

计算概论A—实验班

函数式程序设计

Functional Programming

胡振江，张 伟

北京大学 计算机学院

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第12章： Monads and More

主要知识点：

Functor、Applicative, Monad

两种提升代码抽象层次的方式

Level 1: **Polymorphic** Functions (over types)

```
length1 :: List a -> Int
```

Level 2: **Generic** Functions (over type constructors)

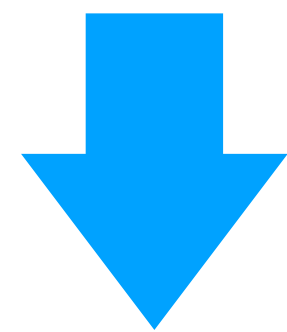
```
length2 :: t a -> Int
```

Functor / 函子

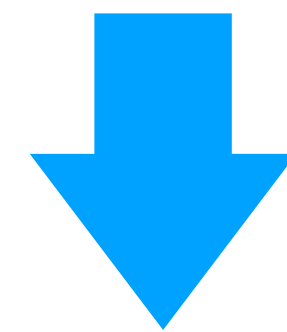
计算的抽象

```
inc :: [Int] -> [Int]
inc [] = []
inc (n:ns) = n+1 : inc ns
```

```
sqr :: [Int] -> [Int]
sqr [] = []
sqr (n:ns) = n^2 : sqr ns
```



抽象



```
map :: (a -> b) -> [a] -> [b]
map f [] = []
map f (x:xs) = f x : map f xs
```

`inc = map (+1)` `sqr = map (^2)`

Functor

```
-- Exported by Prelude
```

```
class Functor f where
```

```
fmap :: (a -> b) -> f a -> f b
```

```
(<$) :: b -> f a -> f b
```

```
(<$) = fmap . const
```

<code>(fmap . const)</code>	<code>b</code>	<code>fa</code>
-----------------------------	----------------	-----------------

<code>fmap</code>	<code>(const b)</code>	<code>fa</code>
-------------------	------------------------	-----------------

```
-- Exported by Prelude
```

```
const :: b -> a -> b
```

```
const x _ = x
```

Functor

```
-- Exported by Prelude  
class Functor f where
```

```
fmap :: (a -> b) -> f a -> f b
```

```
(<$) :: a -> f b -> f a
```

```
(<$) = fmap . const
```

```
ghci> fmap (+1) [1,2,3]  
[2,3,4]
```

```
ghci> fmap (^2) [1,2,3]  
[1,4,9]
```

```
-- Exported by Prelude  
instance Functor [] where
```

```
-- fmap :: (a -> b) -> [a] -> [b]
```

```
fmap = map
```

```
data Maybe a = Nothing | Just a
```

```
instance Functor Maybe where
```

```
  -- fmap :: (a -> b) -> Maybe a -> Maybe b
```

```
  fmap _ Nothing = Nothing
```

```
  fmap g (Just x) = Just (g x)
```

```
ghci> fmap (+1) (Just 3)
```

```
Just 4
```

```
ghci> fmap (+1) Nothing
```

```
Nothing
```

```
ghci> fmap not (Just False)
```

```
Just True
```

```
data Tree a = Leaf a | Node (Tree a) (Tree a)
              deriving (Show)
```

```
instance Functor Tree where
```

```
  -- fmap :: (a -> b) -> Tree a -> Tree b
```

```
  fmap g (Leaf x) = Leaf $ g x
```

```
  fmap g (Node l r) = Node (fmap g l) (fmap g r)
```

```
ghci> fmap length (Leaf "abc")
```

```
Leaf 3
```

```
ghci> fmap even $ Node (Leaf 1) (Leaf 2)
```

```
Node (Leaf False) (Leaf True)
```

```
instance Functor IO where
```

```
  -- fmap :: (a -> b) -> IO a -> IO b
```

```
  fmap g mx = do x <- mx
                 return $ g x
```

```
ghci> fmap show $ return True
"True"
```

Generic Function Definition

```
inc :: Functor f => f Int -> f Int  
inc = fmap (+1)
```

```
ghci> inc $ Just 1  
Just 2
```

```
ghci> inc [1,2,3,4,5]  
[2,3,4,5,6]
```

```
ghci> inc $ Node (Leaf 1) (Leaf 2)  
Node (Leaf 2) (Leaf 3)
```

Functor **Laws**

①

$$\text{fmap id} = \text{id}$$

②

$$\text{fmap (f . g)} = \text{fmap f} . \text{fmap g}$$

✿ For any parameterized type in Haskell, there is at most one function **fmap** that satisfies the required laws.

- ▶ That is, if it is possible to make a given parameterized type into a functor, there is only one way to achieve this.
- ▶ Hence, the instances that we defined for List, Maybe, Tree and IO were all uniquely determined.

`<$>` : An infix synonym for `fmap`

```
-- Exported by Prelude
```

```
(<$>) :: Functor f => (a -> b) -> f a -> f b
```

```
(<$>) = fmap
```

The name of this operator is an allusion to `$`. Note the similarities between their types:

```
( $ )      ::      ( a -> b ) -> a -> b
( <$> )    :: Functor f => ( a -> b ) -> f a -> f b
```

Whereas `$` is function application, `<$>` is function application lifted over a `Functor`.

Applicative

Applicative Functor

如何定义一个一般性的fmap

`fmap0` :: `a -> f a`

`fmap1` :: `(a -> b) -> f a -> f b`

`fmap2` :: `(a -> b -> c) -> f a -> f b -> f c`

`fmap3` :: `(a -> b -> c -> d) -> f a -> f b -> f c -> f d`



两个基本函数

`pure` $::: a \rightarrow f a$

`(<*>)` $::: f (a \rightarrow b) \rightarrow f a \rightarrow f b$

`pure` :: `a` \rightarrow `f a`

`(<*>)` :: `f (a` \rightarrow `b)` \rightarrow `f a` \rightarrow `f b`

`fmap0` :: `a` \rightarrow `f a`

`fmap0` = **`pure`**

`fmap1` :: `(a` \rightarrow `b)` \rightarrow `f a` \rightarrow `f b`

`fmap1` `g` `x` = **`pure`** `g` `<*>` `x`

`fmap1` `g` `x` = **`fmap`** `g` `x` = `g` `<$>` `x`

`fmap2` :: `(a` \rightarrow `b` \rightarrow `c)` \rightarrow `f a` \rightarrow `f b` \rightarrow `fc`

