Type Systems in Programming Languages

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Typing in Programming Languages

- **Typing:** a mechanism for grouping values into types
  - Describe data effectively
  - Prevent nonsensical operations, *e.g.* multiply a string by a set
- Components of this mechanism
  - **Associating a type with every value:** values are grouped into types, and values of the same type exhibit similar behavior under similar operations
    - In complex type systems, certain values can be associated with more than one type.
    - Often, if there is more than one type associated with a value, there is an infinite number of types associated with this value.
  - **Checking rules:** Given a value and an operation, use the type of the value to check whether this operation is allowed on values of this type
    - This becomes more difficult if there are several types associated with the same value
  - **Inference rules:** Given the type of operands, determine:
    - the meaning of an operation
    - the type of the result

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Significance of Type

- **Type determines meaning (semantics):**
  What will be executed as a result of the following expression?

  ```
  a + b
  ```

  - Integer addition, if `a` and `b` are integers, or
  - Floating point addition, if `a` and `b` are of a floating point type, or
  - Conversion to a common type and then addition, if a and b are of different types.
- **Type determines what's allowed (semantically):**
  Is the following expression legal?

  ```
  X[i]
  ```

  - Yes, if `X` is an array type and `i` is of a discrete type.
    - In C, the above is legal also when `X` is a pointer (and `i` is of a discrete type).
  - No, *e.g.* if `X` is a real number and `i` is a function.

Classifying Type Systems

- **Existence**
  - Does the language include a type system at all?
- **Type equivalence and subtyping**
  - When can one type replace another?
  - Structural/name/declaration type equivalence
- **Strength**
  - How strictly are the typing rules enforced?
- **Time of checking**
  - At what stage is type checking performed?
  - Static *vs.* dynamic typing
- **Responsibility**
  - Is the programmer responsible for type declarations or is it the compiler?
  - Explicit/implicit typing
- **Flexibility**
  - To what extent does the type system restrict the user's expressiveness?
  - Polymorphic typing

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Existence of a Type System

A language can be

- **Typed**: The set of values can be broken into groups, with more or less uniform behavior under the same operation of values in each group.
  - C, Pascal, ML, Ada, Java, and most other programming languages
- **Untyped**: Each value has its own unique set of permissible operations, and their semantics are particular to the value.
  - **Lisp** (list processing) :
    - All values are S-expressions, which are not much more than binary trees.
    - Elementary operations are: choosing the right and left subtrees of a tree, and combinations and inverse of these operations.
    - Legality of operations is determined by tree structure and values
  - **Mathematica** (a language for symbolic mathematics):
    - Values are mathematical expressions (represented as S-expressions)
    - Legality and semantics of a manipulation of an expression is determined by the structure and semantics of the expression.
- **Degenerate:** The set of values is so simple that it admits only one type, or a small number of types; appears in most scripting languages
  - **BCPL (C's ancestor):** the only data type is a machine word
  - **DOS Batch Language:** the only data type is a string
  - **C-shell, Bourne-shell, AWK, Rexx:** two data types - strings and numbers - with little distinction between them; minimal support for arrays.
  - **Perl:** Several extensions to the type system beyond AWK.

Type Equivalence and Subtyping

Type Equivalence

- Suppose that an operation expects an operand of type *T*, but receives an operand of type *T'*. **Is this an error?**
  - No, if *T'* is a ***subtype*** of *T*
- Two types that are subtypes of each other are called ***equivalent***
- **Caveat**: because the notion of subtype is more refined than the notion of type equivalence, we will find languages where type equivalence is defined but subtyping is not
- Kinds of type equivalence
  - Structural equivalence
  - Name equivalence
  - Declaration equivalence

Structural Equivalence

- **Have the "same" values…. In Algol-68**:
  - If *T* and *T'* are both primitive, then $T \cong T'$ only if they are identical.
  - Else if
    - $T = A \times B$, $T' = A' \times B'$, or
    - $T = A + B$, $T' = A' + B'$, or $T = A + B$, $T' = B' + A'$, or
    - $T = A \to B$, $T' = A' \to B'$

    and $A \cong A'$, $B \cong B'$ => $T \cong T'$
  - Otherwise?
- **Recursive types:**
  - T = Unit + c(A x T)
  - S = Unit + c(A x S)
  - R = Unit + c(A x S)
  - Intuitively T, S and even R are structurally equivalent, but structural equivalence is not easy to define and test for in recursive types.
- **Points of disagreement between languages**:
  - Do records require field name identity to be structurally equivalent?
  - Do arrays require index range identity to be structurally equivalent?

