Why design a new programming language?

The *Mezzo* case

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Plan

Type-checking: a way to reason about your programs

How do we see type-checking?

- a way of assigning types to objects, thus
- gaining static information about the memory shape of objects, while
- enabling the programmer to reason about their programs.

These properties are static.

You can deduce them by analyzing your program *before* running it.

How do we sell type-checking?

- The ability for the programmer to avoid bugs.
- The ability for the compiler to emit better code.
- Guarantees about safety (e.g. the program won't crash): C#, ML, Java...

Type-checking occupies a sweet spot in our landscape.

Why do we love typing so much?

- Requires no user input; the system can automatically deduce properties.
- Good properties: decidable, reasonable computational complexity.

Plan

1. Some background
2. Going beyond type-checking
3. The story about state
4. Designing a type system with state
5. A glimpse of *Mezzo*
6. Conclusion

How does one push a type system further?

extend type-check more programs;

refine provide stronger guarantees about programs.

Here are some directions that have been explored already.

Direction #1: the proof assistant

One may want to...

- extend the theoretical power of the type system;
- and lose automation;
- the user has to *painfully* write types by hand;
- these types are actually proofs.

Example:

Direction #2: automated theorem provers

One may want to...

- keep a simple type system;
- have a language of pre- and post-conditions on the side;
- delegate the task of proving to SMT-solvers;
- only semi-automated; SMT-solvers are unpredictable and not very robust.

Example: Why3 Where Programs Meet Provers

Direction #3: Abstract interpretation

One may want to...

- design a framework to analyze the range of possible values;
- either in compilers (flags) or external tools (static analyzers).

Example: the Astrée static analyzer.

There's a whole range of possible directions.

There are some design choices that we do not wish to reproduce.

What's our « business model »? Refine the type system of ML to talk about state.

Plan

A pervasive notion

- Most programs carry an inherent notion of state.
- A `socket` may move from « valid `socket` » to « invalid `socket` ».

Yet, no mainstream type system offers facilities for reasoning about state.

Reasoning about state...

```
let x = create_socket () in
(* x @ socket (valid) *)
let y = x in
(* x @ socket (valid), y @ socket (valid) *)
...
(* x @ socket (valid), y @ socket (valid) *)
destroy_socket x;
(* x @ socket (invalid), y @ socket (valid) *)
destroy_socket y;
(* apocalypse! *)
```

Reasoning about state is hard

Are **x** and **y** the same thing?

This is the aliasing problem, which is not decidable in general.

Question

Can we design a better type system that would:

- help the programmer reason about state, thus
- ruling out incorrect behaviors, while
- enabling new programming idioms?

This is the *Mezzo* project.

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Permissions

A variable does not have a fixed type.

Instead, we may possess a permission `x @ t`, allowing us to use `x` in certain ways, depending on `t`.

This permission may disappear, to be replaced by a different one.

Immutable vs. mutable

The system maintains the following invariant:

- if **x** is a mutable object, there exists at most one permission to read and write **x**
- if **x** is an immutable object, there exists arbitrarily many permissions to read **x**

Why the distinction?

This distinction is central in the design of *Mezzo*.

- State changes become type changes.
- Since mutable objects have a unique owner, it is now safe for the type of an object to change.

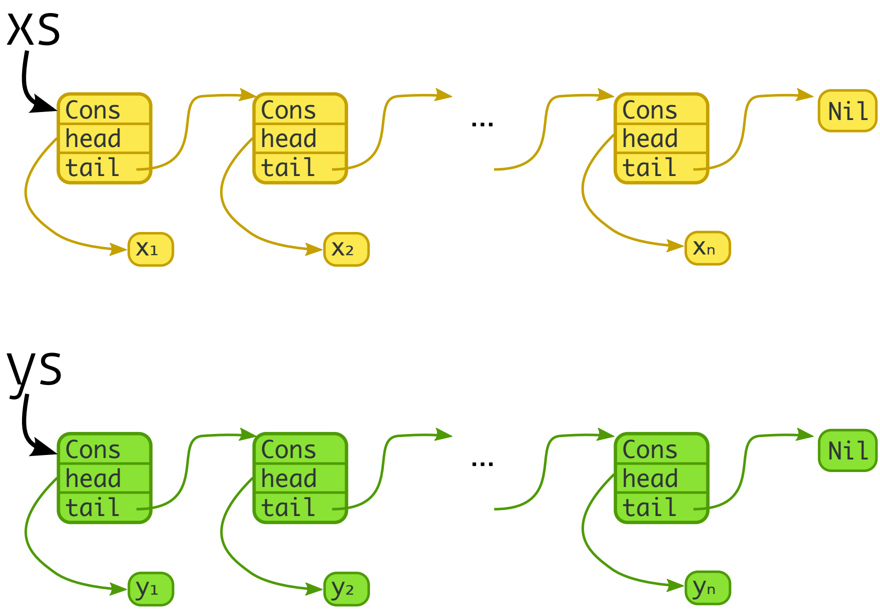
This enables us to *track the state* of objects.

