

EDAP05: Concepts of Programming Languages - Reference Sheet

Karl Hallsby

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1 Language vs. Language Implementation

It is important that we make the distinction between a programming language and the programming language's implementation.

- A programming language and its implementation are completely separate things
 - Technically, they are related, in that a programming language implementation is one way to fulfill the specifications that the programming language introduces
 - You can implement a programming language in different ways. For example, C has these well-known implementations:
 - * gcc
 - * LLVM/clang
 - * MSVC

1.1 Influences on Language Design

The 2 other major influences on the design of programming languages have been:

1. Computer Architecture
2. Programming Design Methodologies

1.1.1 Computer Architecture

The prevalent computer architecture used is the von Neumann Architecture. This is in contrast to the Harvard Architecture, and its descendant Modified Harvard Architecture.

Defn 1 (von Neumann Architecture). In the *von Neumann architecture*, named after John von Neumann, instructions and data are stored in a shared memory location. The central processing unit, CPU, is separate from the memory, meaning it must fetch the instructions and data from memory before doing something. When the CPU computes something, it needs to store the result *back* in memory. The constant fetching of instructions/data and storage of results in memory means there is a bottleneck, the *von Neumann Bottleneck*.

Remark 1.1 (von Neumann Bottleneck). The shared bus between the program memory and data memory leads to the *von Neumann bottleneck*, the limited throughput (data transfer rate) between the CPU and memory compared to the amount of memory. Because the single bus can only access one of the two classes of memory at a time, throughput is lower than the rate at which the CPU can work. This seriously limits the effective processing speed when the CPU is required to perform minimal processing on large amounts of data. The CPU is continually forced to wait for needed data to move to or from memory.

Since CPU speed and memory size have increased much faster than the throughput between them, the bottleneck has become more of a problem.

The execution of a machine code program on a von Neumann Architecture computer occurs in a process called the *fetch-execute cycle*. To find where each instruction is in memory, the CPU needs to have a *program counter*.

Functional or applicative programming languages, where applying functions to parameters does not lend itself to the von Neumann Architecture.

Remark 1.2 (Cache in the von Neumann Architecture). In the original von Neumann Architecture, there was no such thing as *cache* on the CPU. In modern computers, cache is located on the CPU directly, and acts similarly to memory. However, it copies a block of memory into the cache and feeds the CPU from that, refreshing the cache less periodically, and allowing for faster instruction/data access rates. This is an example of the Harvard Architecture in the traditional von Neumann Architecture making a Modified Harvard Architecture.

Remark 1.3 (Alternative Names). The von Neumann Architecture can also be called:

- von Neumann Model
- Princeton Architecture
- Dataflow Model

Remark 1.4 (Alternative Architectures). The von Neumann Architecture is one way to implement a computational model. There are alternatives, namely the Harvard Architecture and its descendant Modified Harvard Architecture.

Defn 2 (Harvard Architecture). The *Harvard architecture* is a computer architecture with separate storage and signal pathways for instructions and data. It contrasts with the von Neumann Architecture, where program instructions and data share the same memory and pathways.

This partition of instructions and data means the CPU can simultaneously read an instruction and perform data memory access. Additionally, the address space for the instructions and data are separate, meaning instruction address zero is not the same as data address zero.

Defn 3 (Modified Harvard Architecture). Most modern computers act as *both* von Neumann Architecture machines and Harvard Architecture machines. These have been called *modified Harvard architectures*. The *modified Harvard architecture* is also a variation of the Harvard Architecture that allows the contents of the instruction memory to be accessed as data. The different types of modified Harvard architectures are discussed in Remark 3.2.

Remark 3.1 (Modern CPU Architecture). In modern CPUs, with both their system memory and on-chip cache, they act as both von Neumann Architecture machines and Harvard Architecture machines. The CPU acts as:

- A Harvard Architecture machine when the CPU is accessing its on-chip cache.
- A von Neumann Architecture machine when the CPU is accessing the system memory.

Remark 3.2 (Types of Modified Harvard Architectures). There are many different types of Modified Harvard Architectures. Some of the major ones are discussed here:

- Split-cache (or almost-von Neumann Architecture architecture)
 - The most common modification builds a memory hierarchy with a CPU cache separating instructions and data.
 - This unifies all except small portions of the data and instruction address spaces, providing the von Neumann model.
- Instruction-Memory-as-Data Architecture
 - Another change preserves the “separate address space” nature of a Harvard Architecture machine, but provides special machine operations to access the contents of the instruction memory as data.
 - Because data is not directly executable as instructions, there are 2 different operations possible:
 1. Read access: initial data values can be copied from the instruction memory into the data memory when the program starts. Or, if the data is not to be modified (it might be a constant value, such as pi, or a text string), it can be accessed by the running program directly from instruction memory without taking up space in data memory (which is often at a premium).
 2. Write access: a capability for reprogramming is generally required; few computers are purely ROM-based. For example, a microcontroller usually has operations to write to the flash memory used to hold its instructions. This capability may be used for purposes including software updates. EEPROM/PROM replacement is an alternative method.
- Data-Memory-as-Instruction Architecture
 - A few Harvard Architecture processors can execute instructions fetched from any memory segment
 - Unlike the original Harvard processor, which can only execute instructions fetched from the program memory segment.
 - Such processors, like other Harvard Architecture processors, and unlike pure von Neumann Architecture, can read an instruction and read a data value simultaneously, **if they’re in separate memory segments**, since the processor has (at least) two separate memory segments with independent data buses.
 - The most obvious programmer-visible difference between this kind of modified Harvard architecture and a pure von Neumann architecture is that – when executing an instruction from one memory segment – the same memory segment cannot be simultaneously accessed as data.

The von Neumann Architecture models variables incredibly well, as memory cells, assignment statements as the writing of data back to memory, and iteration. In fact, the von Neumann Architecture models iteration so well, that it encourages iteration over recursion (when possible), sometimes at the detriment of the overall program.

1.1.2 Programming Design Methodologies

Starting in the 1960s, bigger and more complicated programs were being written for more complicated things (controlling whole facilities, worldwide airline reservation systems, etc.). New software development methodologies appeared, and a shift from procedure-oriented to data-oriented design methodologies emerged.

Data-oriented models emphasize:

- Data design
- Abstract data types to solve problems

This data-oriented design led to the development of object-oriented design.

1.2 Language Categories

There are 3 main categories that languages fall into (that we are considering in this course):

1. Imperative Programming Language

2. Functional Programming Language
3. Logical Programming Language

If you want to view all possible language categories, visit Wikipedia's Programming Paradigms.

Defn 4 (Imperative Programming Language). *Imperative programming languages* have a programming paradigm that uses statements that change a program's state. An imperative program consists of commands for the computer to perform. Imperative programming focuses on describing how a program operates.

Defn 5 (Functional Programming Language). *Functional programming languages* treat computation as the evaluation of mathematical functions and avoids changing-state and mutable data. It is a declarative programming paradigm in that programming is done with expressions or declarations instead of statements. In functional code, the output value of a function depends only on its arguments, so calling a function with the same value for an argument always produces the same result.

This is in contrast to Imperative Programming Languages where, in addition to a function's arguments, global program state can affect a function's resulting value. Eliminating side effects, that is, changes in state that do not depend on the function inputs, can make understanding a program easier, which is one of the key motivations for the development of functional programming.

Defn 6 (Logical Programming Language). *Logic programming languages* are a type of programming language which is largely based on formal logic. Any program written in a logic programming language is a set of sentences in logical form, expressing facts and rules about some problem domain.

2 Programming Language Implementations

There are 3 main ways for a programming language to be implemented:

1. Interpretation
2. Compilation
3. Hybrid Implementation

There are benefits and drawbacks for each of these implementations:

Property	Interpretation	Compilation	Hybrid Implementation
Execution Performance	Slow	Fast	Fast
Turnaround	Fast	Slow (Compile and Link)	Fast (Compile when needed)
Language Flexibility	High	Limited	High

Table 2.1: Pros and Cons for Programming Language Implementations

There is a trade-off to be made between:

- Language flexibility
- CPU time / RAM time

2.1 Interpretation

Defn 7 (Interpretation). If a programming language is implemented with *interpretation*, is *interpreted*, then there is an intermediate program that runs between the source code and what the CPU can run on. When a programming language is interpreted, there is **no** translation of the high-level source language to anything else. The *interpreter* uses the high-level source code directly. This *interpreter* reads the high-level source code, then alternates between:

- Figure out next command
 - This means that the current instruction is parsed in
 - Equivalent commands are generated in the CPU-specific or VM-specific instruction sets from the high-level source code
- Execute Command

Interpretation allows for easy implementation of source-level debugging. Meaning when semantic analysis occurs on the program while running, the errors are returned in a fashion that makes sense with relation to the high-level language. For instance, if there is an array index error, the error could refer to the index itself, the name of the array, and its line.

Remark 7.1 (Interpretation Drawbacks). There is roughly a 10–100 times performance slowdown. The main bottleneck in an interpreted language is the instruction decoding from the high-level source to something the interpreter can use. This is because *every* instruction must be decoded *every* time.

Additionally, interpreted programs take up more space on disk in a form not designed to be space efficient. In memory, interpreted programs take up more space because the symbol table and interpreter must be in memory at the same time to make the program run.

Some examples of languages with an Interpretation implementation are:

- Python
- Perl
- Ruby
- Bash
- AWK
- ...

2.2 Compilation

Defn 8 (Compilation). If a programming language is implemented with *compilation*, is *compiled*, then there are several programs that must be run before the high-level source code can be run.

1. The Compiler
2. The Assembler
3. The Linker
4. The Loader

Defn 9 (Compiler). The *compiler* is the main program needed in a compiled language implementation. It is responsible for taking the high-level source code written in some language, and converting it to assembly code, which can then be run through an Assembler.

The steps involved in a compiler are:

1. Lexical Analysis/Tokenizing: Convert the text in the input file into a set of tokens
2. Syntactic Analysis/Parsing: Convert the tokens into a parse tree representing all the tokens in the program in a hierarchical and prioritative manner
3. Semantic Analysis: “Interpret” the program and ensure that everything expressed in the program is correct.
 - This is where compile-time errors are **usually** caught. Though, this is just a generalization.
 - Type analysis is typically handled here for instance
4. Optimize the Code: The output assembly code could be optimized before actually making the output. Take care of that here.
5. Output Assembly: With the potentially optimized machine-equivalent code from our program, write out the equivalent assembly, and finish the compilation process.

Remark 9.1. The specifics of a Compiler’s implementation are **not** discussed in this course, but it is useful to know the basics of the compilation process. For both the implementation details, please refer to EDAN65:Compilers-Reference Material.

Defn 10 (Assembler). The *assembler* is an intermediate program used after the Compiler has been run. The assembler takes the assembly code that the Compiler outputs and applies a one-to-one mapping. Since all assembly code is just an abstraction and humanization of machine code in a one-to-one mapping fashion, the assembler takes the assembly code and converts it to its equivalent machine code.

Remark 10.1. This particular program is not discussed heavily in this course.

Defn 11 (Linker). The *linker* is an intermediate program, that may be provided by the operating system or may be provided by that language implementation’s tooling. It is run after the Compiler and/or the Assembler have been run.

- Provided by operating system
 - If the programming language implementation relies on the operating system and critical portions of the system.
- Provided by the language implementation’s tooling
 - If the implementation provides certain libraries, it will likely have their own linker too.

Remark 11.1. This particular program is not discussed in this course.

Defn 12 (Loader). The *loader* is the program provided by the operating system that loads the specified program into main memory and begins execution.

Remark 12.1. This particular program is not discussed in this course.

Some examples of languages with a Compilation implementation are:

- C
- C++
- SML
- Haskell
- FORTRAN
- ...

2.3 Hybrid Implementation

Defn 13 (Hybrid Implementation). A programming language can be implemented with a *hybrid implementation*. This means that it takes some aspects of a language implemented by Interpretation and some aspects of the language implemented with Compilation.

Typically what happens is the high-level source language translates the source language to an intermediate language that allows for easy interpretation. This is faster because instructions in the source language are only decoded once.

For example, Java does this with their Just-In-Time (JIT) compilation scheme, which translates all instructions to an intermediate language, then translates those to machine code on-the-fly when needed.

Some examples of Hybrid Implementation are:

- Java
- Scala
- C#
- JavaScript
- ...

One way to implement a language with Hybrid Implementation is with Dynamic Compilation.

2.3.1 Dynamic Compilation

- Idea: behind dynamic compilation is that code is compiled *while executing*.
- Theory: The best of Interpretation and Compilation worlds.
- Practice:
 - Difficult to build
 - Memory usage can increase (sometimes dramatically)
 - Performance can be higher than pre-compiled code, because only the code needed is compiled.

3 Language Critique

There are several very open-ended questions that need to be asked when categorizing and critiquing languages:

1. What programming language is best for *what task*?
2. *What criteria* do we measure?
 - Most criteria do not have good measurement tools.
3. *How* do we obtain measurements for these criteria?

These are all qualities of:

- The language
- The language implementation(s)
- The available tooling for the language and that particular implementation
- The available libraries for the language and that particular implementation
- Other infrastructure
 - User groups
 - Books
 - etc.

Some additional criteria that could be used to evaluate programming languages are:

- Portability: Ease with which programs can be moved from one implementation to another

Characteristic	Criteria		
	Readability	Writability	Reliability
Simplicity	✓	✓	✓
Orthogonality	✓	✓	✓
Data Types	✓	✓	✓
Syntax Design	✓	✓	✓
Support for Abstraction		✓	✓
Expressivity		✓	✓
Type Checking			✓
Exception Handling			✓
Restricted Aliasing			✓

Table 3.1: Language Evaluation Criterian and the Characteristics that Affect Them

- Generality: The applicability to a wide range of applications
- Well-Definedness: The completeness and precision of the language’s official defining document

Some of criteria are given different weightings/importance by different people, thus making each slightly subjective. Additionally, many of these criteria are not precisely defined, nor are they exactly measurable.

3.1 Readability

Defn 14 (Readability). *Readability* is how easily a program can be read and understood *by a human*. Some languages do not support certain functions, but programmers try to make the language do what it is not designed to do. This will lead to complicated and difficult-to-read programs.

The idea of program readability was first presented as the software life-cycle concept (Booch 1987). The initial coding was downplayed compared to earlier, and the maintenance and improvement of the code was brought to the forefront.

3.1.1 Simplicity

There are 2 main factors and 1 minor factor for a language’s simplicity:

1. The number of features present in the language.
2. The Feature Multiplicity of a language.
3. The ability to Overload Operators.

Assembly language is on the most-simple end of the simplicity spectrum. In assembly, the form and meaning of most statements are incredibly simple, but without more complex control statements, the program’s structure is less obvious.

Defn 15 (Feature Multiplicity). *Feature multiplicity* is when there is more than one way to accomplish a particular operation with language built-in features. For example, in Java these are all equivalent when evaluated as standalone expressions:

1. `count = count + 1`
2. `count += 1`
3. `count++`
4. `++count`

```

1 def d(x):
2     r = x[::-1]
3     return x == r

```

Defn 16 (Overload Operator). An *overloaded operator* is one where a single symbol has more than one meaning. For example the + operator can be overloaded to add 2 integers, 2 floating-point numbers, or an integer and a floating-point number. This overloading helps *improve* the Simplicity of a language.

```

1 x = 3 + 4 # Evaluates to 7
2 y = 3.0 + 4.0 # Evaluates to 7.0
3 z = 3 + 4.0 # Evaluates to 7.0

```

3.1.2 Orthogonality

Defn 17 (Orthogonality). *Orthogonality* in a programming language means that a relatively small set of primitive constructs can be combined in a relatively small number of ways to build the control and data structures of a language. Additionally, every possible combination of primitives is legal and meaningful.

The more orthogonal a language, the fewer exceptions to the language rules there can be. These fewer exceptions means there is a higher degree of regularity in the language design, making it easier to learn, read, and understand.

Remark 17.1 (Over-Orthogonality). Too much orthogonality can cause problems. Having too much combinational freedom with primitive constructs and their combinations can make for an extremely complex compound construct. This leads to unnecessary complexity.

```
1 // global variable section
2
3 float f1 = 2.0f * 2.0f;
4 float f2 = sqrt(2.0f); // error
```

3.1.3 Data Types

The use of data types conveys intent when reading and writing the program. For example, a boolean data type conveys a true/false value better than an integer that is 1/0 for true/false respectively.

- `timeOut = 1`
- `timeOut = true`

```
1 enum Color {
2     Red, Green, Blue
3 };
4
5 Color c = readColorFromUser();
```

3.1.4 Syntax Design

There are 2 main syntactic design choices that affect Readability:

1. Reserved/Special Words
2. Form and Meaning

3.1.4.1 Reserved/Special Words What words have been made either Reserved Words or Keywords by the programming language specification?

There are also special words and matching characters that can denote groups of instructions.

- C and its descendants
 - Matching braces
 - `{` and `}`
- Ada/Fortran 95 and their descendants:
 - Distinct closing syntax for each statement group
 - `end if` to end an if statement

Also, can these Reserved Words be used as names for program variables? If so, this will increase overall complexity of a program. The code block below, from Fortran 95, illustrates this point.

```
1 program hello
2     implicit none
3     integer end, do
4     do = 0
5     end = 10
6     do do=do, end
7         print *,do
8     end do
9 end program hello
```

3.1.4.2 Form and Meaning Statements should be designed such that their appearance partially indicates what their purpose is. For example, the UNIX command `grep` gives no hint at what it is supposed to do, unless you know the text editor `ed`.

Semantics, or meaning, should follow directly from syntax or form. In some cases, this principle is violated by 2 language constructs that are identical or similar in appearance, but different in meaning, depending on the context. For example, C's `static` Reserved Words.

3.2 Writability

Writability is a measure of how easy it is to write a program in a language for a given problem domain. This is closely related to the language characteristics presented in Section 3.1, Readability. The definition of the problem domain is incredibly important, because C would not be used to make a GUI, and Visual BASIC would not be used to make an operating system.

3.2.1 Simplicity and Orthogonality

Programmers might not know all the features for a language. Or, they might know about them, but use them incorrectly. This means there should be a smaller number of primitive constructs and a consistent set of rules for combining them. This reduces the number of primitive constructs in a language, and allows a programmer to design a complex solution by only using a simple set of primitive constructs. By reducing the orthogonality of a program, the total possible combinations of constructs is reduced, simplifying the process of reading and writing the program.

3.2.2 Support for Abstraction

Defn 18 (Abstraction). *Abstraction* is the ability to define and then use complicated structures or operations in ways that allow many of the details to be ignored. This is a key concept in modern programming language design.

There are 2 categories of abstraction:

1. Process Abstraction
2. Data Abstraction

3.2.2.1 Process Abstraction Process abstraction is the use of a subprogram to implement some block of code used multiple times. For example, a sorting algorithm. If the code for the algorithm could not be factored out into a separate piece of code, the algorithm would need to be copied everywhere it was used. This would lead to additional complexity and reduce the Readability of the code.

