Compiler Design - Notes Week 8

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11.4 Optimizing Control

11.4.1 Standard Evaluation

Consider compiling the following program fragment:

```
if(x & !y | !w) {
    z = 3;
} else {
    z = 4;
}
return 7;
```

```
    %tmp1 = icmp Eq [[y]], 0
    %tmp2 = and [[x]], %tmp1
    %tmp3 = icmp Eq [[w]], 0
    %tmp4 = or %tmp2, %tmp3
    %tmp5 = icmp Eq %tmp4, 0
    br %tmp5, label %else, label %then

then:
    store [[z]], 3
    br %merge

else:
    store [[z]], 4
    br %merge

merge:
    %tmp6 = laod [[z]]
    ret %tmp 6
```

What we observe is that usually, we want the translation `[[e]]` to produce a value $[[C \vdash e_1 + e_2 : int]]$ = (ty, operand, stream) = `i64, %tmp, [%tmp = add [[e1]] [[e2]]])`.

But, when the compiled expression appears in a test, the program jumps to one label or another after the comparison (besides that, it never uses the value). In many cases, we can avoid *materializing* the value (i.e. storing it in a temporary) and thus produce better code.

11.4.2 Short Circuit Boolean Compilation

Instead of the usual expression translation of the form:

$$[[C \vdash e : t]] = \text{(ty, operand, stream)}$$

we can use a *conditional branch translation of Booleans,* without materializing the value:

$$[[C \vdash e : \text{bool@}]]\ \text{Itrue Ifalse} = \text{stream}$$
$$[[C, rt \vdash \text{if } (e) \text{ then } s_1 \text{ else } s_2 \Rightarrow C']] = [[C']]$$

This takes two extra arguments, namely the "true" branch label and the "false" branch label, and doesn't return a value.

⟦C ⊢ e : bool@⟧ ltrue lfalse = insns

$$\frac{}{⟦C \vdash \text{false} : \text{bool@}⟧\ \text{ltrue lfalse} = \texttt{[br \%lfalse]}}\ \text{FALSE}$$

$$\frac{}{⟦C \vdash \text{true} : \text{bool@}⟧\ \text{ltrue lfalse} = \texttt{[br \%ltrue]}}\ \text{TRUE}$$

Expressions

$$\frac{⟦C \vdash e : \text{bool@}⟧\ \text{lfalse ltrue} = \text{insns}}{⟦C \vdash !e : \text{bool@}⟧\ \text{ltrue lfalse} = \text{insns}}\ \text{NOT}$$

$$\frac{⟦C \vdash e1 : \text{bool@}⟧\ \text{ltrue right} = \text{insns}_1 \quad ⟦C \vdash e2 : \text{bool@}⟧\ \text{ltrue lfalse} = \text{insns}_2}{⟦C \vdash e1 \,|\, e2 : \text{bool@}⟧\ \text{ltrue lfalse} = \quad \texttt{insns}_1\ \texttt{right:}\ \texttt{insn}_2}$$

$$\frac{⟦C \vdash e1 : \text{bool@}⟧\ \text{right lfalse} = \text{insns}_1 \quad ⟦C \vdash e2 : \text{bool@}⟧\ \text{ltrue lfalse} = \text{insns}_2}{⟦C \vdash e1 \,\&\, e2 : \text{bool@}⟧\ \text{ltrue lfalse} = \quad \texttt{insns}_1\ \texttt{right:}\ \texttt{insn}_2}$$

Evaluation

If we reconsider our previous code example, we might translate it, using short circuit evaluation, into the following code fragment:

```
    %tmp1 = icmp Eq [[x]], 0
    br %tmp1, label %right2, label %right1

right1:
    %tmp2 = icmp Eq [[y]], 0
    br %tmp2, label %then, label %right2

right2:
    %tmp3 = icmp Eq [[w]], 0
    br %tmp3, label %then, label %else

then:
    store [[z]], 3
    br %merge

else:
    store [[z]], 4
    br %merge
```

```
merge:
    %tmp5 = load [[z]]
    ret %tmp6
```

