Programming Languages and Compilers (CS 421)
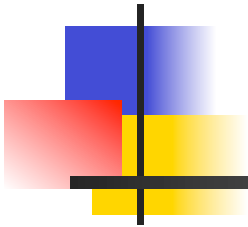
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Based in part on slides by Mattox Beckman, as updated by Vikram Adve and Gul Agha

CPS Transformation

- Step 1: Add continuation argument to any function definition:
  - let f arg = e $\Rightarrow$ let f arg k = e
  - Idea: Every function takes an extra parameter saying where the result goes
- Step 2: A simple expression in tail position should be passed to a continuation instead of returned:
  - return a $\Rightarrow$ k a
  - Assuming a is a constant or variable.
  - "Simple" = "No available function calls."

CPS Transformation

- Step 3: Pass the current continuation to every function call in tail position
  - return f arg $\Rightarrow$ f arg k
  - The function "isn't going to return," so we need to tell it where to put the result.
- Step 4: Each function call not in tail position needs to be converted to take a new continuation (containing the old continuation as appropriate)
  - return op (f arg) $\Rightarrow$ f arg (fun r -> k(op r))
    - op represents a primitive operation
  - return f(g arg) $\Rightarrow$ g arg (fun r-> f r k)

Example

Before:

```
let rec add_list lst =
match lst with
  [ ] -> 0
| 0 :: xs -> add_list xs
| x :: xs -> (+) x
   (add_list xs);;
```
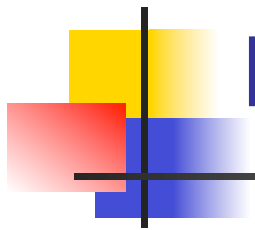
After:

```
let rec add_listk lst k =
                 (* rule 1 *)
match lst with
| [ ] -> k 0 (* rule 2 *)
| 0 :: xs -> add_listk xs k
                  (* rule 3 *)
| x :: xs -> add_listk xs
       (fun r -> k ((+) x r));;
                 (* rule 4 *)
```
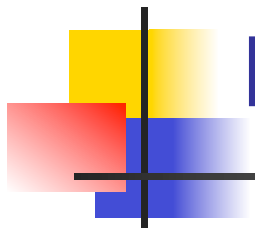
Other Uses for Continuations

- CPS designed to preserve order of evaluation

- Continuations used to express order of evaluation

- Can be used to change order of evaluation

- Implements:
  - Exceptions and exception handling
  - Co-routines
  - (pseudo, aka green) threads

Exceptions - Example

exception Zero;;

exception Zero

let rec list_mult_aux list =

   match list with [ ] -> 1

   | x :: xs ->

   if x = 0 then raise Zero

          else x * list_mult_aux xs;;
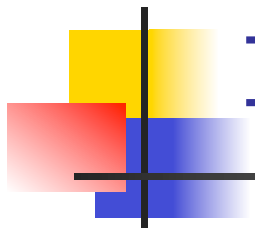
val list_mult_aux : int list -> int = <fun>

Exceptions - Example

let list_mult list =
    try list_mult_aux list with Zero -> 0;;
val list_mult : int list -> int = <fun>
list_mult [3;4;2];;
- : int = 24
list_mult [7;4;0];;
- : int = 0
list_mult_aux [7;4;0];;
Exception: Zero.

Exceptions

- When an exception is raised
  - The current computation is aborted
  - Control is "thrown" back up the call stack until a matching handler is found
  - All the intermediate calls waiting for a return values are thrown away

Implementing Exceptions
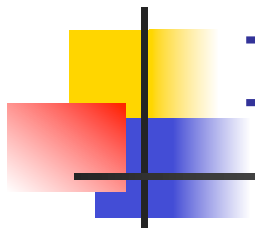
```
# let multkp m n k =
    let r = m * n in
      (print_string "product result: ";
       print_int r; print_string "\n";
       k r);;
val multkp : int -> int -> (int -> 'a) -> 'a
  = <fun>
```

Implementing Exceptions

let rec list_multk_aux list k kexcp =

   match list with [ ] -> k 1

   | x :: xs -> if x = 0 then kexcp 0

      else list_multk_aux xs

          (fun r -> multkp x r k) kexcp;;

val list_multk_aux : int list -> (int -> 'a) -> (int -> 'a)
  -> 'a = <fun>

let rec list_multk list k = list_multk_aux list k k;;

val list_multk : int list -> (int -> 'a) -> 'a = <fun>

Implementing Exceptions

list_multk [3;4;2] report;;

product result: 2

product result: 8

product result: 24
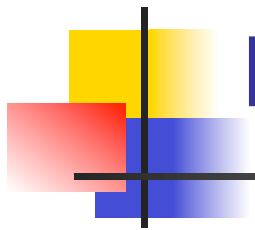
24

- : unit = ()

list_multk [7;4;0] report;;

0

- : unit = ()

