Programming Language Concepts, cs2104
Lecture 02 (2003-08-15)

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Overview

- Organization
- Course overview
- Introduction to programming concepts

Organization

Labs and Tutorials

- Do get Emacs and Mozart installed
  - Did you do tutorial 1
  - You must finish tutorial 2 before next lecture
  - Start with Assignment 1 now (compulsory)
  - Mozart is also available on tembusu (Linux cluster)

Lectures

- Lecture 02
  - More Introduction to programming concepts
  - Why Programming Model?
- Lecture 03 (next week)
  - The Declarative Programming Model I
  - (most of the week I'll be away)
- Lecture 04 (after one week break)
  - The Declarative Programming Model II
  - Declarative Programming Techniques

Reading Suggestions

- As for Lecture 02
  - Browse as you like
  - Abstract and Preface [casual]
  - Introduction 1.1 – 1.15 [careful] [try examples]
  - The rest of Chapter 1 [read through]
  - Appendix A.1 for Oz Development Environment
  - Appendix B.1 and B.2 [as you need]
  - Look at the Oz base envorinment

Last Lecture

- Variable
  - variable declaration
  - store variables
  - assignment
- Data structures
  - numbers and atoms
  - tuples and record
- Functions
  - definition
  - call (application)
- Recursion

This Lecture

- More Data structures (compound data types)
  - tuples, lists, records
- More on variables
  - bound and unbound variables
  - partial values
  - dataflow variables and dataflow synchronization
- More on computing
  - pattern matching
- Why a computation model
  - procedures as opposed to functions

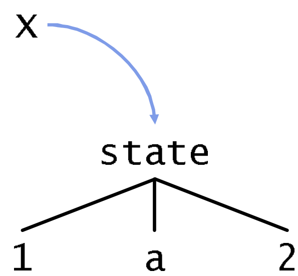
Data Structures

- Already seen:
  - number: integers `1, 2, ~1, 0`
    floating point (floats) `1.0, ~1.21`
  - atom: `a, 'Atom', v123`

- This lecture: compound data structures
  - tuple combining several values
  - list special case of tuple
  - record generalization of tuple

Tuples

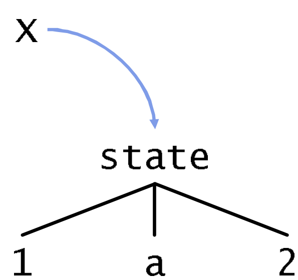
Tuples



`X=state(1 a 2)`

- Combine several values (variables)
  - here: `1`, `a`, `2`
  - position is significant!
- Have a label
  - here: `state`

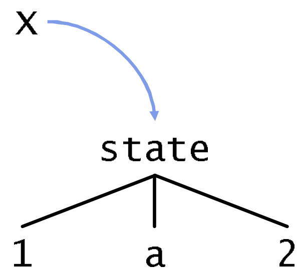
Tuple Operations



`X=state(1 a 2)`

- `{Label X}` returns *label* of tuple `X`
  - here: `state`
  - is an atom
- `{Width X}` returns the *width* (number of fields)
  - here: `3`
  - is a positive integer

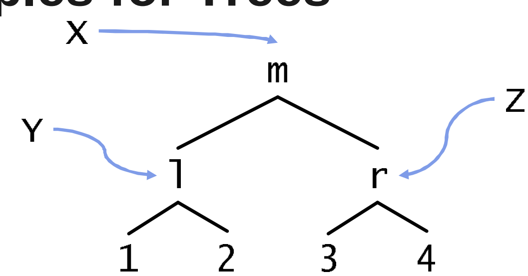
Feature Access (Dot Access)




```
X=state(1 a 2)
```

- Fields are numbered from `1` to `{Width X}`
- `X.N` returns `N`-th *field* of tuple
  - here, `X.1` returns `1`
  - here, `X.3` returns `2`
- In `X.N`, `N` is called *feature*

Tuples for Trees



- Trees can be constructed with tuples:

```
declare
Y=l(1 2) Z=r(3 4)
X=m(Y Z)
```

Equality Operator (==)

- Testing equality with an atom or number
  - simple, must be the same number or atom
  - okay to use
  - we will see pattern matching as something much nicer in many cases
- Testing equality among trees
  - not so straightforward
  - don’t do it, we don’t need it (yet)

