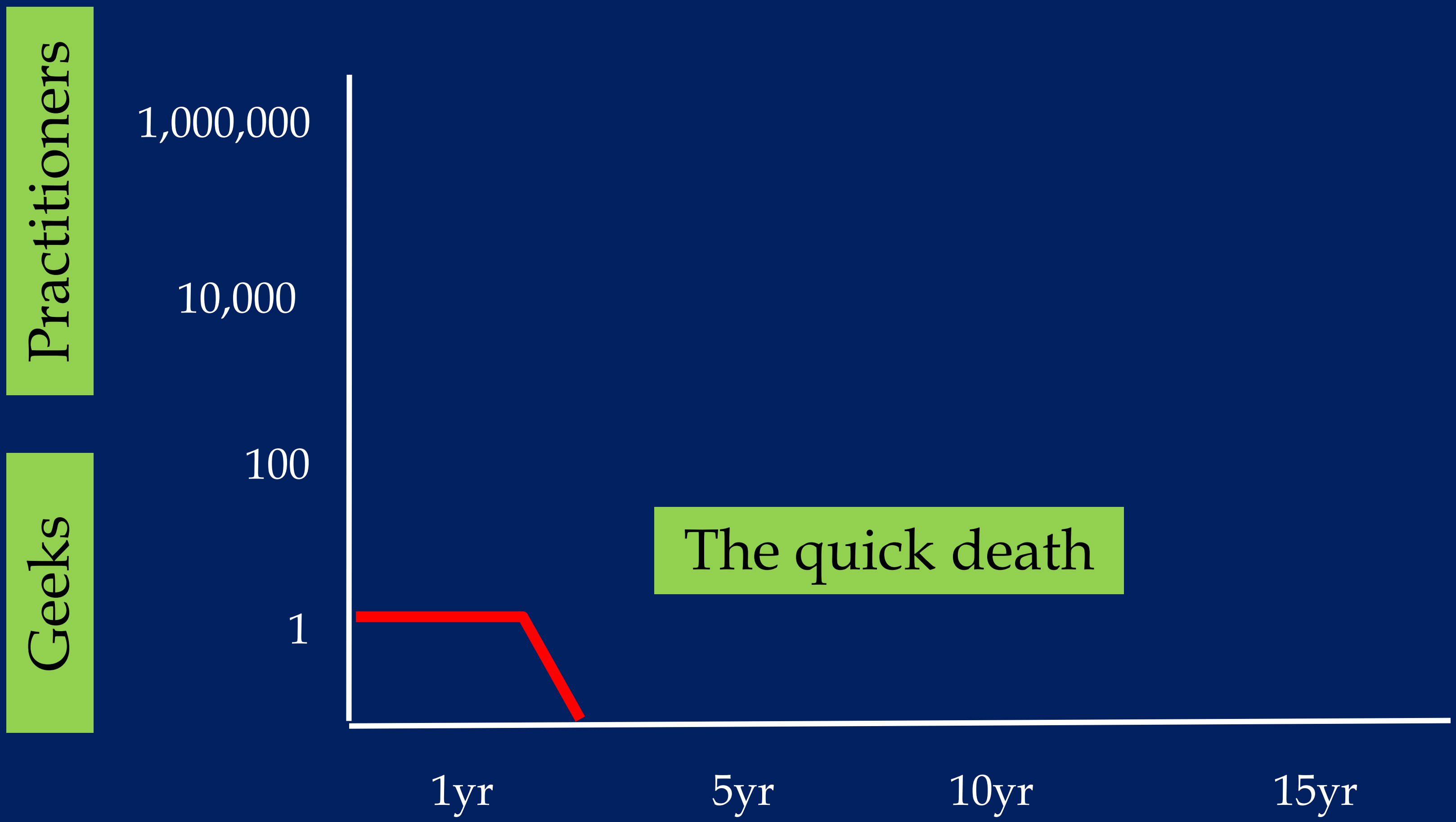
Classes, Jim, but not as we know them

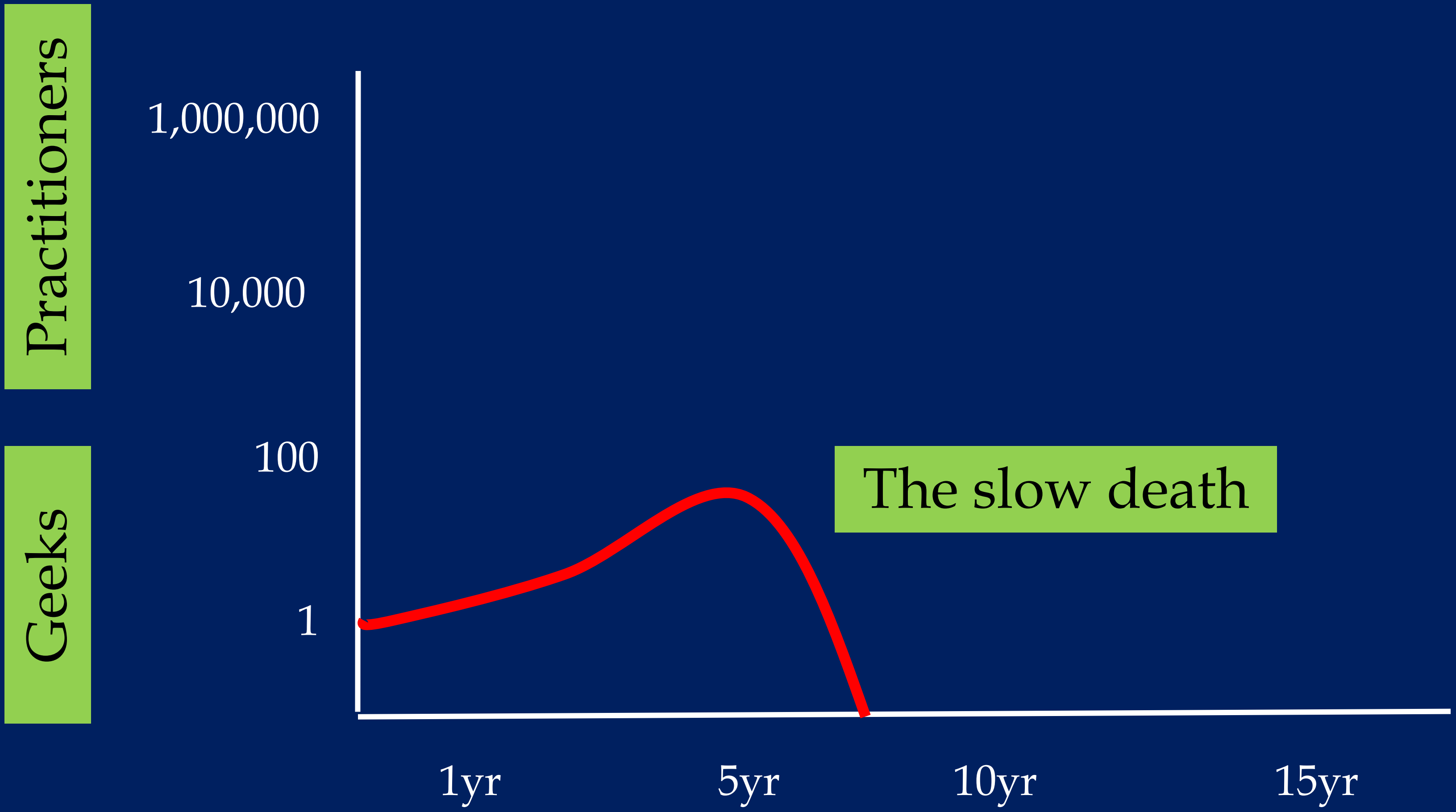
Simon Peyton Jones (Microsoft Research)

