Some thoughts on language

"But if **thought corrupts language**, **language can also corrupt thought**. A bad usage can spread by tradition and imitation even among people who should and do know better."
George Orwell, *Politics and the English Language,* 1946

"If you cannot be the master of your language, you must be its slave."
Richard Mitchell

"A different language is a different vision of life."
Federico Fellini

"The language we use ... determines the way in which we view and think about the world around us."
The Sapir-Whorf hypothesis

Language design goals

Some end goals:

- rapid development
- ease of maintenance
- reliability, safety
- ease of learning
- portability
- efficiency

Some means to these goals:

- readability
- writability
- simplicity [but what does "simple" mean?]
- **orthogonality**
- **expressiveness**

Many goals in conflict
⇒ language design is an engineering & artistic activity
⇒ need to consider target audience's needs

Language design target audiences

Scientific, numerical computing

- Fortran, APL, ZPL

Symbolic computing

- Lisp, Scheme, ML, Prolog, Smalltalk

Systems programming

- C, C++, Modula-3

Applications programming

- C, C++, Modula-3, Java, Lisp, Scheme, ML, Smalltalk, ...

Scripting, macro languages

- csh, Perl, Tcl, Excel macros, ...

Specialized languages

- SQL, $\LaTeX$, PostScript, Unix regular expressions, ...

Main programming language concepts

Separation of syntax, semantics, and pragmatics

- EBNF to specify syntax precisely
- semantics is more important than syntax
- pragmatics: programming style, intended uses, etc.

Control structures

- iteration, conditionals; exceptions
- procedures, functions; recursion
- message passing
- backtracking
- parallelism

Data structures and types

- atomic types: numbers, chars, bools
- type constructors: records, tuples, lists, arrays, functions, ...
- user-defined abstract data types (ADTs); classes
- polymorphic/parameterized types

Static vs. dynamic typing; strong vs. weak typing; type inference
Lexical vs. dynamic scoping
Eager vs. lazy evaluation

Some good language design principles

Strive for a simple, regular model
- for evaluation
- for data reference
- for memory management

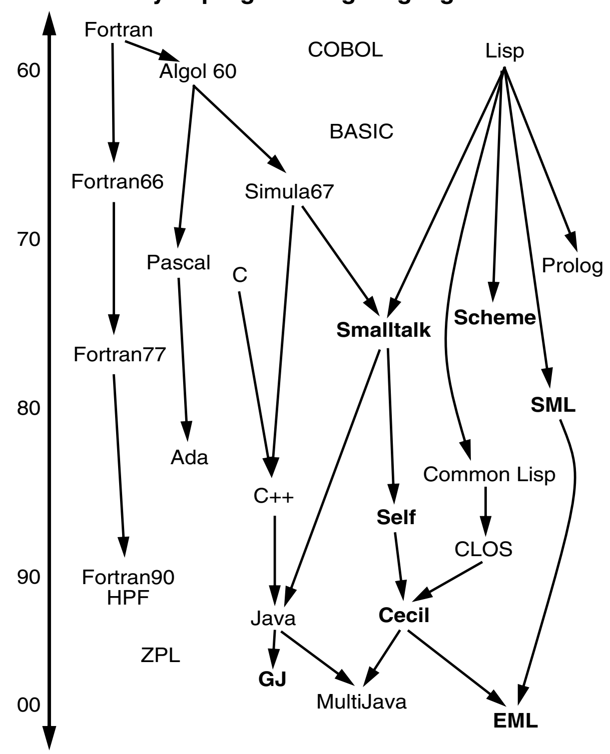
Be expression-oriented

Include sophisticated abstraction mechanisms,
to define and name abstractions once, use many times
- for control, data, types, ...

Include polymorphic static type checking

Have a complete & precise language specification
- full run-time error checking for cases not detected statically

Partial history of programming languages



ML

Main features:
- expression-oriented
- list-oriented, garbage-collected heap-based
- functional
  - functions are first-class values
  - largely side-effect free
- strongly, statically typed
  - polymorphic type system
  - automatic type inference
- pattern matching
- exceptions
- modules
- **highly regular and expressive**

Designed as a **M**eta **L**anguage for automatic theorem proving system in mid 70's by Milner et al.

