Programming Language Concepts, CS2104

Lecture 1

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Programming Language Concepts

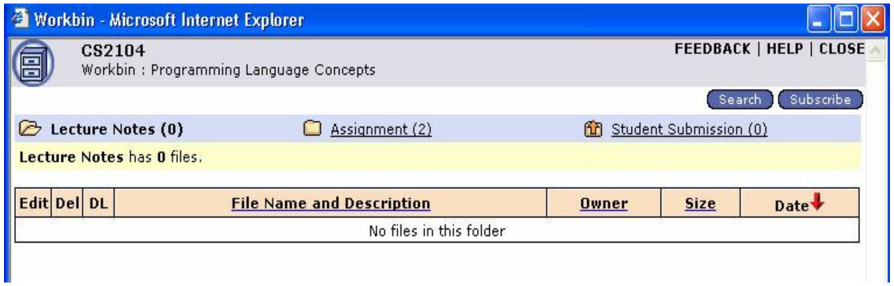
- CS2104 is a 4 credit points module
  - Written final exam 50%
  - Midterm exam 25%
  - Lab/tutorial assignments 25%
- Module homepage
  - http://www.comp.nus.edu.sg/~cs2104
  - IVLE
- Teaching
  - Lectures: Friday, 12:00-14:00, COM1/206
  - Exam: 27 Nov 2007, morning (Tue)

The Team

- Lectures
  - Dr. Chin Wei-Ngan (Consultation : Wed 9-11am but other times OK too but email me first.)
- Lectures based of the book:
  - Peter Van Roy, Seif Haridi: Concepts, Techniques, and Models of Computer Programming, The MIT Press, 2004
  - Slides from CS2104, 2003-2006
- Recommended books:
  - Allen Tucker, Robert Noonan: Programming Languages. Principles and Paradigms, McGraw Hill, 2002

Lab Assignment Submissions

- Student submission through IVLE
- Please use CS2104, Workbin



Lecture Structure

- Reminder of last lecture
- Overview
- Content (new notions + examples)
- Summary
- Reading suggestions

Tutorials/Labs

- Purposes
  - for self-assessment
  - use material from lectures
  - answer questions
  - help deeper understanding
  - prepare lab assignments
  - compulsory tutorial attendance + credits (up to 10%)
- Supervised lab session
  - First lab/assignment: to be announced
  - done by students (with help from teaching assistant)
- You can discuss tutorials/chapters on the IVLE discussion groups

Assignments

- There will be 4 or 5 lab assignments
- Deadline is strict! Don't leave till last-minute.
- Mostly individual programming projects
- Code of conduct
  - no copying (grade penalty for those caught)
  - plagiarism is cheating and can lead to expulsion!

Useful Software

- http://www.mozart-oz.org/
  - programming language: Oz
  - system: Mozart (1.3.0, released on April 15, 2004)
  - interactive system
- Requires `emacs` on your computer
- Available from module webpage: http://www.comp.nus.edu.sg/~cs2104/Materials/index.html
- Install yourself
- First lab/assignment will help on installation

Aim

- Knowledge and skills in
  - Programming languages concepts
  - Corresponding programming techniques
- Acquaintance with
  - Key programming concepts/techniques in computer science
  - Focus on concepts and not on a particular language

Overview

- Introduction of main concepts:
  - Computation model
  - Programming model
  - Reasoning model

Programming

- **Computation model**
  - formal system that defines a language and how sentences (expressions, statements) are executed by an abstract machine
- **Programming model**
  - a set of programming techniques and design principles used to write programs in the language of the computation model
- **Reasoning model**
  - a set of reasoning techniques to let you reason about programs, to increase confidence that they behave correctly, and to estimate their efficiency

Computation Models

- **Declarative** programming (stateless programming)
  - functions over partial data structures
- **Concurrent** programming
  - can interact with the environment
  - can do independent execution of program parts
- **Imperative** programming (stateful programming)
  - uses states (a state is a sequence of values in time that contains the intermediate results of a desired computation)
- **Object-oriented** programming
  - uses object data abstraction, explicit state, polymorphism, and inheritance

Programming Models

- **Exception handling**
  - Error management
- **Concurrency**
  - Dataflow, lazy execution, message passing, active objects, monitors, and transactions
- **Components**
  - Programming in the large, software reuse
- **Capabilities**
  - Encapsulation, security, distribution, fault tolerance
- **State**
  - Objects, classes