Most new programming languages

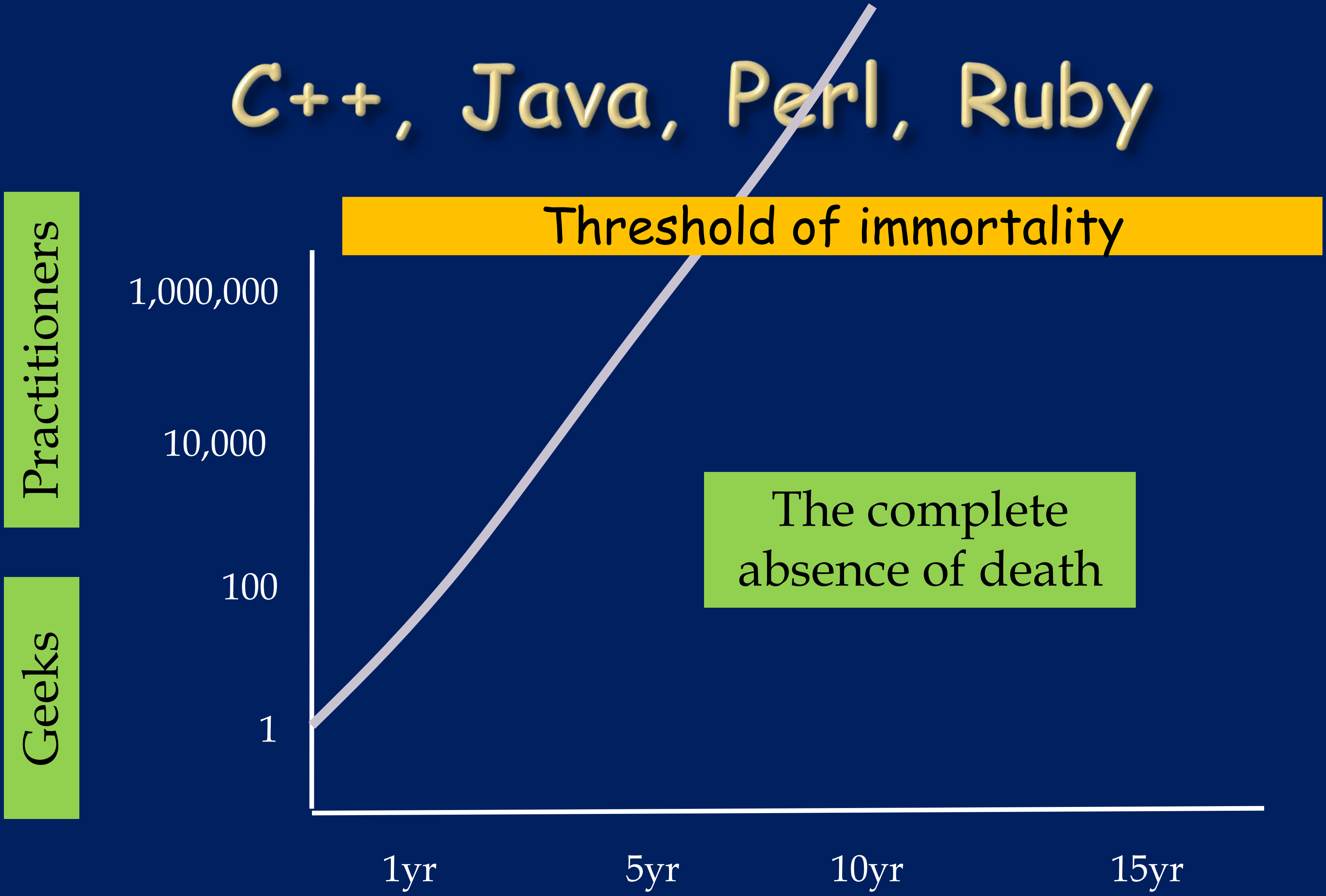


The quick death

Successful research languages



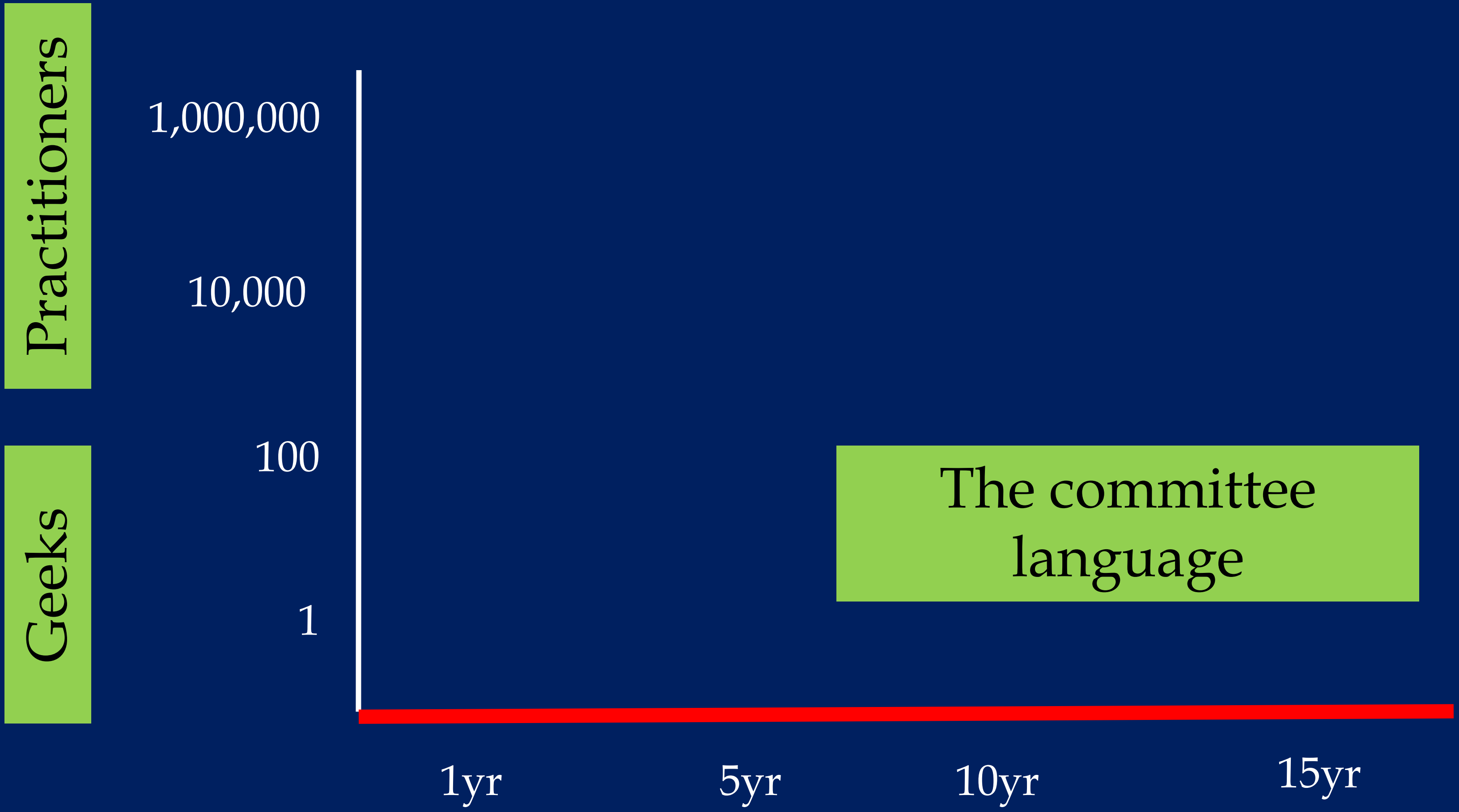
C++, Java, Perl, Ruby



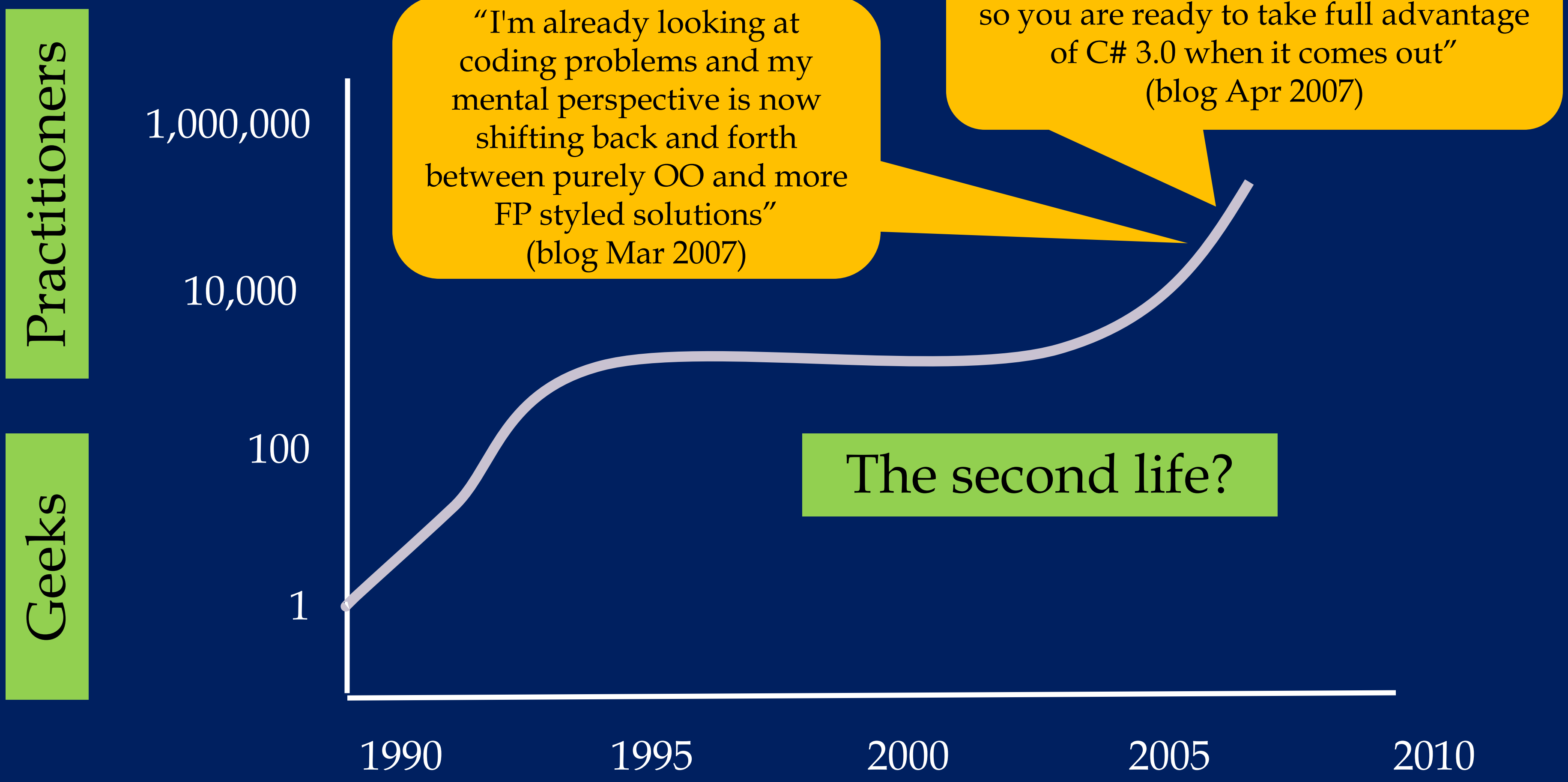
Threshold of immortality

The complete absence of death