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An example for (hypothetical) structural equivalence

```
EmployeeData = record
   id: Integer;
   name: String;
   isManager: Boolean;
   ranking: array [1..3] of Chararcter;
end;
```

```
YearlyEmployee = record
    d: EmployeeData;
    salary: Real;
end;
```

```
Employee1 = record
    d: EmployeeData;
    case Integer of
        0:  yearly_salary: Real;
        1:  hourly_rate: Integer
    end;
end;
```

```
HourlyEmployee = record
    d: EmployeeData;
    salary: Integer;
end;
```

```
Employee2 = record
 case Integer of
    0: y: YearlyEmployee;
    1: h: HourlyEmployee;
 end;
end;
```

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Name Equivalence

- $T \cong T'$ iff T and T' were defined in the same place (original Pascal and Ada):

```
TYPE  T1 = File of Integer;
      T2 = File of Integer;
VAR   f1: T1;
      f2: T2;
Procedure p(Var f: T1);
....
p(f1); (* ok *)
p(f2); (* compile-time error *)
```

Name equivalence across programs

```
program p1(f)
type T = file of Integer;
var  f: T;
begin
 ...
 write(f,...);
 ...
end;
```

```
program p2(f)
type T = file of Integer;
var  f: T;
begin
 ...
 read(f,...); (* Type error *)
 ...
end;
```

- By ***definition*** of Pascal, it follows that
  - two Pascal programs cannot communicate legally through files using any user-defined type, hence the type error above.
  - type `Text`, which is the only predefined type for files in Pascal, allows communication between programs.
- In practice, most ***implementations*** of Pascal do not type check files. Thus, these implementations *subvert* Pascal's type safety, but allow reasonable interfacing.

Declaration Equivalence

- A later Pascal standard (ANSI 1983):
  $T \cong T'$ only if T and T' have the same declaration

```
TYPE  T1 = File of Integer;
      T2 = File of Integer;
VAR   f1: T1;
      f2: T2;
Procedure p(Var f: T1);
....
p(f1); (* ok *)
p(f2); (* ok *)
```

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Subtyping in Pascal

- A weaker notion than type equivalence: an operation that expects an operand of type *T* but receives an operand of type *T'* is legal also if *T* and *T'* are not equivalent, but *T'* is a *subtype* of *T.*
- **Subtyping in Pascal** - only in one case:
  - if *T=[a..b]* and *T'=[c..d]* then *T'* is a subtype of *T* iff *T'* is a subrange of *T.*
- **Limitation**: there is no way to override this definition. For instance:

```
type
        age = 0..120;
        height = 0..250;
```

`age` will be a subtype of `height` even though we don't want to confuse the two notions.

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Derived Types in Ada

```
type
age = derived integer range 0..120;
height = derived integer range 0..250;
```

- `age` is not equivalent to `0..120`
- `height` is not equivalent to `0..250`
- Therefore: `age` is not a subtype of `height`

- **In Modula-3**: values of derived types are ***branded***, so that storage in external files will not create communication problems between programs.

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Subtypes in ADA

```
type
   age = derived integer range 0..120;
   height = derived integer range 0..250;
subtype child_height is height range 0..120;
```

- `age` and `child_height` not equivalent to `0..120`
- `height` is not equivalent to `0..250`
- Therefore: `age` is not a subtype of `height`
- But `child_height` is!
- A *convert* function that expects a height in cm and converts it to inches, can be used with a variable of type `child_height` , but not one of type `age` .

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More about Subtyping in ADA

- Subtyping of ordered primitive types - using subranges:

```
   subtype Probability is Float range
   0.0..1.0;
```

- Subtyping of array types: using subranges as well:

```
subtype String is array (Integer range
<>) of Character;
subtype String5 is String (1..5);
```

- Subtyping of record types:

```
type Sex is (f,m);
type Person (gender: Sex) is record …
end record;
subtype Female is Person (gender => f);
```

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Branding

- Sometimes it is not desirable to define two instances of the same type as type equivalent.
  - **Example:** a string describing a person's name and another string describing his or her address are not type equivalent.
- To distinguish two values of the same type we can **brand** these values by adding a tag to it.
- Simple technique for branding – labeled fields:

```
User = Record
    name: String;
    address: String;
end
```

  - In this example, we brand the string types: Address_Type and Name_Type
- Branding is similar to `typedef`'s in C. However, `typedef` merely gives an alias to an existing type and does not define a new type.
- In Modula-3, branding is performed automatically for values of derived types, so their type is maintained also when stored by one program and read by another program.

