GOALS OF THE COURSE

• Learn fundamental structure of programming languages.
• Understand key issues in language design and implementation.
• Increase awareness of the range of available languages and their uses.
• Learn how to learn a new language.
• Get a small taste of programming language theory.

METHOD OF THE COURSE

• Fairly conventional survey textbook, with broad coverage of languages.
• Homework exercises involve programming problems in real languages.
• Most homework problems will involve modifying implementations of “toy” languages that illustrate key features and issues.
• Exercises will use two modern languages: Python and OCaml.
• Between them, these languages illustrate many of the important concepts in current language designs.

NON-GOALS

• Teaching how to program.
• Teaching how to write significant programs in any particular language(s).
• Surveying/cataloging the features of lots of different languages.
• Comprehensive coverage of programming paradigms (e.g., will skip logic and concurrent programming material).
• Will mostly be concerned with interpreting abstract syntax for the toy languages, and will spend very little time on parsing and code generation. (Not a compiler course!)
**Some Languages**

What languages do you know?

FORTRAN, COBOL, (Visual) BASIC, ALGOL-60, ALGOL-68, PL/I, C, C++, RPG, Pascal, Modula, Oberon, Lisp, Scheme, ML, Haskell, Ada, Prolog, Goedel, Curry, Snobol, ICON, . . .

Don’t forget things like:

- scripting languages: perl, tcl, Python, . . .
- SQL, other database query languages.
- spreadsheet expression languages
- text processing languages, tex, awk, etc.
- application-specific languages.

---

"**Higher-Level" Programming Languages**

Consider a simple (dumb) algorithm for testing primality.

In Python:

```python
def isprime(n):
    # return true if n has no divisor in interval [2,n-1]
    for d in range(2,n):
        if n % d == 0:
            return False
    return True
```

In OCaml (using a recursive function):

```ocaml
let isprime (n:int) : bool =
    (* return true if n has no divisor in interval [2,n-1] *)
    let rec no_divisor (d:int) : bool =
        (* return true if n has no divisor in interval [d,n-1] *)
        (d >= n) || ((n mod d <> 0) && no_divisor (d+1)) in
    no_divisor 2
```

In Intel X86 (32 bit) Assembler:

```
.globl isprime
isprime:
    pushl %ebp ; set up procedure entry
    movl %esp,%ebp
    pushl %esi
    pushl %ebx
    movl 8(%ebp),%ebx ; fetch arg n from stack
    movl $2,%esi ; set divisor d := 2
    cmpl %ebx,%esi ; compare n,d
    jge true ; jump if d >= n
loop:
    movl %ebx,%eax ; set n into ....
    cltd ; ... dividend register
    idivl %esi ; divide by d
    testl %edx,%edx ; remainder 0?
    jne next ; jump if remainder non-0
    xorl %eax,%eax ; set ret value := false(0)
    jmp done
next:
    incl %esi ; increment d
    cmpl %ebx,%esi ; compare n,d
    jl loop ; jump if d < n
true:
    movl $1,%eax ; set ret value := true(1)
    done:
    leal -8(%ebp),%esp ; clean up and exit
    popl %ebx
    popl %esi
    leave
    ret
```
**High-level Languages: General Characteristics**

- Complex Expressions (Arithmetic, Logical, ...)
- Structured Control Operators (Loops, Conditionals, Cases)
- Composite Types (Arrays, Records, etc.)
- Type Declarations and Type Checking
- Multiple storage classes (global/local/heap)
- Procedures/Functions, with private scope, maybe first-class
- Maybe high-level control mechanisms (Exceptions, Back-tracking, etc.)
- Maybe abstract data types, modules, objects, etc.

**Machine Code Characteristics**

- Low-level machine instructions to implement operations.
- Control flow based on labels and conditional branches.
- Explicit locations (e.g. registers) for values and intermediate results.
- Explicit memory management (e.g., stack management for procedures).

**Language Implementation**

Ultimately, we want to execute programs on real hardware.

