Types, Part II

Programming Languages

CS 214

Review

Recall: A type consists of *data and operations*.

The set constructors:

- *product*: A· B· … · N is the basis for *aggregates*;
- *function*: (A) → B is the basis for *operations*; and
- *Kleene closure*: A* is the basis for *sequences*.

These three provide a formal way to construct types:

→ Use the *product* and *Kleene closure* to represent the *data*;

→ Use the *function* constructor to represent the *operations* on the type.

Declarations

One purpose of types is to permit objects to be *declared*.

- A declaration states the attributes of an object (for the compiler).
- Example: If an object's value may vary, it is a *variable*; otherwise it is a *constant*.

- Issue: Where may declarations occur?
  - Many languages restrict the location of declarations:

    <ada-program> ::= procedure identifier ; <declaration-section> <block> ;

    C++ and Lisp unusual in allowing declarations "anywhere"...
  - In Smalltalk they must appear near the start of a method or block:

    <smalltalk-block> ::= [<parameters> '|' <identifiers> '|' <expressions>]
  - Lisp declarations are functions/expressions, and so are permitted anywhere an expression may occur.

Constant Declarations

- Issue: How are constants distinguished from variables?
  - Most imperative languages use a special keyword:

    <ada-const-dec> ::= identifier : constant <type> := <expression> ;

```
PI : constant real := 3.1459;
Mass, Energy : real;
```

  - C++ is similar, but uses the keyword *const*, and in a prefix form.

```
const double PI = 3.1459;
double mass, energy;
```

  - Java is similar to C++, but uses the keyword *final*.

```
final double PI = 3.1459;
double mass, energy;
```

  - Lisp constants are declared using the *defconst* function.

```
(defconst PI 3.14159)
(defvar mass 0.0)
```


Imperative Issue

- Fortran-family languages (e.g., Fortran, C/C++ and Java) declare variables using a form like this: <type> <id-list> ;
  while Algol-family languages (e.g., Ada, Pascal, Modula-2) use a form like this: <id-list> : <type> ;

Which approach is preferable?

```
double mass, energy;
```

1. The compiler 'knows' the type when it gets to the ids
2. Each id in the list can be separately initialized:

```
double mass = 1.0,
       energy = 0.0;
```

```
mass, energy : real;
```

1. The compiler doesn't 'know' the type as it processes the ids.
2. Each id must be initialized elsewhere (or else all ids are limited to the same value):

```
mass, energy : real := 0.0;
```


Fundamental Type Operations

Operation	C++	Ada	Modula-2	Smalltalk	Lisp
+, -, *	+,-,*	+,-,*	+,-,*	+,-,*	+,-,*
real div	/	/	/	/	/
int div	/	/	DIV	//	/
modulus	%	mod	MOD	\\	mod
remainder		rem		rem:	rem
exponentiation		**		raisedTo:	expt
logical-and		and		&	
short-circuit-and	&&	and then	AND	and:	and
logical-or		or		|	
short-circuit-or	||	or else	OR	or:	or
not	!	not	NOT	not	not
equality	==	=	=	=, ==	=, eq, equal
inequality	!=	/=	#, <>	~=, ~~	/=
relationals			uniformly <,>,<=,>=		

Short-Circuit Operators

Logical-and, *logical-or* operators evaluate both operands.

By contrast:

- A *short-circuit-or* operator only evaluates its second operand if its first operand is *false*; and
- A *short-circuit-and* operator only evaluates its second operand if its first operand is *true*.

Short-circuit behavior is more time-efficient, and can be exploited in certain situations:

```
while (ptr != NULL && ptr->value != searchVal)
  ptr = ptr->next;
```

- If && were a logical-and instead of short-circuit-and, this condition would seg-fault when *searchVal* is not in the list...

Modeling Real-World Values

Suppose we want to model the seven "ROY G BIV" colors.

One approach:

```
const int RED=0, ORANGE=1, YELLOW=2, GREEN=3,
          BLUE=4, INDIGO=5, VIOLET=6;
int aColor = BLUE;
```

This approach requires the human to map colors to integers.