Summary: Tuples

- Tuple
  - label
  - width
  - field
  - feature

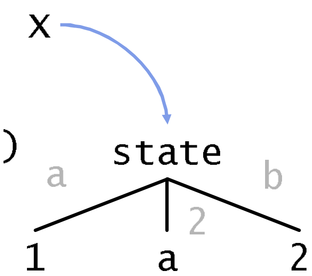
Records

Records

- Records are generalizations of tuples
  - features can be atoms
  - features can be arbitrary integers
    - not restricted to start with 1
    - not restricted to be consecutive
- Records also have label and width
- Needed for assignment 01, will be discussed again

Records

```
X=state(a:1 2:a b:2)
```



- Position is insignificant
- Field access is as with tuples
  `X.a` is `1`

Tuples are Records

- Constructing

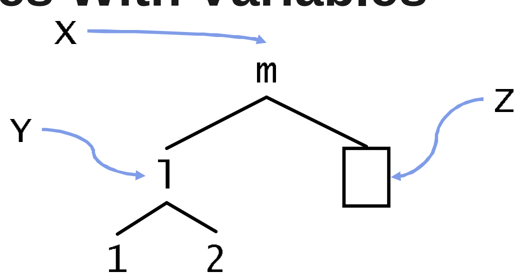
  ```
  declare
  X = state(1:a 2:b 3:c)
  ```

  is equivalent to

  ```
  X = state(a b c)
  ```

Partial Values

Trees With Variables



- Z can be assigned later
- Declare Z without assigning:

```
declare
Y=l(1 2) Z X=m(Y Z)
```

Partial Values

- Assigning a value to a variable
  - we also say: *binding* a variable
  - *unbound* variable: no value assigned yet
  - *bound* variable: value already assigned
- Values can be described partially
  - data structure can contain unbound variables
  - often called *partial values*

Unbound Variables

- In Java, when declaring a variable it is initialized
- In C/C++, when declaring a variable it refers to a memory location containing garbage
- Here, the variable is left unassigned
  - can be used before bound!
- Unbound variables and…
  - … computing?
  - … constructing data structures?

Unbound Variables Computing With Them

- Option A: don't care
  - undefined behavior, do whatever implementation likes
  - unpredictable
- Option B: error on access
  - a little better, because more predictable
- Option C: utilize expressive power!
  - of course, that is what we do!

Computing With Partial Values

- Example

  ```
  X = Y + Z
  ```

  where Y and Z are still unbound
- Computation will stop automatically
  - we say: computation *suspends*
- Computation resumes, if both Y and Z become bound
  - we say: computation *resumes*
- Also
  - automatic synchronization
  - dataflow behavior
  - variables also called *dataflow variables*

Why Dataflow Variables

- Assume multiple *concurrent* computations
  - communicate with dataflow variables
  - one can be producer: bind variable
  - one can be consumer: access variable
- Consumer automatically synchronizes on producer
  - data flows from producer to consumer
- Will be discussed in detail

  Concurrent Programming Model

Remark: Variables

- Two properties
  - single assignment: can be assigned at most once
  - dataflow: automatic synchronization
- Deep connection between them
  - regardless of when a suspended computation resumes, the values available will be the same!
- This makes concurrent programming simple

Programming Errors

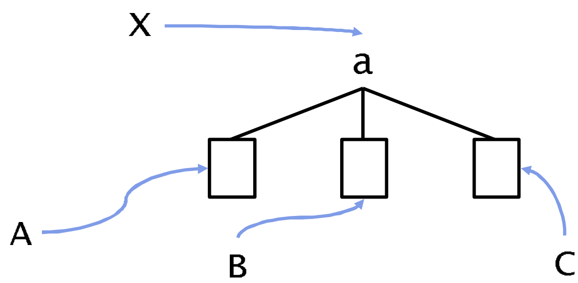
- Bad news
  - we only make use of dataflow later
  - you'll make errors by having computations that just suspend already now (bastard: ==)
  - most likely: forget to bind a variable

- Good news
  - you don't have to restart Oz
  - bind the variable later (the interactive session can do that)
  - just correct the bug and retry (can do that as well)

Unbound Variables Constructing Data Structures

- Leave unbound variables to be filled later
- Common techniques
  - construct skeleton of data structure, fill in details later
  - split computations into parts that do this
- Questions to be answered
  - can variables be bound to variables? Yes!

