PyLLVM

A compiler from a subset of Python to LLVM-IR

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Outline

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3. Related Work
4. Analysis and Benchmarking
5. Conclusion

Motivation

Motivation: Tupleware

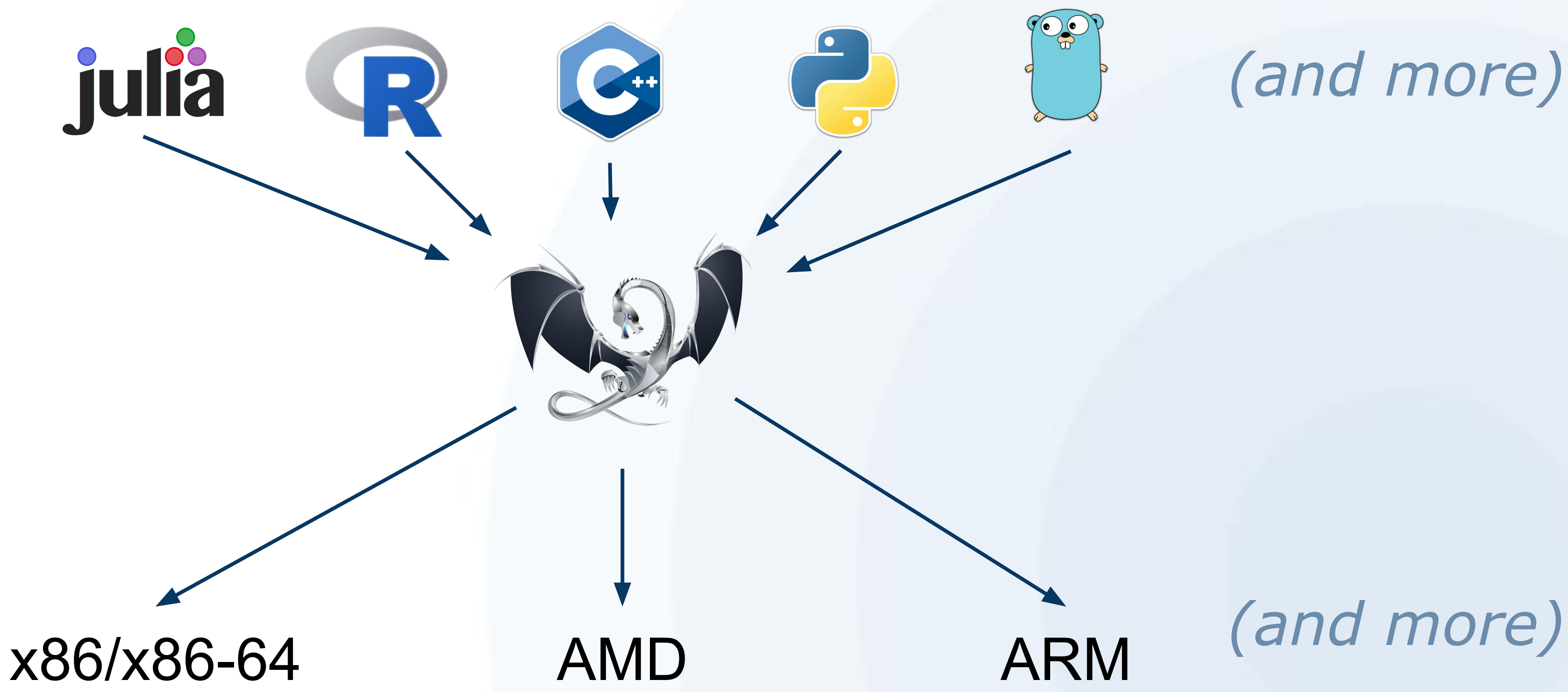
- Distributed analytical framework built at Brown for running algorithms on large datasets

- User supplies:
    1. data
    2. UDF (algorithm)
    3. workflow (map, reduce, join, etc.)

