An overview of Mezzo

François Pottier

INRIA

Bertinoro, June 2015

Acknowledgements

Jonathan Protzenko, Thibaut Balabonski,
Henri Chataing, Armaël Guéneau, Cyprien Mangin.

What is Mezzo?

An *experimental* programming language in the tradition of ML.

Try it out in your browser:

```
http://gallium.inria.fr/~protzenk/mezzo-web/
```

Or install it:

```
opam install mezzo
```

Premise

The types of OCaml, Haskell, Java, C#, etc.:

- describe the *structure* of data,
- but do not distinguish *trees* and *graphs*,
- and do not control who has *permission* to read or write.

Question

Could a more ambitious static discipline:

- *rule out* more programming errors, including *data races*,
- and *enable* new programming idioms,
- while remaining reasonably *simple* and *flexible*?

A quick comparison

In comparison with Tobias Wrigstad's talk (yesterday),

- *data race freedom* and *ownership transfer* are goals too;
- getting rid of GC is not;
- types and permissions *do not* influence code generation; they are erased at runtime.

Outline

- A first example and a few principles
  - Write-once references: usage
  - Mezzo: (some) design principles
  - Write-once references: interface & implementation
  - Mezzo: the good and the bad
- Algebraic data structures
- Sharing mutable data
- Conclusion

A first example and a few principles

Write-once references: usage

Write-once references

A write-once reference:

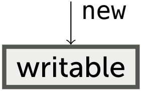
- can be written *at most* once;
- can be read only *after* it has been written.

Let us look at a concrete example of use...

Usage

```
open woref
```

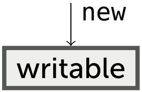
Usage



```
open woref

val r1 = new ()
(* r1 @ writable *)
```

Usage

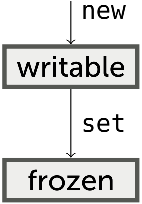

new

writable

```
open woref

val r1 = new ()
(* r1 @ writable *)
val r2 = r1
(* r1 @ writable * r2 = r1 *)
```

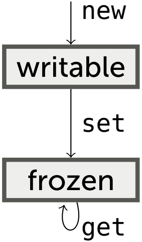
Usage



```
open woref

val r1 = new ()
(* r1 @ writable *)
val r2 = r1
(* r1 @ writable * r2 = r1 *)
val () = set (r1, 3);
(* r1 @ frozen int * r2 = r1 *)
```

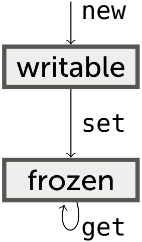
Usage



```
open woref

val r1 = new ()
(* r1 @ writable *)
val r2 = r1
(* r1 @ writable * r2 = r1 *)
val () = set (r1, 3);
(* r1 @ frozen int * r2 = r1 *)
val x2 = get r2
(* r1 @ frozen int * r2 = r1 * x2 @ int *)
```

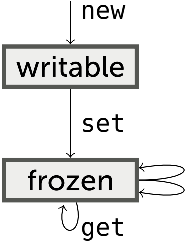
Usage



```
open woref

val r1 = new ()
(* r1 @ writable *)
val r2 = r1
(* r1 @ writable * r2 = r1 *)
val () = set (r1, 3);
(* r1 @ frozen int * r2 = r1 *)
val x2 = get r2
(* r1 @ frozen int * r2 = r1 * x2 @ int *)
val rs = (r1, r2)
(* r1 @ frozen int * r2 = r1 * x2 @ int
 * rs @ (=r1, =r2) *)
```

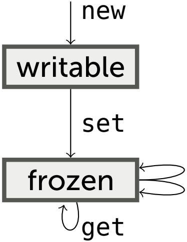
Usage



```
open woref

val r1 = new ()
(* r1 @ writable *)
val r2 = r1
(* r1 @ writable * r2 = r1 *)
val () = set (r1, 3);
(* r1 @ frozen int * r2 = r1 *)
val x2 = get r2
(* r1 @ frozen int * r2 = r1 * x2 @ int *)
val rs = (r1, r2)
(* r1 @ frozen int * r2 = r1 * x2 @ int
 * rs @ (=r1, =r2) *)
(* rs @ (frozen int, frozen int) *)
```

Usage



```
open woref

val r1 = new ()
(* r1 @ writable *)
val r2 = r[illegible]
(* r1 @ [illegible]e * r2 = r1 *)
val () = s[illegible]3);
(* r1 @ froze[illegible]* r2 = r1 *)
val x2 = get r2
(* r1 @ frozen int * r2 = r1 * x2 @ int *)
val rs = (r1, r2)
(* r1 @ frozen int * r2 = r1 * x2 @ int
 * rs @ (=r1, =r2) *)
(* rs @ (frozen int, frozen int) *)
```

A first example and a few principles

Mezzo: (some) design principles

Permissions

Like a program logic, the static discipline is *flow-sensitive*.

- A *current* (set of) *permission*(s) exists *at each program point*.
- *Different* permissions exist at different points.

Permissions do not exist at runtime.

Permissions

Thus, there is no such thing as *the* type of a variable `x`. Instead,

- *at each program point* in the scope of `x`,
- there may be *zero, one, or more* permissions to use `x` in certain ways.

Layout and ownership

Permissions have *layout* and *ownership* readings.

- e.g., `r @ writable`

`x @ t` describes the *shape and extent* of a heap fragment, rooted at `x`, and describes certain *access rights* for it.

“To know about `x`” is “to have access to `x`” is “to own `x`”.

Just two access modes

Every permission is either duplicable or affine.

The basic rules are:

- *Immutable* data is *duplicable*, i.e., shareable.
- *Mutable* data is *affine*, i.e., uniquely owned.
- Mutable data can become immutable; not the converse.

Aliasing

- Writing `let x = y in ...` gives rise to an equation `x = y`.
- It is a permission: `x @ =y`, where `=y` is a *singleton type*.
- In its presence, `x @ t` and `y @ t` are interconvertible.
- Thus, *any name is as good as any other*.
- The same idea applies to `let x = xs.head in ...` .

Value ≠ permission

A value can be copied (always). No permission is required.

```
(* empty *)
let y = (x, x) in
(* y @ (=x, =x) *)
```

Value $\neq$ permission

A duplicable permission *can* be copied. This is implicit.

```
(* x @ int *)
let y = (x, x) in
(* x @ int * y @ (=x, =x) *)
```

Value ≠ permission

A duplicable permission *can* be copied. This is implicit.

```
(* x @ int *)
let y = (x, x) in
(* x @ int * y @ (=x, =x) *)
(* x @ int * y @ (int, int) *)
```

Value $\neq$ permission

An affine permission *cannot* be copied.

```
(* x @ ref int *)
let y = (x, x) in
(* x @ ref int * y @ (=x, =x) *)
```

Value $\neq$ permission

An affine permission *cannot* be copied.

```
(* x @ ref int *)
let y = (x, x) in
(* x @ ref int * y @ (=x, =x) *)
assert y @ (ref int, ref int) (* WRONG! *)
```

In other words, mutable data cannot be shared.

Examples of duplicable versus affine

- `x @ list int` is duplicable: read access can be shared.
- `x = y` is duplicable: equalities are forever.
- `x @ mlist int` and `x @ list (ref int)` are affine: they give exclusive access to part of the heap.

