# The Effects of Unrolling and Inlining on Python Bytecode Optimizations

Yosi Ben Asher, Nadav Rotem
Haifa University

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# The Python Programming Language

- Very popular dynamic programming language combining object-oriented and scripting concepts
- Features a fully dynamic type system named 'duck typing'
- Compiled into bytecode and executed by an interpreter
- Known to be hundreds of times slower than C or Java

# Python disassembly

Technology Theme

```
def func(a,b,c):
    return a[b]*c + b*c + a[0]
```

```
>>> dis.dis(func)
  2           0 LOAD_FAST                0 (a)
              3 LOAD_FAST                1 (b)
              6 BINARY_SUBSCR
              7 LOAD_FAST                2 (c)
             10 BINARY_MULTIPLY
             11 LOAD_FAST                1 (b)
             14 LOAD_FAST                2 (c)
             17 BINARY_MULTIPLY
             18 BINARY_ADD
             19 LOAD_FAST                0 (a)
             22 LOAD_CONST               1 (0)
             25 BINARY_SUBSCR
             26 BINARY_ADD
             27 RETURN_VALUE
```

# Python interpreter code

```
switch (opcode) {
    case NOP:
        goto fast_next_opcode;

    case LOAD_FAST:
        x = GETLOCAL(oparg);
        if (x != NULL) {
            Py_INCREF(x);
            PUSH(x);
            goto fast_next_opcode;
        }
        format_exc_check_arg(PyExc_UnboundLocalError,
            UNBOUNDLOCAL_ERROR_MSG,
            PyTuple_GetItem(co->co_varnames, oparg));
        break;

    case LOAD_CONST:
        x = GETITEM(consts, oparg);
        Py_INCREF(x);
        PUSH(x);
        goto fast_next_opcode;
    ...
    ...
```

# Python object code (integer)

```
static PyObject *
int_add(PyIntObject *v, PyIntObject *w)
{
    register long a, b, x;
    CONVERT_TO_LONG(v, a);
    CONVERT_TO_LONG(w, b);
    x = a + b;
    if ((x^a) >= 0 || (x^b) >= 0)
        return PyInt_FromLong(x);
    return PyLong_Type.tp_as_number->nb_add((PyObject *)v, (PyObject *)w);
}

PyDoc_STRVAR(int_doc,
"int(x[, base]) -> integer\n\ \n\
Convert a string or number to an integer, if possible.  A ...  ;

static PyNumberMethods int_as_number = {
    (binaryfunc)int_add,    /*nb_add*/
    (binaryfunc)int_sub,    /*nb_subtract*/
    (binaryfunc)int_mul,    /*nb_multiply*/
    (binaryfunc)int_classic_div, /*nb_divide*/
    (binaryfunc)int_mod,    /*nb_remainder*/
    ...
```

# Data Flow Optimizations

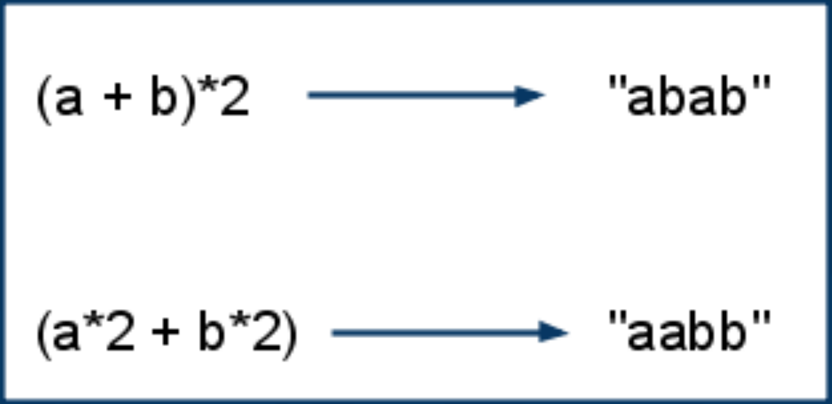
- Data flow optimizations are a set of optimizations that are known to be very effective.
- Typically, this set includes constant propagation, common sub-expression elimination, algebraic simplifications, copy propagation and dead code elimination.
- In general, these optimizations create a more dense code by simplifying expressions and removing dead code.

# Example of Dynamic Typing

```
>>>def add(a, b):  return a + b            # define a new function

>>>add(1, 2)                               # integers
3

>>> add([1,2,3] , [4,5,6])                 # lists
[1,2,3,4,5,6]

>>> add("hello", "world")                  # strings
"hello world"
```

# Failed Data Flow Optimizations

- The following algebraic simplification is valid for integers : (a*2+ b*2)  becomes (a+b) *2
- However, if a and b are strings, it is not valid.



