CHAPTER 4

Data types and polymorphism

The main concepts in this chapter are:

polymorphism: dynamic type checking and dynamic dispatch,
control flow: computing different values depending on a conditional expression,
compile time versus run time: the execution of your compiler that performs transformations of the input program versus the execution of the input program after compilation,
type systems: identifying which types of values each expression will produce, and
heap allocation: storing values in memory.

4.1. Syntax of P_1

The P_0 subset of Python only dealt with one kind of data type: plain integers. In this chapter we add Booleans, lists and dictionaries. We also add some operations that work on these new data types, thereby creating the P_1 subset of Python. The syntax for P_1 is shown in Figure 1. We give only the abstract syntax (i.e., assume that all ambiguity is resolved). Any ambiguity is resolved in the same manner as Python. In addition, all of the syntax from P_0 is carried over to P_1 unchanged.

A Python list is a sequence of elements. The standard `python` interpreter uses an array (a contiguous block of memory) to implement a list. A Python dictionary is a mapping from keys to values. The standard `python` interpreter uses a hashtable to implement dictionaries.

4.2. Semantics of P_1

One of the defining characteristics of Python is that it is a dynamically typed language. What this means is that a Python expression may result in many different types of values. For example, the following conditional expression might result in an integer or a list.

```
>>> 2 if input() else [1, 2, 3]
```

```
key_datum ::= expression ":" expression
subscription ::= expression "[" expression "]"
expression ::= "True" | "False"
             | "not" expression
             | expression "and" expression
             | expression "or" expression
             | expression "==" expression
             | expression "!=" expression
             | expression "if" expression "else" expression
             | "[" expr_list "]"
             | "{" key_datum_list "}"
             | subscription
             | expression "is" expression
expr_list ::= ϵ
            | expression
            | expression "," expr_list
key_datum_list ::= ϵ
                 | key_datum
                 | key_datum "," key_datum_list
target ::= identifier
         | subscription
simple_statement ::= target "=" expression
```

FIGURE 1. Syntax for the P_1 subset of Python. (In addition to the syntax of P_0.)

In a statically typed language, such as C++ or Java, the above expression would not be allowed; the type checker disallows expressions such as the above to ensure that each expression can only result in one type of value.

Many of the operators in Python are defined to work on many different types, often performing different actions depending on the run-time type of the arguments. For example, addition of two lists performs concatenation.

```
>>> [1, 2, 3] + [4, 5, 6]
[1, 2, 3, 4, 5, 6]
```

For the arithmetic operators, `True` is treated as if it were the integer `1` and `False` is treated as `0`. Furthermore, numbers can be used in places where Booleans are expected. The number `0` is treated as `False` and everything else is treated as `True`. Here are a few examples:

```
>>> False + True
```

```
1
>>> False or False
False
>>> 1 and 2
2
>>> 1 or 2
1
```

Note that the result of a logic operation such as `and` and `or` does not necessarily return a Boolean value. Instead, e_1 `and` e_2 evaluates expression e_1 to a value v_1. If v_1 is equivalent to `False`, the result of the `and` is v_1. Otherwise e_2 is evaluated to v_2 and v_2 is the result of the `and`. The `or` operation works in a similar way except that it checks whether v_1 is equivalent to `True`.

A list may be created with an expression that contains a list of its elements surrounded by square brackets, e.g., `[3,1,4,1,5,9]` creates a list of six integers. The nth element of a list can be accessed using the subscript notation `l[n]` where `l` is a list and `n` is an integer (indexing is zero based). For example, `[3,1,4,1,5,9][2]` evaluates to `4`. The nth element of a list can be changed by using a subscript expression on the left-hand side of an assignment. For example, the following fixes the 4th digit of π.

```
>>> x = [3,1,4,8,5,9]
>>> x[3] = 1
>>> print x
[3, 1, 4, 1, 5, 9]
```

A dictionary is created by a set of key-value bindings enclosed in braces. The key and value expression are separated by a colon. You can lookup the value for a key using the bracket, such as `d[7]` below. To assign a new value to an existing key, or to add a new key-value binding, use the bracket on the left of an assignment.

```
>>> d = {42: [3,1,4,1,5,9], 7: True}
>>> d[7]
True
>>> d[42]
[3, 1, 4, 1, 5, 9]
>>> d[7] = False
>>> d
{42: [3, 1, 4, 1, 5, 9], 7: False}
>>> d[0] = 1
>>> d[0]
1
```