Reasoning Models

- **Syntax**
  - Extended Backus-Naur Form (EBNF)
  - Context-free and context-sensitive grammars
- **Semantics**
  - Operational: shows how a statement executes as an abstract machine
  - Axiomatic: defines a statement as a relation between input state and output state
  - Denotational: defines a statement as a function over an abstract domain
  - Logical: defines a statement as a model of a logical theory
- **Programming language**
  - Implements a programming model
  - Describes programs composed of **statements** which compute with **values** and **effects**

Examples of Programming Languages

- CS1102: Java
  - programming with explicit state
  - object-oriented programming
  - concurrent programming (threads, monitors)
- CS2104: Oz (multi-paradigm)
  - declarative programming
  - concurrent programming
  - programming with explicit state
  - object-oriented programming

Oz

- The focus is on the programming model, techniques and concepts, but **not** the particular language!
- Approach
  - informal introduction to important concepts
  - introducing the underlying kernel language
  - formal semantics based on abstract machine
  - in depth study of programming techniques

Declarative Programming Model Philosophy

- Ideal of declarative programming
  - say **what** you want to compute
  - let computer find **how** to compute it
- More pragmatically
  - let the computer provide more support
  - free the programmer from some burden

Properties of Declarative Models

- Focus on functions which compute when given data structures as inputs
- Widely used
  - functional languages: LISP, Scheme, ML, Haskell, …
  - logic languages: Prolog, Mercury, …
  - representation languages: XML, XSL, …
- Stateless programming
  - no update of data structures
  - Simple data transformer

The Mozart System

- Built by Mozart Consortium (Universität des Saarlandes, Swedish Institute of Computer Science, Université catholique de Louvain)
- Interactive interface (the `declare` statement)
  - Allows introducing program fragments incrementally and execute them
  - Has a tool (Browser), which allows looking into the store using the procedure `Browse`
    - `{Browse 21 * 10}` -> display `210`
- Standalone application
  - It consists of a main function, evaluated when the program starts
  - Oz source files can be compiled and linked

Concept of Single-Assignment Store

- It is a **set of variables** that are initially **unbound** and that can be **bound** to one value
- A **value** is a mathematical constant that does not change.

  For e.g : `2`, `~4`, `true`, `'a'`, `[1 2 3]`
- Examples:
  - $\{x_1, x_2, x_3\}$ has three unbound variables
  - $\{x_1$=`2`, x_2=`true`, $x_3\}$ has only one unbound variable

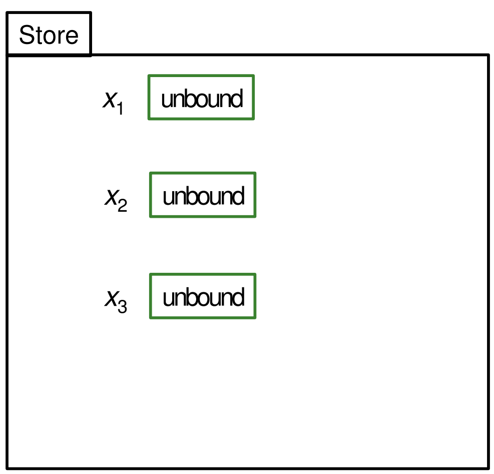
Concept of Single-Assignment Store

- A **store** where all variables are bound to values is called a **value store:**

  {x_1=`2`, x_2=`true`, x_3=`[1 2 3]`}
- Once bound, a variable stays bound to that value
- So, a **value store** is a persistent mapping from variables to values
- A **store entity** is a store variable and its value (which can be unbound).

