A Practical, Typed Variant Object Model
Or, How to Stand On Your Head and Enjoy the View

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Object Encodings

- Record-Based Encodings
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  - Foundation for traditional OO languages
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  - Easier to type
Object Encodings

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- Common [Cardelli ’84] [Cook ’89] . . .
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- Variant-Based Encodings
Object Encodings

- **Record-Based Encodings**
  - Foundation for traditional OO languages
  - Easier to type
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- **Variant-Based Encodings**
  - Actor-based languages (Erlang)
Object Encodings

- Record-Based Encodings
  - Foundation for traditional OO languages
  - Easier to type
  - Common [Cardelli ’84] [Cook ’89] …

- Variant-Based Encodings
  - Actor-based languages (Erlang)
  - Harder to type
Record-Based Object Encoding

(Scala)
1 object a {
2 }

(OCaml)
1 let a = {
2 }
Record-Based Object Encoding

(Scala)
1 object a {
2   val v = 5
3 }

(OCaml)
1 let a = {
2   v = ref 5
3 }

- Object fields are record fields
Record-Based Object Encoding

(Scala)

```scala
object a {
  val v = 5
  def mth(x: Int) : Int = { x + v }
  def foo(x: Unit) {}
}
```

(OCaml)

```ocaml
let a = {
  v = ref 5;
  mth = fun self ->
      fun x -> x + ! self.v;
  foo = fun () -> ()
}
```

- Object fields are record fields
- Methods are fields with functions
Object fields are record fields
Methods are fields with functions
Invocation projects methods
Object fields are record fields
Methods are fields with functions
Invocation projects methods
We ignore self-hiding for now.
Duality

Variants ⇐ ⇒ Records
Variant-Based Encoding

(Scala)

```scala
object a {
  ...
}
```

(OCaml)

```ocaml
let a = fun msg ->
  match msg with
  ...
```
Variant-Based Encoding

(Scala)

1 object a {
2   val v = 5
3 }

(OCaml)

1 let v = ref 5 in
2 let a = fun msg ->
3   match msg with
4     ...

- Fields by closure
Variant-Based Encoding

**(Scala)**

```scala
object a {
  val v = 5
  def mth(x: Int): Int = { x + v }
  def foo(x: Unit) {}
}
```

**(OCaml)**

```ocaml
let v = ref 5 in
let a = fun msg ->
  match msg with
  | 'mth (self, x) ->
    x + ! self.v
  | 'foo () -> ()
```

- Fields by closure
- Methods are message handling cases
Variant-Based Encoding

(Scala)

```scala
object a {
  val v = 5
  def mth(x: Int) : Int = { x+v }
  def foo(x: Unit){}
}

a.mth(3)
```

(OCaml)

```ocaml
let v = ref 5 in
let a = fun msg ->
  match msg with
  | 'mth (self,x) -> x+v
  | 'foo () -> ()
in a ('mth (a,3))
```

- Fields by closure
- Methods are message handling cases
- Invocation is just message passing
Variant-Based Encoding

(SCALA)

```scala
object a {
  val v = 5
  def mth(x: Int) : Int = { x+v }
  def foo(x: Unit) {}
};
a.mth(3)
```

(OCAML)

```ocaml
let v = ref 5 in
let a = fun msg ->
  match msg with
  | 'mth (self,x) ->
    x+!self.v
  | 'foo () -> ()
in a ('mth (a,3))
```

- Fields by closure
- Methods are message handling cases
- Invocation is just message passing
- But this doesn’t typecheck!
Typing Variant Destruction

```
1 match v with
2   | 'Odd y -> y mod 2 = 1
3   | 'Dbl x -> x + x
```

- Typechecking variant destruction is tricky
Typing Variant Destruction

1 `match v with`
2   | ‘Odd y -> y mod 2 = 1
3   | ‘Dbl x -> x + x

- Typechecking variant destruction is tricky
- Most languages (e.g. Caml) fail on unification
Typing Variant Destruction

1 `match v with`
2   | ‘Odd y -> y mod 2 = 1 : int ∪ bool`
3   | ‘Dbl x -> x + x

- Typechecking variant destruction is tricky
- Most languages (e.g. Caml) fail on unification
- Union types
Typing Variant Destruction

```
1 match 'Dbl 2 with
2   | 'Odd y -> y mod 2 = 1 : int ∪ bool
3   | 'Dbl x -> x + x
```