With the introduction of lists and dictionaries, we have entities in the language where there is a distinction between identity (the `is` operator) and equality (the == operator). The following program, we create two lists with the same elements. Changing list `x` does not affect list `y`.

```
>>> x = [1,2]
>>> y = [1,2]
>>> print x == y
True
>>> print x is y
False
>>> x[0] = 3
>>> print x
[3, 2]
>>> print y
[1, 2]
```

Variable assignment is shallow in that it just points the variable to a new entity and does not affect the entity previous referred to by the variable. Multiple variables can point to the same entity, which is called *aliasing*.

```
>>> x = [1,2,3]
>>> y = x
>>> x = [4,5,6]
>>> print y
[1, 2, 3]
>>> y = x
>>> x[0] = 7
>>> print y
[7, 5, 6]
```

EXERCISE 4.1. Read the sections of the Python Reference Manual that apply to P_1: 3.1, 3.2, 5.2.2, 5.2.4, 5.2.6, 5.3.2, 5.9, and 5.10.

EXERCISE 4.2. Write at least ten programs in the P_1 subset of Python that help you understand the language. Look for corner cases or unusual aspects of the language to test in your programs.

4.3. New Python AST classes

Figure 2 shows the additional Python classes used to represent the AST nodes of P_1. Python represents `True` and `False` as variables (using the `Name` AST class) with names `'True'` and `'False'`. Python allows these names to be assigned to, but for P_1, you may assume that they cannot written to (i.e., like `input`). The `Compare` class is

for representing comparisons such as == and !=. The expr attribute of Compare is for the first argument and the ops member contains a list of pairs, where the first item of each pair is a string specifying the operation, such as '==', and the second item is the argument. For P_1 we are guaranteed that this list only contains a single pair. The And and Or classes each contain a list of arguments, held in the nodes attribute and for P_1 this list is guaranteed to have length 2. The Subscript node represents accesses to both lists and dictionaries and can appear within an expression or on the left-hand-side of an assignment. The flags attribute should be ignored for the time being.

```
class Compare(Node):
    def __init__(self, expr, ops):
        self.expr = expr
        self.ops = ops
class Or(Node):
    def __init__(self, nodes):
        self.nodes = nodes
class And(Node):
    def __init__(self, nodes):
        self.nodes = nodes
class Not(Node):
    def __init__(self, expr):
        self.expr = expr
class List(Node):
    def __init__(self, nodes):
        self.nodes = nodes
class Dict(Node):
    def __init__(self, items):
        self.items = items
class Subscript(Node):
    def __init__(self, expr, flags, subs):
        self.expr = expr
        self.flags = flags
        self.subs = subs
class IfExp(Node):
    def __init__(self, test, then, else_):
        self.test = test
        self.then = then
        self.else_ = else_
```

FIGURE 2. The Python classes for P_1 AST nodes.

4.4. Compiling polymorphism

As discussed earlier, a Python expression may result in different types of values and that the type may be determined during program execution (at run-time). In general, the ability of a language to allow multiple types of values to be returned from the same expression, or be stored at the same location in memory, is called *polymorphism*. The following is the dictionary definition for this word.

> **pol•y•mor•phism**
> noun
> the occurrence of something in several different forms

The term "polymorphism" can be remembered from its Greek roots: "poly" means "many" and "morph" means "form".

Recall the following example of polymorphism in Python.

```
2 if input() else [1, 2, 3]
```

This expression sometimes results in the integer `2` and sometimes in the list `[1, 2, 3]`.

```
>>> 2 if input() else [1, 2, 3]
1
2
>>> 2 if input() else [1, 2, 3]
0
[1, 2, 3]
```

Consider how the following program would be flattened into a sequence of statements by our compiler.

```
print 2 if input() else [1, 2, 3]
```

We introduce a temporary variable `tmp1` which could point to either an integer or a list depending on the input.

```
tmp0 = input()
if tmp0:
  tmp1 = 2
else:
  tmp1 = [1, 2, 3]
print tmp1
```

Thinking further along in the compilation process, we end up assigning variables to registers, so we'll need a way for a register to refer to either an integer or a list. Note that in the above, when we print `tmp1`, we'll need some way of deciding whether `tmp1` refers to an integer or a list. Also, note that a list could require many more bytes than what could fit in a registers.

One common way to deal with polymorphism is called *boxing*. This approach places all values on the heap and passes around pointers to values in registers. A pointer has the same size regardless of what it points to, and a pointer fits into a register, so this provides a simple solution to the polymorphism problem. When allocating a value on the heap, some space at the beginning is reserved for a tag (an integer) that says what type of value is stored there. For example, the tag `0` could mean that the following value is an integer, `1` means that the value is a Boolean, etc.

