Typing, Parameter Passing, Lazy Evaluation
Dynamic and Static Typing (EPL 4.1-4.4, VRH 2.8.3)
Parameter Passing (VRH 6.1-6.4.4)
Lazy Evaluation (VRH 4.5)

Carlos Varela
Rensselaer Polytechnic Institute
April 30, 2012

Partially adapted with permission from:
Seif Haridi
KTH
Peter Van Roy
UCL
Data types

• A datatype is a set of values and an associated set of operations
• An abstract datatype is described by a set of operations
• These operations are the only thing that a user of the abstraction can assume
• Examples:
  – Numbers, Records, Lists,… (Oz basic data types)
  – Stacks, Dictionaries,… (user-defined secure data types)
Types of typing

• Languages can be **weakly typed**
  – Internal representation of types can be manipulated by a program
    • e.g., a string in C is an array of characters ending in ‘\0’.

• **Strongly typed** programming languages can be further subdivided into:
  – *Dynamically typed* languages
    • Variables can be bound to entities of any type, so in general the type is only known at **run-time**, e.g., Oz, SALSA.
  – *Statically typed* languages
    • Variable types are known at **compile-time**, e.g., C++, Java.
Type Checking and Inference

• **Type checking** is the process of ensuring a program is well-typed.
  – One strategy often used is *abstract interpretation*:
    • The principle of getting partial information about the answers from partial information about the inputs
    • Programmer supplies types of variables and type-checker deduces types of other expressions for consistency

• **Type inference** frees programmers from annotating variable types: types are inferred from variable usage, e.g. ML.
Example: The identity function

- In a dynamically typed language, e.g., Oz, it is possible to write a generic function, such as the identity combinator:

  \[
  \text{fun } \{\text{Id } X\} \ X \ \text{end}
  \]

- In a statically typed language, it is necessary to assign types to variables, e.g. in a **statically typed variant of Oz** you would write:

  \[
  \text{fun } \{\text{Id } X:\text{integer}\}:\text{integer} \ X \ \text{end}
  \]

These types are checked at compile-time to ensure the function is only passed proper arguments. \{\text{Id 5}\} is valid, while \{\text{Id Id}\} is not.
Example: Improper Operations

- In a dynamically typed language, it is possible to write an improper operation, such as passing a non-list as a parameter, e.g. in Oz:

  ```
  declare fun {ShiftRight L} 0|L end
  {Browse {ShiftRight 4}} % unintended misuse
  {Browse {ShiftRight [4]}} % proper use
  ```

- In a statically typed language, the same code would produce a type error, e.g. in a statically typed variant of Oz you would write:

  ```
  declare fun {ShiftRight L:List}:List 0|L end
  {Browse {ShiftRight 4}} % compiler error!!
  {Browse {ShiftRight [4]}} % proper use
  ```
Example: Type Inference

• In a statically typed language with type inference (e.g., ML), it is possible to write code without type annotations, e.g. using Oz syntax:

```
declare fun {Increment N} N+1 end
{Browse {Increment [4]}} % compiler error!!
{Browse {Increment 4}} % proper use
```

• The type inference system knows the type of ’+’ to be:

\[
\text{<number>} \times \text{<number>} \rightarrow \text{<number>}
\]

Therefore, `Increment` must always receive an argument of type `<number>` and it always returns a value of type `<number>`.
Static Typing Advantages

- Static typing restricts valid programs (i.e., reduces language’s expressiveness) in return for:
  
  - Improving error-catching ability
  - Efficiency
  - Security
  - Partial program verification
Dynamic Typing Advantages

- Dynamic typing allows all syntactically legal programs to execute, providing for:
  - Faster prototyping (partial, incomplete programs can be tested)
  - Separate compilation---independently written modules can more easily interact---which enables open software development
  - More expressiveness in language
Combining static and dynamic typing

• Programming language designers do not have to make an *all-or-nothing* decision on static vs dynamic typing.
  – e.g, Java has a root `Object` class which enables *polymorphism*
    • A variable declared to be an `Object` can hold an instance of any (non-primitive) class.
    • To enable static type-checking, programmers need to annotate expressions using these variables with *casting* operations, i.e., they instruct the type checker to pretend the type of the variable is different (more specific) than declared.
    • Run-time errors/exceptions can then occur if type conversion (casting) fails.