Two classic approaches:

- A **compiler** translates high-level language programs into a lower-level language (e.g. machine code).
- An **interpreter** is a fixed program that can read (the representation of) an arbitrary high-level program and execute it.

Very generally, compilers can generate code that runs faster than interpreted code, but interpreters are quicker and easier to write and maintain than compilers.

Interpreters are also easier to understand, which is why we will be using them for the toy languages in this course. But interpreters can also obscure important machine-level implementation issues, so we will also sometimes consider compiled code.

**Stack Machines**

A **stack machine** is a simple architecture based on a stack of operand values.

- All machine instructions pop their operands from the stack, and push their results back onto the stack
- This makes instructions very simple, because there’s no need to specify operand locations.
- This architecture is often used in abstract machines, such as the Java, Python, or OCaml virtual machines. (Most real machines use register-based architectures instead.)
- Often compile from high-level language to stack machine byte code which is then interpreted (or perhaps compiled further to machine code).
STACK MACHINE EXAMPLE

Here’s the instruction set for a very simple stack machine:

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Stack Before</th>
<th>Stack After</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONST i</td>
<td>s1 ... sn</td>
<td>i s1 ... sn</td>
</tr>
<tr>
<td>LOAD x</td>
<td>s1 ... sn</td>
<td>Vars[x] s1 ... sn</td>
</tr>
<tr>
<td>STORE x</td>
<td>s1 ... sn</td>
<td>s2 ... sn</td>
</tr>
<tr>
<td>PLUS</td>
<td>s1 s2 s3 ... sn</td>
<td>(s1+s2) s3 ... sn</td>
</tr>
<tr>
<td>MINUS</td>
<td>s1 s2 s3 ... sn</td>
<td>(s2-s1) s3 ... sn</td>
</tr>
</tbody>
</table>

Note that STORE x also sets Vars[x] = s1.

And here’s a stack machine program corresponding to the simple statement $c = 3 - a + (b - 7)$:

- CONST 3
- LOAD a
- MINUS
- LOAD b
- CONST 7
- MINUS
- PLUS
- STORE c

Is this code sequence unique?

This illustrates the expressiveness of high-level *expressions* compared to machine code.

PROGRAMMING LANGUAGE CLASSIFICATIONS

Programming paradigms

- Imperative (including object-oriented)
- Functional
- Logic
- Concurrent/Parallel
- Scripting

Programming Contexts

Programming “in the Small”

- Expressions
- Structured Control Flow
- Structured Data
- Types

Programming “in the Large”

- Modules and Separate Compilation
- Code Re-use; Polymorphism
- Object-oriented Programming
- Types

SOME THEMES IN LANGUAGE DESIGN

Expressiveness

- Vocabulary of operations, expressions, statements, etc.
- Support for abstraction, extensibility

Efficiency

- Mapping to the hardware

Program Correctness

- Types
- Reasoning about program behavior
LANGUAGE DESCRIPTION AND DOCUMENTATION

For programmers, compiler-writers, and students . . .

Syntax (Easy)
What do programs look like?
• Grammars; BNF and Syntax Charts

Semantics (Hard)
What do programs do?
• Informal
• Formal: Operational, Denotational, Axiomatic

Learning about a Language
• Reference Manuals, User Guides, Texts and tutorials
• Experimentation

SYNTAX: CONCRETE & ABSTRACT

• Language syntax describes the legal form and structure of programs
• Concrete syntax describes is what a program looks like on the page or screen
• Abstract syntax describes the essential contents of a program as it might be represented internally (e.g. by an interpreter or compiler)
• In this course, we won’t worry much about concrete syntax, but it is worth some brief discussion
• (And we will need to choose some concrete syntax for the programs we interpret)
• Syntax is specified by a grammar.