Boxing comes with a heavy price: it requires accessing memory which is extremely slow on modern CPUs relative to accessing values from registers. Suppose a program just needs to add a couple integers. Written directly in x86 assembly, the two integers would be stored in registers and the addition instruction would work directly

on those registers. In contrast, with boxing, the integers must be first loaded from memory, which could take 100 or more cycles. Furthermore, the space needed to store an integer has doubled: we store a pointer and the integer itself.

To speed up common cases such as integers and arithmetic, we can modify the boxing approach as follows. Instead of allocating integers on the heap, we can instead go ahead and store them directly in a register, but reserve a couple bits for a tag that says whether the register contains an integer or whether it contains a pointer to a larger value such as a list. This technique is somewhat questionable from a correctness perspective as it reduces the range of plain integers that we can handle, but it provides such a large performance improvement that it is hard to resist.

We will refer to the particular polymorphic representation suggested in these notes as `pyobj`. The file `runtime.c` includes several functions for working with `pyobj`, and those functions can provide inspiration for how you can write x86 assembly that works with `pyobj`. The two least-significant bits of a `pyobj` are used for the tag; the following C function extracts the tag from a `pyobj`.

```
typedef long int pyobj;
#define MASK 3      /* 3 is 11 in binary */
int tag(pyobj val) { return val & MASK; }
```

The following two functions check whether the `pyobj` contains an integer or a Boolean.

```
#define INT_TAG 0      /* 0 is 00 in binary */
#define BOOL_TAG 1     /* 1 is 01 in binary */
int is_int(pyobj val) { return (val & MASK) == INT_TAG; }
int is_bool(pyobj val) { return (val & MASK) == BOOL_TAG; }
```

If the value is too big to fit in a register, we set both tag bits to `1` (which corresponds to the decimal 3).

```
#define BIG_TAG 3    /* 3 is 11 in binary */
int is_big(pyobj val) { return (val & MASK) == BIG_TAG; }
```

The tag pattern `10` is reserved for later use.

The following C functions in `runtime.c` provide a way to convert from integers and Boolean values into their `pyobj` representation. The idea is to move the value over by 2 bits (losing the top two bits) and then stamping the tag into those 2 bits.

```
#define SHIFT 2
pyobj inject_int(int i) { return (i << SHIFT) | INT_TAG; }
pyobj inject_bool(int b) { return (b << SHIFT) | BOOL_TAG; }
```

The next set of C functions from `runtime.c` provide a way to extract an integer or Boolean from its `pyobj` representation. The idea is simply to shift the values back over by 2, overwriting the tag bits. Note that before applying one of these projection functions, you should first check the tag so that you know which projection function should be used.

```
int project_int(pyobj val) { return val >> SHIFT; }
int project_bool(pyobj val) { return val >> SHIFT; }
```

The following C structures define the heap representation for big values. The `hashtable` structure is defined in the provided hashtable C library.

```
enum big_type_tag { LIST, DICT };

struct list_struct {
  pyobj* data;
  unsigned int len;
};
typedef struct list_struct list;

struct pyobj_struct {
  enum big_type_tag tag;
  union {
    struct hashtable* d;
    list l;
  } u;
};
typedef struct pyobj_struct big_pyobj;
```

When we grow the subset of Python to include more features, such as functions and objects, the alternatives within `big_type_tag` will grow as will the union inside of `pyobj_struct`.

The following C functions from `runtime.c` provide a way to convert from `big_pyobj*` to `pyobj` and back again.

```
pyobj inject_big(big_pyobj* p) { return ((long)p) | BIG_TAG; }
big_pyobj* project_big(pyobj val)
    { return (big_pyobj*)(val & ~MASK); }
```

The `inject_big` function above reveals why we chose to use two bits for tagging. It turns out that on Linux systems, `malloc` always aligns newly allocated memory at addresses that are multiples of four. This means that the two least significant bits are always zero! Thus, we can use that space for the tag without worrying about destroying

the address. We can simply zero-out the tag bits to get back a valid address.

The `runtime.c` file also provides a number of C helper functions for performing arithmetic operations and list/dictionary operations on `pyobj`.

```
int is_true(pyobj v);
void print_any(pyobj p);
pyobj input_int();
big_pyobj* create_list(pyobj length);
big_pyobj* create_dict();
pyobj set_subscript(pyobj c, pyobj key, pyobj val);
pyobj get_subscript(pyobj c, pyobj key);
big_pyobj* add(big_pyobj* x, big_pyobj* y);
int equal(big_pyobj* x, big_pyobj* y);
int not_equal(big_pyobj* x, big_pyobj* y);
```

You will need to generate code to do tag testing, to dispatch to different code depending on the tag, and to inject and project values from `pyobj`. We recommend accomplishing this by adding a new compiler pass after parsing and in front of flattening. For lack of a better name, we call this the 'explicate' pass because it makes explicit the types and operations.