Standard ML: 1986

SML'97: 1997

Caml: a French version of ML, mid 80's

O'Caml: an object-oriented extension of Caml, late 90's

Interpreter interface

Read-eval-print loop
- **read** input expression
  - reading ends with semi-colon (not needed in files)
  - = prompt indicates continuing expression on next line
- **eval**uate expression
- **print** result
- repeat

```
- 3 + 4;
val it = 7 : int
- it + 5;
val it = 12 : int
- it + 5;
val it = 17 : int
```

`it` (re)bound to last evaluated value,
in case you want to use it again

Basic ML data types and operations

ML is organized around types

- each type defines some set of values of that type
- each type defines a set of operations on values of that type

`int`

- `~`, `+`, `-`, `*`, `div`, `mod`; `=`, `<>`, `<`, `>`, `<=`, `>=`; `real`, `chr`

`real`

- `~`, `+`, `-`, `*`, `/`; `<`, `>`, `<=`, `>=` (no equality);
  `floor`, `ceil`, `trunc`, `round`

`bool`: different from `int`

- `true`, `false`; `=`, `<>`; `orelse`, `andalso`

`string`

- e.g. `"I said \"hi\"\tin dir C:\\stuff\\dir\n"`
- `=`, `<>`, `^`

`char`

- e.g. `#"a"`, `#"\n"`
- `=`, `<>`; `ord`, `str`

Variables and binding

Variables declared and initialized with a `val` binding:

```
- val x:int = 6;
val x = 6 : int
- val y:int = x * x;
val y = 36 : int
```

Variable bindings cannot be changed!

- unlike assignment in C
- like equality in math

Variables can be bound again,
but this **shadows** the previous definition

- e.g. `it`

Variable types can be omitted

- they will be **inferred** by ML based on the type of the r.h.s.

```
- val z = x * y + 5;
val z = 221 : int
```


Strong, static typing

ML is **statically typed**: it will check for type errors statically
(i.e., when programs are entered, not when they're run)

ML is **strongly typed**: it catches all type errors (a.k.a. **type safe**)

- [but which errors are type errors?]

(Can have weakly, statically typed languages, and
strongly, dynamically typed languages, too)

Type errors can look weird, given ML's fancy type system, e.g.:

```
- asd;
Error: unbound variable or constructor: asd
- 3 + 4.5;
Error: operator and operand don't agree
  operator domain: int * int
  operand:         int * real
  in expression:
    3 + 4.5
- 3 / 4;
Error: overloaded variable not defined at type
  symbol: /
  type: int
```


Records

ML records are like C structs

- allow heterogeneous element types, but fixed # of elements

A record type:

```
{name:string, age:int}
```

- field order doesn't matter

A record value:

```
{name="Bob Smith", age=20}
```

Can construct record values from expressions for field values

```
{name = "Bob " ^ "Smith",
 age  = 18+num_years_in_college}
```

As with any other value, can bind record values to variables

```
- val bob = {name="Bob " ^ "Smith",
=             age=18+num_years_in_college};
val bob = {age=20,name="Bob Smith"}
        : {age:int,name:string}
```

More on records

Can extract record fields using `#fieldname` function
(like C's `->` operator, but a regular function)

```
- val bob' = {name= #name(bob),
=             age= #age(bob)+1};
val bob' = {age=21,name="Bob Smith"} : {...}
```

Cannot assign to a record's fields

- an immutable data structure

Tuples

Like records, but fields ordered by position, not label
Useful for pairs, triples, etc.

