

Lecture 6 – First-Order Functions

COSE212: Programming Languages

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2024 Fall

- **VAE – AE with variables**
 - Evaluation with Environments
 - Interpreter and Natural Semantics

- In this lecture, we will learn **first-order functions**.

- **F1VAE – VAE with first-order functions**
 - Concrete and Abstract Syntax
 - Interpreter and Natural Semantics

1. First-Order Functions
2. F1VAE – VAE with First-Order Functions
 - Concrete Syntax
 - Abstract Syntax
3. Interpreter and Natural Semantics for F1VAE
 - Evaluation with Function Environments
 - Function Application
 - Example
4. Static Scoping vs Dynamic Scoping
 - Example

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Let's calculate the square of several numbers in Scala.

```
3 * 3      // 9
42 * 42    // 1764
2434 * 2434 // 5925796
```

With a **first-order function**, we can avoid the repetition of the code.

```
// A `square` function that takes an integer `n` and returns its square.
def square(n: Int): Int = n * n

square(3)      // 9
square(42)     // 1764
square(2434)   // 5924356
```

A **first-order function** consists of 1) a function name, 2) a list of parameters, and 3) a function body, and it can be **invoked** with arguments.

Most programming languages support **first-order functions**.

- Scala

```
def square(n: Int): Int = n * n
```

```
square(3) // 9
```

- Python

```
def square(n): return n * n
```

```
square(3) # 9
```

- C++

```
int square(int n) { return n * n; }
```

```
square(3) // 9
```

- Rust

```
fn square(n: i32) -> i32 { return n * n; }
```

```
square(3) // 9
```

- ...

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Now, we want to extend VAE into F1VAE with **first-order functions**.

```
/* F1VAE */  
def square(n) = n * n;  
square(3) + 2 // 11
```

```
/* F1VAE */  
def add3(n) = n + 3;  
def mul2(m) = m * 2;  
mul2(add3(4)) // 14
```

- An F1VAE **program** is a pair of
 - ① a list of **function definitions**
 - ② an **expression**
- A **function definition** in F1VAE only has a **single parameter**.
- We extend **expressions** with **function applications**.

Let's define the **concrete syntax** of F1VAE in BNF:

- An F1VAE **program** is a pair of
 - ① a list of **function definitions**
 - ② an **expression**
- A **function definition** in F1VAE only has a **single parameter**.
- We extend **expressions** with **function applications**.

```
// programs
<program> ::= <fdef>* <expr>
// function definitions
<fdef> ::= "def" <id> "(" <id> ")" "=" <expr> ";"
// expressions
<expr> ::= ...
        | "{" <expr> "}" // block
        | "val" <id> "=" <expr> ";" <expr> // variable definition
        | <id> // identifier lookup
        | <id> "(" <expr> ")" // function application
```

Let's define the **abstract syntax** of F1VAE in BNF and its **ADT** in Scala:

Programs	$p ::= f^* e$	(Program)
Function Definitions	$\mathbb{F} \ni f ::= \text{def } x(x) = e$	(FunDef)
Expressions	$e ::= \dots$	
	$\text{val } x = e; e$	(Val)
	x	(Id)
	$x(e)$	(App)

```
// programs
case class Program(fdefs: List[FunDef], expr: Expr)
// function definitions
case class FunDef(name: String, param: String, body: Expr)
// expressions
enum Expr:
  ...
  case Val(name: String, init: Expr, body: Expr)
  case Id(name: String)
  case App(fname: String, arg: Expr) // function application
```

For example, let's **parse** the following F1VAE program:

```
/* F1VAE */  
def add3(n) = n + 3;  
def mul2(m) = m * 2;  
mul2(add3(4))
```

Then, the following **abstract syntax tree (AST)** is produced:

```
Program(  
  List(  
    FunDef("add3", "n", Add(Id("n"), Num(3))),  
    FunDef("mul2", "m", Mul(Id("m"), Num(2)))  
  ),  
  App("mul2", App("add3", Num(4)))  
)
```

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Let's evaluate the following F1VAE program:

```
/* F1VAE */  
def add3(n) = n + 3;  
def mul2(m) = m * 2;  
mul2(add3(4)) // 14
```

How to find the function definition of `add3` or `mul2`?

