

# EDAP05: Concepts of Programming Languages - Skills Sheet

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# 1 Language Critique

The book provides a convenient common framework for arguing about the benefits and disadvantages of language features and programming languages in general. Table 1.1 and, more generally, Section 1.3 in the book describe a number of axes along which we can try to understand the effect of language features and the qualities of programming languages.

## 1.1

You should be able to recognise and describe all the characteristics listed in Table 1.1, as well as the three basic criteria listed therein.

- Readability — How easy is it to read the program’s source code and understand what’s happening?
  - Simplicity — How “simple” is the language?
    - \* Is it like brainfuck and hard to read and write (leading to reliability issues), or like Python that is quite literate (in terms of how similar it can be to English)?
  - Orthogonality — How do the number of features present in a language overlap?
    - \* Operator overloading is one instance where we sacrifice orthogonality for a simpler to read and write (and more reliable) language.
    - \* For example, the addition operator is typically overloaded for integers and floating-point numbers, because in math we use the same operator for both, but have different meanings and required operations in computers.
  - Data Types — How closely do data types that we use in the program match our needs? Do these overlap with things that may be present in the real world (in the case of OOP languages)?
  - Syntax Design — Is the syntax, i.e. the way the language must be read and written easy or difficult?
    - \* If it is difficult, is there a reason?
    - \* This may influence the reliability of the language if it is hard to understand how the program is working.
- Writability — How easy is it to write a program’s source code and understand what’s happening? This does not just refer to the writer, but also the reader (who may be the same person or someone else) later.
  - Support for Abstraction — Can we take repeated details of our program and make them more general than before?
    - \* For program operations (subprograms), instead of having to embed common operations everywhere in a program that may need to perform this calculation, can we make it a subprogram that can be called repeatedly and operate as before?
    - \* For data, how naturally can we represent more complicated things? For example, a binary tree in C is a `struct` with 2 pointers and a holding value. In older languages (FORTRAN), it was 3 arrays in parallel.
  - Expressivity — Using the features built into the language, how easy is it to **naturally** express the computation that we want to perform?
    - \* How much of the language’s code do we need to describe some computation?
- Reliability — How sure are we (the writer) that our code is actually doing what we want, without error? If there are errors, how can we ensure that they are handled?
  - Type Checking — Using the data types from earlier, what kind of checking can we perform to ensure our program operates the way we intend it to?
    - \* Think of SML’s type checking, or Rust’s type checking for a strongly-typed and statically checked language.
    - \* C/C++ is weakly-typed because of pointers (which can be overwritten in any way, without regards to the type checker), although it is statically checked.
    - \* Python is strongly-typed, but dynamically checked. This is the reason any variable can be any type at any point of execution, but the operations that can be performed on them are limited.
    - \* JavaScript is weakly-typed and dynamically checked. Being weakly-typed means the language allows errors that could be caught to instead “fly under the radar”, until the thing is used again. Being dynamically checked means that these are only found during runtime of the language.
  - Exception Handling — If an error happens during program execution (a file is not present, network connection lost, etc.) how well can we handle that? How easy is it to read and write a program where these can occur?
  - Restricting Aliasing — Can we restrict the number of things that point to a single memory cell? This is important for type checking and resource deallocation.

## 1.2

For some language feature, you should be able to recognise the characteristics and criteria (from Table 1.1 (Section 1.1)) affected by that feature's presence or absence.

## 1.3

For some language feature, you should be able to recognise how the feature's presence or absence affects the language, based on the three criteria from Table 1.1 (Section 1.1).

## 1.4

For two related language features, you should be able to compare them, based on the three criteria from Table 1.1 (Section 1.1).

## 1.5

For some language feature, you should be able to recognise and explain how it can affect the Cost considerations for training, compile time, execution time, and cost of poor reliability as outlined in Section 1.3.7.

- Training Time — How long does it take programmers to learn this language?
- Compile Time — How long does it take the compiler to compile the program?
  - A slower compiler may catch more errors or generate more optimized machine code
  - A faster compiler allows for quicker development and faster programmer feedback.
- Execution Time — When the program is running, how much time does it take to run?
  - This can be measured in many ways: CPU time, CPU cycles, human time, etc.
- Poor Reliability — If the program runs, but does so unreliably, it must be fixed. What is the cost of fixing the reliability issues with this/these program(s)?