- Goal: language and platform independence

Motivation: The LLVM Compiler Infrastructure Project

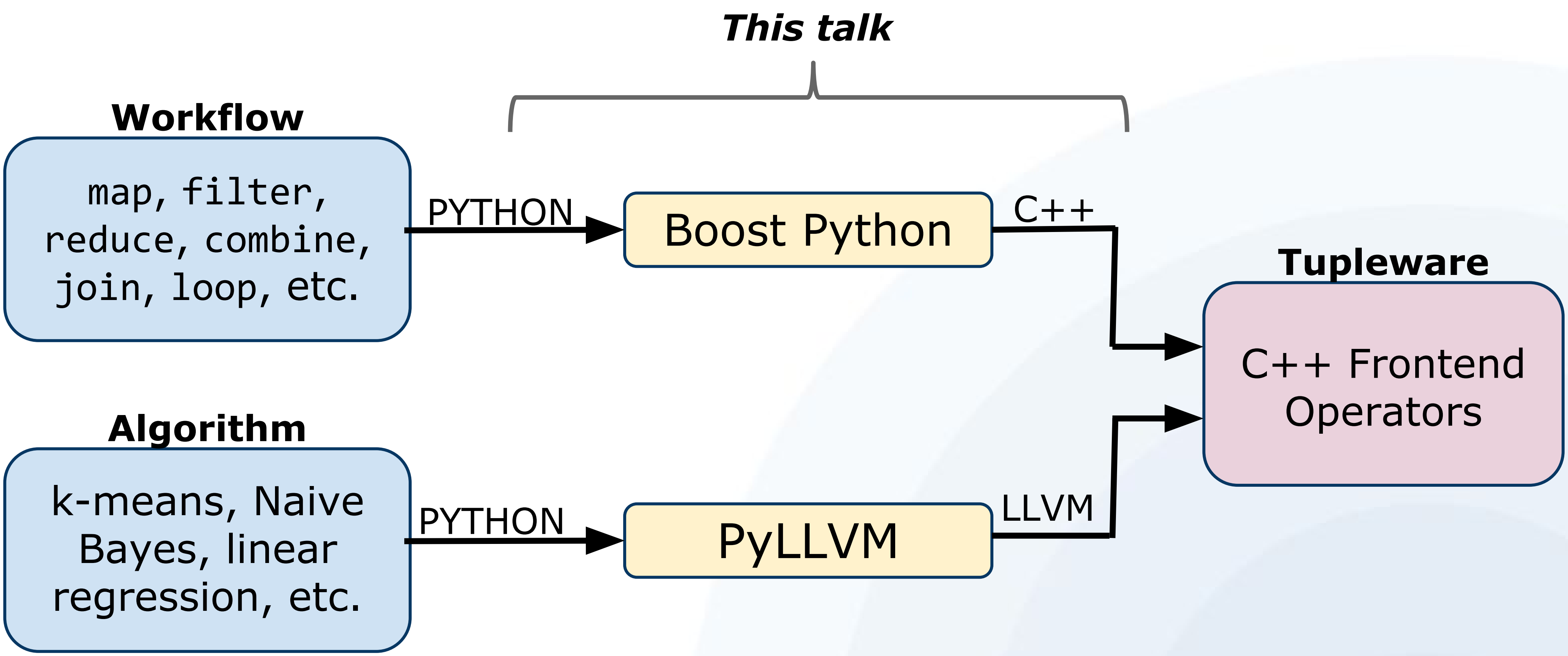
- LLVM-IR is a transportable **intermediate representation** by the LLVM Compiler Project



Mission

The goal of this project is to provide a Python interface with Tupleware's C++ backend to make the user experience as simple and straightforward as possible.