We need to construct a **function environment** that maps function names to function definitions from the **list of function definitions** in a program.

$$[\text{add3} \mapsto f_0, \text{mul2} \mapsto f_1]$$

where

$$\begin{aligned} f_0 &= \text{def add3}(n) = n + 3 \\ f_1 &= \text{def mul2}(m) = m * 2 \end{aligned}$$

For VAE, the interpreter takes an **expression** e with an **environment** σ and returns a number n as the result.

```
type Value = BigInt // values
type Env = Map[String, Value] // environments
def interp(expr: Expr, env: Env): Value = ... // interpreter
```

$$\sigma \vdash e \Rightarrow n$$

Now, we extend it to take a **function environment** Λ , a mapping from function names to function definitions, as well:

```
type Value = BigInt // values
type Env = Map[String, Value] // environments
type FEnv = Map[String, FunDef] // function environments
def interp(expr: Expr, env: Env, fenv: FEnv): Value = ... // interpreter
```

$$\sigma, \Lambda \vdash e \Rightarrow n$$

We have a **list of function definitions** in an F1VAE program, not a **function environment**, a mapping from function names to definitions.

```
case class Program(fdefs: List[FunDef], expr: Expr)
type FEnv = Map[String, FunDef]
```

How to construct a FEnv from a List[FunDef]?

```
def createFEnv(fdefs: List[FunDef]): FEnv =
  fdefs.foldLeft(Map.empty)((fenv: FEnv, fdef: FunDef) => {
    val fname: String = fdef.name
    if (fenv.contains(fname)) error(s"duplicate function: $fname")
    else fenv + (fname -> fdef)
  })
```

It will throw an error if there are **duplicate function names**:

```
createFEnv(List(
  FunDef("add3", "n", Add(Id("n"), Num(3))),
  FunDef("add3", "n", Add(Num(3), Id("n"))),
)) // error: duplicate function: add3
```

For F1VAE, we need to 1) implement the **interpreter**:

```
def interp(expr: Expr, env: Env, fenv: FEnv): Value = ???
```

and 2) define the **natural semantics** with environments and **function environments**:

$$\sigma, \Lambda \vdash e \Rightarrow n$$

Programs	$p ::= f^* e$	(Program)
Function Definitions	$\mathbb{F} \ni f ::= \text{def } x(x) = e$	(FunDef)
Expressions	$e ::= \dots$	
	$ x(e)$	(App)

where

Numbers	$n \in \mathbb{Z}$	(BigInt)
Identifiers	$x \in \mathbb{X}$	(String)
Environments	$\sigma \in \mathbb{X} \xrightarrow{\text{fin}} \mathbb{Z}$	(Env)
Function Environments	$\Lambda \in \mathbb{X} \xrightarrow{\text{fin}} \mathbb{F}$	(FEnv)


```
def interp(expr: Expr, env: Env, fenv: FEnv): Value = expr match
  ...
  case App(f, e) => ???
```

$$\sigma, \Lambda \vdash e \Rightarrow n$$

$$\text{App} \frac{\text{???}}{\sigma, \Lambda \vdash x_0(e_1) \Rightarrow \text{???}}$$

```
def interp(expr: Expr, env: Env, fenv: FEnv): Value = expr match
  ...
  case App(f, e) =>
    val fdef = fenv.getOrElse(f, error(s"unknown function: $f"))
    ...
```

$$\sigma, \Lambda \vdash e \Rightarrow n$$

$$x_0 \in \text{Domain}(\Lambda) \quad \Lambda(x_0) = \text{def } x_0(x_1) = e_2$$

$$\text{App} \frac{\dots}{\sigma, \Lambda \vdash x_0(e_1) \Rightarrow ???}$$

```
def interp(expr: Expr, env: Env, fenv: FEnv): Value = expr match
  ...
  case App(f, e) =>
    val fdef = fenv.getOrElse(f, error(s"unknown function: $f"))
    ... interp(e, env, fenv) ...
```

$$\boxed{\sigma, \Lambda \vdash e \Rightarrow n}$$

$$\text{App} \frac{\begin{array}{l} x_0 \in \text{Domain}(\Lambda) \quad \Lambda(x_0) = \text{def } x_0(x_1) = e_2 \\ \sigma, \Lambda \vdash e_1 \Rightarrow n_1 \quad \dots \end{array}}{\sigma, \Lambda \vdash x_0(e_1) \Rightarrow ???}$$

```
def interp(expr: Expr, env: Env, fenv: FEnv): Value = expr match
...
case App(f, e) =>
  val fdef = fenv.getOrElse(f, error(s"unknown function: $f"))
  ... Map(fdef.param -> interp(e, env, fenv)) ...
```

