Starkiller: A Static Type Inferencer and Compiler for Python

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June 8, 2004

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This talk in 60 seconds

- Starkiller is a static type inferencer and compiler for Python
- It has one goal: speed
- We get speed by moving as many decisions as possible from runtime to compile time
- Starkiller covers the entire language except for exec/eval/dynamic module loading
- An early prototype has been built and benchmarked but much work remains to be done

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Or, more formally

I. Motivation
II. Why Python is slow
III. Starkiller type inference
IV. Starkiller compilation
V. Results and Challenges
VI. Questions

Starkiller != Psyco

- Starkiller and Psyco represent opposite ends of the optimization spectrum
- Both generate specialized versions of code
- Psyco works entirely at runtime analyzing patterns in the dynamic execution
- Starkiller works entirely statically
- Optimal performance requires both be-cause they solve different problems

I. Motivation

- The end of the world
- Saving the world
- Python is slow
- Python is not slow
- Yes it is

The end of the world

- Software sucks. A lot.
  - too buggy, too dangerous
  - too expensive and slow to build
  - too pervasive
  - internet makes it all worse
  - bad software kills people
  - it is going to get worse before it gets better

Saving the world: Python

- Use a High level language
  - fewer lines of code needed
  - fewer lines mean
    - fewer bugs
    - less time/money to build
  - make the worst brain damage impossible
    - no buffer overflows in Python programs
- But Python cannot take over the world
  - no continuations
  - no macro system out of the box
  - too slow

Python is slow

- I've done everything with Python
  - High speed network servers
  - Databases
  - Statistical natural language processing
  - Scientific computing
  - Signal and Image processing
  - AI type job schedulers
- And its been slow

Python is not slow!

- You're a heretic!
- Most apps spend all their time waiting
  - on a socket (network servers)
  - on a slow human (GUIs)
  - on Oracle (databases)
  - on disk IO (most things)
- Fast libraries written in C/C++
- Numeric!
- Die infidel, die!

Yes, Python is slow

- I've used all those lines myself
- I even believe them
- They're relevant most of the time
- But they don't change the fact that Python is slow
- Sometimes, straightforward Python code is much clearer and easier to write than fighting with Numeric
- For the 15% of apps where speed matters, pure Python can't do the job alone
- I don't want to use crappy C/C++

II. Why Python is slow

- The VM is not the (entire) problem
- Dynamic binding
- Numeric boxing
- Dynamic dispatch
- And a cast of thousands...
- But its still better than Java

Those who do not learn from history...

- p2c was a python to C compiler emerged circa 1998
- It generated (lots of) C code that made the same calls into the Python runtime that the VM would
- But it compiled down to machine code!
- So it must be super fast!
- Super == 10-15%
- A lesson: the VM is not a performance bottleneck (yet)

Where should I jump now?

- Quick! Inline the function f in the code below!
- A lesson: dynamic binding seemed like such a good idea at the time...

```
if random() > 0.5:
  def f(x): return x + 1
else:
  def f(x): return x - 1
print map(f, range(4096))
```

Trapped in a box

- Numbers are heap allocated objects referenced by pointer; they are neither special nor unique snowflakes
- New coercion rules make life even worse: integer overflow silently coerces to longs
- A lesson: boxing replaces fast register ALU ops with multiple dereferences of distant (read: not in cache) memory

Our old (performance killing) friend...

- Dynamic dispatch has a long history of ruining performance in OOP languages
- cf virtual/nonvirtual methods in C++, sealing in Dylan
- By postponing until runtime decisions about which bit of code is executed at a polymorphic call site, we lose the ability to optimize well
- You cannot inline code when you don't know what it is

More Pythonic "fun"

- Multiple inheritance
- First class functions with lexical scoping
- No declarations or manifest types
- No structure size/shape information
- getattr and setattr functions allow anyone to get/set any attribute at runtime
- Dynamic inheritance relations
- Dynamic class membership

```
x = table()
x.__class__ = chair
assert isinstance(x, chair)
```

Other languages suck

- Java sucks beyond all measure and comprehension
- C++ and Java suffer the same performace problems as Python when it comes to dynamic dispatch
- Dynamic dispatch prevents the compiler from using all the cool optimizations like inlining
- Inlining is the canary in the coal mine: if you can't inline, you probably can't do loop hoisting, strength reduction, etc.