Separation

`x @ ref int * y @ ref int` implies `x` and `y` are distinct.

Conjunction is *separating* at mutable data.

`z @ (t, u)` means `z @ (=x, =y) * x @ t * y @ u`, for `x`, `y` fresh.

Hence, product is separating.

Separation

The same principle applies to records.

Hence, `list (ref int)` denotes a list of *distinct* references.

Mutable data must be *tree*-structured.

- though `x @ ref (=x)` can be written and constructed.

A first example and a few principles

Write-once references: interface & implementation

Specification

A usage protocol can be described in a module signature:

- A *state* is a (user-defined) type.
- A *transition* is a (user-defined) function.

Specification of write-once refs

This protocol has two states and four transitions.

This is the interface file `woref.mzi`:

```
abstract writable
abstract frozen a
fact duplicable (frozen a)
val new: () -> writable
val set: [a] (consumes r: writable, x: a | duplicable a)
         -> (| r @ frozen a)
val get: [a] frozen a -> a
```

Specification of write-once refs

This protocol has two states and four transitions.

This is the interface file `woref.mzi`:

```
abstract writable
abstract frozen a
fact duplicable (frozen a)
val new: () -> writable
val set: [a] (consumes r: writable, x: a | duplicable a)
         -> (| r @ frozen a)
val get: [a] frozen a -> a
```

a state

Specification of write-once refs

This protocol has two states and four transitions.

This is the interface file `woref.mzi`:

```
abstract writable
abstract frozen a
fact duplicable (frozen a)
val new: () -> writable
val set: [a] (consumes r: writable, x: a | duplicable a)
         -> (| r @ frozen a)
val get: [a] frozen a -> a
```

another state

Specification of write-once refs

This protocol has two states and four transitions.

This is the interface file `woref.mzi`:

```
abstract writable
abstract frozen a
fact duplicable (frozen a)
val new: () -> writable
val set: [a] (consumes r: writable, x: a | duplicable a)
         -> (| r @ frozen a)
val get: [a] frozen a -> a
```

implicit transition from frozen to frozen * frozen

Specification of write-once refs

This protocol has two states and four transitions.

This is the interface file `woref.mzi`:

```
abstract writable
abstract frozen a
fact duplicable (frozen a)
val new: () -> writable
val set: [a] (consumes r: writable, x: a | duplicable a)
         -> (| r @ frozen a)
val get: [a] frozen a -> a
```

explicit transition into writable

Specification of write-once refs

This protocol has two states and four transitions.

This is the interface file `woref.mzi`:

```
abstract writable
abstract frozen a
fact duplicable (frozen a)
val new: () -> writable
val set: [a] (consumes r: writable, x: a | duplicable a)
         -> (| r @ frozen a)
val get: [a] frozen a -> a
```

set requires r (dynamic)
and r @ writable (static)

Specification of write-once refs

This protocol has two states and four transitions.

This is the interface file `woref.mzi`:

```
abstract writable
abstract frozen a
fact duplicable (frozen a)
val new: () -> writable
val set: [a] (consumes r: writable, x: a | duplicable a)
         -> (| r @ frozen a)
val get: [a] frozen a -> a
```

consumes keyword means
r @ writable NOT returned

Specification of write-once refs

This protocol has two states and four transitions.

This is the interface file `woref.mzi`:

```
abstract writable
abstract frozen a
fact duplicable (frozen a)
val new: () -> writable
val set: [a] (consumes r: writable, x: a | duplicable a)
          -> (| r @ frozen a)
val get: [a] frozen a -> a
```

duplicable a
is a permission

Specification of write-once refs

This protocol has two states and four transitions.

This is the interface file `woref.mzi`:

```
abstract writable
abstract frozen a
fact duplicable (frozen a)
val new: () -> writable
val set: [a] (consumes r: writable, x: a | duplicable a)
          -> (| r @ frozen a)
val get: [a] frozen a -> a
```

explicit transition from writable to frozen

Specification of write-once refs

This protocol has two states and four transitions.

This is the interface file `woref.mzi`:

```
abstract writable
abstract frozen a
fact duplicable (frozen a)
val new: () -> writable
val set: [a] (consumes r: writable, x: a | duplicable a)
          -> (| r @ frozen a)
val get: [a] frozen a -> a
```

`get r requires r @ frozen a`

Implementation

This is the implementation file `woref.mz`:

```
data mutable writable =
  Writable { contents: () }
data frozen a =
  Frozen   { contents: (a | duplicable a) }
val new () : writable =
  Writable { contents = () }
val set [a] (consumes r: writable, x: a | duplicable a)
    : (| r @ frozen a) =
  r.contents <- x;
  tag of r <- Frozen (* this is a no-op *)
val get [a] (r: frozen a) : a =
  r.contents
```

Implementation

This is the implementation

a field of type ()

```
data mutable writable =
  Writable { contents: () }
data frozen a =
  Frozen   { contents: (a | duplicable a) }
val new () : writable =
  Writable { contents = () }
val set [a] (consumes r: writable, x: a | duplicable a)
    : (| r @ frozen a) =
  r.contents <- x;
  tag of r <- Frozen (* this is a no-op *)
val get [a] (r: frozen a) : a =
  r.contents
```

Implementation

This is the implementation

a field of type a
where a must be duplicable

```
data mutable writable =
  Writable { contents: () }
data frozen a =
  Frozen   { contents: (a | duplicable a) }
val new () : writable =
  Writable { contents = () }
val set [a] (consumes r: writable, x: a | duplicable a)
    : (| r @ frozen a) =
  r.contents <- x;
  tag of r <- Frozen (* this is a no-op *)
val get [a] (r: frozen a) : a =
  r.contents
```

Implementation

This is the implementation

initially,
r @ writable

```
data mutable writable =
  Writable { contents: () }
data frozen a =
  Frozen   { contents: (a | duplicable a) }
val new () : writable =
  Writable { contents = () }
val set [a] (consumes r: writable, x: a | duplicable a)
    : (| r @ frozen a) =
  r.contents <- x;
  tag of r <- Frozen (* this is a no-op *)
val get [a] (r: frozen a) : a =
  r.contents
```

Implementation

This is the implementation

```
hence,
r @ Writable { contents: () }
```

```
data mutable writable =
  Writable { contents: () }
data frozen a =
  Frozen   { contents: (a | duplicable a) }
val new () : writable =
  Writable { contents = () }
val set [a] (consumes r: writable, x: a | duplicable a)
    : (| r @ frozen a) =
  r.contents <- x;
  tag of r <- Frozen (* this is a no-op *)
val get [a] (r: frozen a) : a =
  r.contents
```

Implementation

This is the implementation

```
data mutable writable =
  Writable { contents: () }
data frozen a =
  Frozen   { contents: (a | duplicable a) }
val new () : writable =
  Writable { contents = () }
val set [a] (consumes r: writable, x: a | duplicable a)
    : (| r @ frozen a) =
  r.contents <- x;
  tag of r <- Frozen (* this is a no-op *)
val get [a] (r: frozen a) : a =
  r.contents
```

after the assignment,
r @ Writable { contents: =x }

Implementation

This is the implementation

hence,

r @ Writable { contents: a }

```
data mutable writable =
  Writable { contents: () }
data frozen a =
  Frozen   { contents: (a | duplicable a) }
val new () : writable =
  Writable { contents = () }
val set [a] (consumes r: writable, x: a | duplicable a)
    : (| r @ frozen a) =
  r.contents <- x;
  tag of r <- Frozen (* this is a no-op *)
val get [a] (r: frozen a) : a =
  r.contents
```