- Typechecking variant destruction is tricky
- Most languages (e.g. Caml) fail on unification
- Union types are insufficient!
Typing Variant Destruction

1. \textbf{match} ‘\texttt{Dbl} 2 with
2. \hspace{1em} | ‘\texttt{Odd} y \rightarrow y \mod 2 = 1 : \texttt{int}!
3. \hspace{1em} | ‘\texttt{Dbl} x \rightarrow x + x

- Typechecking variant destruction is tricky
- Most languages (e.g. Caml) fail on unification
- Union types are insufficient!
- Record construction is heterogeneously typed
Typing Variant Destruction

```ocaml
match ‘Db1 2 with
  | ‘Odd y -> y mod 2 = 1 : int!
  | ‘Db1 x -> x + + x
```

- Typechecking variant destruction is tricky
- Most languages (e.g. Caml) fail on unification
- Union types are insufficient!
- Record construction is heterogeneously typed
- Variant destruction is not
Typing the Variant Encoding

Our objective: a purely type-inferred variant-based object encoding
Typing the Variant Encoding

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This can work! We just need...
Typing the Variant Encoding

Our objective: a purely type-inferred variant-based object encoding

This can work! We just need...

- A couple new expression forms
- Weakly dependent types
- Precise polymorphism
- A whole-program typechecking pass
typing the variant encoding

our objective: a purely type-inferred variant-based object encoding

this can work! we just need...

- a couple new expression forms
- weakly dependent types
- precise polymorphism
- a whole-program typechecking pass

...and then we reap the benefits!
How We Get It: TinyBang

&

Onions

(Extensible, type-indexed records)
How We Get It: TinyBang

&

Onions

(Extensible, type-indexed records)

\( \chi \rightarrow \)

Scapes

(Functions with built-in patterns)
How We Get It: TinyBang

&
Onions
(Extensible, type-indexed records)

+  
χ −>  
Scapes
(Functions with built-in patterns)
Variant-Based Object Encoding

TinyBang

\[ \texttt{\texttt{\textbackslash dbl} } x \rightarrow x + x \]

- Methods are scapes
Variant-Based Object Encoding

TinyBang

1. `dbl x -> x + x`

Methods are scapes: functions with patterns
TinyBang

```lisp
(defun dbl x
  (+ x x))
```

Methods are scapes: functions with patterns

- Invoke methods by passing messages
Variant-Based Object Encoding

TinyBang

1 (`dbl x -> x + x`) `dbl 3`

- Methods are scapes: functions with patterns
- Invoke methods by passing first-class messages
Variant-Based Object Encoding

TinyBang

1 (‘dbl x -> x + x) ‘dbl 3

- Methods are scapes: functions with patterns
- Invoke methods by passing first-class messages (just labeled data)
Many Methods: Onioning Scapes

\begin{verbatim}
‘dbl x -> x + x
\end{verbatim}
Many Methods: Onioning Scapes

1. (‘dbl x -> x + x) &
2. (‘odd y -> y mod 2 == 1)

• Scapes are combined by *onioning*
Many Methods: Onioning Scapes

1. \((\texttt{dbl } x \rightarrow x + x) \land\)
2. \((\texttt{odd } y \rightarrow y \mod 2 == 1))\ (\texttt{dbl } 2)

- Scapes are combined by *onioning*
- Application finds match
Many Methods: Onioning Scapes

```
((
    'dbl x -> x + x) &
( 'odd y -> y mod 2 == 1))
('dbl 2)

object a {
    def dbl(x: Int): Int = { x + x }
    def pos(y: Int): Boolean = { y % 2 == 1 }
}

a.dbll(2)
```
Many Methods: Onioning Scapes

1 \((('db1 \; x \rightarrow x + x) \&\) \\
2 \((('odd \; y \rightarrow y \; mod \; 2 \; == \; 1)) \; (\; ('db1 \; 2)\)\) \\

\Rightarrow \; 4

- Scapes are combined by *onioning*
- Application finds *rightmost* match (asymmetric)
Many Methods: Onioning Scapes

