

**CS4120/4121/5120/5121—Spring 2020**  
**Xi Language Specification**  
Cornell University  
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In this course you will start by building a compiler for a language called Xi, named after the Greek letter  $\Xi$ . This is an imperative, procedural language, like C. The next generation of the language, coming soon, will have object-oriented features. But at present, developers must make do without them.

## 0 Changes

- 4/24: clarified that the length of an array is not part of its type.

## 1 Overview of features

Xi programs consist of a single source file containing definitions of one or more functions. Execution of a program consists of evaluating a call to the function `main`.

The language has two primitive types: integers (`int`) and booleans (`bool`). The array type `T[]` exists for any type `T`, so `T[][]` represents an array of arrays.

Functions may return a value, but need not. A function that does not return a value is called a procedure. A function may take multiple arguments. Unlike in languages such as C and Java, a function may also return multiple results.

Statement and expression forms should largely be familiar to C programmers.

There is no string type, but the type `int[]` may be used for most of the same purposes. Literal string constants have this type.

## 2 Variables

Variables are declared by following them with a type declaration and an optional initialization expression. There are no holes in scope; a variable may not be declared when another variable of the same name is already in scope. Here are some examples of variable declarations in Xi:

```
x:int = 2;
z:int;
b: bool, i:int = f(x);
s: int[] = "Hello";
```

A variable declaration need not initialize the variable, as the declaration of `z` shows. Use of the value of an uninitialized variable has undefined behavior. Xi compilers are not required to detect the use of uninitialized variables<sup>1</sup>.

Identifiers, including variable names, start with any letter and may continue with any sequence of letters, numbers, underscore character (`_`), or single quote characters (`'`).

As in Java, variables are in scope from the point of declaration till the end of their block. A variable declaration may occur in the middle of the block, as in Java. A variable declaration that is the last statement in its block is in scope nowhere.

The value of a variable can be changed imperatively using an assignment statement, as in the following examples:

---

<sup>1</sup>This would be a nice extension to the language. You are permitted to make backward-compatible extensions.

```
x = x + 1
s = {1, 2, 3}
b = !b
```

### 3 Function declarations

A program contains a sequence of function declarations, including the declaration of the function `main`. All functions in the program are in scope in the bodies of all other functions, even if the use precedes the declaration.

A function declaration starts with the name of the function, followed by its argument(s), its return type(s), and the definition of its code. For example, here is a function to compute the GCD of two integers. The body of the function is a block of statements.

```
1 // Return the greatest common divisor of two integers
2 gcd(a:int, b:int):int {
3   while (a != 0) {
4     if (a < b) b = b - a
5     else a = a - b
6   }
7   return b
8 }
```

The result of the function is returned using the `return` statement. To simplify parsing, a `return` statement must be the last statement in its block.

#### 3.1 Multiple results

Unlike in C or Java, a function may return multiple results. This is indicated in the function declaration by giving a list of return types, separated by commas. The result of the function is a list of expressions, separated by commas. For example, the following function returns a pair of integers.

```
1 // Add two rational numbers p1/q1 and p2/q2, returning
2 // two numbers p3, q3 representing their sum, p3/q3.
3 ratadd(p1:int, q1:int, p2:int, q2:int) : int, int {
4   g:int = gcd(q1,q2)
5   p3:int = p1*(q2/g) + p2*(q1/g)
6   return p3, q1/g*q2
7 }
```

Results from a function that returns multiple values can be used only through a *multiple assignment* in which the left-hand side is a sequence of variable declarations. For example, line 1 in the following code has the effect of assigning 11 to `p` and 15 to `q`:

```
1 p:int, q:int = ratadd(2, 5, 1, 3)
2 _, q':int = ratadd(1, 2, 1, 3)
```

The pseudo-declaration `_` can be used to discard one of the results, as in line 2, which assigns 6 to `q'` but discards the corresponding numerator. This kind of declaration can also be used to explicitly discard the result of a function call that returns a single result.

## 4 Data types

### 4.1 Integers

The type `int` describes integers from  $-2^{63}$  to  $2^{63} - 1$ . They support the usual operations: `+`, `-`, `*`, `/`, and `%`, which all operate modulo  $2^{64}$ . In addition, the “high multiplication” operator `*>>` returns the high 64 bits of the 128-bit product of its operands. This operator is helpful for doing certain kinds of number crunching. Division by zero causes the program to halt with an error. Integers can be compared with the usual Java/C relational operators: `==`, `!=`, `<`, `<=`, `>`, and `>=`.

