The Effects of Unrolling and Inlining on Python Bytecode Optimizations

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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

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.

(a + b)*2 → "abab"

(a*2 + b*2) → "aabb"

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

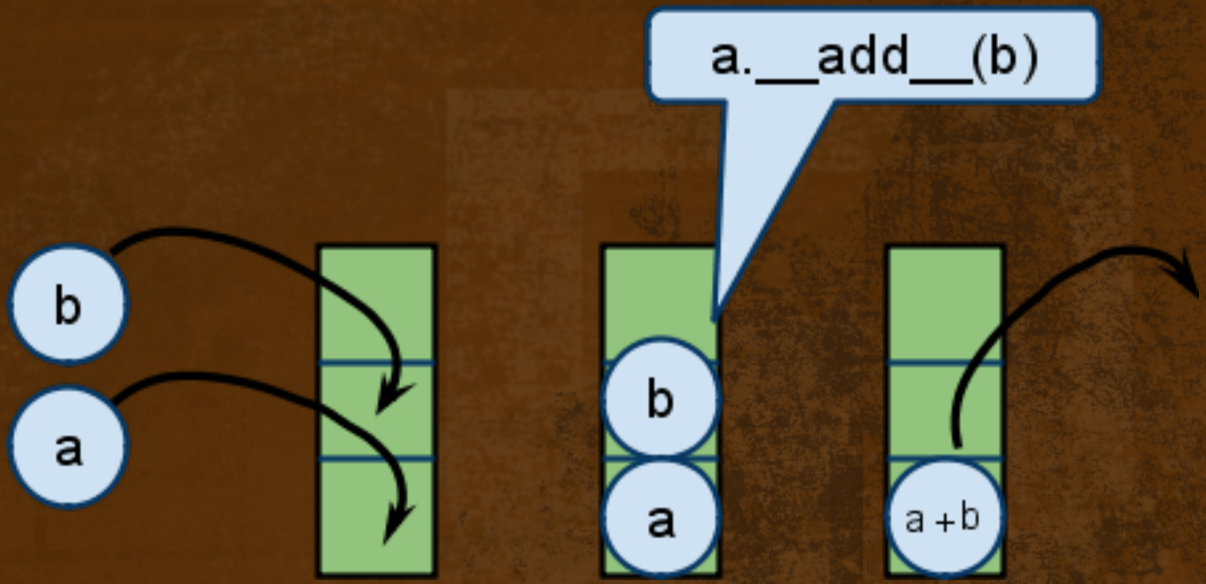
- In this work, we developed optimizations which are unique to dynamic languages.
- We dissasembeled the precompiled Python bytecode and reconstructed into data-dependency trees and optimize them.
- We recovered compiled bytecode files (.pyc files) which contain no AST information.
- We have extended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