# 2 Language Implementation

You should be familiar with the following concepts:

## 2.1

Language implementation via **pure interpretation**, **compilation**, and **hybrid implementation**.

- Pure Interpretation
  - Python
  - The program runs on an interpretation layer between the hardware and itself. (VM usually)
  - Quicker development with faster feedback on issues
  - No compilation (May be possible to compile down to VM-specific code, but not machine code.)
  - Slower execution time (Must interpret each command, break down to possible CPU actions, and write the machine code on-the-fly.)
- Compilation
  - C
  - Program runs ON the computer's hardware
  - Slower development, must compile for some issues to be found (Type Error). Must run for other issues to be found (Null pointer).
  - Compile down to machine code for quick runtime.
  - Fast execution. Human-readable code already in machine code, just need to load into memory and begin execution.
- Hybrid Implementation
  - Java
  - Program may start by being interpreted, but parts in use will start to be compiled while running.
  - Runs some parts through an interpreter, and some pieces are compiled.
  - Theoretically, same kind of fast development as interpreted languages, with the more frequently-used code being compiled for speed.
  - Hypothetically, Fast execution for the parts that are compiled.

## 2.2

Language implementation with the help of a **just-in-time compiler**.

- A Just-In-Time (JIT) compiler starts by having the code run in an interpreted mode.
- After some time, the most frequently used portions of code are compiled, to improve performance, and the interpreted parts are replaced by the compiled parts.
- Java uses this.

## 2.3

The concept of language **run-time system**.

- These are the systems in place that were put in by the compiler/interpreter to help the program run.
- These can include: Error handlers, resource deallocators (Garbage collectors), and type coercers.

# 3 Syntax

Syntax describes the possible structure (or form) of programs of a given programming language. Backus-Naur Form (BNF) grammars have emerged as the standard mechanism for describing language syntax. BNF grammars used to describe languages when communicating with language adopters and compiler implementors. There are also many tools (particularly the yacc and antlr families of programs) for automatically generating parsers, programs that recognise whether an input program matches a grammar and, if it does, execute user-defined actions upon encountering certain language constructs.

## 3.1

You should be able to determine whether a given property of a language is part of the syntax, of the static semantics, or of the dynamic semantics.

- Syntax — This is done with the context-free grammar and parsing the input symbols
- Static Semantics — This is done during the implementation of the compiler/interpreter. These define some of the operations possible and how they should behave.
  - For example, the + operator must be defined to mean addition when given integers and concatenation when given strings.
  - It is required that the syntax be defined and relatively fixed for the semantics to be well-defined.
- Dynamic Semantics — This is done while the program is running. These determine the behaviors of the operators while the program is in-use.

## 3.2

You should be able to read a BNF grammar and understand the difference between terminals and nonterminals.

- Terminals — Symbols that represent a terminating point in the recursion.
  - Typically, these are symbols that mean we have reached the end of our recursion.
  - In a programming language, these are usually keywords.
  - In this course, they are typically symbols that lack the  $\langle$  and  $\rangle$ .
- Nonterminals — Symbols that continue the recursion of a production to another production with the same symbol.
  - These are things used to construct a parse tree of what we have input to the parser/grammar.
  - In this course, they are typically denoted as  $\langle A \rangle$ .

## 3.3

Given a BNF grammar, you should be able to write down examples of programs that can be generated by the grammar.

- This means you must be able to run through and recurse through the grammar.

### 3.4

Given a BNF grammar, you should be able to tell whether a given program can be generated by the grammar. If the program is generated by the grammar, you should also be able to generate a parse tree for the program.

- Essentially, you must run the grammar on the given program and confirm whether the program could be accepted/generated by the grammar.

### 3.5

You should be able to determine whether a given (small) BNF grammar is ambiguous (the problem is undecidable in general, so this skill only pertains to practically relevant examples as covered in the textbook).

