Types

- What is a type?
- Type checking
- Type conversion
- Aggregates: arrays

What is a type?

- **A set of values and the valid operations on those values**
  - **Integers + - * *div* < <= = >= > ...**
  - **Arrays:**

    ```
    lookUp(<array>,<index>)
    assign(<array>,<index>,<value>)
    initialize(<array>), setBounds(<array>)
    ```
  - **User-defined types:**

    ```
    Java interfaces
    ```
- **Program semantics (meaning) embedded in types used**
  - **Additional correctness check provided beyond valid syntax**

3 Views of Types

- Set point of view:
  - *int* = `{1,-2,...}`
  - *char* = `{‘a’,’b’,...}`
  - *list* = `{ (), (a (2 b) ), ... }`
- Abstraction point of view:
  - Set of operations which can be combined meaningfully

    e.g., *Java interfaces*

3 Views of Types

- **Constructive point of view**
  - **Primitive types** e.g., *int, char, bool, enum*{red,green,yellow}
  - **Composite/constructed types:**
    - **reference** **e.g.,** *pointerTo*(***int***)
    - **array** **e.g.,** *arrayOf*(***char***) **or** *arrayOf*(***char*,20**) **or ...**
    - **record/structure** **e.g.,** *record*(**age:*int*, name:*string***)
    - **subrange** **e.g., *int***[1..20] **or *color*[*red..green*]**
    - **union** **e.g.** *union*(***int*, *pointerTo*(*char*)**)
    - **list** **e.g.,** *list*(...)
    - **set** **e.g.,** *setOf*(***color***) **or** setOf(***int*[10..20]**)
    - **function** **e.g., *float* → *int***

    CAN BE NESTED! pointerTo(arrayOf(pointerTo(char)))

Types

- Implicit
  - If variables are typed by usage
    - Prolog, Scheme, Lisp, Smalltalk
- Explicit
  - If declarations bind types to variables at compile time
    - Pascal, Algol68, C, C++, Java
- Mixture
  - Implicit by default but allows explicit declarations
    - Haskell, ML, Common Lisp

Type System

- Rules for constructing types
- Rules for determining/inferring the type of expressions
- Rules for type compatibility:
  - In what contexts can values of a type be used (e.g., in assignment, as arguments of functions,...)
- Rules for type equivalence or type conversion
  - Determining (ensuring) that an expression can be used in some context

Types of Expressions

- **If *f* has type *S* □ *T* and *x* has type *S*, then *f(x)* has type *T***
  - **type of `3 div 2` is *int***
  - **type of `round(3.5)` is *int***
- ***Type error* - using wrongly typed operands in an operation**
  - **`round("Nancy")`**
  - **`3.5 div 2`**
  - **`"abc"+ 3`**

Type Checking

- *Goal:* to find out as early as possible, if each procedure and operator is supplied with the correct type of arguments
  - Type error: when a type is used improperly in a context
  - Type checking performed to prevent type errors
- Modern PLs often designed to do type checking (as much as possible) during compilation

Type Checking

- *Compile-time* (static)
  - At compile-time, uses declaration information or can infer types from variable uses
- *Runtime* (dynamic)
  - During execution, checks type of object before doing operations on it
    - Uses type tags to record types of variables
- Combined (compile- and runtime)

Type Safety

- A *type safe* program executes on all inputs without type errors
  - Goal of type checking is to ensure type safety
  - Type safe does not mean without errors