# Optimizing Python

- Applying compiler optimizations is challenging due to Python's dynamic typing system.
- In order to preserve the correctness of the original program, special considerations must be taken even when implementing the most standard optimizations.

# Bytecode Optimization

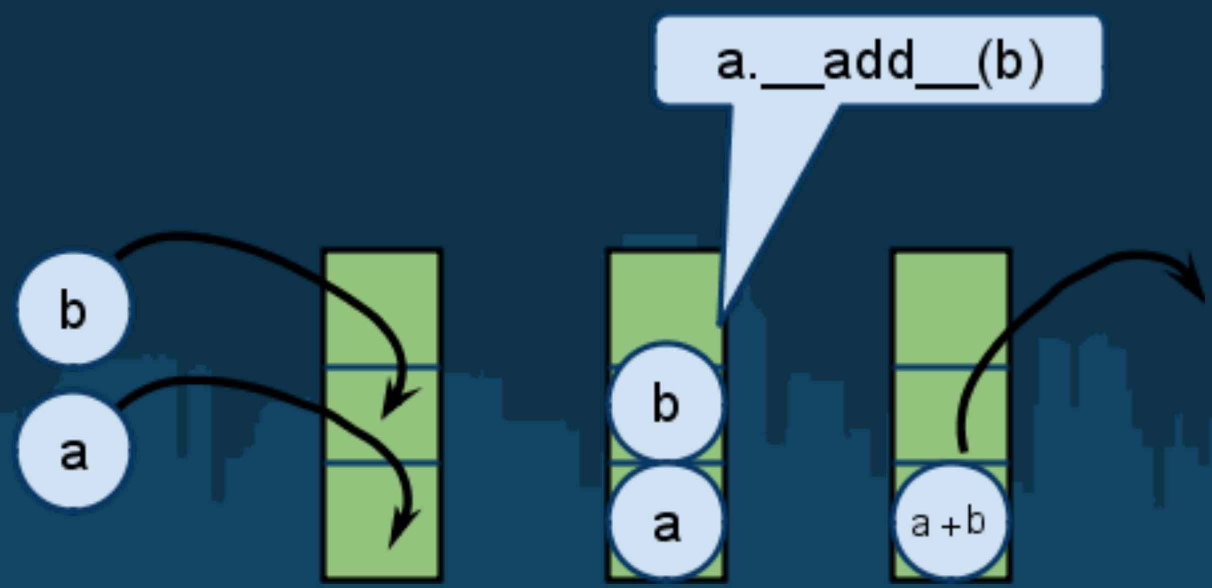
- In this work, we developed optimizations which are unique to dynamic languages.
- We dissasembeled the precompiled Python bytecode and reconstructed into data-dependency trees and optimize them.
- We recovered compiled bytecode files (.pyc files) which contain no AST information.
- We have extended the standard data flow analysis with specific rules to identify cases that are safe.

# Bytecode Structure

- Python uses a stack-based bytecode which is generated from the AST.
- The Python opcodes operate directly on the stack.
- A 'BINARY_ADD' instruction, for example, pops two items from the stack and pushes a single item, which is the sum of the two original items.
- The add instruction tells the lower stack object to call the internal '__add__' method with the other object as a parameter.

# Bytecode Structure

```
LOAD_FAST        0 // "a"
LOAD_FAST        1 // "b"
BINARY_ADD
RETURN_VALUE
```



# Python 'Duck Typing' System

```
class Person():
        def talk(self): print "I am a person"

p = Person()                        # Create a new Person object

def quack(): print "I am a duck"

p.talk = quack                      # Override a function

>>>p.talk()
I am a duck
```

# Unsafe Optimizations and Side Effects

- Consider the following code:

```
for i in xrange(100):
        sum += x*y
```

- In Java, CSE pass would evaluate "x*y" only once.
- However, in Python, a method could be overridden by another method which has a side effect. This method could potentially write a log file every time x is multiplied by y.
- We have no way of knowing in advance what x would do when multiplied by y.

# Our Optimization Passes

# Loop Unrolling

- Loop unrolling is a well-known transformation.
- The first unrolling pass we implemented unrolls numeric loops (xrange loops).
- The unrolling of the 'xrange' iterator is done by changing the 'xrange' constructor when it is created in order to yield values in steps that are greater than one.
- Then, the body of the loop is duplicated and modified to accommodate the changes and execute the next iteration.