III. Starkiller type inference

- Context
- More context
- Basic type inference algorithm
- A quick example
- The big 3 problems
  - parametric polymorphism
  - data polymorphism
  - foreign code

Making Python fast

- Speed == laziness: stop doing work
- Work refers to all the runtime choice points the Python VM has to perform
  - whenever the VM has to find what code to execute next
  - whenever the VM has to check operands to ensure they are of the correct type
- We can eliminate many of those checks using static analysis, specifically type inference

Finding the right pigeon hole

- Compiling to C++ is not enough (cf p2c)
- Need static type inference to eliminate dynamic binding and dispatch
- Starkiller compliments rather than replaces CPython
- Covers the entire language except eval, exec, and dynamic module loading
- Not all run time choice points can be eliminted, but many can

Starkiller type inference

- Based on Ole Agesen's Cartesian Product Algorithm (see his Stanford thesis)
- Represent Python programs as dataflow networks
- Nodes correspond to expressions and have a set of concrete types those expressions can achieve at runtime
- Constraints connect nodes together and enforce a subset relation between them
- Types flow along constraints

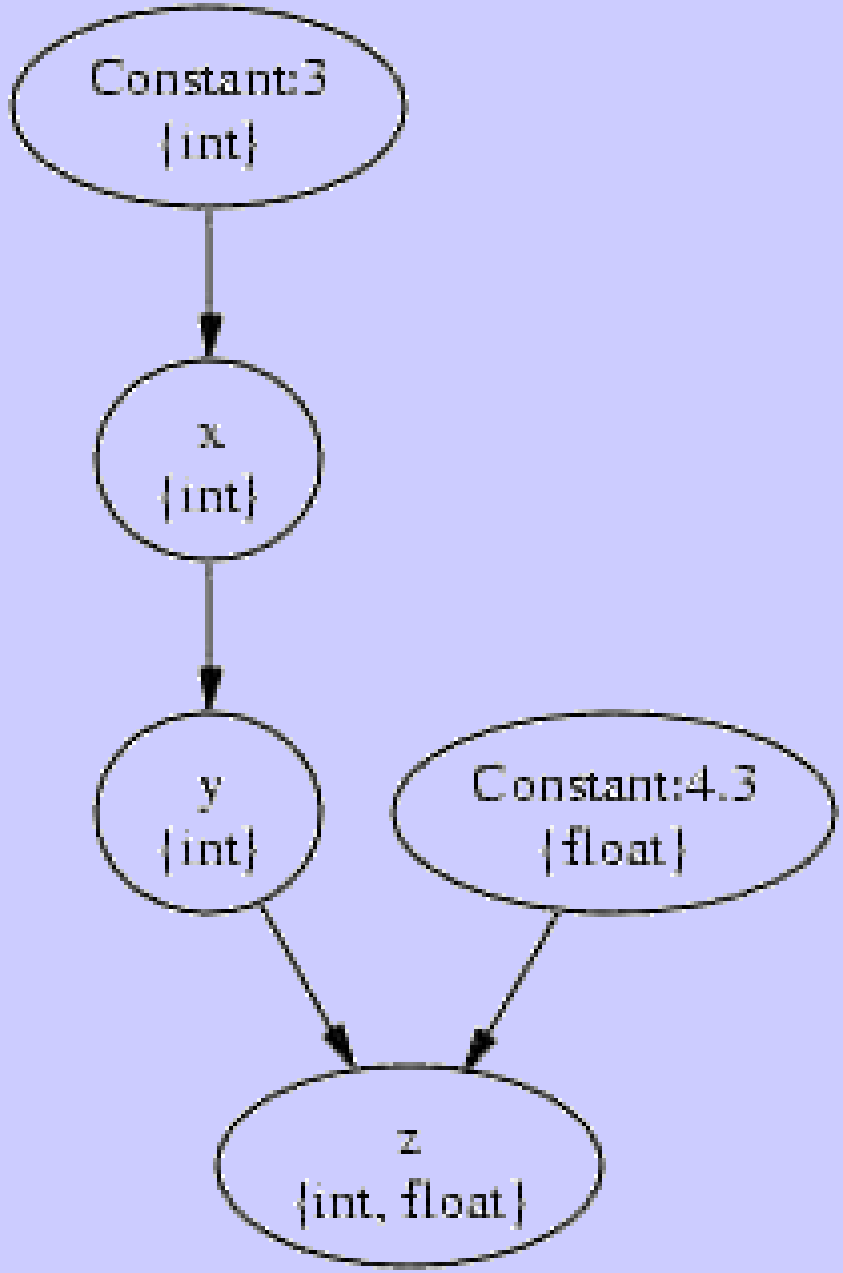
Ex-girlfriends say I'm insensitive

- Starkiller's type inference algorithm is flow-insensitive
- It has no notion of time
- Code like x = 3; doSomething(x); x = 4.3; doSomething(x) will suffer loss of precision
- I don't care. I'm insensitive, remember?