Implementation

This is the implementation

after the tag update,
r @ Frozen { contents: a }

```
data mutable writable =
  Writable { contents: () }
data frozen a =
  Frozen   { contents: (a | duplicable a) }
val new () : writable =
  Writable { contents = () }
val set [a] (consumes r: writable, x: a | duplicable a)
    : (| r @ frozen a) =
  r.contents <- x;
  tag of r <- Frozen (* this is a no-op *)
val get [a] (r: frozen a) : a =
  r.contents
```

Implementation

This is the implementation

```
data mutable writable =
  Writable { contents: () }
data frozen a =
  Frozen   { contents: (a | duplicable a) }
val new () : writable =
  Writable { contents = () }
val set [a] (consumes r: writable, x: a | duplicable a)
    : (| r @ frozen a) =
  r.contents <- x;
  tag of r <- Frozen (* this is a no-op *)
val get [a] (r: frozen a) : a =
  r.contents
```

hence,
`r @ frozen a`

A first example and a few principles

Mezzo: the good and the bad

The good

The uniqueness of read/write permissions:

- *rules out* several categories of errors:
    - data races; hence, *shared-memory concurrency is safe*;
    - representation exposure;
    - violations of (certain) object protocols.
- *allows* the type of an object to vary with time, which enables:
    - explicit memory re-use;
    - gradual initialization;
    - describing (certain) object protocols.

The good

Here are some other positive aspects:

- all of the *power* of ML, and more;
  - higher-order functions, pattern matching, polymorphism, etc.
- no need to annotate types with owners;
  - to have a permission is to own
- *ownership transfer* is easy;
  - just pass (or return, or store, or extract) a permission
- no need to annotate function types with effects.
  - just pass and return a permission

The good

Moving an element *into* or *out of* a container is easy.

Here is a typical container interface:

```
abstract bag a
val new:     [a] () -> bag a
val insert:  [a] (bag a, consumes a) -> ()
val extract: [a] bag a -> option a
```

The bad

The discipline *forbids sharing* mutable data.

For this reason, *borrowing* an element from a container is typically restricted to *duplicable* elements:

```
val find:
  [a]
  duplicable a =>
  (a -> bool) -> list a -> option a
```

This affects user-defined data structures, arrays, regions, etc.

The bad

Fortunately,

- there is *no restriction* on the use of immutable data;
- there are *several ways* of sharing mutable data:
    - (static) nesting; regions;
    - (dynamic) adoption & abandon;
    - (dynamic) locks.

Outline

- A first example and a few principles
- Algebraic data structures
    - (More) Principles
    - Computing the length of a list
    - Melding mutable lists
    - Concatenating immutable lists
- Sharing mutable data
- Conclusion

Algebraic data structures

(More) Principles

Immutable lists

The algebraic data type of immutable lists is defined as in ML:

```
data list a =
  | Nil
  | Cons { head: a; tail: list a }
```

Mutable lists

To define a type of mutable lists, one adds a keyword:

```
data mutable mlist a =
  | MNil
  | MCons { head: a; tail: mlist a }
```

Examples

For instance,

- `x @ list int` provides (read) access to an immutable list of integers, rooted at `x`.
- `x @ mlist int` provides (exclusive, read/write) access to a mutable list of integers at `x`.
- `x @ list (ref int)` offers read access to the spine and read/write access to the elements, which are distinct cells.

Permission refinement

Permission refinement takes place at case analysis.

```
match xs with
| MNil ->

    ...
| MCons ->

    let x = xs.head in

    ...
end
```

In contrast, traditional separation logic has *untagged* union.

Permission refinement

Permission refinement takes place at case analysis.

```
match xs with
| MNil ->

    ...
| MCons ->

    let x = xs.head in

    ...
end
```

a nominal permission:
`xs @ mlist a`

In contrast, traditional separation logic has *untagged* union.

Permission refinement

Permission refinement takes place at case analysis.

```
match xs with
| MNil ->

    ...
| MCons ->

    let x = xs.head in

    ...
end
```

a structural permission:

xs @ MNil

In contrast, traditional separation logic has *untagged* union.

Permission refinement

Permission refinement takes place at case analysis.

```
match xs with
| MNil ->

    ...
| MCons ->

    let x = xs.head in

    ...
end
```

another structural permission:
`xs @ MCons { head: a; tail: mlist a }`

In contrast, traditional separation logic has *untagged* union.

Permission refinement

Permission refinement takes place at case analysis.

```
match xs with
| MNil ->

    ...
| MCons ->

    let x = xs.head in

    ...
end
```

```
automatically expanded to:
xs @ MCons { head: (=h); tail: (=t) }
* h @ a
* t @ mlist a
```

In contrast, traditional separation logic has *untagged* union.

Permission refinement

Permission refinement takes place at case analysis.

```
match xs with
| MNil ->

    ...
| MCons ->

    let x = xs.head in

    ...
end
```

```
or (sugar):
xs @ MCons { head = h; tail = t }
* h @ a
* t @ mlist a
```

In contrast, traditional separation logic has *untagged* union.

Permission refinement

Permission refinement takes place at case analysis.

```
match xs with
| MNil ->

    ...
| MCons ->

    let x = xs.head in

    ...
end
```

```
so, after the read access:
xs @ MCons { head = h; tail = t }
* h @ a
* t @ mlist a
* x = h
```

In contrast, traditional separation logic has *untagged* union.

Principles

This illustrates two mechanisms:

- A nominal permission can be *unfolded* and *refined*, yielding a structural permission.
- A structural permission can be *decomposed*, yielding separate permissions for the block and its fields.

These reasoning steps are implicit and reversible.

Algebraic data structures

Computing the length of a list

Interface

Here is the type of the `length` function for mutable lists.

```
val length: [a] mlist a -> int
```

It should be understood as follows:

- `length` requires one argument `xs`,
  along with the permission `xs @ mlist a`.
- `length` returns one result `n`,
  along with the permission `xs @ mlist a * n @ int`.