• Alice (Saarland U.) is a statically-typed variant of Oz.
Parameter Passing Mechanisms

- Operations on data types have arguments and results. Many mechanisms exist to pass these arguments and results between calling programs and abstractions, e.g.:
  - Call by reference
  - Call by variable
  - Call by value
  - Call by value-result
  - Call by name
  - Call by need

- We will show examples in Pascal-like syntax, with semantics given in Oz language.
Call by reference

```
procedure sqr(a:integer, var b:integer);
begin
    b:=a*a
end

var i:integer;
sqr(25, i);
writeln(i);
```

- The variable passed as an argument can be changed inside the procedure with visible effects outside after the call.
- The $B$ inside Sqr is a synonym (an alias) of the $I$ outside.
- The default mechanism in Oz is call by reference.

C. Varela
Call by variable

procedure sqr(var a:integer);
begin
    a:=a*a
end

var i:integer;
i:=25;
sqr(i);
writeln(i);

proc {Sqr A}
    A:=@A*@A
end

local I = {NewCell 0} in
    I := 25
    {Sqr I}
    {Browse @I}
end

• Special case of call by reference.
• The identity of the cell is passed to the procedure.
• The A inside Sqr is a synonym (an alias) of the I outside.
Call by value

procedure sqr(a:integer);
begin
  a:=a+1;
  writeln(a*a)
end

var i:integer;
i:=25;
sqr(i);
writeln(i);

• A value is passed to the procedure. Any changes to the value inside the procedure are purely local, and therefore, not visible outside.
• The local cell C is initialized with the argument A of Sqr.
• Java uses call by value for both primitive values and object references.
• SALSA uses call by value in both local and remote message sending.
Call by value-result

procedure sqr_inc(inout a:integer);
begin
   a := a * a
   a := a + 1
end

var i:integer;
i := 25;
sqr_inc(i);
writeln(i);

• A modification of call by variable. Variable argument can be modified.
• There are two mutable variables: one inside Sqr (namely D) and one outside (namely C). Any intermediate changes to the variable inside the procedure are purely local, and therefore, not visible outside.
• inout is ADA terminology.

C. Varela
Call by name

procedure sqr(callbyname a:integer);
begin
    a:=a*a
end

var i:integer;
i:=25;
sqr(i);
writeln(i);

proc {Sqr A}
    {A} := @A * @A
end

local C = {NewCell 0} in
C := 25
{Sqr fun {$} C end}
{Browse @C}
end

• Call by name creates a function for each argument (a thunk). Calling the function evaluates and returns the argument. Each time the argument is needed inside the procedure, the thunk is called.
• Thunks were originally invented for Algol 60.
Call by need

procedure sqr(callbyneed a:integer);
begin
    a:=a*a
end

var i:integer;
i:=25;
sqr(i);
writeln(i);

proc {Sqr A}
    B = {A} % only if argument used!!
in
    B := @B * @B
end

local C = {NewCell 0} in
    C := 25
    {Sqr fun {$} C end}
    {Browse @C}
end

• A modification of call by name. The thunk is evaluated at most once. The result is stored and used for subsequent evaluations.
• Call by need is the same as lazy evaluation. Haskell uses lazy evaluation.
• Call by name is lazy evaluation without memoization.
Which one is right or best?

- It can be argued that call by reference is the most primitive.
  - Indeed, we have coded different parameter passing styles using call by reference and a combination of cells and procedure values.
  - Arguably, call by value (along with cells and procedure values) is just as general. E.g., the example given for call by variable would also work in a call by value primitive mode. Exercise: Why?

- When designing a language, the question is: for which mechanism(s) to provide linguistic abstractions?
  - It largely depends on intended language use, e.g., call by name and call by need are integral to programming languages with lazy evaluation (e.g., Haskell and Miranda.)
  - For concurrent programs, call by value-result can be very useful (e.g. Ada.)
  - For distributed programs, call by value is best due to state encapsulation (e.g., SALSA.)
More parameter passing styles

• Some languages for distributed computing have support for call-by-move.
  – Arguments to remote procedure calls are temporarily migrated to the remote location for the time of the remote procedure execution (e.g., Emerald).
  – A dual approach is to migrate the object whose method is to be invoked to the client side before method invocation (e.g., Oz).