`fmap2` `g` `x` `y` = **`pure`** `g` `<*>` `x` `<*>` `y` = `g` `<$>` `x` `<*>` `y`

`fmap3` :: `(a` \rightarrow `b` \rightarrow `c` \rightarrow `d)` \rightarrow `f a` \rightarrow `f b` \rightarrow `fc` \rightarrow `f d`

`fmap3` `g` `x` `y` `z` = **`pure`** `g` `<*>` `x` `<*>` `y` `<*>` `z` = `g` `<$>` `x` `<*>` `y` `<*>` `z`

Applicative Functor

Applicative Functor: 一个简化版本

```
class Functor f => Applicative f where
  -- Lift a value
  pure :: a -> f a
  -- Sequential application.
  (<*>) :: f (a -> b) -> f a -> f b
```

Applicative Functor: 一个简化版本

```
class Functor f => Applicative f where
  -- Lift a value
  pure :: a -> f a
  -- Sequential application.
  (<*>) :: f (a -> b) -> f a -> f b
```

声明 Maybe 为 Applicative 的一个实例

```
instance Applicative Maybe where
  -- pure :: a -> Maybe a
  pure = Just
  -- (<*>) :: Maybe (a -> b) -> Maybe a -> Maybe b
  Nothing <*> _ = Nothing
  (Just g) <*> mx = g <$> mx
```

Applicative Functor: –

```
class Functor f => Applicative f where
  -- Lift a value
  pure :: a -> f a
  -- Sequential application
  (<*>) :: f (a -> b)
```

```
ghci> pure (+1) <*> Just 1
Just 2
ghci> pure (+) <*> Just 1 <*> Just 2
Just 3
ghci> pure (+) <*> Nothing <*> Just 2
Nothing
ghci> Nothing <*> Just 1
Nothing
```

声明 Maybe 为 Applicative 的一个实例

```
instance Applicative Maybe where
  -- pure :: a -> Maybe a
  pure = Just
  -- (<*>) :: Maybe (a -> b) -> Maybe a -> Maybe b
  Nothing <*> _ = Nothing
  (Just g) <*> mx = g <$> mx
```


声明 [] 为Applicative的一个实例

```
instance Applicative [] where
  -- pure :: a -> [a]
  pure x = [x]

  -- (<*>) :: [a -> b] -> [a] -> [b]
  gs <*> xs = [g x | g <- gs, x <- xs]
```

```
ghci> pure (+1) <*> [1,2,3]
[2,3,4]
ghci> pure (+) <*> [1] <*> [2]
[3]
ghci> pure (*) <*> [1,2] <*> [3,4]
[3,4,6,8]
```

声明 IO 为 Applicative 的一个实例

```
instance Applicative IO where
```

```
  -- pure :: a -> IO a
```

```
  pure = return
```

```
  -- (<*>) :: IO (a -> b) -> IO a -> IO b
```

```
  mg <*> mx = do {g <- mg; x <- mx; return (g x)}
```

```
getChars :: Int -> IO String
```

```
getChars 0 = return []
```

```
getChars n = pure (:) <*> getChar <*> getChars (n-1)
```

Generic Function Definition

```
sequenceA :: Applicative f => [f a] -> f [a]
sequenceA [] = pure []
sequenceA (x:xs) = pure (:) <*> x <*> sequenceA xs
```

```
ghci> sequenceA [Just 1, Just 2, Just 3]
Just [1,2,3]
```

```
ghci> sequenceA [Just 1, Nothing, Just 3]
Nothing
```

```
ghci> sequenceA [[1,2,3], [4,5,6], [7,8,9]]
[[1,4,7],[1,4,8],[1,4,9],[1,5,7],[1,5,8],[1,5,9],[1,6,7],[1,6,8],[1,6,9],
[2,4,7],[2,4,8],[2,4,9],[2,5,7],[2,5,8],[2,5,9],[2,6,7],[2,6,8],[2,6,9],
[3,4,7],[3,4,8],[3,4,9],[3,5,7],[3,5,8],[3,5,9],[3,6,7],[3,6,8],[3,6,9]]
```

Applicative Laws

① $\text{pure id} \langle * \rangle x = x$ 其实就是: $\text{fmap id} = \text{id}$

② $\text{pure (g x)} = \text{pure g} \langle * \rangle \text{pure x}$

③ $x \langle * \rangle \text{pure y} = \text{pure (\g -> g y)} \langle * \rangle x$

④ $x \langle * \rangle (y \langle * \rangle z) = (\text{pure (.)} \langle * \rangle x \langle * \rangle y) \langle * \rangle z$

Applicative Laws: 类型分析

pure id $\langle * \rangle$ **x = x**

a -> a

f a

pure (g x) = **pure g** $\langle * \rangle$ **pure x**

f b

a -> b

a

Applicative Laws: 类型分析

$x \langle * \rangle \text{pure } y = \text{pure } (\backslash g \rightarrow g y) \langle * \rangle x$

$f (a \rightarrow b)$

a

$f ((a \rightarrow b) \rightarrow b)$

$x \langle * \rangle (y \langle * \rangle z) = (\text{pure } (.) \langle * \rangle x \langle * \rangle y) \langle * \rangle z$

Applicative Laws: 类型分析

$$x \langle * \rangle \text{pure } y = \text{pure } (\backslash g \rightarrow g y) \langle * \rangle x$$

$f (a \rightarrow b)$

a

$f ((a \rightarrow b) \rightarrow b)$

$f (b \rightarrow c)$

$f (a \rightarrow c)$

$$x \langle * \rangle (y \langle * \rangle z) = (\text{pure } (.) \langle * \rangle x \langle * \rangle y) \langle * \rangle z$$

$f (a \rightarrow b)$

$f a$

Monad

一个小问题：异常处理

```
data Expr = Val Int | Div Expr Expr  
  
eval :: Expr -> Int  
eval (Val n) = n  
eval (Div x y) = eval x `div` eval y
```

```
ghci> eval $ Div (Val 1) (Val 0)  
*** Exception: divide by zero
```

解决方法1

```
safediv :: Int -> Int -> Maybe Int
safediv _ 0 = Nothing
safediv n m = Just (n `div` m)
```

```
eval :: Expr -> Maybe Int
eval (Val n) = Just n
eval (Div x y) = case eval x of
    Nothing -> Nothing
    Just n -> case eval y of
        Nothing -> Nothing
        Just m -> safediv n m
```