A tuple type:

```
string * int
```

- order **does** matter

A tuple value:

```
("Joe Stevens", 45)
```

As with any other value, can bind tuple values to variables

```
- val joe = ("Joe "^"Stevens", 25+num_jobs*10);
val joe = ("Joe Stevens",45) : string * int
```

Can extract record fields using `#n` function

```
- val joe' = (#1(joe), #2(joe)+1);
val joe' = ("Joe Stevens",46) : string * int
```

Cannot assign to a tuple's components

- another immutable data structure

Lists

ML lists are built-in, singly-linked lists

- require homogeneous element types,
  but allow variable # of elements

A list type:

```
int list
```

- in general: `T list`, for any type `T`

A list value:

```
[3, 4, 5]
```

Empty list: `[]` or `nil`

- `null(lst)`: tests if `lst` is `nil`

Can create a list value using the [...] notation

- elements are expressions

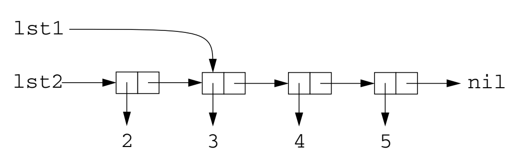
```
- val lst = [1+2, 8 div 2, #age(bob)-15];
val lst = [3,4,5] : int list
```


Basic operations on lists

Add to front of list, non-destructively: `::` (an infix operator)

```
- val lst1 = 3::(4::(5::nil));
val lst1 = [3,4,5] : int list
- val lst2 = 2::lst1;
val lst2 = [2,3,4,5] : int list
```

Adding to the front allocates a new link;
the original list is unchanged and still available




```
- lst1;
val it = [3,4,5] : int list
- lst2;
val it = [2,3,4,5] : int list
```

More on lists

Lists can be nested:

```
- (3 :: nil) :: (4 :: 5 :: nil) :: nil;
val it = [[3],[4,5]]: int list list
```

Lists are homogeneous:

```
- [3, "hi there"];
Error: operator and operand don't agree
  operator domain: int * int list
  operand:         int * string list
  in expression:
    (3 : int) :: "hi there" :: nil
```


Manipulating lists

Look up the first ("head") element: `hd`

```
- hd(l1) + hd(l2);
val it = 5 : int
```

Extract the rest ("tail") of the list: `tl`

```
- val lst3 = tl(lst1);
val lst3 = [4,5] : int list
- val lst4 = tl(tl(lst3));
val lst4 = [] : int list
- tl(lst4);  (* or hd(lst4) *)
uncaught exception Empty
```

Cannot assign to a list's elements

- another immutable data structure

First-class values

All of ML's data values are **first-class**

- there are no restrictions on how they can be created, used, passed around, bound to names, stored in other data structures, ...

One consequence:
can nest records, tuples, lists arbitrarily

- an example of **orthogonal** design

A legal value, and its type:

```
{foo=(3, 5.6, "seattle"),
 bar=[[3,4], [5,6,7,8], [], [1,2]]}
: {bar:int list list, foo:int*real*string}
```

Another consequence:
can create initialized, anonymous values as expressions, instead of using a sequence of statements to first declare (allocate named space) and then assign to initialize

Reference data model

A variable **refers to** a value (of whatever type), uniformly

A record, tuple, or list **refers to** its element values, uniformly

- all values are implicitly referred to by pointer

A variable expression evaluates to
a reference to the value that the variable was bound to

A variable binding makes the l.h.s. variable
refer to its r.h.s. value

No implicit copying upon binding, parameter passing, returning from a function, storing in a data structure

- like Java, Scheme, Smalltalk, ...; all high-level languages
- unlike C, where non-pointer values are copied
  - C arrays?

Reference-oriented values are heap-allocated (logically)

- optimized for scalar values like ints, reals, chars, bools, nil

Garbage collection

ML provides several ways to **allocate** & initialize new values:
`(...)`, `{...}`, `[...]`, `::`

But it provides no way to **deallocate**/free values that are no longer being used

Instead, it provides **automatic garbage collection**:
when there are no more references to a value (either from variables or from other objects), it is deemed garbage, and the system will automatically deallocate the value

Evaluation of automatic garbage collection

+ dangling pointers impossible
  (could not guarantee type safety without this!)
+ storage leaks impossible
+ simpler programming
+ can be more efficient!