# xrange unrolling

Original loop :

```
for i in xrange(n):
  z = i*7 + i*2
```

The iteration range may not be a multiplication of the unroll parameter.

A 'tail' must finish the last iterations.

Transformed loop:

```
m = n-(n % unroll)
# unrolled loop body
for i in xrange(0,m-1,unroll):
   z = i*7 + i*2
   z = (i+1)*7 + (i+1)*2
   ...

# loop tail
for i in xrange(m,n, 1):
  z = i*7 + i*2
```

# Complete Unrolling of Lists

- Using iterators is the 'native' way to iterate over data in Python.
- We have implemented two variants of unrolled iterations.
- The first unroll pass is for lists of known size and content. For example:

```
for x in [1,2,3,4]:
    print x
```

→

```
print 1
print 2
print 3
print 4
```

# Unrolling Iterators of Unknown Size

```
def f(bar):
  sum = 0
  for p in bar:
    sum += p
```

```
def f(bar):
  sum = 0
  it = bar.__iter__()
  try:
    while(1):
      p1 = it.next()  ;  i = 1
      p2 = it.next()  ;  i = 2
      p3 = it.next()  ;  i = 3
      p4 = it.next()  ;  i = 4
      sum += p1+p2+p3+p4
  Except StopIteration:
     # handle tail if needed
           based on value of i
     if i > 1: ...
     if i > 2: ...
```

# Inlining of Functions

- Python function calls are time-consuming in comparison to other compiled languages.
- Inlining is a transformation where a call to a function or a method is replaced by its body, and the called arguments are inserted into the body of the loop.
- Each return call in the original inlined function is translated into a 'store' and 'jump to end' set of opcodes.

# Inlining example

```
def f(x):
 v = 5
 if (x==9):
  return x + v
 return x*3

def g():
 sum = 0
 for i in xrange(n):
  sum += f(7+i)
 return sum
```

```
def new_g():
 sum = 0
 for i in xrange(n):
 $inline_x = 7+i
 $local_v = 5
 if ($inline_x==9):
       _inline_return=x+$local_v
       *goto END_TAG
 _inline_return = x*3
 *goto END_TAG
END_TAG:
sum += _inline_return
return sum
```

# Inlining and Unrolling may assist oneanother

- These transformations help to reduce the 'type uncertainty'.
- Inlined functions have access to type information from the calling function. Parameters may become constants.
- Complete unrolling of constant lists gives concrete knowledge of type.

# Example

```
def func_2():
  t = 123
  for func in [F1,F2,F3]:
    func(t)
```

⇒

```
def func_2():
  t = 123
  F1(t)
  F2(t)
  F3(t)
```

```
def func_9(L):
    sum = 0
    for i in L:
        sum += L

...
func_9([1,2,3,4])
...
```

⇒

```
...
1 + 2 + 3 + 4
...
```

# User-Guided Optimizations

- Some of the possible optimizations are not type-safe.
- We allow the user to specify which methods should be optimized by Python 'decorators' which are source code annotations.
- This method can be further extended to indicate other safety features.

