Review of the C Programming Language

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Reference Manual for the Language

- Required textbook
  - C: A Reference Manual, Fifth Edition by Harbison & Steele

- Has all details of the language
- This is a necessary reference to be able to implement a compiler for the language

Concepts of Language Design and Usage

- This presentation contains many concepts of computer language design and usage
- These concepts are very important in understanding computer languages and also how compilers work
- Feeling at ease with many of these concepts is important to be able to successfully implement a compiler
- This presentation basically follows C89, but may contain some language features that are not present in C89
- Not all C89 language features described in this presentation are part of the language accepted by our class project

Language: Lexical Elements (§2)

- Character Set
- Comments
- Tokens
  - Operators and Separators
  - Identifiers
  - Keywords
  - Constants

Language: Operators

- Operators perform operations
  - For example, the “=” (simple assignment) operator stores the value obtained by evaluating the right-hand-side operand into the location designated by the left-hand-side operand
- Operators produce results
  - For example, the result of the “=” (simple assignment) operator is the value obtained by evaluating the right-hand-side operand after being converted to the type of the left-hand-side operand

- Observation: both unary prefix ++ and unary postfix ++ will increment their operand; the difference is the value of the result of the operator

Unary, Binary, and Ternary Operators

- Operators may take one, two, or three operands

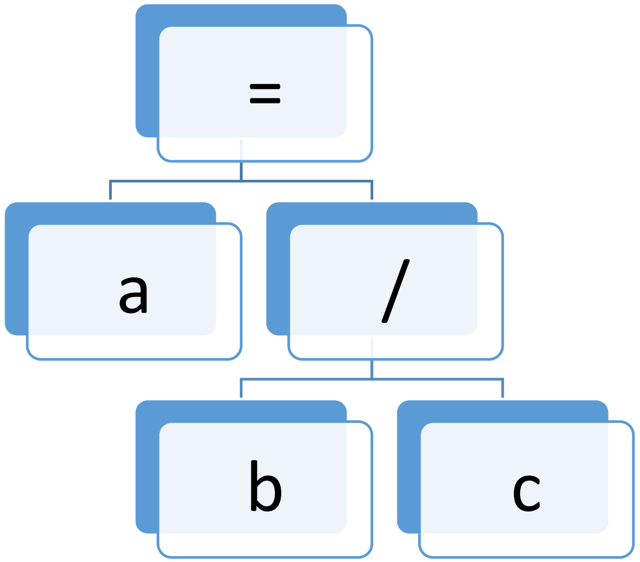
- Unary operators take one operand
- Binary operators take two operands
- The ternary operator takes three operands

Prefix, Infix, and Postfix Operators

- Operators that precede their operand are prefix operators
- Operators that appear between their operands are infix operators
- Operators that follow their operand are postfix operators

Expression Parsing

- Expressions are parsed into a tree-like structure
- For example, the following expression   a = b / c   results in the following tree



Expression Evaluation

- When an expression is evaluated, the top-level operator is executed
- Nested operators are evaluated as determined by the top-level operator in the expression
  - Most operators evaluate all their operands
  - Some operators evaluate some of their operands as determined by other operands
    - Take a look at the "short-circuit" operators: && and ||
    - Also, look at the ternary conditional operator

“As If” Behavior

- The language stipulates how operators, expressions, statements, etc. behave
- The compiler must implement those rules
- However, the compiler is free to ***not*** strictly follow those rules if the program cannot determine whether the rule was followed or not. This is called “as if” behavior because the compiler acts ***as if*** all the rules were followed.
- For example, if a program cannot determine if an expression was evaluated or not (*i.e.,* the evaluation of the expression does not affect the state of the program – that is, the result is not needed and there are no side effects), then the compiler does not need to evaluate that expression

Unary Prefix Operators

- Increment and decrement ++ --
- Size sizeof
  - Yes, sizeof is an operator!
  - When are parentheses needed?
  - What is the value of sizeof array when array is declared as int array[20] and int’s are four bytes in length?
- Bitwise not ~
- Logical not !
- Arithmetic negation and plus - +
- Address of &
- Indirection *
- Casting (*type-name*)
  - Because cast is applied to a single operand, it is defined as a unary operator