Skeleton Construction

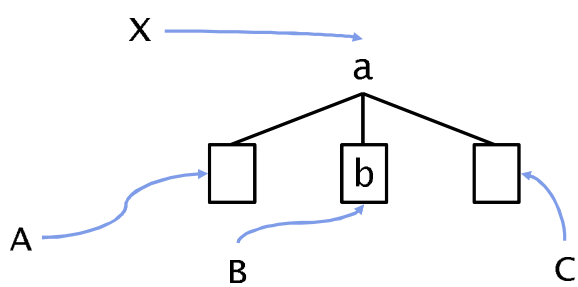


- Skeleton construction

  `declare`

  `A B C X=a(A B C)`

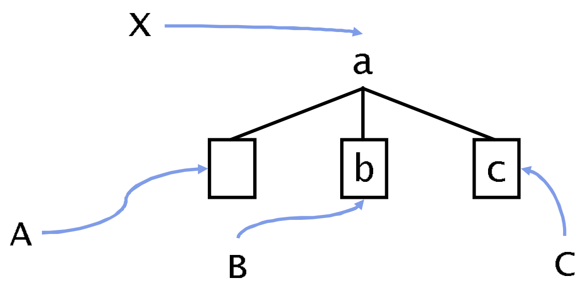
Fill in Values



- By binding variables

  `B=b`

Fill in Values with "dot"

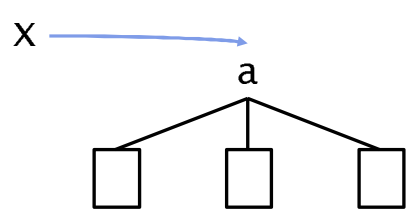


- By binding variables via "dot" access
  `X.3=c`
- Dot returns the (store) variable

Constructing Tuple Skeletons

- `{MakeTuple` *Label* *Width*`}`
  - creates new tuple with label *Label* and width *Width*
  - fields are initialized to variables
- Access to fields then by "dot"

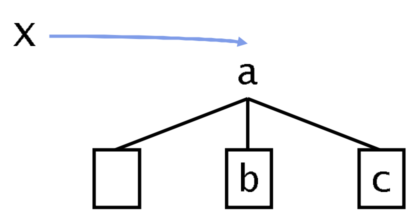
Example Tuple Construction



- Created by execution of

```
declare
X = {MakeTuple a 3}
```

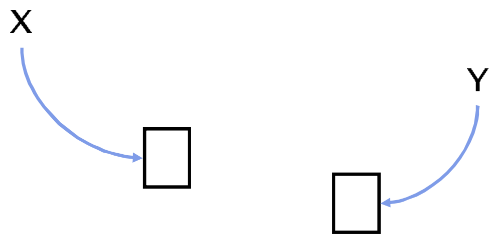

Example Tuple Construction



- After execution of

```
X.2 = b
X.3 = c
```

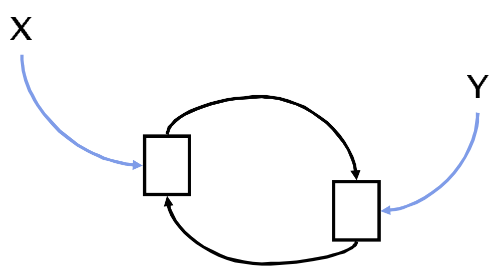
Variable-Variable Binding



- Two store variables after executing

  `declare X Y`

Variable-Variable Binding



- Two store variables after executing

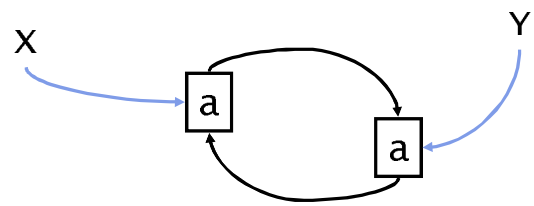
  `declare X Y`

- Do variable-variable binding

  X=Y

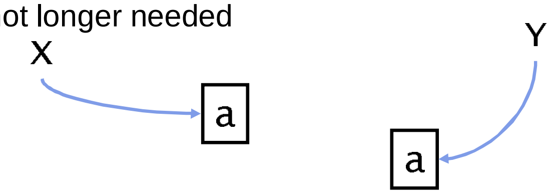
Variable-Variable Binding

- Binding variables together makes them equal
  - binding a variable (or another variables) affects all variables that are bound together
- In our previous example:
  - Executing X=a also binds Y to a