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Subtyping as Subclassing

Consider the *class* `Collection` that allows the following operations:

```
insert (what: integer)
is_member (what: integer) : boolean
remove (what: integer) : boolean
write ()
```

A class `Queue` that allows the same operations plus the following:

```
remove_first () : integer or Unit
```

would be a ***subclass*** of `Collection`.

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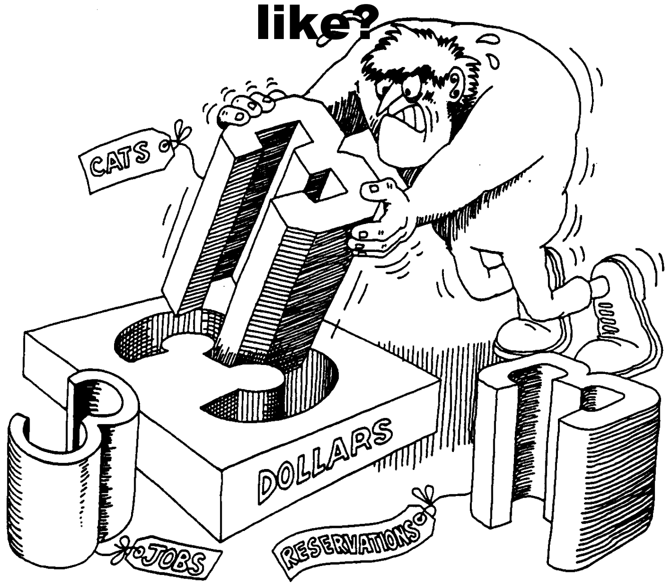
Strong Typing -- What does it look like?



Strong typing prevents mixing abstractions.

Strength of Typing Systems

- **Strongly typed languages**: ML, Eiffel, Modula, Java
  - It is impossible to break the association of a value with a type from within the framework of the language.
  - It is impossible to subject a value to an operation which is not acceptable for its type.
  - **Consequence:** the representation of values can be concealed by the language
- **Weakly typed languages:** values have associated types, but it is possible for the programmer to break or ignore this association.
  - **C** – *we can access the same memory cell in different ways:*
    - *In an array of Booleans, can do boolean operations on the values, or arithmetic ones, etc…*
    - *Parameter passing using pointers*
    - *Access beyond array dimensions (i.e, index value is not of the declared type)*
    - *Union type…misused disjoint union*

Spectrum of Strength

- **S**ome languages are more strongly typed than others:
  - Pascal is more strongly typed than C, with the only ways of breaking the type rules being:
    - *Variant records*
    - *Illegal parameter passing with procedure-valued parameters*
      - *When a procedure B is passed as a parameter to a procedure A, the call in the declaration of A has parameters with types. The types of the parameters of B might not agree with those.*
    - *Through files (in some compilers that just don't check)*

Loopholes in the Type System

Types *usually* hide the fact that a variable is just a box containing bits, however:

Type casting, as in

```
long i, j, *p = &i, *q = &j;
long ij = ((long) p) ^ ((long) q));
```

and *variant records*, as in

```
union {
  float f;
  long l;
} d;
d.f = 3.7;
printf("%ld\n", d.l);
```

allow one to peep into the implementation of types, by subjecting a value to operations not allowed for its type

Time of Enforcement

- **Type checking:** Language implementation must ensure that no nonsensical operations occur.
  - **Multiplication:** check that both operands are numeric.
  - **Logical operation:** check that both operands are truth values.
  - **Component selection:** possible only on arrays and records (different implementation in each).
- Type checking must be performed before the operation, but it could be done either at compile-time or at run-time:
  - **Statically typed languages:** type rules are enforced at compile time. Every variable and every formal parameter have an associated type.
    C, Pascal, Eiffel, ML, …
  - **Dynamically typed languages:** type rules are enforced at run-time. *Variables*, and more generally – *expressions*, have no associated type. Only *values* have fixed types. Type checking must be done prior to each operation.
    Smalltalk, Prolog, Snobol, *APL*, Awk, Rexx, ...