Unary Postfix Operators

- Subscripting   a[k]
  - Because of the matching brackets, this is defined as a unary operator
- Function Call   f(…)
  - Because of the matching parentheses, this is defined as a unary operator
- Direct Selection   .
- Indirect Selection   ->
- Increment and decrement   ++ --

Binary Infix Operators

- Multiplicative   * / %
- Additive   + -
- Left and Right Shift   << >>
- Relational   < > <= >=
- Equality/Inequality   == !=
- Bitwise   & ^ |
- Logical   && ||
- Assignment   = += -= *= /= %= <<= >>= &= ^= |=
- Sequential Evaluation   ,

Logical Operands and Results

- Operators that evaluate ***operands*** for logical values accept 0 to signify false or any non-zero value to signify true
  - These operators are !, &&, ||, and the first operand of ? :
- Operators that produce a logical ***result*** always result in either 0 (for false) or 1 (for true)
  - These operators are !, &&, ||, <, >, <=, >=, ==, !=
  - No value other than 0 or 1 will be the result of these operators
  - Following the "as if" rule, if the result of these operators is not used as a numeric value, but is used directly in another way (say, as the condition in an **if** statement), then the true or false result may result in conditional branching but not in a 0 or 1 value

Details of the Binary Infix Logical Operators

- The && and || operators always evaluate their left-hand operand, but only evaluate their right-hand operand when needed to determine the result of the operator; this is sometimes referred to as ***short-circuit*** behavior
- To be clear, these operators are ***not allowed*** to evaluate their right-hand operands when not needed to determine the result of the operator
- That is, the && operator will evaluate its right-hand operand only when its left-hand operand evaluates to true (non-zero)
- The || operator will evaluate its right-hand operand only when its left-hand operand evaluates to false (zero)
- As for all operators, the “as if” rule applies

Ternary Infix Operator

- Conditional operator   ? :

- Example
  - a ? b : c
  - If   a   is true, b is evaluated and returned as the result of the conditional operator
  - If   a   is false, c is evaluated and returned as the result of the conditional operator

- To be clear, this operator is ***not allowed*** to evaluate the operand that is not required in the description above
- As for all operators, the "as if" rule applies

Associativity (§7.2.1)

- Operators of degree greater than one (*i.e.,* with more than one operand) may be either left- or right-associative
- Associativity determines how operators of the same precedence level are grouped when parentheses are *not* present
- In the C Programming Language, all binary operators are left-associative except for the assignment operators (includes both simple and compound assignment operators)
- In the C Programming Language, the ternary operator (the conditional operator) is right-associative

- See Table 7-3 on page 205 in Harbison & Steele

- Of course, it is possible to specify associativity by using parentheses

Associativity Examples

- Left-associativity examples
  - a – b – c   is equivalent to   ((a – b) – c)
- Right-associativity examples
  - a = b = c   is equivalent to   (a = (b = c))
  - a ? b : c ? d : e   is equivalent to   (a ? b : (c ? d : e))

Precedence(§7.2.1)

- Precedence determines how operators of different precedence levels are grouped when parentheses are not present
- For example, because multiplicative operators have higher precedence than additive operators and because they both have higher precedence than assignment operators (and because additive operators are left-associative),
    - a = b + c * d + e
      is evaluated as if fully parenthesized as follows
      (a = ((b + (c * d)) + e))
- See Table 7-3 on page 205 in Harbison & Steele

Overloading (§4.2.4)

- Overloading is the principle that the same symbol (including operators and identifiers) may have more than one meaning
- For example, the – operator is used both as a unary prefix operator and also as a binary infix operator
- Overloading may also be determined by type
  - For example, the – operator is used both for integral subtraction and for floating-point subtraction. These operations are very different even though they have similar mathematical principles that serve as their inspiration
- Overloading may also be determined by context
  - void as a pointer target type means pointer to anything
  - void as the return value in a function declaration means no return value
  - void as the parameter in a function declaration means accepts no parameters
  - void as the sole type in a cast means discard the value of the expression

Order of Evaluation (§7.12)

