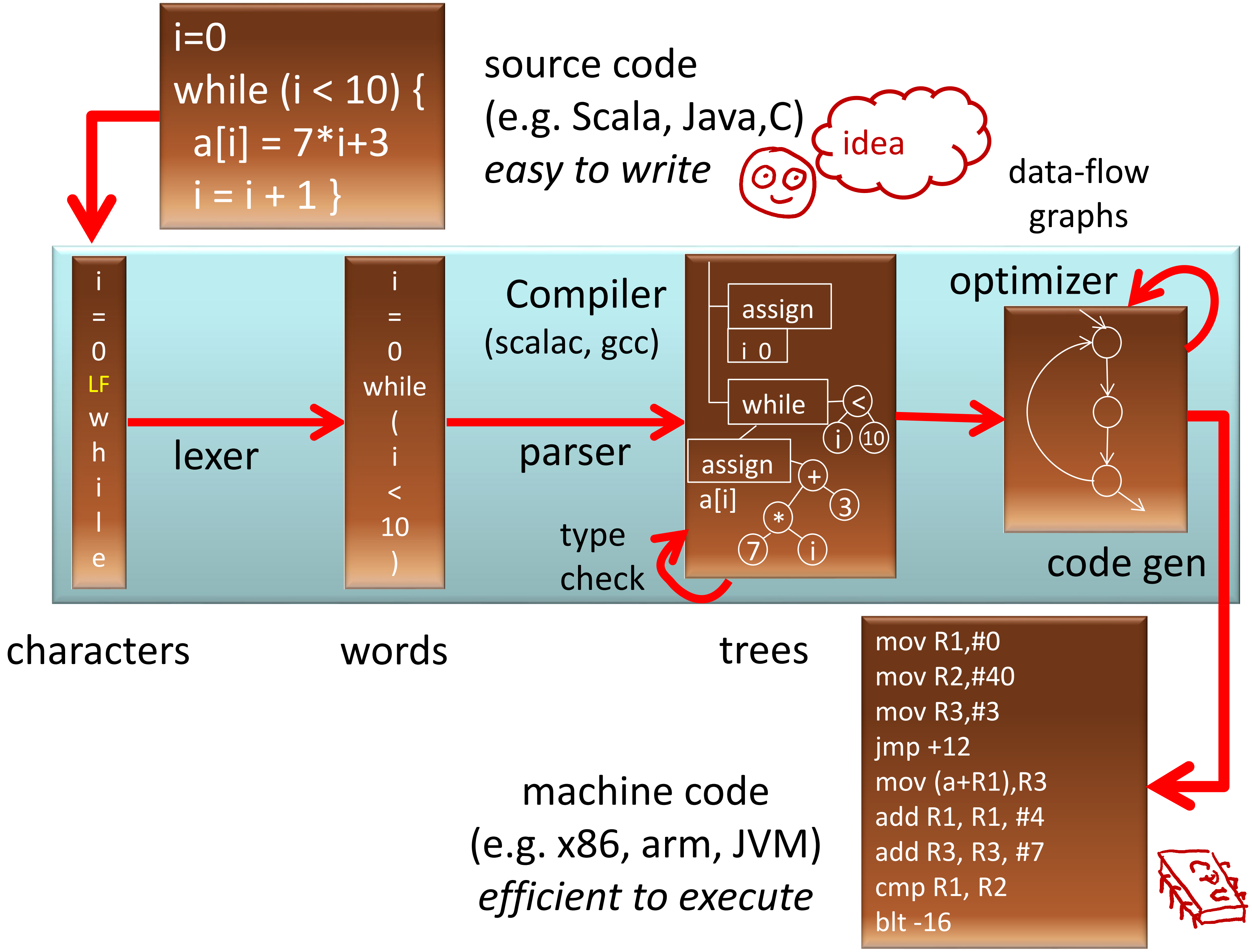
Code Generation: Introduction



```
i=0
while (i < 10) {
  a[i] = 7*i+3
  i = i + 1 }
```

source code
(e.g. Scala, Java,C)
easy to write

characters

words

trees

machine code
(e.g. x86, arm, JVM)
efficient to execute

```
mov R1,#0
mov R2,#40
mov R3,#3
jmp +12
mov (a+R1),R3
add R1, R1, #4
add R3, R3, #7
cmp R1, R2
blt -16
```

Example: gcc

test.c

```
#include <stdio.h>
int main() {
  int i = 0;
  int j = 0;
  while (i < 10) {
    printf("%d\n", j);
    i = i + 1;
    j = j + 2*i+1;
  }
}
```

gcc test.c -S

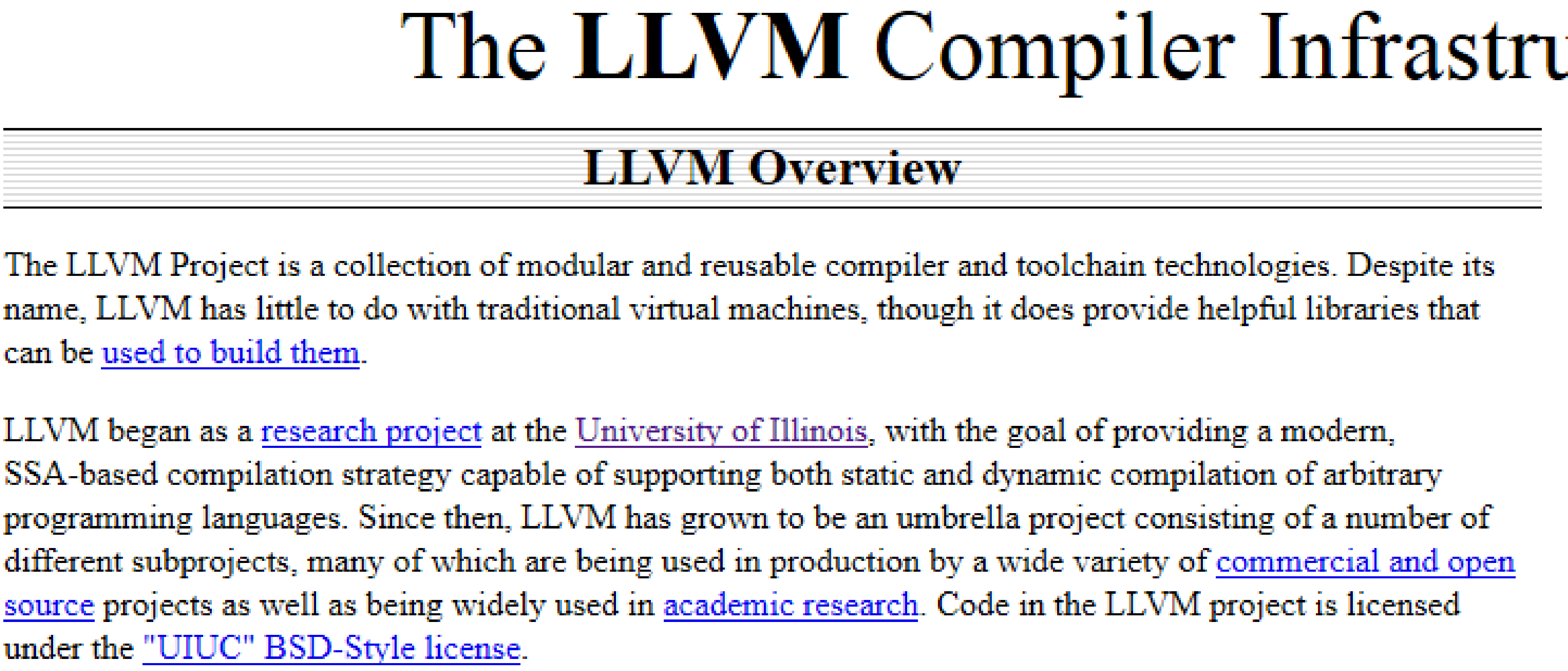
test.s

```
        jmp .L2
.L3:    movl -8(%ebp), %eax
        movl %eax, 4(%esp)
        movl $.LC0, (%esp)
        call printf
        addl $1, -12(%ebp)
        movl -12(%ebp), %eax
        addl %eax, %eax
        addl -8(%ebp), %eax
        addl $1, %eax
        movl %eax, -8(%ebp)
.L2:
        cmpl $9, -12(%ebp)
        jle .L3
```

What did (i<10) compile to?