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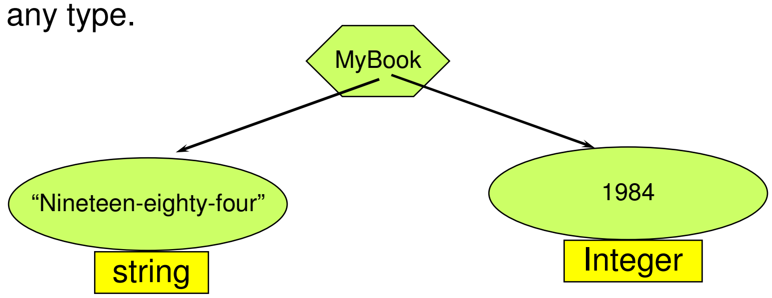
Dynamic Typing

- Types are associated with values.
  Each value carries a tag, identifying its type.
- **Polymorphic variables:** a variable may contain a value of any type.



- **Advantages**:
  - Arrays don't have to be of a homogeneous type
  - When data isn't uniformly typed, we don't need different variables

Dynamic Typing - Example

```
procedure ReadLiteral(var item);
begin
    read a string of nonblanks;
    if  the string constitutes an integer literal
    then
        item := numeric value of the string
    else
        item := the string itself
end
```

22,10,1996
or
22,OCT,1996

```
read(day); ReadLiteral(month); read(year)
if month is a string then
        case month of {
           "Jan": return 1;
           "Feb": return 2;
           ....
        }
    else
        return month;
end
```

Disadvantages of Dynamic Typing

- Space overhead:
  - **Each value is tagged with type information**
- Slow-down:
  - **Extra data to manipulate**
  - **Run-time checking**
- Security:
  - **Many bugs can be detected by static compile-time checks**

 :=  ;

```
Error: type mismatch
```

Static Typing

- In static typing, each variable and parameter is associated with a type.

Type ⟷ Identifier

  - This usually means that all identifiers should be declared before used. However this is not always the case.
  - A variable may contain only values compatible with its associated type.
- All expressions are guaranteed to be type-consistent:
  - No value will be subject to operations it does not recognize.
  - This allows the compiler to engage in massive optimization.

Why Static Typing?

- Computability theory teaches us that an automatic tool is limited as a programming aid to analyze code in advance
  - Cannot (always) determine if the program stops.
  - Cannot (always) determine if the program is correct.
  - Cannot decide almost any other interesting run time property of a program.
- One thing that *can* be done automatically by code analysis is to make sure that no run time *type error* occurs (for static typing).
- We can use every tiny bit of help in our struggle against the complexity of software!
  - A few other automatic aids are:
    - Garbage collection: automatic memory management (run time)
    - Const correctness: no modification of const parameters (compile time)
    - Pre and post (assert) conditions: partial specification of a function (run time)

Benefits of Static Typing

- Enforce the design decisions
- Prevent run time crashes:
  - Mismatch in # of parameters
  - Mismatch in types of parameters
  - Sending an object an inappropriate message
- Early error detection reduces:
  - Development time
  - Cost
  - Effort
- More efficient and more compact object code
  - Values do not carry along the type tag
  - No need to conduct checks before each operation
  - `type SMALL_COUNTER is range 0 .. 255;`

Limits of Static Typing

- Some senseless operations cannot be statically checked.
- Generic examples:
  - **Division by zero:** no typing system for the integers can prevent this without hitting the halting problem.
    - Checks are realized in run time by using machine-level exceptions. These checks carry no overhead.
  - **Exponentiation of certain pairs of real numbers:** similar problems to division by zero.
    - Realized at run time by the procedure that implements exceptions.
  - **Array references:** it is impossible to detect overflow of array indices.
    - Some hardware support, on some machines, but not without overhead.

Other Times of Enforcement

- **Mixed typing:** There is a variety of possibilities between static and dynamic typing, the two extremes.
  - Mixed typing means that some typing rules are checked at compile time, others are checked during runtime.
  - **Pascal**: Most operations are checked at compile time. Array access is checked during runtime.
    - Type information is still with the variables, but checks must be deferred to run time.
    - Some Pascal compilers have a compilation option that drops array reference checks.
- **"Postmortem typing"**: A different name for weak typing.
  - No checking of type errors is made. If a program makes a type error, then it is allowed to merrily carry along with this error to the bitter end…
  - The programmer is then responsible to remove the type errors from his program

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Responsibility for Tagging

- **Type inference:** Compilers have the ability to apply type inference rules to determine the type of *expressions*
- Why not apply this also to variables and other entities?
  - **Explicit typing:** programmer is in charge for annotating variables and other entities with type information
    - **This is done by variable type declarations**
  - **Implicit typing:** the compiler infers type information of an entity from the way it is used
    - **No variable type declarations**
  - **Semi-implicit typing:** type is determined from the lexical structure of an identity
    - **No variable declarations**