– less ability to carefully manage memory use & reuse

GCs exist even for C & C++, as free libraries

Functions

Some function definitions:

```
- fun square(x:int):int = x * x;
val square = fn : int -> int
- fun swap(a:int, b:string):string*int = (b,a);
val swap = fn : int * string -> string * int
```

Some function types:

```
int -> int
int*string -> string*int
```

In general: T_{arg} `->` T_{result}

- use tuple type for multiple arguments
- use tuple type for multiple results (orthogonality!)
- `*` binds tighter than `->`

Some function calls:

```
- square(3);    (* parens not needed! *)
val it = 9 : int
- swap(3 * 4, "billy" ^ "bob"); (*parens needed*)
val it = ("billybob",12) : string * int
```


Expression-orientation

Function body is a single expression

```
fun square(x:int):int = x * x
```

- not a statement list
- no `return` keyword

Like equality in math

- a call to a function is equivalent to its body,
  after substituting its formals for the actuals in the call

`square(3)` $\Leftrightarrow$ (x*x)[x→3] $\Leftrightarrow$ `3*3`

There are no statements in ML, only expressions

- simplicity, regularity, and orthogonality in action

What would be statements in other languages
are recast as expressions in ML

If expression

General form:

if *test* **then** *e1* **else** *e2*

- return value of either *e1* or *e2*,
  based on whether *test* is `true` or `false`
- cannot omit `else` part

```
- fun max(x:int, y:int):int =
=     if x >= y then x else y;
val max = fn : int * int -> int
```

Like `?:` operator in C

- don't need a distinct `if` statement

Static typechecking of if expression

What are the rules for typechecking an `if` expression?
What's the type of the result of `if`?

Some basic principles of typechecking:

- values are members of types
- the type of an expression must include all the values that might possibly result from evaluating that expression at run-time

Requirements on each `if` expression:

- the type of the *test* expression must be `bool`
- the type of the result of the `if` must include whatever values might be returned from the `if`
  - the `if` might return the result of either *e1* or *e2*

A solution: *e1* and *e2* must have the same type, and that type is the type of the result of the `if` expression

Let expression

An expression that introduces a new nested scope with local variable declarations

- unlike `{ ... }` statements in C, which don't compute results

General form:

$$\begin{array}{l} \textbf{let val } id_1 : type_1 = e_1 \\ \quad \ldots \\ \quad \textbf{val } id_n : type_n = e_n \\ \textbf{in} \\ \quad e_{body} \\ \textbf{end} \end{array}$$

- $type_i$ are optional; they'll be inferred from the e_i

Evaluates each e_i and binds it to id_i, in turn

- each e_i can refer to the previous $id_1..id_{i-1}$ bindings

Evaluates e_{body} and returns it as the result of the `let` expression

- e_{body} can refer to all the $id_1..id_n$ bindings

The id_i bindings disappear after e_{body} is evaluated

- they're in a nested, local scope

Example scopes

```
- val x = 3;
val x = 3 : int
- fun f(y:int):int =
=   let
=     val z = x + y
=     val x = 4
=   in
=     (let
=         val y = z + x
=      in
=         x + y + z
=      end)
=     + x + y + z
=   end;
val f = fn : int -> int
- val x = 5;
val x = 5 : int
- f(x);
???
```


"Statements"

For expressions that have no useful result, return empty tuple, of type `unit`:

```
- print("hi\n");
hi
val it = () : unit
```

Expression sequence operator: ; (infix operator)

- evaluates both "arguments", returns second one

```
- val z = (print("hi "); print("there\n"); 3);
hi there
val z = 3 : int
```

Type inference for functions

Type declaration of function result can be omitted

- infer function result type from body expression result type

```
- fun max(x:int, y:int) =
=      if x >= y then x else y;
val max = fn : int * int -> int
```

Can even omit type declarations on arguments to functions

- infer all types based on how arguments are used in body
- constraint-based algorithm to do type inference

```
- fun max(x, y) =
=      if x >= y then x else y;
val max = fn : int * int -> int
```


Functions with many possible types

Some functions could be used on arguments of different types

Some examples:

`null`: can test an `int list`, or a `string list`, or ....