Mission: Python and Tupleware



Example Tupleware Usage

```
from TupleWare import load

def linreg(dims, data, w):
    dot = 1.0
    c = 0
    while c < dims:
        dot += data[c]*w[c]
        c += 1
    label = data[dims]
    dot *= -label
    c2 = 0
    while(c2 < dims):
        g[c2] += dot*data[c2]
        c2 += 1
```

```
def run_map(data):
    TS = load(data)
    TS.map(linreg)
    TS.execute()
```

Tupleware Library Implementation

```
import PyLLVM
import TupleWrapper  # Boost C++ binding

def map(self, udf):
    try:
        # Try to get LLVM-IR from PyLLVM.
        llvm = PyLLVM.compiler(udf)
    except PyLLVM.PyllvmError:
        # Unable to compile the UDF, try backup.
        self.backup_map(udf)
    except Exception as exc:
        # The exception was semantic.
        raise ValueError("Bad Python in UDF", exc)
    else:
        # Valid LLVM IR was generated
        # can now call desired operator
        TupleWrapper.map(llvm)
```

PYLLVM

PyLLVM

- Simple, easy to extend, one-pass static compiler that takes in a subset of Python most likely to be used by Tupleware user-defined functions.
- Based on py2llvm, an unfinished Google Code project from 2010
  - *https://code.google.com/p/py2llvm/*
- Uses llvmpy: wrapper for C++ IR Builder

PyLLVM: Subset of Python

- Anticipated common requirements for Tupleware users:
    - Machine learning algorithms are often simple, easily optimized mathematical functions
- Primarily statically type-inferable code is handled
- No dictionaries, list comprehensions, or objects.

PyLLVM: Overview of Design

- **Abstract Syntax Tree**:
  - Python2.7's `compiler` package: `parse`, `walk`
- **Semantic analysis**
  - `CodeGenLLVM`: Visitor class
    - `SymbolTable`: Keeps track of variables and scope
    - `TypeInference`: Infers expression type
- **Code Generation**
  - `llvmpy`: Generates LLVM-IR: Python bindings to the C++ LLVM IR-Builder

Static Single Assignment

- LLVM instructions are SSA: Registers can only be assigned to once
- Result of being halfway between programming language and machine code
- Do not want to implement entire compiler in SSA form…

Scoping and Variables

SOLUTION: variables are allocated on the stack and addresses stored in `SymbolTable`

- `Symbol`: class representing variable
  - name, type, memory location, etc.

- `SymbolTable`: stack of tuples, each representing a scope
  - Scope contains name and map of varname to `Symbols`

LLVM Types

Types: PyLLVM

LLVM IR Types: Integers, floats, pointers, arrays, vectors, structs, functions

PyLLVM Types: integers, floats, vectors, lists, strings, functions

Inferring Types

- LLVM-IR is statically typed, Python is not
- `TypeInference` infers Python types from nodes of the AST
  - recursively traverses tree until reaches leaf node, infers based on leaf
  - uses symbol table for variables/functions
- Intrinsic math functions return the type they are passed in to avoid multiple functions for integer vs. float

PyLLVM Types

1. **Numerical Values**
2. Vectors
3. Lists
4. Strings
5. Functions
6. Branching and Loops

Numerical Values

- Integers
  - LLVM 32-bit integers
- Floats
  - LLVM 32-bit floating point
- Booleans
  - 1-bit integers
    - converted to 32-bit before being stored
  - `True + True = 2`

PyLLVM Types

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Vectors

- 4-element immutable floating point vector types
  - `vec = vector(1,2,3,4)`
  - `vec.x/y/z/w` or `vec[i]`
- Built in: add, subtract, multiply, divide, compare
- Written specifically for ML functions

PyLLVM Types

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Lists (WIP)

- Static-length mutable lists
  - `range`, `zeros`, `len`
- Based on underlying LLVM array type
  - can be populated with constants or pointers
- `alloca_array`'d onto stack and passed by pointer (unlike vectors)
  - *Any lists returned from functions will be stored on the heap*

PyLLVM Types

1. Numerical Values
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4. **Strings**
5. Functions
6. Branching and Loops

Strings

- Desugared into lists of integers
  - strings are lists of characters
  - characters can be represented as integers
- Symbol table remembers if list variable contains integers or characters
  - For `print`, `cmp`, etc
- That was easy!

