Lecture 4: ANTLR and SVM

Programming Languages (H)

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Overview

- **Last lecture:**
  - Compilers vs. interpreters, big-step operational semantics, L_{If}
- **This lecture:** An introduction to some of the tools you'll be using in the rest of the course
  - The ANTLR parser generator
  - The SVM virtual machine

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Disclaimer

- I believe that functional programming languages (like Haskell and OCaml) are the best tools for implementing compilers and interpreters, because of their support for algebraic datatypes and focus on immutability
  - However – the functional programming course is in fourth year, so we're all stuck with Java ☺
  - I haven't written Java seriously since 2014, so bear with me…
- Nevertheless, I think ANTLR is a pretty good parser generator, and you can still get quite far with Java (even if parts are a bit more awkward to write)
- The examples will still be written in quite a functional style (less mutation), as that will be closer to the formal specifications

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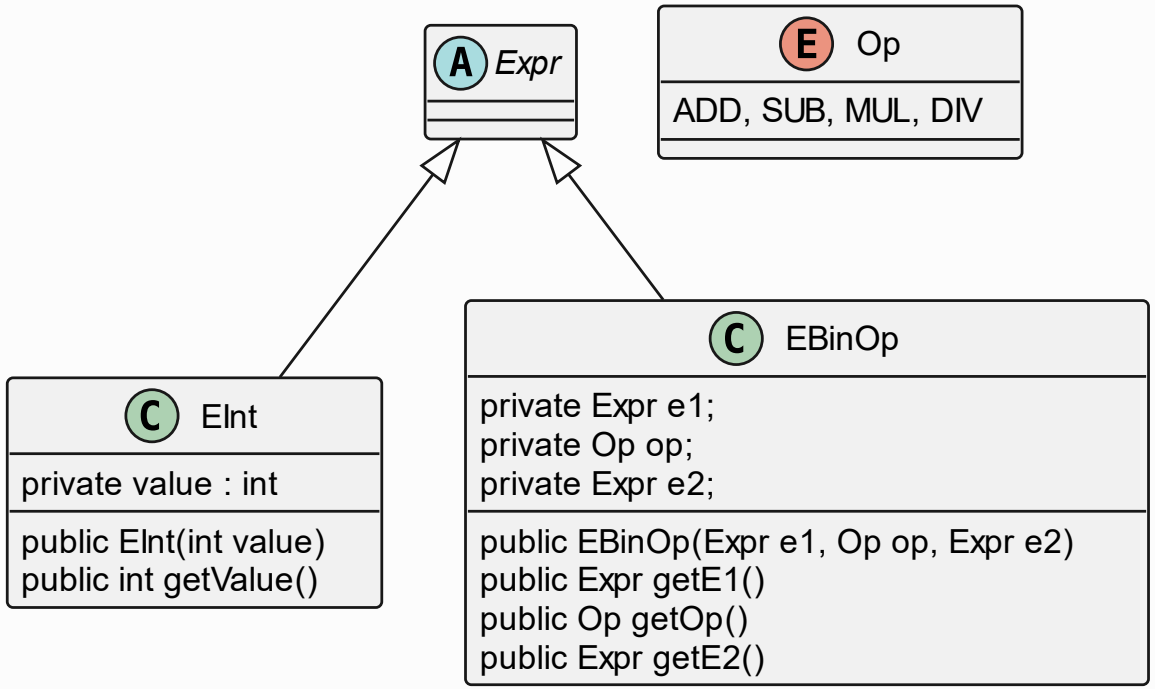
Representing an AST in Java

```
Integers n
Operators ⊙    ::= + | - | * | /
Exprs. L, M, N ::= n
                 | L ⊙ M
```

- We need an abstract class `Expr` to represent expressions
- We need separate classes for integer literals (`EInt`) and binary operators (`EBinOp`), which extend `Expr`
- `EInt` contains the integer value, and `EBinOp` contains the two subexpressions and an operator
- We can represent operators as an `enum`