Why the distinction?

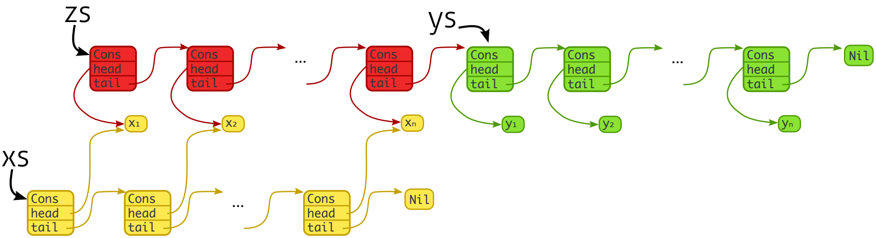
- In a concurrent context, the unique-owner property statically guarantees that the program is data-race free.
- In terms of reasoning, I can now state that no other part of the program may access my mutable memory. This is a separation property.

Plan

A simple example: concatenation of immutable lists.


xs
Cons
head
tail
Cons
head
tail
...
Cons
head
tail
Nil
x1
x2
xn
ys
Cons
head
tail
Cons
head
tail
...
Cons
head
tail
Nil
y1
y2
yn

What happens when one concatenates two **immutable** lists **xs** and **ys**?


zs
ys
xs
Cons
head
tail
x1
x2
xn
y1
y2
yn
...
Nil

This creates sharing.

Harmless sharing

```
let xs : list int = ... in
let ys : list int = ... in
let zs : list int = append(xs, ys) in
...
```

This is harmless. We would like to *accept* this code.

Potentially harmful sharing

What if the lists have *mutable* elements?

```
let xs : list (ref int) = ... in
let ys : list (ref int) = ... in
let zs : list (ref int) = append(xs, ys) in
...
```

Some elements are accessible via **xs** and **zs**, or via **ys** and **zs**. This is potentially dangerous.

We would like to *accept* this code yet *prevent* the programmer from using (say) **xs** and **zs** as if they were physically disjoint.

Reasoning with permissions

In *Mezzo*, the first code snippet gives rise to three permissions:

```
xs @ list int
ys @ list int
zs @ list int
```

All three lists can be freely used in the code that follows.

Reasoning with permissions

The first two lines of the second code snippet give rise to:

```
xs @ list (ref int)
ys @ list (ref int)
```

These permissions are *consumed* at line three, which gives rise to:

```
zs @ list (ref int)
```

At the end, **zs** can be used, but **xs** and **ys** have been invalidated.

How does this work?

The type of the function **append** is:

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

so a call is in principle type-checked as follows:

```
(* xs @ list t * ys @ list t * ... must exist here *)
let zs = append(xs, ys) in
(* zs @ list t                 * ...      exist here *)
```

The available permissions *vary* with time.

How does this work?

The system knows that

- **`xs @ list int`** is a duplicable permission, whereas
- **`xs @ list (ref int)`** is not: it is an affine permission.

A caller of **append** can give up one copy of **`xs @ list int`** and keep one copy. The permission is effectively not consumed.

No such trick is possible with **`xs @ list (ref int)`**.

Thus, **append** is type-checked once, but behaves differently at different call sites.