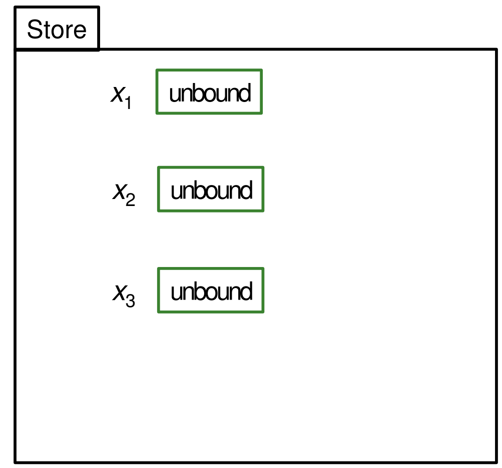
Concept of Single-Assignment Store

- Single-assignment store is set of (store) variables
- Initially variables are unbound
- Example: store with three variables, x_1, x_2, and x_3



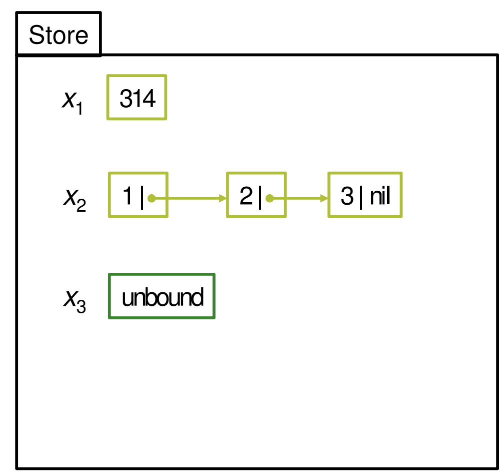
Concept of Single-Assignment Store

- Variables in store may be bound to values
- Example: assume we allow values of type integers and lists of integers



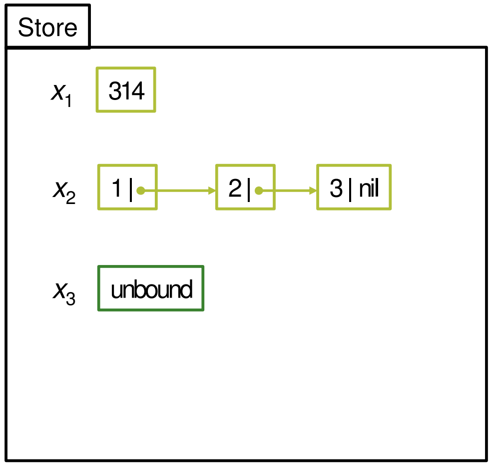
Concept of Single-Assignment Store

- Examples:
  - x_1 is bound to integer 314
  - x_2 is bound to list [1 2 3]
  - x_3 is still unbound



Concept of Declarative Variable

- It is a variable in the single-assignment store
- Created as being *unbound*
- Can be *bound* to exactly one value
- Once bound, stays bound
  - indistinguishable from its value

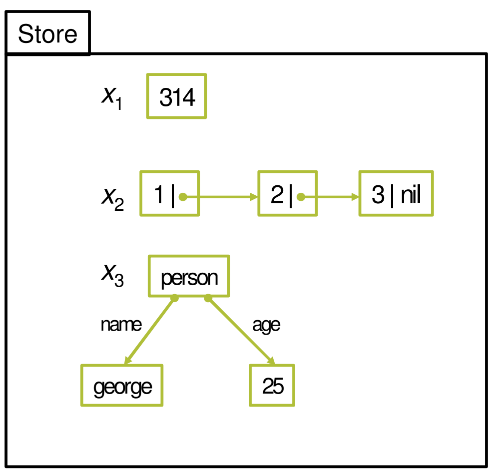


Concept of Value Store

- Store where all variables are bound to values is called a *value store*
- Examples:
  - x_1 bound to integer `314`
  - x_2 bound to list `[1 2 3]`
  - x_3 bound to record

```
person(name: george
       age: 25)
```

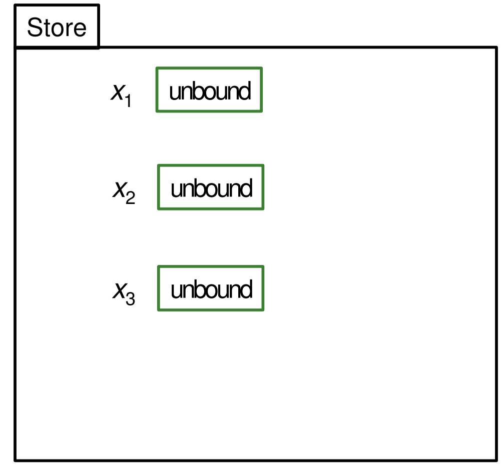
- Functional programming computes functions on values



