C♭ AST→LIR Lowering

1 Overview

We need to translate from the AST data structure to the LIR data structure. Note that:

- LIR still uses `Type` just like AST.
- LIR has `Program` and `Function` like AST, but with different field types (mainly because now that we've done validation and ensured there are no duplicates, we can safely use maps instead of vectors).
- LIR has some new data types, specifically for a function's body, that we use to represent a function's control-flow graph (CFG).

Converting everything but function bodies is trivial, the only complicated part is lowering AST statements and expressions into LIR instructions and organizing them into a LIR control-flow graph. Our strategy for translating a function's body is:

1. Lower the statements into a single "translation vector" whose elements are LIR instructions and also labels `Label(name)`, where `name` is a string.
2. Take the resulting vector and use it to construct the control-flow graph for the corresponding LIR function body.

Section 2 describes the lowering algorithm, and Section 3 describes how to convert a translation vector into a control-flow graph suitable for the LIR function body.

2 Lowering Algorithm

During the lowering process we will need several things:

- To create fresh LIR variables ("fresh" means that they are unique within the enclosing function). To do this we will use a helper function that takes a type and (1) creates a new variable of that type, inserting it into the enclosing function's `locals`; and (2) returns that variable to the caller. To make the variable names consistent they should be called `_t`$\langle n \rangle$, where n is a counter that starts from 1 for each function and increases each time the helper function is called (e.g., `_t1`, `_t2`, etc). We use an underscore in the variable name to ensure that we don't clash with user-defined variable names.
- To create fresh labels. Again we will use a helper function. To make the label names consistent they should be called `lbl`$\langle n \rangle$, where n is a counter that starts from 1 for each function and increases each time the helper function is called (e.g., `lbl1`, `lbl2`, etc).
- To look up type information. We will only need to look up type information for LIR variables. To do so: (1) we look in the locals of the enclosing function; if it isn't there then (2) we look in the parameters of the enclosing function; if it isn't there then (3) we look in the globals for the program. If we're lowering a valid Program then this is guaranteed to find the requested type.

2.1 Lowering Programs

Given a AST::Program `prog`:

- Create an empty LIR::Program `lir`.
- Copy `prog.{globals, externs, structs, functions}` into `lir` (translating into the appropriate data structures) *except* ignore any local variable initializations and leave all function bodies empty.
- For all `func` $\in$ `prog.functions`: add [`func.name` $\rightarrow$ `Ptr(Fn(func.params.types, func.rettyp))`] to `lir.globals`; these are the implicit function pointers made explicit.

Now we are ready to lower the function bodies. For each function `func` $\in$ `prog.functions`:

- Create an vector that will hold the emitted instructions/labels for that function (the "translation vector"). Its first and only element should be `Label("entry")`.
- Eliminate local variable initializations by turning them into assignments and adding them to the beginning of `func.stmts` (taking care to preserve the order of the initializations).
- Compute $[\![\texttt{func.stmts}]\!]^s$, which will fill in the translation vector.
- Enforce having a single `Return` instruction. If there is more than one `Return` in the translation vector:

```
let EXIT be a fresh label
emit Label(EXIT)
if func returns a value then
  let x be a fresh var with type τ s.t. func.rettyp = τ
  emit Return(x)
  replace all previous Return(op) instructions with Assign(x, op); Jump(EXIT)
else
  emit Return(None)
  replace all previous Return(None) instructions with Jump(EXIT)
```

- Take the final translation vector and construct the CFG for `lir.functions[func].body`.

2.2 Lowering Statements

These functions emit LIR instructions into the translation vector without returning anything.

$[\![\texttt{stmts}]\!]^s$: $\forall \texttt{s} \in \texttt{stmts}\,.\,[\![\texttt{s}]\!]^s$

$[\![\texttt{If(guard, tt, ff)}]\!]^s$:

```
let TT, FF, IF_END be fresh labels
emit Branch([[guard]]^e, TT, FF)
emit Label(TT)
[[tt]]^s
emit Jump(IF_END)
emit Label(FF)
[[ff]]^s
emit Jump(IF_END)
emit Label(IF_END)
```

