{Bite}Code Generation

COMP 520: Compiler Design (4 credits)

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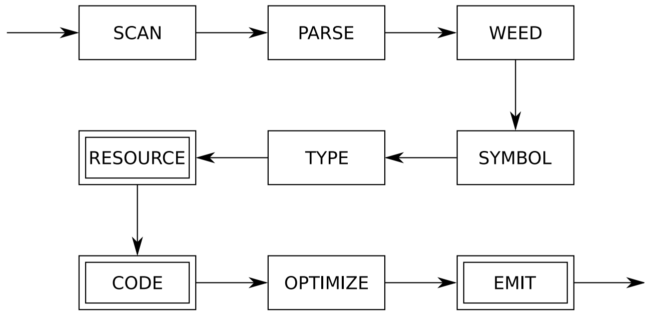
MWF 13:30-14:30, MD 279



McCompiley

Announcements (Wednesday, Feb 15/Friday, Feb 17)

- Milestone 1 due **Friday, February 24th 11:59PM** on GitHub

The *code generation* phase has several sub-phases:

- computing *resources* such as stack layouts, offsets, labels, registers, and dimensions;
- generating an internal representation of machine codes for statements and expressions;
- optimizing the code (ignored for now); and
- emitting the code to files in assembler or binary format.

Resources in JOOS:

- offsets for locals and formals;
- labels for control structures; and
- local and stack limits for methods.

These are values that cannot be computed based on a single statement.

We must perform a global traversal of the parse trees.

Computing offsets and the locals limit:

```
public class Example {

  public Example() { super(); }

  public void Method(int p$\boxed{1}$, int q$\boxed{2}$, Example r$\boxed{3}$) {
      int x$\boxed{4}$;
      int y$\boxed{5}$;
      { int z$\boxed{6}$;
        z = 87;
      }
      { boolean a$\boxed{6}$;
        Example x$\boxed{7}$;
        { boolean b$\boxed{8}$;
          int z$\boxed{9}$;
          b = true;
        }
        { int y$\boxed{8}$;
          y = x;
        }
      }
  }
}
```

The locals limit is the largest offset generated in the method + one extra slot for `this`.

Corresponding JOOS source:

```
int offset, localslimit;

int nextoffset() {
    offset++;
    if (offset > localslimit) localslimit = offset;
    return offset;
}

void resFORMAL(FORMAL *f) {
    if (f!=NULL) {
        resFORMAL(f->next);
        f->offset = nextoffset();
    }
}

void resID(ID *i) {
    if (i!=NULL) {
        resID(i->next);
        i->offset = nextoffset();
    }
}
```

Handling blocks:

```
case blockK:
     baseoffset = offset;
     resSTATEMENT(s->val.blockS.body);
     offset = baseoffset;
     break;
```

Computing labels for control structures:

`if`:	1 label
`ifelse`:	2 labels
`while`:	2 labels
`toString` coercion:	2 labels
`||` and `&&`:	1 label
`==`, `<`, `>`, `<=`, `>=`, and `!=`:	2 labels
`!`:	2 labels

Labels are generated consecutively, for each method and constructor separately.

The Jasmin assembler converts labels to addresses. An address in Java bytecode is a 16-bit offset with respect to the branching instruction. The target address must be part of the code array of the same method.

Corresponding JOOS source:

```
int label;
int nextlabel() {
    return label++;
}

[...]

case whileK:
    s->val.whileS.startlabel = nextlabel();
    s->val.whileS.stoplabel = nextlabel();
    resEXP(s->val.whileS.condition);
    resSTATEMENT(s->val.whileS.body);
    break;

[...]

case orK:
    e->val.orE.truelabel = nextlabel();
    resEXP(e->val.orE.left);
    resEXP(e->val.orE.right);
    break;

[...]
```

