Sequence 5.1 – Building stack frames in LLVM

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Reminder: Stack frames

We have seen earlier that:

- A function can access its local variables and parameters (a function parameter as seen from the function is no different than a local variable).
- A function can access local variables defined outside the function (escaping local variables) if they are lexically visible, as well as outer function parameters.
- Function parameters and escaping local variables are stored in a *frame*, which is itself stored onto the stack. This is also called the *function stack frame*.

Reminder: Stack frames (continued)

- Every frame contains a pointer to the stack frame one level up.
- This pointer is passed as an extra parameter to every function.

Do not hesitate to refer to the sequence from week 3 again should you need to refresh your memory.

Building stack frames in LLVM

We can use a simple yet powerful model in LLVM to build stack frames:

- For every function, we declare a new compound type with:
  - the upper stack frame pointer;
  - every escaping parameter;
  - every escaping local variable created in this function.
- The appropriate stack frame pointer is passed as the first argument of every function call.
- At function entry, a new stack frame object of the proper compound type is allocated using `alloca` and the upper stack frame pointer and escaping parameters are copied.
- Escaping local variables are now uninitialized fields of this frame object.
- Non-escaping local variables and parameters are not stored in the frame.

Isn't that costly though?

- Creating an object using `alloca`, copying the parameters into it, and forcing escaping local variables to be fields of this object residing in physical memory has a cost.
- This cost is the price to pay to get access to those parameters and escaping local variables from an inner function.

However, the `mem2reg` optimization pass of LLVM will take care of removing the extra copies if we do not need to pass a pointer to this frame object to another function, in which case there will be no cost.

Could we optimize it further?

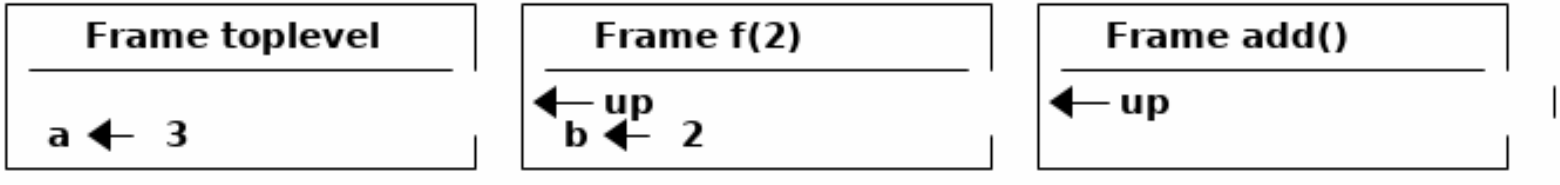
In a production-quality compiler, some optimizations would be implemented. For example:

- If a function does not call other functions, it does not need to build a frame object. This is already taken care of in the `mem2reg` optimization pass of LLVM. Such a function is called a *leaf function*.
- If a function does not use any outer variable and is a leaf function, it does not need to receive the outer frame pointer. Let us call it a *pure function*.
- If a function does not use any outer variable and only call pure functions, then it is itself a pure function and does not need to receive the outer frame pointer.

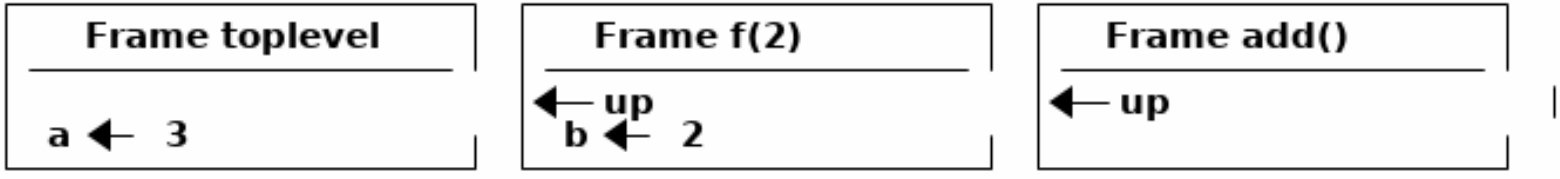
This list of optimizations is in no way exhaustive.

Visualizing a frame (from sequence 3.3)

```
let var a := 3
    function f(b: int) =
      let function add() = a := a + b
    in add() end
in
  f(2); print_int(a)  /* Prints 5 */
end
```



Visualizing frame types in LLVM



We build LLVM types named `ft_` (for *frame type*) followed by the full path of the function. Here is the corresponding LLVM IR:

```
%ft_main = type { i32 }                          # { a }
%ft_main.f = type { %ft_main*, i32 }             # { up, b }
%ft_main.f.add = type { %ft_main.f* }            # { up }
```

Except for `main`, which has no frame up since it represents the toplevel, every frame starts with a pointer to an object of the lexically outer frame type (called *static link*).

Building the frame type in LLVM

Creating a frame in LLVM is easy:

- `llvm::StructType::create(context, members, name)` creates a global structure with the given name in the compilation context. `members` is a vector of types contained in the structure.
- As for any other type, an object can be created on the stack using `Builder.CreateAlloca(frame_type, nullptr, [name])`. The second parameter is `nullptr` because we do not want to create an array, only a value.

Manipulating an object stored in the frame

LLVM makes it easy to refer to objects through `llvm::Value` pointers. Such a value might be:

- a constant;
- a reference to a global variable;
- a reference to a value on the stack;
- a reference pointed onto another `llvm::Value`, possibly with an offset.

In fact, a `llvm::Value` can be viewed as a tree, and can reference other `llvm::Value`.

Referencing an object in the frame

The IR builder in LLVM has methods to help building complex `llvm::Value` objects:

- `CreateStructGEP(type, object, position)` creates a value containing the address of a given field in a struct object whose type is given. `GEP` means *Get Element Pointer*.

Building the frame in LLVM

Here is the IR code for the function `f` defined previously:

```
define void @main.f(%ft_main* %sl, i32 %b) {
  # Allocate frame object
  %frame = alloca %ft_main.f
  # Store outer frame pointer (%sl) at first position in %frame
  %0 = getelementptr inbounds %ft_main.f, %ft_main.f* %frame,
       i32 0, i32 0
  store %ft_main* %sl, %ft_main** %0
  # Store %b parameter at second position in %frame
  %1 = getelementptr inbounds %ft_main.f, %ft_main.f* %frame,
       i32 0, i32 1
  store i32 %b, i32* %1
  # Call add function and give it a pointer to the frame object
  call void @main.f.add(%ft_main.f* %frame)
  ret void
}
```

Conclusion

- A frame compound type is defined for every function.
- The frame contains a slot for the outer frame pointer (except at top-level), every escaping parameter, and every escaping local variable.
- At function entry, the frame is allocated and the outer frame pointer (also called static link) and function parameters are copied into the frame.
- Escaping local variables become fields of the frame object.