$[\![\texttt{While}(\texttt{guard}, \texttt{body})]\!]^s$:
  let WHILE_HDR, WHILE_BODY, WHILE_END be fresh labels
  emit $\texttt{Jump}(\texttt{WHILE\_HDR})$
  emit $\texttt{Label}(\texttt{WHILE\_HDR})$
  emit $\texttt{Branch}([\![\texttt{guard}]\!]^e, \texttt{WHILE\_BODY}, \texttt{WHILE\_END})$
  emit $\texttt{Label}(\texttt{WHILE\_BODY})$
  $[\![\texttt{body}]\!]^s$
  emit $\texttt{Jump}(\texttt{WHILE\_HDR})$
  emit $\texttt{Label}(\texttt{WHILE\_END})$

$[\![\texttt{Assign}(\texttt{lhs}, \texttt{RhsExp}(\texttt{e}))]\!]^s$:
  if $\texttt{lhs}$ is $\texttt{Id}(\texttt{name})$ then emit $\texttt{Copy}(\texttt{Var}(\texttt{name}), [\![\texttt{e}]\!]^e)$
  else
    let x = $[\![\texttt{lhs}]\!]^\ell$
    let y = $[\![\texttt{e}]\!]^e$
    emit $\texttt{Store}(\texttt{x}, \texttt{y})$

$[\![\texttt{Assign}(\texttt{lhs}, \texttt{New}(\texttt{typ}, \texttt{e}))]\!]^s$:
  if $\texttt{lhs}$ is $\texttt{Id}(\texttt{name})$ then emit $\texttt{Alloc}(\texttt{Var}(\texttt{name}), [\![\texttt{e}]\!]^e)$
  else
    let w be a fresh var with type &$\texttt{typ}$
    let x = $[\![\texttt{lhs}]\!]^\ell$
    emit $\texttt{Alloc}(\texttt{w}, [\![\texttt{e}]\!]^e)$
    emit $\texttt{Store}(\texttt{x}, \texttt{w})$

$[\![\texttt{Call}(\texttt{callee}, \texttt{args})]\!]^s$:
  let aops = $\forall a \in \texttt{args}\,.\,[\![\texttt{a}]\!]^e$
  if callee is $\texttt{Id}(\texttt{name})$ and $\texttt{name}$ is an extern then emit $\texttt{CallExt}(\texttt{None}, \texttt{name}, \texttt{aops})$
  else
    let NEXT be a fresh label
    if callee is $\texttt{Id}(\texttt{name})$ and $\texttt{name}$ is a function then emit $\texttt{CallDirect}(\texttt{None}, \texttt{name}, \texttt{aops}, \texttt{NEXT})$
    else emit $\texttt{CallIndirect}(\texttt{None}, [\![\texttt{callee}]\!]^{\ell e}, \texttt{aops}, \texttt{NEXT})$
    emit $\texttt{Label}(\texttt{NEXT})$

$[\![\texttt{Continue}]\!]^s$:
  find the nearest previous $\texttt{Label}(\texttt{WHILE\_HDR})$
  emit $\texttt{Jump}(\texttt{WHILE\_HDR})$

$[\![\texttt{Break}]\!]^s$:
  find the nearest previous $\texttt{Branch}(\_, \_, \texttt{WHILE\_END})$
  emit $\texttt{Jump}(\texttt{WHILE\_END})$

$[\![\texttt{Return}(\texttt{None})]\!]^s$: emit $\texttt{Return}(\texttt{None})$

$[\![\texttt{Return}(\texttt{e})]\!]^s$: emit $\texttt{Return}([\![\texttt{e}]\!]^e)$

2.3 Lowering Expressions

These functions emit LIR instructions into the translation vector that will compute the value of the expression being translated, returning a LIR Operand (a variable or constant) containing the final value of the expression.

$[\![\texttt{Num(n)}]\!]^e$: $\texttt{Const(n)}$

$[\![\texttt{Id(name)}]\!]^e$: $\texttt{Var(name)}$

$[\![\texttt{Nil}]\!]^e$: $\texttt{Const(0)}$

$[\![\texttt{UnOp(Neg, e)}]\!]^e$:
  let lhs be a fresh var of type Int
  emit $\texttt{Arith(lhs, Sub, Const(0),} [\![\texttt{e}]\!]^e\texttt{)}$
  lhs

$[\![\texttt{UnOp(Deref, e)}]\!]^e$:
  let src = $[\![\texttt{e}]\!]^e$
  let lhs be a fresh var of type τ s.t. src:&τ
  emit $\texttt{Load(lhs, src)}$
  lhs

$[\![\texttt{BinOp(op} \in \{\texttt{Add, Sub, Mul, Div}\}\texttt{, left, right)}]\!]^e$:
  let op1 = $[\![\texttt{left}]\!]^e$
  let op2 = $[\![\texttt{right}]\!]^e$
  let lhs be a fresh var of type Int
  emit $\texttt{Arith(lhs, op, op1, op2)}$
  lhs

