Note that `pcall` can be implemented using futures.
That is, instead of
\[(\text{pcall } F X Y Z)\]
we can use
\[
((\text{future } F) \ (\text{future } X) \ (\text{future } Y) \ (\text{future } Z))
\]
In fact the latter version is actually more parallel—execution of \(F\) can begin even if all the parameters aren’t completely evaluated.

**Another Example of Futures**

The following function, `partition`, will take a list and a data value (called pivot). `partition` will partition the list into two sublists:

1. Those elements \(\leq\) pivot
2. Those elements \(>\) pivot

```
(define (partition pivot L)
  (if (null? L)
      (cons () ()
          (let ((tail-part
                   (partition pivot (cdr L))))
          (if (<= (car L) pivot)
              (cons
                  (cons (car L) (car tail-part))
                  (cdr tail-part))
              (cons
                  (car tail-part))
              (cons (car L) (cdr tail-part))))
      (cons () ()))

But this one change isn’t enough! We soon access the `car` and `cdr` of `tail-part`, which forces us to wait for its computation to complete. To avoid this delay, we can place the four references to `car` or `cdr` of `tail-part` into futures too:

```
(define (partition pivot L)
  (if (null? L)
      (cons () ()
          (let ((tail-part
                   (partition pivot (cdar L))))
          (if (<= (car L) pivot)
              (cons
                  (cons (car L) (car tail-part))
                  (cdr tail-part))
              (cons
                  (car tail-part))
              (cons (car L) (cdr tail-part))))
      (cons () ()))
```

We want to add futures to `partition`, but where?
It makes sense to use a future when a computation may be lengthy and we may not need to use the value computed immediately.
What computation fits that pattern?
The computation of `tail-part`. We’ll mark it in a blue box to show we plan to evaluate it using a future:
(define (partition pivot L)
  (if (null? L)
      (cons () () )
      (let ((tail-part
              (partition pivot (cdr L))))
        (if (<= (car L) pivot)
            (cons
              (cons (car L) (car tail-part))
              cdr tail-part)
            (cons
              car tail-part)
            (cons (car L) (cdr tail-part))))))

Now we can build the initial part of the partitioned list (that involving pivot and (car L) independently of the recursive call of partition, which completes the rest of the list. For example,

(partition 17 '(5 3 8 ...))

creates a future (call it future1) to compute

(partition 17 '(3 8 ...))

It also creates future2 to compute (car tail-part) and future3 to compute (cdr tail-part). The call builds

Reading Assignment

- Roosta: Section 13.3
- Introduction to Standard ML (linked from class web page)
- Webber: Chapters 5, 7, 9, 11

ML—Meta Language

SML is Standard ML, a popular ML variant.

ML is a functional language that is designed to be efficient and type-safe. It demonstrates that a functional language need not use Scheme’s odd syntax and need not bear the overhead of dynamic typing.

SML’s features and innovations include:

1. Strong, compile-time typing.
2. Automatic type inference rather than user-supplied type declarations.
3. Polymorphism, including “type variables.”
4. Pattern-directed Programming

fun len([]) = 0
|   len(a::b) = 1+len(b);

5. Exceptions

6. First-class functions

7. Abstract Data Types

coin of int |
bill of int |
check of string*real;
val dime = coin(10);

A good ML reference is

“Elements of ML Programming,”
by Jeffrey Ullman
(Prentice Hall, 1998)

SML is Interactive

You enter a definition or expression, and SML returns a result with an inferred type.

The command

use "file name";

loads a set of ML definitions from a file.

For example (SML responses are in blue):

21;
val it = 21 : int
(2 div 3);
val it = 0 : int
ture;
val it = true : bool
"xyz";
val it = "xyz" : string

Basic SML Predefined Types

- Unit
  Its only value is (). Type unit is similar to void in C; it is used where a type is needed, but no “real” type is appropriate. For example, a call to a write function may return unit as its result.

- Integer
  Constants are sequences of digits. Negative values are prefixed with a ~ rather than a – (~ is a binary subtraction operator). For example, ~123 is negative 123.
  Standard operators include + - * div mod < > <= => = <>

- Real
  Both fractional (123.456) and exponent forms (10e7) are allowed. Negative signs and exponents use ~ rather than – (~10.0e~12).
  Standard operators include + - * / < > <= >=
  Note that = and <> aren’t allowed! (Why?)
  Conversion routines include real(int) to convert an int to a real,
  floor(real) to take the floor of a real,
  ceil(real) to take the ceiling of a real.
  round(real) to round a real,
  trunc(real) to truncate a real.
For example, `real(3)` returns 3.0,