Still...how do we type-check this?

```
let x = create_socket () in
(* ? *)
let y = x in
(* ? *)
...
(* ? *)
destroy_socket x;
(* ? *)
destroy_socket y;
(* ? *)
```

Still...how do we type-check this?

```
let x = create_socket () in
(* ? *)
let y = x in
(* ? *)
...
(* ? *)
destroy_socket x;
(* ? *)
destroy_socket y;
(* ? *)
```

- Keep track of local aliasing relationships.
- Declare types **`valid_socket`** and **`invalid_socket`**
- Declare **`destroy_socket: (consumes x: valid_socket) -> (| x @ invalid_socket)`**

Still...how do we type-check this?

```
let x = create_socket () in
(* x @ valid_socket *)
let y = x in
(* x @ valid_socket * x @ =y *)
...
(* x @ valid_socket * x @ =y *)
destroy_socket x;
(* x @ invalid_socket * x @ =y *)
destroy_socket y;
(* Error: could not find permission y @ valid_socket;
   the only permissions available for it are:
   y @ invalid_socket
*)
```

An escape mechanism

The mechanisms presented so far remain relatively rigid.

We offer a mechanism, called adoption/abandon, that:

- allows one to gain the freedom to alias objects, at the expense of
- paying runtime checks whenever they want to use the object.

The runtime checks guarantee that only one person owns the object. If the programmer makes a mistake, the program aborts.

An escape mechanism (2)

All type systems are a tradeoff between complexity and dynamic checks (Java, C++, C#...).

We drew a line: non-tree-shaped ownership patterns cannot be treated statically.

Plan

The *Mezzo* language

Mezzo is a language that:

- takes the usual ingredients of a type system, but
- provides stronger guarantees, while still
- retaining some key properties: automated reasoning, predictability...

This is achieved through a careful blending of runtime tests / static guarantees.

The *Mezzo* language

Programs written in *Mezzo* enjoy strong guarantees:

- the type system rules out representation exposure;
- avoids unwanted sharing;
- guarantees data-race freedom.

The *Mezzo* language

We also believe that:

- writing a program in *Mezzo* force the programmer to have a clear understanding of ownership,
- thus giving better guarantees about the program, as well as
- making it more amenable to program proof (long-term goal).

The state of *Mezzo*

The type system has been proved sound using the Coq proof assistant.

We have a prototype type-checker that successfully type-checks our library as well as numerous examples (several thousand lines).

Future direction #1

Concurrency.

There are several concurrency patterns.

- How can we axiomatize them? (What is their type?)
- Is it sound? (Can we add these to our proof?)
- Shall we add new concurrency patterns in *Mezzo*?

Future direction #2

Inference.

Inference is a challenge; we want to limit manual intervention from the programmer, but:

- some situations require type annotations;
- can we predict which situations will require manual hints?
- can we improve our prototype with a better type-checking algorithm?

Future direction #3

Arithmetic.

Like in ML, there are bounds-check on array accesses.

- Can we extend the permission mechanism to also talk about arithmetic?
- Can we have the type-checker perform arithmetic reasoning? (SMT-Solver)
- How viable is this approach, can we extend it beyond arithmetic?

More information

You can visit the *Mezzo* website

F. Pottier and J. Protzenko, *Programming with permissions in Mezzo*, to appear in *International Conference on Functional Programming* (ICFP), Sep 2013.

The implementation of append

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

val rec append [a] (
  consumes xs: list a,
  consumes ys: list a
) : list a =
  if xs then
    Cons { head = xs.head; tail = append (xs.tail, ys) }
  else
    ys
```

The (other) implementation of append

```
data mutable cell a =
  | Cell { head: a; tail: () }
```

The (other) implementation of append

```
val rec appendAux [a] (
    consumes dst: cell a,
    consumes xs: list a,
    consumes ys: list a)
: (| dst @ list a)
  =
  if xs then begin
    let dst' = Cell { head = xs.head; tail = () } in
    freeze (dst, dst');
    appendAux (dst', xs.tail, ys)
  end
  else
    freeze (dst, ys)
```

The (other) implementation of **append**

```
val append [a] (
  consumes xs: list a,
  consumes ys: list a
) : list a =
  if xs then begin
    let dst = Cell { head = xs.head; tail = () } in
    appendAux (dst, xs.tail, ys);
    dst
  end
  else
    ys
```

The implementation of **append** (mutable)

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

The implementation of **append** (mutable)

```
val rec append1 [a]
  (xs: MCons { head: a; tail: mlist a },
   consumes ys: mlist a) : () =
  match xs.tail with
  | MNil  -> xs.tail <- ys
  | MCons -> append1 (xs.tail, ys)
  end

val append [a] (consumes xs: mlist a,
                consumes ys: mlist a) : mlist a =
  match xs with
  | MNil  -> ys
  | MCons -> append1 (xs, ys); xs
  end
```