Committee languages



Haskell

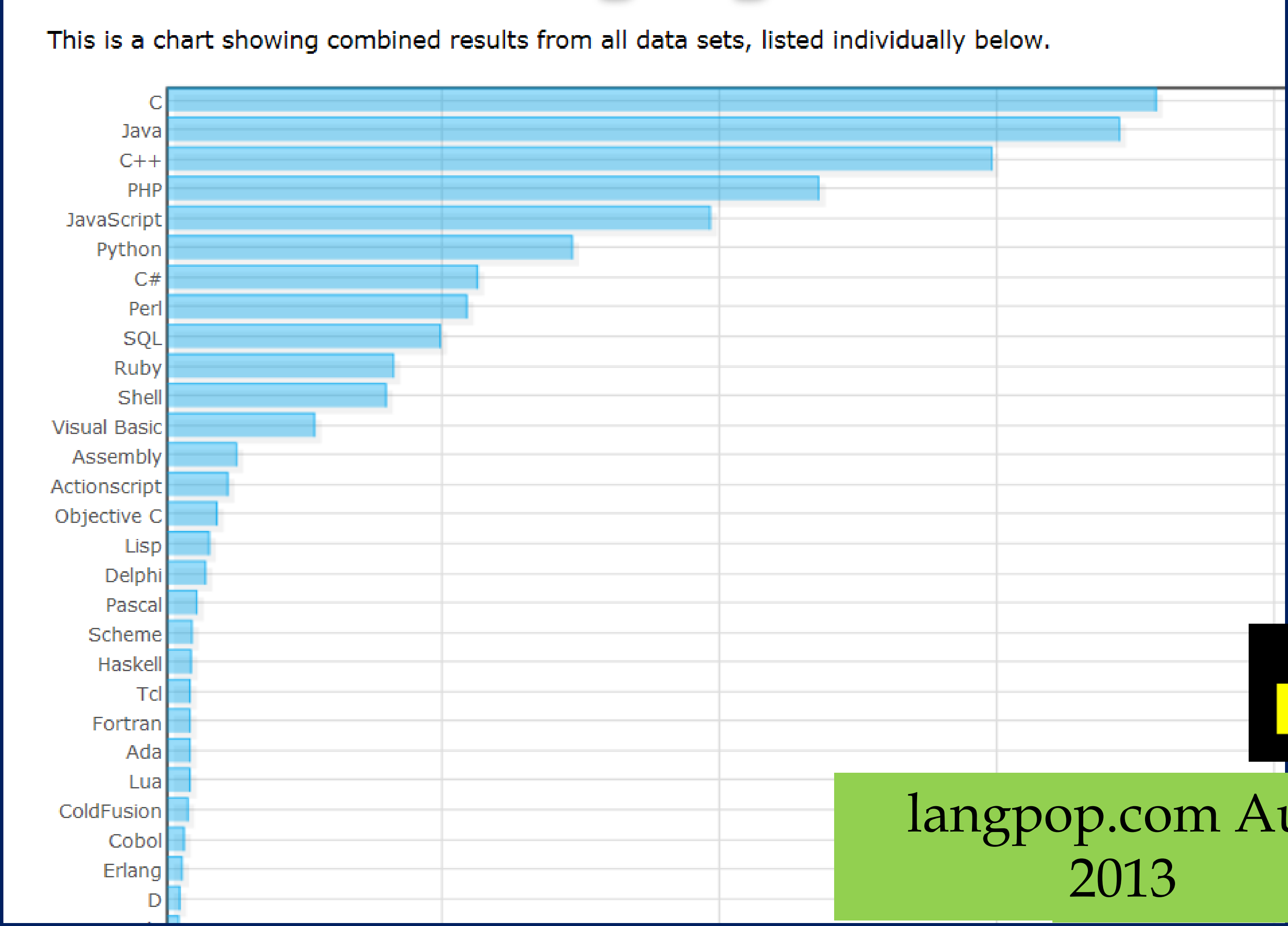


"I'm already looking at coding problems and my mental perspective is now shifting back and forth between purely OO and more FP styled solutions"
(blog Mar 2007)

"Learning Haskell is a great way of training yourself to think