稍显繁杂

解决方法2

```
safediv :: Int -> Int -> Maybe Int  
safediv _ 0 = Nothing  
safediv n m = Just (n `div` m)
```

```
eval :: Expr -> Maybe Int  
eval (Val n) = pure n  
eval (Div x y) = pure safediv <*> eval x <*> eval y
```

类型错误

type: Maybe (Maybe Int)

解决方法2

```
safediv :: Int -> Int -> Maybe Int
safediv _ 0 = Nothing
safediv n m = Just (n `div` m)
```

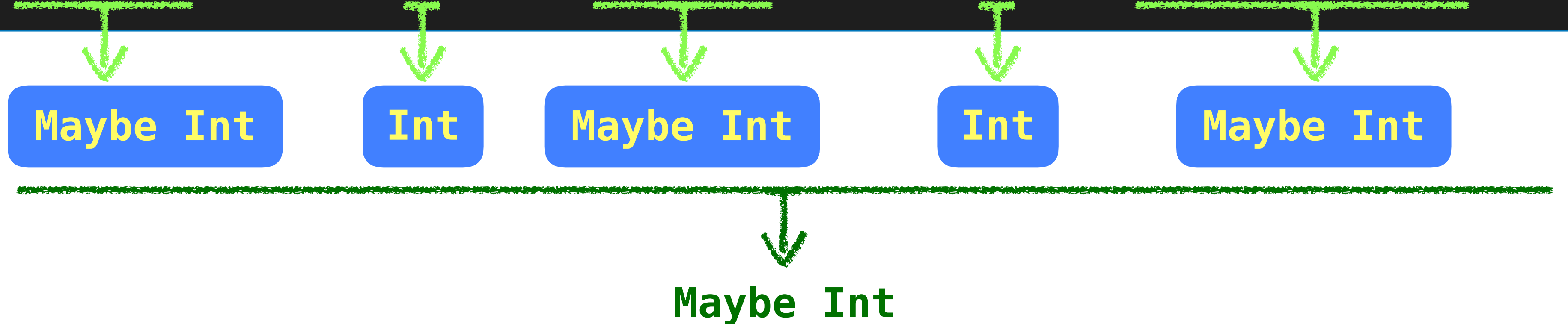
```
eval :: Expr -> Maybe Int      Maybe (Maybe Int)
eval (Val n) = pure n
eval (Div x y) = case pure safediv <*> eval x <*> eval y of
  Just r -> r
  Nothing -> Nothing
```

还是不够简洁

解决方法3: 引入一个新的操作 **bind**

```
(>>=) :: Maybe a -> (a -> Maybe b) -> Maybe b  
mx >>= f = case mx of  
  Nothing -> Nothing  
  Just x   -> f x
```

```
eval :: Expr -> Maybe Int  
eval (Val n) = Just n  
eval (Div x y) = eval x >>= (\n -> (eval y >>= (\m -> safediv n m)))
```



解决方法3: 引入一个新的操作 `bind`

```
(>>=) :: Maybe a -> (a -> Maybe b) -> Maybe b  
mx >>= f = case mx of  
    Nothing -> Nothing  
    Just x   -> f x
```

```
eval :: Expr -> Maybe Int  
eval (Val n) = Just n  
eval (Div x y) = eval x >>= (\n -> (eval y >>= (\m -> safediv n m)))
```

先耍一点朝三暮四的小把戏

```
eval :: Expr -> Maybe Int  
eval (Val n) = Just n  
eval (Div x y) = eval x >>= \n ->  
    eval y >>= \m ->  
    safediv n m
```

```
eval :: Expr -> Maybe Int  
eval (Val n) = Just n  
eval (Div x y) = do n <- eval x  
    m <- eval y  
    safediv n m
```

再撒一点扑朔迷离的语法糖

Monad

```
{- The Monad class defines the basic operations over a monad,  
a concept from a branch of mathematics known as "category theory".  
From the perspective of a Haskell programmer, however,  
it is best to think of a monad as an abstract datatype of actions.  
The do expressions provide a convenient syntax for writing monadic expressions.-}  
class Applicative m => Monad m where
```

```
-- Inject a value into the monadic type.
```

```
return :: a -> m a
```

```
return = pure
```

`a >>= f`

`=`

`do v <- a
f v`

```
-- Sequentially compose two actions,
```

```
-- passing any value produced by the first as an argument to the second.
```

```
(>>=) :: m a -> (a -> m b) -> m b
```

```
-- Sequentially compose two actions, discarding any value produced by the first,
```

```
-- like sequencing operators (such as the semicolon) in imperative languages.
```

```
(>>) :: m a -> m b -> m b
```

```
m >> k = m >>= \_ -> k
```

`a >> b`

`=`

`do a
b`

`=`

`do v <- a
b`

声明 Maybe 为 Monad 的一个实例

```
class Applicative m => Monad m where
  return :: a -> m a
  return = pure

  (>>=) :: m a -> (a -> m b) -> m b

  (>>) :: m a -> m b -> m b
  m >> k = m >>= \_ -> k
```

```
instance Monad Maybe where
  -- (>>=) :: Maybe a -> (a -> Maybe b) -> Maybe b
  Nothing >>= _ = Nothing
  (Just x) >>= f = f x
```


声明 [] 为Monad的一个实例

```
class Applicative m => Monad m where
  return :: a -> m a
  return = pure

  (>>=) :: m a -> (a -> m b) -> m b

  (>>) :: m a -> m b -> m b
  m >> k = m >>= \_ -> k
```

```
instance Monad [] where
  -- (>>=) :: [a] -> (a -> [b]) -> [b]
  xs >>= f = [y | x <- xs, y <- f x]
```