$[\![\texttt{BinOp(op} \in \{\texttt{Equal, NotEq, Lt, Lte, Gt, Gte}\}\texttt{, left, right)}]\!]^e$:
  let op1 = $[\![\texttt{left}]\!]^e$
  let op2 = $[\![\texttt{right}]\!]^e$
  let lhs be a fresh var of type Int
  emit $\texttt{Cmp(lhs, op, op1, op2)}$
  lhs

$[\![\texttt{ArrayAccess(ptr, index)}]\!]^e$:
  let src = $[\![\texttt{ptr}]\!]^e$
  let idx = $[\![\texttt{index}]\!]^e$
  let elem be a fresh var of type &τ s.t. src:&τ
  let lhs be a fresh var of type τ s.t. src:&τ
  emit $\texttt{Gep(elem, src, idx)}$
  emit $\texttt{Load(lhs, elem)}$
  lhs

$[\![\texttt{FieldAccess(ptr, fld)}]\!]^e$:
  let src = $[\![\texttt{ptr}]\!]^e$
  let fldp be a fresh var of type &τ s.t. src:&$\texttt{Struct}_{id}$, id[fld]:τ
  let lhs be a fresh var of type τ s.t. src:&$\texttt{Struct}_{id}$, id[fld]:τ
  emit $\texttt{Gfp(fldp, src, fld)}$
  emit $\texttt{Load(lhs, fldp)}$
  lhs

$[\![\texttt{Call(callee, args)}]\!]^e$:

```
  let aops = ∀a ∈ args.⟦a⟧^e
  let fun = ⟦callee⟧^e
  let lhs be a fresh var of type τ s.t. fun:&(_)→τ
  if callee is Id(name) and name is an extern then emit CallExt(lhs, name, aops)
  else
    let NEXT be a fresh label
    if callee is Id(name) and name is a function then emit CallDirect(lhs, name, aops, NEXT)
    else emit CallIndirect(lhs, fun, aops, NEXT)
    emit Label(NEXT)
  lhs
```

2.4 Lowering Lvals

These functions emit LIR instructions into the translation vector that will compute the location where a value should be stored and return a variable that contains a pointer to that location. Note that the argument should *not* be an `Id`.

$[\![\texttt{Deref(lv)}]\!]^\ell$: $[\![\texttt{lv}]\!]^{\ell e}$

$[\![\texttt{ArrayAccess(ptr, index)}]\!]^\ell$:

```
  let src = ⟦ptr⟧^ℓe
  let idx = ⟦index⟧^e
  let lhs be a fresh var of type τ s.t. src:τ
  emit Gep(lhs, src, idx)
  lhs
```

$[\![\texttt{FieldAccess(ptr, fld)}]\!]^\ell$:

```
  let src = ⟦ptr⟧^ℓe
  let lhs be a fresh var of type &τ s.t. src:&Struct_id, id[fld]:τ
  emit Gfp(lhs, src, fld)
  lhs
```

2.5 Lowering Lvals as Expressions

These functions lower an Lval as if it were an expression, returning a variable containing the final value. Note that the argument *can* be an `Id`.

$[\![\texttt{Id(name)}]\!]^{\ell e}$: `Var(name)`

$[\![\texttt{lv} \neq \texttt{Id(name)}]\!]^{\ell e}$:

```
  let src = ⟦lv⟧^ℓ
  let lhs be a fresh var of type τ s.t. src:&τ
  emit Load(lhs, src)
```

3 Constructing the Control-Flow Graph (CFG)

We need to take the emitted instructions and organize them into a graph of basic blocks (the CFG). Here is the process for constructing the CFG given the translation vector:

1. Identify the *leader* instructions, which are all instructions that immediately follow a `Label`. These are the instructions that will start the basic blocks.
2. For each leader instruction (labeled with `Label(name)`), create a LIR BasicBlock `bb` with label `name`, then copy the leader and all following instructions into `bb`'s statements until we reach the last instruction before the next `Label`; this instruction is the terminal of `bb`.
   - If we lowered correctly then the terminal must be a `Branch`, `Jump`, `Return`, `CallDirect`, or `CallIndirect`, and those instructions can *only* appear as terminals.

There are some inefficiencies in our translation; for example, an empty **if** branch will result in an extra jump instruction. That's fine, because we can optimize these inefficiencies away later.