functionally so you are ready to take full advantage of C# 3.0 when it comes out"
(blog Apr 2007)

The second life?

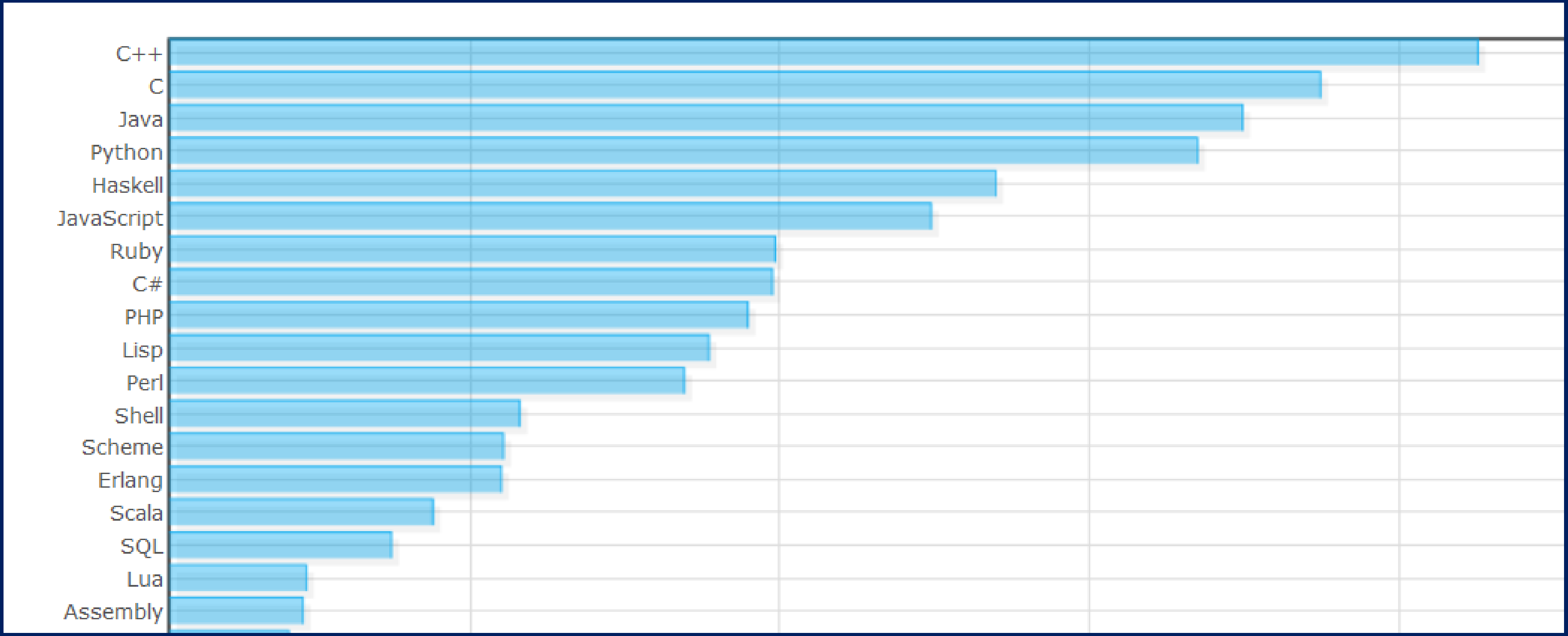
Language popularity
how much language X is used



This is a chart showing combined results from all data sets, listed individually below.

