Advances in Programming Languages

APL11: Heterogeneous Metaprogramming in F#

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Semester 1 Week 7

Topic: Domain-Specific vs. General-Purpose Languages

This is the final lecture on integrating domain-specific languages with general-purpose programming languages. In particular, SQL for database queries.

- Using SQL from Java
- Bridging Query and Programming Languages
- Heterogeneous Metaprogramming in F#

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- Using SQL from Java
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Outline

Review

The LINQ framework for .NET integrates database queries into a host programming language.

The integration goes deep: queries become meaningful data structures in the host language, not just raw strings of syntax.

This provides a more reliable interface for the programmer, as well as rich possibilities for manipulation and optimization by the compiler.

However, to do so requires several language extensions, including:

- Lambda expressions `userlist . filter (id=>(id<max))`
- Extension methods … added to pre-existing classes
- Structural datatypes, type inference `var v = new{left=50,right=100}`
- Expression trees `Expression<Func<int,bool>> accept = (id=>(id<max))`

This last introduces *metaprogramming*, where code itself is exposed to programmatic manipulation.

Outline

Metaprogramming

The term *metaprogramming* covers almost any situation where a program manipulates code, either its own or that of some other program. This may happen in many ways, including for example:

- Textual manipulation of code as strings
- Code as a concrete datatype
- Code as an abstract datatype
- Code generation at compile time or run time
- Self-modifying code
- Staged computation

Strictly speaking, any compiler or interpreter would qualify. However,, the idea of metaprogramming usually indicates specific language features, or especially close integration between the subject and object programs.

Metaprogramming Examples

Macros

```
#define geometric_mean(x,y) sqrt(x*y)

float size = geometric_mean(length,width)

#define BEGIN {
#define END }

#define LOOP(var,low,high) \
    for (int var=low; var<high; var++) BEGIN

int i, total = 0; LOOP(i,1,10) total=total+i; END
```

Here geometric_mean is an inlined function; while the *non-syntactic* LOOP macro builds code at compile time.

Metaprogramming Examples

C++ Templates

```
template<int n>
Vector<n> add(Vector<n> lhs, Vector<n> rhs)
{
  Vector<n> result = new Vector<n>;
  for (int i = 0; i < n; ++i)
    result.value[i] = lhs.value[i] + rhs.value[i];
  return(result);
}
```

This template describes a general routine for adding vectors of arbitrary dimension. Compile-time specialization can give custom code for fixed dimensions if required. The C++ Standard Template Library does a lot of this kind of thing.

Metaprogramming Examples

Java reflection

```
import java.io.*;
import java.lang.reflect.*;

Class c = Class.forName("java.lang.System");   // Fetch System class
Field f = c.getField("out");                    // Get static field
Object p = f.get(null);                         // Extract output stream
Class cc  = p.getClass();                       // Get its class
Class types[] = new Class[] { String.class };   // Identify argument types
Method m = cc.getMethod("println", types);      // Get desired method
Object a[]  = new Object[] { "Hello, world" };  // Build argument array
m.invoke(p,a);                                  // Invoke method
```

Reflection of this kind in Java and many other languages allows for programs to indulge in runtime *introspection*. This is heavily used, for example, by toolkits that manipulate Java *beans*.

Metaprogramming Examples

Javascript eval

```
eval("3+4");                 // Returns 7

a = "5-"; b = "2";
eval(a+b);                   // Returns 3, result of 5-2

eval(b+a);                   // Runtime syntax error

a=  "5-"; b = "1"; c = "a+a+b";
eval(c);                     // Returns the string "5-5-1"
eval(eval(c));               // Returns the number -1
```

Any language offering this has to include at least a parser and interpreter within its runtime.

Metaprogramming Examples

Lisp eval

```
(eval '(+ 3 4))        ; Result is 7

(eval `(+ ,x ,x ,x))) ; Result is 3*x, whatever x is

(eval-after-load "bibtex"
  '(define-key bibtex-mode-map
               [(meta backspace)] 'backward-kill-word))
```

Unlike Javascript eval, code here is structured data, built using quote '(...), with no runtime syntax errors. The backquote or *quasiquote* `(...) allows computed values to be inserted using the *antiquotation* comma ,(...).