- There needs to be more than one way to generate a parse tree given a grammar.

### 3.6

Given a BNF grammar, you should be able to determine the associativity of any operator used therein.

- Left associative operators are left-recursive in their grammar, so the parentheses build up towards the left, with the first operation to be performed deepest in the parse tree on the left, with all subsequent operations higher in the tree and to the right.
- Right associative operators are right-recursive in their grammar, so the parentheses build towards the right, with the first operation to be performed deepest in the parse tree to the right, with all subsequent operation higher in the tree and to the left.

### 3.7

You should be able to describe the difference between an object language and a meta-language.

- Object language — A language that is used for something, for example, C. These can be meta-languages in some cases.
- Meta-language — A language that describes other languages, Context-free grammars, for example.

### 3.8

Understand **arity**, **fixity**, and **precedence**, and **associativity** of operators

- Arity
  1. Unary — An operator that takes a single argument. Logical NOT is an example of this, as well as `i++`.
  2. Binary — An operator that takes 2 arguments. Most mathematical and logical operations are like this.
  3. Ternary — An operator that takes 3 arguments. The ternary `if` operator is an example of this.
- Fixity
  - Prefix — Operator symbol before arguments,  $+ 3 2 = 5$
  - Infix — Operator symbol between arguments,  $3 + 2 = 5$
  - Postfix — Operator symbol after arguments,  $3 2 + = 5$
- Precedence
  - Given several operators in a single line, which one should have the highest priority?
  - Only way to figure this out is to run tests which force certain operations to have mutually disjoint outputs. Meaning for some inputs, you will get different outputs for operations with different precedences.
- Associativity
  - Given several operators of the same precedence, what order should they be evaluated in?
  - Most mathematical and logical operators are left-associative, meaning they should be left-recursive in their grammar.
  - The exceptions to this are exponentiation and function types, which are right-associative, and thus must be right-recursive in their grammar.

## 4 Natural Semantics

There are many ways to describe semantics. In this course, we focus on natural semantics (also known as Big-Step Operational Semantics).

### 4.1

You should be able to read a specification of natural semantics.

### 4.2

You should be able to understand how **expressions** and **values** relate to each other.

1. An expression is built up of values.
2. An expression can return a value or another expression.
3. Values must be defined in terms of some mathematical numerical thing. If  $v$  is input as an integer, then  $v \in \mathbb{Z}$  is the conditional requirement for  $v \Downarrow v$ .

### 4.3

Given a natural semantics and a parse tree (or unambiguous expression), you should be able to compute the semantics of the given program.

- You must use the semantic rules provided, and repeatedly recurse until the semantics of the entire program has been defined.

### 4.4

Given a natural semantics and a BNF grammar, you should be able to tell whether any parts of the semantics are undefined.

- The BNF grammar defines what symbols may be used. So if the semantics uses symbols that the BNF does not define, the semantics are undefined.
- If there are operator symbols defined, but the semantics does not use them, then the semantics are undefined.
- If an operator's semantics do not recurse enough to handle all cases, then they are undefined.

### 4.5

Given an understanding of what a state-free expression language is supposed to do, you should be able to write down a simple natural semantics for it.

- Given a basic state-free expression, like an expression  $1 + x$  where  $x \in \mathbb{Z}$
- Create the necessary rules for such an expression to be able to exist

### 4.6

You should be able to understand the concepts of Environments in the context of natural semantics and be able to utilise it when reading and reasoning about natural semantics.

- These behave like a map, where if a meta-language's variable (meta-variable) has been defined, then it stores a value.
- They are updated like this:  $E[c \mapsto 2]$
- They are read (Meta-variable values are retrieved) from like this:  $E(c) \Rightarrow 2$
- The empty environment is  $E_\emptyset = \{\}$

## 5 Bindings and Lifetimes

### 5.1

You should understand the difference between static and dynamic type binding and be able to take advantage of either property in your programming.

- Static Type Binding

- C-Family Languages
- Once things have been given a type, they cannot change their type for their lifetime.
- Once something has reached the end of its lifetime, it is deallocated.
  - \* The name and storage bindings can be reused.

