qc = new QuadCounter();
               Helper.runPass(c, qc);
               System.out.println(className + "has" + qc.count + "quads");
          }
     }
}
```

`runPass(CFG or quad, visitor)` runs a `ControlFlowGraphVisitor` or `QuadVisitor` over `ControlFlowGraphs` or `Quads`.

QuadIterator

- An alternative to visitors
- Simple interface to iterate through all the quads in a reverse post-order
- Extends java.util.Iterator<Quad>

QuadIterator

- An alternative to visitors
- Simple interface to iterate through all the quads in a reverse post-order
- Extends `java.util.Iterator<Quad>`

```
ControlFlowGraph cfg = …
     QuadIterator iter = new QuadIterator(cfg);
     while (iter.hasNext()) {
          Quad quad = iter.next();
          if (quad.getOperator() instanceof Operator.Invoke) {
               doSomething(cfg.getMethod(), quad);
          }
     }
```

`QuadIterator`

- `next()` and `previous()` return next and previous quad respectively in a reverse-post-order listing
- `successors()` and `predecessors()` return an iterator of possible successor quads and possible predecessor quads respectively

Java Beginners

- Java collections library
  - *List*, *Set*, *Map*, etc.
- Java generics
- Inner class
- …
- Make yourself familiar with these concepts

HW 2: Dataflow framework

- We provide:
  - Solver interface: `Flow.Solver`
  - Analysis interface: `Flow.Analysis`
  - Two analyses that extend `Flow.Analysis`: `ConstantProp` and `Liveness`

- Goal is to complete:
  - `MySolver` skeleton that extends `Flow.Solver`
    - Should work with `ConstantProp` and `Liveness`
  - `ReachingDefs` skeleton that extends `Flow.Analysis`
  - `Faintness` analysis