• Java Remote Method Invocation (RMI) dynamically determines mechanism to use depending on argument types:
  – It uses call by reference in remote procedure calls, if and only if, arguments implement a special (Remote) interface
  – Otherwise, arguments are passed using call by value.
    • => Semantics of method invocation is different for local and remote method invocations!!
  – There is no language support for object migration in Java (as there is in other languages, e.g., SALSA, Oz, Emerald), so call by move is not possible.
Lazy evaluation

- The default functions in Oz are evaluated *eagerly* (as soon as they are called)
- Another way is lazy evaluation where a computation is done only when the result is needed

- Calculates the infinite list:
  
  \[
  0 \mid 1 \mid 2 \mid 3 \mid \ldots
  \]

```oz
declare
  fun lazy {Ints N}
    N|{Ints N+1}
  end
```

C. Varela; Adapted from S. Haridi and P. Van Roy
Lazy evaluation (2)

• Write a function that computes as many rows of Pascal’s triangle as needed
• We do not know how many beforehand
• A function is lazy if it is evaluated only when its result is needed
• The function \texttt{PascalList} is evaluated when needed

\begin{verbatim}
fun lazy {PascalList Row}
    Row | {PascalList \{AddList Row \{ShiftRight Row\}\}}
end
\end{verbatim}
Lazy evaluation (3)

- Lazy evaluation will avoid redoing work if you decide first you need the 10\textsuperscript{th} row and later the 11\textsuperscript{th} row
- The function continues where it left off

```
declare
L = {PascalList [1]}
{Browse L}
{Browse L.1}
{Browse L.2.1}
```

```
L<Future>
[1]
[1 1]
```
Lazy execution

- Without lazyness, the execution order of each thread follows textual order, i.e., when a statement comes as the first in a sequence it will execute, whether or not its results are needed later.
- This execution scheme is called *eager execution*, or *supply-driven* execution.
- Another execution order is that a statement is executed only if its results are needed somewhere in the program.
- This scheme is called *lazy evaluation*, or *demand-driven* evaluation (some languages use lazy evaluation by default, e.g., Haskell).
Example

\[ B = \{F1 \ X\} \]
\[ C = \{F2 \ Y\} \]
\[ D = \{F3 \ Z\} \]
\[ A = B + C \]

- Assume F1, F2 and F3 are lazy functions
- B = \{F1 \ X\} and C = \{F2 \ Y\} are executed only if and when their results are needed in A = B + C
- D = \{F3 \ Z\} is not executed since it is not needed
Example

- In lazy execution, an operation suspends until its result is needed.
- The suspended operation is triggered when another operation needs the value for its arguments.
- In general multiple suspended operations could start concurrently.

\[ A = B + C \]

\[ B = \{F1 \ X\} \]

\[ C = \{F2 \ Y\} \]
Example II

• In data-driven execution, an operation suspends until the values of its arguments results are available
• In general the suspended computation could start concurrently

B = \{F1 \, X\}

C = \{F2 \, Y\}

Data driven

A = B + C
Using Lazy Streams

fun {Sum Xs A Limit}
    if Limit>0 then
    case Xs of X|Xr then
    {Sum Xr A+X Limit-1}
    end
    else A end
end

local Xs S in
    Xs={Ints 0}
    S={Sum Xs 0 1500}
    {Browse S}
end
How does it work?

fun \{\text{Sum} \ Xs \ A \ \text{Limit}\} \\
\quad \text{if} \ \text{Limit}>0 \ \text{then} \\
\quad \quad \text{case} \ Xs \ \text{of} \ X|Xr \ \text{then} \\
\quad \quad \quad \{\text{Sum} \ Xr \ A+X \ \text{Limit}-1\} \\
\quad \quad \end{case} \\
\quad \text{else} \ A \ \text{end} \\
\end{if} \\
\end{end}

fun \text{lazy} \ \{\text{Ints} \ N\} \\
\quad N \mid \{\text{Ints} \ N+1\} \\
\end{end}

local Xs \ S \ \text{in} \\
\quad Xs = \{\text{Ints} \ 0\} \\
\quad S = \{\text{Sum} \ Xs \ 0 \ 1500\} \\
\quad \{\text{Browse} \ S\} \\
\end{end}
Improving throughput