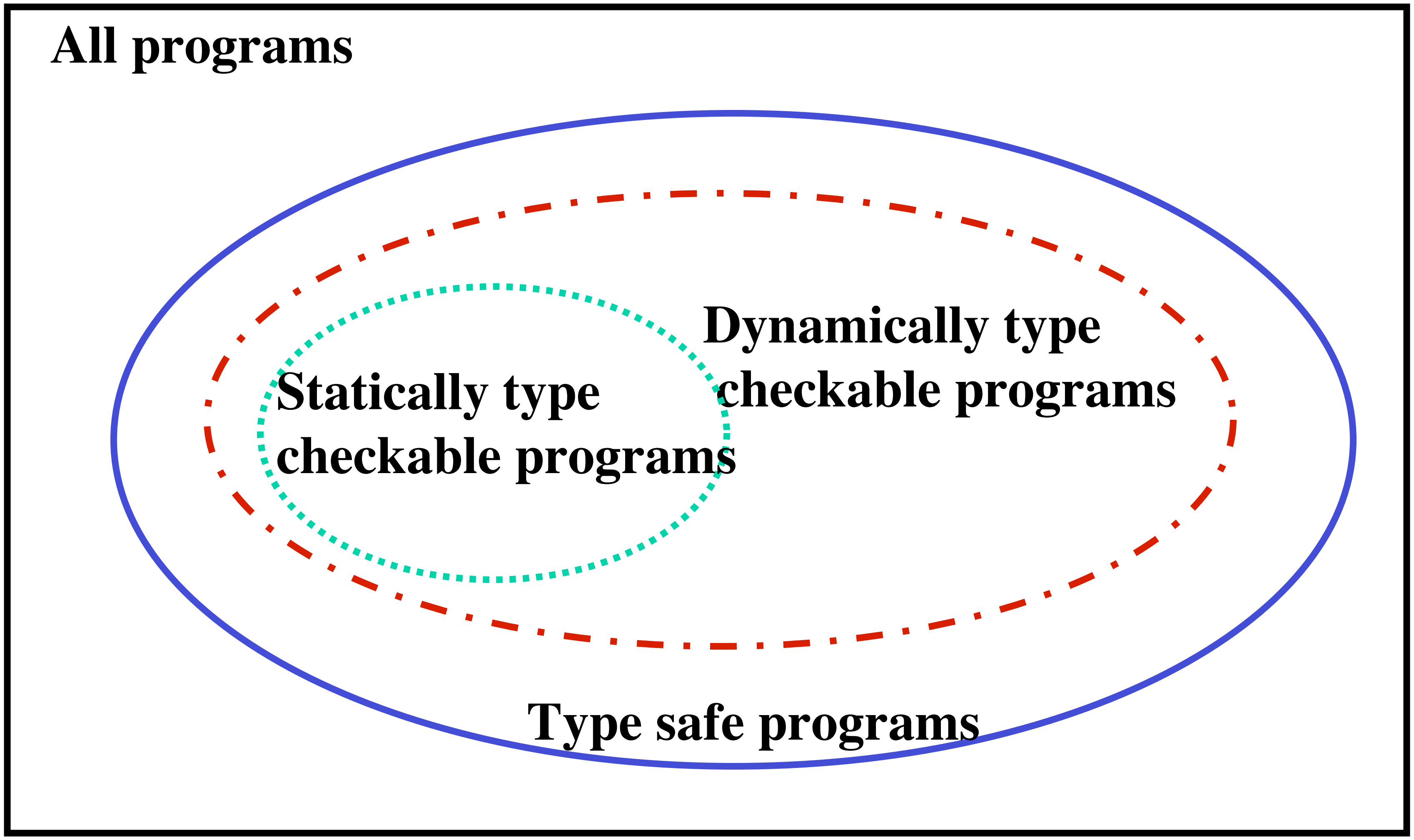
```
read n;
if n>0 then {y:="ab";
             if n<0 then x := y-5;}
```

    - Note that assignment to x is never executed so program is *type safe* (but contains an error).

Strong Typing

- *Strongly typed PL* **By definition, PL requires all programs to be type checkable**
- ***Statically strongly typed PL*** **- compiler allows only programs that can be type checked fully at compile-time**
    - **Algol68, ML**
- ***Dynamically strongly typed PL*** **-Operations include code to check runtime types of operands, if type cannot be determined at compile-time**
    - **Pascal, Java**

Hierarchy of Programs


All programs
Dynamically type checkable programs
Statically type checkable programs
Type safe programs

Type Checking

- **Kind of types used is orthogonal to when complete type checking can be accomplished.**

	static checking	**dynamic checking**
Implicit types	**ML**	**Scheme**
Explicit types	**Algol68**	**C, Pascal**

Difficulties in Static Type Checking

- **If validity of expression depends not only on the types of the operands but on their values, static type checking cannot be accomplished**
  - **Taking successors of enumeration types**
  - **Using unions without type test guard**
  - **Converting ranges into subranges**
  - **Reading values from input**
  - **Dereferencing void * pointers**

Type Conversion

- **Implicit conversion - *coercion***
  - **In C, mixed mode numerical operations**
    - `double d,e;…e=d+2;//`**2 coerced to 2.0**
  - **Usually can use *widening* or conversion without loss of precision**
    - **integer ▯ double, float ▯ double**
    - **But real ▯ int may lose precision and therefore cannot be implicitly coerced!**
  - **Cannot coerce user-defined types or structures**

Type Conversion

- **Explicit conversion**
  - **In Pascal, can explicitly convert types which may lose precision *(narrowing)***
    - `round(s)` **real □ int by rounding**
    - `trunc(s)` **real □ int by truncating**
  - **In C, casting sometimes is explicit conversion**
    - `dqstr((double) n)` **where `n` is declared to be an `int`**
    - `freelist *s; ... (char *) s;` **forces `s` to be considered as pointing to a char for purposes of pointer arithmetic**

Overloading Operators

- Primitive type of *polymorphism*
  - When an operator allows operands of more than one type, in different contexts
- Examples
  - Addition: 2+3 is 5, versus concatenation: “abc”+”def” is “abcdef”
  - Comparison operator used for two different types: 2 == 3 versus “abc” == “def”
  - Integer addition: 1+2 versus real addition: 1.+2.