- The order of evaluation is defined by the precedence and associativity of operators (defined in Table 7-3)
- An implementation of C is allowed to change that order if the reordered evaluation will maintain the same result
  - Must be precisely the same – including values, side-effects, overflow & underflow
- If operands of a single operator are commutative, then the operands can be evaluated in either order
  - As an example, in the expression **`i++ + i`**, the operands are allowed to be evaluated in either order
- Order of evaluation in floating-point expressions is extremely important – do not take this point lightly (also see §22.5)

Order of Evaluation Example Code Fragments

- int i, j; i = 1; j = i++ + i;
  - The resulting value in variable j could be either 2 (from 1 + 1) or 3 (from 1 + 2) depending on whether the subexpression i++ or the subexpression i is evaluated first, respectively
- int i, j; i = 1; j = i + i++;
  - The resulting value in variable j could be either 2 (from 1 + 1) or 3 (from 2 + 1) depending on whether the subexpression i or the subexpression i++ is evaluated first, respectively
- int i, j; i = 1; j = ++i + i;
  - The resulting value in variable j could be either 4 (from 2 + 2) or 3 (from 2 + 1) depending on whether the subexpression ++i or the subexpression i is evaluated first, respectively

Computer Language Operators are Not the Same as Mathematical Operators

- Keep in mind that operators in computer languages are not the same as the similar operator in mathematics
- Several reasons for dissimilarity
  - In mathematics, the number of integral values is infinite – that is, the range of positive and negate integers is unlimited
    - Computers' integers are constrained in range
  - In mathematics, real numbers are used to represent any real value – that is, they have unlimited range and precision (accuracy to any number of decimal places)
    - Computers' floating-point numbers are constrained in both range and precision and, in addition because of their internal representation, computers may not be able exactly represent a real value

Type

- Each constant, identifier, sub-expression, and expression has a type
- A type describes the kind of values that are able to be represented
- Taxonomy of types
  - Scalar types
    - Arithmetic types
      - Integral types: char, short, int, long
      - Floating-point types: float, double, long double
    - Pointer types
  - Aggregate types
    - Array types
    - Structure types
  - Union types
  - Function types
  - Void types
- The language has a means to declare a type – this is a declaration
  - The type description in a declaration is called a declarator
- The language has rules to describe how types are used

Use of Types

- Some operators may accept operands of a limited subset of types
- The function of an operator may be determined by the type(s) of the operands
  - For example, binary addition is very different for integral values and for floating-point values because they have very different internal representations
- The type of the result of an operator may be determined by the type(s) of the operands
- Overall, we call this the “type calculus”

Lvalues vs. Rvalues (part 1 of 2)

- Some expressions can be used to refer to locations in memory
  - Examples
    - a
    - array[i]
    - node.field
  - These are lvalues
- Other expressions represent values
  - Examples (in addition to those above)
    - a * b
    - funct(a, b, c)
  - These are rvalues
  - All lvalues can represent rvalues, but not all rvalues can represent lvalues

- a = 1 + 2;
  - Because of associativity and precedence, this is the same as (a = (1 + 2));
  - The result of the + operator (adding 1 and 2 in this expression) is not an lvalue
    - It cannot be used to refer to the location of an operand, therefore…
    - For example, it cannot appear on the left-hand-side of an assignment operator
    - ~~(1 + 2) = a;~~

Lvalues vs. Rvalues (part 2 of 2)

- The description of each operator in Harbison & Steele includes information as to…
  - Whether each operand must be an lvalue (or if an rvalue is acceptable)
  - Whether the result of the operator may be used as an lvalue (or if it may be used solely in those instances that require an rvalue)

- Examples
  - Assignment operators
    - The lhs (left-hand side) must be a modifiable lvalue
    - The result is never an lvalue
  - Address-of operator
    - The operand must be either a function designator or an lvalue designating an object
    - The result is never an lvalue
  - Indirection operator
    - The operand must be a pointer
    - If the pointer points to an object, then the result is an lvalue referring to the object

Layout of Multidimensional Arrays in Memory

- In C, multidimensional arrays are stored in row-major order (*i.e.,* adjacent elements in memory differ by one in their last subscript)
- Thus, a 2-by-3 array of int (two rows, three columns) declared as

```
int matrix[2][3];
```