The State Monad

❖ 问题：如何用函数描述状态的变化

▶ 状态：一种数据类型

– `type State = Int`

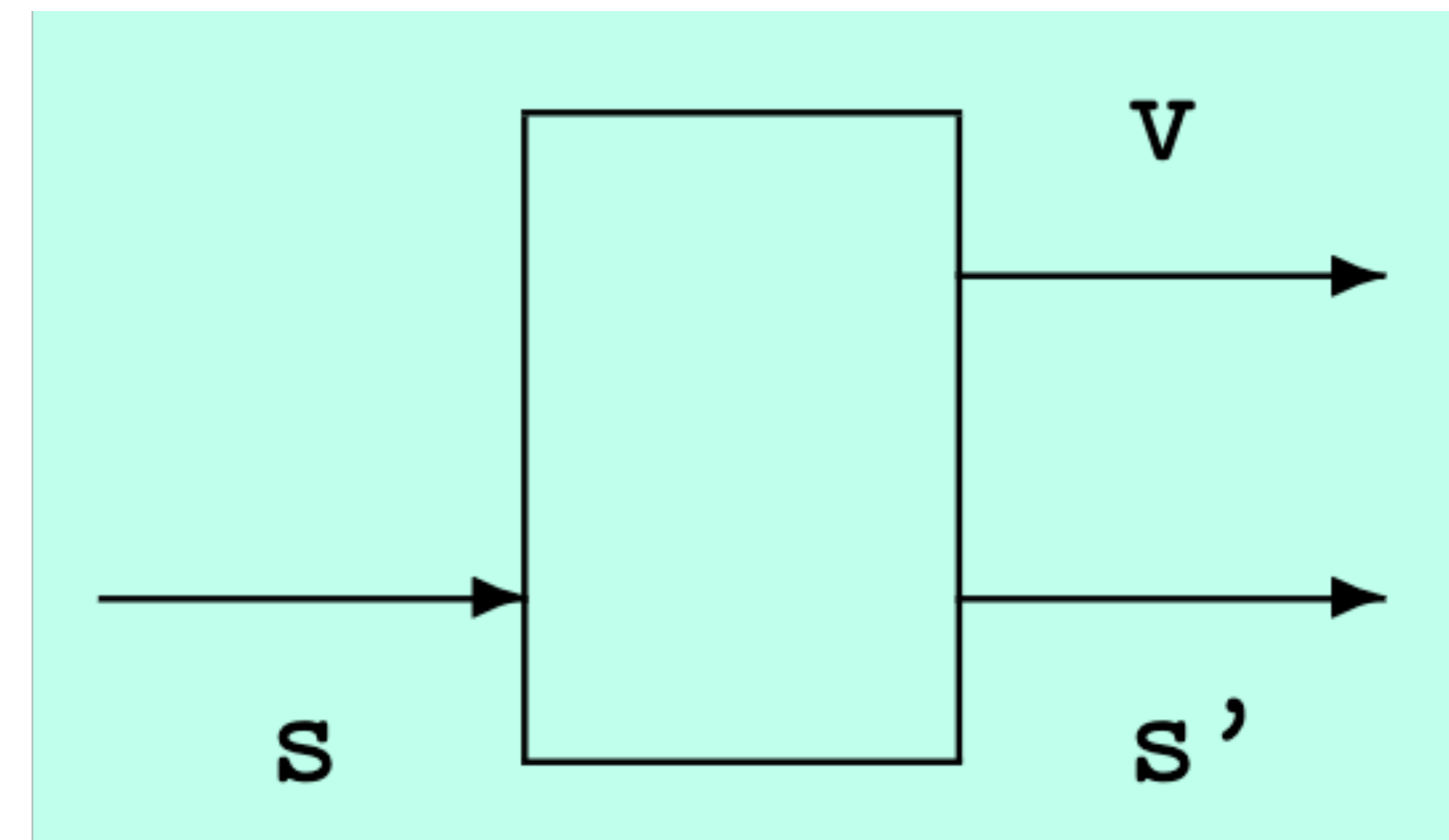
– 仅仅是一个示例；需根据具体问题确定状态的类型

▶ 状态变换器

– `type ST = State -> State`

▶ 带有结果的状态变换器

– `type ST a = State -> (a, State)`



用 newtype 定义 ST

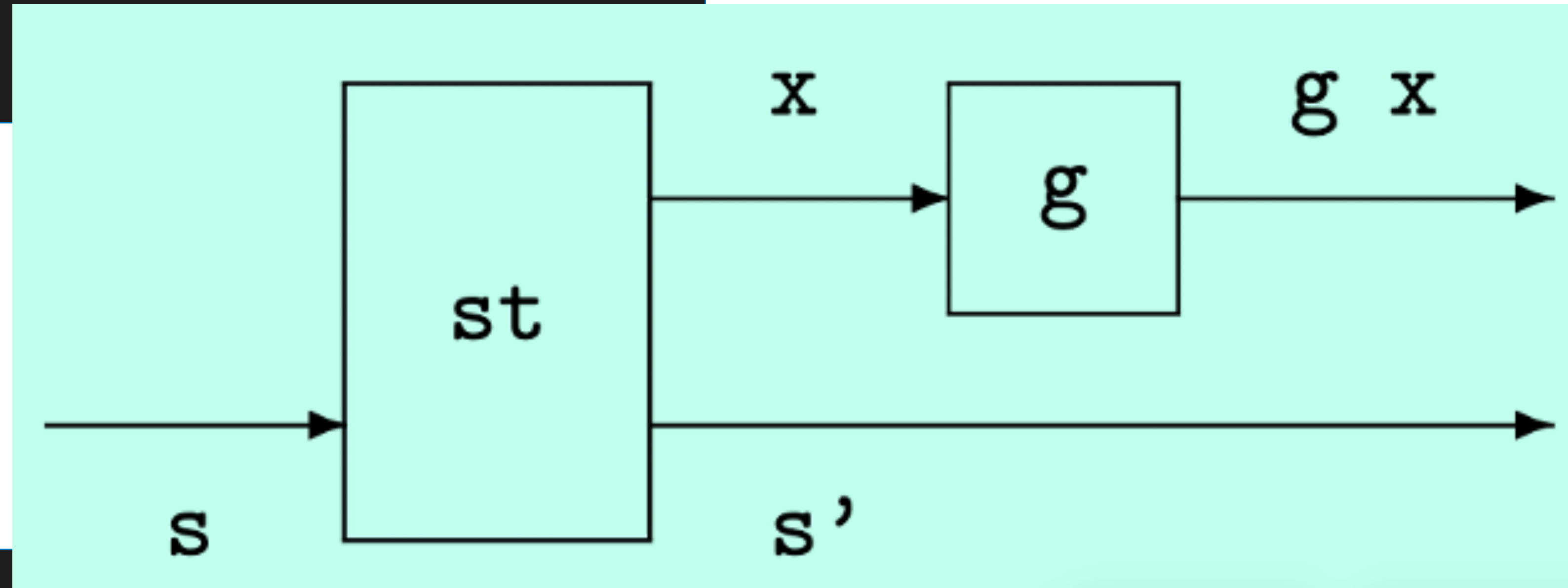
```
newtype ST a = S (State -> (a, State))  
app :: ST a -> State -> (a, State)  
app (S f) s = f s
```