Concept of Single-Assignment Operation

x = *value*

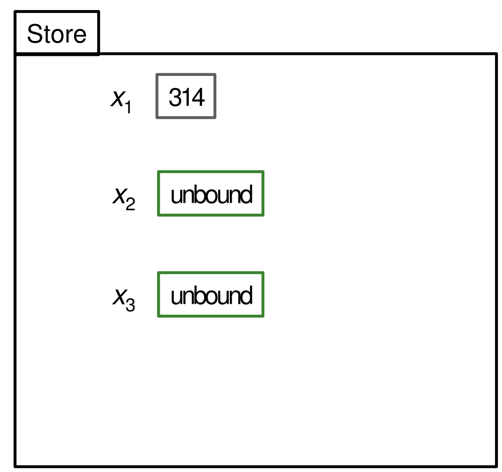
- It is also called "value creation"
- Assumes that *x* is unbound
- Examples:
  - x_1 = `314`
  - x_2 = `[1 2 3]`



Concept of Single-Assignment Operation

x = *value*

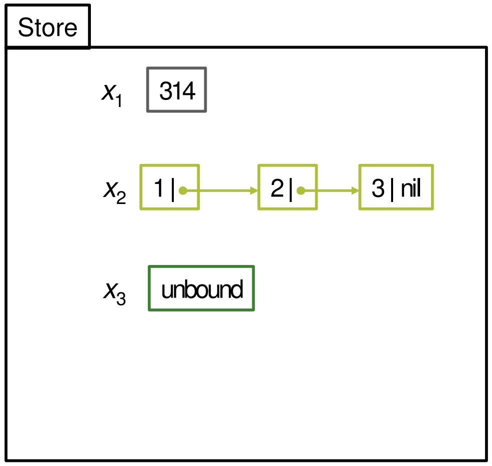
- **x_1 = `314`**
- x_2 = `[1 2 3]`



Concept of Single-Assignment Operation

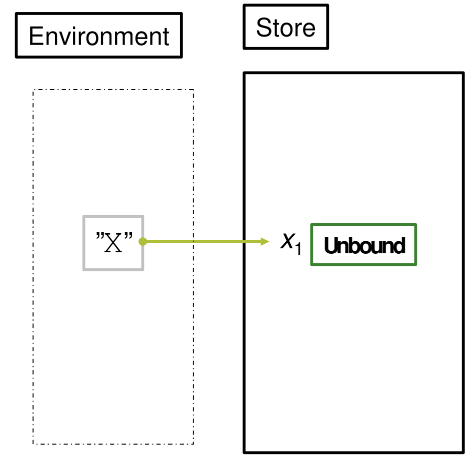
x = *value*

- *Single assignment operation* ('=')
  - constructs *value* in store
  - binds variable *x* to this value
- If the variable is already bound, operation tests compatibility of values
  - if the value being bound is different from that already bound, an error is raised



Concept of Variable Identifier

- Refer to store entities
- Environment maps variable identifiers to store variables
  - `declare X`
  - `local X in … end`
- `X` is variable identifier
- Corresponds to 'environment' {`X` → x_1}



Concept of Variable Identifier

- Variable identifiers start with capital letter: `X`, `Y2`
- The **environment** is a mapping from variable identifiers to store entities
- `declare X = <value>`
  - creates a new store variable *x* and binds it to `<value>`
  - maps variable identifier `X` in environment to store variable *x*, e.g. {`X`→*x*}
```
declare
X = Y
Y = 2
```

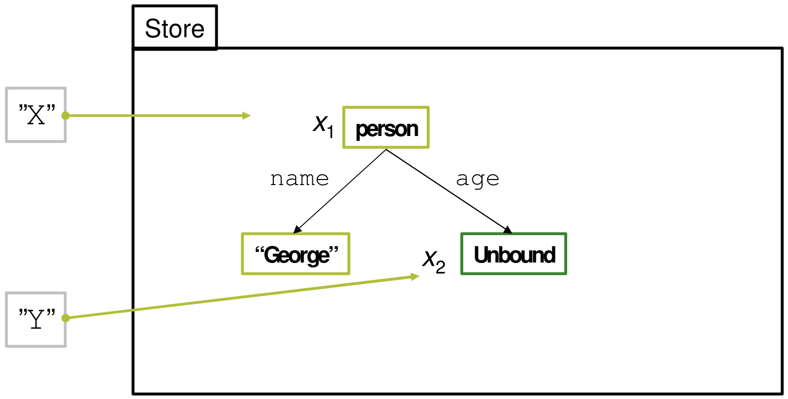
- The environment: E={`X`→*x*, `Y`→*y*}
- The single-assignment store: σ={*x*=*y*, *y*=2}