PyLLVM Types

1. Numerical Values
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5. **Functions**
6. Branching and Loops

Function Definitions

- Can define and call functions from anywhere in the UDF
- Function signature generated and arguments added to the symbol table
- The only time where the compiler does 2 passes:
  - One descent to extract return type of func
  - Pops symbol table scope, calls `delete` on LLVM-IR Builder, and runs pass again

Function Arguments

- Since types are not dynamic, all arguments must have type values
  - `func(i=int, f=float)`
- Type and length of list must be specified
  - `func(l=listi8)`
  - *ONLY* place where subset of Python differs from real Python
- Can be implemented in future, if only PEP484 (Type Hints) had been reality...

Intrinsic Functions

- Simple built-in math library
  - `abs`, `pw`, `exp`, `log`, `sqrt`, `int`, `float`
  - takes in variable type, returns same type
- llvmpy does not provide access to equivalent IR instruction
  - Workaround: declare function as header, LLVM-IR will look up matching function
- `print`
  - handled similarly to intrinsic math functions

PyLLVM Types

1. Numerical Values
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5. Functions
6. **Branching and Loops**

Conditionals: `if`, `for`, `while`

- All supported with some limitations:
    - new variables declared within branches will go out of scope upon exit
    - existing vars can be modified
    - `return` within if statements supported only if every branch contains `return`
- All types have boolean values
    - empty lists are false, nonzero values are true

Related Work

Numba

- JIT specializing Python compiler by Continuum Analytics
- Purpose is to compile functions into executables using LLVM and call them from Python using the Python-C API
- **Goal is to get Python to run fast, generating IR is only a step along the way**

PyLLVM and Numba Comparison

- **Bottom line: same tools, different goals**
- Numba provides comprehensive coverage of Python, and is a more mature project
- In order get LLVM-IR out of Numba, have to run `numba --dump-llvm` or use `pycc`
- PyLLVM build “in-house”

Analysis

- Focused on two specific criteria for analysis
  - Usability of the frontend
  - Code efficiency
  - Difficult to compare compilation time

- Sample algorithms: Naive Bayes, k-means, linear regression, and logical regression.

Analysis: Usability

- PyLLVM does not lose any usability
- Primary advantage of Python is freedom from memory management and other bookkeeping

Python

```
def naive_bayes(data=list,
                counts=list,
                dims=int,
                vals=int,
                labels=int):
  label=data[dims]
  counts[label]=+1
  offset=labels+label*dims*vals
  while(c in range x):
    counts[offset+c*vals+data[c]]=+1
```

C++

```
void naive_bayes(char *data,
                 int *counts,
                 int dims,
                 int vals,
                 int labels) {
  char label=data[dims];
  ++counts[label];
  int offset=labels+label*dims*vals;
  for (int j = 0; j < dims; j++)
    ++counts[offset+j*vals+data[j]];
}
```