JOOS compiler's representation of bytecode

```
typedef struct CODE {
    enum {nopCK,i2cCK,
          newCK,instanceofCK,checkcastCK,
          imulCK,inegCK,iremCK,isubCK,idivCK,iaddCK,iincCK,
          labelCK,gotoCK,ifeqCK,ifneCK,
          if_acmpeqCK,if_acmpneCK, ifnullCK,ifnonnullCK,
          if_icmpeqCK,if_icmpgtCK,if_icmpltCK,
          if_icmpleCK,if_icmpgeCK,if_icmpneCK,
          ireturnCK,areturnCK,returnCK,
          aloadCK,astoreCK,iloadCK,istoreCK,dupCK,popCK,
          swapCK,ldc_intCK,ldc_stringCK,aconst_nullCK,
          getfieldCK,putfieldCK,
          invokevirtualCK,invokenonvirtualCK} kind;
    union {
          char *newC;
          char *instanceofC;
          char *checkcastC;
          struct {int offset; int amount;} iincC;
          int labelC;
          int gotoC;
          int ifeqC;

          [...]
```

```
            int istoreC;
            int ldc_intC;
            char *ldc_stringC;
            char *getfieldC;
            char *putfieldC;
            char *invokevirtualC;
            char *invokenonvirtualC;
      } val;
      struct CODE *next;
  } CODE;
```

Code templates:

- show how to generate code for each language construct;
- ignore the surrounding context; and
- dictate a simple, recursive strategy.

Code template invariants:

- evaluation of a statement leaves the stack height unchanged; and
- evaluation of an expression increases the stack height by one.

Special case of `ExpressionStatement`:

- Expression is evaluated, result is then popped off the stack, except
- for `void` return expressions, nothing is popped.

The statement:

`if (`$\boldsymbol{E}$`)` $\boldsymbol{S}$

has code template:

$\boldsymbol{E}$
`ifeq stop`
$\boldsymbol{S}$
`stop:`

Corresponding JOOS source:

```
case ifK:
     codeEXP(s->val.ifS.condition);
     code_ifeq(s->val.ifS.stoplabel);
     codeSTATEMENT(s->val.ifS.body);
     code_label("stop",s->val.ifS.stoplabel);
     break;
```

The statement:

`if (`$\boldsymbol{E}$`)` $\boldsymbol{S\_1}$ `else` $\boldsymbol{S\_2}$

has code template:

$\boldsymbol{E}$
```
ifeq else
```
$\boldsymbol{S\_1}$
```
goto stop
else:
```
$\boldsymbol{S\_2}$
```
stop:
```

Corresponding JOOS source:

```
case ifelseK:
     codeEXP(s->val.ifelseS.condition);
     code_ifeq(s->val.ifelseS.elselabel);
     codeSTATEMENT(s->val.ifelseS.thenpart);
     code_goto(s->val.ifelseS.stoplabel);
     code_label("else",s->val.ifelseS.elselabel);
     codeSTATEMENT(s->val.ifelseS.elsepart);
     code_label("stop",s->val.ifelseS.stoplabel);
     break;
```

Practice:

```
public class A {

    public A () {
          super();
    }

    public int m (int x) {
          if (x < 0)
                return (x*x);
          else
                return (x*x*x);
    }
}
```

- Resources?
- Jasmin code generated?

```
public int m (int x) {
     if (x < 0)
          return (x*x);
     else
          return (x*x*x);
}
```

```
.method public m(I)I
.limit locals 2
.limit stack 2
   iload_1
   iconst_0
   if_icmplt true_2
   iconst_0
   goto stop_3
true_2:
   iconst_1
stop_3:
   ifeq else_0
   iload_1
   iload_1
   imul
   ireturn
   goto stop_1
else_0:
   iload_1
   iload_1
   imul
   iload_1
   imul
   ireturn
stop_1:
   nop
.end method
```

What would be different for this?

```
public class A {

    public A () {
        super();
    }

    public int m (int x) {
        if (x < 0)
            return (x*x);
        else
            return (x*(x*x));
    }
}
```

```
public int m (int x) {
    if (x < 0)
        return (x*x);
    else
        return (x*(x*x));
}
```

```
.method public m(I)I
.limit locals 2
.limit stack 3
   iload_1
   iconst_0
   if_icmplt true_2
   iconst_0
   goto stop_3
true_2:
   iconst_1
stop_3:
   ifeq else_0
   iload_1
   iload_1
   imul
   ireturn
   goto stop_1
else_0:
   iload_1 ; load x three times
   iload_1
   iload_1
   imul  ; two imuls
   imul
   ireturn
stop_1:
   nop
.end method
```

The statement:

```
while ($\boldsymbol{E}$) $\boldsymbol{S}$
```

has code template:

```
start:
$\boldsymbol{E}$
ifeq stop
$\boldsymbol{S}$
goto start
stop:
```