Instead:

```
enum Color { RED, ORANGE, YELLOW, GREEN,
             BLUE, INDIGO, VIOLET } ;
Color aColor = BLUE;
```

Most imperative languages support such *enumerations*…

Ada:

```
type Color = ( RED, ORANGE, YELLOW, GREEN,
               BLUE, INDIGO, VIOLET ) ;
aColor : Color := BLUE;
```

An enumeration is a type whose values are explicitly listed.

Enumerations: Compiler Side

An enumeration's values must be valid *identifiers*:

<enumeration-type> ::= enum identifier { <id-list> } ;

and the compiler treats a declaration:

```
enum NewType { id0, id1, id2, …, idN-1 };
```

as being (approximately) equivalent to:

```
const int id0 = 0, id1 = 1, id2 = 2, …, idN-1 = N-1;
```

Thus, after processing

```
enum Color { RED, ORANGE, YELLOW, GREEN,
             BLUE, INDIGO, VIOLET };
```

so far as the compiler is concerned:

```
RED == 0 && ORANGE == 1 && YELLOW == 2 && … && VIOLET == 6
```


Enumerations: User Side

Enumerations thus provide an automatic means of mapping:

(identifier) → int

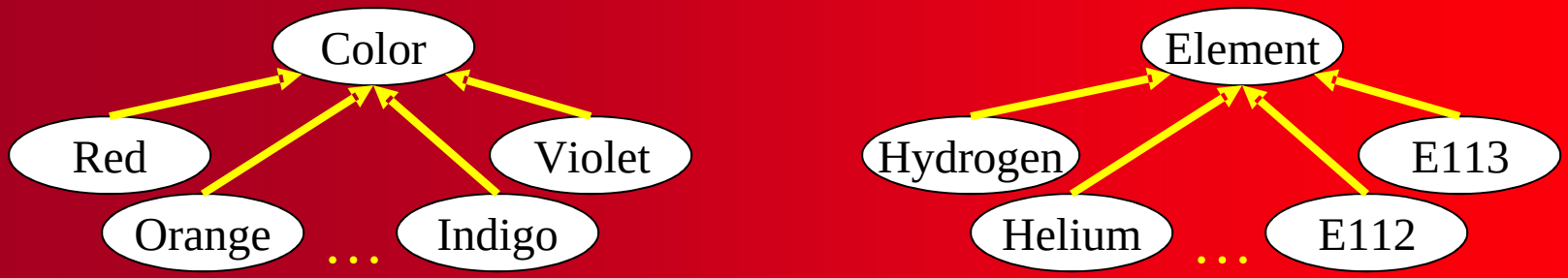
whose chief benefit is better program readability:

```
enum ElementName { HYDROGEN,
                   HELIUM,
                    …
                 };
ElementName anElement;
// ...
switch (anElement) {
  case HYDROGEN:
       atomicNumber = 1; break;
  case HELIUM:
       atomicNumber = 2; break;
  …
}
```

Enumerations allow real-world ‘values’ to be represented using real-world names, instead of (arbitrary) integer codes.

Enumerations and OO

OO purists replace enums with class hierarchies:



This permits the creation of real-world *objects*:

```
// Smalltalk
aColor := new Blue.
```

```
// Smalltalk
anElement := new Helium.
```

as opposed to real-world *values* provided by an enumeration.

For this reason, "pure" OO languages like Smalltalk don't provide an enumeration mechanism.

Subranges

Many imperative languages let us declare a *subrange*: a type whose values are a subset of an existing type's values.

```
// Ada
subtype TestScore is Integer range 0..100;
subtype CapitalLetter is Character range 'A'..'Z';

type DaysOfWeek is (Sunday, Monday, Tuesday, Wednesday,
                    Thursday, Friday, Saturday);
subtype WeekDay  is DaysOfWeek range Monday..Friday;
```

If a subrange variable is declared:

```
WeekDay today;
```

and assigned an invalid value:

```
today := Saturday;
```

then an exception occurs that, if not caught, halts the system.

Validation is an essential feature for *life-critical systems…*

Sequence Types

There are two common structures for storing sequences:

- The *array* (and/or vector) that stores values in contiguous memory locations;
- The *list*, that stores values anywhere there's room.

Arrays are *random-access structures*: any value in the array can be accessed in the same amount of time…

- The address of the value at index *i* can be computed in O(1):

(arrayBaseAddress + (*i* - firstIndex) · ElementSize)

Once declared, the size of an *array* is usually fixed.

A *vector* is an array-like structure whose size can vary.