4.5. The explicate pass

As we have seen in Section 4.4, compiling polymorphism requires a representation at run time that allows the code to dispatch between operations on different types. This dispatch is enabled by using *tagged values*.

At this point, it is helpful to take a step back and reflect on why polymorphism in P_1 causes a large shift in what our compilers must do as compared to compiling P_0 (which is completely monomorphic). Consider the following assignment statement:

(4.1)
```
y = x + y
```

As a P_0 program, when our compiler sees the `x + y` expression at *compile time*, it knows immediately that `x` and `y` must correspond to integers at *run time*. Therefore, our compiler can select following x86 instruction to implement the above assignment statement.

```
addl x, y
```

This x86 instruction has the same run-time behavior as the above assignment statement in P_0 (i.e., they are *semantically equivalent*).

Now, consider the example assignment statement (4.1) again but now as a P_1 program. At compile time, our compiler has no way to know whether `x + y` corresponds to an integer addition, a list concatenation, or an ill-typed operation. Instead, it must generate code that makes the decision on which operation to perform at *run time*. In a sense, our compiler can do less at compile now: it has less certain information at compile time and thus must generate code to make decisions at run time. Overall, we are trading off execution speed with flexibility with the introduction of polymorphic operations in our input language.

To provide intuition for this trade off, let us consider a real world analogy. Suppose you a planning a hike for some friends. There are two routes that you are considering (let's say the two routes share the same initial path and fork at some point). Basically, you have two choices: you can decide on a route before the hike (at "plan time") or you can wait to make the decision with your friends during the hike (at "hike time"). If you decide beforehand at plan time, then you can simplify your planning; for example, you can input GPS coordinates for the route on which you decided and leave your map for the other route at home. If you want to be more flexible and decide the route during the hike, then you have to bring maps for both routes in order to have sufficient information to make at hike time. The analogy to your compiler is that to be more flexible at run time ($\sim$ hike time), then your compilation ($\sim$ hike planning) requires you to carry tag information at run time ($\sim$ a map at hike time).

Returning to compiling P_1, Section 4.4 describes how we will represent the run-time tags. The purpose of the explicate pass is to generate the dispatching code (i.e., the decision making code). After the explicate pass is complete, the *explicit AST* that is produced will make explicit operations on integers and Booleans. In other words, all operations that remain will be apply to integers, Booleans, or `big_pyobj*`s. Let us focus on the polymorphic + operation in the the example assignment statement (4.1). The AST produced by the parser is as follows:

(4.2)
```
Add((Name('x'), Name('y'))) .
```

We need to create an AST that captures deciding which "+" operation to use based on the run-time types of `x` and `y`.

For +, we have three possibilities: integer addition, list concatenation, or type error. We want a case for integer addition, as we can implement that operation efficiently with an `addl` instruction. To decide whether we have list concatenation or error, we decide to leave

that dispatch to a call in `runtime.c`, as a list concatenation is expensive anyway (i.e., requires going to memory). The `add` function

```
big_pyobj* add(big_pyobj* x, big_pyobj* y)
```

in `runtime.c` does exactly what is described here. To represent the two cases in an explicit AST, we will reuse the `Add` node for *integer* addition and a `CallFunc` node to `add` for the `big_pyobj*` addition. Take note that the `Add` node before the explicate pass represents the polymorphic + of P_1, but it represents integer addition in an explicit AST after the explicate pass. Another choice could have been to create an `IntegerAdd` node kind to make it clear that it applies only to integers.

Now that we have decided which node kinds will represent which + operations, we know that the explicit AST for expression (4.2) is informally as follows:

```
IfExp(
  tag of Name('x') is 'int or bool'
    and tag of Name('y') is 'int or bool',

  convert back to 'pyobj'
    Add(convert to 'int' Name('x'), convert to 'int' Name('y')),

  IfExp(
    tag of Name('x') is 'big'
      and tag of Name('y') is 'big',

    convert back to 'pyobj'
      CallFunc(Name('add'),
        [convert to 'big' Name('x'), convert to 'big' Name('y')]),

    CallFunc(... abort because of run-time type error ...)

  )

)
```

Looking at the above explicit AST, our generated code will at run time look at the tag of the polymorphic values for `x` and `y` to decide whether it is an integer add (i.e., `Add(...)`) or a `big_pyobj*` add (i.e., `CallFunc(Name('add'), ...)`).