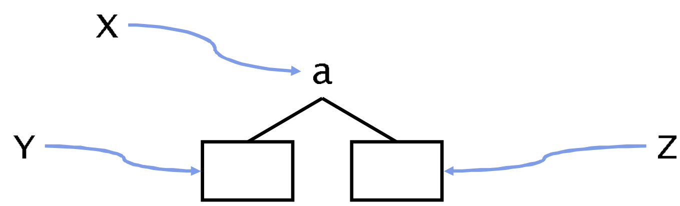


Variable-Variable Binding

- Binding variables together makes them equal
  - binding a variable (or another variables) affects all variables that are bound together
- In our previous example
  - Executing X=a also binds Y to a
  - Now links are not longer needed



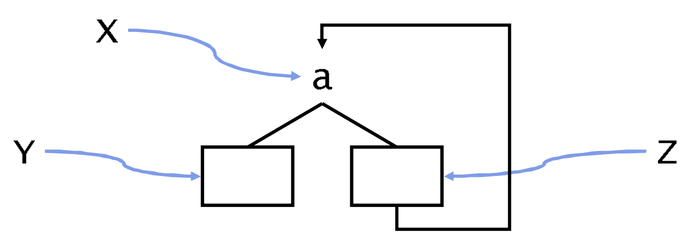
Constructing Graphs



- Example

```
declare
Y Z X=a(Y Z)
```


Constructing Graphs



- Now bind `Z` to `X`

```
Z = X
```

- Possible due to deferred assignment
  - we won't make use of it right now

Remark: Other Cases

- Suppose in X=Y both X and Y are bound
- Case one: no variables involved
  - test whether data structures are the “same”
  - is already involved due to graphs
- Case two: X or Y refer to partial values
  - occurring variables are bound to make X and Y the “same”
  - this process is called *unification*

Remark: Other Cases

- Suppose in X=Y both X and Y are bound
- Case one: no variables involved
  - test whether data structures are the “same”
  - is already involved due to graphs
-
```
declare
X=f(a b) Y=f(a b)
X=Y % passes silently
```
-
```
declare
X=f(a b) Y=f(a c)
X=Y % raises an error
```

Remark: Other Cases

- Suppose in X=Y both X and Y are bound
- Case one: no variables involved
  - test whether data structures are the “same”
  - is already involved due to graphs
- declare

```
X=f(a X) Y=f(a f(a Y))
X=Y  % this is fine
```

- X=Y=f(a f(a f(a …))) % ad infinitum

Remark: Other Cases

- Suppose in X=Y both X and Y are bound
- Case two: X or Y refer to partial values
  - occurring variables are bound to make X and Y the “same”
  - this process is called *unification*
- declare

```
U Z X=f(a U) Y=f(Z b)
```

- U is bound to b, Z is bound to a

Summary: Partial Values

- Bound and unbound variables
- Variable-variable binding
- Skeleton construction
- Automatic synchronization
- Variable-variable equality (unification)

Lists

Lists

- A list contains a sequence of elements
- A list
  - is the empty list, or
  - consists of a *cons* (or *list pair*) with *head* and *tail*
    - head contains an element
    - tail contains a list

Encoding Lists with Tuples

- Lists are encoded with atoms and tuples
  - empty list: the atom `nil`
  - cons: tuple of width 2 with label `'|'`
- Special syntax for cons