3.2.2.2 Data Abstraction For example, representing a binary tree in C++/Java is done by making a tree node class that has 2 pointers and an integer. This abstraction is more natural to think about than what would need to be done in Fortran 77. In Fortran 77, there would need to be 3 parallel integer arrays, where 2 of the integers in each array would be used as subscripts to find their children.

3.2.3 Expressivity

Expressivity has several characteristics.

1. Verbosity of the language
 - The amount of code needed to describe some computation to the computer.
2. Powerful/Convenient way to specify computations.
 - `count++` vs. `count = count + 1` to increment a value in Java

3.3 Reliability

Reliability is a measure of the program performing to its specifications reliably under all conditions.

3.3.1 Type Checking

Defn 19 (Type Checking). *Type checking* is a process for testing for type errors in a given program, by the compiler or the interpreter, depending on its implementation (Interpretation vs. Compilation). Runtime type checking is expensive, so compile-time checking is preferred.

Remark 19.1. The earlier that type checking can occur reduces the potential errors, and corrective actions can be taken.

There are 2 types of type checking possible:

1. Strong Type Checking
2. Weak Type Checking

There are also 2 times when type checking is possible:

1. Static Type Checking
2. Dynamic Type Checking

Defn 20 (Strong Type Checking). *Strong type checking* is a property of a programming language that states that any language implementation finds all type errors and prevents the operations that caused the type error from taking place.

A language that has strong type checking is called a *strongly-typed language*. Such languages are:

- Haskell
- Python
- Ruby
- JavaScript

Remark 20.1 (Cost). Strong Type Checking improves the Reliability of a language, at a Cost to the language's Expressivity, and sometimes also at a Cost to the language's execution time.

Usually this improvement to Reliability is worth it. However, sometimes it is necessary to write directly to memory without regard to the Data Type system. These languages provide “backdoors” to do this.

Defn 21 (Weak Type Checking). *Weak type checking* is the absence of Strong Type Checking.

A language that has weak type checking is called a *weakly-typed language*. Such languages are:

- C
- C++

Defn 22 (Static Type Checking). Any Type Checking that is performed before runtime (at compile time, as part of the static semantics) is called *static type checking*.

Languages that perform static type checking are called *statically typed languages*.

Remark 22.1 (Undecidability of Static Type Checking). Not all Data Types can be checked statically. For example, the subscript used in an array access must be checked dynamically.

This deference is actually **required** for a language to be strongly-typed.

Defn 23 (Dynamic Type Checking). Any Type Checking that is performed at runtime is called *dynamic type checking*.

Languages that perform dynamic type checking are called *dynamically typed languages*.

3.3.2 Exception Handling

The programming language should have the ability to intercept runtime errors, along with other unusual conditions, take corrective actions, the continue normally is traditionally called *exception handling*.

3.3.3 Aliasing

Defn 24 (Aliasing). *Aliasing* is having 2 or more distinct names that can be used to access the same memory location. Most languages allow for 2 pointers to point to the same thing in memory, but others prevent this completely.

Sometimes, Aliasing is used to overcome deficiencies in the language's Support for Abstraction. Others greatly restrict possible Aliasing to increase their Reliability.

3.3.4 Readability and Writability

The Readability and Writability greatly influence a program's Reliability. A program written in a language that exceeds the languages original problem domain will use unnatural approaches to solve the problem. These unnatural approaches are less likely to be correct for all possible situations. Thus, the easier a program is to write, the more likely it is to be correct for all possible situations.

Programs that are difficult to read will affect the writing and maintenance phases of the software's life cycle.

3.4 Cost

There are several parts that increase the cost of a programming language.

1. Training programmers in a new language
 - Function of Simplicity and Orthogonality
 - Function of programmer experience
2. Writing software
 - Function of Writability of the language
3. Compilation time
 - Time to compile a program
 - Resources required to compile a program in a language
4. Run time
 - Performance during runtime
 - Dependent on the effort made to optimize the input source code
5. Financial cost of special software
 - The cost of using the Compiler for a language for instance.
 - Languages with free Compilers or interpreters tend to be accepted more quickly than languages with a financial cost
6. Cost of limited reliability
 - Maintenance time
 - Corrections made to errors in the program
 - Modifications to add new functionality
 - Insurance cost, in special cases
 - Airplanes
 - Nuclear power plants
 - X-Ray machines

4 Backus-Naur Form and Context-Free Grammars

In the 1950s, there were 2 men, Noam Chomsky and John Backus, that were working completely separately who were trying to formally describe language. They actually ended up developing very similar answers to that problem.

Remark. Context-Free Grammars are referred to only as grammars throughout this document. Also, the terms BNF (Backus-Naur Form) and grammar are used interchangeably.

4.1 Context-Free Grammars

Chomsky, a linguist, described 4 classes of grammars that define 4 classes of languages, which are given in Table 4.1

There exists a hierarchy for the definition of Grammars that define Languages. It is called the *Chomsky Hierarchy of Formal Grammars*.

Grammar	Rule Patterns	Type
Regular	$\langle X \rangle \rightarrow a\langle Y \rangle$ or $\langle X \rangle \rightarrow a$ or $\langle X \rangle \rightarrow \epsilon$	3
Context-Free	$\langle X \rangle \rightarrow \gamma$	2
Context-Sensitive	$\alpha\langle X \rangle\beta \rightarrow \alpha\gamma\beta$	1
Arbitrary	$\gamma \rightarrow \delta$	0

Table 4.1: Chomsky Hierarchy of Formal Grammars

Regular grammars have the same power as regular expressions, meaning they can be used to find tokens in a program.

Remark. Where a is a Terminal Symbol, α , β , γ , and δ are *sequences* of symbols (Terminal Symbols or Nonterminal Symbols).

Type(3) \subset Type(2) \subset Type(1) \subset Type(0)

4.2 Backus-Naur Form

It is important to discuss where Backus-Naur form came from, and how it has been modified since. Originally, there was the Canonical Form. This only allowed for one production per line, and did not support options, repetition, etc.

Defn 25 (Canonical Form). The *canonical form* of a Context-Free Grammar is the most formal use of a Context-Free Grammar.

$$\begin{aligned}\langle A \rangle &\rightarrow \langle B \rangle d e C f \\ \langle A \rangle &\rightarrow g \langle A \rangle\end{aligned}\tag{4.1}$$

The Canonical Form is:

- The core formalism for Context-Free Grammars
- Useful for proving properties and explaining algorithms

When John Backus was working on ALGOL 58, his published paper used a new formal notation for specifying programming language syntax. Peter Naur slightly modified Backus's original syntax which developed Backus-Naur Form.

Defn 26 (Backus-Naur Form). The *Backus-Naur form* of a Context-Free Grammar is an extension of the Canonical Form. This form is less formal than the Canonical Form, but it allows for condensation of multiple productions that have the same nonterminal on the left-hand side to the same production. This is done with the $|$ symbol.

For example, Equation (4.2) is equivalent to Equation (4.1).

$$\langle A \rangle \rightarrow \langle B \rangle d e \langle C \rangle f | g \langle A \rangle\tag{4.2}$$

Backus-Naur Form has some inconveniences, and has been extended to avoid these issues. These extensions have been formalized and called Extended Backus-Naur Form. Extended Backus-Naur Form will not be used much in this course, but it is a good way to quickly and succinctly express a Context-Free Grammar.

Defn 27 (Extended Backus-Naur Form). The *Extended Backus-Naur form* of a Context-Free Grammar is an extension of the *Backus-Naur Form*. This is a more informal implementation of a Context-Free Grammar. This informality allows for some additional constructs in the Production rules.

These include:

1. Repetition with the Kleene Star (*), or with $\{ \text{repItem} \}$
 - Means that portion of the Production can be repeated 0 or more times.
2. Single Optionals, denoted as $(\text{op1} | \text{op2} | \dots)$
 - Means select one of the options present between the parentheses.
3. Optional portions of the Production, denoted with $[\text{op}]$
 - Means that portion of the Production is an optional part of the entire Production.

The Extended Backus-Naur Form is:

- Compact, easy to read and write
- Common notation for practical use

4.3 Use Today

Defn 28 (Metalanguage). *Metalanguages* are languages that are used to describe other languages. Context-Free Grammars are one example used as a metalanguage for programming languages.

Defn 29 (Context-Free Grammar). A *context-free grammar* or *CFG* is a way to define a set of *strings* that form a Language. Each string is a finite sequence of Terminal Symbol taken from a finite Alphabet. This is done with one or more Productions, where each production can have both Nonterminal Symbol and Terminal Symbol.

More formally, a Context-Free Grammar is defined as $G = (N, T, P, S)$, where

- N , the set of Nonterminal Symbols
- T , the set of Terminal Symbols
- P , the set of production rules, each with the form

$$\langle X \rangle \rightarrow \langle Y_1 \rangle \langle Y_2 \rangle \dots \langle Y_n \rangle \text{ where } \langle X \rangle \in N, x \geq 0, \text{ and } \langle Y_k \rangle \in N \cup T$$

- S , the start symbol (one of the Nonterminal Symbols, N). $S \in N$.

Defn 30 (Language). A *language* is the set of **all** strings that can be formed by the Productions in the Context-Free Grammar.

Defn 31 (Production). A *production* is a rule that defines the relation between a single Nonterminal Symbol and a string comprised of Nonterminal Symbols, Terminal Symbols, and the Empty String. These can be thought of as abstractions for syntactic structures.

The are denoted as shown below:

$$p_0 : \langle A \rangle \rightarrow \alpha \quad (4.3)$$

Remark 31.1. There *can* be multiple productions for the same Nonterminal Symbol

Defn 32 (Nonterminal Symbol). A *nonterminal symbol*, or just *nonterminal*, is a symbol that is used in the Context-Free Grammar as a symbol for a Production.

Defn 33 (Terminal Symbol). A *terminal symbol*, or just *terminal*, is a symbol that cannot be derived any further. This is a symbol that is part of the Alphabet that is used to form the Language.

Remark 33.1. These terminals could be tokens defined by a regular grammar or a regular expression. They might just be abstractions of sequences or sets of symbols from the Alphabet.

Defn 34 (Start Symbol). The *start symbol* is a Nonterminal Symbol which is specially designated as the start point of a Derivation for a grammar.

Other than the fact a Derivation starts with this Nonterminal Symbol and its associated Production, it is not special.

Defn 35 (Empty String). The *empty string* is a special symbol that is neither a Nonterminal Symbol nor a Terminal Symbol. The empty string is a *metasymbol*. It is a unique symbol meant to represent the lack of a string. It is denoted with the lowercase Greek epsilon, ϵ or ε .

Defn 36 (Alphabet). The finite set of Nonterminal Symbols that can be used to form a Language.

4.3.1 Multiple Productions on Single Line

This is briefly discussed in Definition 26. What this allows us to do is combine multiple Productions that have the same Nonterminal Symbol on the left-hand side to a single line, or single Production.

For example,

$$\begin{aligned} \langle \text{if stmt} \rangle &\rightarrow \text{if}(\langle \text{logic expr} \rangle) \langle \text{stmt} \rangle \\ \langle \text{if stmt} \rangle &\rightarrow \text{if}(\langle \text{logic expr} \rangle) \langle \text{stmt} \rangle \text{ else } \langle \text{stmt} \rangle \end{aligned} \quad (4.4)$$

can be combined to

$$\begin{aligned} \langle \text{if stmt} \rangle &\rightarrow \text{if}(\langle \text{logic expr} \rangle) \langle \text{stmt} \rangle \\ &\quad | \text{if}(\langle \text{logic expr} \rangle) \langle \text{stmt} \rangle \text{ else } \langle \text{stmt} \rangle \end{aligned} \quad (4.5)$$

4.3.2 Describing Lists

A Production is recursive if its left-hand side Nonterminal Symbol appears somewhere on the right-hand side. This recursive property is useful for constructing variable-length lists.

This is a small extension of using Multiple Productions on Single Line.

$$\begin{aligned} \langle \text{ident list} \rangle &\rightarrow \text{identifier} \\ &\quad | \text{identifier}, \langle \text{ident list} \rangle \end{aligned} \quad (4.6)$$

4.3.3 Grammars and Derivations

Defn 37 (Derivation). A *derivation* is the use of Production applications to parse a given input string. Example 4.1 demonstrates this.

Example 4.1: Left-Most Derivation.

Perform a Leftmost Derivation of the sentence

`begin A = B + C; B = C end`

With the grammar

$$\begin{aligned}
 \langle \text{program} \rangle &\rightarrow \text{begin } \langle \text{stmt list} \rangle \text{ end} \\
 \langle \text{stmt list} \rangle &\rightarrow \langle \text{stmt} \rangle \\
 &\quad | \langle \text{stmt} \rangle ; \langle \text{stmt list} \rangle \\
 \langle \text{stmt} \rangle &\rightarrow \langle \text{var} \rangle = \langle \text{expression} \rangle \\
 \langle \text{var} \rangle &\rightarrow A | B | C \\
 \langle \text{expression} \rangle &\rightarrow \langle \text{var} \rangle + \langle \text{var} \rangle \\
 &\quad | \langle \text{var} \rangle - \langle \text{var} \rangle \\
 &\quad | \langle \text{var} \rangle
 \end{aligned}$$

$$\begin{aligned}
 \langle \text{program} \rangle &\Rightarrow \text{begin } \langle \text{stmt list} \rangle \text{ end} \\
 &\Rightarrow \text{begin } \langle \text{stmt} \rangle ; \langle \text{stmt list} \rangle \text{ end} \\
 &\Rightarrow \text{begin } \langle \text{var} \rangle = \langle \text{expression} \rangle ; \langle \text{stmt list} \rangle \text{ end} \\
 &\Rightarrow \text{begin } A = \langle \text{expression} \rangle ; \langle \text{stmt list} \rangle \text{ end} \\
 &\Rightarrow \text{begin } A = \langle \text{var} \rangle + \langle \text{var} \rangle ; \langle \text{stmt list} \rangle \text{ end} \\
 &\Rightarrow \text{begin } A = B + \langle \text{var} \rangle ; \langle \text{stmt list} \rangle \text{ end} \\
 &\Rightarrow \text{begin } A = B + C ; \langle \text{stmt list} \rangle \text{ end} \\
 &\Rightarrow \text{begin } A = B + C ; \langle \text{stmt} \rangle \text{ end} \\
 &\Rightarrow \text{begin } A = B + C ; \langle \text{var} \rangle = \langle \text{expression} \rangle \text{ end} \\
 &\Rightarrow \text{begin } A = B + C ; B = \langle \text{expression} \rangle \text{ end} \\
 &\Rightarrow \text{begin } A = B + C ; B = \langle \text{var} \rangle \text{ end} \\
 &\Rightarrow \text{begin } A = B + C ; B = C \text{ end}
 \end{aligned}$$

In general, Derivations occur from left-to-right, which is one L in the 2 different types of Derivations. Both types of Derivation, Leftmost Derivation and Rightmost Derivation, will yield the same result when a Derivation is successfully completed.

Defn 38 (Leftmost Derivation). *Leftmost derivation*, or *LL* derivation, stands for *left-to-right leftmost derivation*. Starting from the left of the sentence, you always derive the left-most Nonterminal Symbol, until you reach a Terminal Symbol. Once all symbols present in the sentence are Terminal Symbol, you are done.

Defn 39 (Rightmost Derivation). *Rightmost derivation*, or *LR* derivation, stands for *left-to-right rightmost derivation*. Starting from the left of the sentence, you always derive the right-most Nonterminal Symbol, until you reach a Terminal Symbol. Once all symbols present in the sentence are Terminal Symbol, you are done.

Example 4.2: Right-Most Derivation.

Perform a Rightmost Derivation of the sentence

begin $A = B + C$; $B = C$ **end**

With the grammar

$$\begin{aligned}
 \langle \text{program} \rangle &\rightarrow \text{begin } \langle \text{stmt list} \rangle \text{ end} \\
 \langle \text{stmt list} \rangle &\rightarrow \langle \text{stmt} \rangle \\
 &\quad | \langle \text{stmt} \rangle ; \langle \text{stmt list} \rangle \\
 \langle \text{stmt} \rangle &\rightarrow \langle \text{var} \rangle = \langle \text{expression} \rangle \\
 \langle \text{var} \rangle &\rightarrow A | B | C \\
 \langle \text{expression} \rangle &\rightarrow \langle \text{var} \rangle + \langle \text{var} \rangle \\
 &\quad | \langle \text{var} \rangle - \langle \text{var} \rangle \\
 &\quad | \langle \text{var} \rangle
 \end{aligned}$$

$$\begin{aligned}
\langle \text{program} \rangle &\Rightarrow \text{begin } \langle \text{stmt list} \rangle \text{ end} \\
&\Rightarrow \text{begin } \langle \text{stmt} \rangle ; \langle \text{stmt list} \rangle \text{ end} \\
&\Rightarrow \text{begin } \langle \text{stmt} \rangle ; \langle \text{stmt} \rangle \text{ end} \\
&\Rightarrow \text{begin } \langle \text{stmt} \rangle ; \langle \text{var} \rangle = \langle \text{expression} \rangle \text{ end} \\
&\Rightarrow \text{begin } \langle \text{stmt} \rangle ; \langle \text{var} \rangle = \langle \text{var} \rangle \text{ end} \\
&\Rightarrow \text{begin } \langle \text{stmt} \rangle ; \langle \text{var} \rangle = C \text{ end} \\
&\Rightarrow \text{begin } \langle \text{stmt} \rangle ; B = C \text{ end} \\
&\Rightarrow \text{begin } \langle \text{var} \rangle = \langle \text{expression} \rangle ; B = C \text{ end} \\
&\Rightarrow \text{begin } \langle \text{var} \rangle = \langle \text{var} \rangle + \langle \text{var} \rangle ; B = C \text{ end} \\
&\Rightarrow \text{begin } \langle \text{var} \rangle = \langle \text{var} \rangle + C ; B = C \text{ end} \\
&\Rightarrow \text{begin } \langle \text{var} \rangle = B + C ; B = C \text{ end} \\
&\Rightarrow \text{begin } A = B + C ; B = C \text{ end}
\end{aligned}$$

4.3.4 Parse Trees

Parse trees are hierarchical structures that describe the same information as a Derivation in a visual format. Every internal node is labeled with a Nonterminal Symbol and every leaf is labeled with a Terminal Symbol

4.3.5 Ambiguities

Defn 40 (Ambiguous). A Context-Free Grammar is said to be *ambiguous* or has *ambiguities* if there is more than one way to derive the same string in a grammar.