A literal integer constant is denoted by a sequence of digits. Positive integers start with one of the digits 1–9. A character literal as in Java may be used to denote an integer, so `'a'` is the same as 97. Character literals must be in the Unicode [Basic Multilingual Plane](#), which ranges from `U+0000` to `U+FFFF`, 16 bits.<sup>2</sup>

Xi does not support floating point numbers<sup>3</sup>.

### 4.2 Booleans

The type `bool` has two values, `true` and `false`. The operation `&` is a short-circuit ‘and’ and the operation `|` is short-circuit ‘or’. The unary operation `!` is negation. Booleans can also be compared with `==` and `!=`.

### 4.3 Arrays

An array `T[]` is a fixed-length sequence of mutable cells of type `T`. If `a` is an array and `i` is an integer, then the value of the array index expression `a[i]` is the contents of the array cell at index `i`. To be a valid index, an index `i` must be nonnegative and less than the length of the array. If `i` is not valid, this is caught at run time and the program halts with an error message. The expression `length(e)` gives the length of the array `e`.

Array cells may be assigned to using an array index expression on the left-hand side of an assignment, as at lines 9 and 10 of the following procedure, whose effect is to insertion-sort its input array.

```
1 sort(a: int[]) {
2   i:int = 0
3   n:int = length(a)
4   while i < n {
5     j:int = i
6     while j > 0 {
7       if a[j-1] > a[j] {
8         swap:int = a[j]
9         a[j] = a[j-1]
10        a[j-1] = swap
11      }
12      j = j-1
13    }
14    i = i+1
15  }
16 }
```

An array can be constructed by using an *array initializer*, specifying its elements inside braces. Similar to the array initializer syntax in Java and C, elements of the array initializer are separated by comma, and the final element may be followed by a comma. Thus, `{}` can be used as an array of length zero, and `{2,}` can be used as an array of length 1. An array initializer can be used anywhere that an array is expected.

<sup>2</sup>Characters outside this range are considered Supplementary Unicode characters. They can be accessed in Xi using literal integers, or represented using some other abstraction, [as is done in other programming languages](#).

<sup>3</sup>This is to keep the language simple. Programmers wishing to compute on non-integers must use other numeric representations such as rational numbers or [fixed-point representations](#).

A string literal such as "Hello" may also be used as an array initializer. The following two array definitions are therefore equivalent:

```
a: int[] = { 72, 101, 108, 108, 111 }
a: int[] = "Hello"
```

String literals may not span multiple lines in the source file. Like character literals, each character of a string literal must be in the Unicode [Basic Multilingual Plane](#), which ranges from U+0000 to U+FFFF, 16 bits.

An array of arbitrary length  $n$ , whose cells are not initialized, may be created at the point of declaration by including the length in the declaration of the array. The length is not part of the array's type and it need not be a constant:

```
n: int = gcd(10, 2)
a: int[n]
while n > 0 {
  n = n - 1
  a[n] = n
}
```

Use of uninitialized array cells has undefined results.

Arrays may be compared with `==` and `!=` to determine whether they are aliases for the same array. Different arrays with the same contents are considered unequal.

Arrays are implemented by placing the representations of the values of each of their cells contiguously in memory. They also record their lengths.

The operator `+` may be used to concatenate two arrays whose elements are of the same type. This is particularly handy for arrays of `int` representing strings, e.g.:

```
s: int[] = "Hello" + {13, 10}
```

**Multidimensional arrays** Multidimensional arrays are represented by arrays of arrays, as in Java. So the type `int[][]` is represented as an array of pointers to arrays. A multidimensional array can be initialized by providing some or all dimensions in its variable declaration. Consider the following four declarations:

```
1 a: int[][]
2 b: int[3][4]
3 a = b
4 c: int[3][]
5 c[0] = b[0]; c[1] = b[1]; c[2] = b[2]
6 d: int[][] = {{1, 0}, {0, 1}}
```

Line 1 leaves `a` uninitialized. To be used, `a` must be initialized with a pointer to an array of arrays, as on line 3. Line 2 sets `b` to a pointer to an array of 3 elements, each of which is initialized to point to an uninitialized array of 4 elements. Line 4 makes `c` a pointer to an array of 3 elements, but those elements are not initialized to point to arrays. Line 5 initializes the elements of `c` to share the same underlying arrays as `a` and `b`. Line 6 initializes `d` as a  $2 \times 2$  array representing an identity matrix.