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Explicit Typing

- **Example:** variable and parameter declarations in Pascal, Ada, C, etc.
- Type declarations help document programs
  - `X: speed;` (* Good *)
  - `Y: real;` (* Bad *)
  - `Z = 3;` (* Worse *)

Implicit Typing

- The compiler infers the type of an entity from the way it is used
- **Risk**: Inadvertent creation of variables due to typos and spelling errors:
  - **ML's answer:** no variables!
    - **Value declaration**: just like CONST declaration in Pascal
      - ML: `val n = 100`
      - Pascal: `CONST n = 100`
    - **Formal parameters**: declared (without type) in the header of a function.
- **Risk**: Confusing error messages, and type errors
  - **ML's answer:** programmer is allowed to add *type constraints*
- **Risk:** Some complex (recursive and generic) type inference problems are undecidable
  - **ML's answer 1:** careful analysis of the type system to detect when this problem may occur
  - **ML's answer 2:** type constraints

Semi-Implicit Typing

- **Fortran:** All variables which begin with one of the letters `I,J,K,L,M` and `N` are integers; all others are real.
  - **Risk**: inadvertent creation of variables.
  - **Fortran answer:** the declaration `implicit none` excludes automatic creation of variables. The programmer is required to explicitly declare all variables.
- **Basic (older versions):** Suffixes such as %,$ etc. determine the variable's type.
- **Perl**: Essentially the same as Basic.

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Flexibility of Type System

- Type system should be an aide, not a hurdle:
  - Do not issue type error messages on programs which will not make run time type errors.
  - Allow the use of the same code for many different types.
- We refer to the extent to which a type system has these features as the *flexibility* of the type system.
- Too flexible: doesn't alert programmer to mistaken usage of variables, bad use of actual parameters, etc.
  - Adrienne rocket failed because an actual parameter in inches was used in a procedure with a formal parameter in centimeters….should have been a type error!
- Too inflexible: prevents reuse of code, especially in procedures
- Modern tendency: *polymorphism* – to be studied in great detail later…

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Inflexibility of Pascal

```
Type T = Integer;
Procedure sort(
   Function comp(a,b:T):Boolean,
   a: array[1..300] of T
); forward;
```

Could *not* be applied to …

- **Arrays of real:** Procedure body and declaration has to be repeated with `T1=Real`
- `array[1..299] of T`: Array is too small.
- `array[1..500] of T`: Array is too big.
- `array[0..299] of T`: Mismatch in indices.
- `array[1..300] of T`: No name equivalence!!!!
  - Pascal is so fussy and inflexible in its type system that even two identical type declarations are considered distinct. A type declaration made at a certain point in a program is equivalent only to itself.

```
Type T = Integer;
     Tarray = array[1..300] of T
Procedure sort(
   Function comp(a,b:T):Boolean,
   a: Tarray;
); forward;
```

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Responses to Inflexibility

- **C camp:** weak typing
  `int qsort(char *base, int n, int width,int(*cmp)())`
- **Smalltalk/Java camp:** dynamic typing overcomes complex inflexibility problems.
  - In Java dynamic typing is mostly geared towards this problem
- **Ada camp:** polymorphic type systems

```
generic
  type T is private
  with function comp(x: T, y: T)
  procedure sort(a: array(1..max) of T)
  …
procedure int_sort is new sort(int , "<");
```

- The backlash effect:
  - The C camp is leaning toward the Ada camp. ANSI-C, and even more so C++, tend towards strong, yet polymorphic type systems.

```
void qsort(void *base,size_t nel, size_t width,
     int (*compar) (const void *, const void *))
```

  - New additions to Java (e.g., Pizza) introduce generic programming into Java.
  - There were attempts to introduce static typing to Smalltalk!

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Summary: What's Best?

- **Depends on purpose…**
  - **Light-headed:** a scripting language, designed for small, not-to-be maintained, quick and dirty programs which are supposed to be run only a small number of times with little concern about efficiency:
  - No typing or degenerate typing,
    - Weak typing to remove hassles
    - Dynamic typing to achieve flexibility
    - Semi-implicit typing to reduce programmer time
  - **Software engineering oriented:** programs which are developed by several programmers, maintained and changed, run numerous times, and with efficiency concerns
    - Type system must exist to document and protect the program
    - Strong typing to reduce errors
    - Static typing to enhance efficiency, clarity and robustness
    - No semi-implicit typing to prevent inadvertent creation of variables
    - Flexible type system to allow the programmer to concentrate on the important stuff.

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