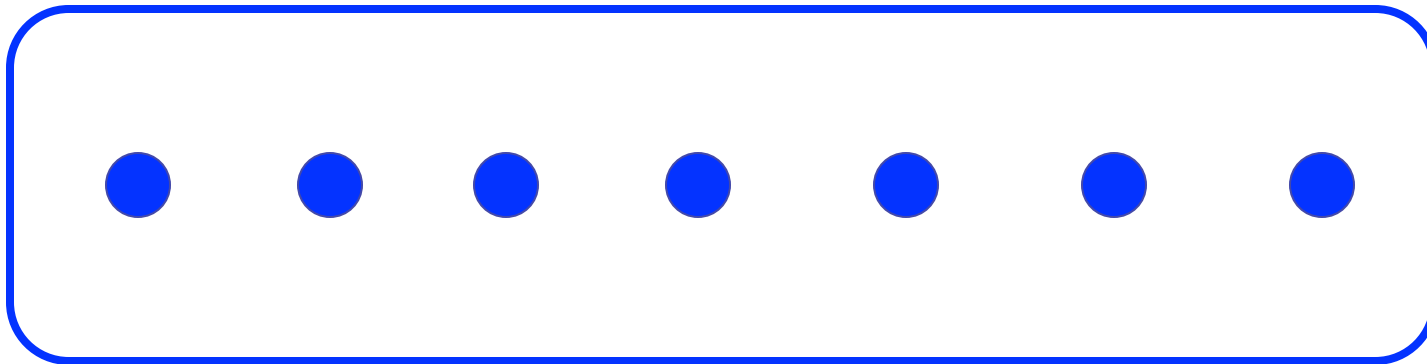# Variants - Syntax (slightly simplified)

- type *name* $= C_1$ *[of ty_1] | . . . | C_n [of ty_n]*
- Introduce a type called *name*
- (fun x -> C_i x) : ty_1 -> *name*
- C_i is called a *constructor*; if the optional type argument is omitted, it is called a *constant*
- Constructors are the basis of almost all pattern matching

Enumeration Types as Variants

An enumeration type is a collection of distinct values

In C and Ocaml they have an order structure; order by order of input

Enumeration Types as Variants

\# type weekday = Monday | Tuesday | Wednesday
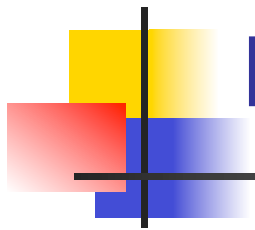 | Thursday | Friday | Saturday | Sunday;;

type weekday =
    Monday
  | Tuesday
  | Wednesday
  | Thursday
  | Friday
  | Saturday
  | Sunday

Functions over Enumerations

```
# let day_after day = match day with
      Monday -> Tuesday
  | Tuesday -> Wednesday
  | Wednesday -> Thursday
  | Thursday -> Friday
  | Friday -> Saturday
  | Saturday -> Sunday
  | Sunday -> Monday;;
val day_after : weekday -> weekday = <fun>
```

Functions over Enumerations

```
# let rec days_later n day =
    match n with 0 -> day
    | _ -> if n > 0
        then day_after (days_later (n - 1) day)
        else days_later (n + 7) day;;
val days_later : int -> weekday -> weekday
    = <fun>
```

Functions over Enumerations

\# days_later 2 Tuesday;;

- : weekday = Thursday
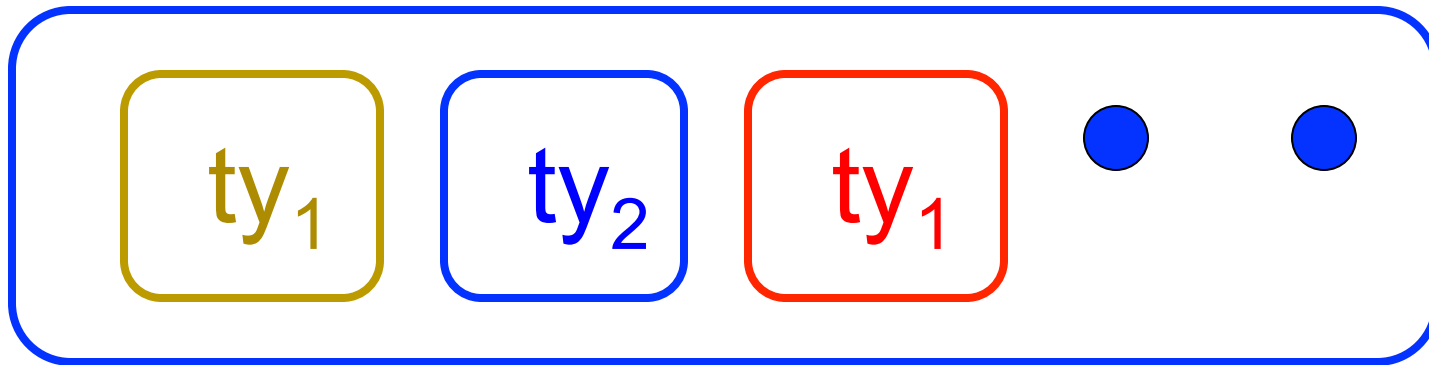
\# days_later (-1) Wednesday;;

- : weekday = Tuesday

\# days_later (-4) Monday;;

- : weekday = Thursday

Disjoint Union Types

- Disjoint union of types, with some possibly occurring more than once

$$ty_1 \quad ty_2 \quad ty_1 \quad \bullet \quad \bullet$$

- We can also add in some new singleton elements

Disjoint Union Types

```
# type id = DriversLicense of int
  | SocialSecurity of int | Name of string;;
type id = DriversLicense of int | SocialSecurity
  of int | Name of string
# let check_id id = match id with
    DriversLicense num ->
      not (List.mem num [13570; 99999])
  | SocialSecurity num -> num < 900000000
  | Name str -> not (str = "John Doe");;
val check_id : id -> bool = <fun>
```