Analysis: Benchmarking

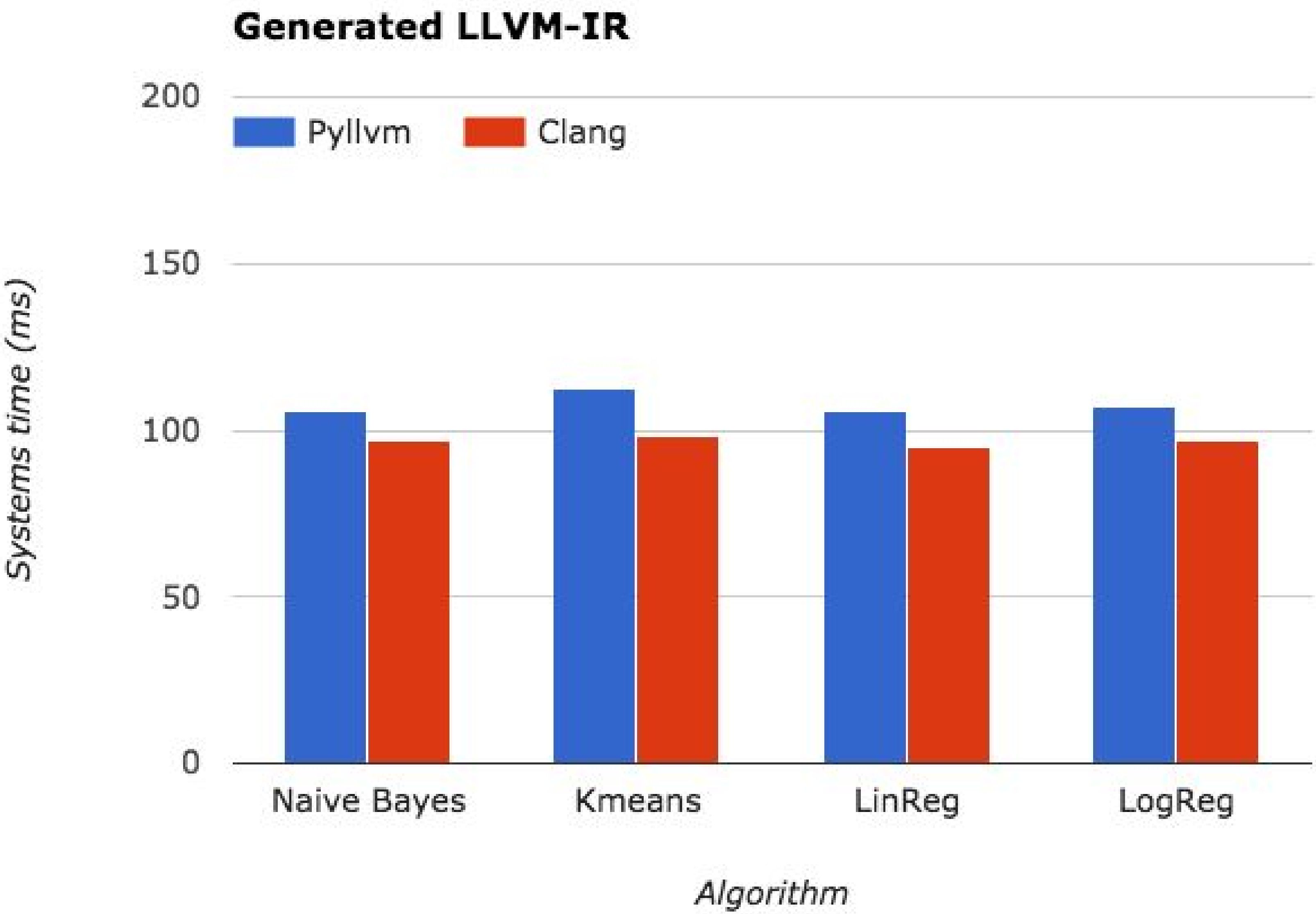
- Compilation**: PyLLVM vs. Numba**
  - Only happens once, cost is minor

- Generated LLVM: **PyLLVM vs. Clang**
  - Tested unoptimized LLVM, ultimately differences likely to be optimized away

Analysis: Executable Runtime

- Generated unoptimized LLVM-IR using `clang`
- Ran generated LLVM-IR using `lli`
- Used system `time` to compare runtime
- Ran algorithm 2500 times, for 500 trials

Analysis: Executable Runtime



Results

- Difference between runtimes for system time is:
  - Naive Bayes: 1%
  - K-means: 12%
  - Linear regression: 9%
  - Logical regression: 9%
- Spike in k-means potentially because sqrt
  - llvmpy does not provide direct access to LLVM’s sqrt instruction

Conclusion

- Overall, were able to achieve goal
  - Able to fully integrate Python as a Tupleware frontend
  - To the user, all of Python is supported (although with performance hit)

- Future work: Dynamically typed variables, dynamic-length and multidimensional lists, new native data types (dicts!)

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Original: code.google.com/p/py2llvm

My work: github.com/aherlihy/PythonLLVM

Tupleware: tupleware.cs.brown.edu

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