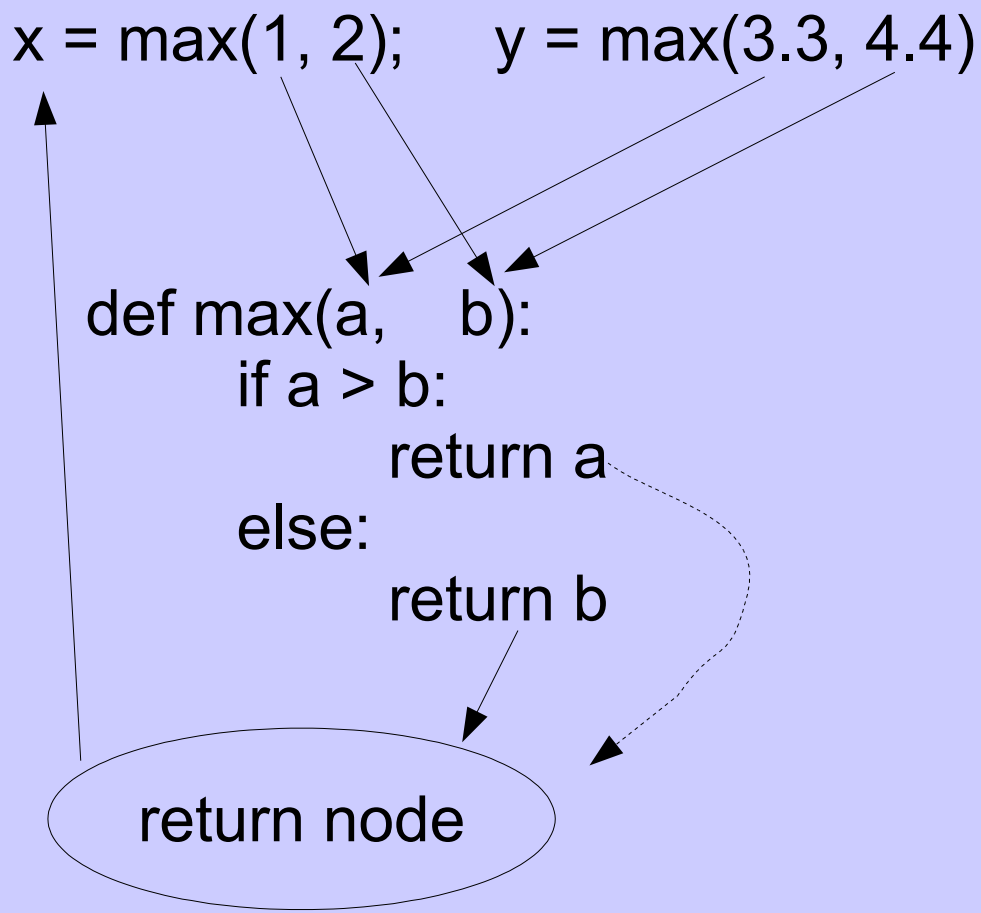
Type inference in action

- A simple example

x = 3
y = x
z = y
z = 4.3



Parametric polymorphism destroys precision



Fighting parametric polymorphism

- bad
  - analyze a fresh copy (a template) of the function for each call site
  - restricted version: only create new analysis templates for the first N layers of call stack
- good: CPA
  - create one template for each monomorphic argument lists and reuse them between call sites
  - at each call site, take the cartesian product of argument type sets to generate a list of monomorphic argument lists
  - connect the call site to one template for each monomorphic argument list

Data polymorphism kills precision

- Consider the code

```
class a: pass
x = a()
y = a()
x.attr = 2
y.attr = 5.5
```

Dealing with data polymorphism

- Model instance types as collections of polymorphic types
- Create a new (polymorphic) type for each call site, but don't flow it through the net-work
- Instead, take the cartesian product of the type's state and use that to generate monorphic state types and flow those through the network

More data polymorphism

- Class definition works just like function definition!
- Instances work in the same way as classes!
- Calling a class triggers the creation of an instance definition node
- ID nodes are the repository for the polymorphic state of an instance
- They generate monomorphic instance state types and send them into the world
- The tricky part is reusing function templates

Functions and definitions

- A Python function defintion creates a first class object at runtime
- Function objects can capture variables defined in their lexical parent(s)
- Starkiller models function definition using a function definition node that has constraints from all default args and expressions the function closes over
- The definition node takes the cartesian product and generates monomorphic function types

Foreign Code

- Type inference cannot see into extension modules
- We could perform type inference on C/C++/Fortran...therein lies doom
- Starkiller gives extension writers a minilanguage for declaring the type inference properties of their extensions
- Most extensions are real simple: int(x) always returns an integer
  - C makes it so hard to be flexible that C libraries often have simple types

Foreigner code, living among us, plotting against us!