The grammar below is ambiguous because there are multiple ways to parse the string: “statement;statement;statement”.

$$\begin{aligned}
p_0 : \langle \text{start} \rangle &\rightarrow \langle \text{program} \rangle \$ \\
p_1 : \langle \text{program} \rangle &\rightarrow \langle \text{statement} \rangle \\
p_2 : \langle \text{statement} \rangle &\rightarrow \langle \text{statement} \text{ “;” statement} \rangle \\
p_3 : \langle \text{statement} \rangle &\rightarrow \text{ID “=” INT} \\
p_4 : \langle \text{statement} \rangle &\rightarrow \epsilon
\end{aligned} \tag{4.7}$$

4.3.5.1 Dangling if-then-else if-then-else statements are usually defined to have an **else** clause, that when present, matches with the nearest previous unmatched **then**. This can be represented with the Productions shown in Equation (4.8).

$$\begin{aligned}
\langle \text{stmt} \rangle &\rightarrow \langle \text{matched} \rangle \mid \langle \text{unmatched} \rangle \\
\langle \text{matched} \rangle &\rightarrow \text{if } \langle \text{logic expr} \rangle \text{ then } \langle \text{matched} \rangle \text{ else } \langle \text{matched} \rangle \\
&\quad \mid \text{any non-if statement} \\
\langle \text{unmatched} \rangle &\rightarrow \text{if } \langle \text{logic expr} \rangle \text{ then } \langle \text{stmt} \rangle \\
&\quad \mid \text{if } \langle \text{logic expr} \rangle \text{ then } \langle \text{matched} \rangle \text{ else } \langle \text{unmatched} \rangle
\end{aligned} \tag{4.8}$$

4.3.6 Operator Precedence

To handle the precedence of operators, we need to define a “priority level” to our Productions. It is good to note that the further *down* an expression is in the parse tree, the higher its priority in mathematics.

$$\begin{aligned}
\langle \text{assign} \rangle &\rightarrow \langle \text{id} \rangle = \langle \text{expression} \rangle \\
\langle \text{id} \rangle &\rightarrow A \mid B \mid C \\
\langle \text{expression} \rangle &\rightarrow \langle \text{expression} \rangle + \langle \text{multiplicative expression} \rangle \\
&\quad \mid \langle \text{multiplicative expression} \rangle \\
\langle \text{multiplicative expression} \rangle &\rightarrow \langle \text{multiplicative expression} \rangle * \langle \text{factor} \rangle \\
&\quad \mid \langle \text{factor} \rangle \\
\langle \text{factor} \rangle &\rightarrow (\langle \text{expression} \rangle) \\
&\quad \mid \langle \text{id} \rangle
\end{aligned} \tag{4.9}$$

4.3.7 Operator Associativity

We need to make sure that operators are associated with each other correctly. If we need to make an operator right associative, we just need to flip the terms in Equation (4.9) around. The operators in Equation (4.9) are left associative as they are right now.

$$\begin{aligned} \langle \text{factor} \rangle &\rightarrow \langle \text{expression} \rangle * \langle \text{factor} \rangle \\ &\quad | \langle \text{term} \rangle \\ \langle \text{term} \rangle &\rightarrow (\langle \text{expression} \rangle) \\ &\quad | \langle \text{id} \rangle \end{aligned} \tag{4.10}$$

5 Natural Semantics

Natural semantics assumes that we know the syntax of the language. We will assume that we have a Backus-Naur Form Context-Free Grammar. We will also assume that ambiguities have been resolved, somehow.

Defn 41 (Semantics). *Semantics* is the act of attaching a meaning to a syntactic construct. For instance, we know the value of 1 to be 1, but does $one = 1$? We have defined the semantics of one to be equivalent to the numeral 1.

We can define these semantic relationships with Evaluation Relations.

Defn 42 (Evaluation Relation). The *evaluation relation* states the relation between a program p and the program's result v :

$$p \Downarrow v \tag{5.1}$$

This is read as “ p evaluates to v ”.

Remark 42.1. The value of the left-hand side is an arbitrary set of operator(s). For instance, if we wanted to specify addition, but using the **add** operator, then p would look $e_1 \text{ add } e_2$. However, on the right-hand side, we *MUST* specify the operation that will take place. The right-hand side is a mathematical construction that the reader will understand.

Defn 43 (Metavariable). A *metavariable* is a variable in the Metalanguage. In Equation (5.1), p and v are metavariables.

p is a metavariable that can contain any input program, and v is a metavariable that can contain any result that the language might compute.

Throughout this section, we will use this Backus-Naur Form Context-Free Grammar.

$$\begin{aligned} \langle \text{expr} \rangle &\rightarrow \text{nat} \\ &\quad | \langle \text{expr} \rangle + \langle \text{expr} \rangle \\ &\quad | \langle \text{expr} \rangle \text{ div } \langle \text{expr} \rangle \end{aligned} \tag{5.2}$$

Let's start with the programming language specified by the Context-Free Grammar below.

$$\langle W \rangle \rightarrow \text{ett} | \text{tv\AA} | \text{tre}$$

This allows only 3 programs, each of which is a single word in Swedish. We can define the semantics (attach meaning) with the following rules:

$$\text{ett} \Downarrow 1$$

$$\text{tv\AA} \Downarrow 2$$

$$\text{tre} \Downarrow 3$$

5.1 Ambiguous Semantics

Just like in Context-Free Grammars, there can be ambiguities in Semantics too. They occur when there is more than 1 specification for a symbol. For example,

$$\langle Q \rangle \rightarrow \text{eins} | \text{zwei} | ?$$

with the Semantics below:

$$\text{eins} \Downarrow 1$$

$$\text{zwei} \Downarrow 2$$

$$? \Downarrow 0$$

$$? \Downarrow 3$$

In this course, we are interested in unambiguous Semantics. When language designers design a programming language, they try to avoid these ambiguities.

We can normally check if a set of semantic rules are unambiguous by checking that the left-hand side of each of the Evaluation Relations does not overlap with another Evaluation Relation. If there is an overlap, then it **must** be shown that the same result will be yielded.

5.2 Conditional Rules

When we want a Metavariable to only get a value under certain conditions, we have a special notation for that. For example, say we want n to be a natural number that is used in the grammar of Equation (5.2). We can write this condition as:

$$\frac{n \in \mathbb{N}}{n \Downarrow \text{asNat}(n)} \quad (5.3)$$

The writers of these semantic grammars favor simplicity, so they might omit the `asNat` function by arguing “separating between natural numbers and their textual representation is overly pedantic, as long as there is no ambiguity”. They might write the rule in Equation (5.3) as:

$$\frac{n \in \mathbb{N}}{n \Downarrow n} \quad (5.4)$$

5.3 Recursion

If we want to construct the addition in Equation (5.2), then we can write:

$$\frac{e_1 \Downarrow n_1 \quad e_2 \Downarrow n_2}{e_1 + e_2 \Downarrow n_1 + n_2} \quad (5.5)$$

5.4 Completeness

A semantic specification is *complete* when all possible cases have been defined, in some way. For example:

$$\frac{e_1 \Downarrow n_1 \quad e_2 \Downarrow n_2}{e_1 \text{ div } e_2 \Downarrow \left\lfloor \frac{n_1}{n_2} \right\rfloor} \quad (5.6)$$

This rule ignores the case when $n_2 = 0$, which means we divide by 0. In mathematics, this is an undefined operation.

There are 2 ways to solve this problem:

1. **Adding a Meta-Rule:** Add an informal rule that states if the Semantics of an operation is not defined, then execution aborts with an error. This is a solution, but it allows the language designer to solve corner cases with strange behavior. This also prevents any forms of error recovery, harming Reliability.
2. **Error Values:** Extend the \Downarrow Evaluation Relation operator so that we can return *error values* along with intended results. This may require adding **MANY** new rules to the language.

Example 5.1: Natural Semantics. Lecture 3

For the given Context-Free Grammar, construct rules for the Natural Semantics of this language? Then, perform a proof/derivation using those rules for the statement $\max(1 + 2)(1 + 1)$? Ignore the parentheses; those are only used to show that the 2 expressions are separate. Assume there is a process before applying the Context-Free Grammar which handles the parentheses.

$$\begin{aligned} \langle \text{expr} \rangle &\longrightarrow \text{num} \\ &| \langle \text{expr} \rangle + \langle \text{expr} \rangle \\ &| \max \langle \text{expr} \rangle \langle \text{expr} \rangle \end{aligned}$$

NOTE: Green will represent input to the rule and blue will represent rule output. When deriving statements with these rules, there may be additional colors to represent various values.

The easiest rule to define is the rule for `num`.

$$\frac{n \in \text{num}}{n \Downarrow n} (\text{num})$$

Next, we define the rule for the addition.

$$\frac{e_1 \in \langle \text{expr} \rangle \quad e_2 \in \langle \text{expr} \rangle \quad e_1 \Downarrow n_1 \quad e_2 \Downarrow n_2}{e_1 + e_2 \Downarrow n_1 + n_2} (\text{add})$$

Remark. In this case, the expression’s rule actually returns the computed number from the expression $n_1 + n_2$, rather than the 2 expressions added together (which would be had if we had written $e_1 + e_2$ instead).

Remark. From here on out, if there is $e_x \Downarrow n_x$, then we also implicitly say $e_x \in \langle \text{expr} \rangle$.

Now we have to define the **max** operation. In this case, we need 2 rules to specify the 2 cases, when the left expression is the relative maximum, and when the right expression is the relative maximum.

$$\frac{e_1 \Downarrow n_1 \quad e_2 \Downarrow n_2 \quad n_1 \geq n_2}{\text{max } e_1 \quad e_2 \Downarrow n_1} \text{(max left)}$$

$$\frac{e_1 \Downarrow n_1 \quad e_2 \Downarrow n_2 \quad n_1 \leq n_2}{\text{max } e_1 \quad e_2 \Downarrow n_2} \text{(max right)}$$

Remark. Although the 2 equations for determining the relative maxima both have an equality aspect, in pure mathematics, that's fine. In mathematical terms, if both rules apply, because $e_1 == e_2$, then, both are technically maxima and should be returned.

However, this will change during implementation, because one of the rules will be checked first, which necessitates that the rules be made mutually exclusive.

Now that all the necessary rules have been developed, we can apply them to the statement $\text{max}(1 + 2)(1 + 1)$.

$$\frac{\frac{1 \in \mathbb{N}}{1 \Downarrow n_1 = 1} \text{(num)} \quad \frac{2 \in \mathbb{N}}{2 \Downarrow n_2 = 2} \text{(num)} \quad \frac{1 \in \mathbb{N}}{1 \Downarrow n_1 = 1} \text{(num)} \quad \frac{1 \in \mathbb{N}}{1 \Downarrow n_2 = 1} \text{(num)} \quad \frac{e_1 = 1 + 2 \Downarrow n_1 = n_1 + n_2 = 1 + 2 = 3}{\text{max}(\underbrace{1 + 2}_{e_1})(\underbrace{1 + 1}_{e_2}) \Downarrow n_1 = 3} \text{(add)} \quad \frac{n_1 \geq n_2 = 3 \geq 2}{\text{(max left)}}$$

We chose the **max left** rule only **after** the values of e_1 and e_2 were calculated.

5.5 Language with Variables

For this section, we are going to use Equation (5.7) as our Context-Free Grammar.

$$\begin{aligned} \langle \text{expr} \rangle &\rightarrow \text{nat} \\ &| \text{id} \\ &| \langle \text{expr} \rangle + \langle \text{expr} \rangle \\ &| \text{let } \text{id} = \langle \text{expr} \rangle \text{ in } \langle \text{expr} \rangle \end{aligned} \tag{5.7}$$

5.5.1 Environments

Defn 44 (Environment). An *environment* is a mathematical object that tells us the bindings of variables. We will use the following notation:

$$E_n = \{v_1 \mapsto m_1, v_2 \mapsto m_2\} \tag{5.8}$$

where v is a variable, and n is the number of variables present. So, for example:

$$E_2 = \{a \mapsto 1, b \mapsto 7\}$$

Remark 44.1 (Empty Environment). The *empty environment* is written

$$E_\emptyset = \{\} \tag{5.9}$$

To retrieve an value from an Environment, where the Environment being used is Equation (5.8), we write:

$$E(a) \Rightarrow 1 \tag{5.10}$$

If we want to update an Environment with a new binding,

$$E_2[c \mapsto 42] = \{a \mapsto 1, b \mapsto 7, c \mapsto 42\} \tag{5.11a}$$

$$E_2[a \mapsto 0] = \{a \mapsto 0, b \mapsto 7\} \tag{5.11b}$$

We define this as:

$$E[x \mapsto v](y) = \begin{cases} v & \iff x = y \\ E(y) & \text{otherwise} \end{cases} \tag{5.12}$$

This means that if $x = y$, then x is remapped (updated) to the value v .

5.5.2 Defining Semantics with Environments

Environments, E , can now become parameters to our Evaluation Relations, \Downarrow . This is written

$$E \vdash p \Downarrow n \quad (5.13)$$

Which means p can be drawn from the environment E , and should evaluate to a number, n (n is defined elsewhere). If p is **not** defined in the Environment, but is possible to evaluate, for example $p = 4$, then nothing happens with the Environment.

Essentially, using $E \vdash p$ means that p has access to the Metavariables present in the Environment, but p is not required to be drawn from E .

Example 5.2: Natural Semantics with Environments. Lecture 3

Given the Context-Free Grammar,

$$\begin{aligned} \langle \text{expr} \rangle &\longrightarrow \text{num} \\ &| \langle \text{expr} \rangle + \langle \text{expr} \rangle \\ &| \text{max} \langle \text{expr} \rangle \langle \text{expr} \rangle \\ &| \text{let } \underline{\text{id}} = \langle \text{expr} \rangle \text{ in } \langle \text{expr} \rangle \\ &| \underline{\text{id}} \end{aligned}$$

Compute the result of `let x = 2 in x + 3`?

We will start by using the rules that we defined in Example 5.1. We will also need to add new semantic rules for `id` and the `let` statement.

$$\frac{i \in \underline{\text{id}}}{E \vdash i \Downarrow E(i)} \text{ (id)}$$

$$\frac{E \vdash e_1 \Downarrow n_1 \quad E[i \mapsto n_1] \vdash e_2 \Downarrow n_2}{E \vdash \text{let } i = e_1 \text{ in } e_2 \Downarrow n_2} \text{ (let)}$$

We start by applying the most applicable rule, the **(let)** rule.

$$\frac{\frac{2 \in \mathbb{N}}{E_0 \vdash 2 \Downarrow 2} \text{ (num)} \quad \frac{\frac{x \in \underline{\text{id}}}{E_0[x \mapsto 2] \vdash x \Downarrow E(x) \Rightarrow 2} \text{ (id)} \quad \frac{3 \in \mathbb{N}}{E_0[x \mapsto 2] \vdash 3 \Downarrow 3} \text{ (num)}}{E_0[x \mapsto 2] \vdash x + 3 \Downarrow 2 + 3 = 5} \text{ (add)} \text{ (let)}$$

Once we've applied the **(let)** rule, we apply the **(num)** rule, because the expression being assigned is just a number. The result of that expression evaluation is piped into the next **(add)** derivation. From there, it is mapped to the input `x`, and the `x+3` is calculated. The first thing is to get the value of `x` from the mapping with the **(id)** rule. Once the $E(x)$ returns the value of the variable `x`, we can use it. The other operand in the addition is found using the **(num)** rule. Then the addition occurs, and the derivation completes.

6 Names

Names or *identifiers* are, obviously, names given to things. They can identify:

- Variables
- Subprograms
- Formal Parameters
- Other program constructs

6.1 Issues

There are 2 questions that need to be asked when designing the names or identifiers possible in a language.

1. Are names case-sensitive? For example, are these identifiers different?
 - `myvariable`
 - `MYVARIABLE`

- `MyVariable`
- `myVariable`

2. Are the special words of the language Reserved Words or are they Keywords?

6.2 Name Forms

How is a name/identifier defined?

- Is there a character limit on the identifier/name?
- Are all characters in the identifier/name significant?
- What characters are allowed in the identifier/name?
- Are there special characters required by a language?
 - `$` being required in front of identifiers in PHP
 - `$`, `@`, `%` specifying a “type” in Perl
 - `@` and `@@` to denote an instance or class variable in Ruby, respectively

Some languages are *case-sensitive*. C, Java, C++, etc. would all treat `rose`, `ROSE`, and `Rose` differently. This could be a detriment to readability, because names that *look* similar are actually not. In terms of writability, the programmer must remember the exact typecasing of the identifier/name.

6.3 Special Names

There are Reserved Words and Keywords. They are similar in that the programming language specification defines that these words have special meanings when constructing programs. However, the 2 differ in how these words can potentially be reused.

Defn 45 (Keyword). *Keywords* are words that are defined by the language constructors to have some special meaning. However, it only has these special meanings in *certain contexts*. This means you can define a keyword as a variable and use it together with the keyword. For example, this is a perfectly valid piece of Fortran code:

```
1 Integer Apple
2 Integer = 4
```

Defn 46 (Reserved Word). *Reserved words* are words that are reserved by the language constructors because those particular words have a meaning in the language. These words cannot be used as identifiers for **ANYTHING** else. For example:

- `while`
- `class`
- `for`

Remark 46.1 (Too Many Reserved Words). The potential problem with Reserved Words is that if a language has a large number of reserved words, the user might have a hard time creating names for themselves. Unfortunately, the most commonly chosen words by programs are usually Reserved Words. For example,

- `LENGTH`
- `BOTTOM`
- `DESTINATION`
- `COUNT`

6.4 Variables

Defn 47 (Variable). A program *variable* is an abstraction of a computer Memory cell or a collection of Memory cells. A variable can be characterized by a sextuple of attributes:

1. Name
2. Address
3. Value
4. Type
5. Storage Bindings and Lifetime
6. Scope

6.4.1 Name

Most Variables have names. These are symbolic references to the value that is actually stored. There are various issues that may arise with the name of a variable, which were discussed earlier.

6.4.2 Address

Defn 48 (Address). The *address* of a Variable is the machine's memory address with which the Variable is associated.

The address of a variable is sometimes called its *L-Value*. This is because the address is required when the name of a variable appears on the left-hand side of an assignment statement.

Remark 48.1 (Alias). An *alias* is having another Variable have the same Address, so the 2 Variables point to the same value in Memory.

For some languages, it is possible for the same Variable to be associated with different addresses at different times during the Variable's lifetime.

6.4.3 Type

Defn 49 (Type). The *type* of a Variable determines the range of values that Variable can store. For example, the `int` type in Java specifies a value range of -2147483648 to 2147483647 . It is a 32-bit signed integer.

6.4.4 Value

Defn 50 (Value). The *value* of a Variable is the contents of the Memory cell or cells associated with the Variable. The value of a variable is sometimes called it *R-Value*. This is because the value of the Variable is required on the right-hand side of an assignment statement. To access the *r-value*, the *l-value* must be determined first.

Remark 50.1 (Abstract Memory Cells). While in hardware, the individual sizes of Memory are fixed, we can think of Memory as having *abstract memory cells*, that can accomodate anything we attempt to put into Memory. This means that a single-precision floating point number technically takes up 4 bytes, 32 bits, of Memory cells, that number only takes one abstract memory cell.

6.5 Binding

Defn 51 (Binding). A *binding* is an association between an attribute and an entity. This association can be between:

- A variable
 - Its type
 - Its value
- An operation
 - Its symbol

The time at which a binding occurs is called the Binding Time.