将 ST 声明为 Functor 的实例

```
newtype ST a = S (State -> (a, State))
```

```
app :: ST a -> State -> (a, State)
```

```
app (S f) s = f s
```



```
instance Functor ST where
```

```
  -- fmap :: (a -> b) -> ST a -> ST b
```

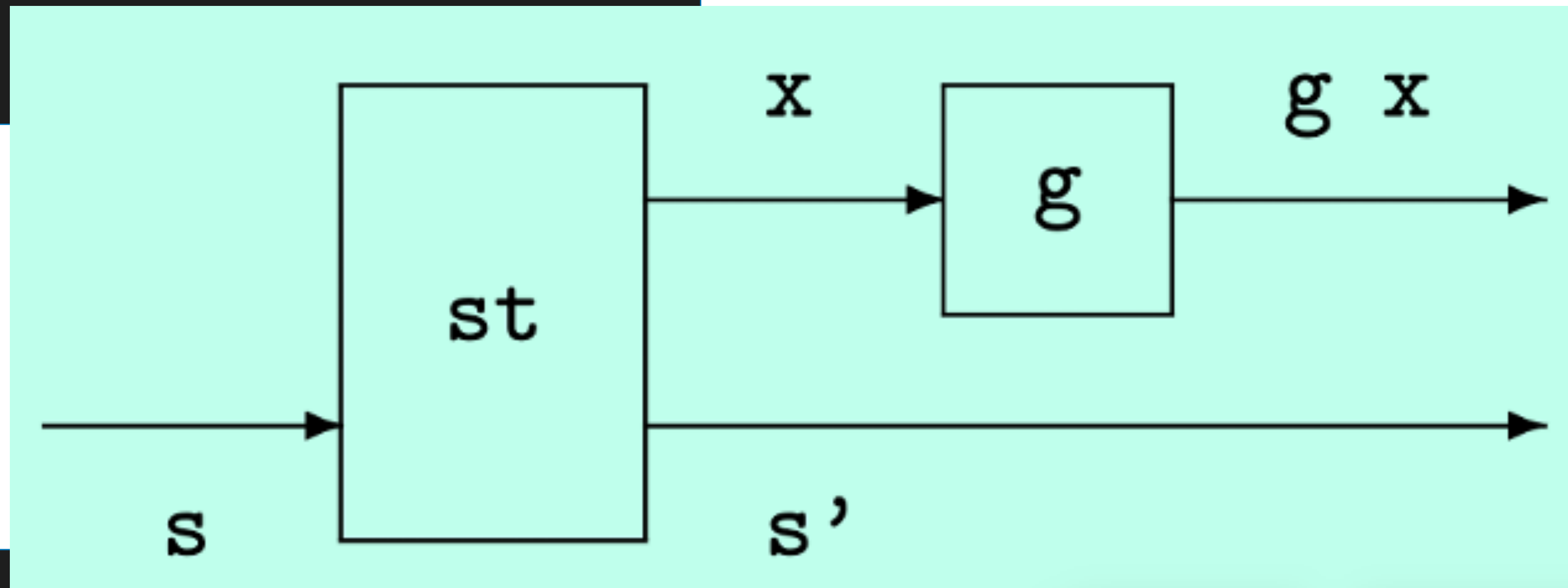
```
  fmap g st = S
```

将 ST 声明为 Functor 的实例

```
newtype ST a = S (State -> (a, State))
```

```
app :: ST a -> State -> (a, State)
```

```
app (S f) s = f s
```



```
instance Functor ST where
```

```
  -- fmap :: (a -> b) -> ST a -> ST b
```

```
  fmap g st = S $ \s -> let (x, s') = app st s in (g x, s')
```

将 ST 声明为 Applicative 的实例

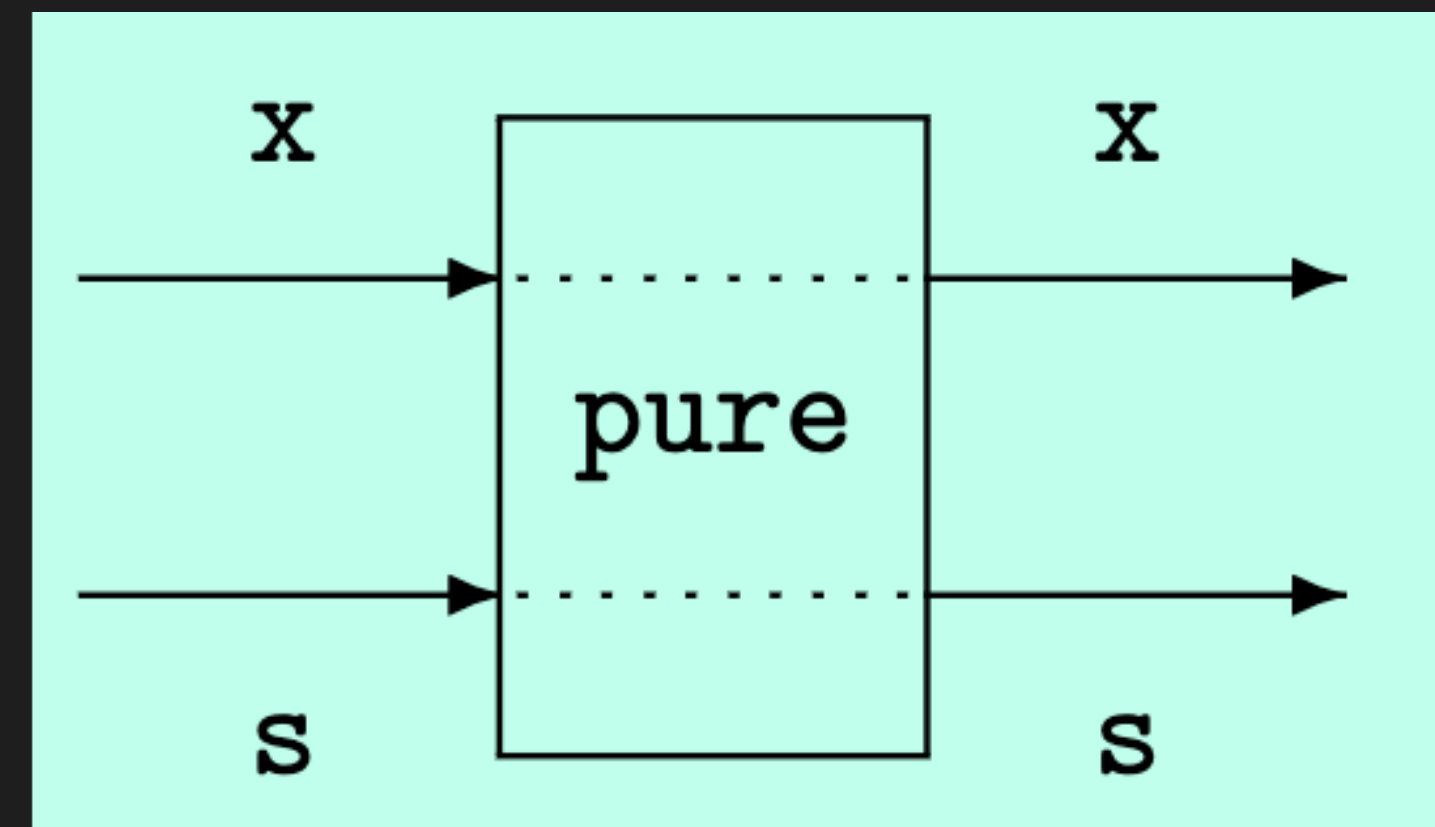
```
instance Applicative ST where
```

```
-- pure :: a -> ST a
```

```
pure x = S
```

```
-- (<*>) :: ST (a -> b) -> ST a -> ST b
```

```
stf <*> stx = S
```



```
newtype ST a = S (State -> (a, State))
```

```
app :: ST a -> State -> (a, State)
```