- in general, work on a list of any type *T*:
  `null: T list -> bool`

`hd`: similarly works on a list of any type *T*, and returns an element of that type:
  `hd: T list -> T`

`swap`: takes a pair of an *A* and a *B*, returns a pair of a *B* and an *A*:
  `swap: A * B -> B * A`

How to define such functions in a statically-typed language?

- in C: can't (or have to use casts)
- in C++: can use templates (but can't check separately)
- in ML: allow functions to have **polymorphic types**

Polymorphic types

A polymorphic type contains one or more **type variables**

- an identifier starting with a quote

E.g.

```
'a list
'a * 'b * 'a * 'c
{x:'a, y:'b} list * 'a -> 'b
```

A polymorphic type describes a set of possible types, where each type variable is replaced with some type

- each occurrence of a type variable must be replaced with the same type

Polymorphic functions

Functions can have polymorphic types:

```
null   : 'a list -> bool
hd     : 'a list -> 'a
tl     : 'a list -> 'a list
(op ::): 'a * 'a list -> 'a list
swap   : 'a * 'b -> 'b * 'a
```

When calling a polymorphic function, need to find the **instantiation** of the polymorphic type into a regular type

- caller knows types of arguments
- can compute how to replace type variables so that the replaced function type matches the argument types
- derive type of result of call

E.g.

`hd([3,4,5])`

- actual argument type: `int list`
- polymorphic type of `hd`: `'a list -> 'a`
- replace `'a` with `int` to make a match
- instantiated type of `hd` for this call: `int list -> int`
- type of result of call: `int`

Polymorphic values

Regular values can polymorphic, too

```
nil: 'a list
```

Each reference to `nil` finds the right instantiation for that use, separately from other references

E.g.

```
(3 :: 4 :: nil) :: (5 :: nil) :: nil
```


Polymorphism versus overloading

Polymorphic function:
same function usable for many different argument types

```
- fun swap(a,b) = (b,a);
val swap = fn : 'a * 'b -> 'b * 'a
```

Overloaded function:
several different functions, but with same name

Resolve overloading to particular function based on:

- static argument types (in ML)
- dynamic argument classes (in object-oriented languages)

```
- 3 + 4;
val it = 7 : int

- 3.0 + 4.5;
val it = 7.5 : real

- (op +);  (* which +? default to int version *)
val it = fn : int*int -> int

- (op +):real*real->real;
val it = fn : real*real -> real
```


Equality types

The = built-in function is polymorphic over all types that "admit equality"

- any type except those containing reals or functions

Use `''a`, `''b`, etc. to stand for these equality types

```
- fun is_same(x, y) =
    if x = y then "yes" else "no";
val is_same = fn : ''a * ''a -> string
- is_same(3, 4);
val it = "no" : string
- is_same({l=[3,4,5],h=("a","b"),w=nil},
          {l=[3,4,5],h=("a","b"),w=nil});
val it = "yes" : string
- is_same(3.4, 3.4);
Error: operator and operand don't agree
[equality type required]
  operator domain: ''Z * ''Z
  operand:         real * real
  in expression:
    is_same (3.4,3.4)
```


Loops, using recursion

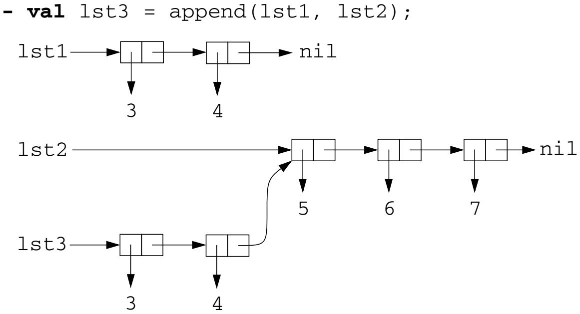
ML has no looping expression

Instead, use recursion to compute a result

E.g., appending one list onto the front of another one (non-destructively, since lists are immutable)

```
fun append(l1, l2) =
  if null(l1)
  then l2
  else hd(l1)::append(tl(l1), l2)

- val lst1 = [3, 4];
- val lst2 = [5, 6, 7];
- val lst3 = append(lst1, lst2);
```