LLVM: Another Interesting C Compiler

http://llvm.org



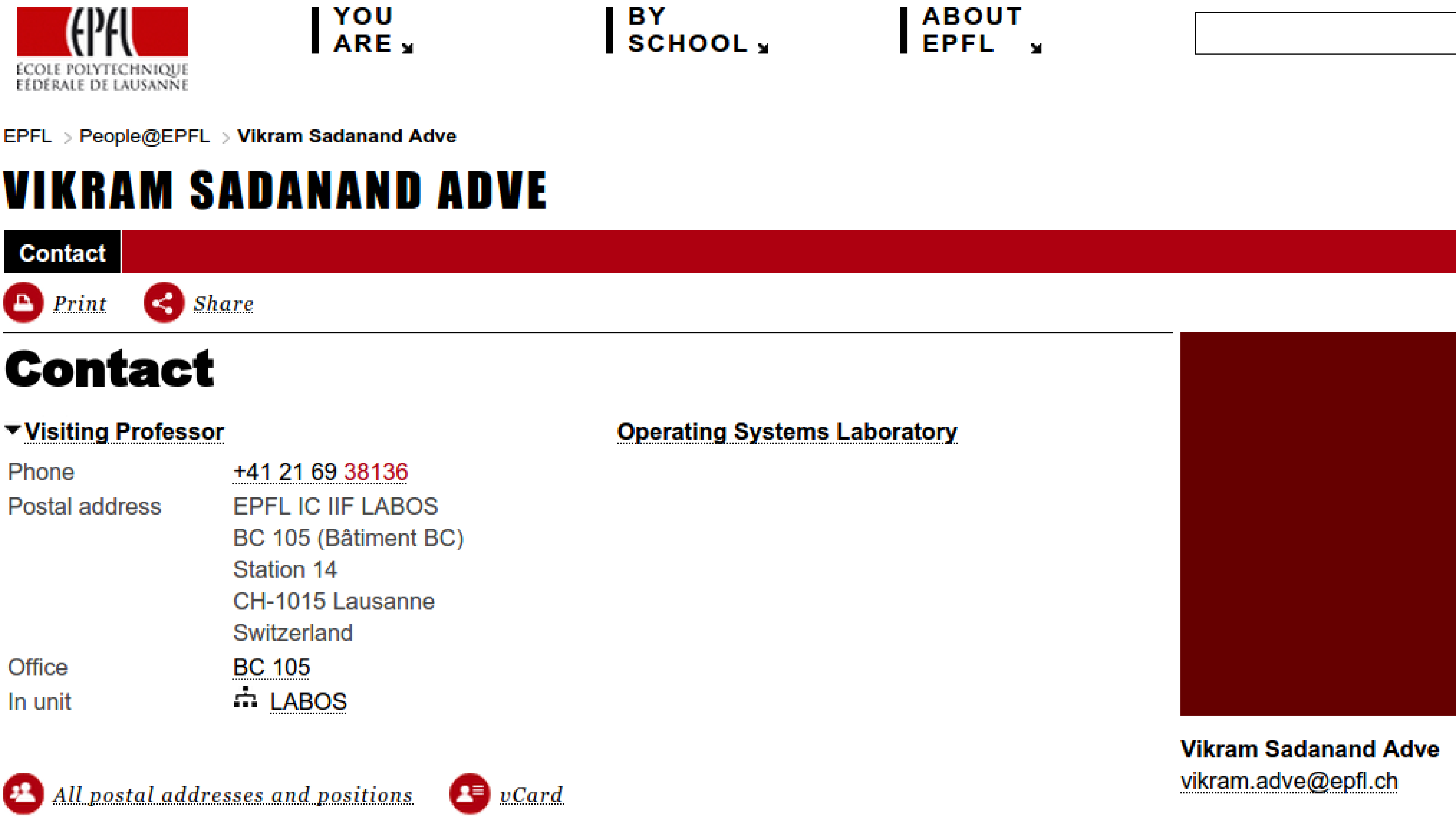
The **LLVM** Compiler Infrastru

LLVM Overview

The LLVM Project is a collection of modular and reusable compiler and toolchain technologies. Despite its name, LLVM has little to do with traditional virtual machines, though it does provide helpful libraries that can be used to build them.

LLVM began as a research project at the University of Illinois, with the goal of providing a modern, SSA-based compilation strategy capable of supporting both static and dynamic compilation of arbitrary programming languages. Since then, LLVM has grown to be an umbrella project consisting of a number of different subprojects, many of which are being used in production by a wide variety of commercial and open source projects as well as being widely used in academic research. Code in the LLVM project is licensed under the "UIUC" BSD-Style license.

http://people.epfl.ch/vikram.adve



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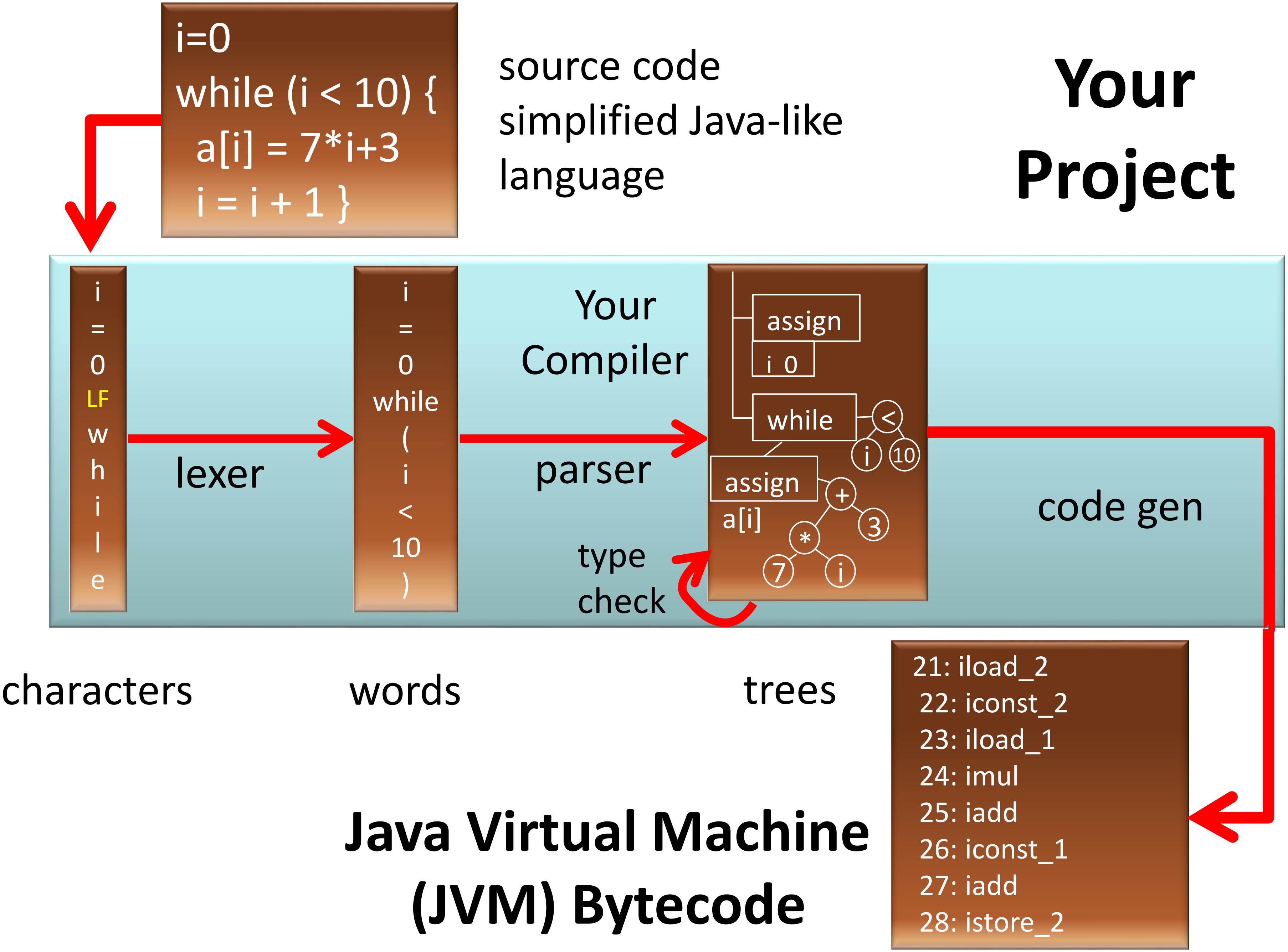
Your Project



```
i=0
while (i < 10) {
  a[i] = 7*i+3
  i = i + 1 }
```

source code
simplified Java-like
language

```
21: iload_2
 22: iconst_2
 23: iload_1
 24: imul
 25: iadd
 26: iconst_1
 27: iadd
 28: istore_2
```

Java Virtual Machine (JVM) Bytecode

javac example

```
while (i < 10) {
  System.out.println(j);
  i = i + 1;
  j = j + 2*i+1;
}
```

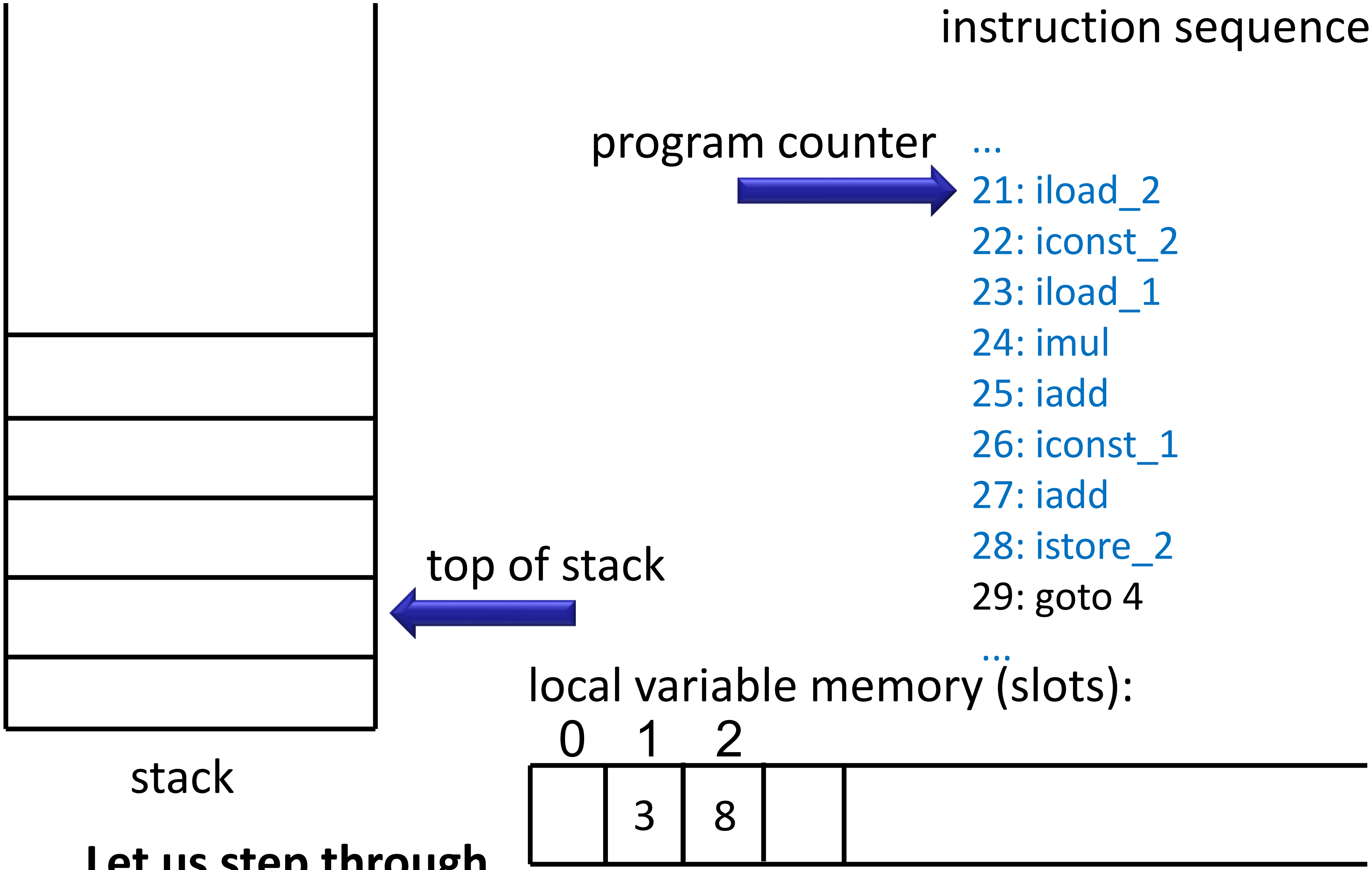
```
javac Test.java
javap –c Test
```

```
4: iload_1
5: bipush 10
7: if_icmpge 32
10: getstatic #2; //System.out
13: iload_2
14: invokevirtual #3; //println
17: iload_1
18: iconst_1
19: iadd
20: istore_1
21: iload_2
22: iconst_2
23: iload_1
24: imul
25: iadd
26: iconst_1
27: iadd
28: istore_2
29: goto 4
32: return
```

Phase after type checking: emits such bytecode instructions

Guess what each JVM instruction for the highlighted expression does.