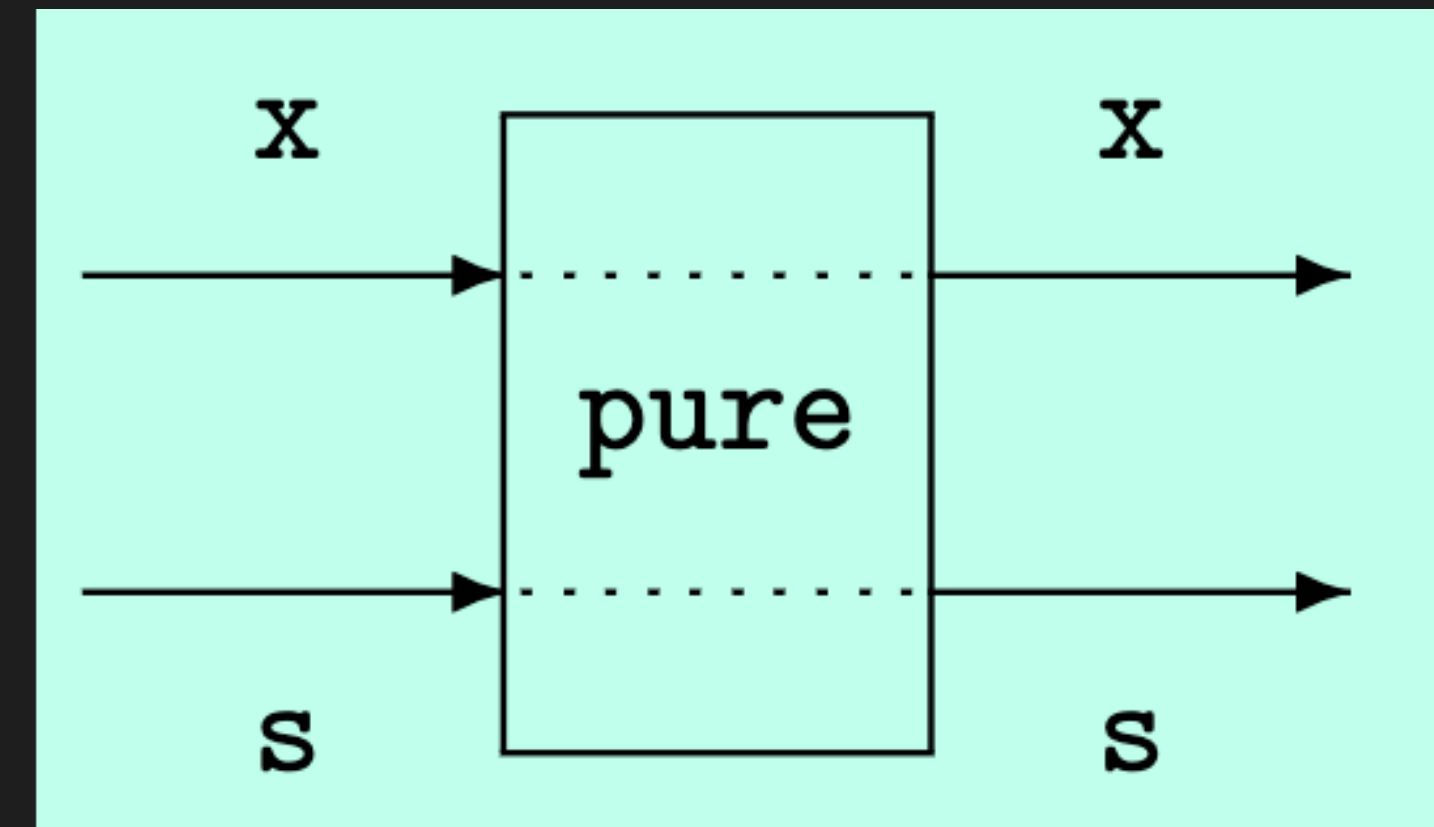
```
app (S f) s = f s
```


将 ST 声明为 Applicative 的实例

```
instance Applicative ST where
```

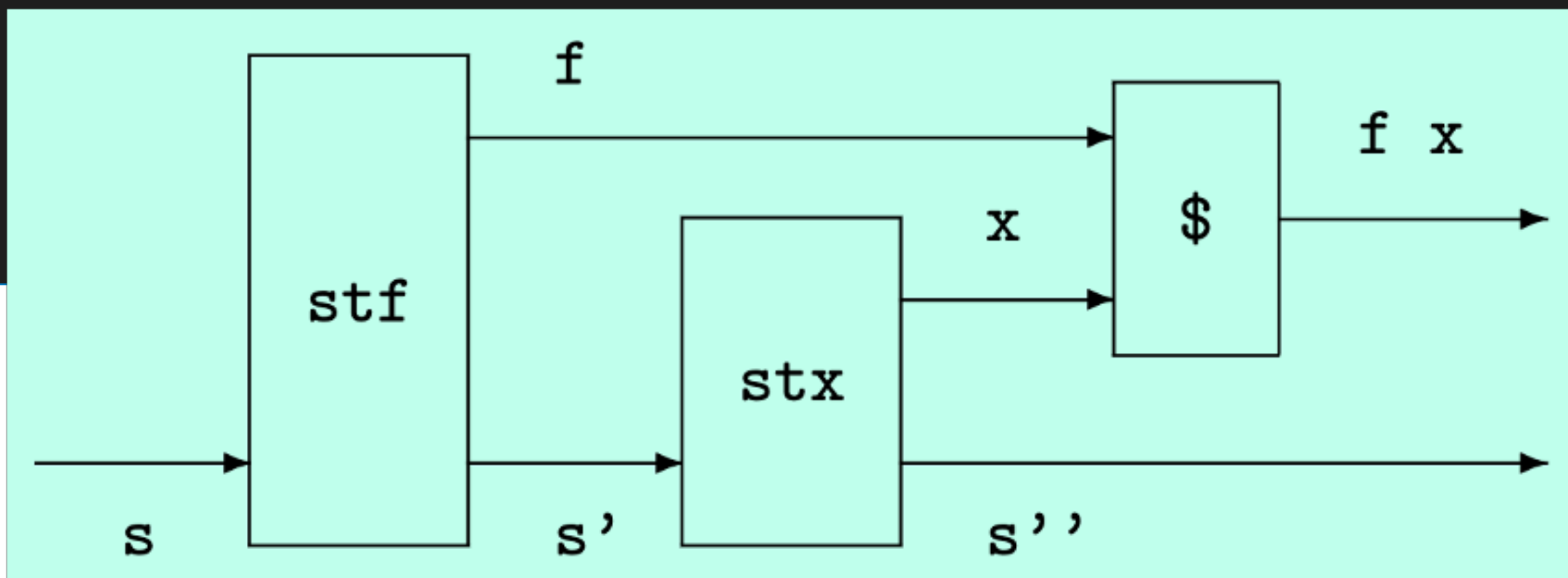
```
  -- pure :: a -> ST a
```

```
  pure x = S $ \s -> (x, s)
```



```
  -- (<*>) :: ST (a -> b) -> ST a -> ST b
```

```
  stf <*> stx = S
```



```
newtype ST a = S (State -> (a, State))
```

```
app :: ST a -> State -> (a, State)
```