What are these "convert" operations? Recall that at run time we need a polymorphic representation of values (i.e., some 32-bit value that can be an 'int', 'bool', 'list', or 'dict'), which we call `pyobj`. It is a `pyobj` that has a tag. However, the integer add at run time (which

corresponds to the `Add` AST node here at compile time) should take "pure" integer arguments (i.e., without tags). Similar, the `add` function call takes `big_pyobj*` arguments (not `pyobj`). We need to generate code that converts `pyobj`s to other types at appropriate places. From Section 4.4, we have described how we get the integer, boolean, or `big_pyobj*` part from a `pyobj` by shifting or masking. Thus, for "convert to whatever" in the above, we need insert AST nodes that represent these *type conversions*. To represent these new type conversion operations, we recommend creating two new AST classes: `ProjectTo` that represents converting from `pyobj` *to* some other type and `InjectFrom` that represents converting to `pyobj` *from* some other type. Analogously, we create a `GetTag` AST class to represent tag lookup, which will be implemented with the appropriate masking.

Note that we might have ben tempted to insert AST nodes that represent directly shifting or masking. While this choice could work, we choose to separate the conceptual operation (i.e., type conversion) from the actual implementation mechanism (i.e., shifting or masking). Our instruction selection phase will implement `ProjectTo` and `InjectFrom` with the appropriate shift or masking instructions.

As a compiler writer, there is one more concern in implementing the explicate pass. Suppose we are implementing the case for explicating `Add`, that is, we are implementing the transformation in general for

`Add((`e_1`, `e_2`))`

where e_1, e_2 are arbitrary subexpressions. Observe in the explicit AST example above, `Name('x')` corresponds to e_1 and `Name('y')` to e_2. Furthermore, observe that `Name('x')` and `Name('y')` each appear four times in the output explicit AST. If instead of `Name`s, we have arbitrary expressions and duplicate them in the same manner, we run into correctness issues. In particular, if e_1 or e_2 are side-effecting expressions (i.e., include `input()`), then duplicating them would change the semantics of the program (e.g., we go from reading once to multiple times). Thus, we need to evaluate the subexpressions once before duplicating them, that is, we can bind the subexpressions to `Name`s and then use the `Name`s in their place.

We introduce a `Let` construct for this purpose:

```
Let(var, rhs, body) .
```

The `Let` construct is needed so that you can use the result of an expression multiple times without duplicating the expression itself, which would duplicate its effects. The semantics of the `Let` is that

```
class GetTag(Node):
    def __init__(self, arg):
        self.arg = arg

class InjectFrom(Node):
    def __init__(self, typ, arg):
        self.typ = typ
        self.arg = arg

class ProjectTo(Node):
    def __init__(self, typ, arg):
        self.typ = typ
        self.arg = arg

class Let(Node):
    def __init__(self, var, rhs, body):
        self.var = var
        self.rhs = rhs
        self.body = body
```

FIGURE 3. New internal AST classes for the output of the explicate pass.

the `rhs` should be evaluated and then assigned to the variable `var`. Then the `body` should be evaluated where the `body` can refer to the variable. For example, the expression

```
Add(( Add((Const(1), Const(2))) , Const(3) ))
```

should evaluate to the same value as

```
Let( Name('x'), Add((Const(1), Const(2))),
     Add(( Name('x') , Const(3) )) )
```

(i.e., they are equivalent semantically).

Overall, to represent the new operations in your abstract syntax trees, we recommend creating the new AST classes in Figure 3.

EXERCISE 4.3. Implement an `explicate` pass that takes a P_1 AST with polymorphic operations and explicates it to produce an explicit AST where all such polymorphic operations have been transformed to dispatch code to monomorphic operations.

4.6. Type checking the explicit AST

A good way to catch errors in your compiler is to check whether the type of value produced by every expression makes sense. For

example, it would be an error to have a projection nested inside of another projection:

```
ProjectTo('int',
  ProjectTo('int', InjectFrom('int', Const(1)))
)
```

The reason is that projection expects the subexpression to be a `pyobj`.

What we describe in this section is a type checking phase applied to the explicit AST produced as a sanity check for your explicate pass. The explicate pass can be tricky to get right, so we want to have way to detect errors in the explicate pass before going through the rest of the compiler. Note that the type checking that we describe here does not reject input programs at compile time as we may be used to from using statically-typed languages (e.g., Java). Rather, any type errors that result from using the checker that we describe here points to a bug in the explicate pass.