1. \( ((
\texttt{\textquote{dbl}} \ x \to \ x + x) \ & \)
2. \( (\texttt{\textquote{odd}} \ y \to \ y \ \texttt{mod} \ 2 \ == \ 1)) \ (\texttt{\textquote{dbl}} \ 2) \)

\[ \Rightarrow \ 4 \]

- Scapes are combined by \textit{onioning}
- Application finds rightmost match (asymmetric)
- Subsumes case expressions
Multi Many Methods: Onioning Scapes

1 ((‘dbl x -> x + x) &
2 (‘odd y -> y mod 2 == 1))) (‘dbl 2)

⇒ 4

- Scapes are combined by onioning
- Application finds rightmost match (asymmetric)
- Subsumes case expressions
- Generalizes First-Class Cases [Blume et. al. ’06]
Typing the Onion

1. (`dbl x -> x + x`) &
2. (`odd y -> y mod 2 == 1`)

(`dbl int ∪ `odd int)` -> (`int ∪ bool`)

- Simple union type loses alignment
Typing the Onion

1 \((\texttt{dbl } x \rightarrow x + x) \&\)
2 \((\texttt{odd } y \rightarrow y \mod 2 == 1)\)

\((\texttt{dbl int } \rightarrow \texttt{int}) \& (\texttt{odd int } \rightarrow \texttt{bool})\)

- Simple union type loses alignment
- *Onion* type does not
Typing the Onion

1 (‘dbl x -> x + x) &
2 (‘odd y -> y mod 2 == 1)

(‘dbl int -> int) & (‘odd int -> bool)

- Simple union type loses alignment
- Onion type does not
- Weakly dependent type
Typing the Onion

1. `(\texttt{dbl} \, x \rightarrow x + x) \&
2. (\texttt{odd} \, y \rightarrow y \mod 2 == 1)

\texttt{(\texttt{dbl} \, \texttt{int} \rightarrow \texttt{int}) \& (\texttt{odd} \, \texttt{int} \rightarrow \texttt{bool})}

- Simple union type loses alignment
- \textit{Onion type} does not
- Weakly dependent type
- Relies heavily on polymorphism
Fields

- Pure variant model: get/set messages
Fields

1. (‘dbl x -> x + x) &
2. (‘odd y -> y \mod 2 == 1) &
3. ‘Z 5

- Pure variant model: get/set messages
- Hybrid model: variant methods, record fields
Fields

1. (`dbl x -> x + x`) &
2. (`odd y -> y mod 2 == 1`) &
3. `Z 5`

- Pure variant model: get/set messages
- Hybrid model: variant methods, record fields
- Similar to type-indexed rows [Shields, Meijer '01]
Fields

1. `(\texttt{dbl} \ x \rightarrow \ x + x) \ & \`
2. `(\texttt{odd} \ y \rightarrow \ y \mod 2 == 1) \ &
3. `\texttt{Z} 5`

- Pure variant model: get/set messages
- Hybrid model: variant methods, record fields
- Similar to type-indexed rows [Shields, Meijer ’01]
- Labels implicitly create cells
Fields

```
def o = ('dbl x -> x + x) &
    ('odd y -> y mod 2 == 1) &
    'Z 5
```

- Pure variant model: get/set messages
- Hybrid model: variant methods, record fields
- Similar to type-indexed rows [Shields, Meijer ’01]
- Labels implicitly create cells
- Field access by projection
Fields

```haskell
1  def o = (‘dbl x -> x + x) &
2      (‘odd y -> y mod 2 == 1) &
3      ‘Z 5
4  in (‘Z z -> z) o
```

- Pure variant model: get/set messages
- Hybrid model: variant methods, record fields
- Similar to type-indexed rows [Shields, Meijer ’01]
- Labels implicitly create cells
- Field access by projection/pattern match
Fields

```markdown
1 def o = ('dbl x -> x + x) &
  ('odd y -> y mod 2 == 1) &
  'Z 5
2 in ('Z z -> z) o

- Pure variant model: get/set messages
- Hybrid model: variant methods, record fields
- Similar to type-indexed rows [Shields, Meijer ’01]
- Labels implicitly create cells
- Field access by projection/pattern match
- But what about self?
```
def ticker =
  'x 0 &
  ('inc _ ->
    self.x = self.x + 1 in self.x)
in ticker 'inc ()
Naïve Self

```python
def ticker =
‘x 0 &
(‘inc _ & ‘self self ->
    self.x = self.x + 1 in self.x)
in ticker ‘inc ()
```