- would be laid out in memory as

```
matrix[0][0]
matrix[0][1]
matrix[0][2]
matrix[1][0]
matrix[1][1]
matrix[1][2]
```

Language: Declarations (§4)

- Restriction on Where Declarations Can Appear
- Storage Class and Function Specifiers
  - Storage class: auto, extern, register, static, typedef
- Type Specifiers and Qualifiers
  - Qualifiers: const, volatile, restrict (C99)
- Declarators
- Initializers
- External Names

Scope (§4.2.1)

- Identifiers are declared in nested scopes
- Scopes exist in different levels
  - File scope (Top-level identifiers)
    - From declaration point to the end of the program file
  - Procedure scope (Formal parameters in function definitions)
    - From declaration point to end of the function body
  - Prototype scope (Formal parameters in function prototype declarations)
    - From declaration point to end of the prototype
  - Block scope (Local identifiers)
    - From declaration point in block to end of the block
  - Function scope (Statement labels)
    - Entire function/procedure body
    - Forward reference to a statement label is allowed
  - Source file (Preprocessor macros)
    - From #define through end of source file or until the first #undef that cancels the definition

Order of Declarations and Statements

- In C89, within any block, all declarations must appear before all statements
- As stated in Compound Statements (§8.4), in C99, declarations and statements may be intermixed
  - In previous versions of C, declarations must precede statements
- In our language which is based most-closely on C89, we will **accept for full credit** an implementation in which all declarations precede all statements within a block

Scope Example

```
int global, id;

int main(int argc, char *argv[]) {
 int local, id;
 {
  int nested_local, id;
  …
  if(error_occurred) {
   goto symbol_length_exceeded;
  }
  …
 }
 symbol_length_exceeded:
 exit(EXIT_FAILURE);
}
```

Overloading Classes for Names (§4.2.4)

- Preprocessor macro names
- Statement labels
- Structure, union, and enumeration tags
  - Always follow **struct**, **union**, or **enum**
- Component names ("members")
  - Associated with each structure or union
  - Use always follows either **.** or **->**
- Other names
  - Includes variables, functions, **typedef** names, and enumeration constants

Visibility (§4.2.2)

- A declaration of an identifier is visible if the use of that identifier will be bound to that declaration
- Declarations may be hidden by successive declarations
- Example:

```
int i;
int main(void) {
  int i;
  i = 17;
}
```

Extent (or Lifetime or Storage Duration) (§4.2.7)

- In C, procedures and variables occupy storage (memory) during some or all of the time a program is executing
  - Procedures have code in memory
  - Variables have location(s) in memory where their value(s) are stored
- **Static** storage duration denotes that memory is allocated at or before the program begins execution and remains allocated until program termination
- **Local** storage duration denotes that memory is allocated at entry to a procedure or block and deallocated at exit from that procedure or block
- **Dynamic** storage duration denotes that memory is allocated and freed explicitly by the user under program control (*e.g.,* by using malloc and free)

Static and Local Storage Duration

- Procedures have static storage duration
- Global (top-level) variables have static storage duration
- Some variables in blocks may have static storage duration
  - These are declared with the **static** storage class specifier
- Formal parameters have local storage duration
- Some variables in blocks may have local storage duration
  - Automatic variables have local storage duration
  - These either do not have the **static** storage class specifier or they have the **auto** class specifier

- Notes: when the **static** storage class specifier is applied to a procedure, it means that the function name is not externally visible (*i.e.,* not visible outside the current program file)

Storage Class Specifiers (§4.3)

- auto
- extern
- register
- static
- typedef
- Defaults
  - Top-level declarations default to **extern**
  - Function declarations within blocks default to **extern**
  - Non-function declarations within blocks default to **auto**

Type Qualifiers (§4.4)

- const
  - A const-qualified lvalue cannot be used to modify an object
- volatile
  - An object accessed through a volatile-qualified lvalue can have its value accessed through means not under the compiler’s/run-time’s control
- restrict
  - Let’s the compiler know that the object accessed through a restrict-qualified lvalue does not currently have any aliases through which the object can be accessed in the compiler