Concept of Variable Identifier

```
declare
X = 21
X = 22
% raise an error
X = 21
% do nothing
declare
X = 22
% from now on, X will be bound to 22
```

Partial Value

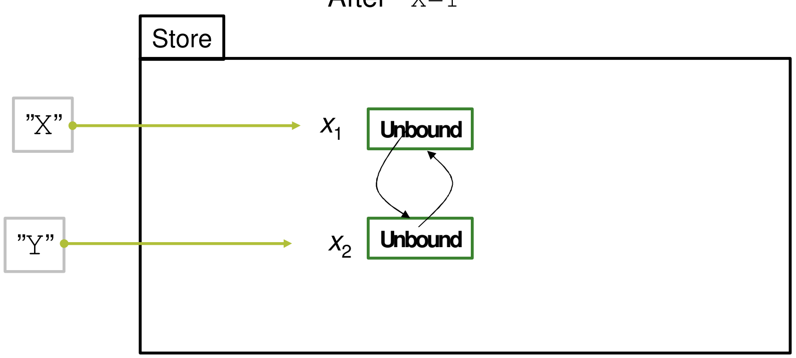
- A partial value is a data structure that *may* contain unbound variables. For example, x_2 is unbound. Hence, x_1 is a partial value.



Variable-Variable Binding

- Variables can be bound to variables. They form an **equivalence set** of store variables after such binding.
- They throw exception if their values are different.

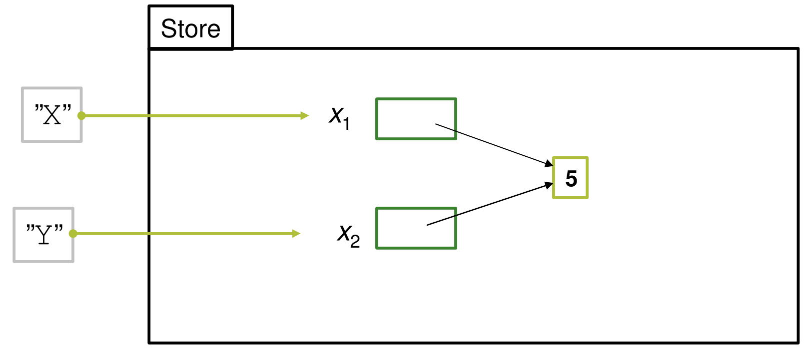
After `X=Y`



Variable-Variable Binding

- After binding one of the variables.

After `X=5`



Concept of Dataflow Variables

- Variable creation and binding can be separated. What happens if we use a variable before it is bound? Scenario is known as **variable use error.**
- Possible solutions:
  1. Create and bind variables in one step (use error cannot occur): functional programming languages
  2. Execution continues and no error message is given (variable's content is "garbage"): C/C++
  3. Execution continues and no error message is given (variable's content is initialized with a default value): Java

Concept of Dataflow Variables

- .....
  4. Execution stops with error message (or an exception is raised): Prolog
  5. Execution is not possible; the compiler detects that there is an execution path to the variable's use that does not initialize it: Java – local variables
  6. Execution waits until the variable is bound and then continues (dataflow programming): Oz

Example of Dataflow Variables

```
declare X Y
Y = X + 1
{Browse Y}
```

Running this Oz code, the Oz Browser does not display anything

```
X = 2
```

Running the previous line, the Oz Browser displays 3

Dynamic Typing in Oz

- A variable type is known only after the variable is bound
- For an unbound variable, its type checking is left for run time.
- An operation with values of wrong type will raise exceptions
- This setting is **dynamically typed.**
- In contrast, Java is a static type language, as the types of all variables can be determined at compile time
- Examples: Types of `X` maybe `Int, Float, ..`
  - `X < 1`
  - `X < 1.0`