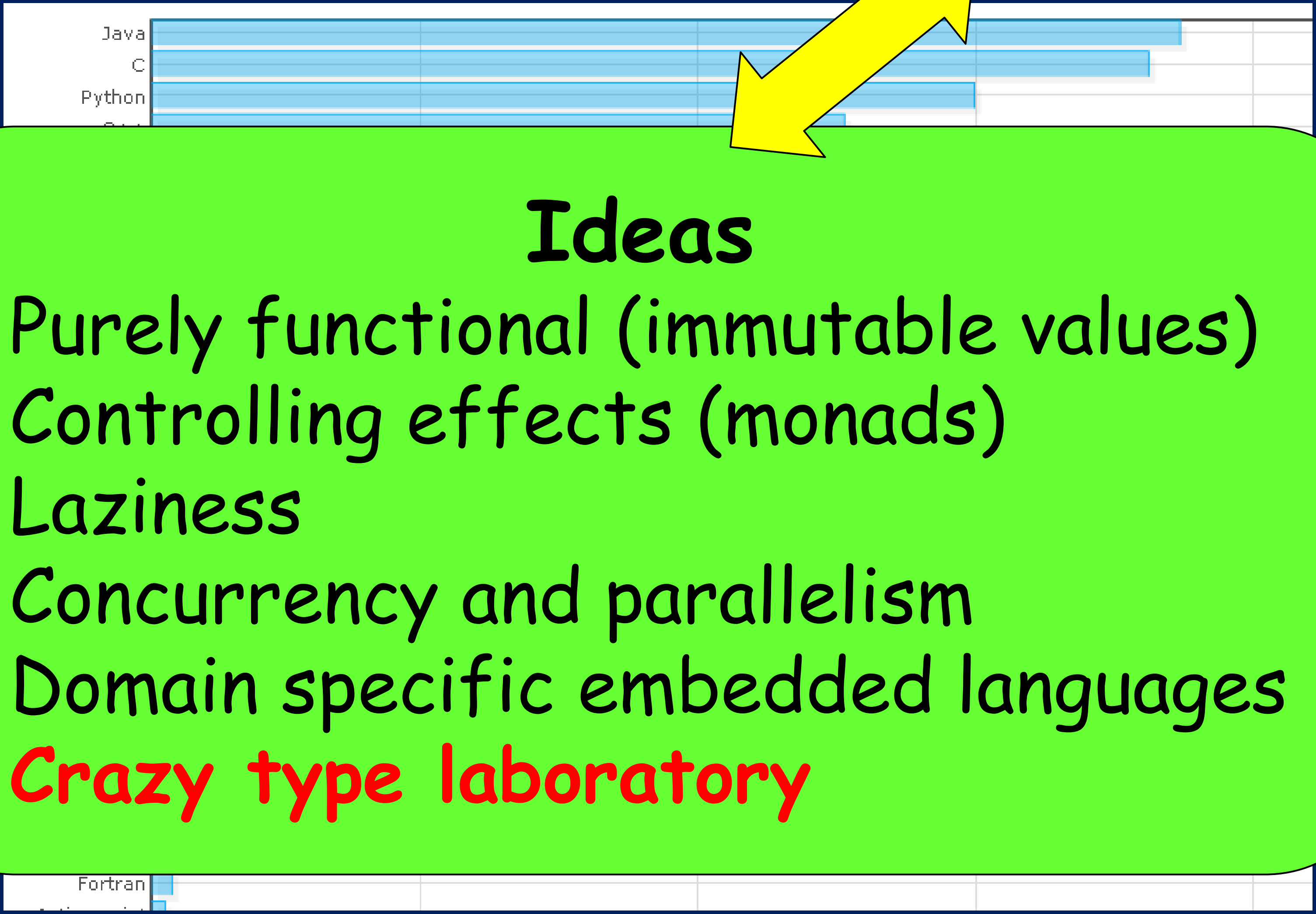
langpop.com Aug 2013

Language popularity
how much language X is talked about



langpop.com Aug 2013

Language popularity
how much language X is talked about



Ideas

- Purely functional (immutable values)
- Controlling effects (monads)
- Laziness
- Concurrency and parallelism
- Domain specific embedded languages
- **Crazy type laboratory**

Haskell in one slide

Type signature (optional)

Higher order

Polymorphism (works for any type a)

```
filter :: (a->Bool) -> [a] -> [a]
filter p [] = []
filter p (x:xs)
      | p x       = x : filter p xs
      | otherwise = filter p xs
```

Haskell in one slide

Type signature

Higher order

Polymorphism
(works for any
type a)

```
filter :: (a->Bool) -> [a] -> [a]
filter p [] = []
filter p (x:xs)
      | p x        = x : filter p xs
      | otherwise = filter p xs
```

Functions defined
by pattern
matching

Guards
distinguish
sub-cases

f x y
rather than
f(x,y)

Haskell in one slide

Type signature

Higher order

Polymorphism (works for any type a)

```
filter :: (a->Bool) -> [a] -> [a]
filter p [] = []
filter p (x:xs)
      | p x       = x : filter p xs
      | otherwise = filter p xs

data Bool = False | True
data [a]  = []    | a:[a]
```

Declare new data types

Problem

```
member :: a -> [a] -> Bool
member x []                 = False
member x (y:ys) | x==y      = True
                | otherwise = member x ys
```

Test for equality

- Can this really work **FOR ANY** type a?
- E.g. what about functions?

```
member negate [increment, \x.0-x, negate]
```

Similar problems

- Similar problems
  - sort :: [a] -> [a]
  - (+) :: a -> a -> a
  - show :: a -> String
  - serialise :: a -> BitString
  - hash :: a -> Int

Unsatisfactory solutions

- Local choice
  - Write (a + b) to mean (a \`plusFloat\` b) or (a \`plusInt\` b) depending on type of a,b
  - Loss of abstraction; eg member is monomorphic
- Provide equality, serialisation for everything, with runtime error for (say) functions
  - Not extensible: just a baked-in solution for certain baked-in functions
  - Run-time errors

Type classes

Works for any type 'a', provided 'a' is an instance of class Num

```
square :: Num a => a -> a
square x = x*x
```

Similarly:

```
sort      :: Ord a  => [a] -> [a]
serialise :: Show a => a -> String
member    :: Eq a   => a -> [a] -> Bool
```

Type classes

Works for any type 'n'
that supports the
Num operations

```
square :: Num n  => n -> n
square x = x*x
```

FORGET all
you know
about OO
classes!

```
class Num a where
  (+)    :: a -> a -> a
  (*)    :: a -> a -> a
  negate :: a -> a
  ...etc..
```

The class
declaration says
what the Num
operations are

```
instance Num Int where
  a + b    = plusInt a b
  a * b    = mulInt a b
  negate a = negInt a
  ...etc..
```

An instance
declaration for a
type T says how the
Num operations are
implemented on T's

```
plusInt :: Int -> Int -> Int
mulInt  :: Int -> Int -> Int
etc, defined as primitives
```

How type classes work

When you write this...

```
square :: Num n => n -> n
square x = x*x
```

...the compiler generates this

```
square :: Num n -> n -> n
square d x = (*) d x x
```

The "`Num n =>`" turns into an extra value argument to the function.
It is a value of data type `Num n`

A value of type (Num T) is a vector (vtable) of the Num operations for type T

How type classes work

When you write this...

```
square :: Num n => n -> n
square x = x*x
```

```
class Num a where
   (+)    :: a -> a -> a
   (*)    :: a -> a -> a
   negate :: a -> a
   ...etc..
```

The class decl translates to:

- A data type decl for Num
- A selector function for each class operation

...the compiler generates this

```
square :: Num n -> n -> n
square d x = (*) d x x
```

```
data Num a
  = MkNum (a->a->a)
          (a->a->a)
          (a->a)
          ...etc...

(*) :: Num a -> a -> a -> a
(*) (MkNum _ m _ ...) = m
```

A value of type (Num T) is a vector of the Num operations for type T

How type classes work

When you write this...

```
square :: Num n => n -> n
square x = x*x
```

...the compiler generates this

```
square :: Num n -> n -> n
square d x = (*) d x x
```

```
instance Num Int where
  a + b    = plusInt a b
  a * b    = mulInt a b
  negate a = negInt a
  ...etc..
```

```
dNumInt :: Num Int
dNumInt = MkNum plusInt
                mulInt
                negInt
                 ...
```

An instance decl for type T translates to a value declaration for the Num dictionary for T

A value of type (Num T) is a vector of the Num operations for type T

How type classes work

When you write this...

```
f ::  Int -> Int
f x = negate (square x)
```

...the compiler generates this

```
f :: Int -> Int
f x = negate dNumInt
          (square dNumInt x)
```

```
instance Num Int where
  a + b    = plusInt a b
  a * b    = mulInt a b
  negate a = negInt a
  ...etc..
```

```
dNumInt :: Num Int
dNumInt = MkNum plusInt
                mulInt
                negInt
                ...
```

An instance decl for type T translates to a value declaration for the Num dictionary for T

A value of type (Num T) is a vector of the Num operations for type T

All this scales up nicely

- You can build big overloaded **functions** by calling smaller overloaded **functions**

```
sumSq :: Num n => n -> n -> n
sumSq x y = square x + square y
```

```
sumSq :: Num n -> n -> n -> n
sumSq d x y = (+) d (square d x)
                    (square d y)
```

Extract addition operation from d

Pass on d to square

All this scales up nicely

- You can build big **instances** by building on smaller **instances**

```
class Eq a where
  (==) :: a -> a -> Bool

instance Eq a => Eq [a] where
  (==) []     []     = True
  (==) (x:xs) (y:ys) = x==y && xs == ys
  (==) _      _      = False
```

```
data Eq = MkEq (a->a->Bool)
(==) (MkEq eq) = eq

dEqList :: Eq a -> Eq [a]
dEqList d = MkEq eql
  where
    eql []     []     = True
    eql (x:xs) (y:ys) = (==) d x y && eql xs ys
    eql _      _      = False
```

Overloaded constants

```
class Num a where
  (+) :: a -> a -> a
  (-) :: a -> a -> a
  fromInteger :: Integer -> a
  ....

inc :: Num a => a -> a
inc x = x + 1
```

Even literals are overloaded

"1" means "fromInteger 1"

```
inc :: Num a -> a -> a
inc d x = (+) d x (fromInteger d 1)
```

Type classes have proved extraordinarily convenient in practice

- Equality, ordering, serialisation
- Numerical operations. Even numeric constants are overloaded
- Monadic operations

```
class Monad m where
  return :: a -> m a
  (>>=)  :: m a -> (a -> m b) -> m b
```

Note the higher-kinded type variable, m

- And on and on....time-varying values, pretty-printing, collections, reflection, generic programming, marshalling, monad transformers....