Tail recursion

Tail recursion: recursive call is last operation before returning

- can be implemented just as efficiently as iteration,
  in both time and space,
  since tail-caller isn't needed after callee returns

Some tail-recursive functions:

```
fun last(lst) =
  let val tail = tl(lst) in
    if null(tail) then
      hd(lst)
    else
      last(tail)
  end

fun includes(lst, x) =
  if null(lst) then
      false
  else if hd(lst) = x then
      true
  else
      includes(tl(lst), x)
```

Some non-tail-recursive functions:
`length`, `append`, ...

Converting to tail-recursive form

Can often rewrite a recursive function into a tail-recursive one

- introduce a helper function
- the helper function has an extra accumulator argument
- the accumulator holds the partial result computed so far
- accumulator returned as full result when base case reached

This isn't tail-recursive:

```
fun fact(n) =
  if n <= 1 then
    1
  else
    n * fact(n-1)
```

This is:

```
fun fact(n0) =
  let fun fact_helper(n, res) =
    if n <= 1 then
      res
    else
      fact_helper(n - 1, res * n)
  in
    fact_helper(n0, 1)
  end
```


Pattern matching

Pattern-matching: a convenient syntax for
extracting components of compound values
(tuple, record, or list)

A pattern looks like an expression to build a compound value,
but with variable names to be bound in some places

- cannot use the same variable name more than once

Use pattern in place of variable on l.h.s. of `val` binding

- anywhere `val` can appear: either at top-level or in `let`
  (orthogonality & regularity)

```
- val x = (false,17);
val x = (false,17) : bool*int

- val (a,b) = x;
val a = false : bool
val b = 17 : int

- val (root1, root2) = quad_roots(3.0,4.0,5.0);
val root1 = 0.786299647847 : real
val root2 = ~2.11963298118 : real
```


More patterns

```
- val [x,y] = 3::4::nil;
val x = 3 : int
val y = 4 : int

- val (x::y::zs) = [3,4,5,6,7];
val x = 3 : int
val y = 4 : int
val zs = [5,6,7] : int list
```

Constants (ints, bools, strings, chars, nil) can be patterns:

```
- val (x,true,3,"x",z) =
        (5.5,true,3,"x",[3,4]);
val x = 5.5 : real
val z = [3,4] : int list
```

If don't care about some component, can use a wildcard: _

```
- val (_::_::zs) = [3,4,5,6,7];
val zs = [5,6,7] : int list
```

Patterns can be nested, too

- orthogonality

Function argument patterns

Formal parameter of a `fun` declaration is a pattern

```
- fun swap (a, b) = (b, a);
val swap = fn : 'a*'b -> 'b*'a
- fun swap2 x = (#1 x, #2 x);
val swap2 = fn : 'a*'b -> 'b*'a
- fun swap3 x =
   let val (a,b) = x in (b,a) end;
val swap3 = fn : 'a*'b -> 'b*'a

- fun best_friend
   {student={name=n,age=_},
    grades=_,
    best_friends={name=f,age=_}::_} =
             n ^ "'s best friend is " ^ f;
val best_friend = fn
  : {best_friends:{age:'a, name:string} list,
     grades:'b,
     student:{age:'c, name:string}}
```

Patterns allowed wherever **binding** occurs

Multiple cases

Often a function's implementation can be broken down into several different cases, based on the argument value

ML allows a single function to be declared via several cases

Each case identified using pattern-matching

- cases checked in order, until first matching case

```
- fun fib 0 = 0
    | fib 1 = 1
    | fib n = fib(n-1) + fib(n-2);
val fib = fn : int -> int

- fun null nil    = true
    | null (_::_) = false;
val null = fn : 'a list -> bool

- fun append(nil,  lst) = lst
    | append(x::xs,lst) = x :: append(xs,lst);
val append = fn : 'a list * 'a list -> 'a list
```

The function has a single type

⇒ all cases must have same argument and result types

Missing cases

What if we don't provide enough cases?