CONTEXT-FREE GRAMMARS

• Used for description, parsing, analysis, etc.
• Based on recursive definition of program structure.
• A grammar is defined by:
  • a set of terminal symbols (strings of characters)
  • a set nonterminal variables, which represent sets of terminals
  • a set of production rules that map nonterminals to strings of terminals and non-terminals
• The language defined by a grammar is the set of strings of terminals that can be derived by applying production rules, starting from a specified nonterminal.
• Grammars have rich theory with connections to automatic parser generation, push-down automata, etc.
• Many possible representations, including BNF (Backus-Naur Form), EBNF (Extended BNF), syntax charts, etc.

BNF was invented ca. 1960 and used in the formal description of Algol-60. It is just a particular notation for grammars, in which
• Nonterminals are represented by names inside angle brackets, e.g., <program>, <expression>, <S>.
• Terminals are represented by themselves, e.g., WHILE, [, ]. The empty string is written as <empty>.

BNF Example...
Program ::= BEGIN Statement-seq END
Statement-seq ::= Statement [' ; ' Statement-seq ]
Statement ::= [ While-statement | For-statement ]
While-statement ::= WHILE Expression DO Statement-seq END
Expression ::= Factor { ( AND | OR ) Factor }
Factor ::= ( Expression ) | Variable
For-statement ::= . . .
Variable ::= . . .

**EBNF**

EBNF is (any) extension of BNF, usually with these features:

- A vertical bar, |, represents a choice,
- Parentheses, ( and ), represent grouping,
- Square brackets, [ and ], represent an optional construct,
- Curly braces, { and }, represent zero or more repetitions,
- Nonterminals begin with upper-case letters.
- Non-alphabetic terminal symbols are quoted, at least when necessary to avoid confusion with the meta-symbols above.

**Syntax Analysis ( Parsing )**

Parser recognizes syntactically legal programs (as defined by a grammar) and rejects illegal ones.

- Successful parse also captures hierarchical structure of programs (expressions, blocks, etc.).
- Convenient representation for further semantic checking (e.g., typechecking) and for code generation.
- Failed parse provides error feedback to the user indicating where and why the input was illegal.

Any context-free language can be parsed by a computer program, but only some can be parsed efficiently. Modern programming languages can usually be parsed efficiently.
**Lexical Analysis**

Programming language grammars usually take simple tokens rather than characters as terminals. Converting raw program text into token stream is the job of the **lexical analyzer**, which

- Detects and identifies keywords and identifiers.
- Converts multi-character symbols into single tokens.
- Handles numeric and string literals.
- Removes whitespace and comments.

**Ambiguity**

A given sentence in \( L(G) \) can have more than one parse tree. Grammars \( G \) for which this is true are called **ambiguous**.

Example: given the grammar on the last slide, the sentence

\[ a \ + \ b \ * \ c \]

has two parse trees:

We may think of the left tree as being the “correct” one, but nothing in the grammar says this.

To avoid the problems of ambiguity, we can:

- Rewrite grammar; or
- Use “disambiguating rules” when we implement parser for grammar.

**Parse Trees**

Graphical representation of a derivation.

Given this grammar:

\[
expr \rightarrow \ expr \ + \ expr \mid \ expr \ * \ expr \mid (expr) \mid \ - \ expr \mid \ id
\]

Example tree for derivation of sentence \(-(x + y)\):

Each application of a production corresponds to an **internal** node, labeled with a **non-terminal**.

Leaves are labeled with **terminals**, which can have **attributes** (in this case the specific identifier name).

The derived sentence is found by reading leaves (or “fringe”) left-to-right.

**Ambiguity in Arithmetic Expressions**

To disambiguate a grammar like

\[
E \rightarrow \ E \ + \ E \mid \ E \ - \ E \mid \ E \ * \ E \mid \ E \ / \ E \mid (E) \mid \ id
\]

we need to make choices about the desired order of operations.

For any expression of the form \( X \ op_1 \ Y \ op_2 \ Z \) we must define:

- **Precedence** - which operation (\( op_1 \) or \( op_2 \)) is done first?
- **Associativity** - if \( op_1 \) and \( op_2 \) have the same precedence, then does \( Y \) “associate” with the operator on the left or on the right?