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 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)
```

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

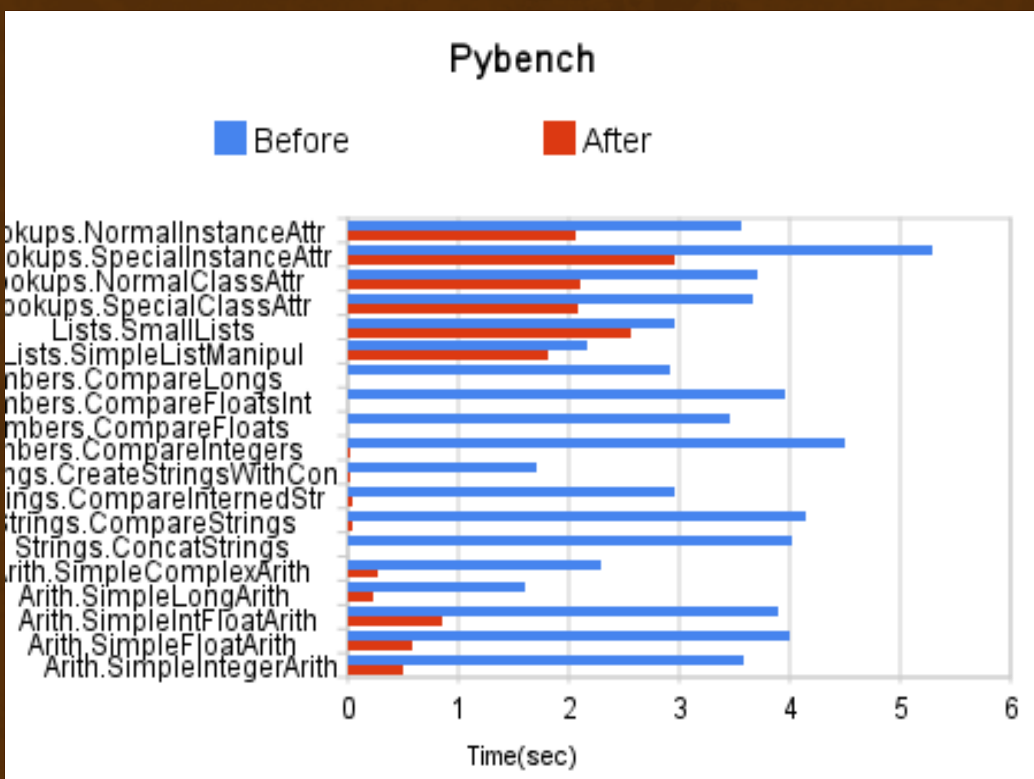
- Value propagation
- Constant propagation
- Common sub-expression elimination
- Loop invariant
- Strength reduction
- Memory optimizations
  - Load elimination
  - Store elimination
- Global variable cache

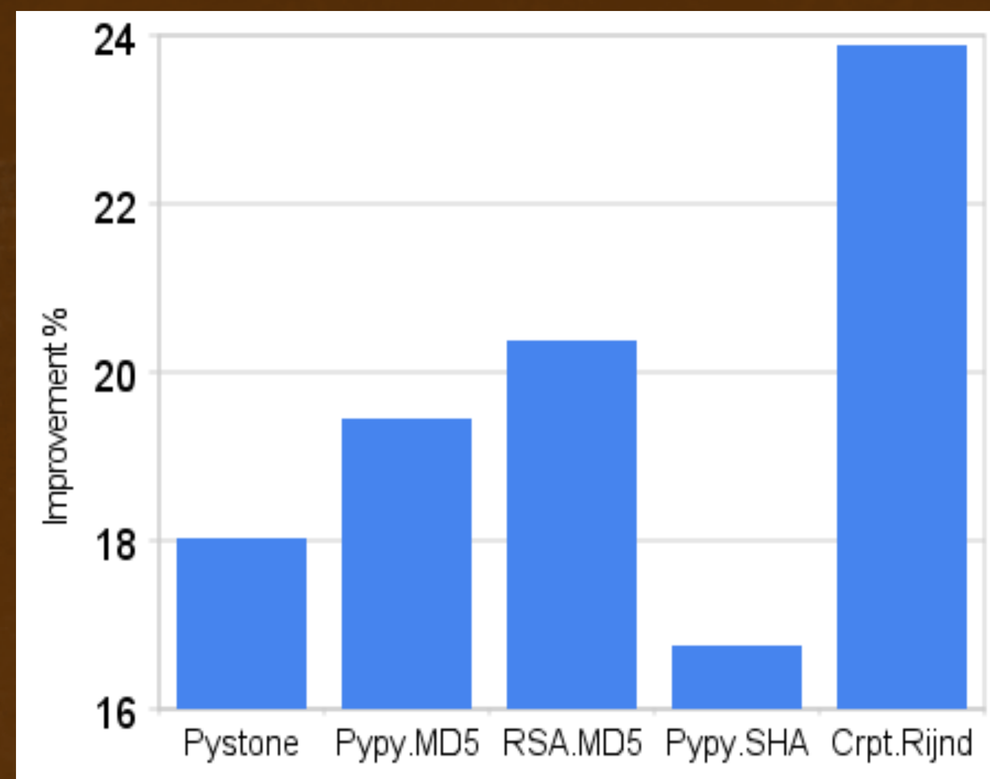
CFG Optimizations

- 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

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
```

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
```