- Dynamic Type Binding

- Python, JavaScript
- Throughout a single thing's lifetime, its type can change as many times as the programmer wants. Only subsequent actions will require the binding to be of a certain type.

## 5.2

Given a syntax, a compiler and a run-time system for a language, you should be able to determine whether the language is using static or dynamic type binding.

- Static

- You try to redefine the type binding for a variable.
- For instance, you declare `x` to be an integer, then later declare `x` to be a string.
- Java/Rust/SML/Haskell, for examples.
- In a strongly-typed language, this would be a (before runtime) compiler error.
- In a weakly-typed language, this error would occur during runtime, and may actually be passed over completely by giving default values or storing the error in the place of the variable's result.

- Dynamic

- You try to redeclare something that is of one type to another and the language allows that.
- Python, for example.
- For instance, you declare `x` to be of type integer, then later declare `x` to be of type string.
- The language allows this, and any subsequent operations happens with the new type binding.
- In a strongly-typed language, this would be allowed, but invalid operations would be found during (before runtime) compilation stage.
- In a weakly-typed language, this would be allowed, but may “fly under the radar” until you try to use the results of an erroneous operation.

## 5.3

Concepts: static binding, stack-dynamic binding, explicit heap-dynamic binding, and implicit heap-dynamic binding.

- Static

- **Global** and **Constant** variable bindings are put here.
- `const int x = 4;`
- The storage binding lasts as long as the program is in execution.
- These can be stored in the actual program binary when it is compiled and saved to disk, because they are unchanging.

- Stack-Dynamic

- The typical variable bindings go here.
- `int x = 4;`
- They are usable within the scope they are declared in.
- Their lifetime is the same as their scope.

- Explicit Heap-Dynamic

- The programmer must **EXPLICITLY** allocate memory from the heap for the storage binding.
- The programmer must **EXPLICITLY** deallocate memory from the heap when the binding reaches its end of life.
- The lifetime of the variable is determined by the programmer.
- `int* x = malloc(); *x = 4; free(x);`
- The lifetime of an explicit heap-dynamic variable storage binding is separate from its scope.

- Implicit Heap-Dynamic



- The compiler/runtime system determines the lifetime of the binding.
- The compiler/runtime system handles the allocation of memory and deallocation of memory.
- The compiler/runtime creates a garbage collection to ensure things are deallocated when their lifetime is over.
- The lifetime of an explicit heap-dynamic variable storage binding is related to its scope, for the most part, they are the same.

## 5.4

Given a syntax, a compiler and a run-time system for a language, you should be able to determine which storage binding(s) the language is using.

- Implicit vs. Explicit Heap-Dynamic:
  - There needs to be a keyword/reserved word for explicit heap operations. If none present, not explicit.
  - The explicit keyword/reserved word may be given in the grammar, or it is a core function built into the language.
  - If none of that, implicit.
- Stack-Dynamic vs. Static:
  - Static bindings are done *statically*, and last the *life of the program*.
  - If the static value is modified INSIDE a subprogram, it is updated **throughout the rest of the program's** execution.
  - Thus, static bindings do not allow for recursion to happen with the static binding's value.
  - If the stack-dynamic value is modified inside a subprogram, and this value is not visibly global, the value is not modified.
- Stack-Dynamic vs. Heap-Dynamic:
  - The difference here is where they are stored.
  - This can be hard to tell, you would need to be able to see the memory in which the program is running.
  - Larger things (arrays) are usually stored on the Heap, while smaller things (integers) are more likely to be stored on the stack.
  - However, the previous rule is **INCREDIBLY** flexible and is not a certainty. (It also depends on language implementation, to a degree.)
  - If there is a way to explicitly allocate memory on the heap, then you can find out much more easily.

## 5.5

Concept: lifetime of a variable.

- The lifetime of a variable is the period of time which it has a value binding.
- This is distinct from being in-scope.
  - In-scope, out of lifetime: An explicit heap-dynamic storage binding, the memory could be freed too early and the value that was there is going to be used later.
  - Out-of-Scope, in lifetime: A stack-dynamic variable is used in a program, but is not passed to the subprogram. It is out-of-scope of the subprogram, but still alive in the parent program.
- For stack-dynamic storage bindings, their lifetime and scope are usually the same, but can be different (as seen above).
- For static storage bindings, they are alive all the time, but may be out-of-scope or shadowed by other bindings with the same name.