Stack Machine: High-Level Machine Code



instruction sequence:

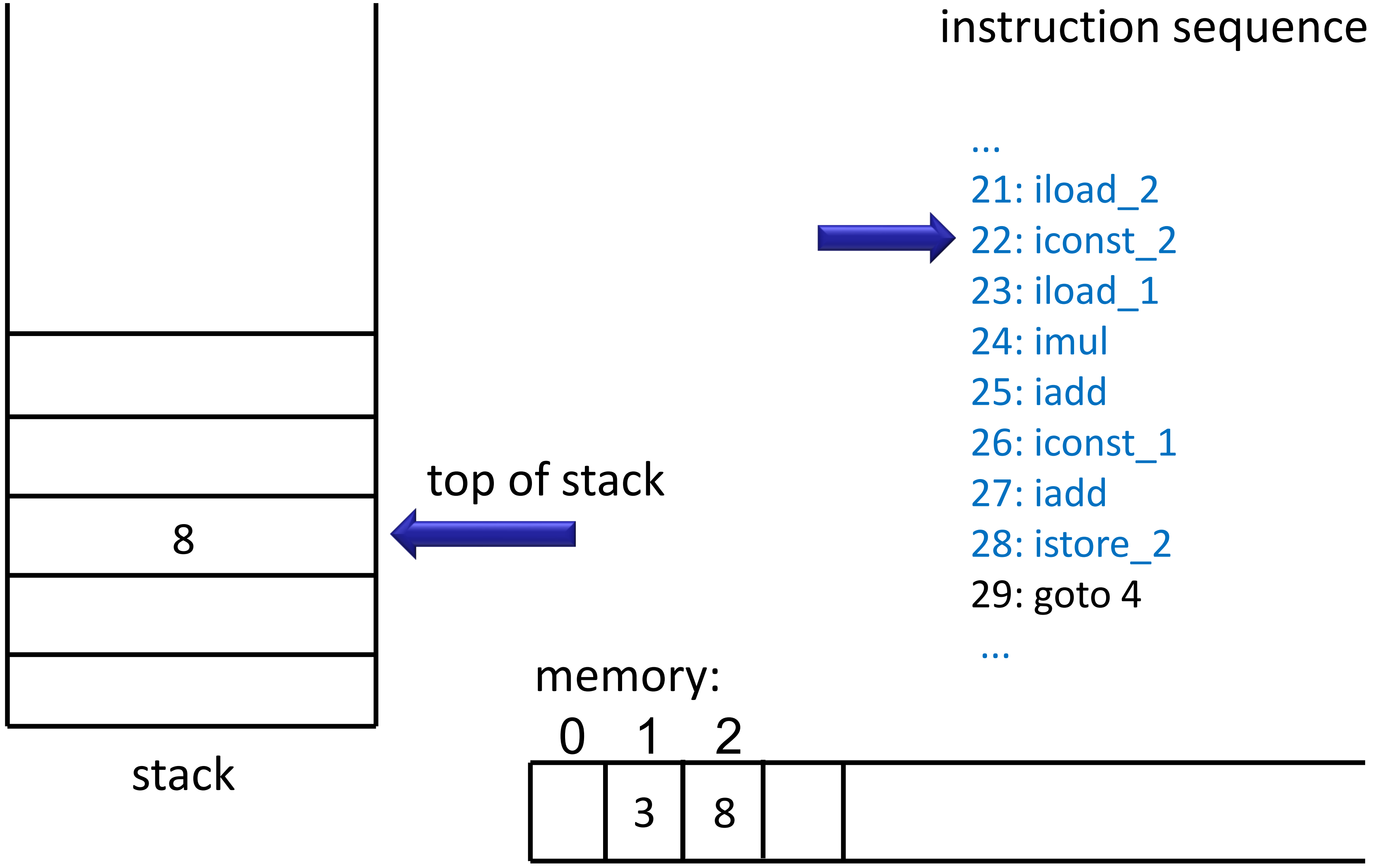
```
...
21: iload_2
22: iconst_2
23: iload_1
24: imul
25: iadd
26: iconst_1
27: iadd
28: istore_2
29: goto 4
...
```

local variable memory (slots):

0	1	2		
	3	8		

Let us step through

Operands are consumed from stack and put back onto stack



instruction sequence:

```
...
21: iload_2
22: iconst_2
23: iload_1
24: imul
25: iadd
26: iconst_1
27: iadd
28: istore_2
29: goto 4
...
```

top of stack

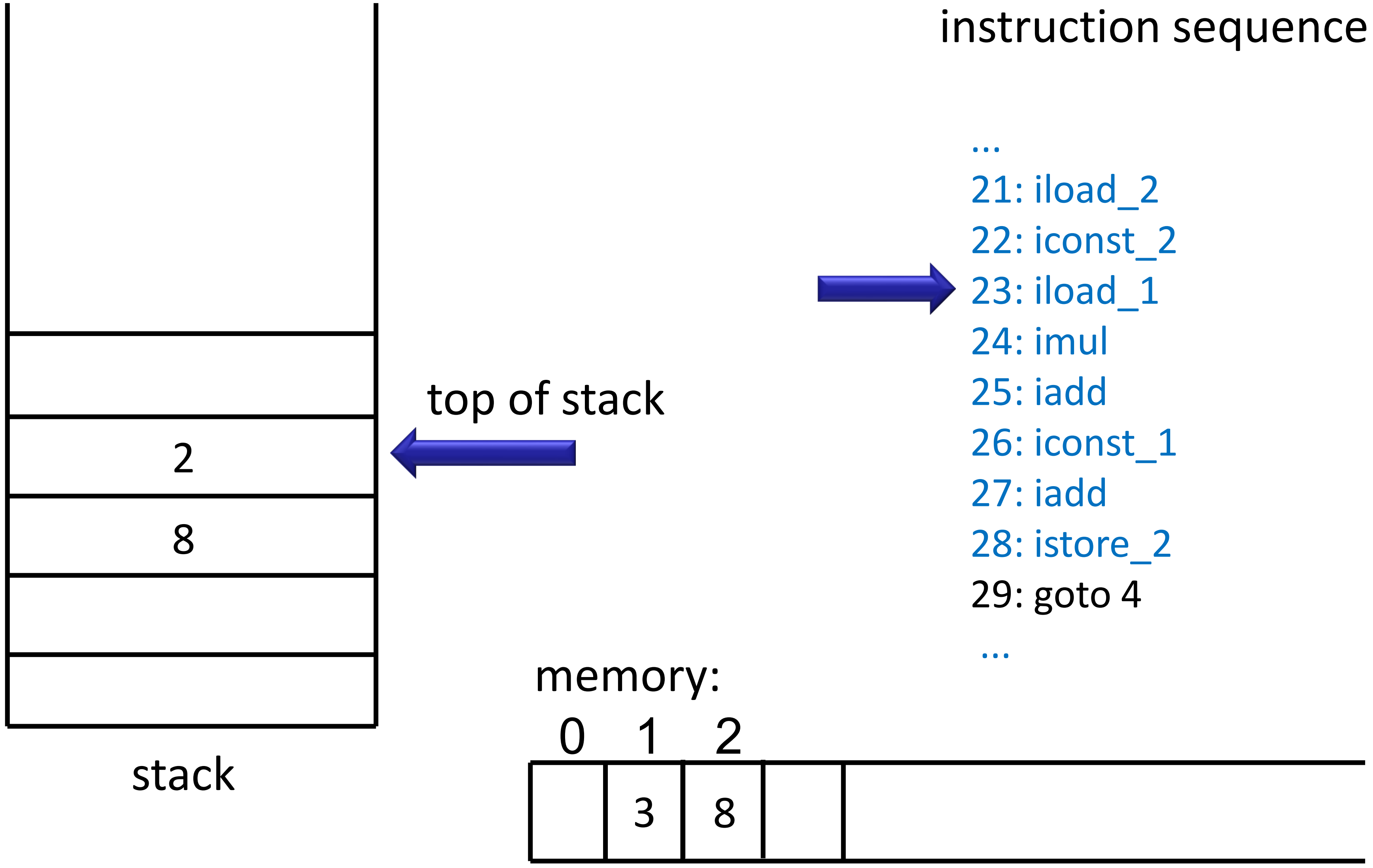
8

stack

memory:

0	1	2
	3	8

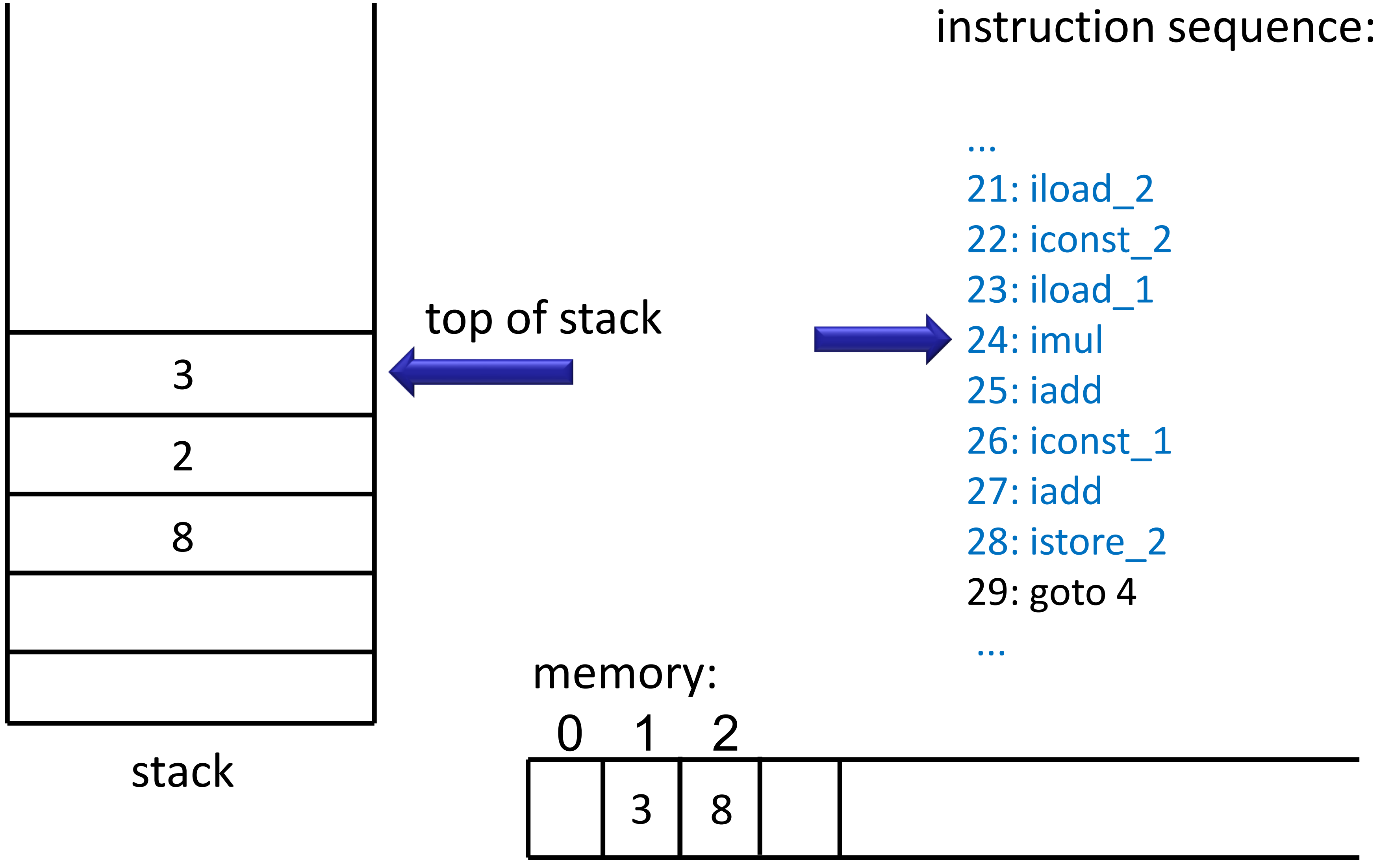
Operands are consumed from stack and put back onto stack



instruction sequence:

```
...
21: iload_2
22: iconst_2
23: iload_1
24: imul
25: iadd
26: iconst_1
27: iadd
28: istore_2
29: goto 4
 ...
```

Operands are consumed from stack and put back onto stack



instruction sequence:

```
...
21: iload_2
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26: iconst_1
27: iadd
28: istore_2
29: goto 4
...
```
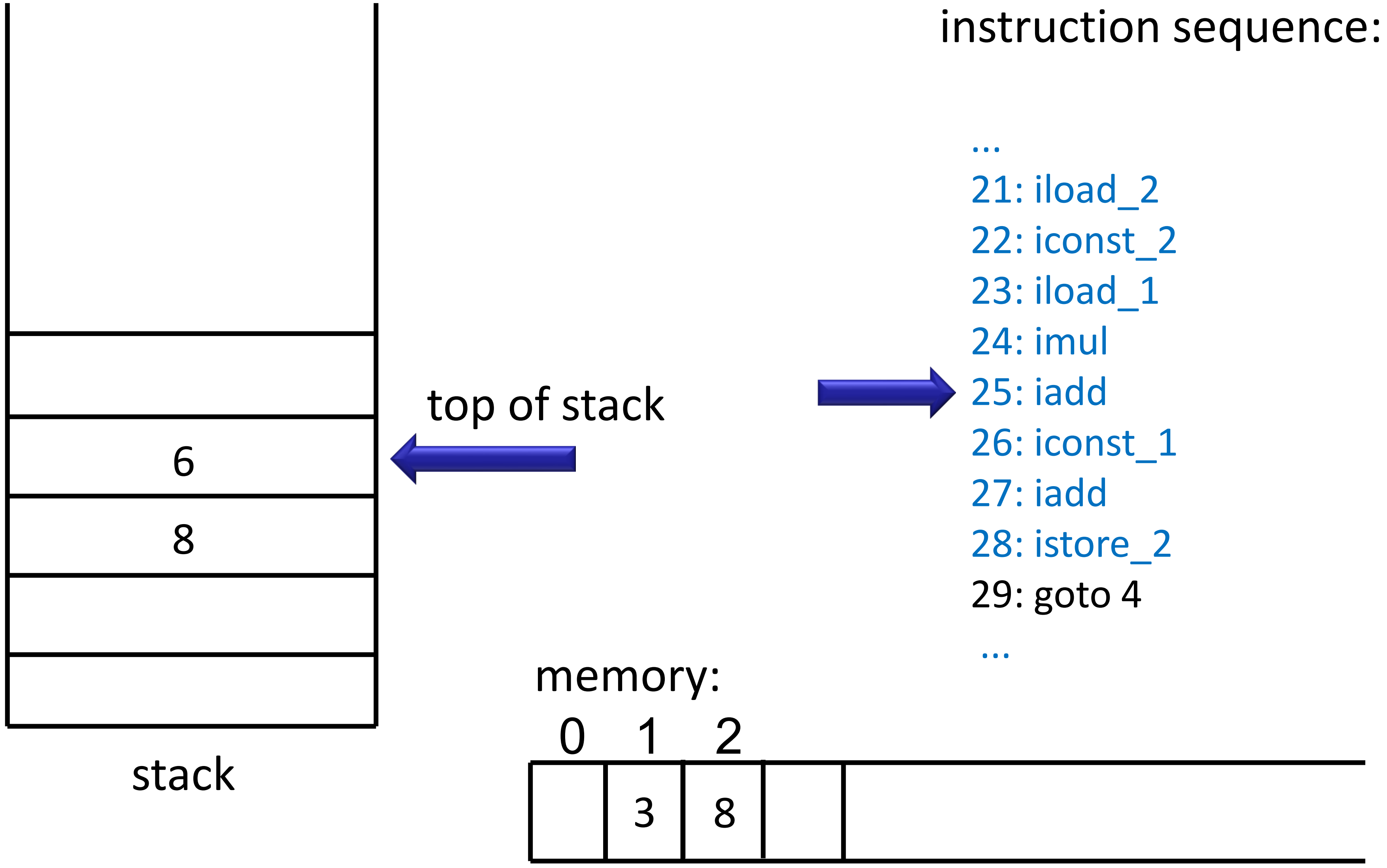

Operands are consumed from stack and put back onto stack



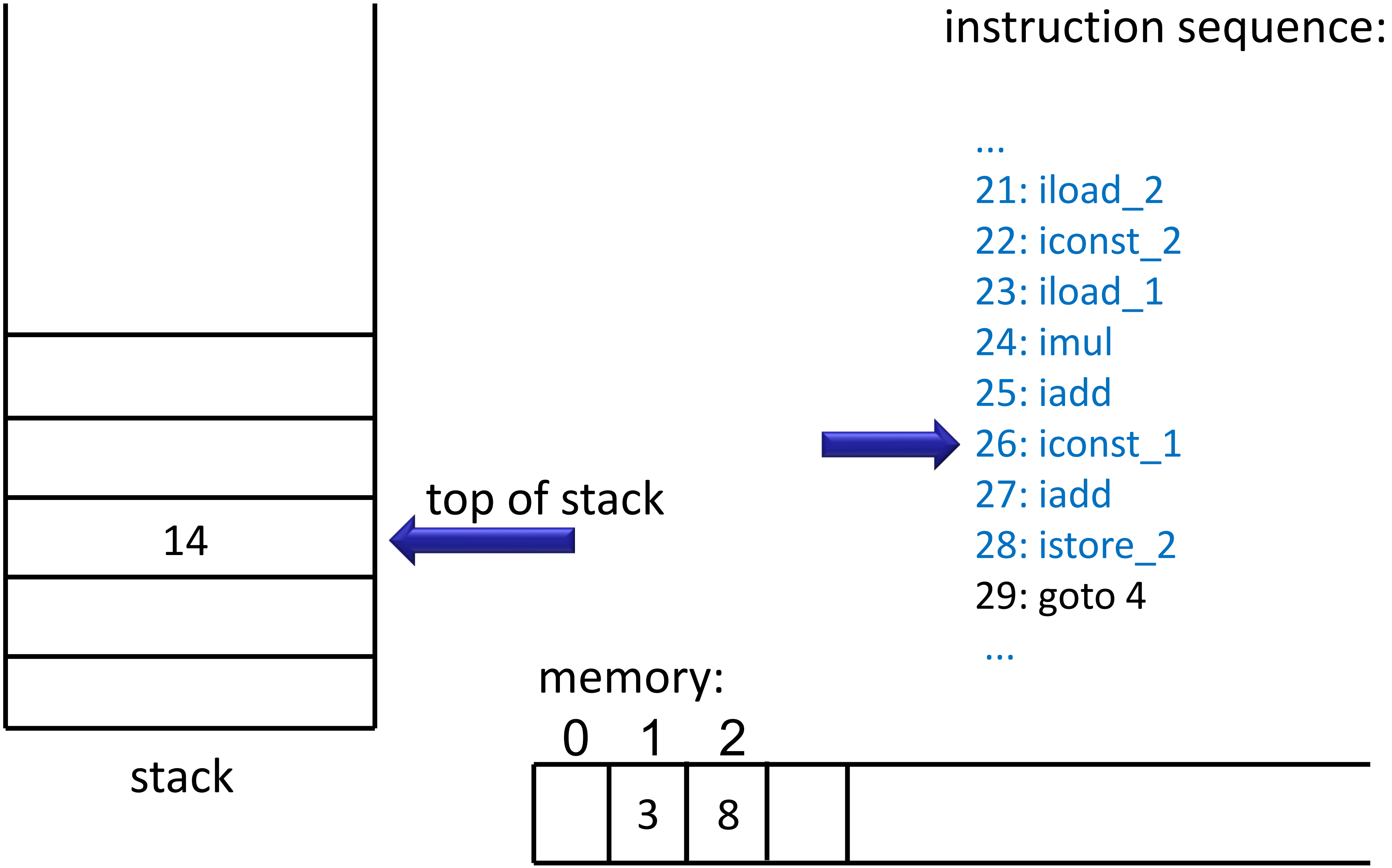
instruction sequence:

```
...
21: iload_2
22: iconst_2
23: iload_1
24: imul
25: iadd
26: iconst_1
27: iadd
28: istore_2
29: goto 4
...
```

memory:

0	1	2	
	3	8	

Operands are consumed from stack and put back onto stack



instruction sequence:

```
...
21: iload_2
22: iconst_2
23: iload_1
24: imul
25: iadd
26: iconst_1
27: iadd
28: istore_2
29: goto 4
...
```

top of stack

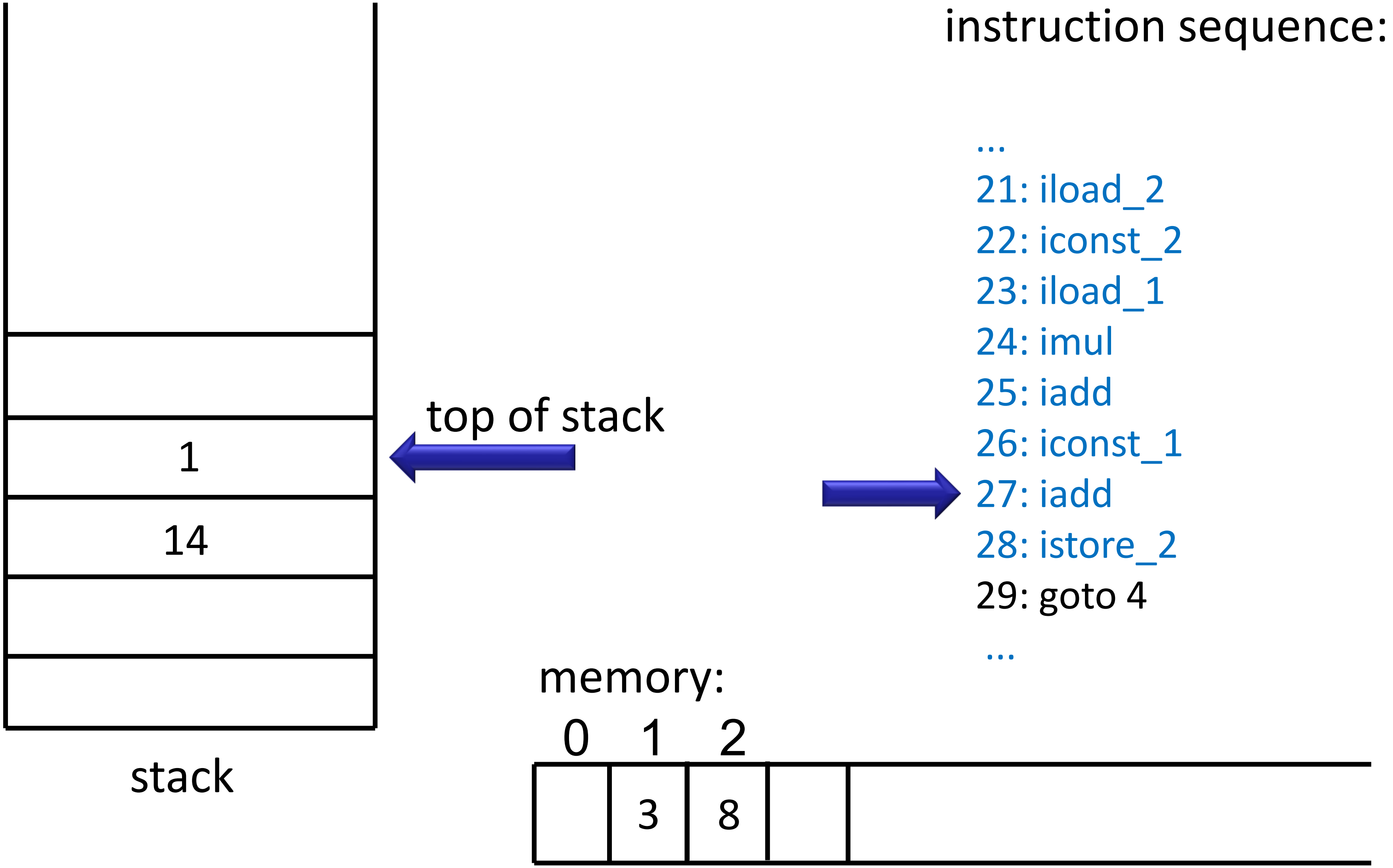
14

stack

memory:

0	1	2
	3	8

Operands are consumed from stack and put back onto stack



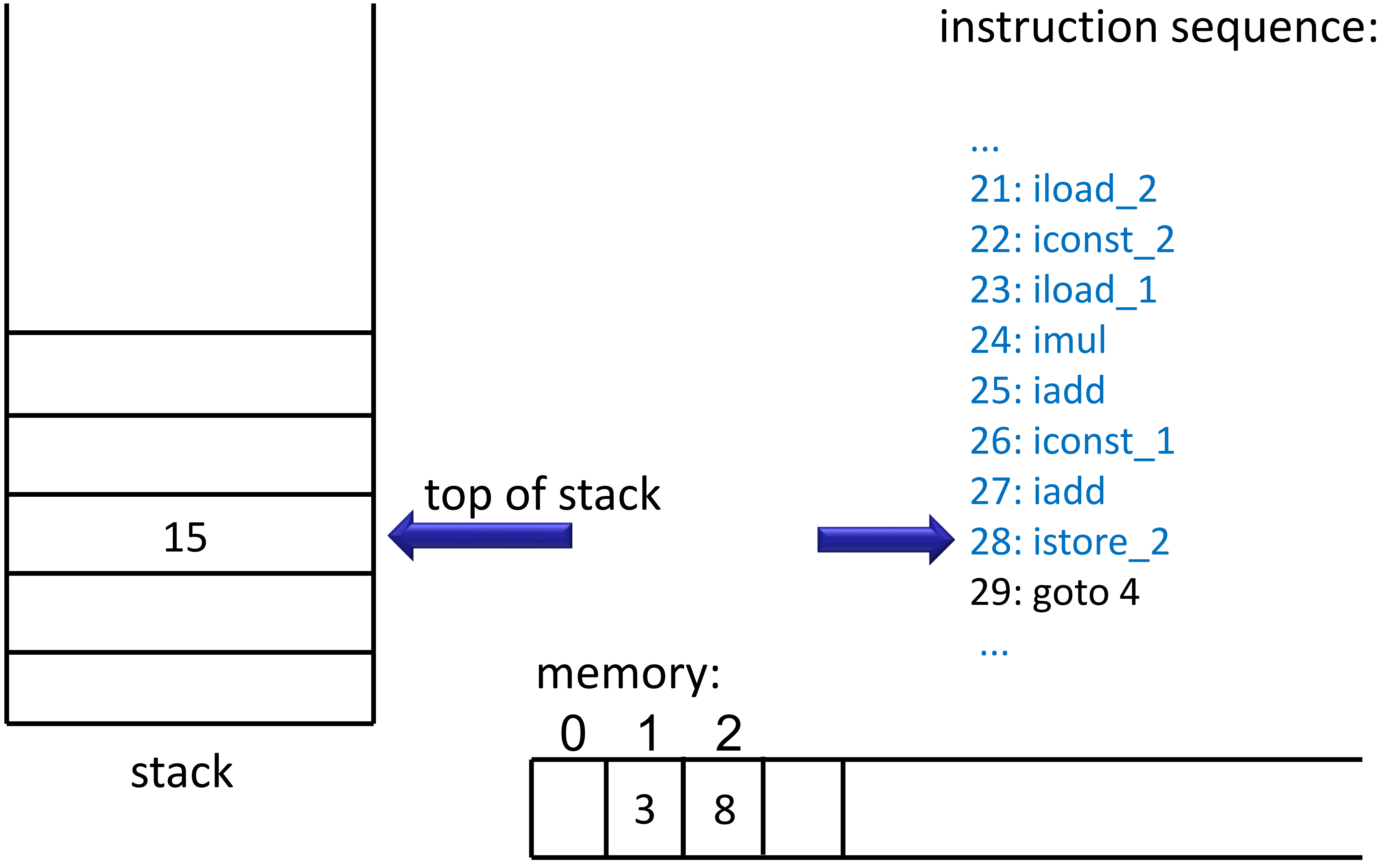
instruction sequence:

```
...
21: iload_2
22: iconst_2
23: iload_1
24: imul
25: iadd
26: iconst_1
27: iadd
28: istore_2
29: goto 4
...
```

memory:

0	1	2	
	3	8	

Operands are consumed from stack and put back onto stack



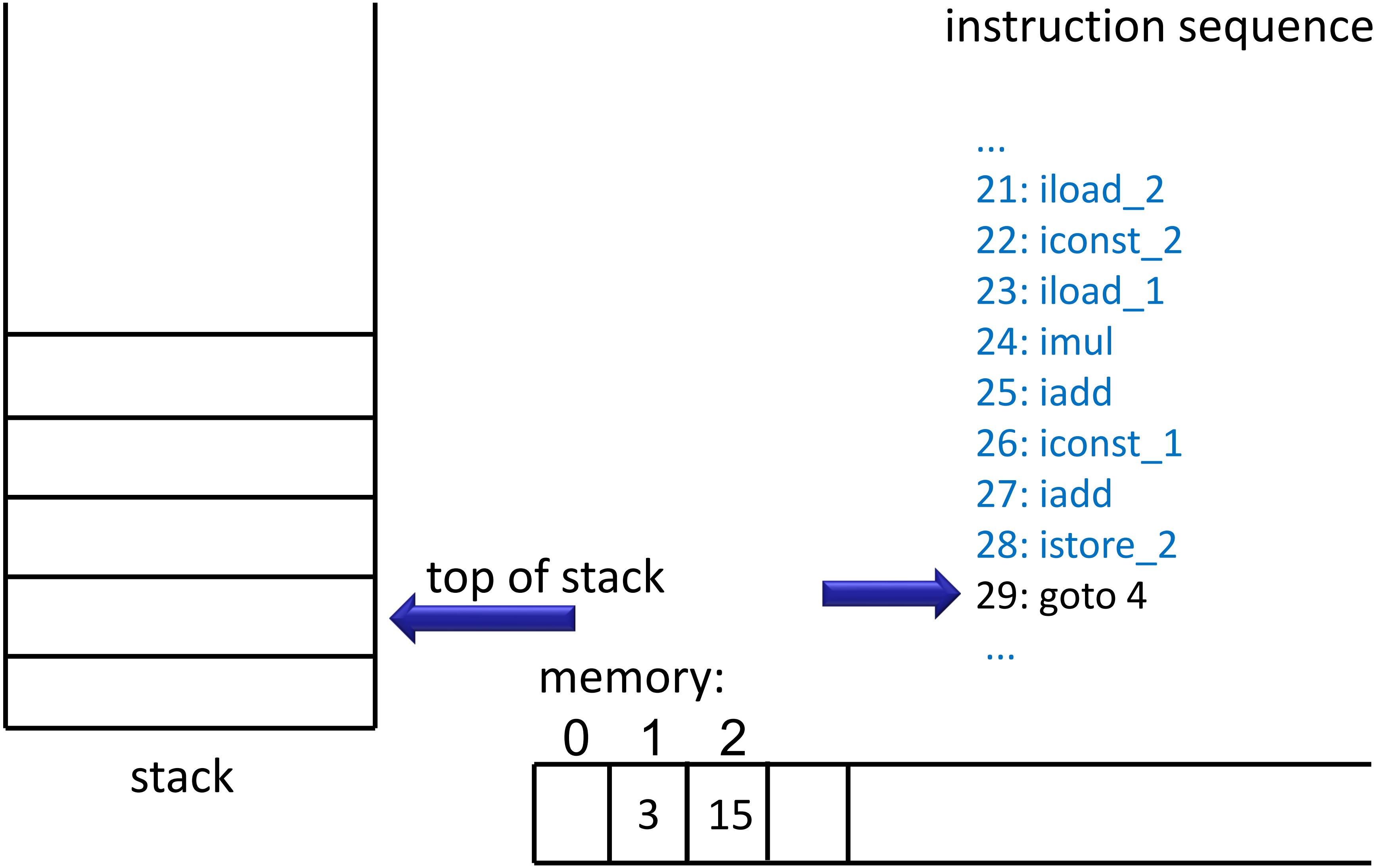
instruction sequence:

```
...
21: iload_2
22: iconst_2
23: iload_1
24: imul
25: iadd
26: iconst_1
27: iadd
28: istore_2
29: goto 4
...
```

memory:

0	1	2		
	3	8		

Operands are consumed from stack and put back onto stack



top of stack

stack

instruction sequence:

```
...
21: iload_2
22: iconst_2
23: iload_1
24: imul
25: iadd
26: iconst_1
27: iadd
28: istore_2
29: goto 4
...
```

memory:

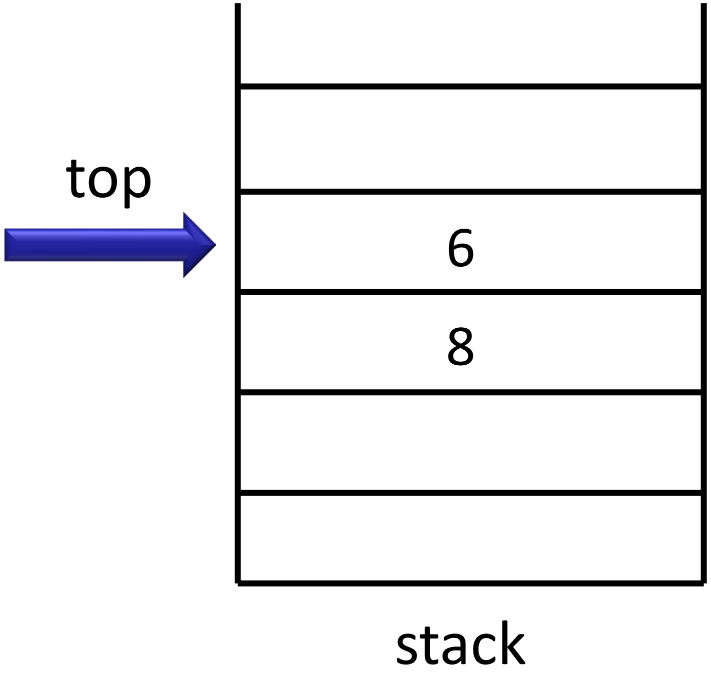
0	1	2		
	3	15		

Instructions in JVM

- Separate for each type, including
  - integer types (iadd, imul, iload, istore, bipush)
  - reference types (aload, astore)
- Why are they separate if not in e.g. x86?
  - Memory safety!
  - Each reference points to a valid allocated object
- Conditionals and jumps
- Further high-level operations
  - array operations
  - object method and field access

Stack Machine Simulator

```
var code : Array[Instruction]
var pc : Int   // program counter
var local : Array[Int]  // for local variables
var operand : Array[Int]  // operand stack
var top : Int


while (true) step

 def step = code(pc) match {
   case Iadd() =>
     operand(top - 1) = operand(top - 1) +   operand(top)
     top = top - 1  // two consumed, one produced
   case Imul() =>
     operand(top - 1) = operand(top - 1) * operand(top)
     top = top - 1  // two consumed, one produced
```



top

6

8

stack

Stack Machine Simulator: Moving Data

```
case Bipush(c) =>
  operand(top + 1) = c   // put given constant 'c' onto stack
  top = top + 1
case Iload(n) =>
  operand(top + 1) = local(n)  // from memory onto stack
  top = top + 1
case Istore(n) =>
  local(n) = operand(top)  // from stack into memory
  top = top - 1  // consumed
}
if (notJump(code(n)))
  pc = pc + 1   // by default go to next instructions
```

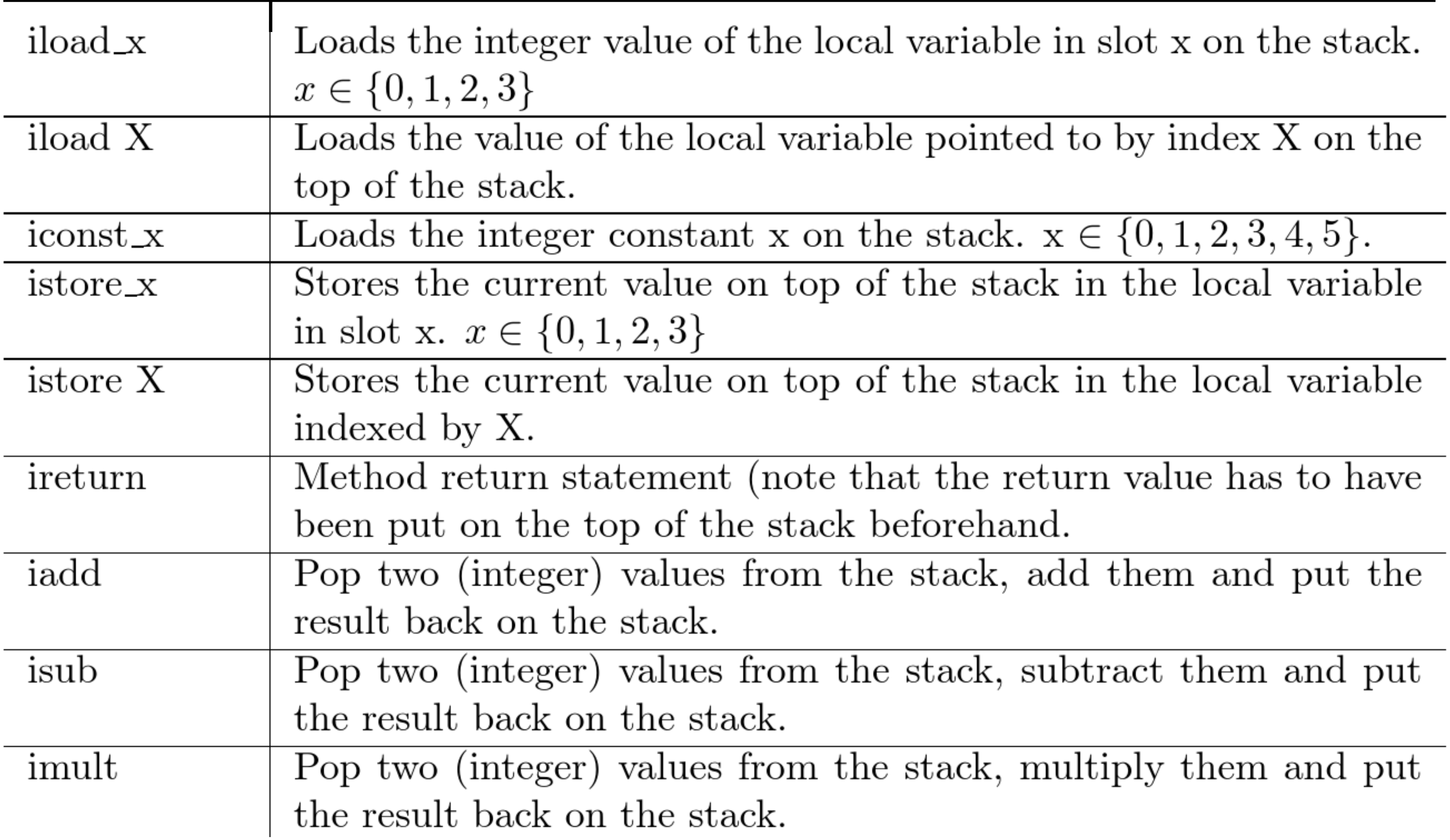
Actual Java Virtual Machine

Official documentation:
http://docs.oracle.com/javase/specs/

http://docs.oracle.com/javase/specs/jvms/se7/html/index.html

```
Use:  javac -g *.java             to compile
      javap -c -l ClassName       to explore
```

Selected Instructions



bipush X	Like iconst, but for arbitrarily large X
iload_x	Loads the integer value of the local variable in slot x on the stack. $x \in \{0, 1, 2, 3\}$
iload X	Loads the value of the local variable pointed to by index X on the top of the stack.
iconst_x	Loads the integer constant x on the stack. x $\in \{0, 1, 2, 3, 4, 5\}$.
istore_x	Stores the current value on top of the stack in the local variable in slot x. $x \in \{0, 1, 2, 3\}$
istore X	Stores the current value on top of the stack in the local variable indexed by X.
ireturn	Method return statement (note that the return value has to have been put on the top of the stack beforehand.
iadd	Pop two (integer) values from the stack, add them and put the result back on the stack.
isub	Pop two (integer) values from the stack, subtract them and put the result back on the stack.
imult	Pop two (integer) values from the stack, multiply them and put the result back on the stack.

idiv	Pop two (integer) values from the stack, divide them and put the result back on the stack.
irem	Pop two (integer) values from the stack, put the result of $x_1\%x_2$ back on the stack.
ineg	Negate the value on the stack.
iinc x, y	Increment the variable in slot x by amount y.
ior	Logical OR for the two integer values on the stack.
iand	Logical AND for the two integer values on the stack.
ixor	Logical XOR for the two integer values on the stack.
ifXX L	Pop one value from the stack, compare it zero according to the operator XX. If the condition is satisfied, jump to the instruction given by label L. XX $\in$ { eq, lt, le, ne, gt, ge, null, nonnull }
if_icmpXX L	Pop two values from the stack and compare against each other. Rest as above.
goto L	Unconditional jump to instruction given by the label L.
pop	Discard word currently on top of the stack.
dup	Duplicate word currently on top of the stack.
swap	Swaps the two top values on the stack.
aload_x	Loads an object reference from slot x.
aload X	Loads an object reference from local variable indexed by X.
iaload	Loads onto the stack an integer from an array. The stack must contain the array reference and the index.
iastore	Stores an integer in an array. The stack must contain the arrayreference, the index and the value, in that order.