Concept of Cell

- A **cell** is a multiple-assignment variable
- A memory cell is also called **explicit state**
- Three functions operate on cells:
  - `NewCell` creates a new cell
  - `:=` (assignment) puts a new value in a cell
  - `@` (access) gets the current value stored in the cell
- declare

```
declare
C = {NewCell 0}
{Browse @C}
C := @C + 1
{Browse @C}
```

Concept of Function

- Function definition

```
fun {<Identifier> <Arguments>}
   [<Declaration Part> in]
   [<Statement>]
    <Expression>
end
```

- The value of the **last expression in the body** is the **returned value** of the function
- Function application (call)

```
X = {<Identifier> <Arguments>}
```


Concept of Function. Examples

```
declare
fun {Minus X}
   ~X
end
{Browse {Minus 15}}
declare
fun {Max X Y}
   if X>Y then X else Y end
end
declare
X = {Max 22 18}
Y = {Max X 43}
{Browse Y}
```


Recursive Functions

- Direct recursion: the function is calling itself
- Indirect (or mutual) recursion: e.g. `F` is calling `G`, and `G` is calling `F`
- General structure
  - base case
  - recursive case
- Typically, for a natural number n
  - base case: n is zero
  - recursive case:
    - n is different from zero
    - n is greater than zero

Inductive Function Definition

- Factorial function: $n! = 1 * 2 * 3 * \ldots * n$
  - inductively defined as

    $0! = 1$

    $n! = n * ((n-1)!)$
  - program as function `Fact`

Inductive Function Definition

- Factorial function definition in Oz

```
fun {Fact N}
   if N == 0 then 1
   else N * {Fact N-1}
   end
end
{Browse {Fact 5}}
```


Correctness

- The most popular reasoning techniques is mathematical induction:
  - Show that for the simplest (initial) case the program is correct
  - Show that, if the program is correct for a given case, then it is correct for the next case
- `{Fact 0}` returns the correct answer, namely `1`
- Assume `{Fact N-1}` is correct. Suppose `N>0`, then `Fact N` returns `N*{Fact N-1}`, which is correct according to the Oz inductive hypothesis!
- `Fact N` for negative `N` goes into an infinite number of recursive calls, so it is wrong!

Complexity

- The execution time of a program as a function of input size, up to a constant factor, is called the program's **time complexity**.

```
declare
fun {Fibo N}
   case N of
      1 then 1
   [] 2 then 1
   [] M then {Fibo (M-1)} + {Fibo (M-2)}
   end
end
{Browse {Fibo 100}}
```

- The time complexity of `{Fibo N}` is proportional to 2^N.

Complexity

```
declare
fun {FiboTwo N A1 A2}
   case N of
      1 then A1
   [] 2 then A2
   [] M then {FiboTwo (M-1) A2 (A1+A2)}
   end
end
{Browse {FiboTwo 100 1 1}}
```

- The time complexity of `{FiboTwo N}` is proportional to `N`.

Concept of Lazy Evaluation

- **Eager** (supply-driven, or data-driven) **evaluation**: calculations are done as soon as they are called
- **Lazy** (demand-driven) **evaluation**: a calculation is done only when the result is needed

```
declare
fun lazy {F1 X} X*X end
fun lazy {Ints N} N|{Ints N+1} end
A = {F1 5}
{Browse A}
```

% it will display: `A`

Note that `{F1 5}` does not execute until it is demanded!

Concept of Lazy Evaluation

- `F1` and `Ints` created "stopped executions" that continue when their results are needed.
- After demanding value of `A` (function * is not lazy!), we get:

```
B = {Ints 3}
C = 2 * A        // A={F1 5}
{Browse A}
```

% it will display: `25`

```
{Browse B}
```

% it will display: `B`

```
case B of X|Y|Z|_ then {Browse X+Y+Z} end
```

% it will cause only first three elements of `B` to be evaluated and then display: `12`

% previous `B` is also refined to: `3|4|5|_`

Concept of Higher-Order Programming

- Ability to pass functions as arguments or results
- We want to write a function for `1+2+…+n` (GaussSum)
- It is similar to `Fact`, except that:
  - "`*`" is "`+`"
  - the initial case value is not "`0`" but "`1`"
- The two operators are written as functions; they will be arguments for the generic function

```
fun {Add X Y} X+Y end
fun {Mul X Y} X*Y end
```