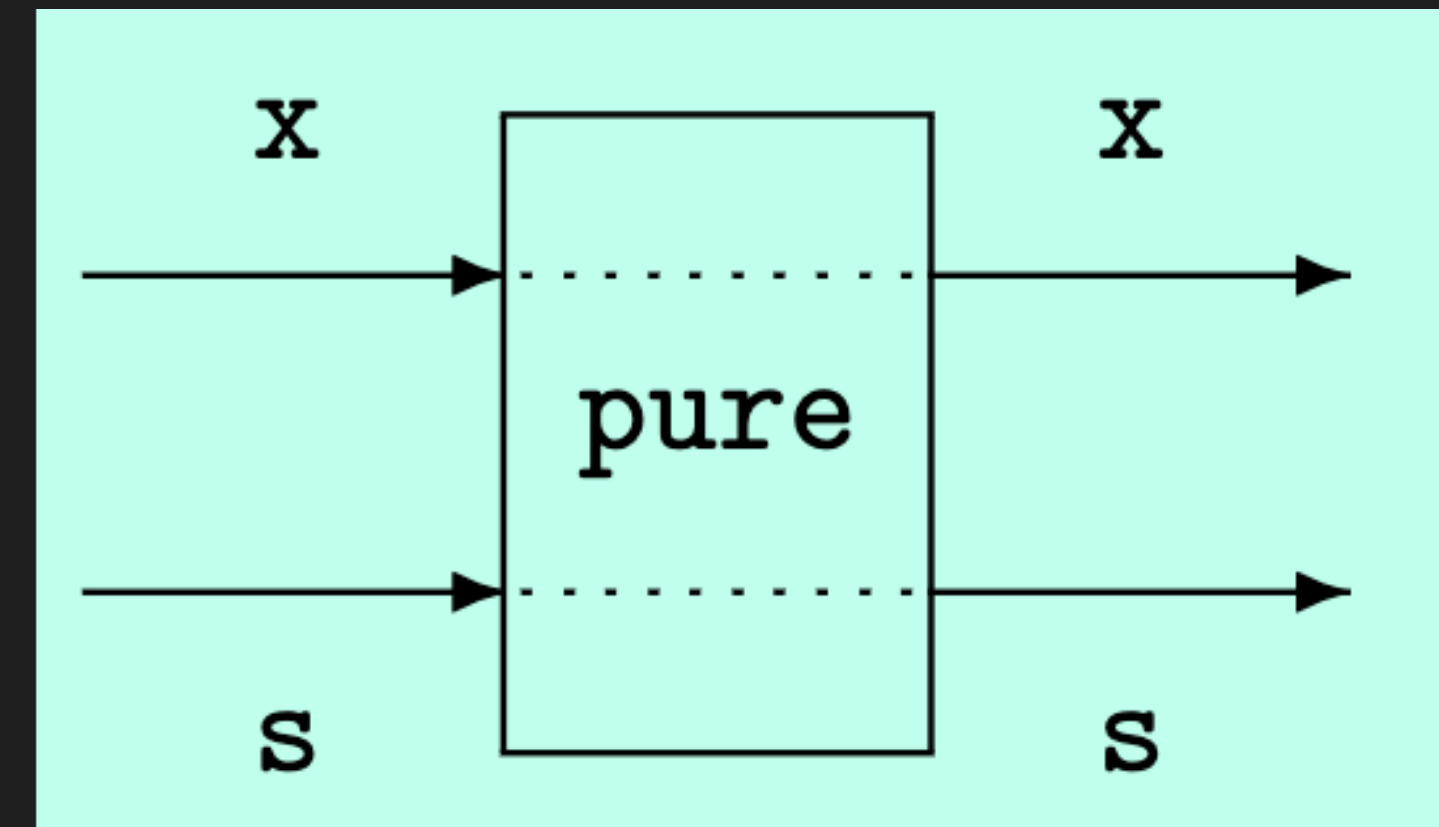
```
app (S f) s = f s
```

将 ST 声明为 Applicative 的实例

```
instance Applicative ST where
```

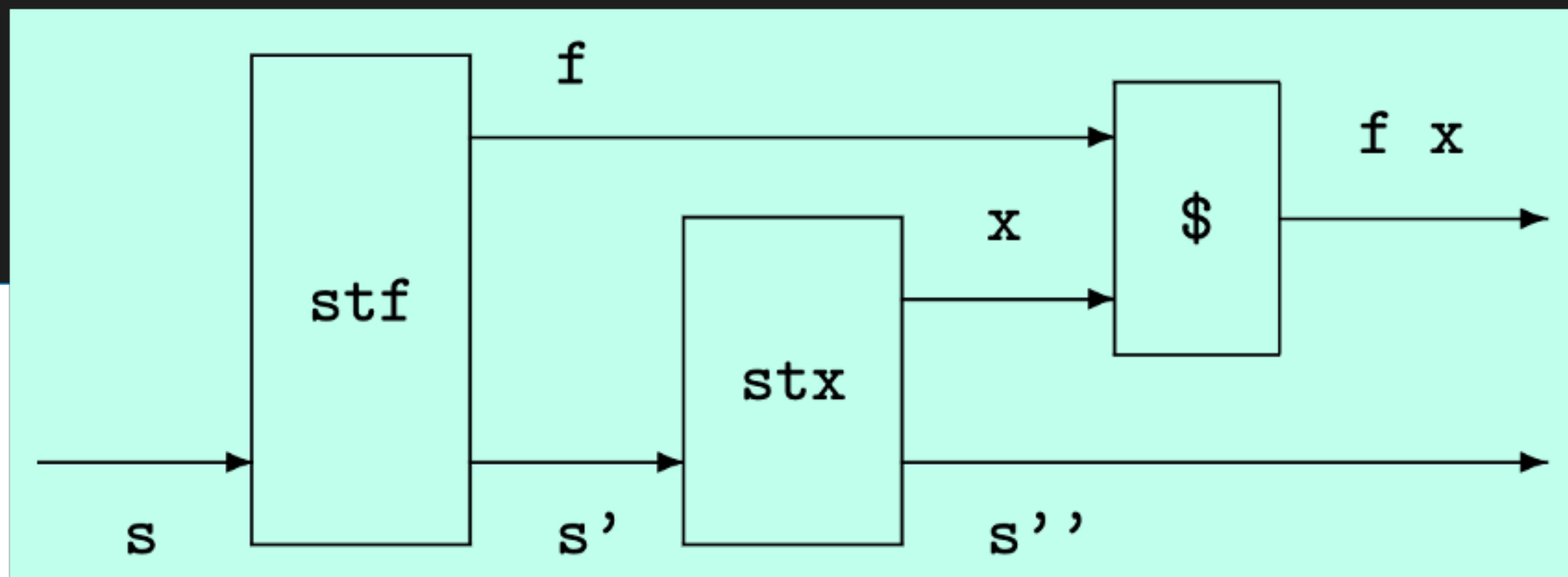
```
-- pure :: a -> ST a
```

```
pure x = S $ \s -> (x, s)
```



```
-- (<*>) :: ST (a -> b) -> ST a -> ST b
```

```
stf <*> stx = S $ \s -> let (f, s') = app stf s  
                             (x, s'') = app stx s'  