Corresponding JOOS source:

```
case whileK:
     code_label("start",s->val.whileS.startlabel);
     codeEXP(s->val.whileS.condition);
     code_ifeq(s->val.whileS.stoplabel);
     codeSTATEMENT(s->val.whileS.body);
     code_goto(s->val.whileS.startlabel);
     code_label("stop",s->val.whileS.stoplabel);
     break;
```

The statement:

$\boldsymbol{E}$

has code template:

$\boldsymbol{E}$

if $\boldsymbol{E}$ has type `void` and otherwise:

```
E
pop
```

Corresponding JOOS source:

```
case expK:
     codeEXP(s->val.expS);
           if (s->val.expS->type->kind!=voidK) {
                 code_pop();
           }
           break;
```

The local variable expression:

$\boldsymbol{x}$

has code template:

```
iload  offset(x)
```

if $\boldsymbol{x}$ has type `int` or `boolean` and otherwise:

```
aload  offset(x)
```

Corresponding JOOS source:

```
case localSym:
     if (e->val.idE.idsym->val.localS.type->kind==refK) {
           code_aload(e->val.idE.idsym->val.localS->offset);
     } else {
           code_iload(e->val.idE.idsym->val.localS->offset);
     }
     break;
```

The assignment to a variable:

$\boldsymbol{x}$=$\boldsymbol{E}$

is an expression on its own and has code template:

```
E
dup
istore   offset(x)
```

if $\boldsymbol{x}$ has type `int` or `boolean` and otherwise:

```
E
dup
astore   offset(x)
```

Corresponding JOOS source:

```
case formalSym:
     codeEXP(e->val.assignE.right);
     code_dup();
     if (e->val.assignE.leftsym->val.formalS->type->kind==refK) {
            code_astore(e->val.assignE.leftsym->val.formalS->offset);
     } else {
            code_istore(e->val.assignE.leftsym->val.formalS->offset);
     }
     break;
```

The expression:

$\boldsymbol{E\_1}$ `||` $\boldsymbol{E\_2}$

has code template:

```
E_1
dup
ifne true
pop
E_2
true:
```

Corresponding JOOS source:

```
case orK:
     codeEXP(e->val.orE.left);
     code_dup();
     code_ifne(e->val.orE.truelabel);
     code_pop();
     codeEXP(e->val.orE.right);
     code_label("true",e->val.orE.truelabel);
     break;
```

Example of short-circuit:

```
public class B {

    public B () {
        super();
    }

    public int m (int x, int y) {
        if ((y != 0) && (x / y > 2))
            return (x/y);
        if ((y !=0 ) || (x != 0))
            return (x*y);
        return(0);
    }
}
```

```
if ((y != 0) && (x / y > 2))
     return (x/y);
```

```
   iload_2
   iconst_0
   if_icmpne true_2
   iconst_0
   goto stop_3
true_2:
   iconst_1
stop_3:
   dup
   ifeq false_1
   pop
   iload_1
   iload_2
   idiv
   iconst_2
   if_icmpgt true_4
   iconst_0
   goto stop_5
true_4:
   iconst_1
stop_5:
false_1:
   ifeq stop_0
   iload_1
   iload_2
   idiv
   ireturn
stop_0:
```

```
if ((y !=0 ) || (x != 0))
    return (x*y);
```

```
    iload_2
    iconst_0
    if_icmpne true_8
    iconst_0
    goto stop_9
true_8:
    iconst_1
stop_9:
    dup
    ifne true_7
    pop
    iload_1
    iconst_0
    if_icmpne true_10
    iconst_0
    goto stop_11
true_10:
    iconst_1
stop_11:
true_7:
    ifeq stop_6
    iload_1
    iload_2
    imul
    ireturn
stop_6:
```

The expression:

$\boldsymbol{E\_1}$ `==` $\boldsymbol{E\_2}$

has code template:

$\boldsymbol{E\_1}$
$\boldsymbol{E\_2}$
```
if_icmpeq true
ldc_int 0
goto stop
true:
ldc_int 1
stop:
```

if E_i has type `int` or `boolean`.