@NumericCode

```
def func(x, y):
    return x*2 + y*2
```

# Bytecode Optimizations

## Basic Block Optimization

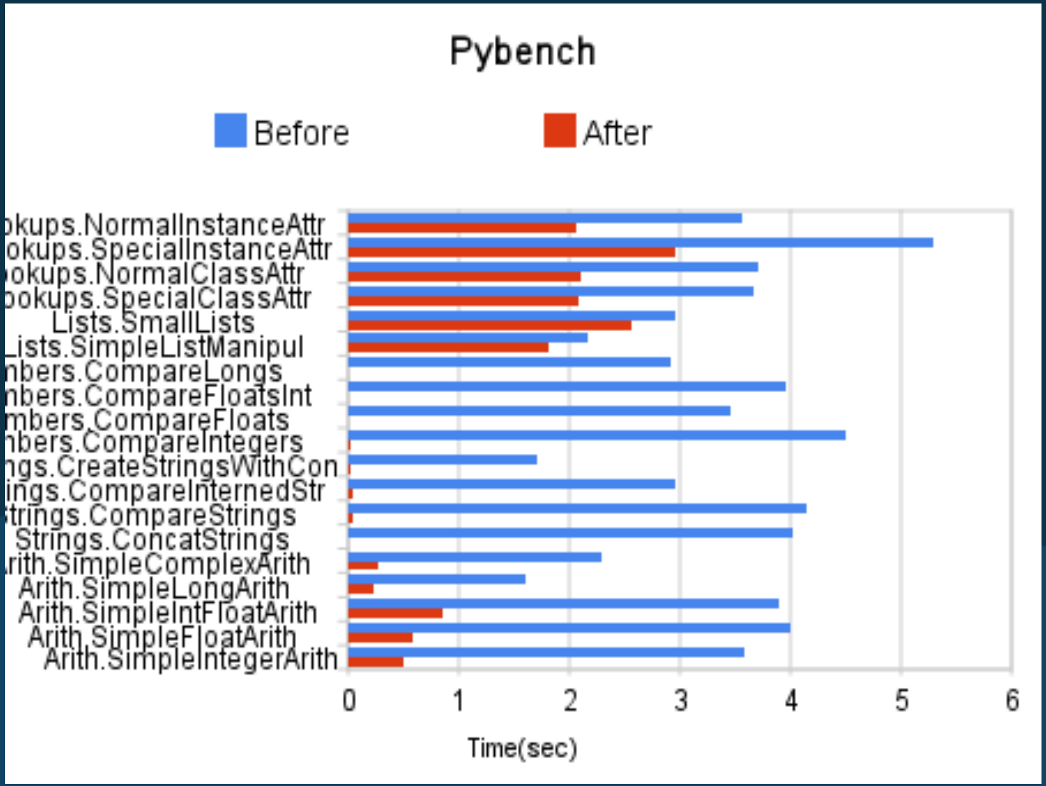
- Value propagation
- Constant propagation
- Common sub-expression elimination
- Loop invariant
- Strength reduction
- Memory optimizations
  - Load elimination
  - Store elimination
- Global variable cache

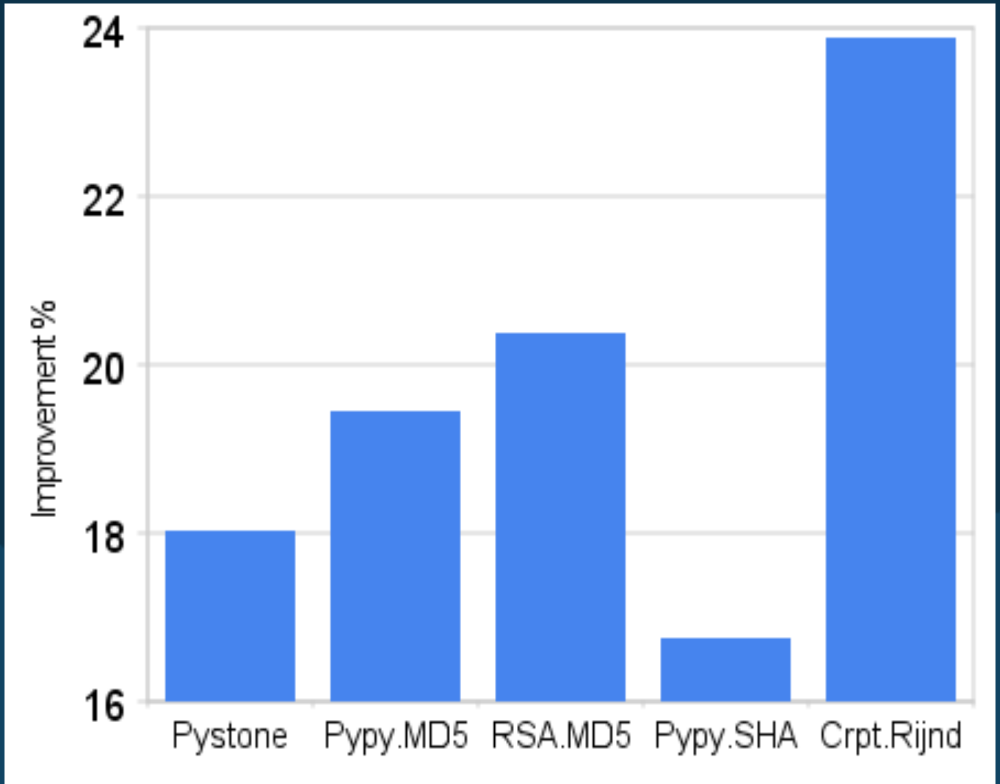
## CFG Optimizations

- Loop Unrolling:
  - Complete unroll
  - Iterator unroll
  - Range unroll
  - Random access transformation
- Method Inlining

# Benckmarks

- The proposed optimizations were tested using several benchmarks: Pystone, Pybench, Crypto, PyPy and several micro tests.
- Results show significant improvement.



# Thank you. Questions ?

# Backup Slides