CSE 341: Programming Languages

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Lecture 16— define-struct; Implementing higher-order functions

Data in Scheme

Recall ML's approach to each-of, one-of, and self-referential types:

```
datatype t =
  Foo of int | Bar of int * int | Baz of string * t
```

Pure Scheme's approach:

- There is One Big Datatype holding *every value*.
- Built-in predicates like `null?`, `number?`, `procedure?`
- Primitives implicitly raise errors for "wrong variant"
- Use pairs (lists) for each-of types
- Can also use for one-of types with explicit "tags"
  - Like our force/delay with a boolean field
  - Symbols better style (e.g., `'apple`, `'banana`)
- Use helper functions like `caddr` (and/or define your own).

Dynamic typing

There is still good reason to have support for *constructors*:

- Make a `foo` that has fields `x`, `y`, `z`
- Test to see if you have a `foo` or not

But with dynamic typing:

- Constructors are not "grouped" into types (just added to the One Big Datatype)
- The fields can hold anything

Orthogonally: We don't have pattern-matching.

`define-struct`

DrScheme extends Scheme with `define-struct`, e.g.:

```
(define-struct card (suit value))
```

Semantics: Introduce several new bindings...

- *constructor* (`make-card`) that takes arguments and make values (like `cons`)
- *predicate* (`card?`) that takes 1 argument, return `#t` only for values made from the right constructor (like `cons?`).
- *accessors* (`card-suit`, `card-value`) that take 1 argument, return a field, or call `error` for values not made from the right constructor (like `car` and `cdr`).
- *mutators* (`set-card-suit!`, `set-card-value!`) that are like accessors except they mutate field contents (like `set-car!` and `set-cdr!`).

Idiom for ML datatypes

Instead of a `datatype` with n constructors, you just use `define-struct` n times.

That "these n go together" is just convention.

Instead of `case`, you have a `cond` with n predicates and one "catch-all" error case.

For homework 5:

```
  ;; a variable, e.g., (make-var "foo")
(define-struct var  (string))
  ;; a constant number, e.g., (make-int 17)
(define-struct int  (num))
(define-struct add  (e1 e2))  ;; add two expressions
(define-struct ifgreater (e1 e2 e3 e4)) ;; etc.
...
```

`define-struct` is special

`define-struct` creates a new variant for The One Big Datatype.

Claim: `define-struct` is not a function.

Claim: `define-struct` is not a macro.

It could be a macro except for one key bit of its semantics: Values built from the constructor cause every *other* predicate (including all built-in ones like `pair?`) to return `#f`.

Advantage: abstraction and bug-catching (clients can't "abuse" your things as though they were something else)

Disadvantage: Can't write "generic" code that has a case for every possible variant in every Scheme program (like `eval`).

Implementing Languages

Mostly CSE 341 is about language meaning, not "how can an implementation do that", but it's important to "dispel the magic".

At super high-level, there are two ways to implement a language A:

- Write an *interpreter* in language B that evaluates a program in A
  - Like we *just saw* for a little expression language
- Write a *compiler* in language B that translates a program in A to a program in language C (and have an implementation of C)

In theory, this is just an implementation decision.

HW5: An interpreter for MUPL in Scheme.

Most interesting thing about MUPL: higher-order functions.

How is one language inside another?

How is:

`(make-negate (make-add (make-const 2) (make-const 2)))`

a “program” instead of

`"- (2 + 2)"`

Because *parsing* — turning a string/file into a tree of datatype-like things is covered in CSE401.

These trees are called abstract-syntax trees (or ASTs).

They are ideal *program representations* for passing to an interpreter.

We can write them by hand, or write a parser, or write code that produces them.

An interpreter

A "direct" language implementation is often just writing our evaluation rules for our language in another language.

- Languages with variables need interpreters with *environments*
- "eval-prog" takes an environment and an expression and returns a value (the subset of expressions that we define to be answers)
- An environment is just a mapping from variables to values (e.g., an association list)
- "eval-prog" uses recursion
  - Example: To evaluate an addition expression, evaluate the two subexpressions under the same environment, then...
- For homework 5, expressions & environments are all we need
  - Exceptions or mutation can require more inputs/outputs to "eval-prog"

Implementing Higher-Order Functions

The magic: How is the "right environment" around for lexical scope (the environment from when the function was defined)?

Lack of magic: Implementation keeps it around!

Interpreter:

- The interpreter has a "current environment"
- To evaluate a function (expression), create a closure (value), a *pair* of the function and the "current environment".
- Application will now apply a closure to an argument: Interpret function body, but instead of using "current environment", use closure's environment extended with the argument.

Note: This is directly implementing the semantics from week 3.

Is that expensive?

Building a closure is easy; you already have the environment.

Since environments are immutable, it's easy to share them.

Still, a given closure doesn't need most of the environment, so for *space efficiency* it can be worth it to make a new smaller environment holding only the function's free variables.

- That is, an approximation of the things a call to the function might look up.
- Challenge problem in homework 5

Compiling Higher-Order Functions

The key to the interpreter approach: The interpreter has an explicit environment and can "change" it to implement lexical scope.

We can also *compile* higher-order functions to a language without higher-order functions:
Instead of an *implicit* environment, we pass an *explicit* environment to every function.

- As with interpreter, we build a closure to evaluate functions.
- But all functions now take one extra argument.
- Application passes a closure's code its own environment for the extra argument.
- Evaluating variables uses this extra argument.
  - Compiler translates them to environment-reads.

Plus: Data-structure optimizations so variable-lookup is O(1)