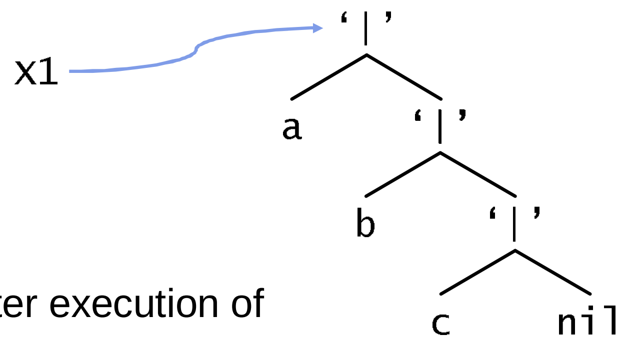
```
X = Y|Z
```

instead of

```
X = '|'(Y Z)
```

But of course: both are equivalent

An Example List



- After execution of

```
declare
X1=a|X2    X2=b|X3    X3=c|nil
```


Simple List Construction

- One can also write

  `X1=a|b|c|nil`

  which abbreviates

  `X1=a|(b|(c|nil))`

  which abbreviates

  `X1=‘|’(a ‘|’(b ‘|’(c nil)))`

- Even shorter

  `X1=[a b c]`

Computing With Lists

- Remember: a cons is a tuple!
- Access head of cons
```
X.1
```
- Access tail of cons
```
X.2
```
- Test whether list X is empty:
```
if X==nil then … else … end
```

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Head And Tail

- Define abstractions for lists
```
fun {Head Xs}
   Xs.1
end

fun {Tail Xs}
   Xs.2
end
```

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Example of Head and Tail

- `{Head [a b c]}`
  returns `a`
- `{Tail [a b c]}`
  returns `[b c]`
- `{Head {Tail {Tail [a b c]}}}`
  returns `c`

- Draw the trees!

How to Process Lists

- Given: list of integers
- Wanted: sum of its elements
  - implement function `Sum`

- Inductive definition over list structure
  - Sum of empty list is `0`
  - Sum of non-empty list `L` is
    `{Head L} + {Sum {Tail L}}`

Sum of a List

```
fun {Sum L}
   if L==nil then
      0
   else
      {Head L} + {Sum {Tail L}}
   end
end
```


General Method

- Lists are processed recursively
  - base case: list is empty (nil)
  - inductive case: list is cons
    access head, access tail
- Powerful and convenient technique
  - *pattern matching*
  - matches patterns of values and provides access to fields of compound data structures

Sum with Pattern Matching

```
fun {Sum L}
    case L
    of nil then 0
    [] H|T then H+{Sum T}
    end
end
```


Sum with Pattern Matching

```
fun {Sum L}
    case L
    of nil then 0
    [] H|T then H+{Sum T}
    end
end
```

Clause

- `nil` is the *pattern* of the clause

Sum with Pattern Matching

```
fun {Sum L}
   case L
   of nil then 0
   [] H|T then H+{Sum T}
   end
end
```

Clause

- `H|T` is the *pattern* of the clause

Pattern Matching

- The first clause uses `of`, all other `[]`
- Clauses are tried in textual order
- A clause matches, if its pattern matches
- A pattern matches, if the width, label and features agree
  - then, the variables in the pattern are assigned to the respective fields
- Case-statement executes with first matching clause

Length of a List

- Inductive definition
  - length of empty list is 0
  - length of cons is 1 + length of tail

```
fun {Length Xs}
   case Xs
   of nil then 0
   [] X|Xr then 1+{Length Xr}
   end
end
```


General Pattern Matching

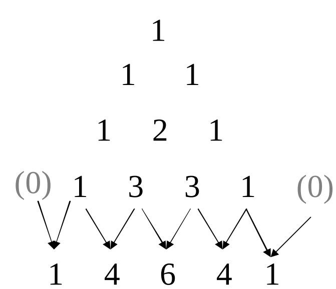
- Pattern matching can be used not only for lists!
- Any value, including numbers, atoms, tuples, records
- Will be practiced in tutorial 2

Lists: Summary

- List is either empty or cons with head and tail
- List processing is recursive processing
- Useful for this is pattern matching

Functions over lists

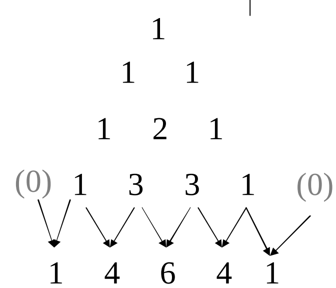
- Compute the function {Pascal N}
- Takes an integer N, and returns the Nth row of a Pascal triangle as a list



