Gradual Typing for Python

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Gradual Typing

- Static and dynamic type systems have complimentary strengths.
- Static typing provides full-coverage error checking, efficient execution, and machine-checked documentation.
- Dynamic typing enables rapid development and fast adaption to changing requirements.
- Why not have both in the same language?

Java

Python

Goals for gradual typing

- Treat programs without type annotations as dynamically typed.
- Programmers may incrementally add type annotations to gradually increase static checking.
- Annotate all parameters and the type system catches all type errors.
- The type system and semantics should place a minimal implementation burden on language implementors.

Implicit coercions to/from dynamic

```
class Point:
    def __init__(self):
        self.x = 0
    def move(self, dx):
        self.x = self.x + dx

a = 1
p = Point()
p.move(a)
```

Parameters with no type annotation are given the dynamic type.

Implicit coercions to/from dynamic

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dynamic

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dynamic

int x int → int

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p.move(a)
```

dynamic

int

int ⇒ dynamic

Parameters with no type annotation are given the dynamic type.

Detecting static type errors

```
class Point:
    def __init__(self):
        self.x = 0
    def move(self, dx : int):
        self.x = self.x + dx

a = 1
p = Point()
p.move(a)
p.move("hi")
```

Detecting static type errors

int

```
class Point:
    def __init__(self):
        self.x = 0
    def move(self, dx : int):
        self.x = self.x + dx

a = 1
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p.move("hi")
```

Detecting static type errors

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int

string

Detecting static type errors

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class Point:
    def __init__(self):
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    def move(self, dx : int):
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a = 1
p = Point()
p.move(a)
p.move("hi")
```

int

string

~~string ⇒ int~~

Type System Primer

Given an expression e, a type T, and a dictionary Γ that maps variables to types, the notation

$$\Gamma \vdash e : T$$

roughly means

$$T = \text{typecheck}(\Gamma, e)$$

and the horizontal bar notation:

$$\frac{P_1 \qquad P_2 \qquad P_3}{Q}$$

means

Q if P_1 and P_2 and P_3

Gradual Typing: replace equality with consistency (~)

$$\frac{\Gamma \vdash e_1 : \mathrm{object}\{\ldots,\ m : S \rightarrow T, \ldots\} \qquad \Gamma \vdash e_2 : S' \qquad S' \sim S}{\Gamma \vdash e_1.m(e_2) : T}$$

Gradual Typing: replace equality with consistency (~)

$$\frac{\Gamma \vdash e_1 : \mathrm{object}\{\ldots,\ m : S \rightarrow T, \ldots\} \qquad \Gamma \vdash e_2 : S' \quad S' \sim S}{\Gamma \vdash e_1.m(e_2) : T}$$

The consistency relation

- Definition: a type is ***consistent***, written ~, with another type when they are equal in the places both are defined.
- Examples:

$\text{int} \sim \text{int}$ $\quad$ $\text{int} \not\sim \text{bool}$ $\quad$ $\text{dyn} \sim \text{int}$ $\quad$ $\text{int} \sim \text{dyn}$

$\text{object}\{x:\text{int}\rightarrow\text{dyn},\ y: \text{dyn}\rightarrow\text{bool}\} \sim \text{object}\{y:\text{bool}\rightarrow\text{dyn},\ x:\text{dyn}\rightarrow\text{bool}\}$

$\text{object}\{x:\text{int}\rightarrow\text{int},\ y:\text{dyn}\rightarrow\text{bool}\} \not\sim \text{object}\{y:\text{dyn}\rightarrow\text{bool},\ x:\text{bool}\rightarrow\text{int}\}$

$\text{object}\{x:\text{int}\rightarrow\text{int},\ y:\text{dyn}\rightarrow\text{dyn}\} \not\sim \text{object}\{x:\text{int}\rightarrow\text{int}\}$