ANTLR

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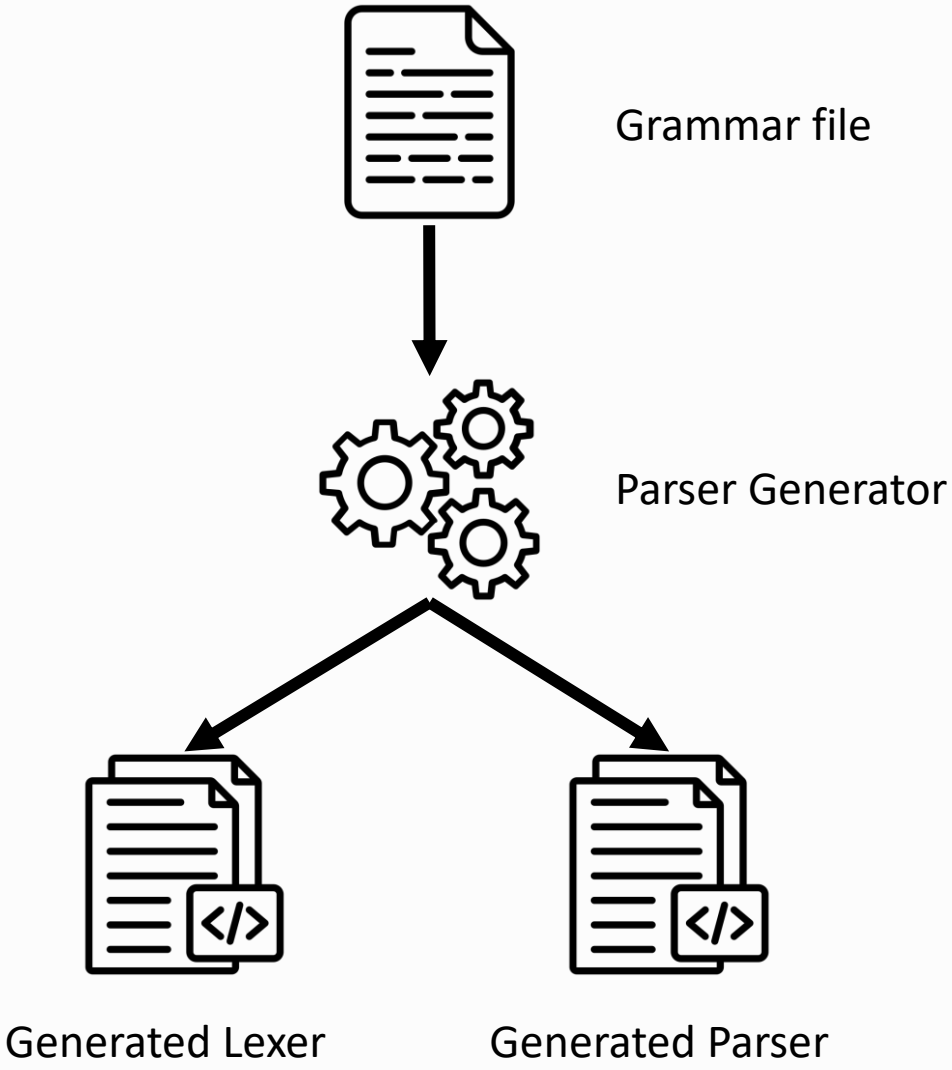
Parser Generators



- A **parser generator** is a program that takes a grammar and produces a lexer and parser
- This means that a language implementer can concentrate on the **design** of the grammar, rather than writing hand-crafted logic each time
- Many different parser generators exist for different languages (e.g. Yacc / Bison for C, Happy / Alex for Haskell, Menhir for OCaml)

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ANTLR

- ANTLR is an open-source parser generator for Java, originally written by Terence Parr, and widely used in industry
- The idea is that you can write a grammar using EBNF syntax, and it will generate a lexer, parser, and **visitor** code to traverse the parse tree
- We will use ANTLR in this course mainly for its parser generation component, as opposed to using visitors directly to implement interpretation / typechecking