Arrays

Most languages let us build arrays and/or vectors:

```
double anArray[8];                                  // C++
double * aVector = new double[n];
vector<double> anotherVector(n);
```

```
type ArrayType is array(1..8) of real;          -- Ada
anArray : ArrayType;
type Vector is array(integer range <>) of real;
type VectorAccess is access Vector;
aVector : VectorAccess;
begin
    aVector := new Vector(1..n);
```

```
(setq anArray (vector 0 1 2 3 4 5 6 7 8))   "Lisp"
```

```
| anArray aVector |                                  "Smalltalk"
anArray := Array new: 8.
aVector := OrderedCollection new: n.
```


Array Indexing

Arrays/vectors are *random-access indexed structures*:
the value stored at index *i* can be accessed in O(1) time:
(arrayBaseAddress + (i – firstIndex) x ElementSize)

The default *firstIndex* is different in different languages:

- C/C++: 0
- Ada: 1, can be programmer-specified
- Lisp: 0
- Smalltalk: 1

At Issue: There is an *efficiency-vs-convenience tradeoff*:

- Accesses to 0-relative arrays require one fewer operation:
  (arrayBaseAddress + (i - 0) · ElementSize)
  = arrayBaseAddress + *i* · ElementSize
- Programmer-specified index values can be very convenient:

```
type LetterCounter is array(CapitalLetter) of integer;
type DailySales is array(WeekDay) of real;
```


Array Access

An important array operation is to access the value at index *i*.

There are two different flavors to this operation:

- the *read* version _____ the value at index *i*;
- the *write* version lets us *modify* the value at index *i*.

Most languages use the same syntax for both operations:

- C/C++:

```
oldValue = anArray[i];                    // read
anArray[i] = newValue;                    // write
```

- Ada:

```
oldValue = anArray(i);                    -- read
anArray(i) = newValue;                   -- write
```

- Lisp:

```
(setq oldValue (aref anArray i))          "read"
(setq (aref anArray i) newValue)          "write"
```

Other languages provide distinct operations for the two:

- Smalltalk:

```
oldValue := anArray at: i.                "read"
anArray at: i put: newValue.              "write"
```


Array Access (ii)

Although C++ uses the same syntax for both read and write, the operations are implemented as *two distinct operations*:

```
template<class Type>
class vector {
 public:
   …
   // returns a read-only reference to v[i]
   const Type& operator[](unsigned i) const; // read version

   // returns a writable reference to v[i]
   Type& operator[](unsigned i);             // write version
   …
};
```

The compiler links a given call to the proper function:

```
oldValue = anArray[i];                  // linked to read version
anArray[i] = newValue;                  // linked to write version
```


Aggregates: Records/Structs

Like an array, an *aggregate* type can store multiple values; but (unlike an array) it can store values of different types.

```
struct Student {    // C++
  int id;
  bool fTime;
  double gpa;
};
```

```
type Student is    -- Ada
  record
    id : integer;
    fTime: boolean;
    gpa : float;
  end record;
```

Smalltalk has no records/structs, as its classes can do anything a record/struct can do...

```
"Lisp"
(defstruct Student
   id fTime gpa)
```

Once we have an aggregate type, we can build variables:

```
// C++
Student stu;
```

```
-- Ada
stu : Student;
```

```
"Lisp"
(setq stu make-Student)
```


Record/Struct Projection

We can then initialize the fields of the record/struct:

```
// C++
stu.id = 1234;
stu.fTime = true;
stu.gpa = 3.0;
```

```
-- Ada
stu.id:= 1234;
stu.fTime:=true;
stu.gpa:= 3.0;
```

```
"Lisp"
(setq (Student-id stu) 1234)
(setq (Student-fTime stu) t)
(setq (Student-gpa stu) 3.0)
```

Most languages use similar syntax to retrieve a field's value:

```
// C++
cout
 << stu.id;
 << stu.fTime
 << stu.gpa;
```

```
-- Ada
put(stu.id);
put(stu.fTime);
put(stu.gpa);
```

```
"Lisp"
(princ (Student-id stu))
(princ (Student-fTime stu))
(princ (Student-gpa stu))
```

These represent the *projection* operation in each language.

Pointers

Most languages permit a programmer to define variables that can store address: also known as *pointer variables*.

