Types, Expressions, and Arrays

CS 536: Science of Programming, Fall 2021

A. Why?

• Expressions represent values relative to a state.
• Types describe common properties of sets of values.
• The value of an array is a function value from index values to array values.

B. Outcomes

At the end of this class, you should
• Know what expressions and their values we'll be using in our language
• Know how states are expanded to include values of arrays

C. Types and Expressions

• Let's start looking at programming language we'll be using.
• The datatypes will be pretty simple (no records or function types, for example).
  • Primitive types: int (integers) and bool (boolean). We can add other types like characters, strings, and floating-point numbers, but for what we're doing, integers and Booleans are enough.
  • Composite types: Multi-dimensional arrays of primitive types of values, with integer indexes.
• Expressions are built from
  • Constants: Integers (0, 1, -1, ...) and Boolean constants (T, F).
  • Simple variables of primitive types.
  • Structured variables: We have arrays. (No records or pointers.) For a 1-dimensional array reference, the syntax is the usual b[e] where e is an integer expression. Arrays are zero-origin and fixed-size. (You can look up the size using size(b).) There are some limitations on the use of arrays (see below).
  • Operations
    • On integers: +, -, *, /, min, max, %, =, ≠, <, ≥, ≥, divides
    • On booleans: ¬, ∧, ∨, →, ↔, =, ≠ (note = and ↔ mean the same thing).
    • On arrays: size
  • Conditional expressions: B ? e₁ : e₂ as in C or Java etc., where B is a boolean expression and e₁ and e₂ have the same simple type. (Can't be arrays or functions, e.g.) You can also write a conditional expression as if B then e₁ else e₂ fi.
The two expressions $e_1$ and $e_2$ must have the same type so that the whole conditional has a consistent type. (Sometimes this is called “balancing”.)

We don't have: Assignment expressions, pointers, records, arrays as values. Also, we don't explicitly declare variables; we'll assume we know or can infer their types. (E.g., $x$ must be an integer in $x+2$.) The default datatype for a variable is integer.

Array Limitations:

- We only have arrays of primitive types of values (no arrays of functions, for example). Arrays indexes are zero-origin; $size(b)$ gives the length of an array. The size can be zero. At runtime, an illegal index causes a runtime error.
- We don't have arrays as values, so we can't assign an array to a variable, and we don't have expressions that yield arrays. You can pass an array as a function argument or parameter; e.g., $sort(b)$ might be a function that sorts $b$ in place.
- Multi-dimensional arrays are allowed, but you can't take a slice of an array. E.g., if $b$ has 2 dimensions, you can use $b[1][3]$ as an expression but not just $b[1]$ (since it would yield a 1-dimensional array). To get the length along each dimension, we can use $size1(b)$, $size2(b)$, etc..
- You can use an array in two contexts: $b[i,j]$ etc., and as a function argument or parameter (including a predicate function). We don't have array variables or array assignments or expressions of type array.

Example 1: $(x < 0 ? x+y : x*y) + z$ means “If $x < 0$ evaluates to true, then we evaluate $x+y$ and add the result to $z$, otherwise evaluate $x*y$ and add the result to $z.”$ (Types: $x, y,$ and $z$ must all be integers.)

Example 2: $(x < 0 ? 0 : sqrt(x))$ yields 0 if $i$ is negative, otherwise it yields the square root$^1$ of $x$.

Example 3: $(i < 0 ? b[0] : b[i] >= size(b) ? b[b[size(b)-1]] : b[i])$ yields $b[i]$ if $i$ is in range; if $i$ is negative, it yields $b[0]$; if $i$ is too large, it yields the last element of $b$.

Example 4: $b[i < 0 ? 0 : i >= size(b) ? size(b)-1 : i]$ yields the same value as Example 3, but it does this by calculating the index first.

Example 5: A (conditional) expression can't yield a function, so

- Example 5a: $(x > 1 ? min(t,u) : max(t,u))$ is legal
- Example 5b: $(x > 1 ? min : max)(t,u)$ is illegal

Example 6: We can't have array-valued expressions, so

- Example 6a: $(x ? a[0] : b[0])$ is legal assuming $a$ and $b$ are one-dimensional arrays.
- Example 6b: $(x ? a : b)[0]$ is illegal

Notation: $c$ and $d$ are constants; $e$ and $s$ are general expressions; $B$ and $C$ are boolean expressions, $a$ and $b$ are array names, and $u, v,$ etc. are variables. Greek letters like $\alpha$ and $\beta$ stand for semantic values.