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L_{Arith} ANTLR Grammar

```
expr: expr DIV expr # Div
    | expr MUL expr # Mul
    | expr ADD expr # Add
    | expr SUB expr # Sub
    | INT # Int
    | '(' expr ')' # Parens
    ;
INT : [0-9]+ ;
WS : [ \t\r\n]+ -> skip ;
MUL: '*' ;
DIV: '/' ;
SUB: '-' ;
ADD: '+' ;
```

- The ANTLR grammar for $_{LArith}$ is very close to its EBNF concrete syntax
- Operator precedence is **handled by ANTLR**: operator parses are tried in order (meaning **we don't need to restrict the grammar unnaturally**)
- Labels, e.g. `# Div`, are hints to ANTLR as to what to call the generated parse tree node
- It's generally good to define terminals separately, in capitals

Background: The Visitor Design Pattern

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Visitor Definition

```
public interface TreeVisitor {
  public void visitNode(Node n);
  public void visitLeaf(Leaf l);
}

public class BaseTreeVisitor
    implements TreeVisitor {
  public void visitNode(Node n) {
    n.getLeft().accept(this);
    n.getRight().accept(this);
  }
  public void visitLeaf(Leaf l) { }
}
```

Visitor Implementations

```
public class PrintLeafVisitor extends BaseTreeVisitor {
  @Override
  public void visitLeaf(Leaf l) {
    System.out.println(l.getValue());
  }
}

public class IncrementLeafVisitor extends BaseTreeVisitor {
  @Override
  public void visitLeaf(Leaf l) {
    l.setValue(l.getValue() + 1);
  }
}
```

- The **visitor pattern** separates the **operation** on each element of a structure from **the act of traversing it**.
- The code above shows two visitors: one that increments the leaves of a binary tree, the other that prints their values.
- We **do not** need to manually inspect the left and right subtrees, only writing the logic for the leaves. The traversal logic is contained in `BaseTreeVisitor`.
- Note that you **don't need to understand how to implement a visitor yourself**, just that it allows us to write the logic for each type of element independently.

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ANTLR Visitors

- ANTLR generates a base Visitor class from the supplied grammar.
- We can either use this to **create instances of our AST nodes** (and then write our own code to traverse them), or **work directly with the generated visitors** (without needing to write our own AST)
- The labs and assignment (and code in my lectures) will use a custom AST.
  - We will only use ANTLR visitors to create instances of our hand-written ASTs.
  - This is because hand-written ASTs have more specific structure and types, are easier to conceptualise, and writing explicit recursive functions is closer to the formal definitions.

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General pointers for using ANTLR Visitors

- Parameterise your visitor with the type you wish to return.
- Override the `visit` method for each generated expression, and implement the desired behaviour.
- The generated AST classes have accessor methods for subexpressions, based on the production names in the grammar. If there are multiple, you can supply the index.

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Generating an AST using an ANTLR Visitor

```
public class LArithASTGenerator
  extends LArithBaseVisitor<Expr> {

  @Override
  public Expr visitAdd(LArithParser.AddContext ctx) {
    Expr e1 = visit(ctx.expr(0));
    Expr e2 = visit(ctx.expr(1));
    return new EBinOp(e1, EBinOp.Op.ADD, e2);
  }

  @Override
  public Expr visitInt(LArithParser.IntContext ctx) {
    int val = Integer.valueOf(ctx.INT().getText());
    return new EInt(val);
  }
  …
}
```

We can **parameterise** the visitor with the type we want each method to return, in this case an Expr

Each rule in the grammar will result in a method in the visitor that we can override (in this case, Add)

We visit both subexpressions (accessed using the `ctx.expr()` method) to get two `Exprs`, and we can use these to construct a new `EBinOp` expression

Terminals are always represented as strings, so we need to use the `getText()` method and convert to an integer

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L_{Arith} starter code

- `antlr/`
  - `LArith.g4`: Larith ANTLR grammar definition
- `ast/`
  - `Expr.java`: Abstract Expression superclass
  - `EInt.java / EBinOp.java`: Expression AST nodes
  - `Value.java / VInt.java`: Value AST nodes
- `LArithASTGenerator.java`: ANTLR visitor to generate AST nodes
- `LArithInterp.java`: Interpreter
- `Main.java`: Entrypoint to read file, then call parser and interpreter