• Use a lazy buffer
• It takes a lazy input stream In and an integer N, and returns a lazy output stream Out
• When it is first called, it first fills itself with N elements by asking the producer
• The buffer now has N elements filled
• Whenever the consumer asks for an element, the buffer in turn asks the producer for another element
The buffer example
The buffer

fun \{\text{Buffer1 In N}\}
   \text{End=}\{\text{List.drop In N}\}

fun \text{lazy} \{\text{Loop In End}\}
   \text{In.1|\{Loop In.2 End.2\}}

end

in
\{\text{Loop In End}\}
end

Traversing the In stream, forces the producer to emit N elements
fun {Buffer2 In N}
   End = thread
      {List.drop In N}
   end

fun lazy {Loop In End}
   In.1|{Loop In.2 End.2}
   end

in
   {Loop In End}
end

Traversing the In stream, forces the producer to emit N elements and at the same time serves the consumer.
fun \{\text{Buffer3 In N}\}
\begin{align*}
\text{End} &= \text{thread} \\
\quad &\{\text{List.drop In N}\} \\
\end{align*}
\text{end}

fun lazy \{\text{Loop In End}\}
\begin{align*}
\text{E2} &= \text{thread End.2 end} \\
\text{In.1|\{Loop In.2 E2\}} \\
\end{align*}
\text{end}
in \begin{align*}
\text{in} \\
\quad &\{\text{Loop In End}\} \\
\end{align*}
\text{end}

Traverse the In stream, forces the producer to emit N elements and at the same time serves the consumer, and requests the next element ahead
Larger Example: The Sieve of Eratosthenes

- Produces prime numbers
- It takes a stream 2...N, peals off 2 from the rest of the stream
- Delivers the rest to the next sieve
Lazy Sieve

fun lazy {Sieve Xs}
  X|Xr = Xs in
  X | {Sieve {LFilter
      Xr
        fun {$ Y} Y mod X \neq 0 end
      }}
  end

fun {Primes} {Sieve {Ints 2}} end
Lazy Filter

For the Sieve program we need a lazy filter

```plaintext
fun lazy {LFilter Xs F}
  case Xs
  of nil then nil
  [] X|Xr then
    if {F X} then X|{LFilter Xr F} else {LFilter Xr F} end
  end
end
```

Define streams implicitly

- Ones = 1 | Ones
- Infinite stream of ones
Define streams implicitly

- \( Xs = 1 \mid \{ \text{LMap } Xs \}
  \text{fun } \{ \$ X \} \ X+1 \text{ end} \}

- What is \( Xs \) ?
The Hamming problem

• Generate the first $N$ elements of stream of integers of the form: $2^a \cdot 3^b \cdot 5^c$ with $a, b, c \geq 0$ (in ascending order)
The Hamming problem

- Generate the first N elements of stream of integers of the form: $2^a \cdot 3^b \cdot 5^c$ with $a, b, c \geq 0$ (in ascending order)
The Hamming problem

• Generate the first N elements of stream of integers of the form: $2^a \cdot 3^b \cdot 5^c$ with $a, b, c \geq 0$ (in ascending order)
Lazy File Reading

fun {ToList FO}
    fun lazy {LRead} L T in
        if {File.readBlock FO L T} then
            T = {LRead}
        else T = nil {File.close FO} end
        L
    end
end
{LRead}

• This avoids reading the whole file in memory
List Comprehensions

• Abstraction provided in lazy functional languages that allows writing higher level set-like expressions
• In our context we produce lazy lists instead of sets
• The mathematical set expression
  \[ \{ x \times y \mid 1 \leq x \leq 10, \ 1 \leq y \leq x \} \]
• Equivalent List comprehension expression is
  \[ [X \times Y \mid X = 1..10 \ ; \ Y = 1..X] \]
• Example:
  \[ [1 \times 1 \ 2 \times 1 \ 2 \times 2 \ 3 \times 1 \ 3 \times 2 \ 3 \times 3 \ \ldots \ 10 \times 10] \]
List Comprehensions