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$^1$ We'll always use an integer version of sqrt that returns the floor of the "real" square root. E.g., $sqrt(5) = 2$. 
Syntactic Values and Semantic Values

- There’s a problem with symbols like “2” or “+”. Sometimes we use them in our programs; this is a syntactic use. But sometimes we mean a mathematical value, the thing denoted by “2” or “two” or so on.
- In these notes I’ll try to be consistent about the following notation, but I won’t do them on the blackboard, and you don’t have to do them on your homeworks etc.
- **Notation**: Writing something in *this fixed-width font* means the item is syntactic (an expression or statement, typically). E.g., “\( \sqrt{2} \)” or “\( 2+2 = 4 \)”. Writing a value out in words means the item is semantic (a value, such as a mathematical number). I’ll often use italics, for extra emphasis. So 17 is syntactic, *seventeen* is semantic, and 17 (not in fixed-width font) is ambiguous.
- The basic problem is that we’re talking about the meanings of programs, so some of the things we talk about are syntactic and some are semantic. Many times, the context tells you which. E.g., \( x \) and \( p \) have to be syntactic items in “Does \( x \) occur in the predicate \( p \)?” If we write \( z \equiv 2+2 \), then 2+2 must be an expression. In “the value of 2+2 in state \( \sigma \) is 2+2, which is 4”, the first 2+2 must be syntactic; the second 2+2 (and the 4) must be semantic. (Only expressions have values in a state, and the values are semantic.). So I might actually write “the value of 2+2 in \( \sigma \) is *two plus two*, which is *four*.”

D. Values of Expressions

- In general, expressions have values relative to a state. E.g., relative to \{ \( x = 1, y = 2 \)\}, the expression \( x+y \) has the value 3. Recall that we write \( \sigma(x) \) for the value of the variable \( x \) and extend this to \( \sigma(e) \) for the value of the expression \( e \).
- The value of \( \sigma(e) \) depends on what kind of expression \( e \) is, so we use recursion on the structure of \( e \) (the base cases are variables and constants and we recursively evaluate subexpressions).
  - \( \sigma(x) = \) the value that \( \sigma \) binds variable \( x \) to
  - \( \sigma(c) = \) the value of the constant \( c \). E.g., \( \sigma(2) = \text{two} \). (Note \( \sigma \) is irrelevant here.)
  - \( \sigma(e_1 + e_2) = \sigma(e_1) + \sigma(e_2) \) [and similar for -, *, etc.]
  - \( \sigma(e_1 < e_2) = \text{T} \) iff \( \sigma(e_1) \) is less than \( \sigma(e_2) \) [similar for \( \leq, =, \) etc.]
  - \( \sigma(e_1 \land e_2) = \text{T} \) iff \( \sigma(e_1) \) and \( \sigma(e_2) \) are both \( \text{T} \) [similar for \( \lor, \) etc.]
  - \( \sigma(B \ ? \ e_1 : e_2) = \sigma(e_1) \) if \( \sigma(B) = \text{T} \)
  - \( \sigma(B \ ? \ e_1 : e_2) = \sigma(e_2) \) if \( \sigma(B) = \text{F} \)
  - We’ll put off the case \( \sigma(b[e]) \), the value of the array indexing expression \( b[e] \) for just a bit until we look at the value of an array variable.
- **Example 7**: Let \( \sigma = \{ x = 1 \} \), let \( \tau = \sigma \cup \{ y = 1 \} \), and let \( e = (x = (y > 0 ? 17 : y)) \), then \( \tau(e) = \text{F} \):
  - \( \tau(e) = \text{T} \) iff \( \tau(x) \) equals \( \tau(y > 0 ? 17 : y) \)
  - For the left side, \( \tau(x) = \sigma(x) = 1 \)
For the right side, $\tau(y > 0) = T$ because $\tau(y) = \text{one}$ and $\tau(0) = \text{zero}$ and one is greater than zero.

So $\tau(y > 0 ? 17 : y) = \tau(17) = \text{seventeen}$ because $\tau(y > 0) = T$.

So $\tau(e) = \text{The result of the test one equals seventeen, which is false}$.

So $\tau(e) = F$.

The empty state: Since a state is a set of bindings, the empty set $\emptyset$ is a state (the empty state). It's proper for any expression or predicate that doesn't include variables. E.g., In state $\emptyset$, the expression $2+2$ evaluates to four. (In fact, since we don't care about bindings for variables that don't appear in an expression, we can say that in any state $\sigma$, $2+2$ evaluates to 4.

Example 8: Let $\sigma = \emptyset$ (the empty state) then

$\sigma(2+2) = \sigma(2+2) = \sigma(4) = ... = \text{four equals} = T$.

The value of an expression has to be a semantic value. So $\sigma(v+w) = \sigma(v)+\sigma(w)$ is okay (with the second plus meaning the semantic operation of mathematical addition), as is $\sigma(v)$ plus $\sigma(w)$.