It is common practice to specify what types are expected by writing down an "if-then" rule for each kind of AST node. For example, the rule for `ProjectTo` is:

> For any expression e and any type T selected from the set { `int`, `bool`, `big` }, if e has type `pyobj`, then `ProjectTo(`T`,` e`)` has type T.

It is also common practice to write "if-then" rules using a horizontal line, with the "if" part written above the line and the "then" part written below the line.

$$\frac{e \text{ has type } \texttt{pyobj} \qquad T \in \{\texttt{int}, \texttt{bool}, \texttt{big}\}}{\texttt{ProjectTo}(T, e) \text{ has type } T}$$

Because the phrase "has type" is repeated so often in these type checking rules, it is abbreviated to just a colon. So the above rule is abbreviated to the following.

$$\frac{e : \texttt{pyobj} \qquad T \in \{\texttt{int}, \texttt{bool}, \texttt{big}\}}{\texttt{ProjectTo}(T, e) : T}$$

The `Let(var, rhs, body)` construct poses an interesting challenge. The variable `var` is assigned the `rhs` and is then used inside `body`. When we get to an occurrence of `var` inside `body`, how do we know what type the variable will be? The answer is that we need a dictionary to map from variable names to types. A dictionary used for this purpose is usually called an *environment* (or in older books, a *symbol table*). The capital Greek letter gamma, written Γ, is typically used for referring to environments. The notation $\Gamma, x : T$ stands for

making a copy of the environment Γ and then associating T with the variable x in the new environment. The type checking rules for `Let` and `Name` are therefore as follows.

$$\frac{e_1 : T_1 \text{ in } \Gamma \qquad e_2 : T_2 \text{ in } \Gamma, x : T_1}{\texttt{Let}(x, e_1, e_2) : T_2 \text{ in } \Gamma} \qquad \frac{\Gamma[x] = T}{\texttt{Name}(x) : T \text{ in } \Gamma}$$

Type checking has roots in logic, and logicians have a tradition of writing the environment on the left-hand side and separating it from the expression with a turn-stile ($\vdash$). The turn-stile does not have any intrinsic meaning per se. It is punctuation that separates the environment Γ from the expression e. So the above typing rules are commonly written as follows.

$$\frac{\Gamma \vdash e_1 : T_1 \qquad \Gamma, x : T_1 \vdash e_2 : T_2}{\Gamma \vdash \texttt{Let}(x, e_1, e_2) : T_2} \qquad \frac{\Gamma[x] = T}{\Gamma \vdash \texttt{Name}(x) : T}$$

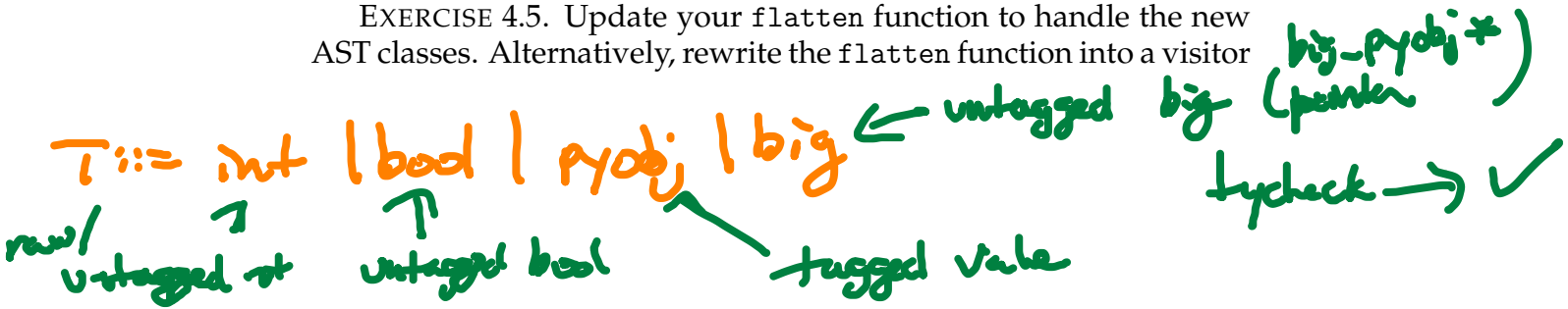
Overall, the statement $\Gamma \vdash e : T$ is an example of what is called a *judgment*. In particular, this judgment says, "In environment Γ, expression e has type T." Figure 4 shows the type checking rules for all of the AST classes in the explicit AST.