Polymorphism in Variants

- The type 'a option is gives us something to represent non-existence or failure

\# type 'a option = Some of 'a | None;;

type 'a option = Some of 'a | None

- Used to encode partial functions
- Often can replace the raising of an exception
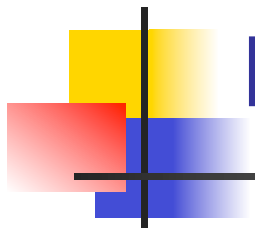
Functions producing option

```
# let rec first p list =
    match list with [ ] -> None
    | (x::xs) -> if p x then Some x else first p xs;;
val first : ('a -> bool) -> 'a list -> 'a option = <fun>
# first (fun x -> x > 3) [1;3;4;2;5];;
- : int option = Some 4
# first (fun x -> x > 5) [1;3;4;2;5];;
- : int option = None
```

Functions over option

```
# let result_ok r =
    match r with None -> false
    | Some _ -> true;;
val result_ok : 'a option -> bool = <fun>
# result_ok (first (fun x -> x > 3) [1;3;4;2;5]);;
- : bool = true
# result_ok (first (fun x -> x > 5) [1;3;4;2;5]);;
- : bool = false
```
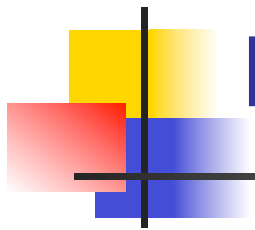
Folding over Variants

```
# let optionFold someFun noneVal opt =
    match opt with None -> noneVal
    | Some x -> someFun x;;
val optionFold : ('a -> 'b) -> 'b -> 'a option ->
  'b = <fun>
# let optionMap f opt =
    optionFold (fun x -> Some (f x)) None opt;;
val optionMap : ('a -> 'b) -> 'a option -> 'b
  option = <fun>
```
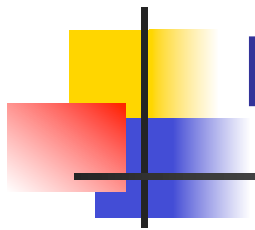
Recursive Types

- The type being defined may be a component of itself
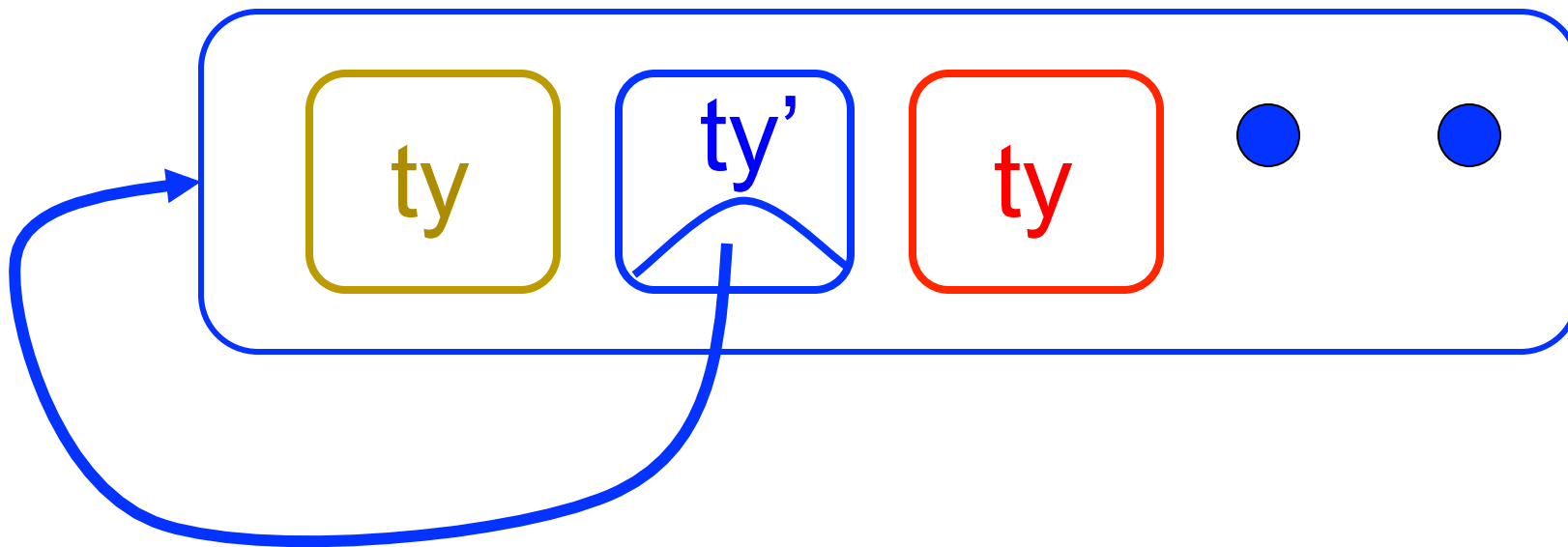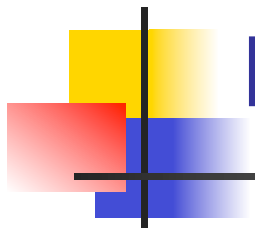
Mapping over Variants

```
# let optionMap f opt =
    match opt with None -> None
    | Some x -> Some (f x);;
val optionMap : ('a -> 'b) -> 'a option -> 'b
  option = <fun>
# optionMap
  (fun x -> x - 2)
  (first (fun x -> x > 3) [1;3;4;2;5]);;
- : int option = Some 2
```