Position of Type Qualifiers

- const int i; /* means i is a const int */
  /* i cannot be modified */
  /* a value can be assigned to i by using an initializer */
- const int *p1; /* means p1 is a pointer to a const int */
  /* p1 can be modified, but the int pointed to by p1 cannot be modified */
- int *const p2; /* means p2 is a const pointer to an int */
  /* p2 cannot be modified, but the int pointed to by p2 can be modified */
- const int *const p3; /* means p3 is a const pointer to a const int */
  /* neither p3 nor the int pointed to by p3 can be modified */

Modifiable lvalue(§7.1)

- An lvalue that permits modification to its designated object is referred to as a *modifiable lvalue*
- An lvalue that does not permit modification to the object it designates has
  - array type
  - incomplete type
  - a const-qualified type
  - structure or union type one of whose members (applied recursively to nested structures and unions) has a const-qualified type

Declaration vs. Definition

- A declaration of an identifier determines the type of the identifier
- A definition of an identifier sets aside storage for that identifier
- If a procedure/function is being declared or defined…
  - A declaration determines the number and type of parameters and the type of the return value
    - A procedure/function declaration is also referred to as a **prototype declaration** if the number of parameters and the types of all of the parameters are declared and no function body is specified
  - A definition includes the body (*i.e.,* implementation or code) of the function

Language: Types (§5)

- Integer Types
- Floating-Point Types
- Pointer Types
- Array Types
- Enumerated Types
- Structure Types
- Union Types
- Function Types
- The Void Type
- Typedef Names

- Many of the types listed above were explained in the preceding slide labeled “Type”

Side Effects

- For a function, a side effect is any modification to a program's state that is exhibited other than through the function's return value
  - Includes: input or output operations, modification of global variables, modification of data structures
- For an operator, a side effect is any modification to a program's state that is exhibited other than through the operator's value of the expression
  - Includes: modification of operands (for example, the autoincrement and autodecrement operators modify their operand)

Logical Values

- When used as a logical operand,
  - A true value is represented by any non-zero value
  - A false value is represented by a zero value
- When a logical type is produced as a result of an operator,
  - A true value is one (1)
  - A false value is zero (0)

Language: Expressions (§7)

- Objects, Lvalues, and Designators
- Expressions and Precedence
- Primary Expressions
- Postfix Expressions
- Unary Expressions
- Binary Operator Expressions
- Logical Operator Expressions
- Conditional Expressions
- Assignment Expressions
- Sequential Expressions
- Constant Expressions
    - Can be evaluated at compile-time (rather than run-time)

- See preceding slides beginning with the slide labeled “Language: Operators”

Sequence Points (§4.4.5, 7.12.1)

- All previous side effects must have taken place before reaching a sequence point
- No subsequent side effects may have occurred when reaching a sequence point
- Sequence points exist:
  - At the end of a full expression
    - An initializer
    - An expression statement
    - The expression in a **return** statement
    - The control expressions in a conditional, iterative, or **switch** statement (incl. each expr. in a **for** statement)
  - After the first operand of &&, ||, ?:, or comma operator
  - After evaluation of arguments and function expr. in a function call
  - At the end of a full declarator
- In Standard C, **if a single object is modified *more than once* between sequence points, the result is undefined**

Language: Statements (§8)

- Expression Statements
- Labeled Statements
- Compound Statements
- Conditional Statements
- Iterative Statements
- Switch Statements
- Break and Continue Statements
- Return Statements
- Goto Statements
- Null Statements

Expression Statements (§8.2)

- Treat an expression as a statement
- Discard the result of evaluating the expression

- Expression statements are used when the evaluation of the expression causes one or more desired side effects

Labeled Statements (§8.3)

- A label may be affixed to any statement in order to allow control to be transferred to that statement via a **goto** or **switch** statement.
- There are three kinds of labels:
    - Named labels
    - `case` label (see the Switch Statements (§8.7) slide below)
    - `default` label (see the Switch Statements (§8.7) slide below)

- Example of a *named* label:

```
int main(void) {
  …
  if(erroneous_behavior) {
    goto error_occurred;
  }
  …
error_occurred:
  …
}
```

Compound Statements (§8.4)

- Where a single statement could appear, a brace-enclosed list of statements may be used

- Example:

```
if(expr)
  return;

if(expr2) {
  a = 73;
  b++;
}
```

Conditional Statements (§8.5)