## 5 Precedence

Expressions in Xi have different levels of precedence. The following table gives the associativity of the various operators, in order of decreasing precedence:

Operator	Description	Associativity
	function call, []	left
-, !	integer and logical negation	—
*, *>, /, %	multiplication, high multiplication, division, remainder	left
+, -	addition, subtraction	left
<, <=, >=, >	comparison operators	left
==, !=	equality operators	left
&	logical and	left
	logical or	left

## 6 Statements

The legal statements, also called commands, are the following:

- An assignment to a variable or to an array element. However, the left-hand side of an assignment (and thus the assignment itself) cannot begin with an open parenthesis (()) or an open brace ({}).
- `if` and `while` statements with syntax similar to that in C and Java except that parentheses are not required in the guard expression of each.
- A return statement. In a procedure, this is written just as `return`; in a function with a return type, the value(s) to be returned follow the `return` keyword, separated by commas. Unlike in Java, a return statement may only be used inside a block and must be the last statement in its block.
- A call to a procedure (but not a function).
- A block of statements, surrounded by braces. A block may be empty or may contain a sequence of statements. Each statement in a block may be terminated by a semicolon, but semicolons are entirely optional, even if statements are on the same line. Anywhere a block of statements is expected, a single statement may be used instead, except in a function definition. However, a return statement may not be used in place of a block.
- A variable declaration, with an optional initialization expression. It may declare multiple variables, in which case there must be an initialization expression that is a function call with the appropriate return types.

## 7 Lexical considerations

The language is case-sensitive. An input file is a sequence of Unicode characters, encoded using UTF-8. Therefore ASCII input is always valid.

Comments are indicated by a double slash `//` followed by any sequence of characters until a newline character.

Keywords (`use`, `if`, `while`, `else`, `return`, `length`) may not be used as identifiers. Nor may the names or values of the primitive types (`int`, `bool`, `true`, `false`).

String and character literals should support some reasonable set of character escapes, including at least `\"`, `\\n`, and `\\'`. In addition, an escape of the form `\\xHHHH`, where `HHHH` stands for 1–4 hexadecimal digits (upper or lower case), representing the Unicode character with the corresponding index. For example `\\x0a` is the same as `\\n`.

## 8 Source files and interfaces

The Xi compiler compiles a source file with extension `.xi` to runnable code. It may also read in interface files that describe external code to be used by the program.

Interface files contain a nonempty set of procedure and function declarations without implementations and may contain end-of-line comments. Interface files have the extension `.ixi`. To use the procedures and functions declared in interface file `F.ixi`, a source file includes the top-level declaration `use F`, optionally

terminated by a semicolon. This causes the compiler to look for `F.ixi`. All such “use” declarations must precede all procedure and function definitions.

Multiple “use” declarations are permitted within one source file. The same function or procedure may be declared in multiple `.ixi` files that are read in and may also be defined in the source file, but its signature must match everywhere it appears. Therefore, it is legal to reference an interface more than once in a source file.

In typical usage, a program defined in `F.xi` would contain a statement “use `F`”, causing the compiler to read the interface `F.ixi` and to check its definitions against declarations appearing in the interface. However, an interface is not required; even if there is an interface, procedures and functions need not be declared in that interface.

## 9 Current library interfaces

Interfaces for I/O and corresponding libraries are available, including the following functions from interface file `io`:

```
1 // I/O support
2
3 print(str: int[]) // Print a string to standard output.
4 println(str: int[]) // Print a string to standard output, followed by a newline.
5 readln() : int[] // Read from standard input until a newline.
6 getChar() : int // Read a single character from standard input.
7 // Returns -1 if the end of input has been reached.
8 eof() : bool // Test for end of file on standard input.
```

Using these functions, we can easily write the canonical “Hello, World!” program:

```
use io

main(args: int[][]) {
  println("Hello, World!")
}
```

Some utility functions are found in the interface file `conv`:

```
1 // String conversion functions
2
3 // If "str" contains a sequence of ASCII characters that correctly represent
4 // an integer constant n, return (n, true). Otherwise return (0, false).
5 parseInt(str: int[]): int, bool
6
7 // Return a sequence of ASCII characters representing the
8 // integer n.
9 unparseInt(n: int): int[]
```