- ML gives a warning message "match nonexhaustive" when function is declared (**statically**)
- ML raises an exception "nonexhaustive match failure" if invoked and no existing case applies (**dynamically**)

```
- fun first_elem (x::xs) = x;
Warning: match nonexhaustive
   x :: xs => ...
val first_elem = fn : 'a list -> 'a

- first_elem [3,4,5];
val it = 3 : int

- first_elem [];
uncaught exception nonexhaustive match failure
```

How would you provide an implementation of this missing case?

Exceptions

If get in a situation where you can't produce a normal value of the right type, then can raise an exception

- aborts out of normal execution
- can be handled by some caller
- reported as a top-level "uncaught exception" if not handled

Step 1: declare an `exception` that can be raised

```
- exception EmptyList;
exception EmptyList
```

Step 2: use the `raise` expression where desired

```
- fun first_elem (x::xs) = x
    | first_elem nil = raise EmptyList;
val first_elem = fn : 'a list -> 'a

- first_elem [3,4,5];
val it = 3 : int

- first_elem [];
uncaught exception EmptyList
```

Handling exceptions

Add handler clause to expressions to handle (some) exceptions raised in that expression

Syntax:

```
expr handle exn_name1 => expr1
          | exn_name2 => expr2
            ...
          | _ => exprn
```

- this is an expression;
  each $expr_i$ must return same type as *expr*

```
- fun second_elem l = first_elem (tl l);
val second_elem = fn : 'a list -> 'a

- (second_elem [3]
     handle EmptyList => ~1) + 5
val it = 4 : int
```


Exceptions with arguments

Can have exceptions with arguments

```
- exception IOError of int;
exception IOError of int;

- (... raise IOError(-3) ...)
     handle IOError(code) => ... code ...
```


Type synonyms

Can give a name to a type, for convenience

- name and type are equivalent, interchangeable

```
- type person = {name:string, age:int};
type person = {age:int, name:string}

- val p:person = {name="Bob", age=18};
val p = {age=18,name="Bob"} : person

- val p2 = p;
val p2 = {age=18,name="Bob"} : person

- val p3:{name:string, age:int} = p;
val p3 = {age=18,name="Bob"}
       : {age:int, name:string}
```


Polymorphic type synonyms

Can define polymorphic synonyms

```
- type 'a stack = 'a list;
type 'a stack = 'a list

- val emptyStack:'a stack = nil;
val emptyStack = [] : 'a stack
```

Synonyms can have multiple type parameters:

```
- type (''key, 'value) assoc_list =
=      (''key * 'value) list;
type ('a,'b) assoc_list = ('a * 'b) list

- val grades:(string,int) assoc_list =
=   [("Joe", 84), ("Sue", 98), ("Dude", 44)];
val grades =
    [("Joe",84),("Sue",98),("Dude",44)]
  : (string,int) assoc_list
```

Datatypes

Users can define their own (polymorphic) data structures

- a new type, unlike type synonyms

Simple example: ML's version of enumerated types

```
datatype sign = Positive | Zero | Negative;
```

Declares both a **type** (`sign`) and a set of alternative **constructor values** of that type (`Positive` etc.)

- order doesn't matter

```
- fun signum(x) =
=   if x > 0 then Positive
=   else if x = 0 then Zero
=   else Negative;
val signum = fn : int -> sign
```

Values can be used in patterns, too

```
- fun signum_value(Positive) = 1
=   | signum_value(Zero)     = 0
=   | signum_value(Negative) = ~1;
val signum_value = fn : sign -> int
```


Datatypes with data

Each constructor can have data of particular type stored with it

- constructors are functions that allocate & initialize new values with that "tag"

Example:

```
- datatype LiteralExpr =
=   Nil |
=   Integer of int |
=   String of string;
datatype LiteralExpr =
  Integer of int | Nil | String of string

- Nil;
val it = Nil : LiteralExpr
- Integer(3);
val it = Integer 3 : LiteralExpr
- String("xyz");
val it = String "xyz" : LiteralExpr
```