$$\boxed{\sigma, \Lambda \vdash e \Rightarrow n}$$

$$\text{App} \frac{\begin{array}{l} x_0 \in \text{Domain}(\Lambda) \quad \Lambda(x_0) = \mathbf{def} \ x_0(x_1) = e_2 \\ \sigma, \Lambda \vdash e_1 \Rightarrow n_1 \quad \dots [x_1 \mapsto n_1] \dots \end{array}}{\sigma, \Lambda \vdash x_0(e_1) \Rightarrow n_2}$$

```
def interp(expr: Expr, env: Env, fenv: FEnv): Value = expr match
  ...
  case App(f, e) =>
    val fdef = fenv.getOrElse(f, error(s"unknown function: $f"))
    interp(fdef.body, Map(fdef.param -> interp(e, env, fenv)), fenv)
```

$$\boxed{\sigma, \Lambda \vdash e \Rightarrow n}$$

$$\text{App} \frac{x_0 \in \text{Domain}(\Lambda) \quad \Lambda(x_0) = \text{def } x_0(x_1) = e_2 \quad \sigma, \Lambda \vdash e_1 \Rightarrow n_1 \quad [x_1 \mapsto n_1], \Lambda \vdash e_2 \Rightarrow n_2}{\sigma, \Lambda \vdash x_0(e_1) \Rightarrow n_2}$$

We skip the other cases because they are only augmented with passing function environments. If you are interested, please refer to this spec:

<https://github.com/ku-plrg-classroom/docs/blob/main/cose212/f1vae/f1vae-spec.pdf>

```
/* F1VAE */
def inc(x) = x + 1;
inc(2) // 3
```

Let's evaluate the above F1VAE program:

$$\text{APP} \frac{\Lambda(\text{inc}) = f \quad \text{NUM} \frac{}{\emptyset, \Lambda \vdash 2 \Rightarrow 2} \quad \text{ADD} \frac{\text{ID} \frac{x \in \text{Domain}(\sigma)}{\sigma, \Lambda \vdash x \Rightarrow 2} \quad \text{NUM} \frac{}{\sigma, \Lambda \vdash 1 \Rightarrow 1}}{\sigma, \Lambda \vdash x + 1 \Rightarrow 3}}{\emptyset, \Lambda \vdash \text{inc}(2) \Rightarrow 3}$$

where

$$\begin{aligned} \Lambda &= [\text{inc} \mapsto f] \\ f &= \text{def inc}(x) = x + 1 \\ \sigma &= [x \mapsto 2] \end{aligned}$$

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The current semantics is called **static scoping** (or **lexical scoping**) because a binding occurrence is determined statically without considering the function application but only the function definition.

```
/* F1VAE */  
def f(x) = x + y;          // y is a free variable  
{ val y = 2; f(1) } + { val y = 4; f(3) }
```

However, we can define the semantics of F1VAE in another way by using the **dynamic scoping** instead; a binding occurrence is determined dynamically when function application is executed:

```
/* F1VAE */  
def f(x) = x + y;          // y = 2 or y = 4 depending on the call-site  
{ val y = 2; f(1) } + { val y = 4; f(3) } // (1 + 2) + (3 + 4) = 10
```


We can design and implement the semantics of F1VAE with the **dynamic scoping** by changing the definition of the function application:

```
def interp(expr: Expr, env: Env, fenv: FEnv): Value = expr match
  ...
  case App(f, e) =>
    val fdef = fenv.getOrElse(f, error(s"unknown function: $f"))
    interp(fdef.body, env + (fdef.param -> interp(e, env, fenv)), fenv)
```

$$\sigma, \Lambda \vdash e \Rightarrow n$$

$$\text{App} \frac{x_0 \in \text{Domain}(\Lambda) \quad \Lambda(x_0) = \text{def } x_0(x_1) = e_2 \quad \sigma, \Lambda \vdash e_1 \Rightarrow n_1 \quad \sigma[x_1 \mapsto n_1], \Lambda \vdash e_2 \Rightarrow n_2}{\sigma, \Lambda \vdash x_0(e_1) \Rightarrow n_2}$$

However, we will use the **static scoping** by default in this course.

```
/* F1VAE */
def add(x) = x + y;
val y = 2; add(1)
```