- Some extensions are unspeakably compli-cated
  - they might call arbitrary functions
  - they might mutate their arguments or some ob-ject that is part of global state
- The external type description language is really Python
  - External type descriptions run as extensions of the Starkiller type inferencer
  - You can use them to raise the dead

IV. Starkiller compilation

- The basics
- Data model
- Closures
- Fast polymorphic dispatch
- Dynamic attributes
- Exceptions
- Generators

Compilation preliminaries

- Functions/classes/modules are represented by C++ objects that can be passed around
- Each function/method template gets compiled as a separate monomorphic block of code
- Since modules are executed exactly once, their attributes are all static
- Conservative GC thanks to Boehm
- No relation between Python and C++ object models

Data model

- Numbers are automatically unboxed
- Everything else is heap allocated and passed by reference
- Container datatypes are built out of STL componants and are type specific

Closures

- Normally, variables are stack allocated
- But, for variables referenced by inner functions, Starkiller allocates them specially from a heap allocated MiniStackFrame
- An MST is common space that the original function and all of its inner functions can safely refer to, even after the original function returns
- The MST persists as long as it remains referenced thanks to the magic of GC

Fast Polymorphic dispatch

- We cannot eliminate all polymorphic dis-patch
- Usually implemented with an indirect branch through a class pointer
  - very slow on modern hardware
- For the common case where there are few possibilites, we exploit the lack of eval to speed things up
- Use gcc's computed-goto extension plus minimal hashing to jump directly into the code without a branch

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Dynamic attributes

- getattr is easy to optimize:
  - use perfect hashing (plus extra if setattr)
- setattr contaminates objects
  - any attribute can be of the type assigned in the setattr call

Exceptions

- All Starkiller defined functions/methods can throw InternalRuntimeError
- A Python try/except block is translated into a C++ try/catch block that dispatches on the exception thrown
- Python library code based on C++ components translate native C++ exceptions into their Python equivalent

Generators

- Generators become functions that return instances of a generator object
- Variables in the generator body become attributes of the object
- yield statements get replaced by code that saves the label corresponding to the next statement to be executed and then returns
- On each invocation of the generator object, control jumps to the label last saved

V. Results and Challenges

- Current status
- Ownership
- Benchmark results
- Challenges (hard)
- Future work (easy)
- Development plan

Where are we now?

- Type inferencer is mostly implemented
  - almost all of the hard parts are done
  - most of the unfinished work is boring detail
- Compiler is in the very early stages
  - a prototype works on simple code that doesn't push it too hard
  - no runtime system, no builtin types except int and float
- Release in a few weeks
  - Compiler/inferencer will be GPL, runtime BSD

Suckling on the government teat

- Who owns Starkiller? MIT!
- Who paid for Starkiller's development?
- You did! Pat yourselves on the back!
- Thank you taxpayers
- “So, that means that you are a whore, MIT is your pimp, and DARPA is the john who likes to play rough. . .Hey Mike, is there anything you won't do for money?”
- A secret: don't tell DARPA I'm not building the sun destroying weapon they think I am

Justify your existance

- Very preliminary benchmark with the proto-type compiler and type inferencer
- All benchmarks are lies
- This one is pathological
- Call the factorial and fibonacci functions
- In a loop. Over and Over.
- CPython completion time: 18:37
- Starkiller completion time: 0:15
- Speedup: 60

Challenges (hard)

- Template shadowing
- False numeric polymorphism
- Partial evaluation
- Overflow coercion
- Free threading
- Restoring eval functionality

Future work (easy)

- Generate typed intermediate language
- Static error detection
- Range analysis to eliminate overflow checks
- Escape analysis for stack allocation
- Automatic range to xrange conversion
- Automatic vectorization and loop fusion

Development Plan

- ✔ Finish thesis and graduate
- ✗ Find job and avoid poverty
- ✔ Find new girlfriend
- ✗ Hack on Starkiller
  - finish inferencer & optimizer
  - do all the easy stuff (future work)

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VI. Questions?

- Reasons for destroying the sun
  - It reduces our dependance on foreign oil
  - It is unpatriotic
  - The sun is responsible for global warming
  - DARPA say sun bad. Must kill sun or lose fund-ing
  - The pale yellow face mocks us, keeps us from hearing the machine
  - It burns, it burns, we hatesss it!
- There is only one logical conclusion: we must destroy the sun!

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