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Programming with permissions: the *Mezzo* language

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*Mezzo* is a functional programming language with effects, in the tradition of ML. *Mezzo* aims to provide a successor to OCaml with a finer control of aliasing and effects. We offer stronger static guarantees on the mutable store: the language can express non-aliasing and separation properties. This fine-grained control of ownership and effects allows *Mezzo* to type-check programs previously deemed unsafe by the OCaml type-checker.

Idioms such as delayed initialization or strong (type-changing) updates are possible: *Mezzo* understands the in-place swap function, which swaps the two components of a pair. Similarly, a tail-recursive, destination-passing style version of map can be type-checked.

*Mezzo* is a language for users: our system tracks effects more accurately than global effect systems, but we use dynamic checks (section 3.1) to keep the system simple. This introduction is hardly self-contained, and the curious reader may wish to refer to [1] for a full introduction to the language.

1 Permissions

The key concept in *Mezzo* is the notion of permission. Permissions describe how objects are laid out in memory: they describe the shape of the heap. Permissions also enable programmers to control the ownership of objects, which turns out to be paramount in a concurrent setting.

A permission is written \( x \oplus t \), meaning “\( x \) may be viewed with type \( t \)”. A permission grants access to an object: \( x \oplus \text{ref int} \) asserts that “we” have the right to access \( x \), and that it is a valid integer reference to boot. Permissions have no existence at runtime.

A permission may also assert what “others” (other threads, other parts of the program) are allowed to do, depending on the mode of the permission. **Duplicate** permissions describe read-only blocks in the heap; such permissions can be freely copied and passed to others – effectively sharing access to the block. **Exclusive** permissions describe read-write blocks in the heap; they cannot be copied, that is, the block has a unique owner.

```
<table>
<thead>
<tr>
<th></th>
<th>duplicate</th>
<th>exclusive</th>
</tr>
</thead>
<tbody>
<tr>
<td>we</td>
<td>read-only</td>
<td>read-write</td>
</tr>
<tr>
<td>others</td>
<td>read-only</td>
<td>—</td>
</tr>
</tbody>
</table>
```

![Figure 1: Access control](image)

At any point in the program, a set (conjunction) of permissions is available; the set may include several permissions that refer to the same object.

1.1 Permission conjunction

The conjunction of two permissions \( p \) and \( q \) is written \( p \land q \). Our conjunction extends the separating conjunction of separation logic:

- on *exclusive* portions of the heap, \( \ast \) behaves as the usual separating statement: \( x \oplus t \ast x' \oplus t' \) asserts that \( x \) and \( x' \) *cannot point to the same memory location* – this is a *must-not-alias* constraint;
- on non-exclusive portions of the heap, the various permissions just need to be consistent with each other: \( x \oplus \text{int} \ast x \oplus \text{int} \) is such a consistent conjunction.

1.2 Manipulating permissions

Here is a datatype definition for duplicable pairs:

```ml
data pair a b = Pair { left: a; right: b }
```

Let \( x = \text{Pair \{ left = 7; right = 3 \}} \) creates such a pair, yielding a new duplicable permission \( x \oplus \text{pair int int} \).

*Mezzo* automatically unfolds this permission and introduces fresh names for the components, thus yielding the following conjunction:

\[
x \oplus \text{Pair \{ left: =l; right: =r \}} \ast l \oplus \text{int} \ast r \oplus \text{int}
\]

The left field of \( x \) has the singleton type \( =l \): this means \( x.left \) and \( l \) refer to the same object – this is a *must-alias* constraint. From now on, we will omit the colon and write Pair \{ left = l; right = r \}.

Should the programmer write let \( y = x.left \), a new permission will be added, namely \( y \oplus =l \), which we write \( y = l \). Thus, a conjunction of permissions can include a set of equations.

1.3 Example: swapping a pair in place

Objects of type pair are duplicable, hence immutable. Uniquely-owned, mutable pairs are defined as follows:

```
exclusive data xpair a b = XPair { left: a; right: b }
```

The code from figure 2 demonstrates how to swap the two components of such a pair (comments indicate the set of available permissions after the line has been executed).

Notice the change in the permission of \( x \) between lines 2 and 3: it accounts for the new aliasing relationship, since the left field now points to \( r \) instead of \( l \). Line 4 works in a similar fashion.

If we wish, we can trade the final conjunction for a weaker, more concise permission, namely \( x \oplus xpair b a \).

