If we have a call

(map slow-function long-list)

where **slow-function** executes slowly and **long-list** is a large data structure, we can expect to wait quite a while for computation of the result list to complete.

Now consider **fastmap**, a version of **map** that uses futures:

```
(define (fastmap f L)
  (if (null? L)
      ()
      (cons
        (future (f (car L)))
        (fastmap f (cdr L))
      )
  )
)
```

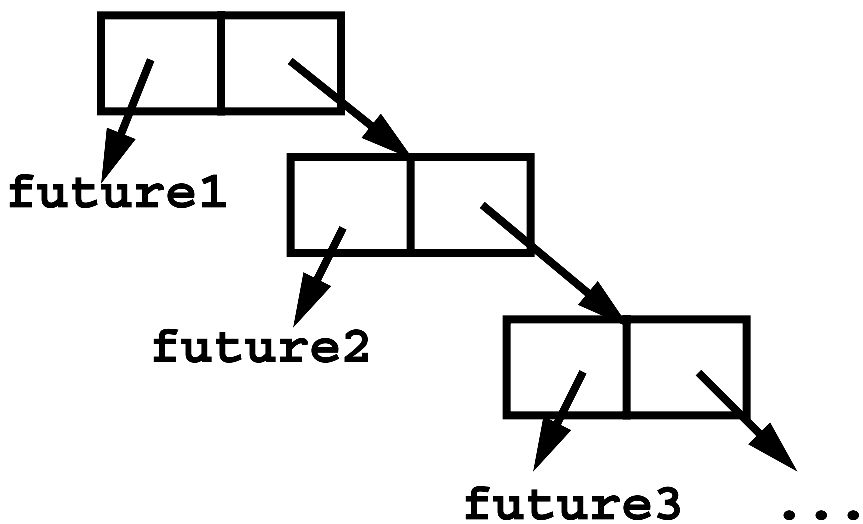
Now look at the call

(fastmap slow-function long-list)

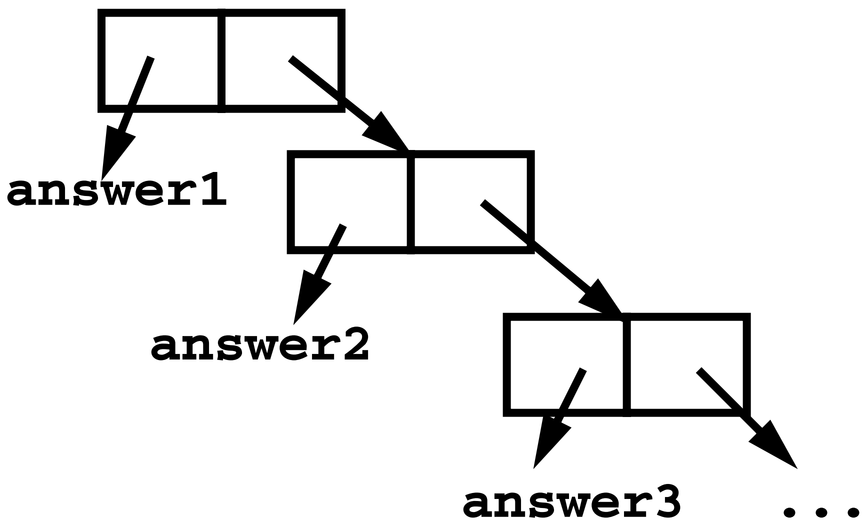
We will exploit a useful aspect of futures—they can be cons'ed together *without delay*, even if the computation isn't completed yet.

Why? Well a **`cons`** just stores a pair of pointers, and it really doesn't matter what the pointers reference (a future or an actual result value).

The call to **`fastmap`** can actually return before *any* of the call to **`slow-function`** have completed:



Eventually all the futures automatically transform themselves into data values:



Note that **`pcall`** can be implemented using futures.

That is, instead of

```
(pcall F X Y Z)
```

we can use

```
((future F)
   (future X) (future Y) (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:

(a) Those elements ≤ **pivot**

(b) 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))
     )
) ) )
```

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))
     )
) ) )
```

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 (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.

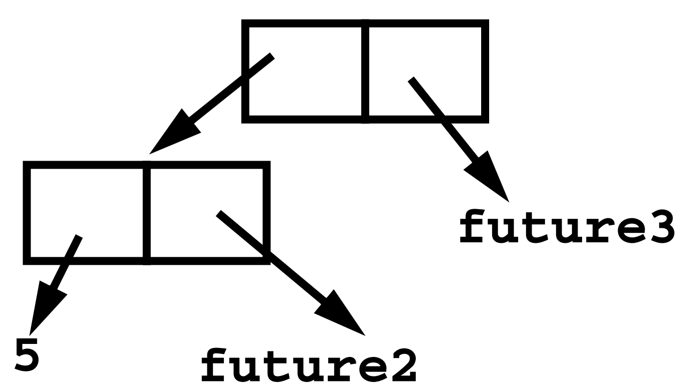
For example,

(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

- 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
true;
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: **`<  >  <=  >=  =  <>`**

- 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"**

- Boolean

  Constants are **true** and **false**. Operators include **andalso** (short-circuit and), **orelse** (short-circuit or), **not**, **=** and **<>**.

  A conditional expression,

  (if boolval v_1 **else** v_2**)** 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
```

Lists

Lists are required to have a single element type for all their elements; their length is unbounded.

Lists are delimited by **[** and **]** 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:

```
[1,2];
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*.