- Add `self` to all parameters
Naïve Self

```python
def ticker =
  'x 0 &
  ( inc _ & self self ->
    self.x = self.x + 1 in self.x)
in ticker 'inc ()
```

- Add `self` to all parameters
  - & is pattern conjunction
Naïve Self

```python
def ticker =
    'x 0 &
    ('inc _ & 'self self ->
        self.x = self.x + 1 in self.x)
in ticker ('inc () & 'self ticker)
```

- Add `self` to all parameters
  - & is pattern conjunction
- Add `self` to all call sites
Naïve Self

```
1 def ticker =
2   `x 0 &
3   (`inc _ & `self self ->
4       self.x = self.x + 1 in self.x)
5 in ticker (`inc () & `self ticker)
```

- Add `self to all parameters
  - & is pattern conjunction
- Add `self to all call sites
- Be happy?
Naïve Self: Type Problems

```python
def obj =
    if something then
        ('foo & 'self s -> s 'bar () &
        ('bar _ -> 1)
    else
        ('foo & 'self s -> s 'baz () &
        ('baz _ -> 2)
    in obj 'foo ()
```
Naïve Self: Problems

\[ \alpha_{SELF} = \]

\[ (\text{`foo } \land \text{ `self } \alpha_1 \to \text{ int}) \land \]

\[ (\text{`bar } \to \text{ int}) \]

where \( \alpha_1 \) has `bar

\[ \cup \]

\[ (\text{`foo } \land \text{ `self } \alpha_2 \to \text{ int}) \land \]

\[ (\text{`baz } \to \text{ int}) \]

where \( \alpha_2 \) has `baz
Naïve Self: Problems

\[
\alpha_{\text{SELF}} :> (\langle \text{foo } \text{& self } \alpha_1 \rightarrow \text{int} \rangle \& \\
\langle \text{bar } \rightarrow \text{int} \rangle)
\]

where \( \alpha_1 \) has ‘bar

\[
\alpha_{\text{SELF}} :> (\langle \text{foo } \text{& self } \alpha_2 \rightarrow \text{int} \rangle \& \\
\langle \text{baz } \rightarrow \text{int} \rangle)
\]

where \( \alpha_2 \) has ‘baz
Self Solutions

- Classic object encodings [Bruce et. al. '98]
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  - Type of self is fixed at instantiation
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Self Solutions

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  - Prototype objects: extensible but not callable
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  - Sealing is permanent
  - Sealing is meta-theoretic
Self Solutions

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- TinyBang
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- **TinyBang**
  - Sealing is encodable (no meta-theory)
Self Solutions

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- Extensible Object Calculus [Fisher et. al. ’98]
  - Prototype objects: extensible but not callable
  - Proper objects: callable but not extensible
  - Prototypes can be sealed into proper objects
  - Sealing is permanent
  - Sealing is meta-theoretic

- TinyBang
  - Sealing is encodable (no meta-theory)
  - Sealed objects can be extended and resealed
Sealing in TinyBang

```python
def rec seal = obj ->
    obj &
    (msg -> obj (‘self (seal obj) & msg))

def point =
    ‘x 2 & ‘y 4 &
    (‘l1 _ & ‘self self -> self.x + self.y)

def sealedPoint = seal point

sealedPoint ‘l1 ()

...```
Resealing Objects

```python
...  
def obj = seal (  
  'x 0 &  
  ( 'inc _ & 'self self ->  
      self.x = self.x + 1 in self.x )) in  
obj 'inc (); obj 'inc ();  
def extobj = seal (  
  obj &  
  ( 'dbl _ & 'self self ->  
      self.x = self.x + self.x in self.x )) in  
extobj 'dbl (); extobj 'inc ()

x = 0
```
Resealing Objects

```python
1 ... def obj = seal (  
  'x 0 &  
  ('inc _ & 'self self ->  
   self.x = self.x + 1 in self.x)) in  
obj 'inc (); obj 'inc ();  
def extobj = seal (  
  obj &  
  ('dbl _ & 'self self ->  
   self.x = self.x + self.x in self.x)) in  
extobj 'dbl (); extobj 'inc ()

x = 1
```
Resealing Objects

... 

def obj = seal ( 
    'x 0 &
    ('inc _ & 'self self ->
    self.x = self.x + 1 in self.x)) in
obj 'inc (); obj 'inc ();
def extobj = seal ( 
    obj &
    ('dbl _ & 'self self ->
    self.x = self.x + self.x in self.x)) in
extobj 'dbl (); extobj 'inc ()

x = 2
Resealing Objects

...  

