Lecture 6 – First-Order Functions

COSE212: Programming Languages

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PLRG

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Recall

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

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

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  - 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

Contents

Contents

First-Order Functions

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

```
1 * 1       // 1
2 * 2       // 4
3 * 3       // 9
42 * 42     // 1764
2434 * 2434 // 5925796
```

First-Order Functions

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

```
1 * 1       // 1
2 * 2       // 4
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(1)    // 1
square(2)    // 4
square(3)    // 9
square(42)   // 1764
square(2434) // 5924356
```

First-Order Functions

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

- Scala

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

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

- Python

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

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

- C++

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

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

- Rust

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

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

- ...

Contents

F1VAE – VAE with First-Order Functions

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
```

F1VAE – VAE with First-Order Functions

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- An F1VAE **program** is a pair of
  1. a list of **function definitions**
  2. an **expression**

- We extend **expressions** with **function applications**.

Concrete Syntax

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

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Concrete Syntax

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

- An F1VAE **program** is a pair of
  1. a list of **function definitions**
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- We extend **expressions** with **function applications**.

```
// programs
<program> ::= <fdef>* <expr>

// function definitions
<fdef>    ::= "def" <id> "(" <id> ")" "=" <expr> ";"

// expressions
<expr>    ::= ...
            | "{" <expr> "}"
            | "val" <id> "=" <expr> ";" <expr>
            | <id>
            | <id> "(" <expr> ")"
```

Abstract Syntax

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

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

Abstract Syntax

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

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Function Definitions	$\mathbb{F} \ni f$	$::=$	`def` $x(x)$`=`e	(`FunDef`)
Expressions	$\mathbb{E} \ni e$	$::=$	$\ldots$	
		$\mid$	`val` x`=`e; e	(`Val`)
		$\mid$	x	(`Id`)
		$\mid$	$x(e)$	(`App`)

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

Abstract Syntax

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)))
)
```

Contents

Evaluation with Function Environments

Let's evaluate the following F1VAE program:

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

Evaluation with Function Environments

Let's evaluate the following F1VAE program:

```
/* F1VAE */
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How to find the function definition of `add3` or `mul2`?

Evaluation with Function Environments

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```
/* 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.

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

where

$$\begin{array}{rcl} f_0 & = & \texttt{def add3}(n)\texttt{=}n + 3 \\ f_1 & = & \texttt{def mul2}(m)\texttt{=}m \times 2 \end{array}$$

Evaluation with Function Environments

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
```

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

Evaluation with Function Environments

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
```

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

Constructing Function Environments

However, an F1VAE program only contains a **list of function definitions**.

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Then, how to construct a **function environment** from a **list of function definitions**?

```scala
def createFEnv(fdefs: List[FunDef]): FEnv = fdefs.foldLeft(Map.empty) {
  case (m: FEnv, fdef: FunDef) =>
    val fname: String = fdef.name
    // check if the function name is already in the function environment
    if (m.contains(fname)) error(s"duplicate function: $fname")
    else m + (fname -> fdef)
}
```

Constructing Function Environments

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Then, how to construct a **function environment** from a **list of function definitions**?

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def createFEnv(fdefs: List[FunDef]): FEnv = fdefs.foldLeft(Map.empty) {
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    // check if the function name is already in the function environment
    if (m.contains(fname)) error(s"duplicate function: $fname")
    else m + (fname -> fdef)
}
```

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

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

Interpreter and Natural Semantics for F1VAE

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

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

Interpreter and Natural Semantics for F1VAE

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**:

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

Programs	$\mathbb{P} \ni p$	$::=$	$f^*\ e$	(Program)
Function Definitions	$\mathbb{F} \ni f$	$::=$	$\texttt{def}\ x(x)\texttt{=}e$	(FunDef)
Expressions	$\mathbb{E} \ni e$	$::=$	$\ldots$	
		$\mid$	$x(e)$	(App)

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

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Function Definitions	$\mathbb{F} \ni f$	$::=$	`def` $x(x)$`=`e	(`FunDef`)
Expressions	$\mathbb{E} \ni e$	$::=$	$\ldots$	
		$\mid$	$x(e)$	(`App`)

where

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

Function Application

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

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

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

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"))
    ...
```

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

$$\texttt{App}\ \frac{x_0 \in \text{Domain}(\Lambda) \qquad \Lambda(x_0) = \texttt{def}\ x_0(x_1)\texttt{=}e_2 \qquad \cdots}{\sigma, \Lambda \vdash x_0(e_1) \Rightarrow \texttt{???}}$$

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(e, env, fenv) ...
```

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

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Function Application

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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)) ...
```

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

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

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Function Application

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```
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  ...
  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)
```

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

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

Contents

Static Scoping vs Dynamic Scoping

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) }
```

Static Scoping vs Dynamic Scoping

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```
/* 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
```

Static Scoping vs Dynamic Scoping

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

```scala
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)
```

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

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

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

Summary

$$
\begin{array}{llcll}
\text{Programs} & \mathbb{P} \ni p & ::= & f^* \; e & (\texttt{Program}) \\
\text{Function Definitions} & \mathbb{F} \ni f & ::= & \texttt{def } x(x)\texttt{=}e & (\texttt{FunDef}) \\
\text{Expressions} & \mathbb{E} \ni e & ::= & \ldots & \\
 & & \mid & x(e) & (\texttt{App})
\end{array}
$$

```
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)
```

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

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

Exercise #3

- Please see this document[1] 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.

[1] https://github.com/ku-plrg-classroom/docs/tree/main/cose212/f1vae.

Next Lecture

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- First-Class Functions

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