Functions over lists

- Compute the function {Pascal N}

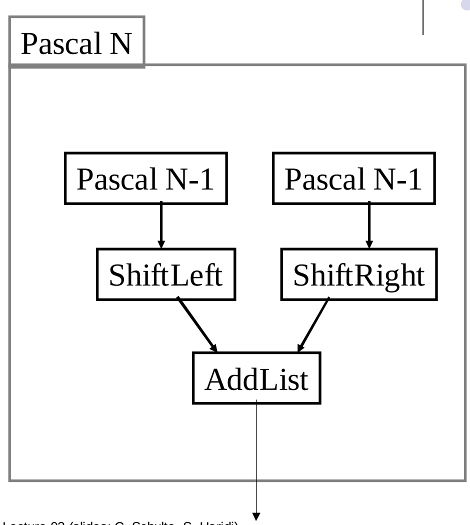
1. For row 1, the result is [1]
2. For row N, shift to left row N-1 and shift to the right row N-1
3. Align and add the shifted rows element-wise to get row N



Shift right [0 1 3 3 1]

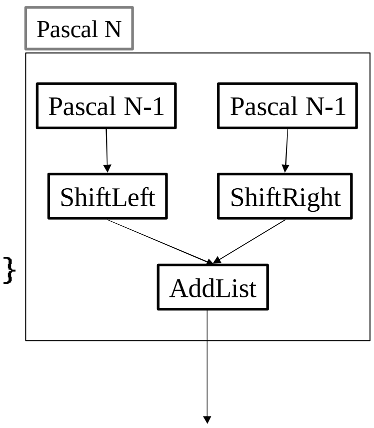
Shift left [1 3 3 1 0]

Functions over lists (2)



Functions over lists (2)

```
declare
fun {Pascal N}
   if N==1 then [1]
   else
      {AddList
       {ShiftLeft {Pascal N-1}}
       {ShiftRight {Pascal N-1}}}
   end
end
```



Functions over lists (3)

```
fun {ShiftLeft L}
   case L of H|T then
      H|{ShiftLeft T}
   else [0]
   end
end
```

```
fun {ShiftRight L}  0|L end
```

Functions over lists (3)

```
fun {AddList L1 L2}
   case L1 of H1|T1 then
      case L2 of H2|T2 then
         H1+H2|{AddList T1 T2}
      end
   else nil end
end
```


Top-down program development

- Understand how to solve the problem by hand
- Try to solve the task by decomposing it to simpler tasks
- Devise the main function (main task) in terms of suitable auxiliary functions (subtasks) that simplifies the solution (ShiftLeft, ShiftRight and AddList)
- Complete the solution by writing the auxiliary functions

Is your program correct?

- ”A program is correct when it does what we would like it to do”
- In general we need to reason about the program:
- **Semantics for the language**: a precise model of the operations of the programming language
- **Program specification**: a definition of the output in terms of the input (usually a mathematical function or relation)
- Use mathematical techniques to reason about the program, using programming language semantics

Mathematical induction

- Select one or more input to the function
- Show the program is correct for the *simple cases* (base case)
- Show that if the program is correct for a *given case*, it is then correct for the *next case*.
- For integers base case is either 0 or 1, and for any integer n the next case is n+1
- For lists the base case is nil, or a list with one or few elements, and for any list T the next case H|T

Correctness of factorial

```
fun {Fact N}
  if N==0 then 1 else N*{Fact N-1} end
end
```

$$\underbrace{1\times 2\times\cdots\times(n-1)}_{Fact(n-1)}\times n$$

- Base Case: {Fact 0} returns 1
- (N>1), N*{Fact N-1} assume {Fact N-1} is correct, from the spec we see the {Fact N} is N*{Fact N-1}
- More techniques to come !