Quickcheck

```
propRev :: [Int] -> Bool
propRev xs = reverse (reverse xs) == xs

propRevApp :: [Int] -> [Int] -> Bool
propRevApp xs ys = reverse (xs++ys) ==
                   reverse ys ++ reverse xs
```

Quickcheck (which is just a Haskell 98 library)

- Works out how many arguments
- Generates suitable test data
- Runs tests

```
ghci> quickCheck propRev
OK: passed 100 tests

ghci> quickCheck propRevApp
OK: passed 100 tests
```

Quickcheck

```
quickCheck :: Testable a => a -> IO ()

class Testable a where
  test :: a -> RandSupply -> Bool

class Arbitrary a where
  arby :: RandSupply -> a

instance Testable Bool where
  test b r = b

instance (Arbitrary a, Testable b)
      => Testable (a->b) where
  test f r = test (f (arby r1)) r2
           where (r1,r2) = split r
```

```
split :: RandSupply -> (RandSupply, RandSupply)
```

Quickcheck

```
propRev :: [Int] -> Bool
```

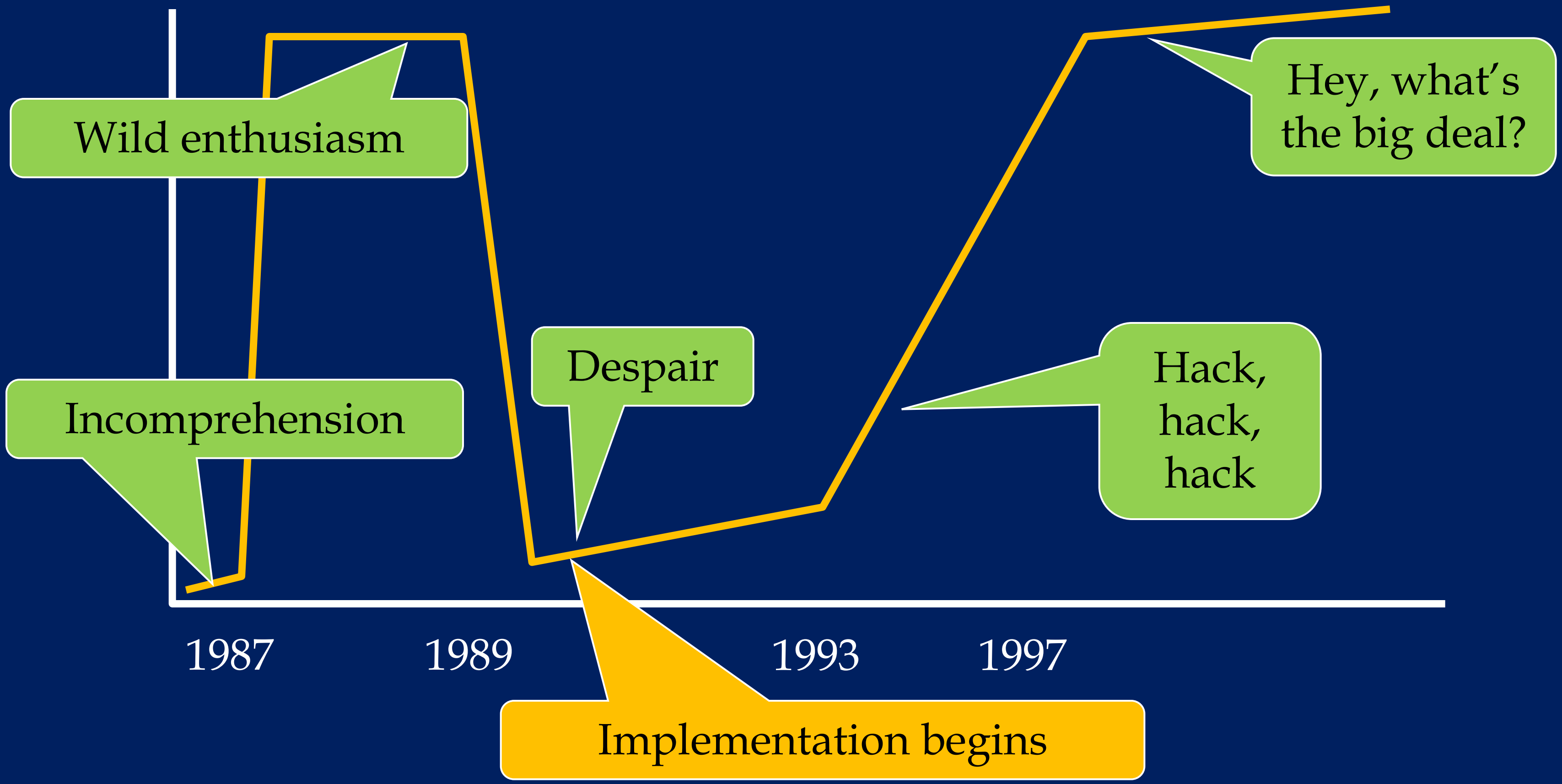
```
test propRev r

= test (propRev (arby r1)) r2
where (r1,r2) = split r

= propRev (arby r1)
```

Using instance for (->)