11.5 Closure Conversion

As we have already seen, in functional languages such as ML, Haskell, Scheme, Python, etc, functions can be:

- passed as arguments (such as `map` or `fold`)
- returned as values (such as `compose`)
- nested, i.e. an inner function can refer to variables bound to an outer function

We can show a simple example with the following code fragment:

```
let add = fun x -> fun y -> x + y
let inc = add 1
let dec = add -1

let compose = fun f -> fun g -> fun x -> f (g x)
let id = compose inc dec
```

But how do we implement such functions in an interpreter or in a compiled language?

11.5.1 Compiling First-class Functions

To implement first-class functions on a processor, there are 2 main problems:

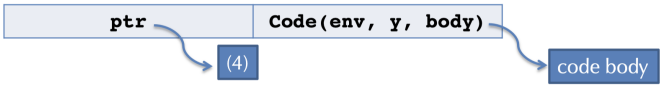
- We must implement substitution of free variables
- We must separate "code" from "data"

We can do those things by:

- *Reify the substitution:* Move the substitution from the meta language to the object language by making the data structure and lookup operation explicit
- *Closure conversion:* Eliminates free variables by packaging up the needed environment in the data structure
- *Hoisting:* Separates code from data, pulling closed code to the top level

Closure Creation Recall the `add` function `let add = fun x -> fun y -> x + y` and consider the inner function `fun y -> x + y`.

When we run the function application `add 4`, the program builds a closure and returns it (the **closure** is a pair of the *environment* and a *code pointer*):



The code pointer takes a pair of parameters: `env` and `y`. The function code is essentially:

```
fun (env y) -> let x = nth env 0 in x + y
```

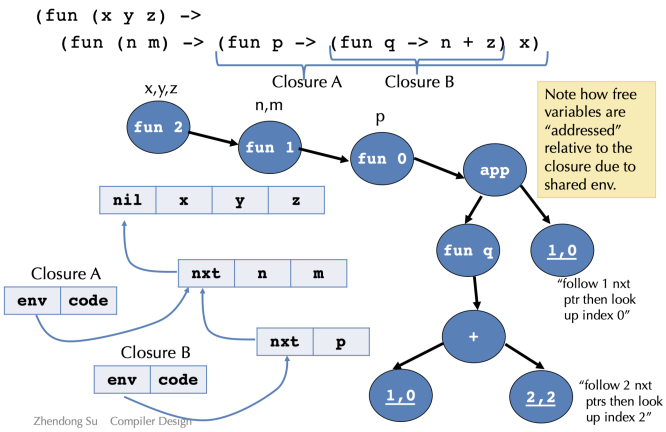
Representing Closures The simple closure conversion doesn't generate very efficient code:

- It stores all the values for variables in the environment, even if they aren't needed by the function body
- It copies the environment values each time a nested closure is created
- It uses a linked-list data structure for tuples

There are many options to solve those shortcomings, such as:

- Store only the values for free variables in the body of the closure
- Share subcomponents of the environment to avoid copying
- Use vectors or arrays rather than linked structures

Array-based closure with N-ary functions:



12. Statically Ruling Out Partiality: Type Checking

12.1 Introduction

12.1.1 Contexts and Inference Rules

We need to keep track of contextual information, such as:

- What variables are in scope?
- What are their types?
- What information do we have about each syntactic construct?

How do we describe this information?

- In the compiler, there's a mapping from variables to information we know about them, i.e. the *context*
- The compiler has a collection of (mutually recursive) functions that follow the structure of the syntax

12.1.2 Type Judgements

In the *judgement* $E \vdash e : t$

- E is a typing environment or a type context
- E maps variables to types and is simply a set of bindings of the form: $x_1 : t_1$, $x_2 : t_2$, ..., $x_n : t_n$

These mappings could be, for example, $x : int$, $b : \text{if } (b)\, 3 \text{ else } x : int$.