Recursive Data Types

type int_Bin_Tree =
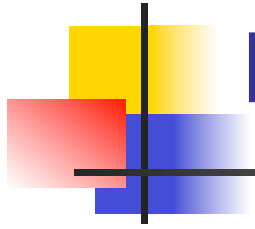Leaf of int | Node of (int_Bin_Tree *
   int_Bin_Tree);;

type int_Bin_Tree = Leaf of int | Node of
   (int_Bin_Tree * int_Bin_Tree)

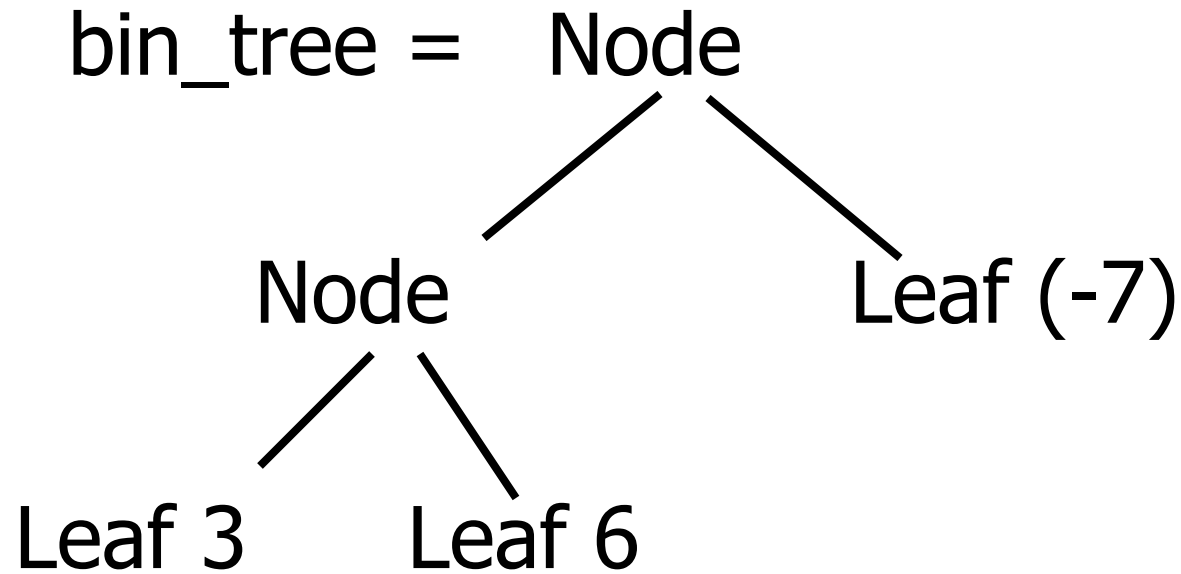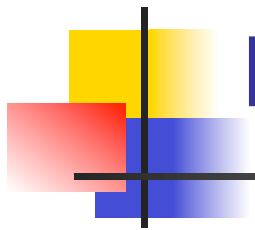# Recursive Data Type Values

let bin_tree =

Node(Node(Leaf 3, Leaf 6),Leaf (-7));;

val bin_tree : int_Bin_Tree = Node (Node (Leaf 3, Leaf 6), Leaf (-7))

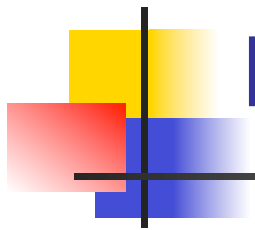# Recursive Data Type Values

bin_tree =   Node

        Node   Leaf (-7)

Leaf 3   Leaf 6

# Recursive Functions

let rec first_leaf_value tree =
   match tree with (Leaf n) -> n
   | Node (left_tree, right_tree) ->
   first_leaf_value left_tree;;
val first_leaf_value : int_Bin_Tree -> int =
  <fun>
let left = first_leaf_value bin_tree;;
val left : int = 3
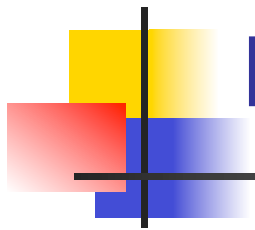
Mapping over Recursive Types

let rec ibtreeMap f tree =
    match tree with (Leaf n) -> Leaf (f n)
    | Node (left_tree, right_tree) ->
      Node (ibtreeMap f left_tree,
          ibtreeMap f right_tree);;
val ibtreeMap : (int -> int) -> int_Bin_Tree ->
  int_Bin_Tree = <fun>
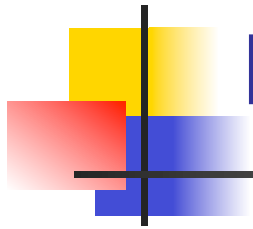
Mapping over Recursive Types

ibtreeMap ((+) 2) bin_tree;;

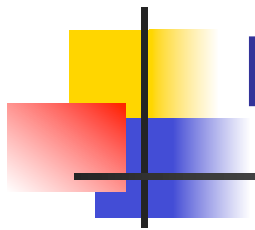- : int_Bin_Tree = Node (Node (Leaf 5, Leaf 8), Leaf (-5))