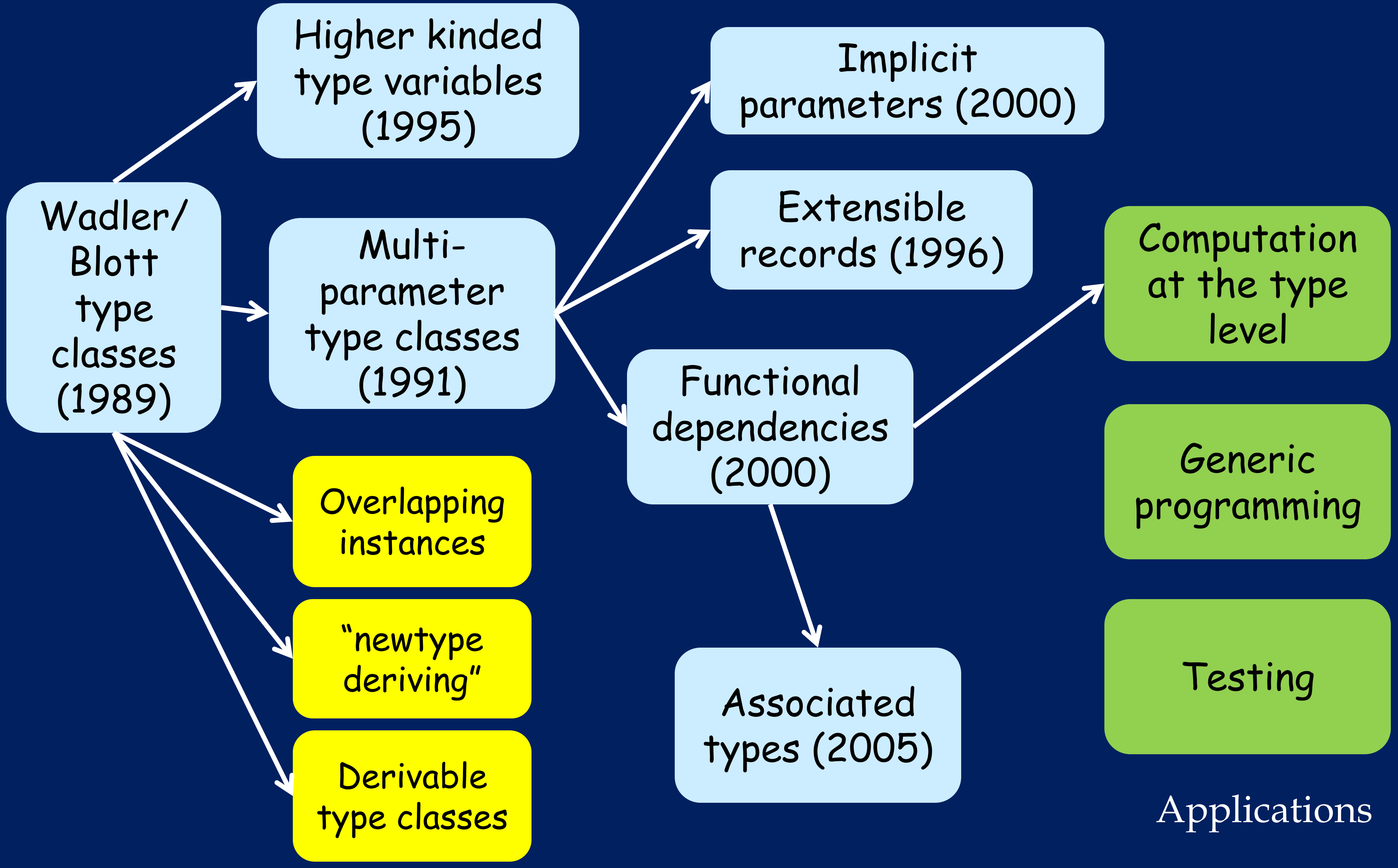
Using instance for Bool

Type classes over time

- Type classes are the most unusual feature of Haskell's type system



Type-class fertility



Wadler/ Blott type classes (1989)

Higher kinded type variables (1995)

Multi-parameter type classes (1991)

Implicit parameters (2000)

Extensible records (1996)

Functional dependencies (2000)

Associated types (2005)

Computation at the type level

Generic programming

Testing

Overlapping instances

"newtype deriving"

Derivable type classes

Variations

Applications

Type classes
and
object-oriented programming

1. Haskell “class” ~ OO “interface”

Haskell "class" ~ OO "interface"

A Haskell class is more like a Java **interface** than a Java **class**: it says what operations the type must support.

```
class Show a where
  show :: a -> String

f :: Show a => a -> ...
```

```
interface Showable {
  String show();
}

class Blah {
  f( Showable x ) {
      ...x.show()...
} }
```

Haskell “class” ~ OO “interface”

- No problem with multiple constraints:

```
f :: (Num a, Show a)
  => a -> ...
```

```
class Blah {
  f( ??? x ) {
        ...x.show()...
} }
```

- Existing types can retroactively be made instances of new type classes (e.g. introduce new Wibble class, make existing types an instance of it)

```
class Wibble a where
  wib :: a -> Bool

instance Wibble Int where
  wib n = n+1
```

```
interface Wibble {
  bool wib()
}

...does Int support
  Wibble?....
```

Type classes and object-oriented programming

1. Haskell "class" ~ OO "interface"
2. Type-based dispatch, not value-based dispatch

Type-based dispatch

- A bit like OOP, except that method suite (vtable) is passed separately?

```
class Show where
  show :: a -> String

f :: Show a => a ->
  ...
```

- No!! Type classes implement **type-based dispatch**, not **value-based dispatch**

Type-based dispatch

```
class Read a where
  read :: String -> a

class Num a where
  negate :: a -> a
  fromInteger :: Integer -> a
```

```
read2 :: (Read a, Num a) => String -> a
read2 s = negate (read s)
```

```
read2 dr dn s = negate dn (read dr s)
```

- The overloaded value is *returned by* `read2`, not passed to it.
- It is the dictionaries (and type) that are passed as argument to `read2`

Type based dispatch

So the links to **intensional polymorphism** are closer than the links to **OOP**.

The dictionary is like a proxy for the (interesting aspects of) the type argument of a polymorphic function.

Intensional polymorphism

```
f :: forall a. a -> Int
f t (x::t) = ...typecase t...

f :: forall a. C a => a -> Int
f x = ...(call method of C)...
```

Haskell

Reflection

```
class Typeable a where
   typeRep :: a -> TypeRep

data TypeRep = TR String [TypeRep]
```

Not really a string, of course

- e.g. typeRep "foo" = TR "List" [TR "Char" []]

```
instance Typeable Int where
   typeRep _ = TR "Int" []

instance Typeable a => Typeable [a] where
   typeRep (x:xs) = TR "List" [typeRep x]
      -- ???
```

Reflection

```
class Typeable a where
   typeRep :: a -> TypeRep

data TypeRep = TR String [TypeRep]
```

- e.g.   typeRep “foo” = TR “List” [TR “Char” []]

```
instance Typeable Int where
   typeRep _ = TR “Int” []

instance Typeable a => Typeable [a] where
   typeRep _ = TR “List”
                  [typeRep (undefined :: a)]
```