Corresponding JOOS source:

```
case eqK:
     codeEXP(e->val.eqE.left); codeEXP(e->val.eqE.right);
     if (e->val.eqE.left->type->kind==refK) {
            code_if_acmpeq(e->val.eqE.truelabel);
     } else {
            code_if_icmpeq(e->val.eqE.truelabel);
     }
     code_ldc_int(0);
     code_goto(e->val.eqE.stoplabel);
     code_label("true",e->val.eqE.truelabel);
     code_ldc_int(1);
     code_label("stop",e->val.eqE.stoplabel);
     break;
```

The expression:

$\boldsymbol{E\_1}$ + $\boldsymbol{E\_2}$

has code template:

```
E_1
E_2
iadd
```

if E_i has type `int` and otherwise:

```
E_1
E_2
invokevirtual   java/lang/String/concat(Ljava/lang/String;)Ljava/lang/String;
```

Corresponding JOOS source:

```
case plusK:
     codeEXP(e->val.plusE.left);
     codeEXP(e->val.plusE.right);
     if (e->type->kind==intK) {
            code_iadd();
     } else {
            code_invokevirtual("java/lang/.../String;");
     }
     break;
```

(A separate test of an `e->tostring` field is used to handle string coercion.)

The expression:

$!\boldsymbol{E}$

has code template:

$\boldsymbol{E}$
```
ifeq true
ldc_int 0
goto stop
true:
ldc_int 1
stop:
```

Corresponding JOOS source:

```
case notK:
     codeEXP(e->val.notE.not);
     code_ifeq(e->val.notE.truelabel);
     code_ldc_int(0);
     code_goto(e->val.notE.stoplabel);
     code_label("true",e->val.notE.truelabel);
     code_ldc_int(1);
     code_label("stop",e->val.notE.stoplabel);
     break;
```

```java
public int m (int x) {
     if (!!!!(x < 0))
            return (x*x);
     else
            return (x*x*x);
}
```

```
.method public m(I)I
.limit locals 2
.limit stack 2
   iload_1
   iconst_0
   if_icmplt true_10
   iconst_0
   goto stop_11
true_10:
   iconst_1
stop_11:
   ifeq true_8
   iconst_0
   goto stop_9
true_8:
   iconst_1
stop_9:
   ifeq true_6
   iconst_0
   goto stop_7
true_6:
   iconst_1
stop_7:
   ifeq true_4
   iconst_0
   goto stop_5
true_4:
   iconst_1
stop_5:
   ifeq true_2
   iconst_0
   goto stop_3
true_2:
   iconst_1
stop_3:
   ifeq else_0
   iload_1
   iload_1
   imul
   ireturn
   goto stop_1
else_0:
   iload_1
   iload_1
   imul
   iload_1
   imul
   ireturn
stop_1:
   nop
.end method
```

Alternative translation of Boolean expressions:

Short-circuit or Jumping code

Motivating example: Expression

$$!\,!\,!\,!\,!\,!\,!\boldsymbol{E}$$

would generate lots of jumps when using the template described earlier. (Other Boolean operations, too.)

Idea: Can encode Boolean logic by more clever introduction and swaps of labels.

Use function *trans*$(\boldsymbol{b}, \boldsymbol{l}, \boldsymbol{t}, \boldsymbol{f})$ with:

$\boldsymbol{b}$ Boolean expression

$\boldsymbol{l}$ label for evaluating current expression

$\boldsymbol{t}$ jump-label in case $\boldsymbol{b}$ evaluates to $\mathbf{true}$

$\boldsymbol{f}$ jump-label in case $\boldsymbol{b}$ evaluates to $\mathbf{false}$

trans($E_1 == E_2, l, t, f$) =

```
l: E_1
   E_2
   if_icmpeq true
   ldc_int 0
   goto f
   true:
   ldc_int 1
   goto t
```

trans(! E, l, t, f) = *trans*(E, l, f, t)

trans(E_1 `&&` E_2, l, t, f) = *trans*(E_1, l, l', f), *trans*(E_2, l', t, f)

trans(E_1 `||` E_2, l, t, f) = *trans*(E_1, l, t, l'), *trans*(E_2, l', t, f)

Jumping code can be longer in comparison but for each branch it will usually execute less instructions.