Defn 52 (Binding Time). The time at which Binding occurs is called the *binding time*. These include:

- Language Design Time
 - Defining `*` to represent multiplication
- Language Implementation Time
 - Having an `int` in C be a 32-bit signed integer
- Compiler Time
 - The type of a variable in a Java program
- Link Time
 - A call to a library subprogram is bound to the subprogram code
- Load Time
 - Variable bound when loaded into Memory
 - Could happen at run time too
- Run Time
 - Variable bound when loaded into Memory
 - Could happen at compile time too

We need to know the Binding Times for the attributes of a program to understand the semantics of the programming language.

6.5.1 Binding of Attributes to Variables

Defn 53 (Static). A Binding is *static* if the Binding first occurs before run time begins and remains unchanged throughout program execution. An example of this is declaring a Variable as an `int` in C. Throughout the whole C program, that Variable can only hold signed 32-bit integers.

```
1 int x = 4;
2 float x = 4.0; // Error here, x already declared
3 x = 4.0 // Error here, x is of int type
```

Defn 54 (Dynamic). A Binding is *dynamic* if the Binding occurs during run time, or can change in the course of program execution. An example of this is declaring a Variable in Python.

```
1 x = 4
2 x = [1, 2, 3]
3 x = 'dynamically bound string'
```

All three lines have a variable declaration, where the Binding occurs during the program's execution and changes during it.

We are only concerned with the distinction between Static and Dynamic Variable Binding. Meaning, we will ignore how hardware may bind and unbind things repeatedly when it is switching and moving things around.

6.5.2 Type Bindings

Before a Variable can be used or referenced in a program, its Type must be declared. A Variable's *type* determines the range of values that can be stored in the Variable. In a more abstract sense, it also determines what kind of operations make sense and are possible to use on these Variables. There are 2 important aspects of this Binding:

1. How the Variable Type is specified
2. When the Binding takes place

There are 2 ways to bind Types to Variables:

1. Static Type Binding
 - Explicit
 - Implicit
2. Dynamic Type Binding

6.5.2.1 Static Type Binding

Defn 55 (Static). *Static* Binding of Variables means that the Type of a Variable is given to the program, either Explicitly or Implicitly before run time begins. Once the Type is declared, it cannot be changed throughout the entire program's execution.

There are 2 ways to Staticly bind a Type to a Variable:

1. Explicitly
2. Implicitly

Defn 56 (Explicit). An *explicit* Static Type Binding is a statement that explicitly sets each Variable to its respective Type. These are statements in a program that lists variable names and specifies that they are of a particular Type. For example,

```
1 int x = 0;
2 float x = 0.0;
3 char x = 'x';
```

Defn 57 (Implicit). An *implicit* Static Type Binding declaration associates Variables with Types through default conventions, rather than Explicit declaration statements. The first appearance of a Variable name is its implicit declaration.

Remark 57.1 (Effects on Reliability). While Implicit can be helpful for programmers, they can be quite detrimental to Reliability because the compilation process cannot determine some type errors and some programmer errors.

Implicit declarations are handled by the language processor (Compiler or Interpreter). There are several ways to have Implicit declarations work, some of which are:

- Naming conventions
 - In **Fortran**, if an identifier starts with
 - * I, J, K, L, M, or N, or their lowercase versions, it is Implicitly declared to be an **Integer** type.
 - * Otherwise, it is Implicitly declared to be a **Real** type.
 - In **Perl**, an identifier must be preceded by a special character denoting the Type. This method forms separate namespaces for each Variable Type.
 - * \$, is a scalar. This holds numbers and strings
 - * @, is an array.
 - * %, is a hash structure.
 - * The separate namespaces means that all 3 of these variables are considered unique, and potentially unrelated.
 - \$apple
 - @apple
 - %apple
- Context or type inference
 - In **C#**, a **var** declaration for a Variable must include an initial value, which determines the Type of the Variable.

```

1  var sum = 0;
2  var total = 0.0;
3  var name = "Fred";

```

- `sum`, `total`, and `name` are an **int**, **float**, and **string**, respectively.

Remark. Both Explicit and Implicit declarations create Static Bindings to Types.

6.5.2.2 Dynamic Type Binding With Dynamic Type Binding, the Type of a Variable:

- Is not specified by a declaration statement
- Cannot be determined by the spelling of the Variable's name

Defn 58 (Dynamic). A *dynamic* Binding happens when a Variable is bound to a Type **when it is assigned a Value**. Such an assignment might also bind the Variable to an Address.

Any Variable can be assigned any Type. A Variable's Type can be changed any number of times during program execution. The name of the Variable is bound to the Variable, then the Variable is bound to a Type and given its Value.

2 programming languages that use this are:

1. Python
2. Ruby

Remark 58.1 (Benefits of Dynamic Binding). The primary benefit of having Dynamic Binding is the programming flexibility it provides.

Remark 58.2 (Drawbacks of Dynamic Binding). The 2 major disadvantages are:

1. Programs are less reliable, because error-detection of the compiler/interpreter is diminished relative to a compiler/interpreter for a language with Static Type Bindings.
2. The Cost is quite high because of the Type Checking that must occur at run time. Also, every variable must have a run-time descriptor to describe the Variable's current Type.

Remark. Dynamic Type Binding is usually implemented with Interpretation. This is because:

- The overall Cost of Type handling is hidden by the Cost of the interpreter.
- The Type of an operation's operands must be known to translate the instruction to the correct machine code instruction, which isn't possible with Dynamic Type Binding.

6.5.3 Storage Bindings and Lifetime

The Memory cell to which a Variable is bound must be pulled from the pool of available Memory. The act of binding the Value to a Variable is called Allocation. The act of unbinding is called Deallocation.

Defn 59 (Allocation). *Allocation* is the act of binding a Value to a Memory cell for a Variable.

Defn 60 (Deallocation). *Deallocation* is the process of placing a Memory cell that has been unbound from a variable back into the pool of available Memory.

Defn 61 (Lifetime). The *lifetime* of a Variable is the time in which the Variable is bound to a Memory cell. The lifetime of a Variable starts when it is bound to a cell and ends when it has been unbound from that cell.

We will split the discussion of Storage Bindings and Lifetime of scalar Variables into 4 categories, according to their Lifetimes.

- Static Variables
- Stack-Dynamic Variables
- Explicit Heap-Dynamic Variables
- Implicit Heap-Dynamic Variables

6.5.3.1 Static Variables

Defn 62 (Static Variable). *Static variables* are those that are bound to Memory cells before program execution begins and remain bound until the program terminates. They are placed in the “static” section of Memory. Static Variables can be used as globally accessible Variables, or ensure that subprograms are history-sensitive.

The pros and cons of Static Variables are:

- Pros
 - Efficiency. All Memory addressing is done with absolute addresses, making things very fast.
 - No cost to allocate and deallocate the Memory during run-time.
 - Programs can be history sensitive.
- Cons
 - Reduced flexibility. If there is a language that only has Static Variables, then recursive subprograms are impossible.
 - Memory cannot be shared between inactive and active subprograms.

Remark. In C and C++, **static** can be set on functions, making the Variables declared in the function Static Variable.

Remark. In Java, C++, and C#, **static** can appear on classes, meaning class Variables are created statically some time before the class is first instantiated.

6.5.3.2 Stack-Dynamic Variables

Defn 63 (Stack-Dynamic Variable). *Stack-dynamic variables* are those whose storage Bindings are created when their declaration statements are elaborated. These are allocated from the run-time Call Stack. Thus, when a function on the Call Stack is **returned** from, all the variables here lose their value.

Remark 63.1. These are the variables that are most commonly used, and are usually function-local variables

Remark 63.2. In languages that allow for variable declaration anywhere in the function, like Java and C++, the Stack-Dynamic Variables may be bound to storage at the beginning of the block, thus starting the variable’s Lifetime. In these cases, the Variable becomes visible at the declaration, but the storage Binding occurs when the block begins execution. So, it is both in Scope and has begun its Lifetime, but has no useful value.

The advantages and disadvantages of Stack-Dynamic Variables, compared to Static Variables, are:

- Advantages
 - Allows for recursive subprograms that have local variables
 - All subprograms can share the same memory space for their locals, allowing for a smaller memory footprint, by only having some variables bound to storage at once.
- Disadvantages
 - Runtime overhead of Allocation and Deallocation.
 - Slower accessing of Stack-Dynamic Variables because of indirect addressing.
 - Subprograms cannot be history-sensitive with just Stack-Dynamic Variables.

Defn 64 (Elaboration). *Elaboration* of a Variable declaration refers to the storage Allocation and Binding process indicated by the declaration, which takes place when execution reaches that code.

This occurs at run time.

6.5.3.3 Explicit Heap-Dynamic Variables

Defn 65 (Explicit Heap-Dynamic Variable). *Explicit heap-dynamic variables* are nameless (abstract) memory cells that are allocated and deallocated by explicit run-time instructions written by the programmer. These Variables are allocated to and deallocated from the Heap. They can only be referenced through pointers or reference variables.

The pointer/reference can only be created and returned by:

- An operator (in C++), **new**
- A subprogram (in C), **malloc**

Some languages include ways to destroy these pointers/references:

- An operator (in C++), **delete**
- A subprogram (in C), **free**

The advantages and disadvantages of these types of Variables are:

- Advantages
 - Explicit Heap-Dynamic Variable are often used to construct dynamic data structures, like linked lists and trees. These are built conveniently using pointers and data.
- Disadvantages
 - The difficulty of using pointer/reference variables correctly.
 - The Cost of using these pointers/reference variables.
 - Complexity of the required storage management implementation (Although, this is a question of Heap management, which is costly and complicated and completely separate discussion).

An example of an Explicit Heap-Dynamic Variable is shown below.

```
1 int *intnode; // Create a pointer
2 intnode = new int; // Create the heap-dynamic variable
3 ...
4 delete intnode; // Deallocate the heap-dynamic variable to which intnode points
```

The Heap is highly disorganized because of the unpredictability of its use. There are 2 ways to manage the Heap:

1. Explicit Deallocation

- The programmer must explicitly free the Memory themselves.
- C and C++ require this with their **free** and **delete** subprograms/operators, respectively.

2. Implicit Deallocation

- The programming language has facilities, called *garbage collection* that automatically manages the Heap.
- There are many algorithms that handle garbage collection, some of which are faster, others slower.

6.5.3.4 Implicit Heap-Dynamic Variables

Defn 66 (Implicit Heap-Dynamic Variable). *Implicit heap-dynamic variables* are bound to Heap storage **only when they are assigned Values**. In many regards, Implicit Heap-Dynamic Variables and Explicit Heap-Dynamic Variables are quite similar.

However, Implicit Heap-Dynamic Variables have **ALL** their attributes bound **EVERY** time they are assigned. The advantages and disadvantages of these types of Variables are:

- Advantages
 - Highest degree of flexibility, allowing for highly generic code
- Disadvantages
 - Run time overhead of maintaining all the dynamic attributes, which could include subscript types and ranges
 - Loss of some error detection by the compiler/interpreter

6.6 Scope

Defn 67 (Scope). The *scope* of a Variable is the range of statements in which the Variable is Visible.

Scope might seem similar to Lifetime, but they are different. Here are 2 examples that illustrate this point:

1. At the second `print(x)`, `x` is *in scope* (visible), but is *dead* (deallocated).

```
1  int f(void) {  
2      int *x;  
3      x = (int *) calloc(sizeof(int), 1);  
4      print(x);  
5      free(x);  
6      print(x);  
7  }
```

2. When executing inside of `g(y)`, the `x` in function `f` is *alive* (allocated), but is *out of scope* (not visible).

```
1  def f(x):  
2      return g(7)  
3  def g(y):  
4      print (y)  
5      return
```

Defn 68 (Visible). A Variable is *visible* in a statements if it can be referenced in that statement.

Remark 68.1 (In-Scope). Sometimes, a Variable that is Visible is called *in-Scope*.

Defn 69 (Local Variable). A Variable is a *local variable* in a program unit or block if it is declared there. Variables defined within subprograms are also local variables. The Scope is usually the body of the subprogram in which they are defined.

Remark 69.1 (Storage Binding). If the Local Variable is a Stack-Dynamic Variable, it is bound to storage when the subprogram begins and unbound when that execution terminates.

Defn 70 (Nonlocal Variable). The nonlocal variables of a program are visible with that particular program unit or block, but are not declared there.

Remark 70.1 (Global Variables). Global variables are a special case of Nonlocal Variables. These are discussed in Section 6.6.5.

6.6.1 Static Scope

Defn 71 (Static Scoping). *Static scoping* is a way to statically determine the scope of a Variable. When there is a reference to a Variable, the attributes of the Variable can be determined by finding the statement in which it is declared (either explicitly or implicitly). This makes it easy for a human reader and compiler/interpreter to figure out the Type of every Variable in the program.

There are 2 types of statically-scoped languages:

1. Subprograms can be nested inside programs (Python)
2. Subprograms cannot be nested inside programs (Java)

Remark 71.1 (Lexical Scoping). Static Scoping is sometimes called *lexical scoping*.

Static Scoping creates a tree-like structure, where each Variable declared in a program unit/block has a Static Parent. Then, each Static Parent has a list of Static Ancestors.

Defn 72 (Static Parent). If the Variable referenced is not present as a Local Variable, then we have to go to the next outer program unit or block, the *static parent*.

Defn 73 (Static Ancestor). The *static ancestors* are all the Static Parents to that particular program unit/block.

This is illustrated by finding `x` in `sub2()` in this JavaScript function.

```
1  function big() {  
2      function sub1() {  
3          var x = 7;  
4          sub2();  
5      }
```

```

5   }
6   function sub2() {
7       var y = x;
8   }
9   var x = 3;
10  sub1();
11  }

```

The `x` in `sub2()` refers to the `x=3` in `big()`, because `sub1()` is not a Static Ancestor of `sub2()`. However, inside of `sub1()`, the use of the variable `x` would refer to the `x=7` value, and never the `x=3` value.

In some languages, if a Variable is declared in a sub-program unit/block, like in `sub1()`, then preceding the Variable name with the outer program unit/block will give the outer Variable Value.

6.6.2 Dynamic Scope

Defn 74 (Dynamic Scoping). *Dynamic scoping* is based on the calling sequence of subprograms, and not their spatial relationship to each other. Thus, the scope can only be determined at run time.

Some languages that implement this are:

- APL
- SNOBOL4
- Early LISP
- Perl (Allowed, but must be said explicitly)
- Common LISP (Allowed, but must be said explicitly)

To illustrate Dynamic Scoping, look at the code block below, and assume it is in a language that uses Dynamic Scoping.

```

1  function big() {
2      function sub1() {
3          var x = 7;
4          sub2();
5      }
6      function sub2() {
7          var y = x;
8      }
9      var x = 3;
10     sub1();
11     sub2();
12 }

```

The call to `sub1()` by `big()`, which then calls `sub2()`. In that running of `sub2()`, the use of `x` cannot be determined locally (within that function). Thus, it goes to its dynamic parent, `sub1()` and finds a declaration for `x`. Thus, the `y` in `sub2()` evaluates to `y=7`.

The next instruction, the call to `sub2()` by `big()`, produces a different result. In that running of `sub2()`, the use of `x` cannot be determined locally (within that function). Thus, it goes to its dynamic parent, `big()` and finds a declaration for `x`. Thus, the `y` in `sub2()` evaluates to `y=3`.

6.6.3 Blocks

New Static Scopes can be defined in the middle of executing code. This allows a small section to have its own Local Variables.

Defn 75 (Block). A *block* is a section of code that has its own Local Variables. These Local Variables are **not** shared with any Static Ancestors.

The use of Blocks create a Block-Structured Language.

Defn 76 (Block-Structured Language). The use of Blocks to create the Static Scopes creates a *block-structured language*.

Consider the following C function:

```

1  void sub() {
2      int count;

```

```

3     ...
4     while (...) {
5         int count;
6         count++;
7     }
8     ...
9 }

```

The `count` inside the `while` loop is that loop's local count, and does not reference the `count` in `sub`.

6.6.3.1 Blocks in Functional Languages Since Variables in Functional Programming Languages actually evaluate and store expressions, they behave differently. Each functional language handles this differently, so you will have to look at the language specification to find out exactly how Variables are scoped.

6.6.4 Declaration Order

Some languages require that all Variable declarations occur at the beginning of a function (C89).

In some languages, Variables cannot be used before they have been declared.

- Some of these languages allow for Variables to be declared anywhere in the function, but can only be referenced **after** their declaration until the end of their scope.
- Some of these languages allow for Variables to be declared anywhere in the function, but if used before their declaration, they use a value like `undefined` (JavaScript).

This is a highly language-dependent thing, and one must consult with the language specification to figure out exactly how it works.

6.6.5 Global Scope

Defn 77 (Global Variable). These are usually Variables that sit outside of all functions. They can be accessed from anywhere in the program. They can also be defined and/or declared in other files in the program's project.

It is important to note the difference between a Global Variable's declaration and definition.

- Declaration: The Types and attributes are bound, but the Memory space required is **not** allocated.
- Definition: The Types and attributes are bound, but the Memory space required **is** allocated.

Remark. This is a highly language-dependent thing, and one must consult with the language specification to figure out exactly how it works.

7 Data Types

Defn 78 (Data Type). A *data type* defines a collection of data values and a set of predefined operations on those values. The data types present in a language used for a particular problem should closely mirror the objects in the real-world the program is solving.

They can be mathematically defined as

$$v : \tau \tag{7.1}$$

where v is a value and τ is a type.

Remark 78.1 (Has the Type). To say “ v has the type τ ”

$$v \in \tau \tag{7.2}$$

User-defined data types allow for:

- Improved readability with better named Data Types.
- Improved modifiability with programmers having to change just one common data type somewhere for a large change throughout a program.

If we take user-defined Data Types further, we end up with *abstract data types*. These force an interface for a particular data type, which is then visible to the user, and the data and background operations are hidden away.

Because of the wide variety of Data Types present today, it is more useful to think about Variables in terms of Descriptors.

Defn 79 (Descriptor). A *descriptor* is the collection of attributes of a Variable. In an implementation, a descriptor is an area of Memory that stores the attributes of a Variable.

There are a 2 cases for these:

1. If all attributes are static, then they are known at compile-time, and the Compiler can use the symbol table to construct everything.
2. If all attributes are dynamic, then the symbol table and all attributes must be stored in Memory during program execution.

Descriptors are used for Type Checking and building the code for Allocation and Deallocation operations.

Defn 80 (Type Error). A *type error* is an attempt to perform an operation that requires an input value of type τ with a value v even though $v : \tau$ does not hold.

Defn 81 (Type Preservation). A type system has the *type preservation* (or *subject reduction*) property if for any $e \Downarrow v$, $e : \tau$ implies $v : \tau$.

There are 3 properties we want to have a type preserving type system to have:

1. *Type Preservation*: The predictions of the type system agree with the evaluation rules.
2. *Progress*: The type system only assigns a type if the evaluation rules will not get “stuck” due to a missing semantic rule. This is not the same as guaranteeing that the program itself terminates, meaning but it does guarantee that the language implementation will never run into a situation in which it doesn’t know what to do next.
3. *Termination*: We want the type system to be decidable, that is, we want an automatic mechanism that performs type checking.