- This week's lab has two parts:
  - The first is exploring the (completed) interpreter for L_{Arith}
  - The second is extending this code to implement the additional features from L_{if}
- There are also scripts to help you compile and run, and some example programs

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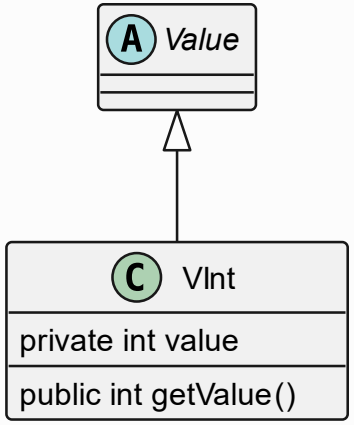
Implementing an Interpreter (Overview)

- Remember the form of our operational semantics judgement, which says that an expression M will evaluate to a value V.

$$M \Downarrow V$$

- It helps to write a class hierarchy representing Values (in L_{Arith}, this will only contain `VInt`). Values are **only introduced at runtime and are never parsed in**.



- Our interpreter is therefore a function from an Expr to a Value.

```
public Value interpExpr(Expr e) { … }
```

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Implementing an Interpreter (Values)

- To write an interpreter, we need different cases based on each rule in the operational semantics
- The value rule just states that a number is already a value, so we just need to create a `VInt` with the same value.

Note: e is of type Expr. We need to do **instance tests** to check which kind of expression e is, and then **cast** it to an EInt

$$\frac{}{n \Downarrow n}$$

```
if (e instanceof EInt) {
  EInt exprInt = (EInt) e;
  return new VInt(exprInt.getValue());
}
```

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Implementing an Interpreter (Binary Operators)

$$\frac{L \Downarrow V \qquad M \Downarrow W}{L \odot M \Downarrow V \mathbin{\widehat{\odot}} W}$$

Key idea: recursively evaluate subexpressions, switch on the operator, and apply the concrete operation

Note: `unwrapInt` is a function that extracts an integer from a Value

```
  …
} else if (e instanceof EBinOp) {
  EBinOp exprBinOp = (EBinOp) e;
  Value v1 = interpExpr(exprBinOp.getE1());
  Value v2 = interpExpr(exprBinOp.getE2());
  int i1 = unwrapInt(v1);
  int i2 = unwrapInt(v2);
  switch (exprBinOp.getOp()) {
    case ADD: return new VInt(i1 + i2);
    case SUB: return new VInt(i1 - i2);
    case MUL: return new VInt(i1 * i2);
    case DIV: return new VInt(i1 / i2);
    default:
      throw new RuntimeException("Invalid op");
}
```

SVM

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SVM Overview

- Last lecture, we touched on **virtual machines**: instruction sets + virtual architecture for running programs in a platform-independent way.
- SVM is a simple(ish) VM used for teaching, and suitable for implementing simple imperative languages. It'll be used in Michele's part of the course.
- Much like both the JVM and WebAssembly, SVM is **stack-based**: instructions use an operand stack rather than having explicit parameters.

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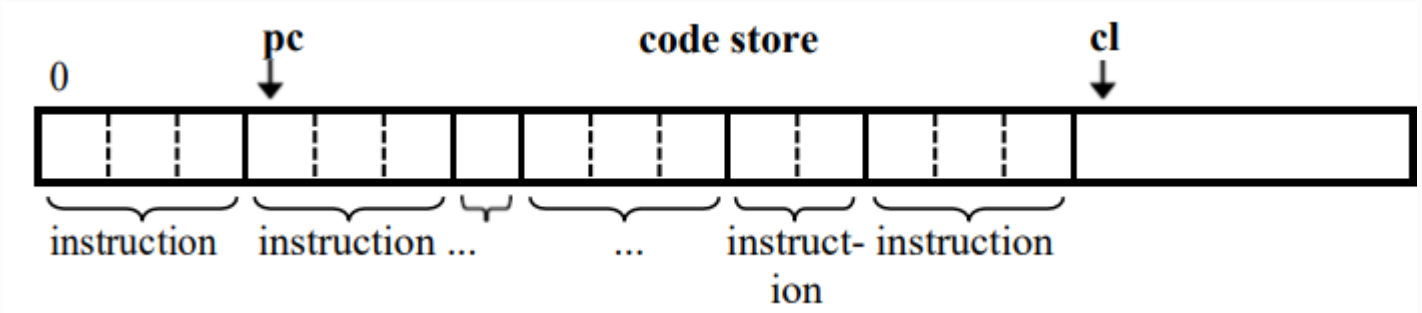
Machine State (Code Store)