In other words, we need rules to tell us whether the expression is equivalent to \((X \ op_1 \ Y) \ op_2 \ Z\) or to \(X \ op_1 \ (Y \ op_2 \ Z)\).

The “usual” rules (based on common usage in written math) give \(* \) and \(/ \) higher precedence than \(+ \) and \(- \), and make all the operators left-associative.

So, for example, \( a \ - \ b \ - \ c \ * \ d \) is equivalent to \((a \ - \ b) \ - (c \ * \ d)\). But this is a matter of **choice** when defining the language.
**Rewriting Arithmetic Grammars**

One way to enforce precedence/associativity is to build them into the grammar using extra non-terminals, e.g.:

- `factor → (expr) | id`
- `term → term * factor | term / factor | factor`
- `expr → expr + term | expr - term | term`

Example: `a * b - c + d * e`

**Limitations of Context-free Grammars**

Context-free grammars are very useful for describing the structure of programming languages and identifying legal programs. But there are many useful characteristics of legal programs that cannot be captured in a grammar (no matter how clever we are).

For example, in many programming languages, every variable in a legal program must be declared before it is used. But this property cannot be captured in a grammar. So checking legality of programs typically requires more than syntax analysis. Most compilers use a secondary “semantic” analysis phase to check non-syntactic properties, such as type-correctness. Of course, sometimes illegal programs cannot be detected until runtime.

**Parse Trees vs. Abstract Syntax Trees**

Parse trees reflect details of the concrete syntax of a program, which is typically designed for easy parsing.

For processing a language, we usually want a simpler, more abstract view of the program. (No firm rules about AST design: matter of taste, convenience.)

Simple concrete grammar:

- `S → while '(' E ')' do S | ID '=' E`
- `E → E '+' T | E '-' T | T`
- `T → ID | NUM | '(' E ')'`

```
while (n) do n = n - (b + 1)
```
**Parse Trees vs. Abstract Syntax Trees (2)**

Possible abstract syntax tree for `while (n) do n = n - (b + 1)`

```
  While
  /   \\nId n  Assgn n
     /
    Sub
   /  \
Id n Add
   / \
Id b Num 1
```

Note that tree nodes may have *attributes* (such as the name of an `Id`) and/or *sub-trees*.

**Abstract Syntax Captures the Essence**

Concrete syntax is important for usability, but fundamentally superficial. The same abstract syntax can be used to represent many different concrete syntaxes.

Examples:
- C-like:
  ```c
  while (n) do n = n - (b + 1);
  ```
- Fortran-like:
  ```fortran
  do while(n .NE. 0)
    n = n - (b + 1)
  end do
  ```

**Tree Grammars**

AST’s obey a tree grammar. Rules have form

```
label : kind → (attr₁ ... attrₘ) kind₁ ... kindₙ
```

where the LHS classifies the possible node *labels* into *kinds*, and the RHS describes the label’s atomic *attributes* (if any, in parentheses) and the kinds of its subtrees (if any).

Example:

```
While : Stmt → Exp Stmt
Assgn : Stmt → (string) Exp
Add : Exp → Exp Exp
Sub : Exp → Exp Exp
Id : Exp → (string)
Num : Exp → (int)
```

**Concrete Syntax Examples (2)**

- COBOL-like:
  ```cobol
  PERFORM 100-LOOP-BODY
  WITH TEST BEFORE
  WHILE N IS NOT EQUAL TO 0
  100_LOOP-BODY.
  ADD B TO 1 GIVING T
  SUBTRACT T FROM N GIVING N
  ```
- Use Chinese keywords in place of *while* and *do*.
- Use a graphical notation.
AST's have recursive structure and irregular shape and size, so it makes sense to store them as heap data structures using one record for each tree node.