7.1 Primitive Data Types

Defn 82 (Primitive Data Type). *Primitive data types* are Data Types that are **not** defined in terms of other data types. Nearly all programming languages provide these. Some are reflections of hardware, like integers, and others require only little software support for their implementation, floating-point numbers for instance.

7.1.1 Numeric Types

This section will discuss the 4 main types of numeric Data Types present in most programming languages.

Defn 83 (Numeric Data Type). *Numeric data types* are Data Types that handle numbers.

7.1.1.1 Integer Integers are the most common Numeric Data Type. Many languages support several sizes. Java supports 4: `byte`, `short`, `int`, and `long`. There can be unsigned integers as well.

If there are signed integers, the negative integers are stored in Memory in Twos Complement.

Defn 84 (Twos Complement). *Twos complement* is a way to store negative integers. To find the twos complement:

1. The magnitude of the integer is found in binary
2. The logical complement of that is computed
3. One (1) is added to the logical complement

Remark 84.1. Using Twos Complement is similar to adding by a negative number to an integer instead of performing subtraction.

7.1.1.2 Floating-Point

Defn 85 (Floating-Point). *Floating-point* Data Types model real (fractional/rational) numbers. However, these representations are only approximations for many real values. For example, π cannot be represented in floating-point notation.

Most programming languages implement 2 types of floating-point Data Types.

1. `float`: The standard size, 32 bits (4 bytes). Represent the real number as a decimal and exponent, like scientific notation.
 - The first bit is a *sign bit* (1 for negative)
 - The next 8 bits are for the *exponent*, normalized so that a real number raised to -127 , i.e. x^{-127} , has an exponent bit value of 0.
 - This does mean that x^{128} would have a bit-valued exponent of 255.
 - The last 23 bits are for the fraction, called the *mantissa*. This is the fractional portion of the scientific notation, represented in binary, with the first 1 of the bit sequence left off.

2. **double**: Used in cases where larger/smaller fractions or larger/smaller exponents are needed, 64 bits (8 bytes).

- The first bit is a *sign bit* (1 for negative)
- The next 11 bits are for the *exponent*, normalized so that a real number raised to -1023 , i.e. x^{-1023} , has an exponent bit value of 0.
 - This does mean that x^{1024} would have a bit-valued exponent of 2048.
- The last 52 bits are for the fraction, called the *mantissa*. This is the fractional portion of the scientific notation, represented in binary, with the first 1 of the bit sequence left off.

Floating-Point numbers are specified in IEEE Floating-Point Standard 754.

Defn 86 (Floating-Point Precision). *Precision* is the accuracy of the fraction part of the Floating-Point number, and how well it represents the real number's value.

Defn 87 (Floating-Point Range). *Range* is a combination of the range of fractions and the range of the exponents.

7.1.1.3 Complex Some programming languages support complex numbers natively, and they also support complex-number mathematical operations natively. The imaginary portion of the number is typically denoted with *j* or *J*.

7.1.1.4 Decimal In a computer, decimal numbers are stored in Binary Coded Decimal. There is also special hardware to support hardware-level mathematical operations on these types of numbers. If this hardware is not present, the calculations can be simulated in software.

Defn 88 (Binary Coded Decimal). *Binary Coded Decimal*, or *BCD*, is a way to represent decimal numbers with perfect accuracy, albeit at the expense of some space. There is a one-to-one mapping of the binary representations of these numbers to decimal, and anything greater than 9 is discarded.

Decimal	Binary Coded Decimal
0	0000
1	0001
2	0010
3	0011
4	0100
5	0101
6	0110
7	0111
8	1000
9	1001
X	1010
X	1011
X	1100
X	1101
X	1110
X	1111

Table 7.1: Binary Coded Decimal

Remark 88.1. These numbers are usually stored 2 per byte, because each only takes 4 bits.

7.1.2 Boolean Types

Defn 89 (Boolean Data Type). *Boolean data types* only store 2 values: **true** and **false**. Some older language implementations did not support these, but most do today. If a language does not support a boolean data type, then 0 is considered false, and 1 is considered true.

Remark 89.1 (Storage in Memory). Although a single bit can represent a Boolean Data Type, single bits of Memory cannot be efficiently access on many machines. Thus, Boolean Data Types are usually stored in a single byte.

7.1.3 Character Types

Characters are stored in Memory as numeric encodings. These are usually single characters, **not multiple characters together (strings)**.

Characters were originally handled by ASCII, but now there are several encodings, with Unicode being more commonly used now. Unicode supports all human languages, glyphs, and other characters, like emojis. The first 128 characters of Unicode match up with ASCII for intercompatibility.

ASCII required 8 bits, Unicode (UTF-16) uses 16.

7.2 Character String Types

Defn 90 (Character String Type). A *character string type* is one in which the values consist of sequences of characters.

7.2.1 Design Issues

There are 2 questions that need to be answered when designing a language implementation when it comes to strings.

- Should strings be a special kind of character array or a primitive type?
- Should strings have static or dynamic lengths?

7.2.2 Strings and Their Operations

The most common string operations are:

- Assignment
 - What happens when a string is longer than expected? C/C++’s `strcpy` function
- Concatenation
- Substring Reference
 - Discussed more in the context of arrays, where substring references are called slices.
- Comparison
 - How do we compare 2 strings, where one is longer than the other?
- Pattern Matching

In C and C++, strings are terminated with the null character, `00`. This way we do not need to track the length of a string.

Object-Oriented Languages (Java, Ruby, C#) use classes to represent strings. The only field in these objects is a constant string.

Python supports strings as a primitive type, and supports array-like operations on them.

Some languages have Regular Expressions built in, like Perl, JavaScript, Ruby, and PHP. Others have libraries that handle Regular Expressions.

Defn 91 (Regular Expression). A *regular expression*, sometimes called a *regex* is a way to define a sequence of characters to form strings.

7.2.3 String Length Options

Defn 92 (Static Length String). A *static length string* has its length set at the time of string creation. It is static, in that the length cannot be changed later in the program’s execution.

Defn 93 (Dynamic Length String). A *dynamic length string* has its length set at the time of string creation. However, strings can change their length, and there is no set maximum size they can have.

Defn 94 (Limited Dynamic Length String). A *dynamic length string* has its length set at the time of string creation. However, the string can be redefined later in the program, so long as the new string is the same length or shorter than when the string Variable was defined.

7.2.4 Evaluation

Primitive string type implementations would require there to be predefined functions for many string operations. If there aren’t, then programming in that language becomes more cumbersome.

Dynamic Length Strings are the most flexible, but the overhead of their implementation should be weighed against that flexibility.

7.2.5 Implementation of Character String Types

Software is used to implement string storage, retrieval, and manipulation. When a language uses character arrays to store character string types, the language usually supplies few operations.

A Descriptor for a Static Length String has 3 fields:

1. Name of the type
2. The type's length in characters
3. Address of the first character

A Descriptor for a Limited Dynamic Length String has 4 fields:

1. Name of the type
2. The type's maximum length in characters
3. The length of the currently stored string
4. The address of the first character

A Descriptor for a Dynamic Length String is more difficult to handle because of its dynamic nature. There are 3 approaches to storing these:

1. Strings stored in a linked list. If the string gets longer, individual nodes can be allocated from anywhere in the Heap.
 - A drawback of this is that extra storage of the links
 - The necessary complexity of string operations
2. Store strings as arrays of pointers to individual characters on the Heap
 - This uses more memory, but processing is faster than the linked list approach.
3. Store complete strings in adjacent cells, and when a new longer string comes along, store the whole thing in a new area in the Heap and deallocate the old location.
 - Less storage required compared to the linked list approach
 - Allocation and deallocation of the string is more difficult

7.3 User-Defined Ordinal Types

Defn 95 (Ordinal Type). An *ordinal type* is a Type in which the range of possible values can be associated with the set of positive integers.

For example, in Java, the primitive ordinal types are: `int`, `char`, and `boolean`.

Remark 95.1. There are 2 User-Defined Ordinal Types that are supported by most programming languages:

- Enumeration Types
- Subrange Types

7.3.1 Enumeration Types

Defn 96 (Enumeration Type). An *enumeration type* is one in which all of the possible values, which are named constants, are provided (enumerated) in the definition. Enumeration types provide a way of defining and grouping collections of named constants, called *enumeration constants*.

This is an example of an enumeration type in C#:

```
1 enum days {Mon, Tue, Wed, Thu, Fri, Sat, Sun};
```

Remark 96.1. Typically, each of the enumeration constants is implicitly assigned an integer literal, though they can be given integer literals explicitly too.

The design issues for Enumeration Types are:

- Is an enumeration constant allowed to appear in more than one Enumeration Type definition, and if so, how is the type of an occurrence of that enumeration constant in the program checked?
- Are enumeration constants coerced to integers?
- Are any other types coerced to an Enumeration Type?

7.3.1.1 Designs In languages without native support of Enumeration Types, they are simulated with integer values. For example,

```
1 int red = 0, blue = 1;
```

However, this can lead to unexpected behavior. For example, the variables `red` and `blue` can be added together. In essence, there would be no Type Checking. The value for those variables could be overwritten somewhere. Though, that issue would be solved by making the variable a constant instead.

C and Pascal introduced the use of Enumeration Types. These implicitly use default values, integers, as the enumeration constants. However, the values can be set explicitly, by the programmer. With these Enumeration Types, we have and avoid these issues:

```
1 enum colors {red, blue, green, yellow, black};
2 colors myColor = blue, yourColor = red;
3 myColor++; // Valid code, sets myColor from blue to green
4 myColor = 4; // Illegal
5 myColor = (colors) 4; // Legal because 4 is being typecast
```

These help prevent some issues, but not all.

The next iteration was in Ada. They allowed for *overloaded literals* in their Enumeration Types. This means there were enumeration constants shared between 2 Enumeration Types in the same referencing environment. In this case, the value must be determinable from the context of the Enumeration Type. Sometimes, a more explicit specification must be used. Additionally, because the enumerations constants were **not** coerced to integers, nor were the **enumeration variables**, the range of operations and range of values for the enumeration constants was limited. This allowed the compiler to pick up many more errors.

Remark. None of the relatively recent scripting kinds of languages include Enumeration Types. These include Perl, JavaScript, PHP, Python, Ruby, and Lua.

7.3.1.2 Evaluation Enhancements to both Readability and Reliability.

- Readability is enhanced by better named values
- Reliability is enhanced by being able to perform Type Checking on the Enumeration Types.
 - No arithmetic operations allowed on Enumeration Types.
 - No enumeration variable can be assigned a value outside the Enumeration Type's assigned range.

7.3.2 Subrange Types

Defn 97 (Subrange Type). A *subrange type* is a contiguous sequence of an Ordinal Type. For example, this is a subrange: 12..14.

7.3.2.1 Ada's Design Ada included Subrange Types in Subtypes.

Defn 98 (Subtype). A *subtype* in Ada is an extension, usually constrained, version of existing types. For example,

```
1 type Days is (Mon, Tue, Wed, Thu, Fri, Sat, Sun);
2 subtype Weekdays is Days range Mon..Fri;
3 Day1 : Days;
4 Day2 : Weekdays;
5 ...
6 Day2 := Day1; -- Will only work if Day1 has Mon-Fri, fails if Day1 = Sat or Sun
```

The compiler generates range-checking code for every assignment to the subrange type. Subranges require run-time range checking.

7.3.2.2 Evaluation Subrange Types improve Readability by making it clear that Variables of Subtypes can only store a certain range of values. Reliability is increased with Subrange Types because assigning a value to a subrange variable outside its range is detected as an error.

7.3.3 Implementation of User-Defined Ordinal Types

Enumeration Types are usually implemented on integers. However, without restrictions on ranges of values and possible operations, this does **not** improve Reliability.

Subrange Types are implemented the same way as their parent types, except range checks are implicitly included by the compiler in every assignment of a variable or expression to a subrange variable.

7.4 List Types

Lists were first supported in LISP.

Defn 99 (List). A *list* is a data structure heavily used in Functional Programming Languages. They are similar to arrays in other languages, but they may lazily evaluated and may be infinite.

Remark 99.1. Lists, because of their (potentially, depends on the language) inherently infinite nature, have always been part of Functional Programming Languages, but are making their way to Imperative Programming Languages too.

Remark. Karl Hallsby went a little ham on this section because he uses Emacs and writes ELisp to customize it. He is also *really* interested in Functional Programming Languages.

Lists in Scheme, LISP, and Common LISP are written as such:

```
1 (A B C D) ; List of 4 elements
2 (A (B C) D) ; List of 3 elements, with the middle being a 2 element nested list
```

In LISP and its descendants, data and code have the same syntactic form, meaning this could be interpreted as a function call to A with B and C being parameters; or as a list of 3 elements.

```
1 (A B C)
```

Lists in Scheme, LISP, and Common LISP can be considered linked-lists with immutable nodes. This means there are operations to get the current node's data and to get the next nodes in the rest of the list.

```
1 ; The ' in front of a list means to interpret the list as data and not a function call
2 (CAR '(A B C)) ; Returns the element A
3 (CDR '(A B C)) ; Returns the list (B C)
```

There are 2 ways these lists can be constructed:

1. CONS takes 2 parameters and returns a list with the first parameter as the first element and the second parameter as the remainder of the list.

```
1 (CONS 'A '(B C)) ; Returns (A B C)
```

2. LIST takes any number of parameters and returns a new list with the parameters as the new list's elements

```
1 (LIST 'A 'B '(C D)) ; Returns (A B (C D))
```

The empty list () is also denoted as **nil**. **nil** also serves as the **false** value of the language, and everything else is **true**.

Defn 100 (List Comprehension). A *list comprehension* is an idea from set notation and set theory. Essentially, a list comprehension applies a function to every element in a given Array/List, and a new Array/List is constructed from the results.

2 examples of this are shown below, the first in Haskell, the second in Python 3.

```
1 [n * n | n <- [1..10]]
```

```
1 [x * x for x in range(1, 11, 1)]
```

7.5 Arrays

Defn 101 (Array). An *array* is **TODO**.

7.6 Associative Arrays

Defn 102 (Associative Array). An *associative array* is an unordered collection of data elements that are indexed by an equal number of values, called *keys*. The user-defined keys must be stored in the structure, along with the values to be stored.

To store the keys, they must be *hashed*. This is done with a hash function.

Remark 102.1 (Alternative Names). There are many alternative names for Associative Arrays.

- Hashtable
- Hashmap
- Associative Array
- Dictionary

Remark 102.2 (Improving Capabilities). What the associative array/dictionary/hashtable are allowed to store depends on the language. In Python and Ruby, objects and Primitive Data Types can be stored. In PHP, integers or strings can be keys. In Ruby, any object can be a key.

7.6.1 Structure and Operations

The code examples here are done in Perl, but it is similar in most other languages. For more specific code, you will have to visit the language's documentation.

```
1 # Defining an associative array
2 %salaries = ("Gary" => 75000, "Perry" => 57000, "Mary" => 55750);
3
4 # Switch from % for hash to £ for single values in the hash
5 # That should be a dollar sign, not a Stirling Pound symbol
6
7 # Changing a value in the associative array
8 $salaries{"Perry"} = 58850;
9
10 # Removing a key-value pair from the associative array
11 delete $salaries{"Gary"};
```

The size of a Perl Associative Array is dynamic and will grow and shrink as needed.

Associative Arrays are very useful if there is a lot of searching that needs to be done, because the hashing of the key, then the search term allows for $O(1)$ lookup speeds for an element located anywhere in the Associative Array.

7.6.2 Implementing Associative Arrays

The implementation for an Associative Array differs between languages. However, in all languages, eventually the Associative Array can get “full”. This is when the collision chance of 2 hashes modulo the length of the structure gets too high. This means that if an element is already stored, and something new were hashed and modulo-d the length of the structure, there is a very high probability that the new element would “collide” with the old one.

To handle this, Associative Arrays are grown. Every key-value pair will need to have their key recalculated. This is a slightly time-costly operation, $O(n)$, but the spatial-cost is much higher, because there are 2 potentially very large arrays in memory at the same time.

7.7 Record Types

Defn 103 (Record). A *record* is an aggregate of data elements in which the individual elements are identified by names and accessed through offsets from the beginning of the structure, similar to arrays. The offset from the head of the record to reach any Field is known statically, because the sizes and Types are known at compile time.

Records are used to model a collection of data in which the individual elements, the Fields are not of the same Type or size.

Remark 103.1 (Clarification). An important clarification here is that the Record, defined in Definition 103 is **NOT** a record in a database **in any way**.

Remark 103.2. A Record is similar to a heterogeneous array, but they differ in one key way. A heterogeneous array is an array of pointers to areas of Memory that may be discontinuous. However, all the Fields in a Record all reside in adjacent Memory locations.

Remark 103.3 (Record vs. Object). A Record and an object are quite similar. However, the differences between them depend on the language.

Defn 104 (Field). A *field* is an element a Record. These are fixed length, with fixed Type, meaning the Memory address can be statically calculated to reach any Field in the Record.

Fields are referenced by their identifier, rather than an index.

7.7.1 Definitions of Records

There are 2 design questions that need to be asked when defining Records.

1. What is the syntactic form of references to Fields?
2. Are elliptical references allowed?

Below are 2 blocks of code, the first from COBOL, the second from Ada. Both describe an employee.

```
1 01 EMPLOYEE-RECORD.  
2   02 EMPLOYEE-NAME.  
3       05 FIRST      PICTURE IS X(20).  
4       05 MIDDLE     PICTURE IS X(20).  
5       05 LAST       PICTURE IS X(20).  
6   02 HOURLY-RATE    PICTURE IS 99V99.
```

The numbers 01, 02, and 05 are *level numbers*, which indicate relative hierarchical values. Any line that is followed by a line with a higher-level number is itself a record. **PICTURE** clauses show the formats of the storage locations. **X(20)** is a 20 character alphanumeric string and **99V99** is a 4 decimal digit number with the decimal in the middle.

However, Ada does not have the level numbers like COBOL, so they allow for nesting Record structures inside Record declarations.

```
1 type Employee_Name_Type is record  
2     First : String (1..20);  
3     Middle : String (1..20);  
4     Last : String (1..20);  
5 end record;  
6 type Employee_Record_Type is record   Employee_Name: Employee_Name_Type;  
7     Hourly_Rate: Float;  
8 end record;  
9 Employee_Record: Employee_Record_Type;
```

In Java and C#, Records can be defined as data classes, whilst nested Records defined as nested classes. Lua's tables serve this purpose.

7.7.2 References to Record Fields

There are many ways to refer to individual Fields. We will look at the way COBOL referenced Fields, and the Dot Notation.

Defn 105 (Dot Notation). Most programming languages use *dot notation* for Field references, where components necessary to reach the Field are connected with periods. The outermost Record goes on the left, and gets more specific as it grows to the right.