```python
def obj = seal (  
  `x 0 &  
  (`inc _ & `self self ->  
    self.x = self.x + 1 in self.x)) in  
  obj `inc (); obj `inc ();  
def extobj = seal (  
  obj &  
  (`dbl _ & `self self ->  
    self.x = self.x + self.x in self.x)) in  
  extobj `dbl (); extobj `inc ()
```

\[ x = 4 \]
Resealing Objects

```
def obj = seal (  
    'x 0 &  
    ( 'inc _ & 'self self ->  
        self.x = self.x + 1 in self.x )) in  
obj 'inc (); obj 'inc ();  
def extobj = seal (  
    obj &  
    ( 'dbl _ & 'self self ->  
        self.x = self.x + self.x in self.x )) in  
extobj 'dbl (); extobj 'inc ()
```

\[ x = 5 \]
Resealing Objects

1 ... 

2 def obj = seal (...) in
3 obj 'inc (); obj 'inc ();
4 def extobj = seal (...) in
5 extobj 'dbl (); extobj 'inc ()
... 

2 def obj = seal (...) in
3 obj 'inc (); obj 'inc ();
4 def extobj = seal (...) in
5 extobj 'dbl (); extobj 'inc ()
Resealing Objects

```
... 
_def obj = seal (…) in
.obj ‘inc () ; obj ‘inc () ;
def extobj = seal (…) in
.extobj ‘dbl () ; extobj ‘inc ()

‘self extobj & ‘inc ()
```
Resealing Objects

```
...  
def obj = seal (...) in
    obj `inc (); obj `inc ();
def extobj = seal (...) in
    extobj `dbl (); extobj `inc ()

`self obj & `self extobj & `inc ()
```
...  
\[
\text{def ~} \text{obj = seal (...) in} \\
\text{obj ~} \text{inc (); obj ~} \text{inc ();} \\
\text{def ~} \text{extobj = seal (...) in} \\
\text{extobj ~} \text{dbl (); extobj ~} \text{inc ()} \\
\text{self ~} \text{obj & self ~} \text{extobj & inc ()}
\]
Other Features

```python
def point = seal (‘x 0 & ‘y 0 &
               (‘l1 _ & ‘self self ->
                self.x + self.y)) in
def mixin = (‘nearZero _ & ‘self self ->
               (self ‘l1 ()) <= 4) in
def mixedPoint = seal (point & mixin) in
mixedPoint ‘nearZero ()
```

- Mixins
Other Features

```python
1  def point = ... in
2  def mixin = ((`nearZero _ & `self self ->
3                (self `l1 ()) <= 4)) in
4  def mixedPoint = seal (point & mixin) in
5  mixedPoint `nearZero ()
```

- Mixins
- Higher-order object extension
Other Features

```python
def obj = seal (  
  'x 0 & ('inc _ & 'self self ->
  self.x = self.x + 1 in self.x)) in
def obj2 = seal (  
  (obj &. 'x) & 'y 0 &
  ('inc _ & 'self self ->
  self.y = self.y + self.x in self.y)) in
...
```

- Mixins
- Higher-order object extension
- Data sharing
Other Features