The first part of the SVM state is a **code store** containing the machine's bytecode.



There are two registers associated with the code store:

- A **program counter** (pc) that tracks the current instruction
- A **code limit** (cl) that marks the end of the code store

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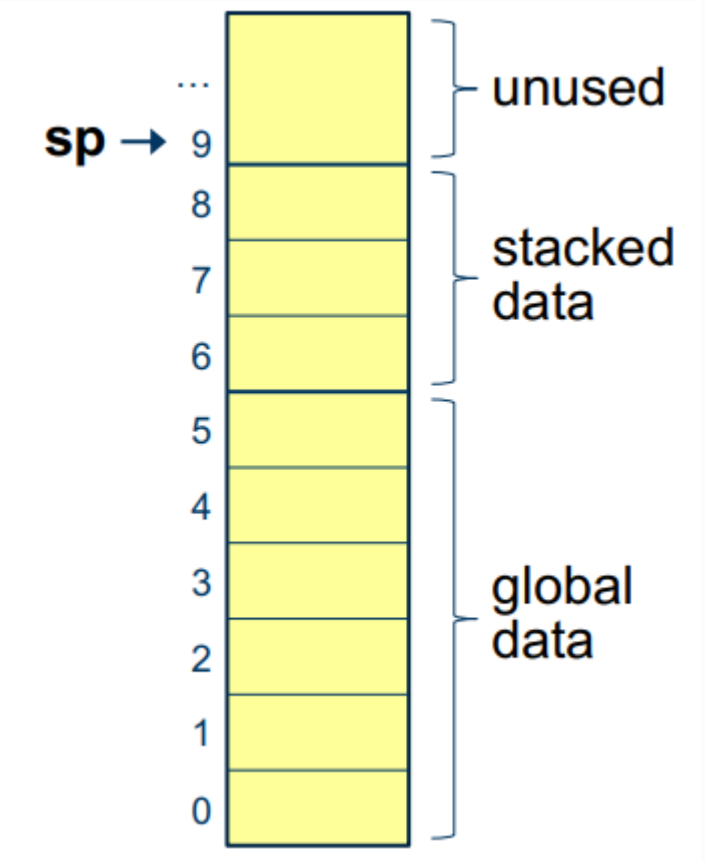
Machine State (Data Store)

- The second part of the SVM state is a **data store** containing the program's data (simplified diagram on the right).
- Roughly speaking, there is a **stack pointer** (sp) that denotes the top of the stack, some data that occurs on the stack, and then global data.
- The full definition includes additional information to remember return addresses, etc.
- Finally, the machine contains a **status** register that indicates whether the program is running, halted, or failed.



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Simplified SVM Instruction Set (1)

Opcode	Mnemonic	Description
6	ADD	pop w_2; pop w_1; push (w_1 + w_2)
7	SUB	pop w_2; pop w_1; push (w_1 – w_2)
8	MUL	pop w_2; pop w_1; push (w_1 × w_2)
9	DIV	pop w_2; pop w_1; push (w_1 / w_2)
10	CMPEQ	pop w_2; pop w_1; push (if w_1 = w_2 then 1 else 0)
11	CMPLT	pop w_2; pop w_1; push (if w_1 < w_2 then 1 else 0)
14	INV	pop w; push (if w = 0 then 1 else 0)