There are 2 examples below of accessing the middle name of the Employee Records we made in the previous section.

```
1 MIDDLE OF EMPLOYEE-NAME OF EMPLOYEE-RECORD
```

```
1 Employee_Record.Employee_Name.Middle;
```

There are 2 ways to make a reference to a Record Field.

1. Fully Qualified References
2. Elliptical References

Defn 106 (Fully Qualified Reference). A *fully qualified reference* to a record field is one in which to access a Field, the programmer **MUST** specify all intermediate Records to go through.

An alternative to fully qualified reference is the Elliptical Reference.

Defn 107 (Elliptical Reference). An *elliptical reference* allows a programmer to specify the Field and omit any to all parent Records; so long as the resulting reference is unambiguous in the referencing environment (the Scope).

These are a programmer convenience, but are **incredibly** difficult to compile, because of the elaborate data structures and procedures required to correctly identify the referenced field. There is also a slight loss of Readability.

7.7.3 Evaluation of Record Types

Records are valuable to programming and programming languages. Their design is straightforward and use is safe.

Records and Arrays are quite similar, but differ in some key ways

- Arrays:
 - All data values have the same Type. This allows for easy subscripting of Memory addresses
- Record
 - When the collection of data values is heterogeneous
 - The different data Fields are not processed the same way
 - The Fields are not processed in any particular order
 - Fields are like named subscripts
 - Since Field names are static, they provide efficient access to fields.

7.7.4 Implementation of Record Types

The Fields of Records are stored in adjacent Memory locations. But because each Field may be of a different size, the offset address, relative to the beginning of the Record is associated with each field. These are calculated at compile-time. This way, there are no runtime calculations that need to be done.

7.8 Tuple Types

Defn 108 (Tuple). A *tuple* is a Type that is similar to a Record, except the elements are **not** named.

Remark 108.1. Tuples can be used to return multiple values from a function in languages that do not natively support that.

Remark 108.2. Python natively supports these. These behave similarly to Lists, but are immutable.

```
1 myTuple = (3, 5.8, 'apple')
```

7.9 Union Types

Defn 109 (Union). A *union* is a Data Type whose Variables may store different Type Values at different times during program execution.

The union will allocate the maximum space required by all the Types of the union, and only use the parts it needs, based on what Types are actually in use.

7.9.1 Design Issues

- Should Type Checking be required?
 - This Type Checking will have to be dynamic, running during program execution.
- Should Unions be embedded in Record?

7.9.2 Discriminated vs. Free Unions

The `union` construct in C/C++ is used to specify Union structures. These are called Free Unions. These stand in stark contrast to Discriminated Unions.

Defn 110 (Free Union). A *free union* is a Union that have **NO** Type Checking enforced on their use. For example, this C snippet:

```
1 union flexType {
2     int intEl;
3     float floatEl;
4 };
5 union flexType el1;
6 float x;
7 ...
8 el1.intEl = 27;
9 x = el1.floatEl; // NOT type checked, because current type of el1 cannot be determined
```

The last assignment is not type checked, because the the current Type of `el1` cannot be checked. So, 27 is assigned to the float variable `x`, which is nonsense.

Defn 111 (Discriminated Union). A *discriminated union* makes use of a *tag* or *discriminant* as a Data Type indicator. These allow for the Type Checking of Unions during runtime.

7.9.3 Ada Union Types

Ada allows the use to specify variables for a variant Record that will only store one of the possible Type values in the variant.

Defn 112 (Constrained Variant Variable). A *constrained variant variable* is when a language allows the programmer to specify the types present in a variant Data Type, allowing for static Type Checking. These enforce that variants can only be changed by assigning the entire record at a time.

This is shown in the code snippet below.

```
1 type Shape is (Circle, Triangle, Rectangle); -- Construct enumeration for types of shapes possible
2 type Colors is (Red, Green, Blue); -- Construct enumeration for colors
3 type Figure (Form : Shape) is record -- Figure has variant Form records of type Shape (from enumeration)
4     Filled : Boolean;
5     Color : Colors;
6     case Form is
7         when Circle =>
8             Diameter : Float;
9         when Triangle =>
10            Left_Side : Integer;
11            Right_Side : Integer;
12            Angle : Float;
13         when Rectangle =>
14            Side_1 : Integer;
15            Side_2 : Integer;
16     end case
17 end record;
18 ...
19 Figure_1 : Figure; -- Unconstrained variant record of the record type Figure, and has no initial values
20 Figure_2 : Figure(Form => Triangle); -- Constrain the variant record to a Triangle
21 -- Figure_1's type can be changed by the assignment of a whole record
22 Figure_1 := (Filled => True,
23             Color => Blue,
24             Form => Rectangle,
25             Side_1 => 12,
26             Side_2 => 3);
```

7.9.4 Evaluation

Unions are potentially unsafe constructs in some languages, because they cannot be type checked. C and C++ are not strongly typed for this reason. However, Ada, ML, Haskell, and F# are strongly typed, because they can perform Type Checking on Unions. Some languages, like Java and C# do not even include the ability to construct a Union.

7.9.5 Implementation of Union Types

Unions are implemented by using the same address for a single Union, no matter its variant. Enough storage is allocated for the largest possible variant. Then, depending on the variant, the space will be used according to how the Union was defined. The tag of the Union variant is stored in its Descriptor.

7.10 Type Equivalence

This section does not deal with Type Compatibility, which works for scalar Data Types, but rather Type Equivalence.

Defn 113 (Type Compatibility). *Type compatibility* dictates the Data Type of operands that are acceptable for each of the operations of the language. This is called compatibility because there are cases when the Data Type of the operand can be implicitly converted by the compiler or run-time system to make the operand acceptable to the operator.

An example of this is the addition of an integer number and a real number. The integer number is typecast to a real number, then the addition is performed.

Type Compatibility rules are strict for predefined scalar types. However, structured Data Types such as Arrays, Record, and others require more complex rules. Since Data Type coercion is unlikely, the question is if the 2 Data Types are equivalent.

Defn 114 (Type Equivalence). *Type equivalence* is a strict form of Type Compatibility. It is when an operand of one Data Type can be substituted for another operand of the same type, without Data Type coercion.

The design of type equivalence rules influence the design of Data Types and operations provided for values of those types.

There are 2 approaches to determining Type Equivalence:

1. Name Type Equivalence
2. Structure Type Equivalence

There is a general algorithm for determining if two Data Types are equivalent. "... when all constant expressions are replaced by their values and all type names are replaced by their definitions. In the case of recursive types, the expansion is the infinite limit of the partial expansions ...". Meaning you replace everything you can, and if there is an infinite recursion somewhere, you cut it off eventually, usually when you pass the same point again.

There are 4 types of equivalence that can be established.

1. Primitive Equivalence
2. Structure Type Equivalence
3. Reference Equivalence
4. User-Defined Equivalence

Different languages use different approaches and combinations of these types of Type Equivalence. You would have to look at the language's specification to find out exactly what is used where. Additionally, object-oriented languages present their own, unique, type of Type Compatibility with object compatibility and its relationship to the inheritance hierarchy.

Defn 115 (Name Type Equivalence). *Name type equivalence* means that 2 Variables have Type Equivalence if they are defined in:

- The same declaration
- In Declarations that use the same Data Type name

This is easier to implement, but more restrictive. In a strict interpretation, a Variable whose Type is a subrange of the integers would **not** be equivalent to an integer Type Variable. For example,

```
1  type Indextype is 1..100;
2  count : Integer;
3  index : Indextype;
```

count and index could **not** be substituted for each other.

Remark 115.1. To use Name Type Equivalence, all Types must have names. If the language supports anonymous Data Types, then they must be given internal names by the compiler/interpreter.

Defn 116 (Primitive Equivalence). *Primitive equivalence* directly compares two values by comparing their bit patterns in memory.

Defn 117 (Structure Type Equivalence). *Structure type equivalence* means 2 Variables have Type Equivalence if their types have identical structures. The entire structure's Types must be compared to determine equivalence. This may potentially involve recursing through the structure or iterating over the structure. However, this is more flexible than Name Type Equivalence, but more difficult to implement.

Ada, with its hyper-strict Type Equivalence has defined 2 ways to make new types.

1. Derived Type
2. Subtype

Defn 118 (Reference Equivalence). *Reference Equivalence* checks whether two pointers/references point to the same address in Memory.

Defn 119 (User-Defined Equivalence). *User-defined equivalence* performs arbitrary equality checking but isn't provided by the language itself, and must be specified by the programmer.

Defn 120 (Derived Type). A *derived type* is a new Data Type that is based on some previously defined Data Type, that **is not equivalent, but may have an identical structure**. Derived types inherit all the properties of their parent types.

Take the following Ada code snippet as an example.

```
1 type Celsius is new Float;  
2 type Fahrenheit is new Float;
```

These are not equivalent, though they have identical structures. They are also not type equivalent to any other Float type.

Defn 121 (Subtype). A *subtype* is a possibly range-constrained version of an existing type. A subtype **is equivalent with its parent type**.

Take the following Ada code snippet as an example.

```
1 subtype Small_type is Integer range 0..99;
```

The Small_type is equivalent to the Integer type.

8 Expressions

Defn 122 (Expression). An *expression* is a combination of one or more Operands and operators that the programming language interprets (according to its particular rules of precedence and of association) and computes to produce another value.

Remark 122.1 (Overloading). An expression can be overloaded if there is more than one definition for an operator. These operators can be statically overloaded by defining multiple semantic rules with their operation being defined for each of the types τ that can be used in the rule.

Defn 123 (Operand). An *operand* is a:

- Constant
- Variable
- Another Expression
- Result from function calls

Defn 124 (Well-Typed). An Expression is *well-typed* if and only if we can show $e : \tau$ for some type τ .

8.1 Arithmetic Expressions

One of the main goals of high-level languages was to have automatic evaluation of Expressions similar to those in math, science, and engineering. Most of these characteristics came from mathematics directly.

8.1.1 Arity

Defn 125 (Arity). *Arity* is the number of Operands that must be present to evaluate that Expression. In most programming languages, there are 3:

1. Unary
2. Binary
3. Ternary

Defn 126 (Unary). A *unary* operation requires a single Operand. For example, negation, $-x$

Defn 127 (Binary). A *binary* operation requires 2 Operands. For example, addition, $y + z$

Remark 127.1. These are usually use Infix notation.

Defn 128 (Ternary). A *ternary* operation requires 3 Operands. For example, $w = \text{if } x ? y : z$.

Remark 128.1. As far as I know, the only ternary operator is a single-line if statement.

8.1.2 Fixity

Defn 129 (Fixity). *Fixity* is the position of an operation relative to an Operand. There are 3 possible positions:

1. Prefix
2. Infix
3. Suffix

Defn 130 (Prefix). *Prefix* notation has the operators before the Operands that it operates on. For example:

- $-x$
- $+ x y$

Defn 131 (Infix). *Infix* notation has the operators between the Operands that it operates on. This necessitates that the expression uses at least 2 Operands, making this a potential Binary operator. For example:

- $x+y$

Defn 132 (Suffix). *Postfix* or *suffix* notation has the operator after the Operands that it operates on. For example:

- $x!$
- $x y +$

8.1.3 Operator Evaluation Order

8.1.3.1 Precedence

Defn 133 (Operator Precedence Rules). *Operator precedence rules* partially define the order in which operators of different precedence levels are evaluated. This is based on the hierarchy or operator priorities, as defined by the language designer.

Remark 133.1. Operator Associativity Rules also define the order in which operators are evaluated in an Expression.

There may be unary addition, called the *identity operator*, because it usually no associated operation. Unary “subtraction” changes the sign of the operand, negating it.

	Ruby	C-Based Languages
Highest	**	postfix ++, --
	Unary +, -	Prefix ++, --, Unary +, -
	*, /, %	*, /, %
Lowest	Binary +, -	Binary +, -

Table 8.1: Precedence of Arithmetic Operators

8.1.3.2 Associativity

Defn 134 (Operator Associativity Rules). *Operator associativity rules* partially define the order in which operators of **the same** precedence levels are evaluated. There can be:

- Left associativity: When evaluating an expression, parentheses that determine the order of evaluation are accumulated to the left, meaning the left-hand side is evaluated first.
- Right associativity: When evaluating an expression, parentheses that determine the order of evaluation are accumulated to the right, meaning the right-hand side is evaluated first.
- Nonassociativity: When evaluating an expression, parentheses that determine the order of evaluation are unknown and must be **explicitly** specified.

Remark 134.1. There are very few operators that are right-associative. As far as I know, only the exponentiation operator that can be right associative.

Language	Associativity Rule
Ruby	Left: *, /, +, - Right: **
C-Based languages	Left: *, /, %, Binary +, Binary - Right: ++, --, Unary +, Unary -
Ada	Left: All except ** Right: None Nonassociative: **

Table 8.2: Associativity of Arithmetic Operators

Remark. **This section only applies to integer arithmetic operators.** Floating-point arithmetic is different because of the way numbers are represented and their finite precision.

8.1.3.3 Parentheses Parentheses can alter the Operator Precedence Rules and Operator Associativity Rules. A parenthesized part of an expression has precedence over its adjacent unparenthesized parts.

For example, the addition will be done first here

$$(A + B) * C$$

8.1.3.4 Ruby Expressions Everything (literally everything, including literals) is an object in Ruby. Ruby supports the arithmetic and logic operations that are included in C-based languages, but they are slightly different. For example, the expression `a + b` is a call to the `+` method of the `a` object, and passes a reference to the `b` object as a parameter to the `+` method. This means that the operator can be overloaded by the programmer, which is useful for user-defined Data Types.

8.1.3.5 LISP Expressions LISP is similar to Ruby in that arithmetic and logic operations are computed by subprograms. However, in LISP and its descendants, the subprograms (operators) **must** be called explicitly. For example, to write $A + B * C$ in LISP¹.

```
1 (+ A (* B C)) ; Computes A + B * C
```

8.1.3.6 Conditional Expressions Conditional expressions can be used as an expression with the Ternary variant. For example,

```
1 if (count == 0) {  
2   average = 0;  
3 } else {  
4   average = sum / count;  
5 }
```

is equivalent to

```
1 average = (count == 0) ? 0 : sum / count;
```

¹When a LISP list is interpreted as code, the first element is the function name, and the rest are passed parameters.

8.1.4 Operand Evaluation Order

How do we determine and what steps must be taken to get the value of the Operand used in the current Expression?

8.1.4.1 Side Effects

Defn 135 (Side Effect). A *side effect* of a function is when the function changes either one of its parameters or a Global Variable.

Defn 136 (Pure). A function can be called *pure* when the function **does not** change its parameters or a Global Variable.

Remark 136.1. These are used in both mathematics and Functional Programming Languages.

Remark 136.2. This is **incredibly** important for multi-core/multi-thread processing, where the order that the data is accessed and potentially written to can change the program's state. This means that 2 threads could be using the same information with 2 different contexts, which is problematic.

If a function has Side Effects, then the order in which the Operands are evaluated may affect the operation.

There are 2 possible solutions to this:

1. Language designer can disallow functional Side Effects, essentially making all functions used in an Expression Pure.
 - However, implementing this is difficult in Imperative Programming Languages
 - Eliminates some flexibility for the programmer
 - Access to Global Variables would have to be disallowed, which the compiler may want to do to improve speed.
2. Language definition could state that Operands in Expressions are to be evaluated in a particular order and demand implementors guarantee that order.
 - Some code optimization techniques that reorder the Operand evaluations could no longer be used.

8.1.4.2 Referential Transparency and Side Effects

Defn 137 (Referential Transparency). A program has *referential transparency* if any 2 Expressions in the program that have the same value can be substituted for another, without affecting the action of the program.

Remark 137.1. A function/program that has Referential Transparency should also be a Pure program/function.

Remark 137.2. In a Functional Programming Language **ALL** functions/programs have Referential Transparency, by definition.

There are several advantages:

- Semantics of referentially transparent programs are easier to understand.
- A programmed function is equivalent to a mathematical function in that it is Pure.

8.2 Data Type Conversions

Defn 138 (Data Type Conversion). A *Data Type conversion* is the act of converting one Data Type from one to another. There are 2 effects of this:

1. Narrowing Conversion
2. Widening Conversion

Conversions can be:

- Implicit
- Explicit

Defn 139 (Narrowing Conversion). A *narrowing conversion* converts a Value of one Data Type to another that cannot store approximations of all the Values in the original Data Type. For example, converting a **double** to a **float** in Java.

Remark 139.1 (Safety). Narrowing Conversions are not always safe. The magnitude of the converted value may be changed in during the process of conversion.

For example, in Java, converting the **double** 1.3E25 to an **int** will result in a very different number.

Defn 140 (Widening Conversion). A *widening conversion* converts a Value of one Data Type to another that **can store approximations of ALL** the Values in the original Data Type. For example, converting an **int** to a **float** in Java.

Remark 140.1 (Safety). Widening Conversions are almost always safe, because the magnitude of the original value is maintained. However, sometimes they result in reduced accuracy. For example, converting an **int** to a **float** will drastically increase the range of potential values, but may decrease precision.

8.2.1 Coercion in Expressions

Operators that allow operands in an operation to have different Data Types are called Mixed-Mode Operations.

Defn 141 (Mixed-Mode Operation). *Mixed-mode operations* are operations that allow the operands to have different Data Types. However, there must be an implicit Data Type Conversion present, because computers can only handle single-type operations.

Remark 141.1 (Relation to Overloaded Operations). We will handle operations as if there are distinct operations for every Data Type input. However, if the language has overloaded operators and uses Static Type Checking, then the compiler/interpreter chooses the correct operation. If the operands are of different Data Types and the operation is legal, then the compiler/interpreter must choose one to be coerced, supply the code for the coercion, then perform the operation.

The advantages and disadvantages of this implicit Data Type Conversion are:

- Advantages
 - Much greater flexibility in operators/operands and operations.
- Disadvantages
 - Reliability problems may arise

The real question is whether the compiler/interpreter should handle these issues, or if the programmer should.

In languages that support `byte` and `short`, or their equivalents, and operations are performed on them, they undergo implicit Widening Conversion to `ints`.

8.2.2 Explicit Data Type Conversion

Most languages have facilities to explicitly perform a Data Type Conversion, both widening and narrowing. Sometimes warnings are presented to the programmer.

In C-based languages, an explicit Data Type Conversion is called a *type cast*. The specific syntax of these casts depends on the language. Refer to the language specification to find the exact details for explicit Data Type Conversions.

8.2.3 Errors in Expressions

Any number of errors can occur during an expression's evaluation.

- If the language requires type checking, type errors can occur
- Limitations of computer arithmetic (Limited bit representation)
 - *Overflow*: If the result was too large. In a signed integer system, the first bit is reserved as a sign bit, and if addition flips this first bit, the number becomes a large negative number.
 - *Underflow*: If the result was too small. In a signed integer system, the first bit is reserved as a sign bit, and if this bit is flipped, the number becomes a large positive number.
- Limitations of arithmetic
 - Cannot divide by zero

Overflow, underflow, division by zero, and some other errors are run-time errors, which are sometimes called *exceptions*.