Example: Twice

```
class Expr1 {
   public static int twice(int x) {
           return x*2;
   }
}
```

```
javac -g Expr1.java;  javap -c -l Expr1
```

```
public static int twice(int);
 Code:
  0:   iload_0    // load int from var 0 to top of stack
  1:   iconst_2   // push 2 on top of stack
  2:   imul       // replace two topmost elements with their product
  3:   ireturn    // return top of stack
}
```

Example: Area

```
class Expr2 {
   public static int cubeArea(int a, int b, int c) {
            return (a*b + b*c + a*c) * 2;
   }
}
```

```
javac -g Expr2.java;  javap -c -l Expr2
```

```
LocalVariableTable:
 Start   Length   Slot   Name    Signature
 0       14       0      a        I
 0       14       1      b        I
 0       14       2      c        I
```

```
public static int cubeArea(int, int, int);
 Code:
  0:   iload_0
  1:   iload_1
  2:   imul
  3:   iload_1
  4:   iload_2
  5:   imul
  6:   iadd
  7:   iload_0
  8:   iload_2
  9:   imul
  10:  iadd
  11:  iconst_2
  12:  imul
  13:  ireturn
}
```

What Instructions Operate on

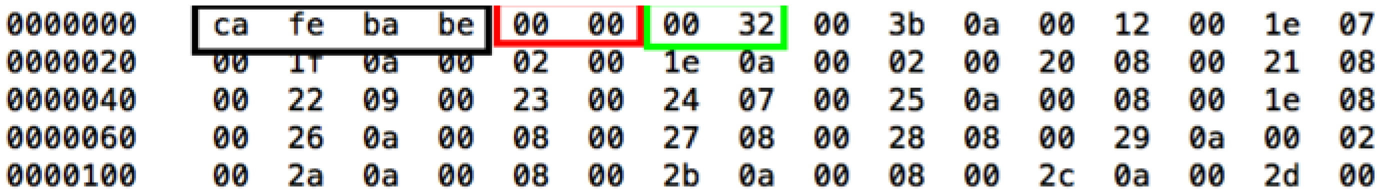
- operands that are part of instruction itself, following their op code
  (unique number for instruction - iconst)
- operand stack - used for computation (iadd)
- memory managed by the garbage collector (loading and storing fields)
- constant pool - used to store ‘big’ values instead of in instruction stream
  - e.g. string constants, method and field names
  - mess!

CAFEBABE

Library to make bytecode generation easy and fun!

https://github.com/psuter/cafebabe/wiki

Named after magic code appearing in .class files when displayed in hexadecimal:



```
0000000   ca  fe  ba  be  00  00  00  32  00  3b  0a  00  12  00  1e  07
0000020   00  1f  0a  00  02  00  1e  0a  00  02  00  20  08  00  21  08
0000040   00  22  09  00  23  00  24  07  00  25  0a  00  08  00  1e  08
0000060   00  26  0a  00  08  00  27  08  00  28  08  00  29  0a  00  02
0000100   00  2a  0a  00  08  00  2b  0a  00  08  00  2c  0a  00  2d  00
```

More on that in the labs!

Towards Compiling Expressions: Prefix, Infix, and Postfix Notation

Overview of Prefix, Infix, Postfix

Let *f* be a binary operation, e_1 e_2 two expressions

We can denote application $f(e_1,e_2)$ as follows

- in **prefix** notation $f\ e_1\ e_2$
- in **infix** notation $e_1\ f\ e_2$
- in **postfix** notation $e_1\ e_2\ f$

- Suppose that each operator (like *f*) has a known number of arguments. For nested expressions
  - infix requires parentheses in general
  - prefix and postfix do not require any parantheses!

Expressions in Different Notation

For infix, assume * binds stronger than +

There is no need for priorities or parens in the other notations

arg.list	+(x,y)	+(*(x,y),z)	+(x,*(y,z))	*(x,+(y,z))
prefix	+ x y	+ * x y z	+ x * y z	* x + y z
infix	x + y	x*y + z	x + y*z	x*(y + z)
postfix	x y +	x y * z +	x y z * +	x y z + *

Infix is the only problematic notation and leads to ambiguity

Why is it used in math? Amgiuity reminds us of algebraic laws:

x + y looks same from left and from right (commutative)

x + y + z parse trees mathematically equivalent (associative)

Convert into Prefix and Postfix

prefix

infix ((x + y) + z) + u x + (y + (z + u))

postfix

draw the trees:

Terminology:

prefix = Polish notation
(attributed to Jan Lukasiewicz from Poland)

postfix = Reverse Polish notation (RPN)

Is the sequence of characters in postfix opposite to one in prefix if we have binary operations?

What if we have only unary operations?

Compare Notation and Trees

arg.list	+(x,y)	+(*(x,y),z)	+(x,*(y,z))	*(x,+(y,z))
prefix	+ x y	+ * x y z	+ x * y z	* x + y z
infix	x + y	x*y + z	x + y*z	x*(y + z)
postfix	x y +	x y * z +	x y z * +	x y z + *

draw ASTs for each expression

How would you pretty print AST into a given form?

Simple Expressions and Tokens

```
sealed abstract class Expr
case class Var(varID: String) extends Expr
case class Plus(lhs: Expr, rhs: Expr) extends Expr
case class Times(lhs: Expr, rhs: Expr) extends Expr

sealed abstract class Token
case class ID(str : String) extends Token
case class Add extends Token
case class Mul extends Token
case class O extends Token   // (
case class C extends Token   // )
```

Printing Trees into Lists of Tokens

```
def prefix(e : Expr) : List[Token] = e match {
  case Var(id) => List(ID(id))
  case Plus(e1,e2)   => List(Add()) ::: prefix(e1) ::: prefix(e2)
  case Times(e1,e2) => List(Mul()) ::: prefix(e1) ::: prefix(e2)
 }
 def infix(e : Expr) : List[Token] = e match { // needs to emit parantheses
  case Var(id) => List(ID(id))
  case Plus(e1,e2) => List(O())::: infix(e1) ::: List(Add()) ::: infix(e2) :::List(C())
  case Times(e1,e2) => List(O())::: infix(e1) ::: List(Mul()) ::: infix(e2) :::List(C())
 }
 def postfix(e : Expr) : List[Token] = e match {
  case Var(id) => List(ID(id))
  case Plus(e1,e2)  => postfix(e1) ::: postfix(e2) ::: List(Add())
  case Times(e1,e2) => postfix(e1) ::: postfix(e2) ::: List(Mul())
 }
```

LISP: Language with Prefix Notation

- 1958 – pioneering language
- Syntax was meant to be abstract syntax
- Treats all operators as user-defined ones, so syntax does not assume the number of arguments is known
  - use parantheses in prefix notation: write f(x,y) as (f x y)

```
(defun factorial (n)
  (if (<= n 1)
      1
      (* n (factorial (- n 1)))))
```

PostScript: Language using Postfix

- .ps are ASCII files given to PostScript-compliant printers
- Each file is a program whose execution prints the desired pages
- http://en.wikipedia.org/wiki/PostScript%20programming%20language

PostScript language tutorial and cookbook

Adobe Systems Incorporated

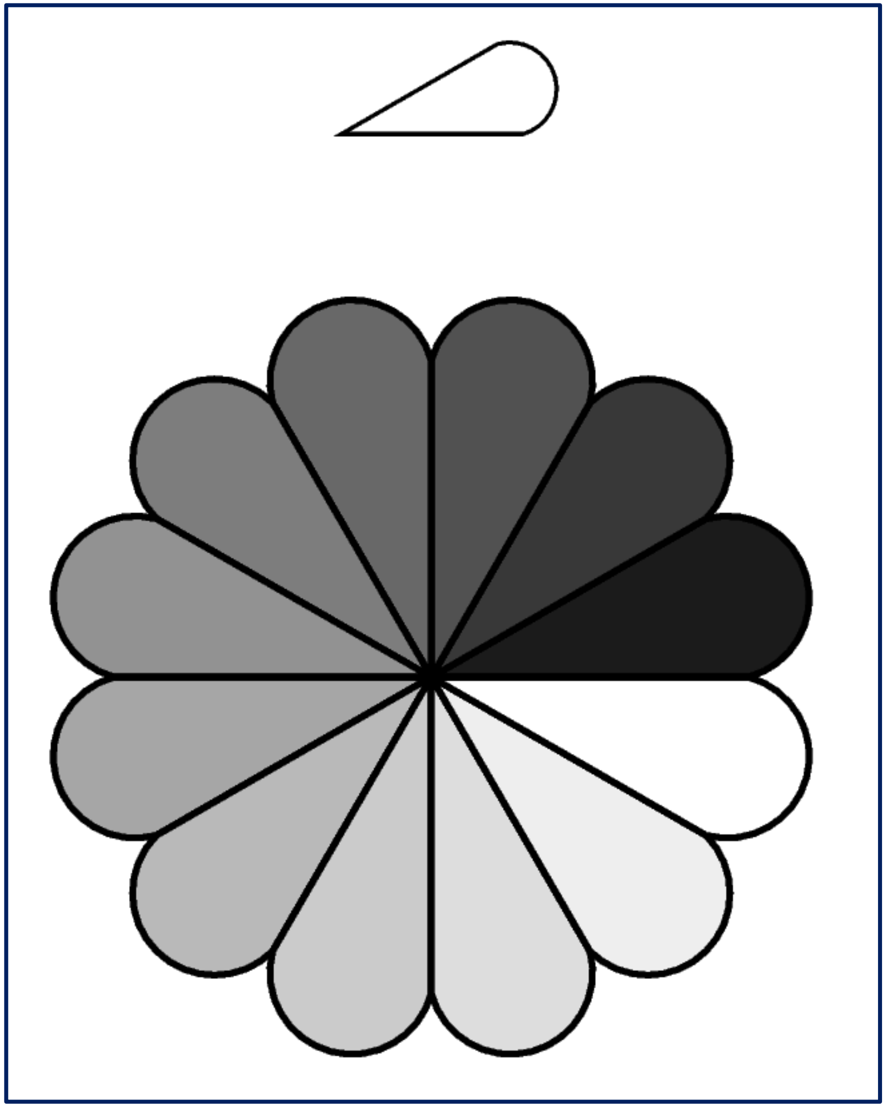
Reading, MA : Addison Wesley, 1985

ISBN 0-201-10179-3 (pbk.)