Folding over Recursive Types

```
# let rec ibtreeFoldRight leafFun nodeFun tree =
    match tree with Leaf n -> leafFun n
    | Node (left_tree, right_tree) ->
      nodeFun
      (ibtreeFoldRight leafFun nodeFun left_tree)
      (ibtreeFoldRight leafFun nodeFun right_tree);;
val ibtreeFoldRight : (int -> 'a) -> ('a -> 'a -> 'a) ->
  int_Bin_Tree -> 'a = <fun>
```

Folding over Recursive Types

let tree_sum =

   ibtreeFoldRight (fun x -> x) (+);;

val tree_sum : int_Bin_Tree -> int = <fun>

tree_sum bin_tree;;

- : int = 2

Mutually Recursive Types

type 'a tree = TreeLeaf of 'a
   | TreeNode of 'a treeList
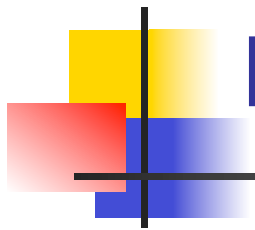and 'a treeList = Last of 'a tree
   | More of ('a tree * 'a treeList);;

type 'a tree = TreeLeaf of 'a | TreeNode of 'a treeList

and 'a treeList = Last of 'a tree | More of ('a tree * 'a treeList)

Mutually Recursive Types - Values

let tree =
  TreeNode
   (More (TreeLeaf 5,
          (More (TreeNode
                 (More (TreeLeaf 3,
                        Last (TreeLeaf 2))),
          Last (TreeLeaf 7)))));;

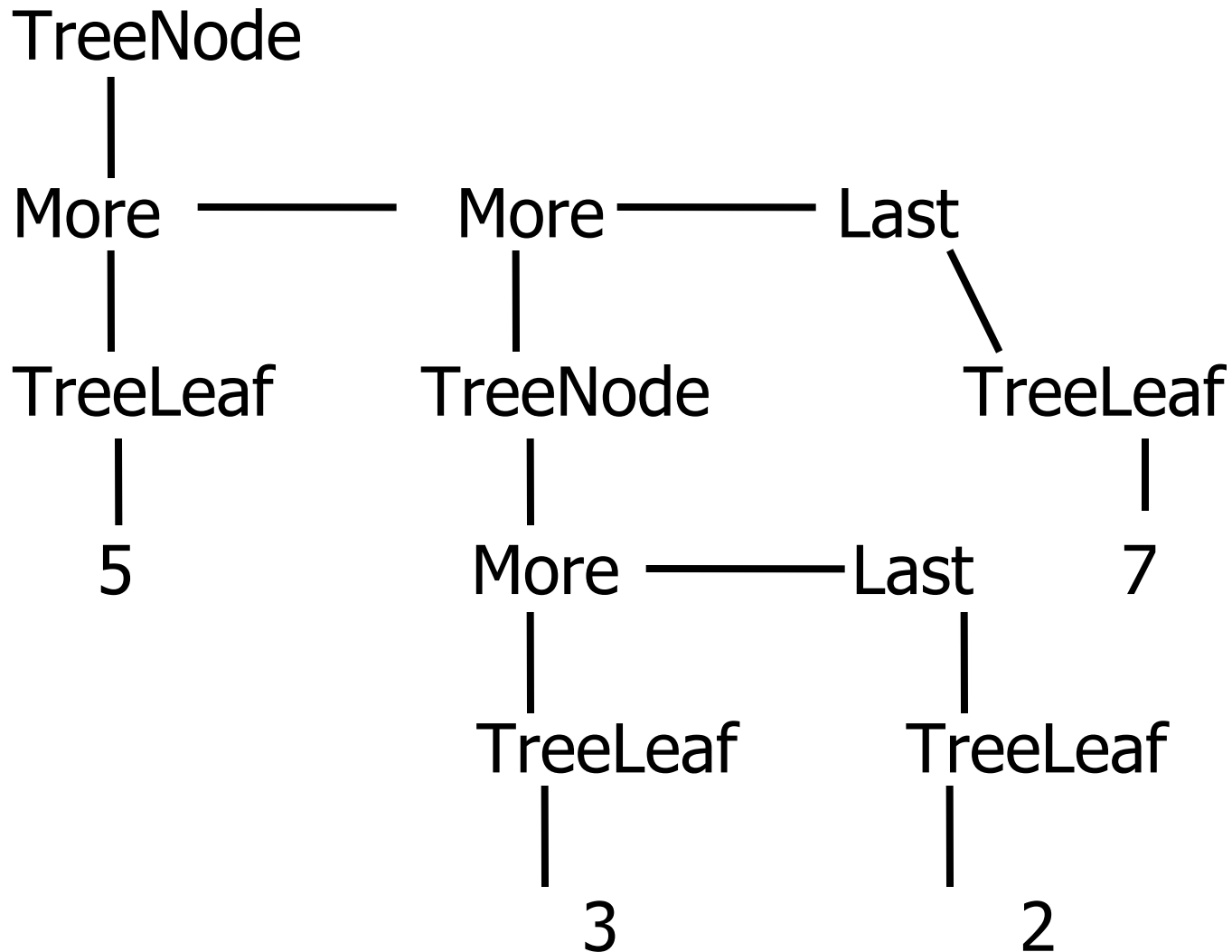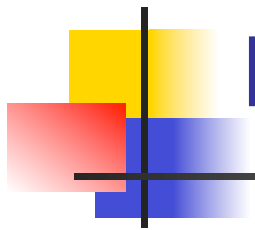# Mutually Recursive Types - Values