In Java, heap records are objects. We define classes corresponding to the various kinds and a subclass for each label, e.g.

```java
abstract class Stmt {}
class While extends Stmt {
    Exp test; Stmt body;
}
class Assign extends Stmt {
    String lhs; Exp rhs;
}
abstract class Exp {
    Exp left; Exp right;
}
class Num extends Exp {
    int value;
}
```

Nodes are created by constructor calls, e.g., `Exp e = new Num(42)`.

In Python, heap records are again objects, and we define classes corresponding to the various labels, e.g.

```python
class While:
    def __init__(self, test, body):
        self.test = test
        self.body = body
class Assign:
    def __init__(self, lhs, rhs):
        self.lhs = lhs
        self.rhs = rhs
class Add:
    def __init__(self, left, right):
        self.left = left
        self.right = right
class Num:
    def __init__(self, num):
        self.num = num
```

Nodes are again created by invoking constructors, e.g. `e = Num(42)`.

But note that the type relationships among the classes and fields are lost, since Python doesn't have static types.

In Ocaml, we can use algebraic datatypes to define a suitable set of variants, e.g.:

```ocaml```
type stmt = While of exp * stmt       | Assign of string * exp           | ...
    and exp = Add of exp * exp         | ...                               | Num of int
```

These declarations also define constructors, so we can say, e.g., `e:exp = Num(42)`.

All these approaches generate roughly the same heap structures, e.g. for

```
while (n) do n = n - (b + 1)
```

```
<table>
<thead>
<tr>
<th>WHILE</th>
<th>Stmt</th>
</tr>
</thead>
<tbody>
<tr>
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<td>ID</td>
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<td>NUM</td>
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</table>
```

```
AST's in Java
```

```
AST's in Python
```

```
Heap Structure
```

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EXTERNAL REPRESENTATION OF ASTs

Although ASTs are designed as an internal program representation, it can be useful to give them an external form too that can be read or written by other programs or by humans.

Any external representation of ASTs must accurately reflect the internal tree structure as well as the “fringe” of the tree. Can’t use tree grammar to parse, since it is typically ambiguous!

One approach (deriving from the programming language LISP) is to use parenthesized prefix notation to represent trees.

Each node in the tree is represented by the expression

\[(\text{label} \ attr_1 \ldots \ attr_m \ child_1 \ child_n)\]

where label is the node label, the attr_i are the label’s attributes (if any), and the child_i are the label’s sub-trees (if any), each of which is itself a node expression. To make things more readable, we might use abbreviations for common labels, e.g., + for Add. We may also represent simple leaf nodes by their bare attributes, e.g., use 3 for (Num 3), as long as no confusion can arise.

PARSING PARANTHEZIZED PREFIX NOTATION

Note that this BNF description contains essentially the same information as our AST internal datatype declarations (except for the descriptive field names).

Parsing this representation is easy! Why?

• Everything is either an atom (keyword, symbol, numeric literal, etc.) or a parenthesized list of atoms
• Each node in the AST corresponds to a list or atom.
• The first item in each list is always a symbol that identifies the node type and implies the kind and number of the remaining things in the list.
• The lexical analyzer just needs to identify the atoms and list delimiters.

EXTERNAL AST EXAMPLE

So the representation of our AST example could be

\[(\text{While} \ (\text{Id} \ n) \ (\text{Assgn} \ n \ (- \ (\text{Id} \ n) \ (+ \ (\text{Id} \ b) \ (\text{Num} \ 1))))\]

where the indentation is optional, but makes the representation easier for humans to read. The BNF for this syntax can be given as:

\[<\text{stmt}> ::= <\text{While}> <\text{expr}> <\text{stmt}> | <\text{Assgn}> <\text{name}> <\text{expr}>\]

\[<\text{expr}> ::= (+ <\text{expr}> <\text{expr}> ) | (- <\text{expr}> <\text{expr}> ) | <\text{name}> | <\text{int}>\]

Concrete and abstract syntax are isomorphic.