The expression:

```
this
```

has code template:

```
aload 0
```

Corresponding JOOS source:

```
case thisK:
     code_aload(0);
     break;
```

The expression:

```
null
```

has code template:

```
ldc_string "null"
```

if it is `toString` coerced and otherwise:

```
aconst_null
```

Corresponding JOOS source:

```
case nullK:
     if (e->tostring) {
          code_ldc_string("null");
     } else {
          code_aconst_null();
     }
     break;
```

The expression:

$\boldsymbol{E}$. $\boldsymbol{m}$ ($\boldsymbol{E\_1}$, . . . , $\boldsymbol{E\_n}$)

has code template:

```
E
E_1
.
.
.
E_n
invokevirtual  signature(class(E),m)
```

class($\boldsymbol{E}$*)* is the declared class of $\boldsymbol{E}$.

signature(C,$\boldsymbol{m}$*)* is the signature of the first implementation of $\boldsymbol{m}$ that is found from *C*.

The expression:

```
super.m(E_1, ..., E_n)
```

has code template:

```
aload 0
E_1
.
.
.
E_n
invokespecial  signature(parent(thisclass)),m)
```

thisclass is the current class.

parent(C) is the parent of *C* in the hierarchy.

signature(C, $\boldsymbol{m}$*)* is the signature of the first implementation of $\boldsymbol{m}$ that is found from *parent(C)*.

Corresponding JOOS source:

```
case invokeK:
     codeRECEIVER(e->val.invokeE.receiver);
     codeARGUMENT(e->val.invokeE.args);
     switch (e->val.invokeE.receiver->kind) {
          case objectK: {
                SYMBOL *s = lookupHierarchyClass(
                      e->val.invokeE.method->name,
                      e->val.invokeE.receiver-> objectR->type->class);
                      code_invokevirtual(codeMethod(
                            s,e->val.invokeE.method)
                );
                break;
          }
          case superK: {
                CLASS *c = lookupHierarchyClass(
                      e->val.invokeE.method->name,
                      currentclass->parent);
                      code_invokenonvirtual(codeMethod(
                            c,e->val.invokeE.method)
                );
                break;
          }
     }
     break;
```

A `toString` coercion of the expression:

$\boldsymbol{E}$

has code template:

```
new  java/lang/Integer
dup
E
invokespecial  java/lang/Integer/⟨init⟩(I)V
invokevirtual  java/lang/Integer/toString()Ljava/lang/String;
```

if $\boldsymbol{E}$ has type `int`, and:

```
new  java/lang/Boolean
dup
E
invokespecial  java/lang/Boolean/⟨init⟩(Z)V
invokevirtual  java/lang/Boolean/toString()Ljava/lang/String;
```

if $\boldsymbol{E}$ has type `boolean`, and:

```
new  java/lang/Character
dup
E
invokespecial  java/lang/Character/⟨init⟩(C)V
invokevirtual  java/lang/Character/toString()Ljava/lang/String;
```

if $\boldsymbol{E}$ has type `char`.

A `toString` coercion of the expression:

$\boldsymbol{E}$

has code template:

```
E
dup
ifnull nulllabel
invokevirtual  signature(class(E), toString)
goto stoplabel
nulllabel:
pop
ldc_string "null"
stoplabel:
```

if $\boldsymbol{E}$ does not have type `int`, `boolean`, or `char`.

Computing the stack limit:

```
public void Method() {
     int x, y;
     x = 12; y = 87;
     x:=2*(x+y*(x-y));
}
```

```
.method public Method()V
  .limit locals 3
  .limit stack 5
  ldc 12          ← 1
  dup             ← 2
  istore_1        ← 1
  pop             ← 0
  ldc 87          ← 1
  dup             ← 2
  istore_2        ← 1
  pop             ← 0
  iconst_2        ← 1
  iload_1         ← 2
  iload_2         ← 3
  iload_1         ← 4
  iload_2         ← 5
  isub            ← 4
  imul            ← 3
  iadd            ← 2
  imul            ← 1
  dup             ← 2
  istore_1        ← 1
  pop             ← 0
  return
.end method
```

The stack limit is the maximum height of the stack during the evaluation of an expression in the method.

This requires detailed knowledge of:

- the code that is generated; and
- the virtual machine.