What do we need to know to decide whether $\text{if } (b)\, 3 \text{ else } x$ has type int in the environment $x : int$, $b : bool$?

- b must be a bool, i.e. $x : int, b : bool \vdash b : bool$
- 3 must be an int, i.e. $x : int, b : bool \vdash 3 : int$
- x must be an int, i.e. $x : int, b : bool \vdash x : int$

12.1.3 Simply-typed Lambda Calculus

$$\text{INT}\quad \frac{}{E \vdash i : \text{int}} \qquad \text{VAR}\quad \frac{x : T \in E}{E \vdash x : T} \qquad \text{ADD}\quad \frac{E \vdash e_1 : \text{int} \quad E \vdash e_2 : \text{int}}{E \vdash e_1 + e_2 : \text{int}}$$

$$\text{FUN}\quad \frac{E, x : T \vdash e : S}{E \vdash \text{fun } (x{:}T) \text{ -> } e \ : T \text{ -> } S} \qquad \text{APP}\quad \frac{E \vdash e_1 : T \text{ -> } S \quad E \vdash e_2 : T}{E \vdash e_1\ e_2 : S}$$

12.1.4 Type Checking Derivations

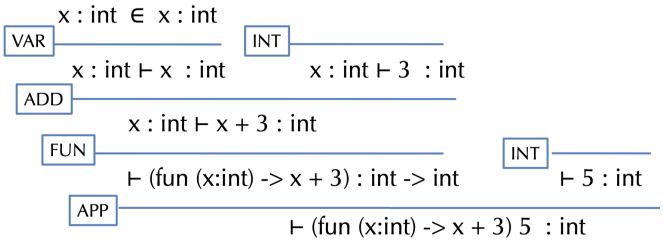
We can make a derivation of a proof tree:

- Nodes are judgements
- Edges connect premises to a conclusion (according to the inference rules)
- Leaves are axioms (i.e., rules with no premises)

The *goal of the type checker* is to verify that such a tree exists.

Example: Find a tree for the following code using the previously given inference rules:

$$\vdash (\text{fun}(x : int) \to x + 3)5 : int$$



Notes:

- The OCaml function `typecheck` verifies the existence of this tree
- Recursive calles for running `typecheck` follow the same shape as the tree above
- $x : int \in E$ is implemented by the `lookup` function

12.1.5 Type Safety

Theorem: If $\vdash e : t$, then there exists a value v such that $e \Downarrow v$.

This is a *very* strong property:

- Well-typed programs never execute undefined code like $3 + (\text{fun } x \to 2)$
- Simply-typed lambda calculus terminates, i.e. not Turing complete

12.1.6 Type Safety For General Languages

Theorem: If $\vdash P : t$ is a well-typed program, then either: - the program terminates in a well-defined way, or - the program continues computing forever

Note:

- Well-defined termiantion could includes halting with a return value or raising an exception
- Type safety rules out undefined behavior_
  - abusing "unsafe" casts, such as converting pointers to integers, etc.
  - treating non-code values as code and vice-versa
  - breaking the type abstraction of the language

12.2 Basic Types

12.2.1 Arrays

NEW
$$\frac{E \vdash e_1 : \text{int} \qquad E \vdash e_2 : T}{E \vdash \text{new } T[e_1](e_2) \ : T[]}$$

e_1: size of newly alloc. array
e_2: initializes the array

INDEX
$$\frac{E \vdash e_1 : T[] \qquad E \vdash e_2 : \text{int}}{E \vdash e_1[e_2] \ : T}$$

UPDATE
$$\frac{E \vdash e_1 : T[] \quad E \vdash e_2 : \text{int} \quad E \vdash e_3 : T}{E \vdash e_1[e_2] = e_3 \text{ ok}}$$

Note: These rules don't ensure array indices are within bounds, which should be checked *dynamically*

12.2.2 Tuples

TUPLE
$$\frac{E \vdash e_1 : T_1 \quad \ldots \quad E \vdash e_n : T_n}{E \vdash (e_1, \ldots, e_n) : T_1 * \ldots * T_n}$$