Implementation

```
val rec length_aux [a] (accu: int, xs: mlist a) : int =
  match xs with
  | MNil ->
      accu
  | MCons ->
      length_aux (accu + 1, xs.tail)
  end

val length [a] (xs: mlist a) : int =
  length_aux (0, xs)
```

Implementation

```
val rec length_aux [a] (accu: int, xs: mlist a) : int =
  match xs with
  | MNil ->
      accu
  | MCons ->
      length_aux (accu + 1, xs.tail)
  end

val length [a] (xs: mlist a) : int =
  length_aux (0, xs)
```

initially:
xs @ mlist a

Implementation

```
val rec length_aux [a] (accu: int, xs: mlist a) : int =
  match xs with
  | MNil ->
      accu
  | MCons ->
      length_aux (accu + 1, xs.tail)
  end

val length [a] (xs: mlist a) : int =
  length_aux (0, xs)
```

```
upon entry into the first branch:
xs @ MNil
```

Implementation

```
val rec length_aux [a] (accu: int, xs: mlist a) : int =
  match xs with
  | MNil ->
      accu
  | MCons ->
      length_aux (accu + 1, xs.tail)
  end

val length [a] (xs: mlist a) : int =
  length_aux (0, xs)
```

upon exit of the first branch:
xs @ MNil

Implementation

```
val rec length_aux [a] (accu: int, xs: mlist a) : int =
  match xs with
  | MNil ->
      accu
  | MCons ->
      length_aux (accu + 1, xs.tail)
  end

val length [a] (xs: mlist a) : int =
  length_aux (0, xs)
```

upon exit of the first branch:

xs @ mlist a

Implementation

```
val rec length_aux [a] (accu: int, xs: mlist a) : int =
  match xs with
  | MNil ->
      accu
  | MCons ->
      length_aux (accu + 1, xs.tail)
  end

val length [a] (xs: mlist a) : int =
  length_aux (0, xs)
```

upon entry into the second branch:
xs @ MCons { head = h; tail = t }
h @ a
t @ mlist a

Implementation

```
val rec length_aux [a] (accu: int, xs: mlist a) : int =
  match xs with
  | MNil ->
      accu
  | MCons ->
      length_aux (accu + 1, xs.tail)
  end

val length [a] (xs: mlist a) : int =
  length_aux (0, xs)
```

after the call, nothing has changed:
xs @ MCons { head = h; tail = t }
h @ a
t @ mlist a

Implementation

```
val rec length_aux [a] (accu: int, xs: mlist a) : int =
  match xs with
  | MNil ->
      accu
  | MCons ->
      length_aux (accu + 1, xs.tail)
  end

val length [a] (xs: mlist a) : int =
  length_aux (0, xs)
```

thus, by recombining:

xs @ MCons { head: a; tail: mlist a }

Implementation

```
val rec length_aux [a] (accu: int, xs: mlist a) : int =
  match xs with
  | MNil ->
      accu
  | MCons ->
      length_aux (accu + 1, xs.tail)
  end

val length [a] (xs: mlist a) : int =
  length_aux (0, xs)
```

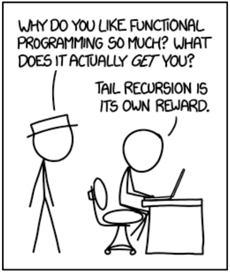
thus, by folding:
xs @ mlist a

Tail recursion versus iteration

The analysis of this code is surprisingly simple.

- This is a *tail-recursive* function, i.e., a loop in disguise.
- As we go, there is a *list* ahead of us and a *list segment* behind us.
- Ownership of the latter is *implicit*, i.e., *framed out*.

Recursive reasoning, iterative execution.



Algebraic data structures

Melding mutable lists

Melding mutable lists (1/2)

```
val rec meld_aux [a]
  (xs: MCons { head: a; tail: mlist a },
   consumes ys: mlist a) : () =
  match xs.tail with
  | MNil  ->
      xs.tail <- ys
  | MCons ->
      meld_aux (xs.tail, ys)
  end
```

Melding mutable lists (1/2)

xs is not consumed: at the end,
it is still a valid non-empty list

```
val rec meld_aux [a]
  (xs: MCons { head: a; tail: mlist a },
   consumes ys: mlist a) : () =
  match xs.tail with
  | MNil  ->
      xs.tail <- ys
  | MCons ->
      meld_aux (xs.tail, ys)
  end
```

Melding mutable lists (1/2)

at the end, ys is accessible through xs,
hence must no longer be used directly

```
val rec meld_aux [a]
  (xs: MCons { head: a; tail: mlist a },
   consumes ys: mlist a) : () =
  match xs.tail with
  | MNil  ->
      xs.tail <- ys
  | MCons ->
      meld_aux (xs.tail, ys)
  end
```

Melding mutable lists (1/2)

```
xs @ MCons { head: a; tail = t }
t @ MNil
ys @ mlist a
```

```
val rec meld_aux [a]
  (xs: MCons { head: a; tail: mlist a },
   consumes ys: mlist a) : () =
  match xs.tail with
  | MNil  ->
      xs.tail <- ys
  | MCons ->
      meld_aux (xs.tail, ys)
  end
```

Melding mutable lists (1/2)

```
xs @ MCons { head: a; tail = ys }
t @ MNil
ys @ mlist a
```

```
val rec meld_aux [a]
  (xs: MCons { head: a; tail: mlist a },
   consumes ys: mlist a) : () =
  match xs.tail with
  | MNil  ->
      xs.tail <- ys
  | MCons ->
      meld_aux (xs.tail, ys)
  end
```

Melding mutable lists (1/2)

```
xs @ MCons { head: a; tail: mlist a }
t @ MNil
```

```
val rec meld_aux [a]
  (xs: MCons { head: a; tail: mlist a },
   consumes ys: mlist a) : () =
  match xs.tail with
  | MNil  ->
      xs.tail <- ys
  | MCons ->
      meld_aux (xs.tail, ys)
  end
```

Melding mutable lists (1/2)

```
xs @ MCons { head: a; tail: mlist a }
```

```
val rec meld_aux [a]
  (xs: MCons { head: a; tail: mlist a },
   consumes ys: mlist a) : () =
  match xs.tail with
  | MNil  ->
      xs.tail <- ys
  | MCons ->
      meld_aux (xs.tail, ys)
  end
```

Melding mutable lists (1/2)

```
xs @ MCons { head: a; tail = t }
t @ MCons { head: a; tail: mlist a }
ys @ mlist a
```

```
val rec meld_aux [a]
  (xs: MCons { head: a; tail: mlist a },
   consumes ys: mlist a) : () =
  match xs.tail with
  | MNil  ->
      xs.tail <- ys
  | MCons ->
      meld_aux (xs.tail, ys)
  end
```

Melding mutable lists (1/2)

```
xs @ MCons { head: a; tail = t }
t @ MCons { head: a; tail: mlist a }
```

```
val rec meld_aux [a]
  (xs: MCons { head: a; tail: mlist a },
   consumes ys: mlist a) : () =
  match xs.tail with
  | MNil  ->
      xs.tail <- ys
  | MCons ->
      meld_aux (xs.tail, ys)
  end
```

Melding mutable lists (1/2)

```
xs @ MCons { head: a; tail = t }
t @ mlist a
```

```
val rec meld_aux [a]
  (xs: MCons { head: a; tail: mlist a },
   consumes ys: mlist a) : () =
  match xs.tail with
  | MNil  ->
      xs.tail <- ys
  | MCons ->
      meld_aux (xs.tail, ys)
  end
```

Melding mutable lists (1/2)

`xs @ MCons { head: a; tail: mlist a }`

```
val rec meld_aux [a]
  (xs: MCons { head: a; tail: mlist a },
   consumes ys: mlist a) : () =
  match xs.tail with
  | MNil  ->
      xs.tail <- ys
  | MCons ->
      meld_aux (xs.tail, ys)
  end
```

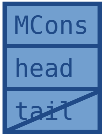
Melding mutable lists (2/2)

```
val meld [a] (consumes xs: mlist a,
              consumes ys: mlist a) : mlist a =
  match xs with
  | MNil  -> ys
  | MCons -> meld_aux (xs, ys); xs
  end
```

Algebraic data structures

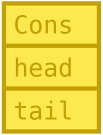
Concatenating immutable lists

Three states



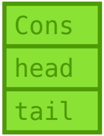
An `MCons` cell:

- mutable,
- uninitialized `tail`,
- type: `MCons { head: a; tail: () }`



An isolated `Cons` cell:

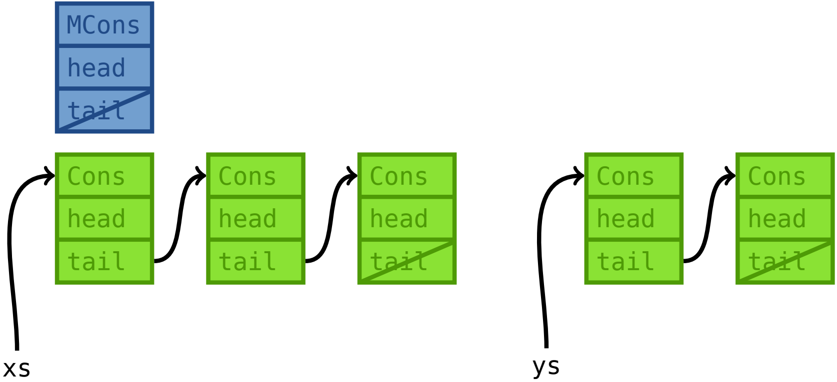
- immutable,
- *not* the start of a well-formed list,
- type: `Cons { head: a; tail = t }`



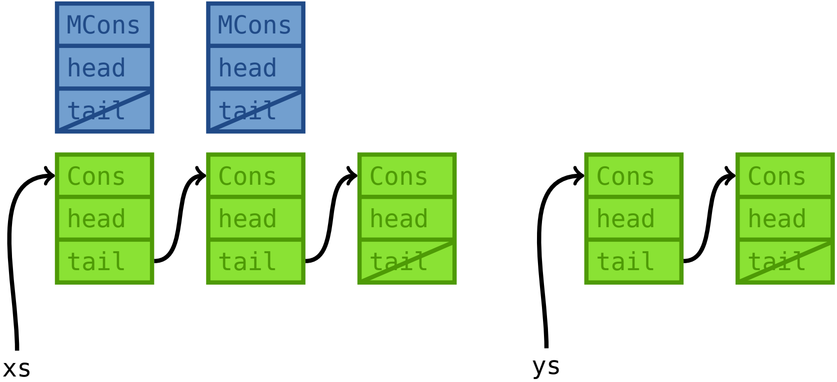
A `list` cell:

- immutable,
- the start of a well-formed list,
- type `list a`

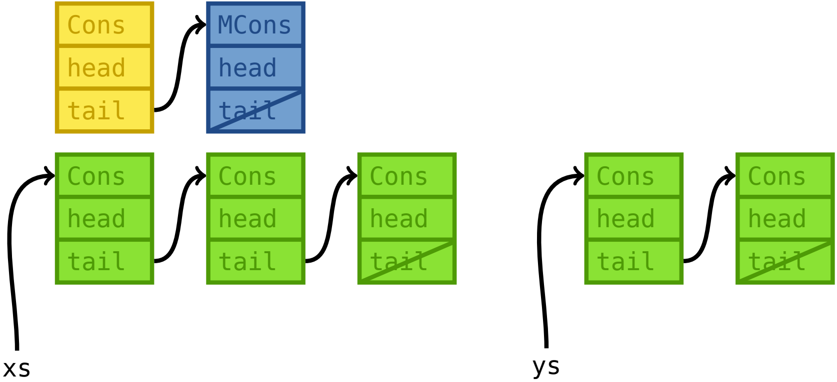
The big picture



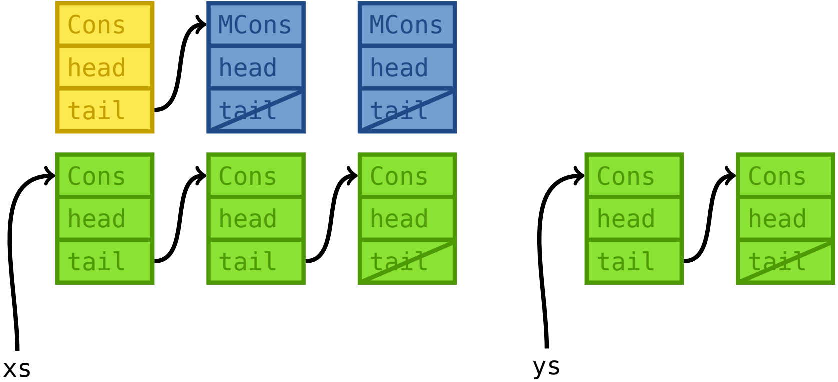
The big picture


MCons
head
tail
MCons
head
tail
Cons
head
tail
Cons
head
tail
Cons
head
tail
xs
Cons
head
tail
Cons
head
tail
ys