Metaprogramming Examples

MetaOCaml

```
# let x = .< 4+2 >. ;;
val x : int code = .< 4+2 >.

# let y = .< .~x + .~x >. ;;
val y : int code = .< (4+2)+(4+2) >.

# let z = .! y ;;
val z : int = 12
```

Arbitrary OCaml code can be quoted `.< >.`, antiquoted with `.~` and executed with `.!`. All these can be nested, giving a *multi-stage* programming language with detailed control over exactly what parts are evaluated when in the chain from source to execution.

Metaprogramming Examples

MetaOCaml

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val x : int code = .< 4+2 >.

# let y = .< .~x + .~x >. ;;
val y : int code = .< (4+2)+(4+2) >.

# let z = .! y ;;
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```

Various research projects have implemented multi-stage versions of Scheme, Standard ML, Java/C# and so on.

Metaprogramming Examples

MetaOCaml

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# let x = .< 4+2 >. ;;
val x : int code = .< 4+2 >.

# let y = .< .~x + .~x >. ;;
val y : int code = .< (4+2)+(4+2) >.

# let z = .! y ;;
val z : int = 12
```

This is *homogeneous* metaprogramming: the language at all stages is OCaml. There is a version of MetaOCaml that supports *heterogeneous* metaprogramming, with final execution of the code *offshored* into C.

(pun)

Outline

F#

F# is a succinct, expressive and efficient functional and object-oriented language for .NET which helps you write simple code to solve complex problems. http://research.microsoft.com/fsharp, 2010-11-01

Easy F#

```
let rec fact n = match n with 0 -> 1 | n -> n * fact (n-1)

let build first last = System.String.Join( " ", [|first;last|] )

let name = build "Joe" "Smith"
```

To a (poor) first approximation, F# is OCaml syntax with .NET libraries.

F# Sales Pitch

F# at Microsoft Research

F# brings you type safe, succinct, efficient and expressive functional programming language on the .NET platform. It is a simple and pragmatic language, and has particular strengths in data-oriented programming, parallel I/O programming, parallel CPU programming, scripting and algorithmic development. It lets you access a huge .NET library and tools base and comes with a strong set of Visual Studio development tools. F# combines the advantages of typed functional programming with a high-quality, well-supported modern runtime system.

http://research.microsoft.com/fsharp, 2010-11-01

F#

Interoperability with the .NET framework and other .NET languages is central to F#.

- Core syntax is OCaml: with higher-order functions, lists, tuples, arrays, records, . . .
- Objects are as in C#: with classes, inheritance, dot notation for field and method selection, . . .
- .NET toys: extensive libraries, concurrent garbage collector, install-time/run-time (JIT) compilation, debuggers, profilers, . . .
- Creates and consumes .NET/C# types and values; can call and be called from other .NET languages.
- Generates and consumes .NET code: can exchange first-class functions with other languages.

F# Timeline

- Developed by Don Syme at Microsoft Research Cambridge (MSR).
- Started as Caml.NET, with a first preview release of F# compiler in 2002/2003.
- 2005: MSR release V1.0, with basic Visual Studio integration.
- September 2008: Official Microsoft *Community Technology Preview* (CTP) release
- April 2010: Visual Studio 2010 and .NET 4.0 releases with C#, VB, C++ and F# as its core languages.
- August 2010: F# 2.0 update release, improving integration with assorted development tools. Now part of mainstream .NET cycle.

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"This is one of the best things that has happened at Microsoft
ever since we created Microsoft Research over 15 years ago"

S. Somasegar, Head of Microsoft Developer Division, 2007-10-17

Some F# References

F# Developer Center
http://fsharp.net

Microsoft Research F# http://research.microsoft.com/fsharp

Visual F# Developer Library
http://msdn.microsoft.com/en-us/library/dd233154.aspx

Tomáš Petříček: Blog with several F# articles
http://tomasp.net/

19 January 2010 — Don Syme: Geek of the Week
http://www.simple-talk.com/opinion/geek-of-the-week/don-syme-geek-of-the-week/

Advertisement: ICSA Colloquium

A Framework for High-Level Programming of Heterogeneous Manycore Systems-on-Chip

Wim Vanderbauwhede
University of Glasgow
http://www.gannetcode.org/

Room G.07a, Informatics Forum
1530 Thursday 4 November 2010

Institute for Computing Systems Architecture
http://www.icsa.inf.ed.ac.uk

Coursework Support

Timing

Coursework is due in before 4pm Friday 12 November.

Week 7	Tuesday 2 November	Friday 5 November
Week 8	Tuesday 9 November	Friday 12 November
Week 9	Tuesday 16 November	Friday 19 November
Week 10	Tuesday 23 November	Friday 26 November

Assessment and Feedback

The assignment will be assessed using the University common marking scheme and essay grade descriptors, as distributed in earlier lectures.

You will receive written feedback by Friday 26 November, following the categories in the essay grade descriptors.

Office Hour

Wednesday 3 November 1.30–2.30pm, Informatics Forum 5.04.

Outline

F# Metaprogramming Paper

D. Syme
Leveraging .NET meta-programming components from F#: Integrated queries and interoperable heterogeneous execution.
In *ML '06: Proceedings of the ACM SIGPLAN 2006 Workshop on ML*, pages 43–54. ACM Press, September 2006.

LINQ Metaprogramming in C#

Recall again that LINQ→SQL passes on the information needed to evaluate a query as an *expression tree*. By analyzing this, a complex expression combining several query operations might be executed in a single SQL call to the database.

Expression trees are built as required, and may include details of C# source code. For example:

```
Expression<Func<int,bool>> accept = (id=>(id<max));
```

Now "accept" is not an executable function, but a data structure representing the given lambda expression.

This is quotation, but implicit: rather than having syntax to mark quotation of "(id => (id<max))", the compiler deduces this from its type "Expression". F# is different: code quotation is explicit, as in LISP or MetaOCaml.

Quotations in F#

Simple quote

```
> open Microsoft.FSharp.Quotations

> let a = <@ 3 @>;;
val a : Expr<int>

> a;;
val it : Expr<int> = <@ (Int32 3) @>
```

F# provides explicit quotation markers. Here the interactive response exposes the internal structure of an expression.

Quotations in F#

Larger quote

```
> <@ "Hello " + "World" @>;;
val it : Expr<string>
= <@
    (App (App (Microsoft.FSharp.Core.Operators.op_Addition)
                ((String "Hello")))
          ((String "World")))
  @>
```

A more complex quotation gives a more complex expression. Although verbose, the structure is exactly that of the original expression.

Quotations in F#

Function quote

```
> <@ fun x -> x+1 @>;;
val it : Expr<(int -> int)>
= <@
 fun x#39844.4 ->
   (App
      (App (Microsoft.FSharp.Core.Operators.op_Addition) x#39844.4)
      ((Int32 1)))
   @>
```

An expression of function type includes details of the function body. Here x#39844.4 is a variable name chosen by the expression printer.

Quotation Templates

Quote with hole

```
> let f = <@ 5 + _ @>;;
val f : (Expr<int> -> Expr<int>)

> f a;;                    // Remember that a is <@ 3 @>
val it : Expr<int>
= <@
(App (App (Microsoft.FSharp.Core.Operators.op_Addition) ((Int32 5)))
     ((Int32 3)))
   @>
```

A quotation with one or more holes gives a function mapping expressions to expressions. An function "`lift : 'a -> Expr<'a>`" allows antiquotation, plugging in runtime values.

Quotation Templates

Splicing into a quotation

```
> let f x y = <@ %x + %y @>;;
val f : (Expr<int> -> Expr<int> -> Expr<int>)

> f a (lift (2+5));;              // Remember that a is <@ 3 @>
val it : Expr<int>
= <@
(App (App (Microsoft.FSharp.Core.Operators.op_Addition) ((Int32 3)))
    ((Int32 7)))
  @>                              // The expression <@ 3 + 7 @>
```

Quotation holes are one-off: the splicing operator "%" helps to write more complex functions that build large expressions from smaller ones.

Application: F# to SQL by LINQ

Query in memory

```
val ( |> ) : 'a -> ('a -> 'b) -> 'b // Pipeline operator

let query =
      fun db ->
        db.Employees
        |> where (fun e -> e.City = "Edinburgh" )
        |> select (fun e -> (e.Name,e.Address))
```

The query function will inspect an in-memory datastructure db.Employees, filtering those working in Edinburgh and projecting out their name and address.

Here where and select are versions of filter and map acting on records from the db.Employees data type.

Application: F# to SQL by LINQ

Query via SQL