Primitive Types

- Issues
  - type checking
  - representation in the machine
- Boolean
  - use of integer 0/non-0 versus `true/false`
- Char versus string
- Integer
  - length fixed by standards or implementation (portability issues)
  - multiple lengths (C: short, int, long)
  - signs
- Float/real (all issues of ints plus)
  - should value comparison be allowed?
  - rep: sign(1 bit)/mantissa(23 bits)/exponent(8 bits)

Definition of Arrays

- Homogeneous, indexed collection of values
- Access to individual elements through subscript
- Choices made by a PL designer
  - Subscript syntax
  - Subscript type, element type
  - When to set bounds, compile-time or runtime?
  - How to initialize?
  - What built-in operations allowed?

Array Type

- What is part of the array type?
  - Size?
  - Bounds?
    - Pascal: bounds are part of type
    - C,Algol68: bounds are not part of type
    - Must be fixed at compile-time in Pascal but can be set at runtime in C and Fortran
  - Dimension? always part of the type
- Choice has ramifications on kind of type checking needed

Choices for Arrays

- **Global lifetime, static shape (in global memory)**
- **Local lifetime**
  - **Static shape (kept in fixed length portion of frame)**
  - **Shape bound at elaboration time when control enters a scope**
    - **(e.g., Ada, Fortran allow defn of array bounds when fcn is elaborated; kept in variable length portion of frame)**
- **Arrays as objects (Java)**
  - **Shape bound at elaboration time (kept in heap)**
    - **int[] a;…a = new int[size]**
- **Dynamic shape (can change during execution) must be kept on heap**

Arrays in Algol68

- **Array type only includes dimensionality, not bounds**

  `[1:12] int month;[1:7] int day;` *row int*

  `[0:10,0:10]real matrix;`

  `[-4:10,6:9]real table` *row row real*

  Note `table` and `matrix` are type equivalent!

- **Example - [1:10] [1:5,1:5] int kinglear;**

  kinglear is a vector of 10 elements each of which is a *row row int* array of 25 elements, so kinglear is of type *row of (row row int)* in contrast to the type *row row row int*

  kinglear[j] is legal wherever *row row int* is legal

  kinglear[j][1,2] is legal wherever *int* is legal

  kinglear[1, 2, 3] is ILLEGAL!

Algol 68 Array Operations

- *Trimming:* **yields some cross section of an original Algol68 array (slicing an array into subarrays)**
- *Subscripting:* **limiting 1 dimension to a single index value**

```
[1:10]int a,b; [1:20]real x; [1:20,1:20]real xx;
b[1:4]  := a[1:4] -- assigns 4 elements
b:= a -- assigns all of a to b, same effect as b[1:10]:=a[1:10]
xx[4,1:20]:= x --assigns 20 elements to row 4 of xx
xx[8:9,7]  := x[1:2] --assigns x[1] to xx[8,7] and
  x[2] to xx[9,7]
```

Arrays -Implementation

- For fixed length array, symbol table keeps track of name, element type, bounds etc. during compilation; can allocate in static storage or on frame of declaring method.
- For arrays whose length is not knowable at compile-time, we use a *dope vector,* a descriptor of fixed size on the stack frame, and then allocate space for the array data separately
- Dope vector contains:
  – Name, type of subscript, bounds, type of elements, number of bytes in each element, pointer to first storage location of array
  – Allows calculation of actual frame address of an array element from these values

Array Addressing

- X[low:high] of E bytes each data item. What's the address of X[j]?

  addr(X) + (j-low) *E <= addr(X) +(high-low)*E

  - Note: addr(X)-low*E is a compile-time constant
  - X[ ] row real (4 bytes each);
  - X[3] is addr(X[0]) + (3-0)*4 = addr(X) + 12
  - X[0], X[1] is at address X[0]+4, X[2] is at address X[0]+8, etc

Array Addressing

- Assume arrays are stored in row major order y[0,0], y[0,1], y[0,2], …, y[1,*], y[2,*],…
- Consider memory a sequence of locations
- Then if have y[low1:hi1,low2:hi2] in Algol68, location y[j,k] is

  addr(y[low1,low2]) + (hi2-low2+1)*E*(j-low1)

  +(k-low2)*E *#locs per row* *#rows in front of row j*

  # elements in row j in front of element [j,k]

Example

y[0:2, 0:5] in Algol68, an int array. Assume row major storage and find address of y[1,3].

address of y[1,3] = addr(y[0,0])+(5-0+1)*4*(1-0)+(3-0)*4

6 elements per row

1 row before row 1

3 elements in row 1 before 3

= addr(y[0,0])+24+12

= addr(y[0,0])+36

- **Analogous formula holds for column major order.**

Types Require Work

- for programmer - has to start typing process
  - Usually needs <u>declarations</u> for user-defined constants, variables, functions
    - *e.g.* procedural languages: C,C++,Pascal, Ada,...
- for PL implementer
  - Implementing type checking
  - For dynamically typed languages, carrying around type information with (all/some) values at runtime -- wastes space and time
- for PL designer
  - Balance tradeoffs above.