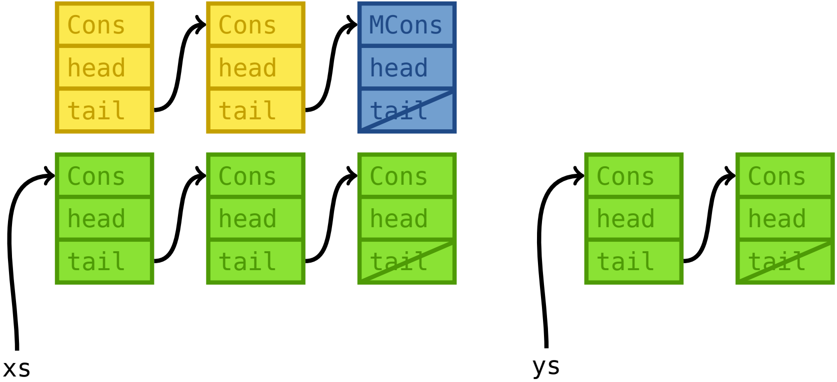
The big picture



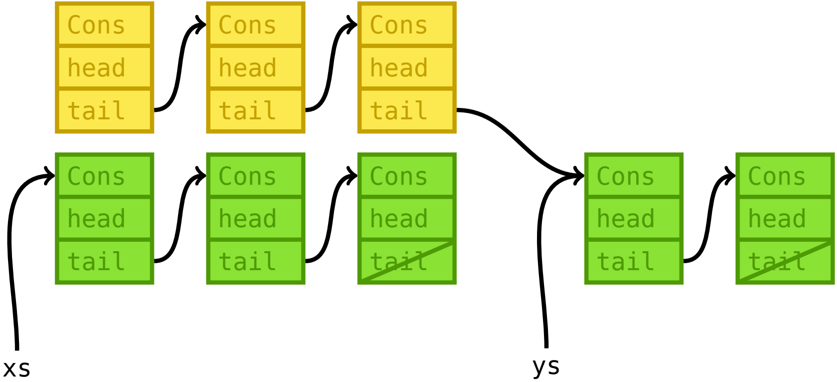
The big picture



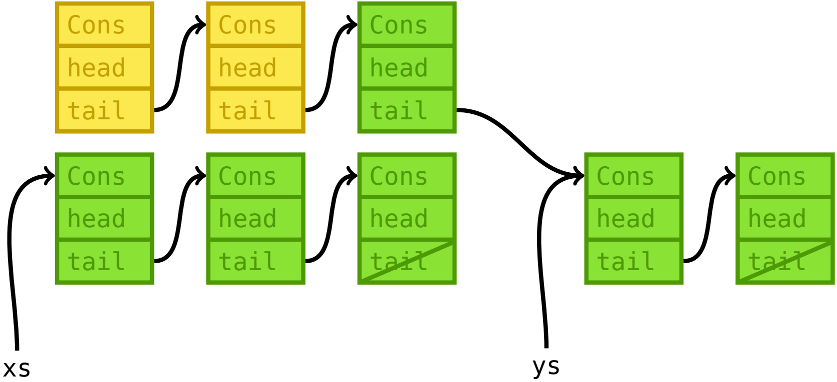
The big picture



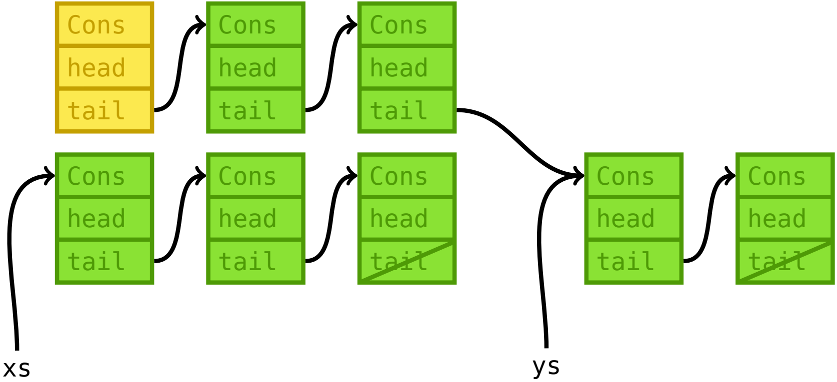
The big picture



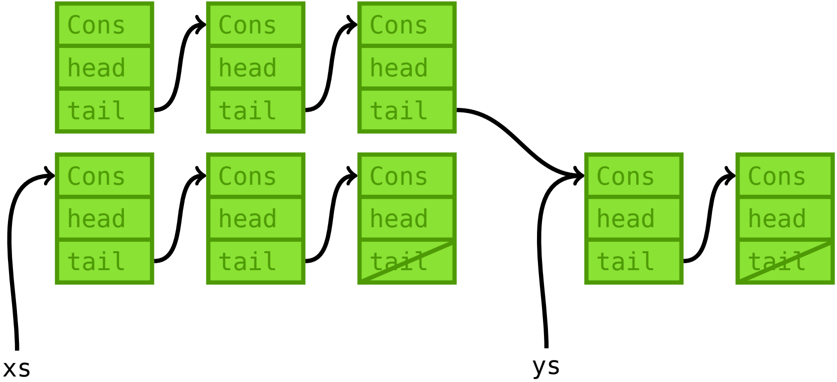
The big picture



The big picture



The big picture



Concatenating immutable lists (1/2)

```
val rec append_aux [a] (consumes (
  dst: MCons { head: a; tail: () },
  xs: list a, ys: list a
)) : (| dst @ list a) =
  match xs with
  | Cons ->
      let dst' = MCons { head = xs.head; tail = () } in
      dst.tail <- dst';
      tag of dst <- Cons;
      append_aux (dst', xs.tail, ys)
  | Nil ->
      dst.tail <- ys;
      tag of dst <- Cons
  end
```

Concatenating immutable lists (1/2)

```
val rec append_aux [a] (consumes (
  dst: MCons { head: a; tail: () },
  xs: list a, ys: list a
)) : (| dst @ list a) =
  match xs with
  | Cons ->
      let dst' = MCons { head = xs.head; tail = () } in
      dst.tail <- dst';
      tag of dst <- Cons;
      append_aux (dst', xs.tail, ys)
  | Nil ->
      dst.tail <- ys;
      tag of dst <- Cons
  end
```

all three inputs are consumed

Concatenating immutable lists (1/2)

```
val rec append_aux [a] (consumes (
  dst: MCons { head: a; tail: () },
  xs: list a, ys: list a
)) : (| dst @ list a) =
  match xs with
  | Cons ->
      let dst' = MCons { head = xs.head; tail = () } in
      dst.tail <- dst';
      tag of dst <- Cons;
      append_aux (dst', xs.tail, ys)
  | Nil ->
      dst.tail <- ys;
      tag of dst <- Cons
  end
```

dst is initially unfinished

Concatenating immutable lists (1/2)

```
val rec append_aux [a] (consumes (
  dst: MCons { head: a; tail: () },
  xs: list a, ys: list a
)) : (| dst @ list a) =
  match xs with
  | Cons ->
      let dst' = MCons { head = xs.head; tail = () } in
      dst.tail <- dst';
      tag of dst <- Cons;
      append_aux (dst', xs.tail, ys)
  | Nil ->
      dst.tail <- ys;
      tag of dst <- Cons
  end
```

xs and ys are initially valid

Concatenating immutable lists (1/2)

```
val rec append_aux [a] (consumes (
  dst: MCons { head: a; tail: () },
  xs: list a, ys: list a
)) : (| dst @ list a) =
  match xs with
  | Cons ->
      let dst' = MCons { head = xs.head; tail = () } in
      dst.tail <- dst';
      tag of dst <- Cons;
      append_aux (dst', xs.tail, ys)
  | Nil ->
      dst.tail <- ys;
      tag of dst <- Cons
  end
```

upon return, dst is valid

Concatenating immutable lists (1/2)

```
val rec append_aux [a] (consumes (
  dst: MCons { head: a; tail: () },
  xs: list a, ys: list a
)) : (| dst @ list a) =
  match xs with
  | Cons ->
      let dst' = MCons { head = xs.head; tail = () } in
      dst.tail <- dst';
      tag of dst <- Cons;
      append_aux (dst', xs.tail, ys)
  | Nil ->
      dst.tail <- ys;
      tag of dst <- Cons
  end
```

dst.tail is initialized

Concatenating immutable lists (1/2)

```
val rec append_aux [a] (consumes (
  dst: MCons { head: a; tail: () },
  xs: list a, ys: list a
)) : (| dst @ list a) =
  match xs with
  | Cons ->
      let dst' = MCons { head = xs.head; tail = () } in
      dst.tail <- dst';
      tag of dst <- Cons;
      append_aux (dst', xs.tail, ys)
  | Nil ->
      dst.tail <- ys;
      tag of dst <- Cons
  end
```

dst is frozen

Concatenating immutable lists (1/2)

```
val rec append_aux [a] (consumes (
  dst: MCons { head: a; tail: () },
  xs: list a, ys:
)) : (| dst @ lis
  match xs with
  | Cons ->
      let dst' =                                        in
      dst.tail <- dst';
      tag of dst <- Cons;
      append_aux (dst', xs.tail, ys)
  | Nil ->
      dst.tail <- ys;
      tag of dst <- Cons
  end
```

```
xs @ Cons { head = h; tail = t }
dst @ Cons { head: a; tail = dst' }
dst' @ MCons { head: a; tail: () }
t @ list a
ys @ list a
```