- Allow control flow to be altered based on the value of an expression
- **if**(*expression*)
  statement
- **if**(*expression*)
  statement
  else
  statement

Iterative Statements (§8.6)

- Allow control flow to loop based on the value of an expression
- **while**(*control-expression*)
  statement
- **do**
  statement
  while(*control-expression*);
- **for**(*initial-clause*$_{opt}$; *control-expression*$_{opt}$; *iteration-expression*$_{opt}$)
  statement

Switch Statements (§8.7)

- Allow control flow to follow a multiway branch based on the value of an expression
- **switch**(*integral-expression*)
  switch-statement-body
- Within the *switch-statement-body*, **case** and **default** labels may appear
  - **case** *integral-constant-expression*:
  - **default**:
- **case** and **default** labels are bound to the innermost containing **switch** statement
- Control flow will proceed directly through case and default labels
  - A **break** statement is needed to cause a branch to the end of a **switch** statement

Break and Continue Statements (§8.8)

- Cause control flow to branch to a defined location
  - **break**;
  - **continue**;
- **break** and **continue** can appear within loops
- **break** can appear within a switch statement
- **break** causes control flow to be transferred just past the closest enclosing loop or switch statement (*i.e.,* the *body* of the loop or switch statement)
- **continue** causes control flow to be transferred to the end of the body of the closest enclosing loop (*i.e.,* **while**, **do**, or **for**)
  - From that point, any and all *control-expression* and loop *iteration-expression* are reevaluated

Return Statements (§8.9)

- Cause the current procedure or function to return to the caller
- Returns a value, if specified by the declaration of the function

- **return** *expression*$_{opt}$;

Goto Statements (§8.10)

- Cause control to be transferred to the specified labeled statement
- **goto** *named-label*;

Functions (§9)

- Function Definitions
- Function Prototypes
- Formal Parameter Declarations

Parameter-Passing Conventions

- Call-by-value (C, Ada)
- Call-by-reference (C++)
- Call-by-result (Pascal, Ada)
- Call-by-value-result (Pascal, Ada)
- Call-by-name (largely archaic) (Algol 60)
  - As if by textual substitution into the function body, but avoiding becoming bound to a declaration within that function
  - Reevaluated – often by using a **thunk** – each time the parameter is referenced
- Call-by-need (Haskell, R)
  - Similar to call-by-name, but parameter is evaluated only once and memoized
- Call-by-future (C++11 **std::future** & **std::promise**)
  - Concurrent evaluation which blocks when value is needed

Function Prototype Declarations and Function Definitions

- Parameter names are optional in function prototype declarations (§9.2)
  - It is better style to include the names to document the purpose of the parameters
- Clearly, parameter names are required in function definitions

- Actual function arguments are converted, *as if by assignment*, to the type of the formal parameters (see §9)

Array as a Formal Parameter

- If an array is declared as a ***formal*** parameter, the *leftmost* dimension need not be specified and, if specified, it is ignored (see §4.5.3 & §5.4.3)
  - All other bounds are required for the compiler to properly subscript into the array
- If an array is declared as a ***formal*** parameter, the *top-level* “array of T” is rewritten to have type “pointer to T” (see §9.3) and that array dimension (if it is specified) is ignored

Array as an Actual Argument

- As mentioned above, when a prototype declaration is present, actual arguments are converted to the formal parameter type, *as if by assignment* (§6.3.2), and if possible
- If an array is passed as an actual argument, the top-level “array of T” is converted to have type “pointer to T” using the same rules as for simple assignment (§7.9.1)

Use of Initializers in Array Definitions (§4.6.4)

- The elements of an array (or some of those elements) may be initialized when that array is defined, as in
  - int A[3] = {0, 1, 2};
- This applied to multidimensional arrays as well, as in
  - int A[2][3] = { {0, 1, 2}, {3, 4, 5} };
- If the number of initializers is less than the number of array elements, then the remaining elements are initialized to the default initialization values if the array were static
  - It is an error if too many initializers are specified
- The bounds of an initialized array need not be specified and, if so, the bounds are inferred from the initializer length
  - This includes the use of string literals as initializers for type array of char
  - In this case, an additional element in the array is allocated for the terminating NUL char