PROJ
$$\frac{E \vdash e : T_1 * \ldots * T_n \quad 1 \le i \le n}{E \vdash \#i \ e \ : \ T_i}$$

12.2.3 References

REF
$$\frac{E \vdash e : T}{E \vdash \text{ref } e : T \text{ ref}}$$

DEREF
$$\frac{E \vdash e : T \text{ ref}}{E \vdash !e \ : T}$$

ASSIGN
$$\frac{E \vdash e_1 : T \text{ ref} \qquad E \vdash e_2 : T}{E \vdash e_1 := e_2 \ : \text{unit}}$$

Note the similarity with the rules for arrays

12.3 Types, More Generally

12.3.1 What are Types?

A **type** is just apredicate on the set of values in a system, i.e. the type `int` can be thought of as a boolean function that returns "true" on integers and "false" otherwise.

For efficiency and tractability, the predicates are usually very simple.

We can easily add new types that distinguish different subsets of values:

```
type tp =
    | IntT                  (* type of integers *)
    | PosT | NegT | ZeroT   (* refinements of ints *)
    | BoolT                 (* type of booleans *)
    | TrueT | FalseT        (* subsets of booleans *)
    | AnyT                  (* any value *)
```

When introducing those new types, we also need to redefine the typing rules.

12.3.2 What about "if" ?

Two cases are very easy:

$$\text{IF-T}\ \frac{E \vdash e_1 : \text{True} \quad E \vdash e_2 : T}{E \vdash \text{if } (e_1)\ e_2 \text{ else } e_3 : T} \qquad \text{IF-F}\ \frac{E \vdash e_1 : \text{False} \quad E \vdash e_3 : T}{E \vdash \text{if } (e_1)\ e_2 \text{ else } e_3 : T}$$

But what if we don't know statically which branch will be taken? Consider the following type checking problem:

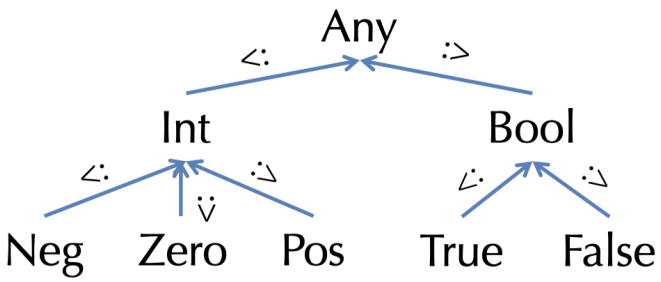
$$x : bool \vdash \text{if } (x)\, 3 \text{ else } -1 :?$$

The true branch has type Pos while the false branch has type Neg, so what should be the result type of the whole if-statement?

12.3.3 Subtyping and Upper Bounds

If we view types as sets of values, there is a natural *inclusion relation:* $Pos \subseteq Int$. This subset relation gives rise to a **subtype relation:** $Pos <: Int$.

Such inclusions give rise to a **subtyping hierarchy:**



The subtyping relation is a *partial order:*

- Reflexive: $T <: T$ for any type T
- Transitive: $T : 1 <: T_2$ and $T_2 <: T_3$ then $T_1 <: T_3$
- Antisymmetric: $T_1 <: T_2$ and $T_2 <: T_1$ then $T_1 = T_2$

A subtyping relation $T_1 <: T_2$ is **sound** if it approximates the underlying semantic subset relation. Formally, we write $[[T]]$ for the subset of closed values of type T, i.e. $[[T]] = \{v \mid \vdash v : T\}$. If $T_1 <: T_2$ implies $[[T_1]] \subseteq [[T_2]]$, then $T_1 <: T_2$ is *sound.*

For types T_1, T_2, we define their **least upper bound** (LUB) w.r.t. the hierarchy. Examples: LUB(True, False) = $Bool$, LUB(Int, $Bool$) = Any.

Note: The LUB of T_1 and T_2 is sometimes written as $T_1 \vee T_2$.