Complexity

- Pascal runs very slow, try {Pascal 24}
- {Pascal 20} calls: {Pascal 19} twice, {Pascal 18} four times, {Pascal 17} eight times, ..., {Pascal 1} 2^{19} times
- Execution time of a program up to a constant factor is called program's *time complexity*.
- Time complexity of {Pascal N} is proportional to 2^N (exponential)
- Programs with exponential time complexity are impractical

```
declare
fun {Pascal N}
  if N==1 then [1]
  else
    {AddList
     {ShiftLeft {Pascal N-1}}
     {ShiftRight {Pascal N-1}}}
  end
end
```

Faster Pascal

- Introduce a local variable L
- Compute {FastPascal N-1} only once
- Try with 30 rows.
- FastPascal is called N times, each time a list on the average of size N/2 is processed
- The time complexity is proportional to N^2 (polynomial)
- Low order polynomial programs are practical.

```
fun {FastPascal N}
  if N==1 then [1]
  else
     local L in
       L={FastPascal N-1}
       {AddList {ShiftLeft L} {ShiftRight L}}
     end
  end
end
```


Higher-order programming

- Assume we want to write another Pascal function which instead of adding numbers performs exclusive-or on them
- It calculates for each number whether it is odd or even (parity)
- Either write a new function each time we need a new operation, or write one generic function that takes an operation (another function) as argument
- The ability to pass functions as argument, or return a function as result is called *higher-order programming*
- Higher-order programming is an aid to build generic abstractions

Variations of Pascal

- Compute the parity Pascal triangle

  fun {Xor X Y} if X==Y then 0 else 1 end end

1	1
1 1	1 1
1 2 1	1 0 1
1 3 3 1	1 1 1 1
1 4 6 4 1	1 0 0 0 1

Higher-order programming

```
fun {GenericPascal Op N}
   if N==1 then [1]
   else L in L = {GenericPascal Op N-1}
      {OpList  Op {ShiftLeft L} {ShiftRight L}}
   end
end
```

Higher-order programming

```
fun {OpList Op L1 L2}
  case L1 of H1|T1 then
     case L2 of H2|T2 then
           {Op H1 H2}|{OpList Op T1 T2}
     end
  else nil end
end
```


Higher-order programming

```
fun {Add N1 N2} N1+N2 end
fun {Xor N1 N2}
  if N1==N2 then 0 else 1 end
end

fun {Pascal N} {GenericPascal Add N} end
fun {ParityPascal N}
  {GenericPascal Xor N}
end
```

This Lecture

- Data structures
  - tuples, lists, records
- More on variables
  - bound and unbound variables
  - partial values
  - dataflow variables and dataflow synchronization
- More on computing
  - pattern matching
- Higher order programs (functions)
- Why a computation model
  - procedures as opposed to functions

Towards the Model

This is the outlook section

Confusion

- By now you should feel uneasy and slightly embarrassed (maybe even confused)
- We haven't explained how computation actually proceeds
- No, you are fine? Wait and see…

Another Length

```
fun {L Xs N}
   case Xs
   of nil then N
   [] X|Xr then {L Xr N+1}
   end
end
fun {Length Xs}
   {L Xs 0}
end
```

Comparison

- This length is six-times faster then our first one!
  - hey, it has one argument more!
  - so what
  - what could be the difference
  - and what is more: it takes considerable less memory!
  - actually, it runs in constant memory!
- Our model will answer
  - intuition: even though recursive it executes like a loop

There Is No Free Lunch!

- Before we can answer the questions we have to make the language small
  - sort out what is primitive: kernel language
  - what can be expressed
- Kernel language
  - based on procedures
  - no functions

What Is a Procedure?

- It does not return a value
  - Java: methods with `void` as return type
- But how to return a value anyway?
  - Idea: use an unbound variable
  - Why: we can supply value later (before return)
  - Aha: so that's why we have been dwelling on this!

Our First Procedure: Sum

```
proc {Sum Xs N}
   case Xs
   of nil then N=0
   [] X|Xr then N=X+{Sum Xr}
   end
end
```

- Hey, we call `Sum` as if it was a function
  - that's okay. It is just syntax
  - we'll sort that out next week

Being More Primitive

```
proc {Sum Xs N}
   case Xs
   of nil then N=0
   [] X|Xr then
      local M in {Sum Xr M} N=X+M end
   end
end
```

- Local declaration of variables
- Needed to fully base kernel language on procedures

Summary

- Tuples and records
- Variables
- Lists
- Pattern matching
- Towards the model

Have a Nice Weekend!