Stupid A- JOOS source:

```
int limitCODE(CODE *c) {
    return 25;
}
```

Code is emitted in Jasmin format:

```
.class public C
.super parent(C)

.field protected x_1 type(x_1)
.
.
.
.field protected x_k type(x_k)

.method public m_1 signature(C,m_1)
   .limit locals l_1
   .limit stack s_1
   S_1
.end method

.
.
.

.method public m_n signature(C,m_n)
   .limit locals l_n
   .limit stack s_n
   S_n
.end method
```

The signature of a method `m` in a class `C` with argument types $\boldsymbol{\tau_1, \ldots, \tau_k}$ and return type $\boldsymbol{\tau}$ is represented in Jasmin as:

`C/m` (*rep(*$\boldsymbol{\tau_1}$*)*. . . *rep(*$\boldsymbol{\tau_k}$*)*) rep($\boldsymbol{\tau}$)

where:

- *rep(*`int`*)* = `I`
- *rep(*`boolean`*)* = `Z`
- *rep(*`char`*)* = `C`
- *rep(*`void`*)* = `V`
- *rep(*`C`*)* = `LC`**;**

A tiny JOOS class:

```
import joos.lib.*;

public class Tree {
    protected Object value;
    protected Tree left;
    protected Tree right;

    public Tree(Object v, Tree l, Tree r) {
          super();
          value = v;
          left = l;
          right = r;
    }

    public void setValue(Object newValue) {
          value = newValue;
    }
}
```

The compiled Jasmin file:

```
.class public Tree
.super java/lang/Object
.field protected value Ljava/lang/Object;
.field protected left LTree;
.field protected right LTree;

.method public <init>(Ljava/lang/Object;LTree;LTree;)V
.limit locals 4
.limit stack 3
   aload_0
   invokenonvirtual java/lang/Object/<init>()V
   aload_0
   aload_1
   putfield Tree/value Ljava/lang/Object;
   aload_0
   aload_2
   putfield Tree/left LTree;
   aload_0
   aload_3
   putfield Tree/right LTree;
   return
.end method
```

```
.method public setValue(Ljava/lang/Object;)V
.limit locals 2
.limit stack 3
   aload_0
   aload_1
   putfield Tree/value Ljava/lang/Object;
   return
.end method
```

Hex dump of the class file:

```
cafe babe 0003 002d 001a 0100 064c 5472
6565 3b07 0010 0900 0200 0501 0015 284c
6a61 7661 2f6c 616e 672f 4f62 6a65 6374
3b29 560c 0018 0001 0100 0654 7265 652e
6a01 000a 536f 7572 6365 4669 6c65 0100
0443 6f64 6507 000d 0c00 0e00 1209 0002
0017 0100 2128 4c6a 6176 612f 6c61 6e67
2f4f 626a 6563 743b 4c54 7265 653b 4c54
7265 653b 2956 0100 106a 6176 612f 6c61
6e67 2f4f 626a 6563 7401 0005 7661 6c75
650c 0011 0019 0100 0454 7265 6501 0006
3c69 6e69 743e 0100 124c 6a61 7661 2f6c
616e 672f 4f62 6a65 6374 3b0a 0009 000f
0100 0873 6574 5661 6c75 6509 0002 000a
0100 046c 6566 740c 0016 0001 0100 0572
6967 6874 0100 0328 2956 0021 0002 0009
0000 0003 0006 000e 0012 0000 0006 0016
0001 0000 0006 0018 0001 0000 0002 0001
0011 000c 0001 0008 0000 0020 0003 0004
0000 0014 2ab7 0013 2a2b b500 152a 2cb5
000b 2a2d b500 03b1 0000 0000 0001 0014
0004 0001 0008 0000 0012 0003 0002 0000
0006 2a2b b500 15b1 0000 0000 0001 0007
0000 0002 0006
```