Pattern-matching on datatypes

The only way to access components of a value of a datatype is via pattern-matching

Constructor "calls" can be used in patterns to test for and take apart values with that "tag"

```
- fun toString(Nil) = "nil"
=   | toString(Integer(i)) = Int.toString(i)
=   | toString(String(s)) = "\"" ^ s ^ "\"";
val toString = fn : LiteralExpr -> string
```


Recursive datatypes

Many datatypes are recursive:
one or more constructors are defined in terms of the datatype itself

```
- datatype Expr =
=   Nil |
=   Integer of int |
=   String of string |
=   Variable of string |
=   Tuple of Expr list |
=   BinOpExpr of {arg1:Expr,
=                 operator:string,
=                 arg2:Expr} |
=   FnCall of {function:string, arg:Expr};
datatype Expr = ...

(*  (3, "hi")  *)
- val expr1 = Tuple [Integer(3), String("hi")];
val expr1 = Tuple [Integer 3,String "hi"]
          : Expr
```

(`Nil`, `Integer`, and `String` of `LiteralExpr` are **shadowed**)

Another example expression value

```
(*  f(3+x, "hi")  *)
= val expr2 =
=  FnCall {
=    function="f",
=    arg=Tuple [
=      BinOpExpr {arg1=Integer(3),
=                 operator="+",
=                 arg2=Variable("x")},
=      String("hi")]};
val expr2 = ... : Expr
```


Recursive functions over recursive datatypes

Often manipulate recursive datatypes with recursive functions

- pattern of recursion in function matches pattern of recursion in datatype

```
- fun toString(Nil) = "nil"
=   | toString(Integer(i)) = Int.toString(i)
=   | toString(String(s)) = "\"" ^ s ^ "\""
=   | toString(Variable(name)) = name
=   | toString(Tuple(elems)) =
=         "(" ^ listToString(elems) ^ ")"
=   | toString(BinOpExpr{arg1,operator,arg2})=
=         toString(arg1) ^ " " ^ operator
=           ^ " " ^ toString(arg2)
=   | toString(FnCall{function,arg}) =
=         function ^ "(" ^ toString(arg) ^ ")"
= and listToString([]) = ""
=   | listToString([elem]) = toString(elem)
=   | listToString(e::es) =
=         toString(e) ^ "," ^ listToString(es);
val toString = fn : Expr -> string
val listToString = fn : Expr list -> string
```


Mutually recursive functions and datatypes

If two or more functions are defined in terms of each other, recursively, then must be declared together, and linked with `and`

E.g.

```
fun toString(...) = ... listToString ...
and listToString(...) = ... toString ...
```

If two or more mutually recursive datatypes, then declare them together, linked by `and`

E.g.

```
datatype Stmt = ... Expr ...
and Expr = ... Stmt ...
```


Record pattern syntactic sugar

Instead of writing `{a=a, b=b, c=c}` as a pattern, can write `{a,b,c}`

E.g.

```
... BinOpExpr{arg1,operator,arg2} ...
```

is short-hand for

```
... BinOpExpr{arg1=arg1,
              operator=operator,
              arg2=arg2} ...
```

Polymorphic datatypes

Datatypes can be polymorphic

```
- datatype 'a List = Nil
=                  | Cons of 'a * 'a List;
datatype 'a List = Cons of 'a * 'a List | Nil

- val lst = Cons(3, Cons(4, Nil));
val lst = Cons (3,Cons (4,Nil)) : int List

- fun Null(Nil) = true
=   | Null(Cons(_,_)) = false;
val Null = fn : 'a List -> bool

- fun Hd(Nil) = raise Empty
=   | Hd(Cons(h,_)) = h;
val Hd = fn : 'a List -> 'a

- fun Sum(Nil) = 0
=   | Sum(Cons(x,xs)) = x + Sum(xs);
val Sum = fn : int List -> int
```