```
val ( |> ) : 'a -> ('a -> 'b) -> 'b

let query = SQL
  <@ fun db ->
       db.Employees
       |> where  (fun e -> e.City = "Edinburgh" )
       |> select  (fun e -> (e.Name,e.Address)) @>
```

Quoting the internals now gives a query function that will inspect an external database instead.

Application: F# to SQL by LINQ

Query via SQL

```
val ( |> ) : 'a -> ('a -> 'b) -> 'b

let query = SQL
    <@ fun db ->
        db.Employees
        |> where  (fun e -> e.City = "Edinburgh" )
        |> select  (fun e -> (e.Name,e.Address)) @>
```

The SQL function takes a quoted expression and passes it to LINQ; which compiles it to SQL and then hands it off to the database engine as:

SELECT Name, Address **FROM** Employees **WHERE** City = "Edinburgh"

Application: F# to SQL by LINQ

Query via SQL

```
val ( |> ) : 'a -> ('a -> 'b) -> 'b

let query = SQL
    <@ fun db ->
        db.Employees
        |> where  (fun e -> e.City = "Edinburgh" )
        |> select  (fun e -> (e.Name,e.Address)) @>
```

Notice that the SQL function is working with an expression representing F# source, including lambdas and first-flass functions “where” and “select”.

Application: F# to SQL by LINQ

Query via SQL

```
val ( |> ) : 'a -> ('a -> 'b) -> 'b

let query = SQL
    <@ fun db ->
        db.Employees
        |> where  (fun e -> e.City = "Edinburgh" )
        |> select  (fun e -> (e.Name,e.Address)) @>
```

This heterogeneous metaprogramming leads to some mismatches between F# and SQL semantics: for example, SQL date/time is rounded to 3msec, less precise than .NET, and the definition of Math.Round is different.

Application: F# Runtime Code Generation

Powers of x

```
> let rec power (n,x) = if n = 0 then 1 else x*power(n−1,x);;
val power : int * int −> int

> let power4 = fun x −> power (4,x);;
val power4 : int −> int

> power4 5;;
val it : int = 625
```

Although power4 always calls power with the fixed value 4, this will still run the general-purpose code which uses a loop and a counter.

Application: F# Runtime Code Generation

Powers of x

```
> let rec metapower (n,x) =
-   if n = 0
-     then  <@ 1 @>
-     else  <@ _ * _ @> (lift x) (metapower(n-1,x)) ;;
val metapower : int * int -> Expr<int>

> let metapower4 = fun x -> metapower (4,x) ;;
val metapower4 : int -> Expr<int>
```

This metapower function computes x^n as an expression rather than a value.

Application: F# Runtime Code Generation

Powers of x

```
> metapower4 5;;

val it : Expr<int>
= <@
  (App (App (Microsoft.FSharp.Core.Operators.op_Multiply) (5))
     (App (App (Microsoft.FSharp.Core.Operators.op_Multiply) (5))
        (App (App (Microsoft.FSharp.Core.Operators.op_Multiply) (5))
           (App (App (Microsoft.FSharp.Core.Operators.op_Multiply) (5))
              ((Int32 1)))))) @>
```

Executing metapower4 runs the loop over F# code, not values, giving us the expression that would compute 5^4.

Application: F# Runtime Code Generation

Powers of x

```
> metapower4 5;;

val it : Expr<int>
= <@
  (App (App (Microsoft.FSharp.Core.Operators.op_Multiply) (5))
     (App (App (Microsoft.FSharp.Core.Operators.op_Multiply) (5))
        (App (App (Microsoft.FSharp.Core.Operators.op_Multiply) (5))
           (App (App (Microsoft.FSharp.Core.Operators.op_Multiply) (5))
              ((Int32 1)))))) @>
```

This expression can be passed to LINQ, for appropriate compilation and then execution as .NET bytecode.

Application: F# Runtime Code Generation

Powers of x