EXERCISE 4.4. Implement a type checking function that makes sure that the output of the explicate pass follows the rules in Figure 4. Also, extend the rules to include checks for statements.

4.7. Update expression flattening

The output AST from the explicate pass contains a number of new AST classes that were not handled by the `flatten` function from chapter 1. The new AST classes are `IfExp`, `Compare`, `Subscript`, `GetTag`, `InjectFrom`, `ProjectTo`, and `Let`. The `Let` expression simply introduces an extra assignment, and therefore no `Let` expressions are needed in the output. When flattening the `IfExp` expression, I recommend using an `If` statement to represent the control flow in the output. Alternatively, you could reduce immediately to labels and jumps, but that makes liveness analysis more difficult. In liveness analysis, one needs to know what statements can preceed a given statement. However, in the presense of jump instructions, you would need to build an explicit control flow graph in order to know the preceeding statements. Instead, I recommend postponing the reduction to labels and jumps to after register allocation, as discussed below in Section 4.10.

EXERCISE 4.5. Update your `flatten` function to handle the new AST classes. Alternatively, rewrite the `flatten` function into a visitor



$$\frac{n \text{ is an integer}}{\Gamma \vdash \texttt{Const}(n) : \texttt{int}} \qquad \frac{b \text{ is a Boolean}}{\Gamma \vdash \texttt{Const}(b) : \texttt{bool}} \qquad \frac{\Gamma[x] = T}{\Gamma \vdash \texttt{Name}(x) : T}$$

$$\frac{\Gamma \vdash e_1 : \texttt{int} \quad \Gamma \vdash e_2 : \texttt{int}}{\Gamma \vdash \texttt{Add}(e_1, e_2) : \texttt{int}} \qquad \frac{\Gamma \vdash e : \texttt{int}}{\Gamma \vdash \texttt{UnarySub}(e) : \texttt{int}}$$

$$\frac{\Gamma \vdash e_1 : \texttt{bool} \quad \Gamma \vdash e_2 : T \quad \Gamma \vdash e_3 : T}{\Gamma \vdash \texttt{IfExp}(e_1, e_2, e_3) : T}$$

$$\frac{\Gamma \vdash e : T \quad T \in \{\texttt{int}, \texttt{bool}, \texttt{big}\}}{\Gamma \vdash \texttt{InjectFrom}(T, e) : \texttt{pyobj}} \qquad \frac{\Gamma \vdash e : \texttt{pyobj} \quad T \in \{\texttt{int}, \texttt{bool}, \texttt{big}\}}{\Gamma \vdash \texttt{ProjectTo}(T, e) : T}$$

$$\frac{\Gamma \vdash e : \texttt{pyobj}}{\Gamma \vdash \texttt{GetTag}(e) : \texttt{int}} \qquad \frac{\Gamma \vdash e_1 : \texttt{pyobj} \quad \Gamma \vdash e_2 : \texttt{pyobj}}{\Gamma \vdash \texttt{Compare}(e_1, [(\texttt{is}, e_2)]) : \texttt{bool}}$$

$$\frac{\Gamma \vdash e_1 : T \quad \Gamma \vdash e_2 : T \quad T \in \{\texttt{int}, \texttt{bool}\} \quad op \in \{\texttt{==}, \texttt{!=}\}}{\Gamma \vdash \texttt{Compare}(e_1, [(op, e_2)]) : \texttt{bool}}$$

$$\frac{\Gamma \vdash e_1 : T_1 \quad \Gamma, x : T_1 \vdash e_2 : T_2}{\Gamma \vdash \texttt{Let}(x, e_1, e_2) : T_2}$$

$$\frac{\Gamma \vdash e_1 : \texttt{pyobj} \quad \Gamma \vdash e_2 : \texttt{pyobj}}{\Gamma \vdash \texttt{Subscript}(e_1, e_2) : \texttt{pyobj}}$$

FIGURE 4. Type checking rules for expressions in the explicit AST.

class and then create a new visitor class that inherits from it and that implements visit methods for the new AST nodes.

4.8. Update instruction selection

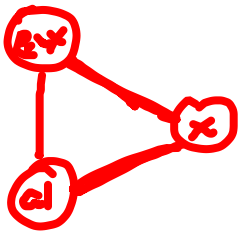
The instruction selection phase should be updated to handle the new AST classes `If`, `Compare`, `Subscript`, `GetTag`, `InjectFrom`, and `ProjectTo`. Consult Appendix 6.4 for suggestions regarding which x86 instructions to use for translating the new AST classes. Also, you will need to update the function call for printing because you should now use the `print_any` function.