## 5.6

Concepts: allocation and deallocation of a heap-dynamic variable.

- Allocation
  - If implicit, programmer doesn't need to worry about allocation, at worst has to write a constructor.
  - If explicit,
    - \* Programmer must tell compiler/runtime system **how much** memory to allocate.
    - \* Programmer must keep track of the pointer/reference that points to that memory.

- \* Programmer must make sure that the pointer is used correctly (including pointer arithmetic)
- Deallocation
  - If implicit, programmer doesn't need to worry about deallocation, at worst, has to write a destructor. Lets the garbage collector handle it.
    - \* Many garbage collector algorithms.
      - Reference counter
        1. Keep count of how many pointers point to things in memory.
        2. If  $count \leq 0$ , deallocate.
        3. Cannot handle linked lists or circular structures.
      - Mark-and-sweep
        1. Start by identifying all memory as safe (includes stack-dynamic and static variables).
        2. Follow all pointers to heap and traverse the heap, marking everything for deletion.
        3. Once done iterating over pointers and recursively descending, delete everything marked
  - If explicit,
    - \* Programmer must tell compiler/runtime system to deallocate the memory at some specified time.
    - \* Most of these errors are only found during runtime (Rust has special capabilities to figure this out),
      - If programmer forgets → **memory-leak**.
      - If programmer deallocates twice → **double-free**.
      - If programmer deallocates, but still uses it → **corrupted memory**.

## 5.7

Concept: binding time, especially the difference between static and dynamic binding times.

- Static Binding Time
  - These are things that are bound when the program is compiled (before it is run).
  - Static storage bindings are done statically, during compilation.
  - That goes along with their names too.
  - The binding of names and types to functions is static.
- Dynamic Binding Time
  - The binding of storage is dynamic for all categories except static.
  - In a dynamically typed language, the type bindings for variables is dynamic.
  - In an OOP language, you can dynamically type objects if you declare them with a supertype.

## 6 Scoping

### 6.1

You should understand the difference between static scoping and dynamic scoping and be able to exploit either in your programming.

- Static Scoping
  - The scope of the variable is determined by its placement within the program.
  - This is done by looking at **scopes** and their nesting (In block-delimited languages, scopes are usually the same as BLOCKS) and determining parents.
  - The benefit of these are:
    - \* Readability:
      - Easy to find out exactly what the program is going to do, just by reading the program.
    - \* Writability:
      - By knowing exactly what the program will do with a quick read of the source code, you can more quickly write.
    - \* Reliability:
      - All variables can be determined statically, before the program runs.
      - So, if the program compiles these without errors, you are assured that every use of a variable is allowed by the language.

- But, you now have more things to check during static semantic analysis.

- Dynamic Scoping
  - The scope of the variable is determined by the order in which subprograms were called.
  - Although variables may be redefined in a subprogram, the original value is not lost.
  - The original value is restored when the scope that changed it ends.

## 6.2

Given a language implementation, you should be able to write a program to determine whether the language uses static or dynamic scoping.

- You need to generate at least 3 scopes, 2 of which are nested in the first and are siblings.
- This can be done with subprograms.
- One of the child scopes must get to the other scope.
- Results from code below:
  - Static Scoping: When `sub1()` prints `x`, it will print 4. When `main()` prints `x`, it will print 4.
  - Dynamic Scoping: When `sub1()` prints `x`, it will print 6. When `main()` prints `x`, it will print 4.
- Because `sub1()` and `sub2()` are sibling scopes, when the `x` in `sub1()` is looked up in the referencing environment for its value, it looks up to `main()`.

---

```
int main() {  
    int sub1() {  
        printf("%d", x);  
    }  
    int sub2() {  
        int x = 6;  
        sub1();  
    }  
    int x = 4;  
    sub2();  
    printf("%d", x);  
}
```

---

## 6.3

Concept: referencing Environment.