Concatenating immutable lists (1/2)

```
val rec append_aux [a] (consumes (
  dst: MCons { head: a; tail: () },
  xs: list a, ys:
)) : (| dst @ lis
  match xs with
  | Cons ->
      let dst' =                                     in
      dst.tail <- dst';
      tag of dst <- Cons;
      append_aux (dst', xs.tail, ys)
  | Nil ->
      dst.tail <- ys;
      tag of dst <- Cons
  end
```

```
dst @ Cons { head: a; tail = dst' }
dst' @ MCons { head: a; tail: () }
t @ list a
ys @ list a
```

Concatenating immutable lists (1/2)

```
val rec append_aux [a] (consumes (
  dst: MCons { head: a; tail: () },
  xs: list a, ys:
)) : (| dst @ lis
  match xs with
  | Cons ->
      let dst' =                                            in
      dst.tail <- dst';
      tag of dst <- Cons;
      append_aux (dst', xs.tail, ys)
  | Nil ->
      dst.tail <- ys;
      tag of dst <- Cons
  end
```

dst @ Cons { head: a; tail = dst' }

dst' @ list a

Concatenating immutable lists (1/2)

```
val rec append_aux [a] (consumes (
  dst: MCons { head: a; tail: () },
  xs: list a, ys:
)) : (| dst @ lis
  match xs with
  | Cons ->
    let dst' =                                        in
    dst.tail <- dst';
    tag of dst <- Cons;
    append_aux (dst', xs.tail, ys)
  | Nil ->
    dst.tail <- ys;
    tag of dst <- Cons
  end
```

`dst @ Cons { head: a; tail: list a }`

Concatenating immutable lists (1/2)

```
val rec append_aux [a] (consumes (
  dst: MCons { head: a; tail: () },
  xs: list a, ys:
)) : (| dst @ lis
  match xs with
  | Cons ->
      let dst' =                                        in
      dst.tail <- dst';
      tag of dst <- Cons;
      append_aux (dst', xs.tail, ys)
  | Nil ->
      dst.tail <- ys;
      tag of dst <- Cons
  end
```

dst @ list a

Concatenating immutable lists (2/2)

```
val append [a] (consumes (xs: list a, ys: list a))
: list a =
  match xs with
  | Cons ->
      let dst = MCons { head = xs.head; tail = () } in
      append_aux (dst, xs.tail, ys);
      dst
  | Nil ->
      ys
  end
```

Remark

The type of `append`:

```
[a] (consumes (list a, list a)) -> list a
```

is a subtype of:

```
[a] (list a, list a | duplicable a) -> list a
```

The arguments are consumed *only if not duplicable*.

Outline

- A first example and a few principles
- Algebraic data structures
- Sharing mutable data
    - Regions (and nesting)
    - Adoption and abandon
    - Locks
- Conclusion

What have we so far?

An affine permission is a (static) *unique token*.

We have seen that we can

- *aggregate* several tokens,
  yielding a token for a (tree-structured) composite object
- conversely, *split* a token for a tree
  into separate tokens for the root and sub-trees

What have we so far?

We have seen that *pointer* and *permission* are distinct concepts: either one can exist without the other.

We have exploited this *at a very local scale*, e.g. when type-checking `meld` and `append`.

Yet, we have *not* exploited this in algebraic data type definitions.

- we always marry a pointer to a sub-tree
  and a permission to access it

What have we so far?

As long as we stick to this style, we cannot express:

- *aliasing*, where an object is accessible via two pointers;
- *shared memory*, where an object is accessible to two threads.

What do we need?

We need ways of saying, roughly,

- "this is a pointer…"
- "…without a permission…"
- "…but here is *how to get the permission* when needed."

Sharing mutable data

Regions (and nesting)

Regions

A region is a *group* of objects (of identical type).

There is *one permission for the group*, instead of one per object.

A region does not exist at runtime. It is imaginary.

See e.g. Haskell's ST monad. See also Cyclone (Swamy et al., 2006).

Regions

An affine type of regions - internally defined as the unit type:

```
abstract region
val newregion: () -> region
```

A *duplicable* type of mutable references that inhabit a region:

```
abstract rref (r : value) a
fact duplicable (rref r a)
```

These objects can be shared without restriction.

Regions

```
val newrref: (consumes x: a | r @ region) -> rref r a
val get: (x: rref r a | duplicable a | r @ region) -> a
val set: (x: rref r a, consumes y: a | r @ region) -> ()
```

All three are polymorphic in `r` and `a`. Quantifiers omitted.

The token `r @ region` is required to use *any* reference in `r`.

The references are collectively “owned by the region”.

Limitations

Regions have *no runtime cost*.

However,

- `get` is *restricted to duplicable elements* (prev. slide).
- Handling affine elements requires a more clumsy mechanism for *focusing* on *at most one element* at a time.
- Focusing on two elements, also known as *multi-focusing*, would entail a proof obligation: $\mathtt{x} \neq \mathtt{y}$.
- Membership in a region *cannot* be revoked.

A word about nesting

Nesting (Boyland, 2010) is a static mechanism for organizing permissions into a hierarchy.

The hierarchy is constructed as the program runs
and grows with time.

Nesting *can* be axiomatized in Mezzo (by adding a few primitive operations which do nothing at runtime).

Regions can be defined as a library on top of nesting.

Like regions, nesting has limitations (prev. slide).

Sharing mutable data

Adoption and abandon

Towards runtime regions

What if something like regions existed *at runtime*?

Old idea, if one thinks of a region as a “memory allocation area”.

- Tofte and Talpin, 1994

Here, however, there is a single garbage-collected heap.

We are thinking of a “region” as a “unit of ownership”.

Towards runtime regions

Imagine a “region” is a runtime object that maintains
a list of its “members”.

We prefer to speak of *adopter* and *adoptees*.

Conceptually,

- *Adoption* (a.k.a. `give`) adds an adoptee to the list.
- *Abandon* (a.k.a. `take`) extracts an adoptee from the list,
    - and fails *at runtime* if it isn't in the list!

Adoption and abandon

This removes the difficulties with static regions.

- an adopter-adoptee relationship *can* be revoked.
- "focusing" amounts to *taking* an adoptee away from its adopter, then *giving* it back.
- "focusing" on multiple elements is permitted.
  - they must be distinct, or the program *fails* at runtime!

One typical application

A FIFO queue as a linked list with `first` and `last` pointers.

There is *aliasing*. This cannot be type-checked in vanilla Mezzo.

We let the "queue" object adopt all of the "list cell" objects.

The code type-checks (but could fail at runtime if we mistakenly break our intended invariant).

See P. and Protzenko, ICFP 2013.

Implementation

Searching a linked list of adoptees would be too slow.

Instead, *each adoptee points to its adopter* (if it has one).

Every object has a special `adopter` field, which may be `null`.

- Adoption, `give x to y`, means:

```
x.adopter <- y
```

- Abandon, `take x from y`, means:

```
if x.adopter == y
then x.adopter <- null
else fail
```

Static discipline, in one slide

An adopter *owns* its adoptees.

Adoption and abandon are very much like *inserting* and *extracting* an element out of a *container*:

- both require a permission for the adopter;
- adoption *consumes* a permission for the new adoptee; abandon allows *recovering* it.

Static discipline, in one slide

An adopter *owns* its adoptees.

Adoption and abandon are very much like *inserting* and *extracting* an element out of a *contai*

- both require a permissio adopter;
- adoption *consumes* a permissi or the new adoptee; abandon allows *recovering* it.