It's tempting to write things like $\sigma(v+w) = v+w$ or $v$ plus $w$, but these are errors. Since $\sigma(...)$ is a semantic value, we can't write $\sigma(...)$ = the expression $v+w$. Writing $v$ plus $w$ is even worse because it tries to run a semantic operation (addition) on two syntactic objects.

E. Arrays and Their Values

Compare the usual way we write states on the blackboard. Below, the left state is $\sigma = \{x = 1, y = F\} = \{(x, 1), (y, F)\}$. The right one, $\tau$, defines an array variable $b$ and an integer $x$.

We’ll take the value of an array to be a function from index values to stored values, so $\tau(b[0]) = 3$, $\tau(b[1]) = 5$, and $\tau(b[2]) = 9$. We could write $\tau = \{(b[0] = 3, b[1] = 5, b[2] = 9, x = 5) = \{(b[0], 3), (b[1], 5), (b[2], 9), (x, 5)\}$, but a more convenient notation would be nice.

Notation: Let $\beta$ be the function with $\beta(0) = 3, \beta(1) = 5, \beta(2) = 9$, then we can say $\tau = \{b = \beta, x = 5\} = \{(b, \beta), (x, 5)\}$. (I’m using a greek letter $\beta$ because the function is semantic, taking index values to memory values.). Since a function is a set of ordered pairs, we can also write $\beta = \{(0, 3), (1, 5), (2, 9)\}. Since $\beta$ is actually a sequence, let's allow ourselves to abbreviate this to $\beta = (3, 5, 9)$. (Note this last notation looks like the graphical picture of $\tau$.)

We we have a number of ways to express $\tau$, all valid. Going from shortest to longest we have

$\tau = \{b = \beta, x = 5\}$ where $\beta = (3, 5, 9)$
$\tau = \{b[0] = 3, b[1] = 5, b[2] = 9, x = 5\}$
$\tau = \{b = \beta, x = 5\} = \{(b[0] = 3, \beta(1) = 5, \beta(2) = 9\}$
$\tau = \{b = \beta, x = 5\}$
**Value of An Array Indexing Expression**

- Going back to the definition of the value of an expression in a state, here's the array case:
  \[
  \sigma(b[e]) = \beta(\alpha) \text{ where } \beta = \sigma(b) \text{ and } \alpha = \sigma(e). \]
  The variable \( b \) is an array name, so \( \sigma(b) \) is a function we're calling \( \beta \). We call \( \beta \) on the value of the index expression \( e \), hence \( \alpha = \sigma(e) \), and the value \( \beta(\alpha) \) is the meaning of \( b[e] \).

- You can also write \( \sigma(b[e]) = (\sigma(b))(\sigma(e)) \) if you don't want to define \( \alpha \) and \( \beta \). Function application is left-associative, so \( \sigma(b)(\sigma(e)) = (\sigma(b))(\sigma(e)) \). I.e., \( \sigma(b) \) is a function we're applying to \( \sigma(e) \).

- So another way to write the definition is \( \sigma(b[e]) = \sigma(b)(\sigma(e)) = \beta(\alpha) \text{ where } \beta = \sigma(b) \text{ and } \alpha = \sigma(e) \).

- With our earlier example then, \( \sigma(b[x-4]) = \sigma(b)(\sigma(x-4)) = \beta(\sigma(x) \text{ minus four}) = \beta(5 \text{ minus four}) = \beta(1) = 5 \), where \( \beta \) is as described earlier, \( \beta = (3, 5, 9) \).

**Example 9:** Let \( \sigma = \{ x = 1, b = \alpha \} \) where \( \alpha = (2, 0, 4) \). Then
  - \( \sigma(x) = 1 \)
  - \( \sigma(x+1) = \sigma(x) + \sigma(1) = 1 + 1 = 2 \)
  - \( \sigma(b) = \alpha \)
  - \( \sigma(b[x+1]) = (\sigma(b))(\sigma(x+1)) = \alpha(2) = 4 \)

- If we don't want to write out the intermediate steps first, we could write
  - \( \sigma(b[x+1]) = (\sigma(b))(\sigma(x+1)) = \alpha(\sigma(x) + 1) = \alpha(1 + 1) = \alpha(2) = 4. \)

**Example 10:** Let \( \sigma = \{ x = 1, b = \alpha \} \) where \( \alpha = (2, 0, 4) \), then
  - \( \sigma(b[x+1] - 2) = \sigma(b[x+1]) - \sigma(2) = (\sigma(b))(\sigma(x+1)) - 2 \)
    \[= (\sigma(b))(\sigma(x+1)) - 2 = \sigma(2) - 2 = 4 - 2 = 2. \]