- This is a **list of variables to their types, values, and any other information that must be maintained** about the variable.
- Functions also go in referencing environments.
- This can be thought of as the list of names that are usable at any given point in time, and the environment maps these names to their other information.

## 7 Types

1. Concepts: the types of integers, floating-point numbers (floats), and decimal numbers (decimals)
2. Concept: the type of booleans
3. Concept: enumeration type
4. Concepts: character and string types
5. Concept: subrange types
6. Concept: record types
7. Concept: tuple types
8. Concept: list types
9. Concept: associative array types
10. Concept: union types, both free and discriminated
11. Concept: operator overloading
12. Concepts: strong typing and weak typing

13. Concepts: type checking and the differences between dynamic type checking, static type checking.
14. Concepts: type equivalence, including the difference between nominal and structural type equivalence
15. Concept: type constructors
16. Concept: typing rules as part of type systems, and how to read such rules and utilise them in your reasoning about program semantics
17. Concept: the type preservation property, also known as subject reduction, of type systems
18. Concepts: type parameters and parametric polymorphism
19. Concept: function types for subroutines
20. Concept: type classes
21. Concept: subtyping
22. Concept: covariance and contravariance of type parameters, and the arrow rule
23. Concept: bounded parametric polymorphism
24. Concept: definition-site variance and use-site variance of type parameters
25. Concept: Algebraic Datatypes as in Standard ML and their use in pattern-matching
26. Concept: Automatic Type Inference

## 8 Expressions

1. Concept: arithmetic expressions
2. Concepts: boolean expressions and relational expressions
3. Concepts: Different forms of object equality, including reference equality and structural equality
4. Concept: operand evaluation order and how it affects the outcome of programs
5. Concept: short-circuit evaluation and how it affects the outcome of programs
6. Concept: referential transparency and side effects
7. Concept: list comprehensions and their semantics
8. Concept: type coercion expressions, both explicit and implicit, including narrowing conversions and widening conversions
9. Concept: conditional expressions

## 9 Statements and Control Structures

1. Concept: assignment statements, including compound assignment
2. Concept: two-way selection statements
3. Concept: multiple-selection statements
4. Concept: counter-controlled loops
5. Concept: logically controlled loops
6. Concept: datastructure-controlled loops

## 10 Subprograms and Parameter Passing

1. Concepts: subprograms, including formal arguments and actual arguments
2. Concept: local variables in subprograms
3. Concept: nested subprograms
4. Concepts: parameter passing modes
  - (a) by value
  - (b) by result
  - (c) by value-result
  - (d) by reference
  - (e) by name
  - (f) by need
5. Concepts: subprograms as parameters, subprograms as return values, Closures
6. Concept: activation records

## 11 Pointers, References, and Arrays

1. Concepts: pointers and references
2. Concept: the dangling pointer problem

3. Concepts: garbage collection in the forms of reference counting and mark-and-sweep collection
4. Concept: arrays in the forms of
  - (a) static arrays
  - (b) fixed stack-dynamic arrays
  - (c) fixed heap-dynamic arrays
  - (d) heap-dynamic arrays

## 12 Abstract Datatypes

1. Concepts: information hiding and encapsulation
2. Concept: abstract datatypes
3. Concept: generic abstract datatypes, that is, abstract datatypes that take one or more type parameters

## 13 Object-Oriented Programming

1. Concept: object-oriented language
2. Concept: dynamic dispatch, also known as dynamic binding of methods
3. Concept: inheritance
4. Concept: method overriding
5. Concept: the combined use of static types and dynamic types in statically typed object-oriented languages

## 14 Functional Programming

1. Concept: local let bindings of variables
2. Concept: anonymous functions, also known as lambda expressions
3. Concept: first-class functions
4. Concepts: pattern matching, including wildcards
5. Concepts: exhaustiveness and redundancy in pattern matching
6. Concept: lists as algebraic datatypes
7. Concept: the map function
8. Concept: currying
9. Functional Programming in Standard ML

## 15 Exceptions and Continuations

1. Concepts: exceptions and exception handlers