val tree : int tree =
 TreeNode
 (More
    (TreeLeaf 5,
     More
      (TreeNode (More (TreeLeaf 3, Last
(TreeLeaf 2))), Last (TreeLeaf 7))))
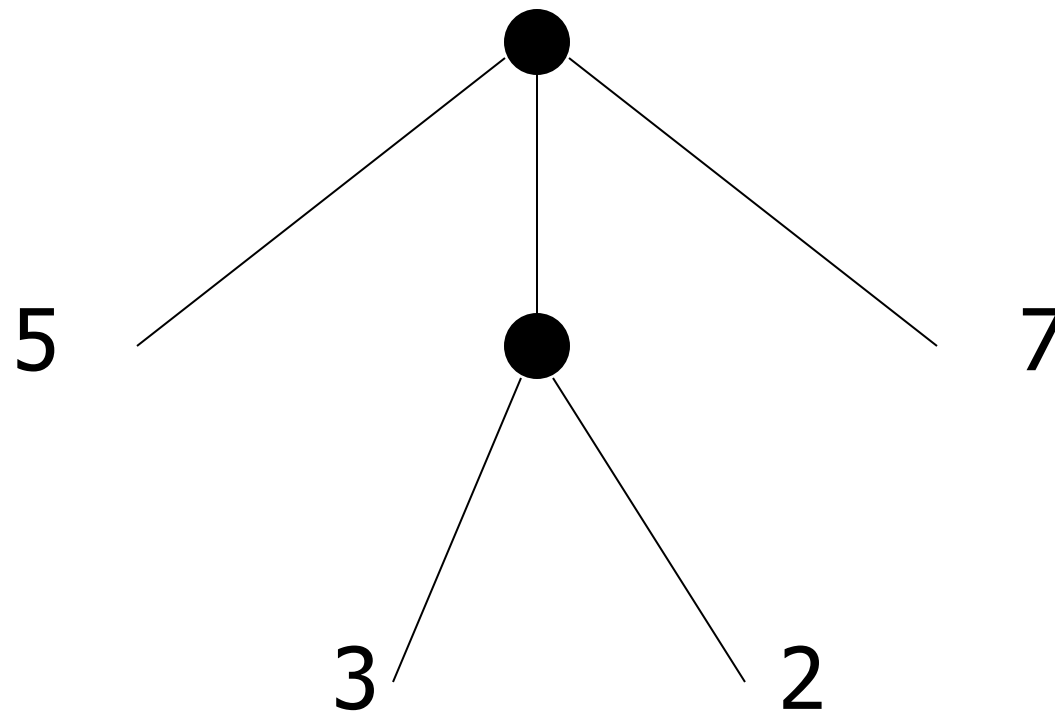
Mutually Recursive Types - Values

TreeNode
|
More ——— More ——— Last
| | \
TreeLeaf   TreeNode   TreeLeaf
| | |
5   More ——— Last   7
| |
TreeLeaf   TreeLeaf
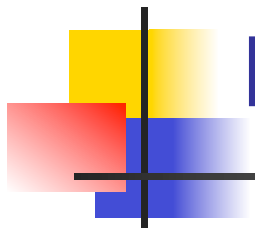| |
3   2

Mutually Recursive Types - Values

A more conventional picture

Mutually Recursive Functions

```
# let rec fringe tree =
    match tree with (TreeLeaf x) -> [x]
  | (TreeNode list) -> list_fringe list
and list_fringe tree_list =
    match tree_list with (Last tree) -> fringe tree
  | (More (tree,list)) ->
    (fringe tree) @ (list_fringe list);;

val fringe : 'a tree -> 'a list = <fun>
val list_fringe : 'a treeList -> 'a list = <fun>
```
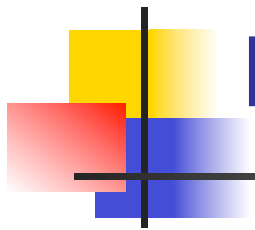
Mutually Recursive Functions

fringe tree;;
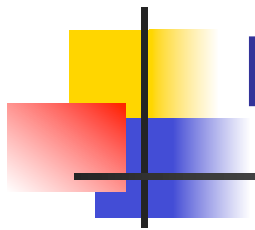
- : int list = [5; 3; 2; 7]

Nested Recursive Types
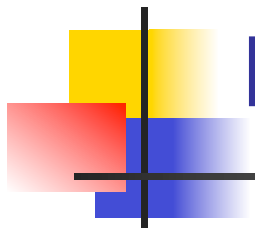
type 'a labeled_tree =

TreeNode of ('a * 'a labeled_tree list);;

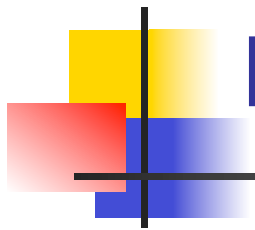type 'a labeled_tree = TreeNode of ('a * 'a labeled_tree list)