Concept of Higher-Order Programming

- The generic function is:

```
fun {GenericFact Op InitVal N}
   if N == 0 then InitVal
   else {Op N {GenericFact Op
                     InitVal (N-1)}}
   end
end
```

Concept of Higher-Order Programming

- The instances of this generic function may be:

```
fun {FactUsingGeneric N}
         {GenericFact Mul 1 N}
end
fun {GaussSumUsingGeneric N}
         {GenericFact Add 0 N}
end
```

- They can be called as:

```
{Browse {FactUsingGeneric 5}}
{Browse {GaussSumUsingGeneric 5}}
```


Concept of Concurrency

- Is the ability of a program to run independent activities (not necessarily to communicate)
- A **thread** is an executing program
- Concurrency is introduced by creating threads

```
thread P1 in
   P1 = {FactUsingGeneric 5}
   {Browse P1}
end
thread P2 in
   P2 = {GaussSumUsingGeneric 5}
   {Browse P2}
end
```


Concept of Dataflow

- Is the ability of an operation to wait until all its variables become bounded

```
declare X in
thread {Delay 5000} X = 10 end
thread {Browse X * X} end
thread {Browse 'start'} end
```

- The second `Browse` waits for `X` to become bound
- `X = 10` and `X * X` can be done in any order, so dataflow execution will always give the same result

```
declare X in
thread {Delay 5000} {Browse X * X} end
thread X = 10 end
thread {Browse 'start'} end
```

- Dataflow concurrency (Chapter 4)

Concept of Object

- It is a function with internal memory (cell)

```
declare
local C in
   C = {NewCell 0}
   fun {Incr}
      C := @C + 1
      @C
   end
   fun {Read} @C end
end
```

- `C` is a counter object, `Incr` and `Read` are its interface
- The `declare` statement makes the variables `Incr` and `Read` globally available. `Incr` and `Read` are bounded to functions

Concept of Object-Oriented Programming

- Encapsulation
  - Variable `C` is visible only between `local` and last `end`
  - User can modify `C` only through `Incr` function (the counter will work correctly)
  - User can call only the functions (methods) from the interface

```
{Browse {Incr}}
{Browse {Read}}
```

- Data abstraction (Section 6.4)
  - Separation between interface and implementation
  - User program does not need to know the implementation
- Inheritance (Chapter 7)

Concept of Class

- It is a "factory" which creates objects

```
declare
fun {ClassCounter} C Incr Read in
   C = {NewCell 0}
   fun {Incr}
      C := @C + 1
      @C
   end
   fun {Read}
      @C
   end
   counter(incr:Incr read:Read)
end
```


Concept of Class

- `ClassCounter` is a function that creates a new cell and returns new functions: `Incr` and `Read` (recall higher-order programming)
- The record result groups the methods so that they can be accessed by its fields.

```
declare
Counter1 = {ClassCounter}
Counter2 = {ClassCounter}
```

- The methods can be accessed by "." (dot) operator

```
{Browse {Counter1.incr}}
{Browse {Counter2.read}}
```


Concept of Nondeterminism

- It is concurrency + state
- The order in which threads access the state can **change** from one execution to the next
- The time when operations are executed is not known
- Interleaving (mixed order of threads statements) is dangerous (one of most famous concurrent programming error :
  - [N.Leveson, C.Turner: An investigation of the Therac-25 accidents. *IEEE Computer*, 26(7):18-41, 1993])
- Solution: An operation is **atomic** if no intermediate states can be observed (Chapter 8)

Summary

- Oz, Mozart
- Variable, Type, Cell
- Function, Recursion, Induction
- Correctness, Complexity
- Lazy Evaluation
- Higher-Order Programming
- Concurrency, Dataflow
- Object, Classes
- Nondeterminism

Reading suggestions

- From [van Roy,Haridi; 2004]
  - Chapter 1
  - Appendix A
  - Exercises 1.18.1-1.18.10
- From [Tucker, Noonan; 2002]
  - Chapter 1
  - Exercises 1.1-1.7 from [Tucker, Noonan; 2002]
- First lab/assignment: Fri 24 Aug 2007 (15:00-18:00 Venue : ?) Compulsory attendance. Choose a 1-hr session.