```
> metapower4 5;;

val it : Expr<int>
= <@
  (App (App (Microsoft.FSharp.Core.Operators.op_Multiply) (5))
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           (App (App (Microsoft.FSharp.Core.Operators.op_Multiply) (5))
              ((Int32 1)))))) @>
```
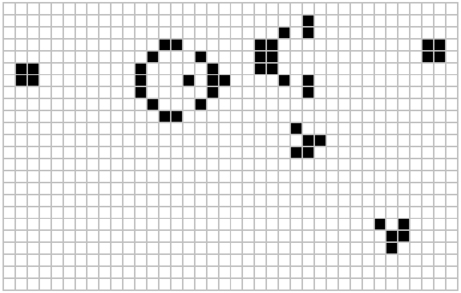

LINQ provides lightweight code generation: at runtime the code is built, JIT compiled, run, and then garbage collected away.

Conway's Game of Life

1. A cell with exactly three neighbours comes to life.
2. A live cell with two or three neighours stays alive.
3. All other cells die.



http://en.wikipedia.org/wiki/Conway's_Game_of_Life
http://www.conwaylife.com/wiki/

Application: Accelerating F# by Outsourcing

```
let matrix f = Array2.init x y f    // Build x*y array filled with f x y
...
let neg a = matrix (fun i j -> - a.(i,j))
let  (.+)   a b = matrix (fun i j -> a.(i,j)  +  b.(i,j))
let (.&&)  a b = matrix (fun i j -> a.(i,j) && b.(i,j))
..
let rotate a dx dy = matrix (fun i j -> a.((i+dx)%x,(j+dy)%y))
let count a = matrix (fun i j -> int_of_bool a.(i,j))

let nextGeneration(a) =            // Take one step in Conway's Life
  let N dx dy = rotate (count a) dx dy in
  let sum = N (-1) (-1)  .+ N (-1) 0   .+ N (-1) 1
          .+ N   0  (-1)                .+ N   0  1
          .+ N   1  (-1)  .+ N  1  0   .+ N   1  1  in
      (sum .= three) .| | (sum .= two) .&& a);;
```

Application: Accelerating F# by Outsourcing

```
open Microsoft.ParallelArrays                     // Use e.g. GPU pixel shader
let shape = [| x; y |]                            // Fixed dimensions x,y
..
let And (a:FPA) (b:FPA) = FPA.Min (a, b)  // Built−in operations on
let Or  (a:FPA) (b:FPA) = FPA.Max (a, b)  // floating−point arrays
..
let Rotate (a:FPA) i j = a.Rotate([| i;j |])
..
let nextGenerationGPU (a:FPA) =          // Take one step in Conway's Life
  let N dx dy = Rotate a dx dy in
  let sum = N (−1) (−1)  .+ N (−1) 0   .+ N (−1) 1
        .+ N   0  (−1)                 .+ N   0  1
        .+ N   1  (−1)  .+ N   1  0   .+ N   1  1  in
      Or (Equals sum three) (And (Equals sum two) a);;
```

Application: Accelerating F# by Outsourcing

Using the *Accelerator* data-parallel library to drive an alternative computing engine is neat, but we did have to rewrite the code.

Application: Accelerating F# by Outsourcing

Using the *Accelerator* data-parallel library to drive an alternative computing engine is neat, but we did have to rewrite the code.

As an alternative to writing new code for this particular application, we can write a general GPU translator that works over any expression:

```
val accelerateGPU : ('a[,] -> 'a[,]) expr -> 'a[,] -> 'a[,]
```

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All we need do to run life on the GPU is then:

```
let nextGenerationGPU' = accelerateGPU <@ nextGeneration @>
```

Application: Accelerating F# by Outsourcing

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All we need do to run life on the GPU is then:

```
let nextGenerationGPU' = accelerateGPU <@ nextGeneration @>
```

Caveat: The semantic mismatches are now more serious — actual floating-point arithmetic on GPU and CPU is not bit-identical.

Summary

- Metaprogramming ranges from syntactic expansion through hygienic macros to staged computation and runtime code generation.
- F# is an ML for .NET, with an emphasis on interlanguage working.
- Quotations and templates bring metaprogramming to F#.
- F# can use LINQ to generate SQL . . .
- . . . or native code at runtime . . .
- . . . or to outsource execution wherever seems best.