djas -w Tree.class

```
; magic number 0xCAFEBABE
; bytecode version 45.3

; constant pool count 26
; cp[1] (offset 0xf) -> CONSTANT_NameAndType 9, 25
; cp[2] (offset 0x22) -> CONSTANT_Utf8 "java/lang/Object"
; cp[3] (offset 0x27) -> CONSTANT_Fieldref 12, 21
; cp[4] (offset 0x30) -> CONSTANT_Utf8 "<init>"
; cp[5] (offset 0x3b) -> CONSTANT_Utf8 "setValue"
; cp[6] (offset 0x3e) -> CONSTANT_Class 2
; cp[7] (offset 0x43) -> CONSTANT_NameAndType 4, 10
; cp[8] (offset 0x48) -> CONSTANT_Fieldref 12, 1
; cp[9] (offset 0x4f) -> CONSTANT_Utf8 "left"
; cp[10] (offset 0x55) -> CONSTANT_Utf8 "()V"
; cp[11] (offset 0x5c) -> CONSTANT_Utf8 "Code"
; cp[12] (offset 0x5f) -> CONSTANT_Class 22
; cp[13] (offset 0x64) -> CONSTANT_Fieldref 12, 18
; cp[14] (offset 0x71) -> CONSTANT_Utf8 "SourceFile"
; cp[15] (offset 0x86) -> CONSTANT_Utf8 "Ljava/lang/Object;"
; cp[16] (offset 0xaa) -> CONSTANT_Utf8 "(Ljava/lang/Object;LTree;LTree;)V"
; cp[17] (offset 0xaf) -> CONSTANT_Methodref 6, 7
; cp[18] (offset 0xb4) -> CONSTANT_NameAndType 24, 25
; cp[19] (offset 0xcc) -> CONSTANT_Utf8 "(Ljava/lang/Object;)V"
; cp[20] (offset 0xd4) -> CONSTANT_Utf8 "value"
; cp[21] (offset 0xd9) -> CONSTANT_NameAndType 20, 15
; cp[22] (offset 0xe0) -> CONSTANT_Utf8 "Tree"
; cp[23] (offset 0xe9) -> CONSTANT_Utf8 "Tree.j"
; cp[24] (offset 0xf1) -> CONSTANT_Utf8 "right"
; cp[25] (offset 0xfa) -> CONSTANT_Utf8 "LTree;"

; access flags = 0x21 [ ACC_SUPER ACC_PUBLIC ]
; this_class index = 12
; super_class index = 6
; interfaces_count = 0

; fields_count = 3

; fields[0] (offset 0x104) :
;     access_flags 0x4 [ ACC_PROTECTED ]
;     name_index 20 (value)
;     descriptor_index 15 (Ljava/lang/Object;)
;     attributes_count 0

; fields[1] (offset 0x10c) :
;     access_flags 0x4 [ ACC_PROTECTED ]
;     name_index 9 (left)
;     descriptor_index 25 (LTree;)
;     attributes_count 0

; fields[2] (offset 0x114) :
;     access_flags 0x4 [ ACC_PROTECTED ]
;     name_index 24 (right)
;     descriptor_index 25 (LTree;)
;     attributes_count 0

; methods_count 2

; methods[0] (offset 0x11e) :
;     access_flags 0x1 [ ACC_PUBLIC ]
;     name_index 4 (<init>)
;     descriptor_index 16 ((Ljava/lang/Object;LTree;LTree;)V)
;     attributes_count 1
;     method_attributes[0] :
;         name_index 11 (Code)
;         attribute_length 41
;         max_stack 3
;         max_locals 4
;           code_length 29
;           code :
;                  0: aload_0
;                  1: invokespecial 17 (java/lang/Object/<init> ()V)
;                  4: aload_1
;                  5: dup
;                  6: aload_0
;                  7: swap
;                  8: putfield 3 (Tree/value Ljava/lang/Object;)
;                 11: pop
;                 12: aload_2
;                 13: dup
;                 14: aload_0
;                 15: swap
;                 16: putfield 8 (Tree/left LTree;)
;                 19: pop
;                 20: aload_3
;                 21: dup
;                 22: aload_0
;                 23: swap
;                 24: putfield 13 (Tree/right LTree;)
;                 27: pop
;                 28: return
;           exception_table_length 0
;           attributes_count 0

; methods[1] (offset 0x155) :
;       access_flags 0x1 [ ACC_PUBLIC ]
;       name_index 5 (setValue)
;       descriptor_index 19 ((Ljava/lang/Object;)V)
;       attributes_count 1
;       method_attributes[0] :
;           name_index 11 (Code)
;           attribute_length 21
;           max_stack 3
;           max_locals 2
;           code_length 9
;           code :
;                   0: aload_1
;                   1: dup
;                   2: aload_0
;                   3: swap
;                   4: putfield 3 (Tree/value Ljava/lang/Object;)
;                   7: pop
;                   8: return
;           exception_table_length 0
;           attributes_count 0


; attributes_count 1

; class_attributes[0] (offset 0x17a) :
;     name_index 14 (SourceFile)
;     attribute_length 2
;     sourcefile_index 23

; End of file reached successfully. Enjoy :)
```

The testing strategy for the code generator involves two phases.

First a careful argumentation that each code template is correct.

Second a demonstration that each code template is generated correctly.