If we evaluate the above F1VAE program with a **static scoping**:

$$\begin{array}{c}
 \text{NUM} \frac{}{\emptyset, \Lambda \vdash 2 \Rightarrow 2} \quad \text{APP} \frac{\Lambda(\text{add}) = f \quad \text{NUM} \frac{}{\sigma_0, \Lambda \vdash 1 \Rightarrow 1} \quad \text{ADD} \frac{\text{ID} \frac{x \in \text{Domain}(\sigma_1)}{\sigma_1, \Lambda \vdash x \Rightarrow 1} \quad \text{ID} \frac{y \notin \text{Domain}(\sigma_1)}{\sigma_1, \Lambda \vdash y \Rightarrow \text{FAIL}}{\sigma_1, \Lambda \vdash x + y \Rightarrow \text{FAIL}}}{\sigma_0, \Lambda \vdash \text{add}(1) \Rightarrow \text{FAIL}}}{\emptyset, \Lambda \vdash \text{val } y = 2; \text{ add}(1) \Rightarrow \text{FAIL}}
 \end{array}$$

where

$$\begin{aligned}
 \Lambda &= [\text{add} \mapsto f] \\
 f &= \text{def add}(x) = x + y \\
 \sigma_0 &= [y \mapsto 2] \\
 \sigma_1 &= [x \mapsto 1]
 \end{aligned}$$

it cannot be evaluated because y is a **free variable** in the add function.

```
/* F1VAE */
def add(x) = x + y;
val y = 2; add(1)
```

However, if we evaluate it with a **dynamic scoping**:

$$\begin{array}{c}
 \text{NUM} \frac{}{\emptyset, \Lambda \vdash 2 \Rightarrow 2} \quad \text{APP} \frac{\Lambda(\text{add}) = f \quad \text{NUM} \frac{}{\sigma_0, \Lambda \vdash 1 \Rightarrow 1} \quad \text{ADD} \frac{\text{ID} \frac{x \in \text{Domain}(\sigma_1)}{\sigma_1, \Lambda \vdash x \Rightarrow 1} \quad \text{ID} \frac{y \in \text{Domain}(\sigma_1)}{\sigma_1, \Lambda \vdash y \Rightarrow 2}}{\sigma_1, \Lambda \vdash x + y \Rightarrow 3}}{\sigma_0, \Lambda \vdash \text{add}(1) \Rightarrow 3}}{\emptyset, \Lambda \vdash \text{val } y = 2; \text{ add}(1) \Rightarrow 3} \\
 \text{VAL} \frac{}{}
 \end{array}$$

where

$$\begin{aligned}
 \Lambda &= [\text{add} \mapsto f] \\
 f &= \text{def add}(x) = x + y \\
 \sigma_0 &= [y \mapsto 2] \\
 \sigma_1 &= \sigma_0[x \mapsto 1] = [y \mapsto 2, x \mapsto 1,]
 \end{aligned}$$

it evaluates to 3 because y is **dynamically bound** to 2.

Programs	$p ::= f^* e$	(Program)
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Expressions	$e ::= \dots$	
	$x(e)$	(App)

```

type FEnv = Map[String, FunDef]
def interp(expr: Expr, env: Env, fenv: FEnv): Value = expr match
  ...
  case App(f, e) =>
    val fdef = fenv.getOrElse(f, error(s"unknown function: $f"))
    interp(fdef.body, Map(fdef.param -> interp(e, env, fenv)), fenv)

```

$$\sigma, \Lambda \vdash e \Rightarrow n$$

$$\text{App} \frac{\begin{array}{l} x_0 \in \text{Domain}(\Lambda) \quad \Lambda(x_0) = \text{def } x_0(x_1) = e_2 \\ \sigma, \Lambda \vdash e_1 \Rightarrow n_1 \quad [x_1 \mapsto n_1], \Lambda \vdash e_2 \Rightarrow n_2 \end{array}}{\sigma, \Lambda \vdash x_0(e_1) \Rightarrow n_2}$$

<https://github.com/ku-plrg-classroom/docs/tree/main/cose212/f1vae>

- Please see above document on GitHub:
 - Implement `interp` function.
 - Implement `interpDS` function.
- It is just an exercise, and you **don't need to submit** anything.
- However, some exam questions might be related to this exercise.

- First-Class Functions

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