- The general form is
- \[
\left[ f(x, y, \ldots, z) \mid x \leftarrow \text{gen}(a_1, \ldots, a_n) \ ; \ \text{guard}(x, \ldots) \\
y \leftarrow \text{gen}(x, a_1, \ldots, a_n) \ ; \ \text{guard}(y, x, \ldots) \\
\ldots
\right]
\]
- No linguistic support in Mozart/Oz, but can be easily expressed
Example 1

- $z = [x#x \mid x \gets \text{from}(1,10)]$
- $Z = \{\text{LMap} \{\text{LFrom} 1 \ 10\} \ \text{fun} \{\$ \ X\} \ X\#X \ \text{end}\}$

- $z = [x#y \mid x \gets \text{from}(1,10), y \gets \text{from}(1,x)]$
- $Z = \{\text{LFlatten}
         \{\text{LMap} \{\text{LFrom} 1 \ 10\} \ \text{fun} \{\$ \ X\} \ \{\text{LMap} \{\text{LFrom} 1 \ X\} \ \text{fun} \{\$ \ Y\} \ X\#Y \ \text{end} \} \end{end} \}$
Example 2

- \( z = [x\#y \mid x \leftarrow \text{from}(1,10), y \leftarrow \text{from}(1,x), x+y\leq 10] \)
- \( Z = \{ \text{LFilter} \}
\quad \{ \text{LFlatten} \}
\quad \{ \text{LMap} \} \{ \text{LFrom} 1 \ 10 \}
\text{fun} \{ x \} \{ \text{LMap} \} \{ \text{LFrom} 1 \ x \}
\text{fun} \{ y \} x\#y \text{ end}
\text{end}
\text{end}
\}
\text{fun} \{ x\#y \} x+y\leq 10 \text{ end} \} \}
Implementation of lazy execution

The following defines the syntax of a statement, ⟨s⟩ denotes a statement

⟨s⟩ ::= skip \hspace{1cm} \textit{empty statement}
  \quad | \quad \ldots
  \quad | \quad \text{thread} \langle s_1 \rangle \text{end} \hspace{1cm} \textit{thread creation}
  \quad | \quad \{\text{ByNeed} \ \text{fun}\{\$\} \langle e \rangle \text{end} \langle x \rangle \} \hspace{1cm} \textit{by need statement}

\hspace{1cm} \text{zero arity function}
\hspace{2cm} \text{variable}
A function value is created in the store (say f) and the function f is associated with the variable x. Execution proceeds immediately to the next statement.
A function value is created in the store (say f) with the variable x, and the function f is associated with the variable x. Execution proceeds immediately to the next statement.
Accessing the ByNeed variable

• $X = \{ \text{ByNeed fun} \{\$\} 111*111 \text{ end} \} \ ($by thread T0$)$

• Access by some thread T1
  – if $X > 1000$ then $\{ \text{Browse hello#X} \}$ end

  or

  – $\{ \text{Wait X} \}$
  – Causes $X$ to be bound to 12321 (i.e. 111*111)
Implementation

Thread T1
1. X is needed
2. start a thread T2 to execute F (the function)
3. only T2 is allowed to bind X

Thread T2
1. Evaluate $Y = \{F\}$
2. Bind X the value $Y$
3. Terminate T2
4. Allow access on X
Lazy functions

```plaintext
fun lazy {Ints N}
    N | {Ints N+1}
end

fun {Ints N}
    fun {F} N | {Ints N+1} end
in {ByNeed F}
end
```
Exercises

90. VRH Exercise 6.10.2 (page 482).
91. Explain why the call by variable example given would also work over a call by value primitive parameter passing mechanism. Give an example for which this is not the case.
92. Explain why call by need cannot always be encoded as shown in the given example by producing a counter-example. (Hint: recall the difference between normal order evaluation and applicative order evaluation in termination of lambda calculus expression evaluations.)
93. Create a program in which call by name and call by need parameter passing styles result in different outputs.
94. Can type inference always deduce the type of an expression?
   – If not, give a counter-example. How would you design a language to help it statically infer types for non-trivial expressions?
Exercises

95. Write a lazy append list operation LazyAppend. Can you also write LazyFoldL? Why or why not?

96. Exercise VRH 4.11.10 (pg 341)

97. Exercise VRH 4.11.13 (pg 342)

98. Exercise VRH 4.11.17 (pg 342)