A PostScript Program

```
/inch {72 mul} def
/wedge
        { newpath
          0 0 moveto
          1 0 translate
          15 rotate
          0 15 sin translate
          0 0 15 sin -90 90 arc
          closepath
        } def
gsave
  3.75 inch 7.25 inch translate
  1 inch 1 inch scale
  wedge 0.02 setlinewidth stroke
grestore
gsave
  4.25 inch 4.25 inch translate
  1.75 inch 1.75 inch scale
  0.02 setlinewidth
  1 1 12
        { 12 div setgray
          gsave
            wedge
            gsave fill grestore
            0 setgray stroke
          grestore
          30 rotate
        } for
grestore
showpage
```

If we send it to printer (or run GhostView viewer gv) we get



```
 4.25 inch 4.25 inch translate
 1.75 inch 1.75 inch scale
 0.02 setlinewidth
 1 1 12
        { 12 div setgray
         gsave
          wedge
          gsave fill grestore
          0 setgray stroke
         grestore
         30 rotate
        } for
grestore
showpage
```

Why postfix? Can evaluate it using stack

```
def postEval(env   : Map[String,Int], pexpr : Array[Token]) : Int = {  // no recursion!
  var stack : Array[Int] = new Array[Int](512)
  var top : Int = 0;   var pos : Int = 0
  while (pos < pexpr.length) {
    pexpr(pos) match {
      case ID(v) =>  top = top + 1
                     stack(top) = env(v)
      case Add() => stack(top - 1) = stack(top - 1) + stack(top)
                     top = top - 1
      case Mul() => stack(top - 1) = stack(top - 1) * stack(top)
                     top = top - 1
    }
    pos = pos + 1
  }
  stack(top)
}
```

x -> 3, y -> 4, z -> 5

infix: x*(y+z)

postfix: x y z + *

Run 'postfix' for this env

Evaluating Infix Needs Recursion

The recursive interpreter:

```
def infixEval(env : Map[String,Int], expr : Expr) : Int =
expr match {
   case Var(id) => env(id)
   case Plus(e1,e2) => infix(env,e1) + infix(env,e2)
   case Times(e1,e2) => infix(env,e1) * infix(env,e2)
}
```

Maximal stack depth in interpreter = expression height

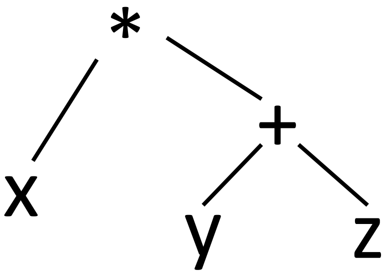
Compiling Expressions

- Evaluating postfix expressions is like running a stack-based virtual machine on compiled code
- Compiling expressions for stack machine is like translating expressions into postfix form

Expression, Tree, Postfix, Code

infix: x*(y+z)

postfix: x y z + *



bytecode:

iload 1	x → 1
iload 2	y → 2
iload 3	z → 3
iadd	+
imul	*

Show Tree, Postfix, Code

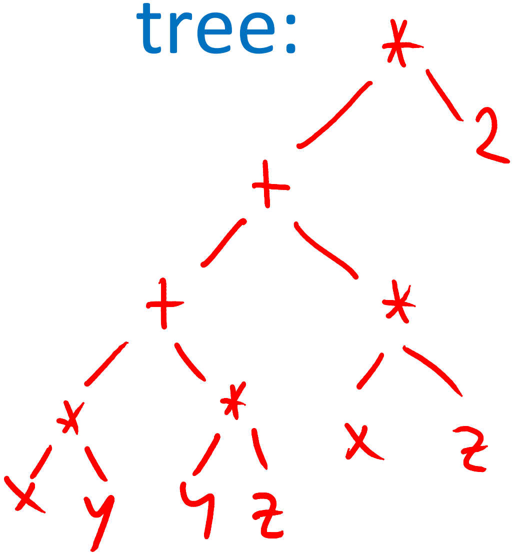
infix: (x*y + y*z + x*z)*2 tree:

postfix: bytecode:

Show Tree, Postfix, Code

infix: $(\overset{\overset{0}{\uparrow}}{x}*\overset{\overset{1}{\uparrow}}{y} + y*\overset{\overset{2}{\uparrow}}{z} + x*z)*2$

tree:



postfix:

x
y
*
y
z
*
+
x
z
*
+
2
*

bytecode:

iload_0
iload_1
imul
ilood_1
iload_2
imul
iadd
iload_0
iload2
imul
iadd
iconst_2
imul

“Printing” Trees into Bytecodes

To evaluate e_1*e_2 interpreter

- evaluates e_1
- evaluates e_2
- combines the result using *

Compiler for e_1*e_2 emits:

- code for e_1 that leaves result on the stack, followed by
- code for e_2 that leaves result on the stack, followed by
- arithmetic instruction that takes values from the stack and leaves the result on the stack

```
def compile(e : Expr) : List[Bytecode] = e match { // ~ postfix printer
  case Var(id) => List(ILoad(slotFor(id)))
  case Plus(e1,e2)  => compile(e1) ::: compile(e2) ::: List(IAdd())
  case Times(e1,e2) => compile(e1) ::: compile(e2) ::: List(IMul())
}
```

Local Variables

For **int**: instructions **iload** and **istore** from JVM Spec.

- Assigning indices (called *slots*) to local variables using function
  slotOf : VarSymbol → {0,1,2,3,…}
- How to compute the indices?
  - assign them in the order in which they appear in the tree

```
 def compile(e : Expr) : List[Bytecode] = e match {
   case Var(id) => List(ILoad(slotFor(id)))
   …
}
```

id= e

```
def compileStmt(s : Statmt) : List[Bytecpde] = s match {
 case Assign(id,e) => compile(e) ::: List(IStore(slotFor(id)))
   …
}
```

Global Variables and Fields

Static Variables

Consult JVM Spec and see

- **getstatic**
- **putstatic**

as well as the section on **Runtime Constant Pool**.

Instance Variables (Fields)

To access these we use

- **getfield**
- **putfield**

In lower-level machines x.f is evaluated as mem[x + offset(f)]

With inheritance, offset(f) must be consistent despite the fact that we do not know exactly what the run-time class of x will be

- this can be very tricky to implement efficiently with multiple inheritance
- general approach: do a run-time test on the dynamic type of an object to decide how to interpret field or method access

Factorial Example

```
class Factorial {
  public int fact(int num){
       int num_aux;
       if (num < 1)
         num_aux = 1 ;
       else
         num_aux=
          num*(this.fact(num-1));
       return num_aux;
  }
}
```

```
public int fact(int);
 Code:
  0:   iload_1
  1:   iconst_1
  2:   if_icmpge      10
  5:   iconst_1
  6:   istore_2
  7:   goto    20
  10:  iload_1
  11:  aload_0
  12:  iload_1
  13:  iconst_1
  14:  isub
  15:  invokevirtual   #2; //Met. fact:(I)I
  18:  imul
  19:  istore_2
  20:  iload_2
  21:  ireturn
```

aload_0 refers to receiver object (0th argument), since ‘fact’ is not static

Correctness

If we execute the compiled code, the result is the same as running the interpreter.

```
exec(env,compile(expr)) == interpret(env,expr)
```

interpret : Env x Expr -> Int

compile : Expr -> List[Bytecode]

exec : Env x List[Bytecode] -> Int

Assume 'env' in both cases maps var names to values.

With much more work, can prove correctness of entire compiler:

CompCert - A C Compiler whose Correctness has been Formally Verified

exec(env,compile(expr)) == interpret(env,expr)

Attempted proof by induction:

exec(env,compile(Times(e1,e2))) ==
exec(env,compile(e1) ::: compile(e2) ::: List(`*`))

We need to know something about behavior of intermediate executions.

exec : Env x List[Bytecode] -> Int

run : Env x List[Bytecode] x List[Int] -> List[Int]
// stack as argument and result

exec(env,bcodes) == **run**(env,bcodes,List()).head

run(env,bcodes,stack) = newStack

Executing sequence of instructions

run : Env x List[Bytecode] x List[Int] -> List[Int]

Stack grows to the right, top of the stack is last element

Byte codes are consumed from left

Definition of run is such that

- run (env,`*` :: L, S ::: List(x1, x2)) == run(env,L, S:::List(x1*x2))
- run (env,`+` :: L, S ::: List(x1, x2)) == run(env,L, S:::List(x1+x2))
- run(env,ILoad(n) :: L, S) == run(env,L, S:::List(env(n)))

By induction one shows:

- run (env,L1 ::: L2,S) == run(env,L2, run(env,L1,S))

execute instructions L1, then execute L2 on the result

New correctness condition

exec : Env x List[Bytecode] -> Int

run : Env x List[Bytecode] x List[Int] -> List[Int]

Old condition:

exec(env,compile(expr)) == interpret(env,expr)

New condition:

run(env,compile(expr),S) == S:::List(interpret(env,expr))

for short (T - table), [x] denotes List(x)

run(T,C(e),S) == S:::[I(T,e)]

Proof of one case:

```
run(T,C(e),S) == S:::[I(T,e)]
```

```
run(T,C(Times(e1,e2)),S) ==
run(T,C(e1):::C(e2):::[`*`],S) ==
run(T,[`*`], run(T,e2, run(T,e1,S) )) ==
run(T,[`*`], run(T,e2, S:::[I(T,e1)]) ) ==
run(T,[`*`], S:::[I(T,e1),I(T,e2)]) ==
S:::[I(T,e1) * I(T,e2)] ==
S:::[I(T,Times(e1,e2)]
```