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Simplified SVM Instruction Set (2)

Opcode	Mnemonic	Description
0	LOADG d	w <- word at address d; push w
1	STOREG d	pop w; word at address d <- w
4	LOADC v	push v
…		
16	HALT	status <- halted
17	JUMP c	pc <- c
18	JUMPF c	pop w; if w = 0 then pc <- c
19	JUMPT c	pop w; if w =/= 0 then pc <- c

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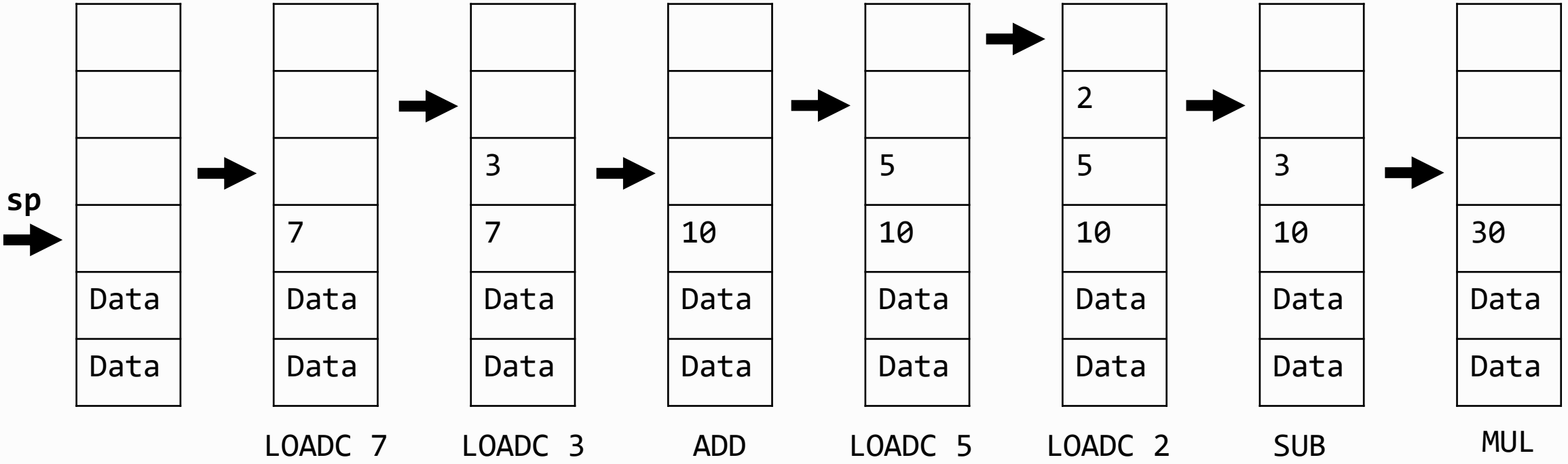
Example SVM Evaluation

Suppose we want to evaluate `(7 + 3) * (5 - 2)` in SVM



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SVM Implementation

```
public void interpret () {
  // Initialise state
  status = RUNNING;
  sp = 0; fp = 0; pc = 0;
  do {
    // Fetch the next instruction:
    byte opcode = code[pc++];
    // Inspect opcode and execute:
    switch (opcode) {
      case ADD:
        int w2 = data[--sp];
        int w1 = data[--sp];
        data[sp++] = w1 + w2;
        break;
      …
    }
  } while (status == RUNNING);
}
```

- There's a full specification of SVM on Moodle, along with an interpreter – take a look if you're interested!
- Virtual machines don't have to be complicated. It's essentially one big loop that continually fetches and executes each instruction until the machine is halted.

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Conclusion

- In this lecture we've seen:
  - How to represent an AST using Java classes
  - How to use ANTLR to generate a lexer, parser, and visitor code
  - How to write an interpreter from an operational semantics
  - An overview of the SVM virtual machine
- Next time, we'll be looking at variables and binding, and first-class functions: important lecture!
- Please come to the labs to get some hands-on PL implementation experience with help from myself and our wonderful GTA team