This code snippet changes the type of \( x \): we call this a *strong update*. We’ll see in the following section how to turn this code snippet into a function.
2 Effects in function types

2.1 Some base types

Tuple types are written \((t_1, \ldots, t_n)\). If \(z\) is the tuple expression \((x, y)\), then we have \(z \equiv (x, y)\). Furthermore, if \(x @ t \equiv t @ u\) is also available, then we can recombine these three permissions to obtain \(z @ (t, u)\).

Package types allow one to bundle permissions along with a type: we write \((t\ p)\) to store permission \(p\) along with a value of type \(t\). The left-hand-side exists at runtime; the right-hand side does not.

2.2 Some accurate function types

Let us now consider the simple case of \texttt{swap1}, a function that takes a pair and returns a new pair with its components swapped. The function does not perform an in-place update: it returns a fresh pair.

\begin{verbatim}
val swap1: pair a b -> pair b a
let swap1 (Pair \{ left = l; right = r \}) = Pair \{ right = l; left = r \}
\end{verbatim}

Functions must be annotated with their signature in \texttt{Mezzo}. This signature may read like ML, but it conveys requirements about the permissions consumed and returned by the function. This naïve version of the swap function fails to type-check; let us now see why.

In order to call \texttt{swap1} \(x\), the permission \(x @ (\text{pair }a\ b)\) must be available to the caller, to be consumed by \texttt{swap1}. Moreover, we understand this permission to be returned to the caller. Therefore, \texttt{swap1} \(x\) will return to the caller both the original permission on \(x\) and a new value with type \texttt{pair }b\ a\.

However, after calling \texttt{swap1}, the components of the pair will be pointed to by both the old pair and the fresh one. Therefore, for the body of \texttt{swap1} to type-check, its signature must demand that \(a\) and \(b\) be duplicable types.

\begin{verbatim}
val swap: duplicable (a, b) =>
  pair a b -> pair b a
\end{verbatim}

The body of the function will now type-check. Interestingly enough, the following signature is also valid:

\begin{verbatim}
val swap2: (consumes x: pair a b) -> pair b a
\end{verbatim}

Here, the argument \(x\) is consumed by the function; that is, the permission referring to it is not returned to the caller. This type is more general: we leave it up to the caller to (implicitly) save a copy of the permission on \(x\), by duplicating the permission before calling \texttt{swap2}, if possible.

Finally, if we want to write an in-place version of \texttt{swap} that operates on exclusive pairs, we need to express the fact that the function modifies the type of its argument.

\begin{verbatim}
val xswap: (consumes x: xpair a b) -> ( | x @ xpair b a)
\end{verbatim}

Figure 2: A fragment of code that performs a swap

Here, \texttt{xswap} operates in place; therefore, it returns a tuple with no value components, i.e. the unit type. The permission on the argument is not returned; instead, a different permission for \(x\) is returned to the caller, reflecting the fact that the type of \(x\) has now changed.

3 Beyond simple permissions

3.1 An adoption mechanism for sharing

Basic permissions only allow for ownership trees; for mutable data structures with sharing, \texttt{Mezzo} uses a mechanism called adoption. It allows one to alias mutable objects, but uses runtime checks to ensure only one person at a time may “view” the mutable object. These dynamic checks may fail: we believe this is the price to pay to keep the system reasonably simple and expressive.

3.2 Concurrency

Permissions embody access control: only one thread at a time may own an exclusive permission, i.e. access a mutable location in the heap. Moreover, the adoption feature is thread-safe: several threads may try to acquire an object through the \texttt{abandon} operation, but runtime-checks make sure only one thread obtains an exclusive permission in the end. Finally, we provide a library for locks, exposed as duplicable objects that protect a permission. Therefore, programs written in \texttt{Mezzo} are data-race free.

The interaction of \texttt{Mezzo} and concurrency is still being worked on; we do not have sophisticated mechanisms such as fractional permissions yet, but this is an area of the design of \texttt{Mezzo} that is likely to evolve.

4 The current status of \texttt{Mezzo}

We are presently working on a prototype type-checker; the prototype can already type-check simple programs. Challenges include providing useful error messages, and elaborating heuristics for expressions with no principal type. In parallel, we are working on a formal proof of correctness for \texttt{Mezzo}, using the Coq proof assistant. We proved subject reduction for a core subset of \texttt{Mezzo}; we are looking forward to extend this proof to the whole language.

References