The value argument is never looked at; it plays the role of a type argument

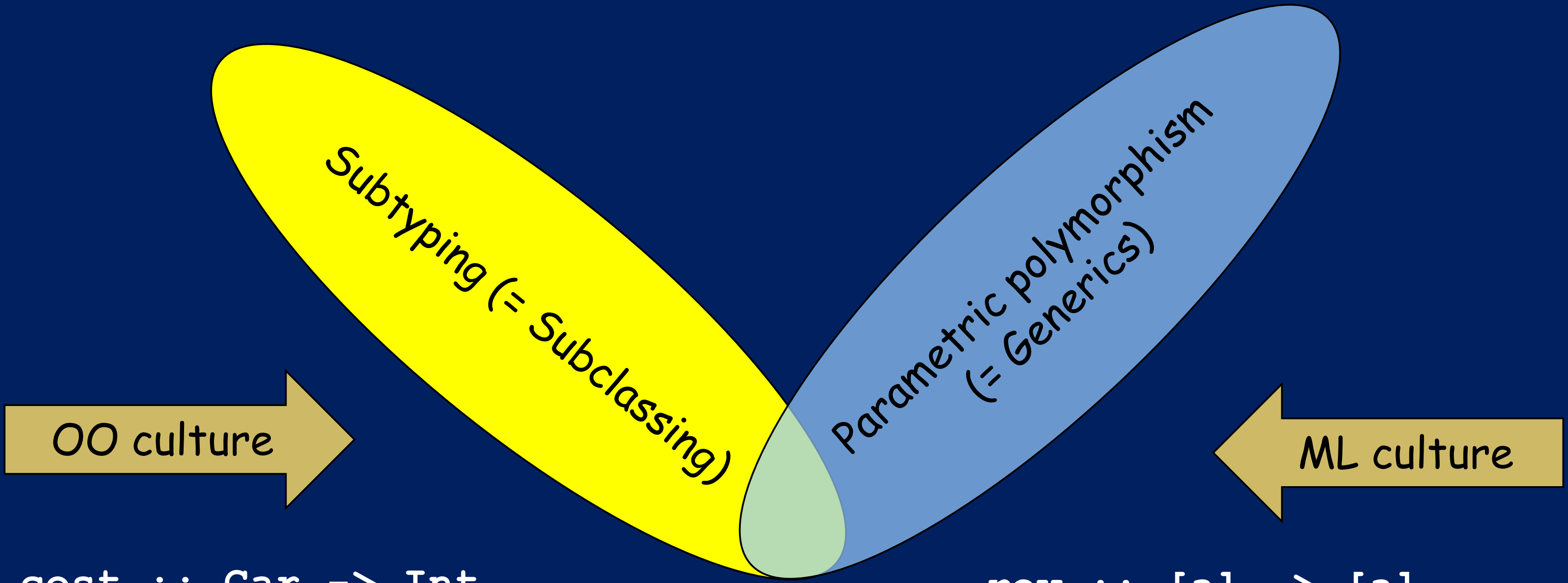
Hence ⊥ is fine

Type classes
and
object-oriented programming

1. Haskell "class" ~ OO "interface"
2. Type-based dispatch, not value-based dispatch
3. Generics (i.e. parametric polymorphism) , not subtyping

Two approaches to polymorphism

- Polymorphism: same code works on a variety of different argument types



Subtyping (= Subclassing)

Parametric polymorphism (= Generics)

OO culture

ML culture

`cost :: Car -> Int`

cost works on Fords, Renaults...

`rev :: [a] -> [a]`

rev works on [Int], [Char],...

Generics, not subtyping

- Haskell has no sub-typing

```
data Tree = Leaf | Branch Tree Tree

f :: Tree -> Int
f t = ...
```

f's argument must be (**exactly**) a Tree

- Ability to act on argument of various types achieved via type classes:

```
square :: (Num a) => a -> a
square x = x*x
```

Works for any type supporting the Num interface

Generics, not subtyping

- Means that in Haskell you must **anticipate** the need to act on arguments of various types

```
f :: Tree -> Int
        vs
f' :: Treelike a => a -> Int
```

(in OO you can **retroactively** sub-class Tree)

No subtyping: inference

- Type annotations:
  - Implicit = the type of a fresh binder is inferred

```
f x = ...
```

  - Explicit = each binder is given a type at its binding site

```
void f( int x ) { ... }
```

- Cultural heritage:
  - Haskell: everything implicit
    type annotations occasionally needed
  - Java: everything explicit;
    type inference occasionally possible

No subtyping: inference

- Type annotations:
  - Implicit = the type of a fresh binder is inferred
    `f x = ...`
  - Explicit = each binder is given a type at its binding site
    `void f( int x ) { ... }`
- Reason:
  - Generics alone => type engine generates **equality constraints**, which it can solve
  - Subtyping => type engine generates **subtyping constraints**, which it cannot solve (uniquely)

OOP can lose information

- In Java (ish):

```
INum inc( INum x )
```

Result: will support INum

Argument: must support INum

- In Haskell:

```
inc :: Num a => a -> a
```

Result has precisely same type as argument

- Compare...

```
x::Float

...(x.inc)...
```

INum

```
x::Float

...(inc x)...
```

Float

Why doesn't this bite in OOP?

- In practice, because many operations work by side effect, result contra-variance doesn't matter too much

```
x.setColour(Blue);
x.setPosition(3,4);
```

None of this changes x's type

- In a purely-functional world, where setColour, setPosition return a new x, result contra-variance might be much more important
- F#'s immutable libraries don't use subclassing (binary methods big issue here too; eg set union)

It bites enough that C# and Java both have a solution

- Java and C# both (now) support **constrained generics**

```
A inc<A>( A x)
  where A:INum {
    ...blah...
}
```

- Very like

```
inc :: Num a => a -> a
```

- (but little used in practice, I believe)

Variance

```
interface IEnumerator<out T> {
   T Current;
   bool MoveNext();
}
```

Legal iff T is only **returned** by methods, but not passed to a method, nor side-effected

- Why? So that this works

```
m( IEnumerator<Control> )
IEnumerator<Button> b
...m(b)...
```

  - Button is a subtype of Control, so
  - IEnumerator<Button> is a subtype of IEnumerator<Control>

Variance

- OOP: must embrace variance
  - Side effects => invariance
  - Generics: type parameters are co/contra/invariant (Java wildcards, C#4.0 variance annotations)
  - Interaction with higher kinds?

```
class Monad m where
  return :: a -> m a
  (>>=)  :: m a -> (a -> m b) -> m b
```

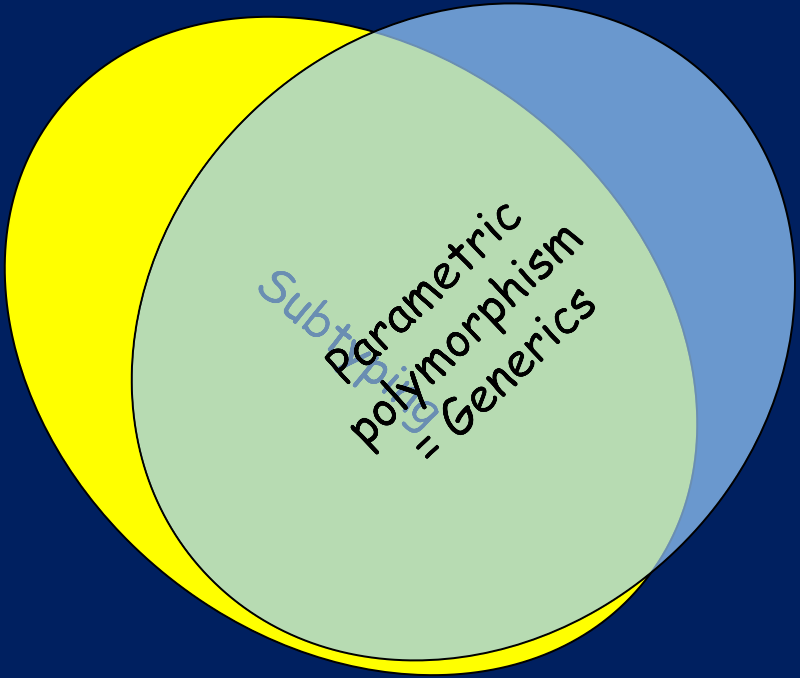
(Only Scala can do this, and it's very tricky!)

- Variance simply does not arise in Haskell.
- And we need constrained polymorphism anyway!

Two approaches to polymorphism

- Each approach has been elaborated considerably over the last decade

Add interfaces, generics, constrained generics



Subtyping

Parametric polymorphism = Generics

Add type classes , type families, existentials

- What differences remain?
- Can one develop a unified story?

Conclusions

- Parametric polymorphism and subtyping both address polymorphism
- Subtyping alone definitely isn't enough
- Having both is Jolly Complicated (honourable mention for Scala).
- Having *all* of both is infeasible (higher kinds, kind polymorphism, ...)
- Parametric polymorphism alone seems pretty close to "enough"

Open question

In a language with
- Generics
- Constrained polymorphism

do you (really) need subtyping too?

James Gosling: What would you take out? What would you put in? To the first, James evoked laughter with the single word: Classes. He would like to replace classes with delegation since **doing delegation right would make inheritance go away**.

http://www.newt.com/wohler/articles/james-gosling-ramblings-1.html