EXERCISE 4.6. Update your instruction selection pass to handle the new AST classes.

4.9. Update register allocation

Looking back at Figure 5, there are several sub-passes within the register allocation pass, and each sub-pass needs to be updated to deal with the new AST classes.

In the liveness analysis, the most interesting of the new AST classes is the `If` statement. What liveness information should be propagated into the "then" and "else" branch and how should the results from the two branches be combined to give the result for the entire `If`? If we could somehow predict the result of the test expression, then we could select the liveness results from one branch or the other as the results for the `If`. However, its impossible to predict this in general (e.g., the test expression could be `input()`)), so we need to make a conservative approximation: we assume that either branch could be taken, and therefore we consider a variable to be live if it is live in either branch.



The code for building the interference graph needs to be updated to handle `If` statements, as does the code for finding all of the local variables. In addition, you need to account for the fact that the register `al` is really part of register `eax` and that register `cl` is really part of register `ecx`.

The graph coloring algorithm itself works on the interference graph and not the AST, so it does not need to be changed.

The spill code generation pass needs to be updated to handle `If` statements and the new x86 instructions that you used in the instruction selection pass.

Similarly, the code for assigning homes (registers and stack locations) to variables must be updated to handle `If` statements and the new x86 instructions.

4.10. Removing structured control flow

Now that register allocation is finished, and we no longer need to perform liveness analysis, we can lower the `If` statements down to x86 assembly code by replacing them with a combination of labels and jumps. The following is a sketch of the transformation from `If` AST nodes to labels and jumps.

```
if x:
  then instructions
else:
  else instructions
```

$\Longrightarrow$

IfStmt

```
cmpl $0, x
je else_label_5
then instructions
jmp end_label_5
else_label_5:
else instructions
end_label_5:
```

EXERCISE 4.7. Write a compiler pass that removes `If` AST nodes, replacing them with combinations of labels and jumps.

4.11. Updates to print x86

You will need to update the compiler phase that translates the x86 intermediate representation into a string containing the x86 assembly code, handling all of the new instructions introduced in the instruction selection pass and the above pass that removes `If` statements.

Putting all of the above passes together, you should have a complete compiler for P_1.

EXERCISE 4.8. Extend your compiler to handle the P_1 subset of Python. You may use the parser from Python's `compiler` module, or for extra credit you can extend your own parser. Figure 5 shows the suggested organization for your compiler.

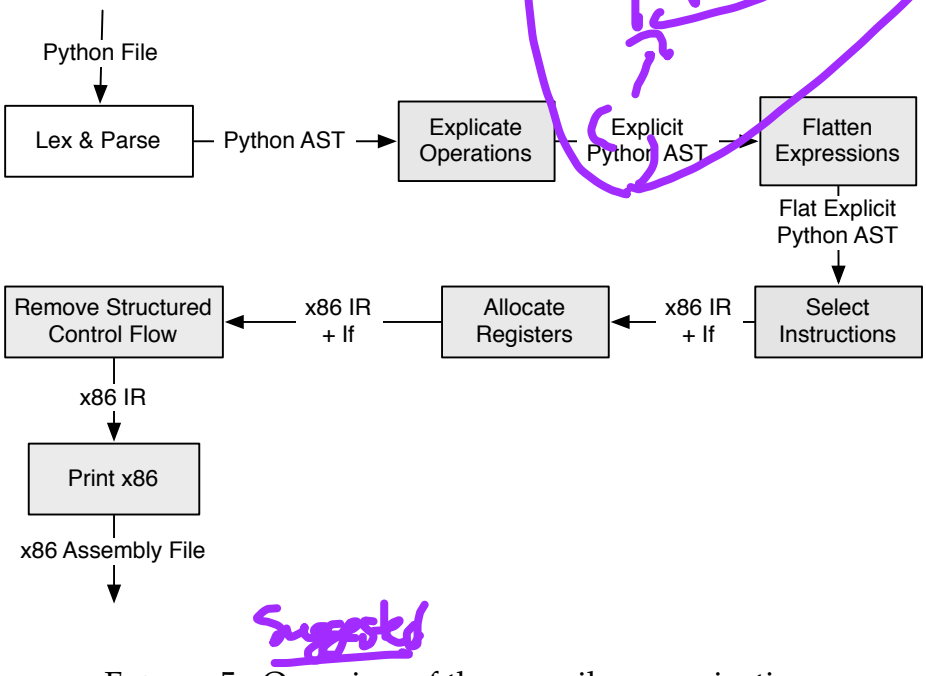


FIGURE 5. Overview of the compiler organization.