These can be used to build lists of linked nodes:

```
// C++
struct Node {
   SomeType value;
   Node * next;
};
```

```
-- Ada
type Node;
type NodePtr is access Node;
type Node is record
   value: SomeType;
   next: NodePtr;
end record;
```

Smalltalk and Java have no pointer types because every *class variable is actually a pointer variable.*

Lisp variables are also pointers:

```
"Lisp"
(defstruct Node
   value next)
```


Dynamic Allocation & Deallocation

Each language supports dynamic memory allocation, most commonly via the *new* operation:

```
// C++
Node * nPtr = new Node;
```

```
-- Ada
nPtr: NodePtr := new Node;
```

```
"Smalltalk"
| nPtr |
nPtr := Node new.
```

```
"Lisp"
(setq nPtr (make-Node))
```

Many languages also provide a *deallocation* operation:

```
// C++
delete nPtr;
```

Ada, Lisp, and Smalltalk instead provide a *garbage collector* that eliminates memory leaks by automatically reclaiming unused memory (i.e., when no pointers to it exist).

Pointer Assignment and Copying

Each language provides a means of assigning pointer values:

```
// C++
Node * tempPtr;
tempPtr = nPtr;
```

```
-- Ada
tempPtr: NodePtr;
tempPtr := nPtr;
```

```
"Smalltalk"
| nPtr tempPtr|
…
tempPtr := nPtr.
```

```
"Lisp"
(setq tempPtr nPtr)
```

Most languages also allow copying of the object pointed to:

```
// C++
tempPtr = new Node;
*tempPtr = *nPtr;
```

```
-- Ada
tempPtr := new Node;
tempPtr.all := nPtr.all;
```

```
"Smalltalk"
tempPtr := nPtr copy;
```

```
"Lisp"
(setq tempPtr (copy-Node nPtr))
```


Other Pointer Operations

Languages provide a notation for the "empty" pointer:

```
// C++
nPtr = NULL;
```

```
-- Ada
nPtr:= null;
```

```
"Smalltalk"
nPtr := nil.
```

```
"Lisp"
(setq nPtr nil)
```

Most languages also permit the fields of an aggregate to be accessed via a pointer:

```
// C++
nPtr->value = 1234;
nPtr->next = new Node;
```

```
-- Ada
nPtr.value:= 1234;
nPtr.next:= new Node;
```

Smalltalk "fields" are accessed via accessor and mutator methods

```
"Lisp"
(setq (Node-value nPtr) 1234)
(setq (Node-next nPtr) (make-Node))
```


Type Systems

A *type system* is a set of rules by which a language associates types with expressions.

The system generates a *type-error* when its rules do not permit a type to be associated with an expression.

Example: Early Fortran versions had only integers and reals.

- Declarations not required: implicit typing of identifiers

  Identifiers beginning with I-N are integers; all others are reals.

- Literals with decimal points are real; others are integers.
- Type System Rule: If E1 and E2 are expressions of the same type T, then E1+E2, E1-E2, E1*E2, and E1/E2 produce a result of type T.

  I+N produces a value of type integer; X+Y produces a value of type real.

  Expressions like X+I (e.g., 0.5+1)or N-Y generate type errors.

Type System Formalism

If *f* is a function from (S) → T, and s ∈ S, then *f*(s) ∈ T.

Ada defines: +(int · int) → int
and +(real · real) → real
but neither +(real · int) → real nor +(int · real) → real
so both 2 + 3 and 2.0 + 3.0 are valid expressions;
but neither 2.0 + 3 nor 2 + 3.0 are valid expressions.

Arithmetic expressions mixing reals and integers cause type errors.

Ada's other arithmetic operators behave the same way.

Why would Ada's designers choose such a type system?

- Ada is designed for building life-critical systems ...
- Ada's type system is perhaps the most strict of any HLL.
- Ada compilers catch errors that slip by in other languages.

Coercion

Ada is unusual in rejecting mixed-type arithmetic expressions; its goal is to prevent the unwanted loss of information.

Most HLLs permit arithmetic types to be freely intermixed.

To prevent information loss,

such languages take an expression: 2 + 1.5

"expand" the "smaller" operand: 2.0 + 1.5

and then perform the "larger" operation: +(real · real)

The automatic conversion of an operand's type to prevent rejection by the type system is called a *type coercion*.