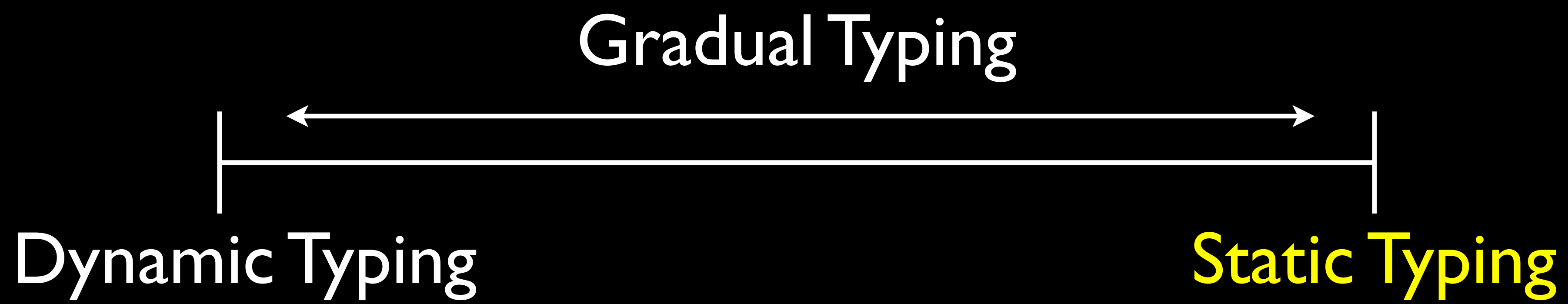
Consistency

$$\frac{}{\text{dynamic} \sim T} \qquad \frac{}{T \sim \text{dynamic}}$$

$$\frac{S_1 \sim T_1 \qquad S_2 \sim T_2}{S_1 \rightarrow S_2 \sim T_1 \rightarrow T_2}$$

$$\frac{\begin{array}{c}\text{dom}(\Gamma_1) = \text{dom}(\Gamma_2) \\ \text{for all x in dom}(\Gamma_1).\ \Gamma_1(x) = T_1 \text{ and } \Gamma_2(x) = T_2 \\ \text{implies } T_1 \sim T_2\end{array}}{\text{object}\{\Gamma_1\} \sim \text{object}\{\Gamma_2\}}$$

Gradual Typing for Python



Note: type annotation syntax based on Python 3k

A Static Type System for Python

- Nominal vs. Structural Types
- Subtyping vs. Matching
- Generics with match bounds

Nominal vs. Structural

```
class Thing1:
    def __init__(self):
        self.x = 0
    def move(self, dx : int):
        self.x = self.x + dx

p = Thing1()
```

```
class Thing2:
    def __init__(self):
        self.x = 0
    def move(self, dx : int):
        self.x = self.x + dx

p = Thing2()
```

Nominal vs. Structural

```
class Thing1:
    def __init__(self):
        self.x = 0
    def move(self, dx : int):
        self.x = self.x + dx

p = Thing1()
```

Thing1

```
class Thing2:
    def __init__(self):
        self.x = 0
    def move(self, dx : int):
        self.x = self.x + dx

p = Thing2()
```

Thing2

Nominal vs. Structural

```
class Thing1:
    def __init__(self):
        self.x = 0
    def move(self, dx : int):
        self.x = self.x + dx

p = Thing1()
```

object{move: int→none}

Thing1

```
class Thing2:
    def __init__(self):
        self.x = 0
    def move(self, dx : int):
        self.x = self.x + dx

p = Thing2()
```

object{move: int→none}

Thing2

Subtyping vs. Matching

- There's two approaches to structural typing
- Structural Subtyping: thoroughly explored by Luca Cardelli and many others.
- Matching: invented by Kim Bruce, similar to OCaml's approach to objects, less well explored.

The Problem with Subtyping: Binary Methods

```
class Point:
    def __init__(self : Point):
        self.x = 0.0; self.y = 0.0
    def equal(self : Point, other : Point) -> bool:
        return x == other.x and y == other.y

class ColorPoint(Point):
    def __init__(self : ColorPoint):
        Point.__init(self)
        self.c  = ‘red’
    def equal(self : ColorPoint, other : ColorPoint) -> bool:
        return Point.equal(self, other) and self.c == other.c
```

The Problem with Subtyping: Binary Methods

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class Point:
    def __init__(self : Point):
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```

ColorPoint = object{__init__ : () -> ColorPoint, equal: ColorPoint -> bool }

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   def equal(self : ColorPoint, other : ColorPoint) -> bool:
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```

compile error,
covariance disallowed

ColorPoint = object{__init__ : () -> ColorPoint, equal: ColorPoint -> bool }

The Problem with Subtyping: Binary Methods

```
class Point:
    ...

class ColorPoint(Point):
    ....
    def equal(self : ColorPoint, p : Point) -> bool:
        other = dynamic_cast<|ColorPoint|>(p)
        return Point.equal(self, other) and self.c == other.c

class Point3D(Point):
    ...

p1 = ColorPoint()
p2 = Point3D()
p1.equal(p2) // no compile error, instead get run-time error, bad!
```

ew!