8.3 Relational and Boolean Expressions

8.3.1 Relational Expressions

Defn 142 (Relational Operator). A *relational operator* is an operator that compares the values of its two Operands. These are **ALWAYS** Binary operators.

Defn 143 (Relational Expression). A *relational expression* has 2 Operands and a Relational Operator. The value of a relational expression is Boolean, except when a language does not have a Boolean Data Type. **These expressions have a lower precedence than arithmetic expressions.**

This operation determines truth or falsehood.

Relational Expressions can be very simple (integers) or very complex (strings). The usual list of Relational Operators is shown below

1. `==`, Equal to
2. `!=`, Not Equal to

- C-based languages use !=
- Ada uses /=
- Lua uses ≐
- Fortran 95+ uses .NE.² or <>
- ML and F# use <>

3. >=, Greater than or Equal to
4. <=, Less than or Equal to
5. >, Greater than
6. <, Less than

There is also a special case for equality relational operators

- ==, Equals to, after Data Type coercion
- ===, Equals to, without Data Type coercion
- eql?, Equals to, without Data Type coercion, for Ruby

8.3.2 Boolean Expressions

Defn 144 (Boolean Expression). A *boolean expression* consists of Boolean variables, constants, Relational Expressions, and Boolean operators. The most common Boolean operators are:

- AND
- OR
- NOT, Logical complement
- XOR, exclusive OR

Boolean operators **only** take Boolean operands. Now that we have added 2 more types of expressions onto our precedence list, we need to fill in the rest.

Highest	Postfix ++, --
	Unary +, -, Prefix ++, --
	*, /, %
	Binary +, -
	<, >, <=, >=
	==, ===, !=
	&&
Lowest	

Table 8.3: Precedence Table with All Expression Types

Programming languages should implement a Boolean Data Type for truth-based comparisons. However, versions of C before C99 did not have a Boolean type, forcing programmers to use 0 to represent **false** and anything else being **true**.

8.4 Short-Circuit Evaluation

Defn 145 (Short-Circuit Evaluation). A *short-circuit evaluation* of an Expression happens when a result is determined without evaluating all the Operands in the Expression.

This is **mostly** used for Boolean Expressions. The 2 possible Short-Circuit Evaluations are for AND and OR. They are based off the operator's truth tables, shown in Tables 8.4 to 8.5.

	0	1
0	0	0
1	0	1

Table 8.4: AND Truth Table

The 2 possible Short-Circuit Evaluations are:

1. If the first Operand in an AND Boolean Expression is **false**, then it short-circuit evaluates to false.

²This is because the punchcards used when Fortran was first developed did not have the > or < symbols.

	0	1
0	0	1
1	1	1

Table 8.5: OR Truth Table

2. If the first Operand in an OR Boolean Expression is **true**, then it short-circuit evaluates to true.

Short-Circuit Evaluation has some side effects:

- The second Operand is **never** evaluated, and if its a function, there might be Side Effects, or a lack of them.

Some languages specify special version of the Boolean operators to explicitly handle Short-Circuit Evaluation separately. Most simply choose to only support Short-Circuit Evaluation, and make sure the programmer keeps it in mind while working.

9 Assignment Statements

Assignments are one of the central constructs in Imperative Programming Languages. Assignments allow programmers to dynamically change the bindings of Bindings to Variables.

9.1 Simple Assignments

Nearly all languages use the = symbol as the assignment operator. In these languages, the use of == as the equivalence Relational Operator is common.

2 notable exceptions to this assignment symbol are:

1. ALGOL 60, with :=
2. Ada, with :=

They chose this set of symbols so as to be able to use the = as the equivalence Relational Operator. The destination of the Value has varied widely in many languages. Additionally, the appearance of an assignment as a stand-alone statement is also dependent on language.

9.2 Conditional Targets

Some languages allow for assignments to take place in conditional Blocks. These assignments bind the Value to a *conditional target*.

In Perl for example,

```
1 ($flag ? $count1 : $count2) = 0;
```

which is equivalent to

```
1 if ($flag) {
2     $count1 = 0;
3 } else {
4     $count2 = 0;
5 }
```

9.3 Compound Assignment Operators

Defn 146 (Compound Assignment Operator). A *compound assignment operator* is a shorthand method of specifying a commonly needed form of assignment. The overwriting of a Variable's Value with some new value that is dependent on the Variable's previous Value.

For example:

```
1 sum += value;
2 # This is equivalent to
3 sum = sum + value;
```

Remark 146.1 (Supported Operators). If a language supports an addition Compound Assignment Operator, then it is likely that it supports it for all the other binary arithmetic operations. They are likely to be denoted `-=`, `*=`, `/=`, and `%=` for subtraction, multiplication, division, and modulo, respectively.

9.4 Unary Assignment Operators

Many C-based languages support 2 special unary arithmetic operators, that are abbreviated assignment statements. These are:

1. Increment by 1, usually written `++`
 - This is equivalent to `i = i + 1`, where `i` is a defined, in-scope, alive integer Variable
2. Decrement by 1, usually written `--`
 - This is equivalent to `i = i - 1`, where `i` is a defined, in-scope, alive integer Variable

Both of these can be Prefix and Suffix operators. The different fixities mean different things.

- Prefix, `sum = ++count`
 - First increment `count`
 - Then assign the result to `sum`
- Suffix, `sum = count++`
 - First assign the value of `count` to `sum`
 - Increment the value stored in `count` by 1
 - Note, the value in `sum` will be the value that was in `count` **BEFORE** the increment occurred.

Remark (Multiple Unary Operators Associativity). When there are multiple unary operators on a single Variable at a single time, they are **RIHT-TO-LEFT ASSOCIATIVE**. Thus,

```
1 - count ++
2 # is handled like
3 - (count++)
4 # rather than
5 (- count) ++
```

9.5 Assignment as an Expression

In C-based languages, the assignment statement also produces a result that is the same as the value assigned. This means that the assignment statement can be treated as an Expression, and an Operand as well, and used as such. For example, this is a valid while-loop in C.

```
1 while ((ch = getchar()) != EOF) { ... }
```

This statement gets a character from the standard input, which is usually the keyboard. If the letter input to the program is **not** the End-Of-File character, then the statement(s) in the while-loop's body execute. The character was **ALSO** assigned to the character Variable, `ch`.

9.5.1 Side Effects

Allowing this action in programs means that Expressions can be more difficult to read and understand. Instead of thinking of these kinds of Expressions as Expressions, they must be thought of as a list of instructions with a strange order of execution. For example,

```
1 a = b + (c = d / b) - 1;
2 // This gets translated to
3 c = d / b;
4 a = b + c - 1;
```

In C programs, this is a big cause of problems. Because both `if (x = y)` and `if (x == y)` are valid, but the second is performing a Relational Operator, while the first is performing an assignment. Java and C# have avoided this problem by **only** allowing boolean expressions in their `if` statements.

10 Statement-Level Control Structures

10.1 Iterative Statements

Defn 147 (Iterative Statement). An *iterative statement* is one that causes a statement or collection of statements to be executed zero or more times. These are frequently called *loops*.

There are 2 questions that need to be answered to design iterative statements.

1. How is the iteration controlled?
2. Where should the control mechanism appear in the loop statement, i.e. when is it executed in relation to the code in the statement body?

Remark 147.1 (Iteration Statement). An *iteration statement* is the combination of the Body and the control mechanism.

Counter-Controlled Loops and Counter-Controlled Loops, and a combination of the 2, are the main ways to control an Iterative Statement. The 2 main choices of when to execute the control mechanism of the loop are:

1. At the beginning of the loop, before the body. Pretest
2. At the end of the loop, after the body. Posttest

Defn 148 (Body). The *body* of an Iterative Statement is the collection of statements whose execution is controlled by the iteration statement.

Defn 149 (Pretest). A *pretest* Iterative Statement means the test for loop completion, the control mechanism, is evaluated before the loop Body executes.

Defn 150 (Posttest). A *posttest* Iterative Statement means the test for loop completion, the control mechanism, is evaluated after the loop Body executes.

10.1.1 Counter-Controlled Loops

Defn 151 (Counter Iteration Statement). A *counter iteration statement* has:

- A *loop variable*, where the count value is maintained
- The *loop parameters*. These include
 - A means of specifying the *initial* and *terminal* values of the loop variable
 - The *step size*, the difference between sequential loop variable values

Logically Controlled Loops are more **general** than Counter-Controlled Loops, they are not necessarily more commonly used. The greater complexity of Counter-Controlled Loops means that their design is more demanding.

Remark (Machine Instructions). Sometimes there are machine-level instructions for performing Counter-Controlled Loops. However, these are rare, because a language can outlive a processor's ISA.

10.1.1.1 Design Issues

- What are the Data Type, and Scope of the loop variable?
- Should it be legal for the loop variable or loop parameters to be changed in the loop, and if so, does it affect the loop control?
- Should the loop parameters be evaluated only once, or once for each iteration?

10.1.1.2 The for Statement of Ada

The Ada for statement can be generalized to

```
1 for variable in [reverse] discrete_range loop
2     -- Body statements
3 end loop;
```

- The `discrete_range` is a Subrange Type of an integer or Enumeration Type, such as `1..10` or `Monday..Friday`.
- The `reverse` Reserved Word indicates the values of the `discrete_range` are assigned in reverse order.
- The `variable` is only in scope of the loop
 - It is implicitly declared at the beginning of the `for` statement
 - and implicitly undeclared after loop termination
 - It also shadows/masks variables with the same name as it

- The body cannot assign the loop variable a new value

The operational semantics are given below.

```
[define for_var (its type is that of the discrete range)]
[evaluate discrete range]
loop:
  if [there are no elements left in the discrete range] goto out
  for_var = [next element of discrete range]
  [loop body]
  goto loop
out:
  [undefine for_var]
```

10.1.1.3 The for Statement of the C-Based Languages

The C for statement can be generalized to

```
1 for (expression_1; expression_2; expression_3) {
2     // Body statements
3 }
```

- **expression_1** is usually an assignment statement to create the loop variable, which can produce results
 - This is only evaluated once, before the loop begins
 - In early versions of C, these could **not** be definitions (`int count = 0;`)
- **expression_2** is the loop control, it makes comparisons against the loop variable
 - This is evaluated before every iteration of the loop body
- **expression_3** manipulates the loop variable
 - This is evaluated after every iteration of the loop body
- All 3 of these expressions are optional.
 - Having no **expression_2** means the comparison is always true, which may result in an infinite loop
 - If **expression_1** is absent, no loop variable is initialized, but that doesn't stop other Variables declared elsewhere from being part of the control.

Because C expressions can be used as statements, expression evaluations are shown as statements in this operational semantics.

```
expression_1
loop:
  if expression_2 = 0 goto out
  [loop body]
  expression_3
  goto loop
out:
  ...
```

C's design choices for its for loop are as follows:

- No explicit loop variables or loop parameters
- All involved variables can be changed in the loop body
- Expressions are evaluated in the order shown before.
 - There can even be multiple expressions present in each of the **expressions**.
- You can branch into a C for loop body

10.1.1.4 The for Statement of Python

The Python for statement can be generalized to

```
1 for loop_variable in object:
2     # Body statements
3 [else:
4     # Else clause]
```

- The **loop_variable** is assigned the one of the values in the object, which is often a range, for each iteration.
- The **else** clause is executed if the loop terminates **normally**

10.1.2 Logically Controlled Loops

Collections of statements must be executed repeatedly, but should be controlled by a Boolean expression rather than a counter. Logically controlled loops are convenient for this. They are also more general than Counter-Controlled Loops.

10.1.2.1 Design Issues

- Should the control be Pretest or Posttest?
- Should the logically controlled loop be a special form of a counting loop or a separate statement?

10.1.2.2 Examples C-based programming languages have both Pretest and Posttest Logically Controlled Loops. These loops have these respective forms:

```
1 while (control_expression) {  
2     // Loop body  
3 }
```

```
1 do  
2     // Loop body  
3 while (control_expression);
```

The Pretest (**while**) executes as long as the `control_expression` evaluates to true. The Posttest (**do-while**) executes as long as the `control_expression` evaluates to true. However, the **do-while** loop will cause the loop body to be executed at least once.

The operational semantics are given below, with the **while** coming first, then the **do-while**.

```
loop:  
    if control-expression is false go to outlive  
    [loop body]  
    goto loop  
out:  
    ...
```

```
loop:  
    [loop body]  
    if control_expression is true goto loop
```

In C, it is possible to branch into these statement's bodies. Java's **while** and **do-while** statements are similar, but they require the `control_expression` be boolean type.

10.1.3 Iteration Based on Data Structures

A general data-based iteration statement uses a user-defined data structure and user-defined iteration to go through the elements in the structure. An example of this is in Python, shown below

```
1 for count in range(0, 9, 2)  
2     # Body
```

This would set the value of `count` to 0, 2, 4, 6, 8 before each iteration.

The user-defined iterator function must be history sensitive. It should also terminate when it fails to find more elements.

User-defined Iteration Statements are more commonly used and more important in object-oriented programming, because of the heavy use of abstract data types for data structures. In Java, this is done by having a class implement the **Iterable** interface. It is called the **foreach** loop, and is written as

```
1 for (String myElement : myList) {  
2     ...  
3 }
```

11 Subprograms

This is a way to perform Process Abstraction. This generally improves Readability and Reliability.

11.1 General Characteristics

- Each subprogram has a single entry point
- The calling program unit is suspended during the execution of the called subprogram, which implies there is only one subprogram in execution at any given time
- Control always returns to the caller when the subprogram terminates

Alternatives to these generalizations result in coroutines and concurrent units.

11.2 Basic Definitions

Defn 152 (Subprogram Definition). A *subprogram definition* describes the interface to and the actions of the subprogram abstraction

Defn 153 (Subprogram Call). A *subprogram call* is the explicit request that a specific subprogram be executed.

Remark 153.1 (Call). This is generally shortened to just a *call*.

Defn 154 (Active). A subprogram is said to be *active* if it has been called, but not yet completed its execution.

Defn 155 (Subprogram Header). A *subprogram header* is the first part of a Subprogram Definition. This serves several purposes:

1. Specifies that the following syntactic unit is a Subprogram Definition of some kind.
2. Provides a name for the subprogram, if it's not an anonymous subprogram.
3. Optionally specify a list of parameters.

Defn 156 (Subprogram Body). The *subprogram body* defines the actions that the subprogram takes when there is a Subprogram Call. The body may be delimited with curly-braces, { and }. It may be whitespace delimited, Python. It may also have an **end** statement that ends the execution of that block.

Python is unique in that its Subprogram Definitions can be executed in control-statement blocks. For example,

```
1 if conditional_expression :
2     def func(...):
3         ...
4 else:
5     def func(...):
6         ...
```

This means that there are 2 possible Subprogram Definitions possible during runtime, and which one is currently valid depends on the result of the `conditional_expression`.

Defn 157 (Parameter Profile). The *parameter profile* of a subprogram contains the number, order, and types of its Formal Parameters.

Defn 158 (Protocol). The *protocol* of a subprogram is its Parameter Profile, and if its a function, its return type.

Defn 159 (Subprogram Declaration). A *subprogram declaration* is the act of providing type and name information, but not giving any Subprogram Body. This is needed in languages that do not allow forward references to subprograms.

Remark 159.1 (Prototype). In C/C++, if a subprogram needs to be declared, it is called a *prototype*. These are generally specified in *header* files, with a file extension of `.h`.

11.3 Parameters

Subprograms typically want access to nonlocal data to perform their computations. There are 2 ways to gain access to this nonlocal data:

1. Direct access to nonlocal Variables (Global Variables)
2. Parameter passing

Data that is passed to the subprogram as a parameter is accessed through names local to the subprogram. Parameter passing is more flexible, because if direct access is used, new storage needs to be allocated for computation results. Direct access also leads to issues with Variables being visible to places they shouldn't be. Pure Functional Programming Languages avoid this by having all their data being immutable.

Defn 160 (Formal Parameter). A *formal parameter* are the parameters present in the Subprogram Header. These are sometimes thought of as “dummy variables” because they aren't normal Variables. They are only bound to storage when the subprogram is called, and that storage is often through some other program Variables.

Remark 160.1 (Parameter). Sometimes Formal Parameters are just called *parameters*, usually when Actual Parameters are called Arguments.

Defn 161 (Actual Parameter). An *actual parameter* is the parameter that is bound to the Formal Parameter of a subprogram.

Remark 161.1 (Argument). Sometimes Actual Parameters are called *arguments*, usually when Formal Parameters are called Parameters.

The binding of Actual Parameters to Formal Parameters is usually done by position. So, the first Actual Parameter is bound to the first Formal Parameter. However, this is only a good method when the number of parameters is small.

When the Formal Parameter list gets long, it is hard to get all of the Actual Parameters in the right order. One solution is to use Keyword Parameters.

Defn 162 (Keyword Parameter). *Keyword parameters* have the name of the Formal Parameter usable by the Actual Parameter to bind the Value.

For example, if `sumer` has the Formal Parameters `length`, `list`, and `sum`:

```
1 sumer(length = my_length, list = my_array, sum = my_sum)
```

Advantages and Disadvantages of keyword parameters:

- Advantages
 - No need to remember Formal Parameter order.
- Disadvantages
 - Need to remember the name of the Formal Parameters.

Remark 162.1 (End of Actual Parameter). In an Actual Parameter list, all parameters after a Keyword Parameter **must** be keyworded, because the list may not be well-formed enough for parameters to line up by position.

Languages that support default values on Formal Parameters handle them differently. In Python, regular Formal Parameters and ones with default values can be in any order. However, in C++, which does not support Keyword Parameters, Formal Parameters with default values must be at the end of the Subprogram Header. This is illustrated in the next 2 code blocks, which are in Python and C++, respectively.

```
1 def compute_pay(income, exemptions = 1, tax_rate)
```

```
1 float compute_pay(float income, float tax_rate, int exemptions = 1)
```

Other languages have more varied and interesting ways to pass Actual Parameters to subprograms. Look at the language specification for more details.

11.4 Local Referencing Environments

Issues related to Variables defined within subprograms.

11.4.1 Local Variables

The definition of Local Variables is given in Definition 69. These can be either Static Variable or Stack-Dynamic Variable.

If Local Variables are Stack-Dynamic Variable, they are bound to storage when the subprogram begins and unbound when that execution terminates. The advantages and disadvantages of Stack-Dynamic Variable are:

- Advantages

- Allows for recursive subprograms
- Inactive subprograms can share Memory with the active subprogram
- Disadvantages
 - The cost of the time required to allocate, initialize, and deallocate these variables
 - The indirect Memory accesses to the data
 - When all Variables are Stack-Dynamic Variable, subprograms cannot be history sensitive.

However, the advantages and disadvantages of Static Variable are:

- Advantages
 - No runtime overhead to allocate/deallocate the storage
 - Direct Memory access (Absolute addressing)
- Disadvantages
 - Inability to support recursion
 - Cannot share Memory with inactive subprograms.

Most contemporary programming languages make their Local Variables Stack-Dynamic Variable by default. However, this can usually be overridden with a `static` keyword.