Some languages use the term promotion to describe this; others describe it as *widening*.

Overloading

Note: operators like +, -, *, ... are *context-sensitive*. In *a* + *b*:

+ means "perform integer addition" if *a* and *b* are integers;

+ means "perform real addition" if *a* and *b* are reals.

Overloaded symbols have different meanings in different contexts.

Formally: For any function *f*(D) → R :

- The set of all possible arguments D is the function's *domain*;
- The set of all possible results R is the function's *range*.

An overloaded function is *defined for more than one domain*.

+, -, *, / are overloaded in most HLLs

To process such operations, the compiler must check the context (operand types) and find a definition with the matching domain.

A type error occurs when no definition with that domain is found.

Type Checking

A type system enforces its rules by *type checking*:

- Analyzing the code, looking for type errors
- Only permitting programs without type errors to execute.
- A program with no type errors is described as *type safe*.

Type checking is accomplished at two levels:

1. *Static checking*: check for type-errors at *compile-time*.
2. *Dynamic checking*: check for type-errors at *run-time*.

Ada performs both static and dynamic checking, but the language is designed to maximize the number of errors that can be detected statically (i.e, by the compiler).

Static Checking Examples

a. In C++ expressions of the form: x % y

the compiler looks up the types of x and y
(in a data structure called the *symbol table*)
and rejects the expression if both are not of type int.

b. In C++ expressions of the form: sqrt(x)

the symbol table contains both the type *T* of argument x
and the domain-set *D* for which sqrt() is defined,
allowing the compiler to reject the expression if $T \notin D$.

- Original (K&R) C did not require that function prototypes contain parameter types, making it impossible for the compiler to type-check function calls (ANSI-C corrected this).

Dynamic Checking Examples

Dynamic checking is checking for errors only detectable at run-time by inserting checks before an expression's code.

Expression: x / y

```
// without dynamic checks
        mov x, R0
        div R0, y
```

```
-- with dynamic checking
        mov x, R0
        mov y, R1
        cmp R1, #0
        be  DivideByZero
        div R0, R1
```

A[i]

```
// without dynamic checks
        mov A, R0
        add R0, i
```

```
-- with dynamic checking
        mov A, R0
        mov i, R1
        cmp R1, firstIndex
        blt  IndexTooLow
        cmp R1, lastIndex
        bgt IndexTooHigh
        add R0, R1
```

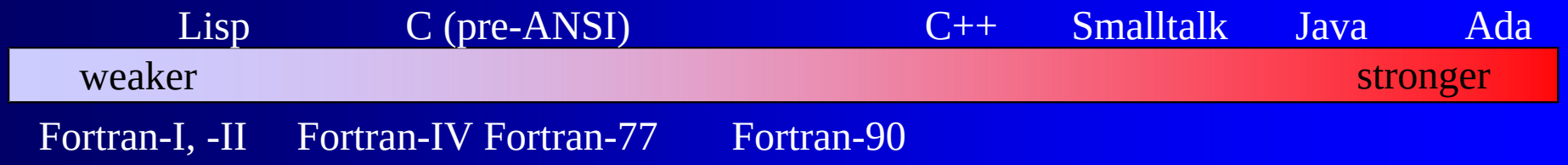
Dynamic checking is time- and space-expensive...

Type Strength

A language is *strongly-typed* if it has a strict type system.

A language is *weakly-typed* if it has a loose type system.

From this perspective, languages lie somewhere on a continuum, based on the the strength of their type system:



Language type systems have tended to stronger as they evolve through different versions.

- The importance of type-strength has increased as the systems being built have increased in size, complexity, and importance.

Type Compatibility

What determines if two types *T1* and *T2* are compatible (e.g., can *T1* arguments be passed to *T2* parameters)?

```
typedef int IntArray[32];
IntArray x, y;
// Are x, y compatible?
```

```
int x[32];
void f(int y[32]);
// Are x, y compatible?
```

```
struct Student {
  int id;
  string name;
};
Student stu;
```

```
struct Employee {
   int id;
   string name;
};
Employee emp;
```

```
// Are stu, emp compatible?
```

```
struct Student {
  int studentID;
  string studentName;
};
Student stu;
```

```
struct Employee {
   int empID;
   string empName;
};
Employee emp;
```

```
// Are stu, emp compatible?
```


Equivalence

Compatibility depends on whether a language views two types as *equivalent*.