```python
def obj = seal (  
‘x 0 &  
(‘inc n:int & ‘self self ->  
    self.x = self.x + n in self.x) &  
(‘inc n:unit & ‘self self ->  
    self ‘inc 1) in  
oobj (‘inc ()); obj (‘inc 4)
```

- Mixins
- Higher-order object extension
- Data sharing
- Overloading
Other Features

etc.

- Mixins
- Higher-order object extension
- Data sharing
- Overloading
- Classes, inheritance, etc.
Type Inference
Type Inference

- Subtype constraint system
Type Inference

- Subtype constraint system
- Assign each subexpression a type variable
Type Inference

- Subtype constraint system
- Assign each subexpression a type variable
- Derive initial constraint set over expression
Type Inference

- Subtype constraint system
- Assign each subexpression a type variable
- Derive initial constraint set over expression
- Perform knowledge closure on constraints
Type Inference

- Subtype constraint system
- Assign each subexpression a type variable
- Derive initial constraint set over expression
- Perform knowledge closure on constraints
- Check resulting closure for consistency
Type Inference

- Subtype constraint system
- Assign each subexpression a type variable
- Derive initial constraint set over expression
- Perform knowledge closure on constraints
- Check resulting closure for consistency
- **Soundness** is proven over inference system
Constraint Types

\[ \text{int} \cup \text{unit} \]
Constraint Types

\[
\text{int} \cup \text{unit} \\
\iff \\
\alpha \setminus \{\text{int} <: \alpha, \text{unit} <: \alpha\}
\]
Constraint Closure

\[ 5 + 3 \]
Constraint Closure

\[ 5 + 3 \]

\( \alpha_1 \)

\( \alpha_2 \)
Constraint Closure

\[ 5 + 3 \]

\[ \alpha_1 \]

\[ \alpha_2 \]

\[ \alpha_3 \]
Constraint Closure

\[ 5 + 3 \]

\text{int} \quad \alpha_1 \quad \alpha_2 \quad \alpha_3
Constraint Closure

$5 + 3$

$\text{int}$

$\alpha_1$

$\alpha_2$

$\alpha_3$
Constraint Closure

\[ \alpha_1 \quad \alpha_2 \quad + \]

\[ \text{int} \]

5 + 3
Constraint Closure

5 + 3

int

$\alpha_1$

$\alpha_2$

$\alpha_3$

$+$
Constraint Closure

\[ 5 + 3 \]
Constraint Closure

5 + 3

```
int
\( \alpha_1 \)
\( \alpha_2 \)
\( + \)
\( \alpha_3 \)
```
Constraint Closure

5 + 3
Constraint Closure

\[ \text{int} \rightarrow \alpha_1 \rightarrow + \rightarrow \alpha_3 \]

\[ 5 + 3 \]
Constraint Closure

5 + 3

int

\( \alpha_1 \)

\( \alpha_2 \)

\( \alpha_3 \)

+
Functions

\[ x \rightarrow x + x \]
Functions

\[ x \rightarrow x + x \]
Functions

\[ x \rightarrow x + x \]
Functions

\[ x \rightarrow x + x \]
Functions

\[ x \rightarrow x + x \]
Functions

\[ x \rightarrow x + x \]
Application

\[(x \rightarrow x + x) \, 5\]
Application

\[(x \rightarrow x + x) \ 5\]
Application

\((x \rightarrow x + x)^5\)
Application

\[(x \rightarrow x + x)^5\]
Application

\[(x \rightarrow x + x) \ 5\]
Application

\[(x \rightarrow x + x) \ 5\]
Application

\[(x \rightarrow x + x) \ 5\]
Application

\[(x \rightarrow x + x) \; 5\]
Application

\((x \rightarrow x + x) \ 5\)
Application

\[(x \rightarrow x + x) \ 5\]
Application

\((x \rightarrow x + x)\ 5\)
Application

\((x \rightarrow x + x) \ 5\)
Application

\[(x \rightarrow x + x) \, 5\]
Application

\[(x \rightarrow x + x) \ 5\]
Application

\((x \to x + x) \ 5 : \ \text{int}\)
Polymorphism
Polymorphism

- Let-bound polymorphism
Polymorphism

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  - Type-parametric methods fail
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- Local polymorphism
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  - Each call site is freshly polyinstantiated
Polymorphism

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  - Type-parametric methods fail
- Local polymorphism
  - Objects are not local
  - Requires type annotations
- TinyBang uses call-site polymorphism
  - Each call site is freshly polyinstantiated
  - Recursion reuses variable contours
def id = x → x in (id () & id 1)
def id = x -> x in (id () & id 1)
Polymorphic Application

```python
def id = x -> x in (id () & id 1)
```
def id = x → x in (id () & id 1)
def id = x → x in (id () & id 1)
BigBang

- Aims to infer types for script-like programs

Uses type information for better performance
Desugars down to TinyBang
Provides syntax for classes, modules, etc.
Enough polymorphism for scripting intuitions
...without divergence or exponential blow-up
BigBang

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Questions?