Nested Recursive Type Values

let ltree =
TreeNode(5,
  [TreeNode (3, []);
   TreeNode (2, [TreeNode (1, []);
                 TreeNode (7, [])]);
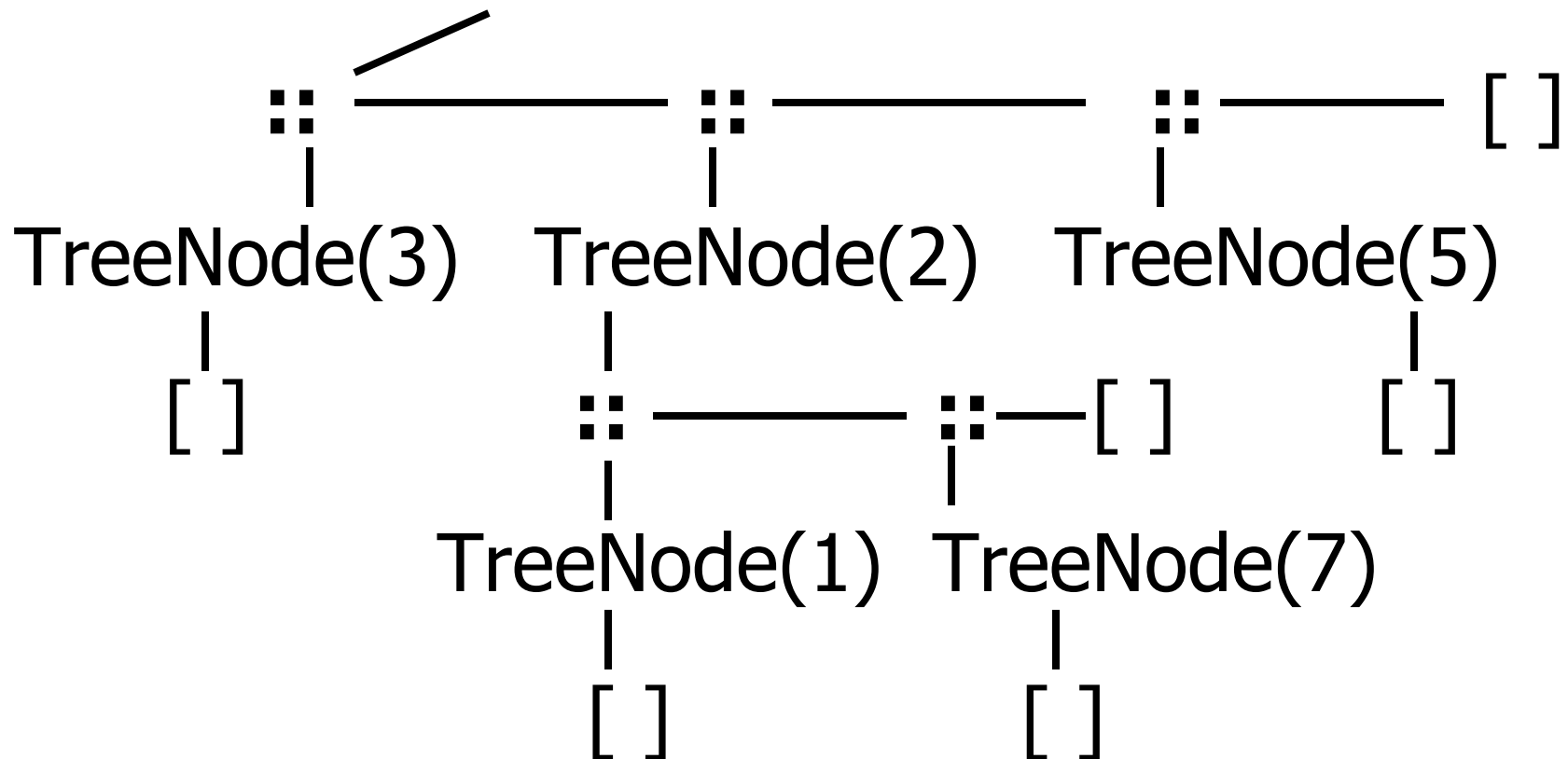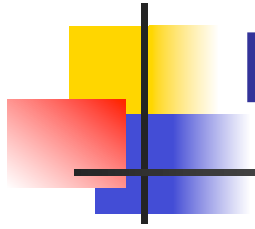   TreeNode (5, [])]);;

Nested Recursive Type Values

val ltree : int labeled_tree =

  TreeNode

  (5,

   [TreeNode (3, []); TreeNode (2,
   [TreeNode (1, []); TreeNode (7, [])]);

    TreeNode (5, [])])
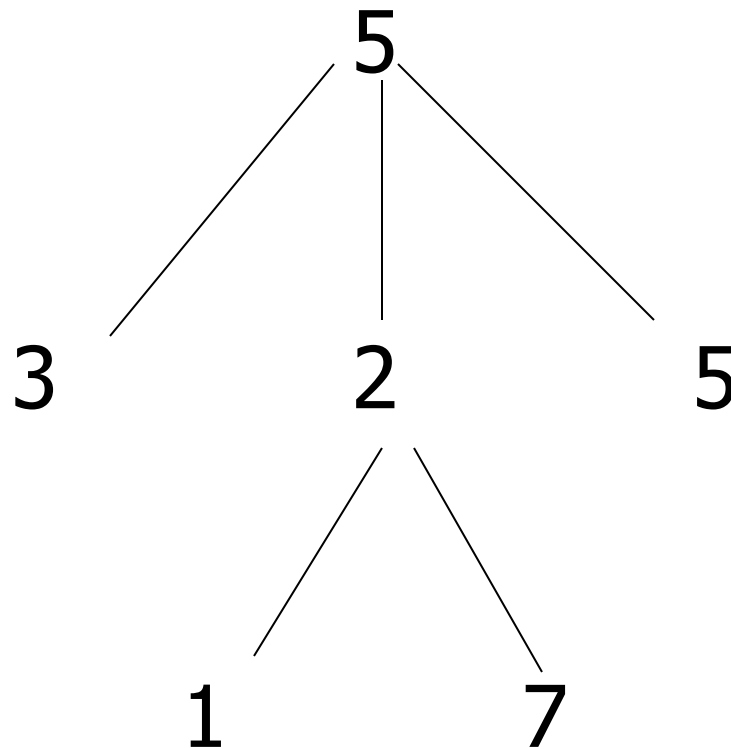
Nested Recursive Type Values