Matching & Binary Methods

```
class Point:
  def __init__(self : selftype):
    self.x = 0.0; self.y = 0.0
  def equal(self : selftype, other : selftype) -> bool:
    return x == other.x and y == other.y

class ColorPoint(Point):
  def __init__(self : selftype):
    Point.__init(self)
    self.c  = 'red'
  def equal(self : selftype, other : selftype) -> bool:
    return Point.equal(self, other) and self.c == other.c
```

OK!

Look Ma, no dynamic cast!

Matching & Binary Methods

```
p1 = ColorPoint()
p2 = ColorPoint()
p1.equal(p2) // OK!

p3 = Point3D()
p1.equal(p3) // compile error, good!
```

Matching: Under the Hood

$$\frac{\Gamma \vdash e : T \quad T \mathrel{<\#} \text{object}\{m : S\}}{\Gamma \vdash e.m : [\text{selftype}{:=}T]S}$$

Matching + Consistency

$$\frac{\text{dom}(\Gamma_2) \subseteq \text{dom}(\Gamma_1) \qquad \text{for all } x \text{ in dom}(\Gamma_2).\ \Gamma_2(x) = T_2 \text{ and } \Gamma_1(x) = T_1 \text{ implies } T_1 \sim T_2}{\text{object}\{\Gamma_1\} <\# \text{ object}\{\Gamma_2\}}$$

Generics

- Lots of Python code is polymorphic
- Generics are needed to provide enough flexibility in the type system to handle this.
- (Of course, you can always fall back on using type dynamic when you want to.)

Generic Functions

```
def pow<| T |>(f : fun(T,T), n : int) -> fun(T,T):
    def pow_f(x : T):
        while n > 0:
            x = f(x); n -= 1
        return x
    return pow_f

def add1(x : int) -> int: return x + 1

add5 = pow<|int|>(add1, 5)
add5 = pow(add1, 5)
```

Generic Functions

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def pow<| T |>(f : fun(T,T), n : int) -> fun(T,T):
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explicit instantiation

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add5 = pow(add1, 5)
```

explicit instantiation

implicit instantiation

Generic Classes and Methods

```
class Point<|T|>:
    def __init__(self, x : T, y : T):
        self.x = x; self.y = y

    def map<|U|>(self, f : fun(T,U)) -> Point<|U|>:
        return Point<|U|>(f(self.x), f(self.y))

>>> p = Point<|int|>(1, 3)
>>> p.map(float)
Point<|float|>(1.0, 2.0)
```

Generic Classes and Methods

```
class Point<|T|>:
    def __init__(self, x : T, y : T):
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>>> p = Point<|int|>(1, 3)
>>> p.map(float)
Point<|float|>(1.0, 2.0)
```

Match-bound Generics

```
typealias Iterator = forall(T, object({next: method(selftype, T)}))
typealias Iterable = forall(T, It <# Iterator<|T|>,
                                    object({__iter__: method(selftype, It) }))

def mymap<| T, R, It <# Iterable<|T|> |>( f :  fun(T, R), l : It) -> list<|R|>:
    res = list<|R|>()
    for x in l: res.append(f(x))
    return res

def doubledown(a : int) -> int:
    return 2 * a

alist = [1,2,3]
mymap(doubledown, alist)
```

Match-bounds: Under the Hood

$$\frac{\Gamma \vdash e : \forall\,(X_1 \mathrel{<\#} T_1, \ldots, X_n \mathrel{<\#} T_n).\ R \qquad S_1 \mathrel{<\#} T_1,\ \ldots,\ S_n \mathrel{<\#} T_n}{\Gamma \vdash e\langle|S_1, \ldots, S_n|\rangle : [X_1 := S_1, \ldots, X_n := S_n]\ R}$$

Future Work

- Public release of the type checker
- Corpus analysis to test whether our type system is a good fit for Python programs
- Integration with Jython
- Implement run-time type checks
- Compiler optimizations to take advantage of the type information provided by gradual typing

Conclusion

- Gradual typing integrates static and dynamic typing in the same language, based on a new relation on types called consistency
- For Python, we hope a type system based on structural matching and generics will provide a good fit.
- To see a demo, find Joe during a break, or better yet, over a beer!

Why add types to a dynamic language?

- Large applications suffer from “dynamicitis”
- Values of many different kinds flow through the same point within the system. Checking code appears everywhere.
- E.g., in Django, there are places where True, ‘t’, , ‘T’, ‘True’, and 1 are all potential values that must be dealt with
- Annotate interfaces with types to establish invariants and document expectations

Why not ML-style inference?

- Inference alone does not provide the flexibility of dynamic typing.
- Combining inference and gradual typing may provide the best of both worlds.
- See *Gradual Typing and Unification-based Inference* by Siek and Vachharajani.