Sharing mutable data

Locks

Towards hidden state

Regions and adoption-and-abandon serve a common purpose:

- move from one-token-per-object to *one-token-per-group*;
- introduce a *duplicable* type of pointer-into-the-group;
- thus permitting *aliasing* within a group.

Towards hidden state

A problem remains, though:

- every bit of mutable state is controlled by *some* unique token;
- i.e., every side effect *must* be advertised in a function's type;
- thus, multiple clients *must* coordinate and exchange a token.

There is a certain lack of modularity.

Example

Consider a “counter” abstraction, encapsulated as a function.

- it has *abstract* state: its type is `{p : perm} ((| p) -> int | p)`.
- it *cannot* be shared by two threads,
  - unless they *synchronize* and exchange `p`;
  - without synchronization, there would be a *data race*!

A well-typed Mezzo program is data-race free.

Example

Consider a “counter” abstraction, encapsulated as a function.

- it has *abstract* state: its type is `{p : perm} ((| p) -> int | p)`.
- it *cannot* be shared by two threads,
    - unless they *synchronize* to exchange `p`;
    - without synchronization, there would be a *data race*!

Demo!

A well-typed Mezzo program is data-race free.

Locks and hidden state

Introducing a *lock* at the same time:

- removes the data race,
- allows the counter to have type `() -> int`.

The counter now has *hidden state*.

Let's see how this works...

Locks (1/2)

The axiomatization of locks begins with two abstract types:

```
abstract lock (p: perm)
fact duplicable (lock p)

abstract locked
```

The permission `p` is the *lock invariant*.

Locks (2/2)

The basic operations are:

```
val new:
      (| consumes p)    -> lock p
val acquire:
      (l: lock p)       -> (| p * l @ locked)
val release:
      (l: lock p | consumes (p * l @ locked)) -> ()
```

All three are polymorphic in `p`. Quantifiers omitted.

The key idea

From concurrent separation logic (O'Hearn, 2007).

While the lock is unlocked, one can think of `p` as *owned by the lock*.

The lock is *shareable*, since `lock p` is duplicable.

Hence, a lock allows *sharing* and *hiding* mutable state.

Hiding as a design pattern

The pattern of *hiding* a function's internal state can be encoded once and for all as a second-order function:

```
val hide : [a, b, p : perm] (
  f : (a | p) -> b
| consumes p
) -> (a -> b)
```

Hiding as a design pattern

```
val hide   [a, b, p : perm] (
  f : (a | p) -> b
| consumes p
)  : (a -> b) =
  let l : lock p = new () in
  fun (x : a) : b =
    acquire l;
    let y = f x in
    release l;
    y
```

Hiding as a design pattern

```
l @ lock p
```

```
val hide   [a, b, p : perm   (
  f : (a | p) -> b
| consumes p
)  : (a -> b) =
  let l : lock p = new () in
  fun (x : a) : b =
    acquire l;
    let y = f x in
    release l;
    y
```

Hiding as a design pattern

l @ lock p
because it is duplicable

```
val hide   [a, b, p : perm] (
  f : (a | p) -> b
| consumes p
)  : (a -> b) =
  let l : lock p = new () in
  fun (x : a) : b =
    acquire l;
    let y = f x in
    release l;
    y
```

Hiding as a design pattern

```
l @ lock p
l @ locked
p
```

```
val hide   [a, b, p : perm] (
  f : (a | p) -> b
| consumes p
)  : (a -> b) =
  let l : lock p = new () in
  fun (x : a) : b =
    acquire l;
    let y = f x in
    release l;
    y
```

Hiding as a design pattern

```
l @ lock p
l @ locked
p
```

```
val hide   [a, b, p : p rm] (
  f : (a | p) -> b
| consumes p
)  : (a -> b) =
  let l : lock p = new () in
  fun (x : a) : b =
    acquire l;
    let y = f x in
    release l;
    y
```

Hiding as a design pattern

`l @ lock p`

```
val hide   [a, b, p : erm] (
  f : (a | p) -> b
| consumes p
)  : (a -> b) =
  let l : lock p = new () in
  fun (x : a) : b =
    acquire l;
    let y = f x in
    release l;
    y
```

Rules of thumb

Regarding *regions* versus *adoption and abandon*,

- they serve the same purpose, namely *one-token-per-group*;
- use regions if possible, otherwise adoption and abandon.

Regarding *locks*,

- they serve a different purpose, namely *no-token-at-all*;
- they are typically used *in conjunction* with the above.
  - a lock protects a token that controls a group of objects.

Outline

- A first example and a few principles
- Algebraic data structures
- Sharing mutable data
- Conclusion

Sources of inspiration

Mezzo draws inspiration from many sources. Most influential:

- *Linear and affine types* (Wadler, 1990) (Plasmeijer et al., 1992).
  - not every value can be copied!
- *Alias types* (Smith, Walker & Morrisett, 2000), L^3 (Ahmed, Fluet & Morrisett 2007).
  - copying a value is harmless,
  - but not every capability can be copied!
  - keep track of equations between values via singleton types.
- Regions and focusing in *Vault* (Fähndrich & DeLine, 2002);
- *Separation logic* (Reynolds, 2002) (O'Hearn, 2007).
  - ownership is in the eye of the beholder.
  - separation by default; local reasoning.
  - a lock owns its invariant.

What distinguishes Mezzo?

It is a *high-level* programming language:

- algebraic data types preferred to records and null pointers;
- (tail) recursion preferred to iteration;
- garbage collection, first-class functions, polymorphism, etc.
- to some extent, lightweight types (i.e., no owner annotations).

Shortcomings

It is far from perfect:

- type inference can be unpredictable;
- it takes a black belt to understand type errors;
- there is currently no interoperability with OCaml.

Food for thought

At the present time I think we are on the verge of discovering at last what programming languages should really be like. [...]

Food for thought

At the present time I think we are on the verge of discovering at last what programming languages should really be like. […] My dream is that by 1984 we will see a consensus developing for a really good programming language […]

Food for thought

> *At the present time I think we are on the verge of discovering at last what programming languages should really be like. […] My dream is that by 1984 we will see a consensus developing for a really good programming language […]*

Donald E. Knuth, 1974.

Thank you

More information online:

`http://gallium.inria.fr/~protzenk/mezzo-lang/`

What distinguishes Mezzo?

Technically, some novel features of Mezzo are:

- the permission discipline *replaces* the type discipline;
- *a new view of algebraic data types*, with nominal and structural permissions, and a new “tag update” instruction;
- a new, lightweight treatment of the distinction between duplicable and affine data;
- *adoption and abandon*.

Who we are

The project was launched in late 2011 and has involved

- Jonathan Protzenko (Ph.D student, soon to graduate),
- Thibaut Balabonski (post-doc researcher),
- Henri Chataing, Armaël Guéneau, Cyprien Mangin (interns),
- and myself (INRIA researcher).

Where we are

We currently have:

- a *type soundness proof* for a subset of Mezzo;
- a working *type-checker*;
- a “compiler” down to untyped OCaml.

What next?

Many questions!

- Can we improve *type inference* and type error reports?
- Is this *a good mix* between static and dynamic mechanisms?
- What about temporary *read-only views* of mutable objects?
- Can we express complex *object protocols*?
- What about specifications & *proofs* of programs?