Ltree = TreeNode(5)

```
         ::————————————::—————————::——————[ ]
         |              |          |
    TreeNode(3)    TreeNode(2)   TreeNode(5)
         |              |          |
        [ ]         ::————————::—[ ]      [ ]
                    |         |
                TreeNode(1)  TreeNode(7)
                    |            |
                   [ ]          [ ]
```

Mutually Recursive Functions

let rec flatten_tree labtree =
   match labtree with TreeNode (x,treelist)
    -> x::flatten_tree_list treelist
  and flatten_tree_list treelist =
  match treelist with [] -> []
  | labtree::labtrees
    -> flatten_tree labtree
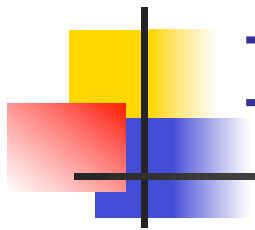   @ flatten_tree_list labtrees;;

Mutually Recursive Functions

val flatten_tree : 'a labeled_tree -> 'a list = <fun>

val flatten_tree_list : 'a labeled_tree list -> 'a list = <fun>

flatten_tree ltree;;

- : int list = [5; 3; 2; 1; 7; 5]

- Nested recursive types lead to mutually recursive functions

Infinite Recursive Values

let rec ones = 1::ones;;
val ones : int list =
  [1; 1; 1; 1; ...]
match ones with x::_ -> x;;
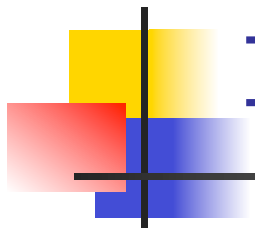Characters 0-25:
Warning: this pattern-matching is not exhaustive.
Here is an example of a value that is not matched:
[]
  match ones with x::_ -> x;;
  ^^^^^^^^^^^^^^^^^^^^^^^^^^
- : int = 1

Infinite Recursive Values

let rec lab_tree = TreeNode(2, tree_list)

and tree_list = [lab_tree; lab_tree];;

val lab_tree : int labeled_tree =

TreeNode (2, [TreeNode(...); TreeNode(...)])

val tree_list : int labeled_tree list =

[TreeNode (2, [TreeNode(...);
 TreeNode(...)]);

TreeNode (2, [TreeNode(...);
 TreeNode(...)])]

Infinite Recursive Values

\# match lab_tree

   with TreeNode (x, _) -> x;;

- : int = 2

Records

- Records serve the same programming purpose as tuples

- Provide better documentation, more readable code

- Allow components to be accessed by label instead of position
    - Labels (aka *field names* must be unique)
    - Fields accessed by suffix dot notation

Record Types

- Record types must be declared before they can be used in OCaml

```
# type person = {name : string; ss : (int * int
  * int); age : int};;
type person = { name : string; ss : int * int *
  int; age : int; }
```

- person is the type being introduced
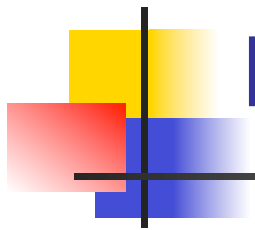- name, ss and age are the labels, or fields

Record Values

- Records built with labels; order does not matter

let teacher = {name = "Elsa L. Gunter"; age = 102; ss = (119,73,6244)};;

val teacher : person =
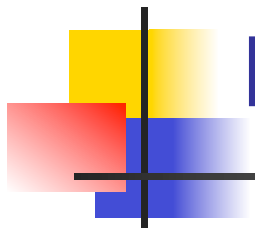 {name = "Elsa L. Gunter"; ss = (119, 73, 6244); age = 102}

Record Pattern Matching

let {name = elsa; age = age; ss = (_,_,s3)} = teacher;;

val elsa : string = "Elsa L. Gunter"
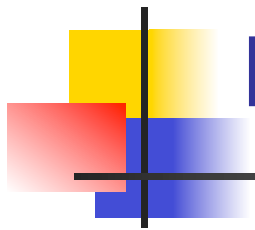
val age : int = 102

val s3 : int = 6244

Record Field Access

let soc_sec = teacher.ss;;

val soc_sec : int * int * int = (119, 73, 6244)

Record Values

# let student = {ss=(325,40,1276);
  name="Joseph Martins"; age=22};;

val student : person =

  {name = "Joseph Martins"; ss = (325, 40,
  1276); age = 22}

student = teacher;;

- : bool = false

New Records from Old

let birthday person = {person with age = person.age + 1};;

val birthday : person -> person = <fun>

birthday teacher;;

- : person = {name = "Elsa L. Gunter"; ss = (119, 73, 6244); age = 103}

New Records from Old

let new_id name soc_sec person =
 {person with name = name; ss = soc_sec};;
val new_id : string -> int * int * int -> person
  -> person = <fun>

new_id "Guieseppe Martin" (523,04,6712)
  student;;
- : person = {name = "Guieseppe Martin"; ss
  = (523, 4, 6712); age = 22}