12.3.4 "if" Typing Rule Revisited

For statically unknown conditionals, we want the return value to be the LUB of the types of the branches:

$$\text{IF-BOOL}\ \frac{E \vdash e_1 : \text{bool} \quad E \vdash e_2 : T_1 \qquad E \vdash e_3 : T_2}{E \vdash \text{if } (e_1)\ e_2 \text{ else } e_3 : \mathbf{LUB(T_1,T_2)}}$$

12.3.5 Subsumption Rule

When we add subtyping judgements of the form $T <: S$, we can uniformly integrate it into the type system generically:

$$\text{SUBSUMPTION}\quad \frac{E \vdash e : T \qquad T <: S}{E \vdash e : S}$$

Subsumption allows values of type T to be treated as S whenever $T <: S$.

12.3.6 Downcasting

What happens if we have an Int, but need something of type Pos?

- At compile time, we don't know whether the Int is greater than zero
- At runtime, we do

We can add a **checked downcast:**

$$\frac{E \vdash e_1 : \text{Int} \qquad E, x : \text{Pos} \vdash e_2 : T_2 \qquad E \vdash e_3 : T_3}{E \vdash \text{ifPos } (x = e_1)\ e_2 \text{ else } e_3 : T_2 \vee T_3}$$

At runtime, the $ifPos$ checks whether $e_1 > 0$.

12.4 Subtyping Other Types

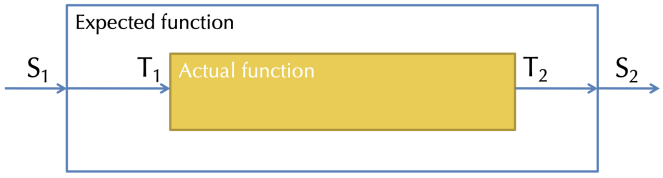
12.4.1 Subtyping for Tuples

Intuition: whenever a program expects something of type $S_1 * S_2$, it is sound to give it type $T_1 * T_2$, if $T_1 <: S_1$ and $T_2 <: S_2$:

$$\frac{T_1 <: S_1 \qquad T_2 <: S_2}{(T_1 * T_2) <: (S_1 * S_2)}$$

12.4.2 Subtyping for Function Types

On way to see it is explained by the following graph:



We need to convert an S_1 to a T_1 and T_2 to S_2, so the argument type is **contravariant** and the output type is **covariant:**

$$\frac{S_1 <: T_1 \quad T_2 <: S_2}{(T_1 \to T_2) <: (S_1 \to S_2)}$$

12.4.3 Immutable Records

The records type is given by: $\{lab_1 : T_1 : lab_2 : T_2; ...; lab_n : T_n\}$. Each lab_i is a label drawn from a set of identifiers.

$$\text{RECORD}\quad \frac{E \vdash e_1 : T_1 \quad E \vdash e_2 : T_2 \quad \dots \quad E \vdash e_n : T_n}{E \vdash \{lab_1 = e_1; lab_2 = e_2; \dots ; lab_n = e_n\} : \{lab_1:T_1; lab_2:T_2; \dots ; lab_n:T_n\}}$$

$$\text{PROJECTION}\quad \frac{E \vdash e : \{lab_1:T_1; lab_2:T_2; \dots ; lab_n:T_n\}}{E \vdash e.lab_i : T_i}$$

We can do two different forms of *subtyping for immutable records:*

- **Depth subtyping**
  - Corresponding fields may be subtypes

$$\text{DEPTH}\quad \frac{T_1 <: U_1 \quad T_2 <: U_2 \quad \dots \quad T_n <: U_n}{\{lab_1:T_1; lab_2:T_2; \dots ; lab_n:T_n\} <: \{lab_1:U_1; lab_2:U_2; \dots ; lab_n:U_n\}}$$

- **Width subtyping**
  - Subtype record may have **more** fields

$$\text{WIDTH}\quad \frac{m \le n}{\{lab_1:T_1; lab_2:T_2; \dots ; lab_n:T_n\} <: \{lab_1:T_1; lab_2:T_2; \dots ; lab_m:T_m\}}$$

12.5 Mutability & Subtyping

12.5.1 NULL

What is the type of `null`? Consider the following:

```
int[] a  = null;     // OK
int x    = null;     // not OK
string s = null;    // OK
```

Null has *any reference type*, it is *generic.*

This requires a defined behavior when dereferencing `null` (e.g. Java's NullPointerException) and a safety check for every dereference operation.