11.4.2 Nested Subprograms

The idea was to create a hierarchy of logic and Scopes. The motivation was that if a subprogram is only used within one other subprogram, why not place it there, and hide it from the rest of the program?

Static Scoping is usually used in languages that allow nested subprograms. Language support of this feature depends **heavily** on the language. You will have to check the language specification to find out if the programming language supports them.

11.5 Parameter-Passing Methods

How are Actual Parameters passed to the subprograms?

11.5.1 Semantic Models of Parameter Passing

Formal Parameters are characterized by 1 of 3 distinct Semantics models:

1. They can receive data from the corresponding Actual Parameter. This is called **In Mode**.
2. They can transmit data to the Actual Parameter. This is called **Out Mode**.
3. They can do both 1 and 2. This is called **Inout Mode**.

Defn 163 (In Mode). Formal Parameters can receive data from the corresponding Actual Parameter. This is called *in mode*. This is generally used when passing Actual Parameters to a subprogram.

Defn 164 (Out Mode). Formal Parameters can transmit data to the corresponding Actual Parameters. This is called *out mode*.

This is generally used when returning a value from a subprogram.

Defn 165 (Inout Mode). The Formal Parameters can both transmit and receive data from the corresponding Actual Parameters. This is called *inout mode*.

This is generally used when a Subprogram Call takes in Actual Parameters and returns a value.

There are 2 conceptual models of how data transfers take place in parameter transmission:

1. An actual value is copied (to the caller, to the callee, or both).
2. Or an access path is transmitted. This is usually a pointer/reference.

11.5.2 Implementation Models of Parameter Passing

11.5.2.1 Pass-by-Value

11.5.2.2 Pass-by-Result

11.5.2.3 Pass-by-Value-Result

11.5.2.4 Pass-by-Reference

11.5.2.5 Pass-by-Name

11.5.2.6 Pass-by-Need

A Computer Components

A.1 Central Processing Unit

Defn A.1.1 (Central Processing Unit). The *Central Processing Unit*, *CPU*, is a chip that performs all actions in the computer. It calculates mathematical and logical values and acts based on them. It has several components built onto it, and can be thought of as the “brain” of the computer.

The design of a CPU determines some of the functionality it has. Therefore, more specialized processors can be made for special tasks, and more general processors can be built to handle a wide variety of calculations.

A.1.1 Registers

Defn A.1.2 (Register). A *register* is a data storage mechanism built directly onto the Central Processing Unit. It is several hundred times faster than the system Memory. Registers are generally used when the currently running program is performing calculations. Since they are so fast, they are used as both source and destination operands in instructions.

Remark A.1.2.1. Depending on the Central Processing Unit architecture, there may be cases when Registers behave slightly differently between processors. This is something that can only be found by checking the Central Processing Unit manufacturer’s documentation.

A.1.2 Program Counter

A.1.3 Arithmetic Logic Unit

A.1.4 Cache

A.2 Memory

Defn A.2.1 (Memory). *Memory*, or *RAM* (*Random Access Memory*), is a Volatile data storage mechanism. It is directly connected to the Central Processing Unit. This is the location that the Central Processing Unit writes to when it cannot or should not store something in the Central Processing Unit’s Registers.

Remark A.2.1.1 (Volatility). Memory is volatile because each of the cells is a small capacitor. In between the clock cycles on the Central Processing Unit and Memory, the capacitors discharge. On the clock cycle, the capacitors are refreshed with electrical power, which does one of 2 things:

1. Keep the data bits the same, 1 to 1.
2. Update the data bits from 0 to 1.

Defn A.2.2 (Volatile). If a data storage mechanism is called *volatile*, it means that once the storage mechanism loses power, the data is lost. This is in contrast to Non-Volatile data storage mechanisms.

A.2.1 Stack

Defn A.2.3 (Call Stack). The *call stack* is an imaginary construct that resembles the traditional stack data structure. It is a way to visualize and organize the way memory is used during the execution of a program and its function/methods. It is filled with Stack Frames. This **does not** hold the code that is used in the function, rather it is everything that is needed for the function to be able to run.

Defn A.2.4 (Stack Frame). A *stack frame*, *activation frame*, or *activation record* are objects that represent necessary portions of a function. These include:

- A Dynamic Link
- Local Variables
- Temporary Variables
- Static Links
- Function Arguments
- Return Address

Additionally, there are 2 registers used as pointers to move around and interact with the stack frame.

1. FP is in register `%rbp`. It is the Frame Pointer.
2. SP is in register `%rsp`. It is the Stack Pointer.

Defn A.2.5 (Dynamic Link). The *dynamic link* or *dynlink* is a memory address pointer and sits at the bottom of a Stack Frame. It is a pointer back to the previous function's dynamic link. This ensures that any function can find its parent/calling function.

The dynamic link also serves as a means to access any variable that might be needed by this function. To access any variable in *this* function, you can subtract a byte multiple that you need to access the proper value. To access any variable in the calling function, you can add a byte multiple that would correspond to the proper variable.

In the x86_64 architecture, instruction set, and convention that we used, the register `%rbp` was the dynamic link.

Remark A.2.5.1. Note: Due to the conventions we used, when accessing arguments passed to the function, we treated them as local variables, just further down in the call stack. This also means that we need to skip over the Return Address block in memory.

Remark A.2.5.2. Because we used the `%rbp` register to store our current Dynamic Link's address, the dynamic link might also be called the *base pointer*.

Defn A.2.6 (Local Variable). *Local variables* are handled very simply. They get an appropriate amount of memory allocated to them on the stack, and that is it.

There is no way to give a variable a name in assembly. (Usually. Depends on the architecture and instruction set). However, there is no way to name something in memory. But, because the size of all the objects is known at compile-time, allocating the proper amount of memory required by each variable is possible.

Remark A.2.6.1. This holds true for strongly-typed, static, compiled languages, like Java, C, C++, etc. However, Python is slightly different in this regard, and handles it differently.

Defn A.2.7 (Temporary Variable). A *temporary variable* is one that is allocated on this function's Stack Frame while calculating values. Once the calculations are completed, these values are deallocated. These temporary variables can also point to objects on the Heap. When the function has finished running, then these values are deallocated, along with all other Local Variables in use.

For example, since assembly-level addition only allows for 2 operands, but in general, addition can have more than 2 operands in use, there needs to be a way to store the value used in the addition. While we can accumulate and use that value in the addition, the values being added together are *not* modified.

Defn A.2.8 (Static Link). The *static link* is an implicit argument, meaning it **ALWAYS** gets pushed onto the stack as a Function Argument, when appropriate.

Appropriate in this context could mean several things:

- When an object is alive, and when it is being acted on by a function.
 - In this case, the static link points to an instance of a class on the Heap.
- When a language allows for nested function declarations.
 - Then the static link points to the Dynamic Link of the outer function
 - This allows access to the outer function's Local Variables like normal, and allows us to go back later.

Defn A.2.9 (Function Argument). *Function arguments* are handled very simply. If a function call takes an argument, then the argument is calculated, and then that argument is pushed onto the stack in *this* Stack Frame.

Remark A.2.9.1. If more than one argument is passed to a function, there are 2 ways to push values onto the Stack Frame:

1. In the order they are passed to the function
 - Say a function with 3 arguments is called, then the stack would have arguments in this order
 - (a) argument0 (Lowest memory address)
 - (b) argument1
 - (c) argument2 (Highest memory address)
2. In reverse order
 - Say the same function is called with the same 3 arguments, then the stack would have arguments in this order
 - (a) argument2 (Lowest memory address)
 - (b) argument1
 - (c) argument0 (Highest memory address)

When the values that were passed need to be accessed, and if the memory sizes of things are known at compile time, then we can calculate how far down we need to go in the stack to find the value. This is done by adding a positive value to the `%rbp`

Defn A.2.10 (Return Address). The *return address* is used by the `%rip` register. It is calculated and pushed onto the Stack Frame stack when the `CALL` macro is used. It is the thing that allows us to jump around in the code from the `text` area of our program.

Remark A.2.10.1. The `%rip` register is the *register instruction pointer*. It holds the value of the *next* instruction to execute. Technically, it is the Program Counter's value.

Defn A.2.11 (Garbage Collection). *Garbage collection* is the act of deallocating objects that may still be on the heap and organizing the heap. Since the heap allocates continuous “blocks” of memory required by an object, the heap may have the necessary memory to allocate an object, but in discontinuous locations.

Defn A.2.12 (Frame Pointer). The *frame pointer* is a pointer that **ALWAYS** points to the current function's Dynamic Link. The frame pointer is commonly abbreviated as *FP*. This is the thing that allows us to access Local Variables, Function Arguments, and everything else inside of the Stack Frame. The value is held in the `%rbp` register.

Defn A.2.13 (Stack Pointer). The *stack pointer* is a pointer that **ALWAYS** points to the top of the current Stack Frame. The stack pointer is commonly abbreviated as *SP*. This value is held in the `%rsp` register. This is the pointer that allows us to push and pop onto this function's Stack Frame.

Defn A.2.14 (Class Descriptor). The *class descriptor* is a portion of memory set aside for the methods that are in an object.

A.2.2 Heap

Defn A.2.15 (Heap). The *heap* is a memory organization construct that helps visualize the way memory is used during the execution of a program. It is **SIGNIFICANTLY** larger than the Call Stack.

In an object-oriented language, this is where instances of classes exist. These objects are allocated on a first-come first-serve basis. When the object is allocated, the amount of memory that the object requires is allocated ***in a continuous block***. The problem is that if the heap has been extensively used, then there might be enough total memory required to allocate an object, but because it is not in a continuous block, the object cannot be allocated.

This makes deallocation more complex, because when they are deallocated, the program might still view the memory as in-use. Additionally, because of the continuous block allocation nature of the heap, it must be organized every once in a while. This is called Garbage Collection.

Remark A.2.15.1. In an object-oriented language, like Java, when objects are stored on the heap, **ONLY** their class fields are stored there. The class methods are stored elsewhere, in the Class Descriptor.

A.3 Disk

Defn A.3.1 (Non-Volatile). If a data storage mechanism is called *non-volatile*, it means that once the storage device loses power, the data is still safely stored. This is in contrast to Volatile data storage mechanisms.

A.4 Fetch-Execute Cycle

B History of Programming Languages

- B.1 Zuse's Plankalkül
- B.2 Pseudocodes
- B.3 Fortran
- B.4 Functional Programming: LISP
- B.5 ALGOL 60
- B.6 COBOL
- B.7 Timesharing: BASIC
- B.8 PL/I
- B.9 Early Dynamic Languages: APL and SNOBOL
- B.10 Data Abstraction: SIMULA 67
- B.11 Orthogonality: ALGOL 68
- B.12 ALGOL Descendants
- B.13 Logical Programming: Prolog
- B.14 Ada
- B.15 Object-Oriented Programming: Smalltalk
- B.16 Combine Imperative and OOP Features: C++
- B.17 Java
- B.18 Scripting Languages
- B.19 Flagship .NET Language: C#
- B.20 Markup/Programming Hybrid Languages

C Trigonometry

C.1 Trigonometric Formulas

$$\sin(\alpha) + \sin(\beta) = 2 \sin\left(\frac{\alpha + \beta}{2}\right) \cos\left(\frac{\alpha - \beta}{2}\right) \quad (\text{C.1})$$

$$\cos(\theta) \sin(\theta) = \frac{1}{2} \sin(2\theta) \quad (\text{C.2})$$

C.2 Euler Equivalents of Trigonometric Functions

$$e^{\pm j\alpha} = \cos(\alpha) \pm j \sin(\alpha) \quad (\text{C.3})$$

$$\cos(x) = \frac{e^{jx} + e^{-jx}}{2} \quad (\text{C.4})$$

$$\sin(x) = \frac{e^{jx} - e^{-jx}}{2j} \quad (\text{C.5})$$

$$\sinh(x) = \frac{e^x - e^{-x}}{2} \quad (\text{C.6})$$

$$\cosh(x) = \frac{e^x + e^{-x}}{2} \quad (\text{C.7})$$

C.3 Angle Sum and Difference Identities

$$\sin(\alpha \pm \beta) = \sin(\alpha) \cos(\beta) \pm \cos(\alpha) \sin(\beta) \quad (\text{C.8})$$

$$\cos(\alpha \pm \beta) = \cos(\alpha) \cos(\beta) \mp \sin(\alpha) \sin(\beta) \quad (\text{C.9})$$

C.4 Double-Angle Formulae

$$\sin(2\alpha) = 2 \sin(\alpha) \cos(\alpha) \quad (\text{C.10})$$

$$\cos(2\alpha) = \cos^2(\alpha) - \sin^2(\alpha) \quad (\text{C.11})$$

C.5 Half-Angle Formulae

$$\sin\left(\frac{\alpha}{2}\right) = \sqrt{\frac{1 - \cos(\alpha)}{2}} \quad (\text{C.12})$$

$$\cos\left(\frac{\alpha}{2}\right) = \sqrt{\frac{1 + \cos(\alpha)}{2}} \quad (\text{C.13})$$

C.6 Exponent Reduction Formulae

$$\sin^2(\alpha) = \frac{1 - \cos(2\alpha)}{2} \quad (\text{C.14})$$

$$\cos^2(\alpha) = \frac{1 + \cos(2\alpha)}{2} \quad (\text{C.15})$$

C.7 Product-to-Sum Identities

$$2 \cos(\alpha) \cos(\beta) = \cos(\alpha - \beta) + \cos(\alpha + \beta) \quad (\text{C.16})$$

$$2 \sin(\alpha) \sin(\beta) = \cos(\alpha - \beta) - \cos(\alpha + \beta) \quad (\text{C.17})$$

$$2 \sin(\alpha) \cos(\beta) = \sin(\alpha + \beta) + \sin(\alpha - \beta) \quad (\text{C.18})$$

$$2 \cos(\alpha) \sin(\beta) = \sin(\alpha + \beta) - \sin(\alpha - \beta) \quad (\text{C.19})$$

C.8 Sum-to-Product Identities

$$\sin(\alpha) \pm \sin(\beta) = 2 \sin\left(\frac{\alpha \pm \beta}{2}\right) \cos\left(\frac{\alpha \mp \beta}{2}\right) \quad (\text{C.20})$$

$$\cos(\alpha) + \cos(\beta) = 2 \cos\left(\frac{\alpha + \beta}{2}\right) \cos\left(\frac{\alpha - \beta}{2}\right) \quad (\text{C.21})$$

$$\cos(\alpha) - \cos(\beta) = -2 \sin\left(\frac{\alpha + \beta}{2}\right) \sin\left(\frac{\alpha - \beta}{2}\right) \quad (\text{C.22})$$

C.9 Pythagorean Theorem for Trig

$$\cos^2(\alpha) + \sin^2(\alpha) = 1^2 \quad (\text{C.23})$$

C.10 Rectangular to Polar

$$a + jb = \sqrt{a^2 + b^2} e^{j\theta} = r e^{j\theta} \quad (\text{C.24})$$

$$\theta = \begin{cases} \arctan\left(\frac{b}{a}\right) & a > 0 \\ \pi - \arctan\left(\frac{b}{a}\right) & a < 0 \end{cases} \quad (\text{C.25})$$

C.11 Polar to Rectangular

$$r e^{j\theta} = r \cos(\theta) + j r \sin(\theta) \quad (\text{C.26})$$

D Calculus

D.1 Fundamental Theorems of Calculus

Defn D.1.1 (First Fundamental Theorem of Calculus). The *first fundamental theorem of calculus* states that, if f is continuous on the closed interval $[a, b]$ and F is the indefinite integral of f on $[a, b]$, then

$$\int_a^b f(x) dx = F(b) - F(a) \quad (\text{D.1})$$

Defn D.1.2 (Second Fundamental Theorem of Calculus). The *second fundamental theorem of calculus* holds for f a continuous function on an open interval I and a any point in I , and states that if F is defined by

$$F(x) = \int_a^x f(t) dt,$$

then

$$\begin{aligned} \frac{d}{dx} \int_a^x f(t) dt &= f(x) \\ F'(x) &= f(x) \end{aligned} \quad (\text{D.2})$$

Defn D.1.3 (argmax). The arguments to the *argmax* function are to be maximized by using their derivatives. You must take the derivative of the function, find critical points, then determine if that critical point is a global maxima. This is denoted as

$$\operatorname{argmax}_x$$

D.2 Rules of Calculus

D.2.1 Chain Rule

Defn D.2.1 (Chain Rule). The *chain rule* is a way to differentiate a function that has 2 functions multiplied together.

If

$$f(x) = g(x) \cdot h(x)$$

then,

$$\begin{aligned} f'(x) &= g'(x) \cdot h(x) + g(x) \cdot h'(x) \\ \frac{df(x)}{dx} &= \frac{dg(x)}{dx} \cdot h(x) + g(x) \cdot \frac{dh(x)}{dx} \end{aligned} \quad (\text{D.3})$$

E Complex Numbers

Complex numbers are numbers that have both a real part and an imaginary part.

$$z = a \pm bi \quad (\text{E.1})$$

where

$$i = \sqrt{-1} \quad (\text{E.2})$$

Remark (i vs. j for Imaginary Numbers). Complex numbers are generally denoted with either i or j . Since this is an appendix section, I will denote complex numbers with i , to make it more general. However, electrical engineering regularly makes use of j as the imaginary value. This is because alternating current i is already taken, so j is used as the imaginary value instead.

$$Ae^{-ix} = A [\cos(x) + i \sin(x)] \quad (\text{E.3})$$

E.1 Complex Conjugates

If we have a complex number as shown below,

$$z = a \pm bi$$

then, the conjugate is denoted and calculated as shown below.

$$\bar{z} = a \mp bi \quad (\text{E.4})$$

Defn E.1.1 (Complex Conjugate). The conjugate of a complex number is called its *complex conjugate*. The complex conjugate of a complex number is the number with an equal real part and an imaginary part equal in magnitude but opposite in sign.

The complex conjugate can also be denoted with an asterisk (*). This is generally done for complex functions, rather than single variables.

$$z^* = \bar{z} \quad (\text{E.5})$$

E.1.1 Complex Conjugates of Exponentials

$$\overline{e^z} = e^{\bar{z}} \quad (\text{E.6})$$

$$\overline{\log(z)} = \log(\bar{z}) \quad (\text{E.7})$$

E.1.2 Complex Conjugates of Sinusoids

Since sinusoids can be represented by complex exponentials, as shown in Appendix C.2, we could calculate their complex conjugate.

$$\begin{aligned} \overline{\cos(x)} &= \cos(x) \\ &= \frac{1}{2} (e^{ix} + e^{-ix}) \end{aligned} \quad (\text{E.8})$$

$$\begin{aligned} \overline{\sin(x)} &= \sin(x) \\ &= \frac{1}{2i} (e^{ix} - e^{-ix}) \end{aligned} \quad (\text{E.9})$$

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- [Seb12] Robert W. Sebesta. *Concepts of Programming Languages*. 10th ed. Pearson Education Inc., 2012.