There are two broad categories of equivalence:

- Languages that use structural equivalence view two types as equivalent if they have *the same memory structure*.
- Languages that use name equivalence view two types as equivalent if they are declared using the same name.

To illustrate, suppose that we have these declarations:

```
struct Student {                    struct Employee {
  int studentID;                       int empID;
  string studentName;                  string empName;
};                                  };
Student stu;                        Employee emp;
// Are stu, emp equivalent?
```


Structural Equivalence (SE)

Structural equivalence relies on three "rules":

- SE1: *A type name is structurally equivalent to itself.*

```
Student stu1;
Student stu2;
```

→ Since their types have the same name, *stu1* and *stu2* are structurally equivalent.

- SE2: *Two types formed by applying the same constructor to SE types are structurally equivalent.*

```
Student stu;
Employee emp;
```

→ Since both are members of (int x string), *stu* and *emp* are structurally equivalent.

- SE3: *If one type is an alias of another, the two types are structurally equivalent.*

```
typedef Student Transfer;
Student stu;
Transfer trans;
```

→ Since *Transfer* is an alias of *Student*, *stu* and *trans* are structurally equivalent.

Name Equivalence (NE)

There are different varieties of name equivalence:

- Pure NE: To be equivalent, types must have the same name.

```
-- Ada uses pure name equivalence
type IntArray is array(1..32) of Integer;
type IntList is array(1..32) of Integer;

a1: IntArray;
a2: IntList;
a3: IntArray;
a4: array(1..32) of Integer;
a5: array(1..32) of Integer;
```

→ Since *a1* and *a3* are declared with the same name, they are equivalent.

→ If we declare: `procedure print(IntArray anArray);`
then Ada's type system will only accept a1 and a3 as arguments.

→ *a2's* type has a name, but it is a different name from the others.

→ *a4* and *a5's* types have no name: anonymous types in Ada.

Name Equivalence (ii)

- Transitive NE: *A type name is equivalent to itself (pure NE), plus it can be declared equivalent to other type names.*

```
-- C++ uses transitive name equivalence
struct Student {                          struct Employee {
  int idNumber;                              int idNumber;
  string name;                               string name;
};                                        };
typedef Student Transfer;
Student stu;                              Employee emp;
Transfer trans;
```

→ *stu* and *trans* are compatible; *emp* is not compatible to either.

→ If we declare: `void print(Student aStudent);`
then the type system will only accept *stu* or *trans* as arguments, but will reject *emp* as an argument.

Which is better?

- Consider type-checking on aggregates:
  - Type-checking is much simpler under name equivalence, as the type-checker just has to do a single comparison (T1 == T2).
  - Under structural equivalence, the type-checker must do *an exhaustive field-by-field comparison* (e.g., nested records??).
- Name equivalence encourages abstraction:
  - NE encourages detail-hiding (ADT) by rejecting anonymous types:

```
procedure Put(seq: Sequence);
```

→ Any Sequence accepted.

```
procedure Put(seq: array(1..32) of Integer);
```

→ Nothing accepted.

  - SE discourages abstraction by accepting anonymous types:
    SE may permit programs to be written faster (abstraction takes time).
    Such programs may be harder to maintain; may be type-unsafe.

Summary

A type consists of *data and operations*.

The set constructors: *product*, *function*, and *Kleene closure* provide a formal way to represent type construction, using *product* and *Kleene closure* to represent the *data*, and *function* to represent the *operations* on the new type.

Enumerations let us use *real-world values* for type data.

Subranges constrain the values of existing data types.

Arrays and vectors are sequences stored in *adjacent memory locations* that permit *O(1)* time access to any value.

Lists are sequences stored in *dynamically allocated nodes*, that require *O(n)* time (on average) to access a value.

Summary (ii)

Aggregates store *multiple values of arbitrary types*.

Pointers store *addresses*, permit us to build linked nodes.

A *type system* performs type-checking using *structural equivalence* or a version of name *equivalence*.

Type-checking may be:

- *Static*: done at *compile-time*; and/or
- *Dynamic*: done at *run-time*.

The more type-checking a language requires, the stronger its type-system, and the fewer type-errors slip past.

Ada has a very strong type-system.