12.5.2 Subtyping and References

What is the proper subtyping relationship for **references** and **arrays?**

Covariant reference types are unsound, i.e. `(NonZero ref) <: (Int ref)` is unsound! The contravariant reference types are also unsound, that is, if `T_1 <: T_2`, then `ref T_2 <: ref T_1` is unsound too.

In conclusion, mutable structures are **invariant** in the sens that: `T_1 ref <: T_2 ref` implies `T_1 = T_2`. The same holds for arrays, OCaml-style mutable records, object fields, etc.

12.6 Structural vs. Nominal Types

IS the type equality defined by the *structure* or *name* of the data? Example:

```
type cents = int
type age   = int

let foo (x:cents) (y:age) = x + y
```

Type abbreviations as seen in this OCaml example are treated *structurally.* In contrast, `newtypes` (as seen in Haskell) are treated by *name.*

12.7 OAT's Type System

12.7.1 OAT's Treatment of Types

- Primitive (i.e. non-reference) types: `int` and `bool`
- Definitely non-null reference types: (named) mutable structs with width subtyping, strings, arrays (including length information)
- Possibly-null reference types: `R?`, subtyping `R <: R?`, checked downcast syntax `if?`

Example:

```
int sum(int[]? arr) {
    var z = 0;
    if?(int[] a = arr) {
        for(var i = 0; i < length(a); i = i + 1) {
            z = z + a[i];
        }
    }
    return z;
}
```

12.7.2 OAT Features

- Named structure types with mutable fields
- Typed function pointers
- Polymorphic operations: `length`, and `==` or `!=`
- Type-annotated null values: `t null` always has type `t?`
- Definitely-not-null values: "atomic" array initialization syntax

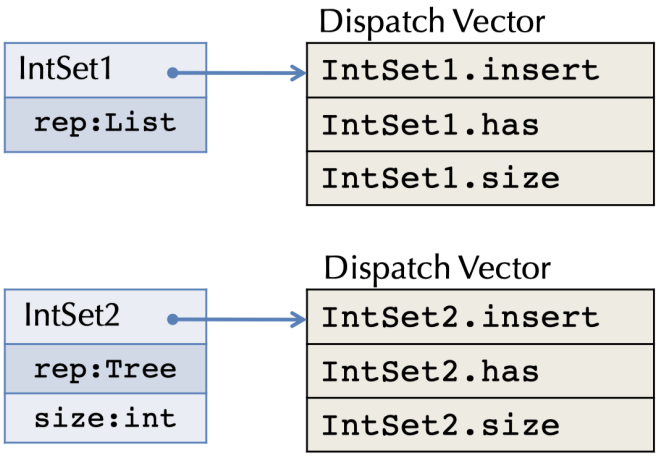
13. Compiling Classes And Objects

13.1 Code Generation for Objects

- *Classes:*
  - Generate data structure types
  - Generate the class tables for dynamic dispatch
- *Methods:*
  - Method body code is similar to functions/closures
  - Method calls require dispatch
- *Fields:*
  - Issues are the same as for records
  - Generating access code
- *Constructors:*
  - Object initialization
- *Dynamic types:*
  - Checked downcasts
  - `instanceof` and similar type dispatch

13.2 Compiling Objects

Objects contain a pointer to a **dispatch vector** (also called *virtual table* or *vtable*) with pointers to method code.



Code receiving `set:IntSet` only knows that `set` has an initial dispatch vector pointer and the layout of that vector.