`floor(3.1)` returns 3,
`ceiling(3.3)` returns 4,
`round(~3.6)` returns ~4,
`trunc(3.9)` returns 3.
Mixed mode expressions, like
1 + 2.5 aren’t allowed; you must do explicit conversion, like
`real(1) + 2.5`

- **Strings**
  Strings are delimited by double quotes. Newlines are \n, tabs are \t, and \" and \\\\ escape double quotes and backslashes. E.g. "Bye now\n"
The ^ operator is concatenation.
"abc" ^ "def" = "abcdef"
The usual relational operators are provided: < > <= >= = <>

- **Boolean**
  Constants are true and false. Operators include andalso (short-circuit and), orelse (short-circuit or), not, = and <>.
A conditional expression,
(if boolval v₁ else v₂) is available.

- **Tuples**
  A tuple type, composed of two or more values of any type is available.
Tuples are delimited by parentheses, and values are separated by commas.
Examples include:
(1,2);
val it = (1,2) : int * int
("xyz",1=2);
val it = ("xyz",false) :
string * bool
(1,3.0,false);
val it = (1,3.0,false) :
int * real * bool
(1,2,(3,4));
val it = (1,2,(3,4)) :
int * int * (int * int)

Equality is checked componentwise:
(1,2) = (0+1,1+1);
val it = true : bool
(1,2,3) = (1,2) causes a compile-time type error (tuples must be of the same length and have corresponding types to be compared).
#i selects the i-th component of a tuple (counting from 1). Hence
#2(1,2,3);
val it = 2 : int

- **Characters**
  Single characters are delimited by double quotes and prefixed by a #. For example, #"a" or #"\t". A character is not a string of length one. The str function may be used to convert a character into a string. Thus
str(#"a") = "a"

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(1,2,(3,4));
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int * int * (int * int)

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Lists

Lists are required to have a single element type for all their elements; their length is unbounded. Lists are delimited by [ ] and elements are separated by commas. Thus [1,2,3] is an integer list. The empty (or null) list is [] or nil. The cons operator is ::

Hence [1,2,3] ≡ 1::2::3::[]

Lists are automatically typed by ML:

val it = [1,2] : int list

Cons

Cons is an infix operator represented as ::

The left operand of :: is any value of type T.
The right operand of :: is any list of type T list.
The result of :: is a list of type T list.
Hence :: is polymorphic.
[] is the empty list. It has a type 'a list. The symbol 'a, read as "alpha" or "tic a" is a type variable.
Thus [] is a polymorphic constant.

List Equality

Two lists may be compared for equality if they are of the same type. Lists L1 and L2 are considered equal if:

(1) They have the same number of elements
(2) Corresponding members of the two lists are equal.

List Operators

hd ≡ head of list operator ≈ car
tl ≡ tail of list operator ≈ cdr
null ≡ null list predicate ≈ null?
@ ≡ infix list append operator ≈ append

Records

Their general form is

{name₁=val₁, name₂=val₂, ... }

Field selector names are local to a record.
For example:

val it = {a=1,b=2} :
  (a:int, b:int)
  {a=1,b="xyz"};
val it = {a=1,b="xyz"} :
  (a:int, b:string)
  {a=1.0,b={c=[1,2]}};
val it = {a=1.0,b={c=[1,2]}} :
  (a:real, b:{c:int list})
The order of fields is irrelevant; equality is tested using field names.
\{(a=1, b=2) = (b=2, a=2-1)\};
val it = true : bool

#id extracts the field named id from a record.
#b \{(a=1, b=2)\};
val it = 2 : int

Identifiers

There are two forms:

- Alphanumeric (excluding reserved words)
  Any sequence of letters, digits, single quotes and underscores; must begin with a letter or single quote. Case is significant. Identifiers that begin with a single quote are type variables.
  Examples include:
  abc a10 'polar sum_of_20

- Symbolic
  Any sequence (except predefined operators) of
  ! % & + - / : < = > ? @ \ ~ ^ | # *
  Usually used for user-defined operators.
  Examples include: ++ <-> !=

Comments

Of form
(* text *)
May cross line boundaries.

Declaration of Values

The basic form is
val id = expression;
This defines id to be bound to expression; ML answers with the name and value defined and the inferred type.
For example
val x = 10*10;
val x = 100 : int

Redefinition of an identifier is OK, but this is redefinition not assignment;
Thus
val x = 100;
val x = (x=100);
is fine; there is no type error even though the first x is an integer and then it is a boolean.
val x = 100 : int
val x = true : bool
Examples

val \( x = 1; \)
val \( x = 1 : \text{int} \)
val \( z = (x,x,x); \)
val \( z = (1,1,1) : \text{int} * \text{int} * \text{int} \)
val \( L = [z,z]; \)
val \( L = [(1,1,1),(1,1,1)] : \)
\( (\text{int} * \text{int} * \text{int}) \text{ list} \)
val \( r = \{a=L\}; \)
val \( r = \{a=[(1,1,1),(1,1,1)]\} : \)
\( \{a:(\text{int} * \text{int} * \text{int}) \text{ list}\} \)

After re-binding, the “nearest” (most recent) binding is used.