                             in (f x, s'')
```



```
newtype ST a = S (State -> (a, State))
```

```
app :: ST a -> State -> (a, State)
```

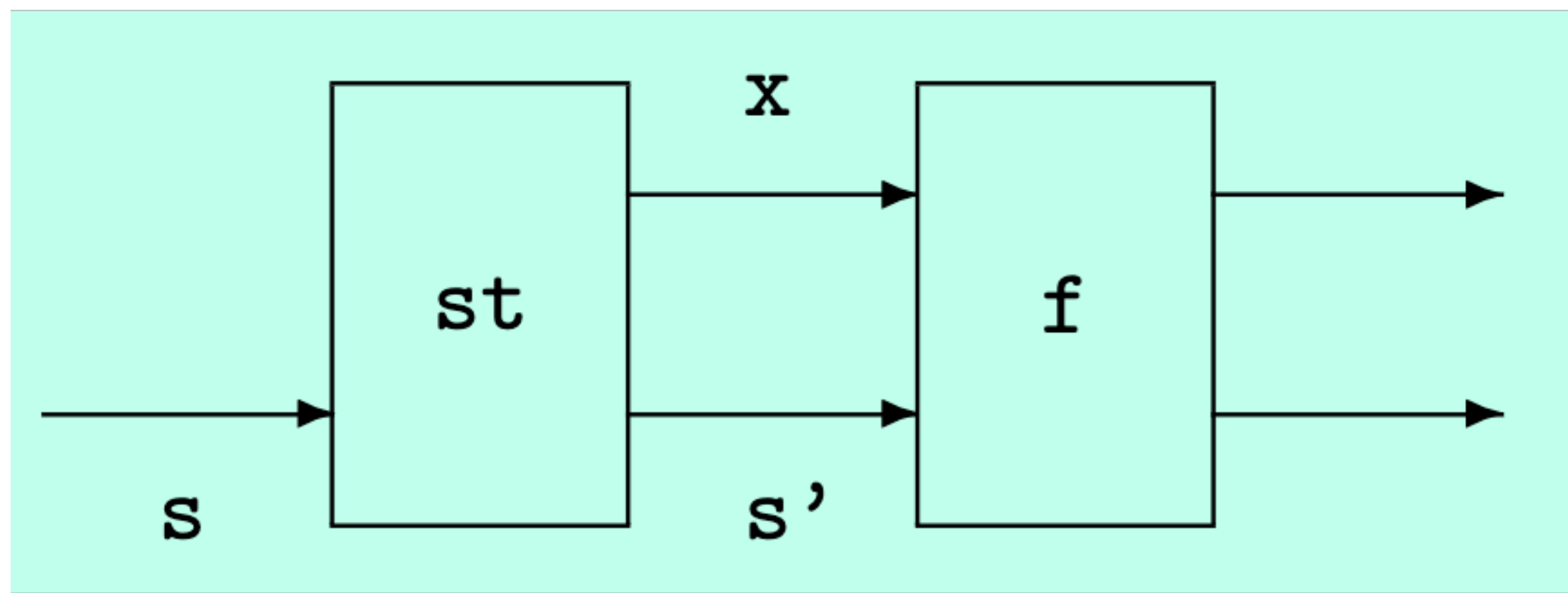
```
app (S f) s = f s
```


将 ST 声明为 Monad 的实例

```
instance Monad ST where
```

```
-- (>>=) :: ST a -> (a -> ST b) -> ST b
```

```
st >>= f = S
```



```
newtype ST a = S (State -> (a, State))
```

```
app :: ST a -> State -> (a, State)
```

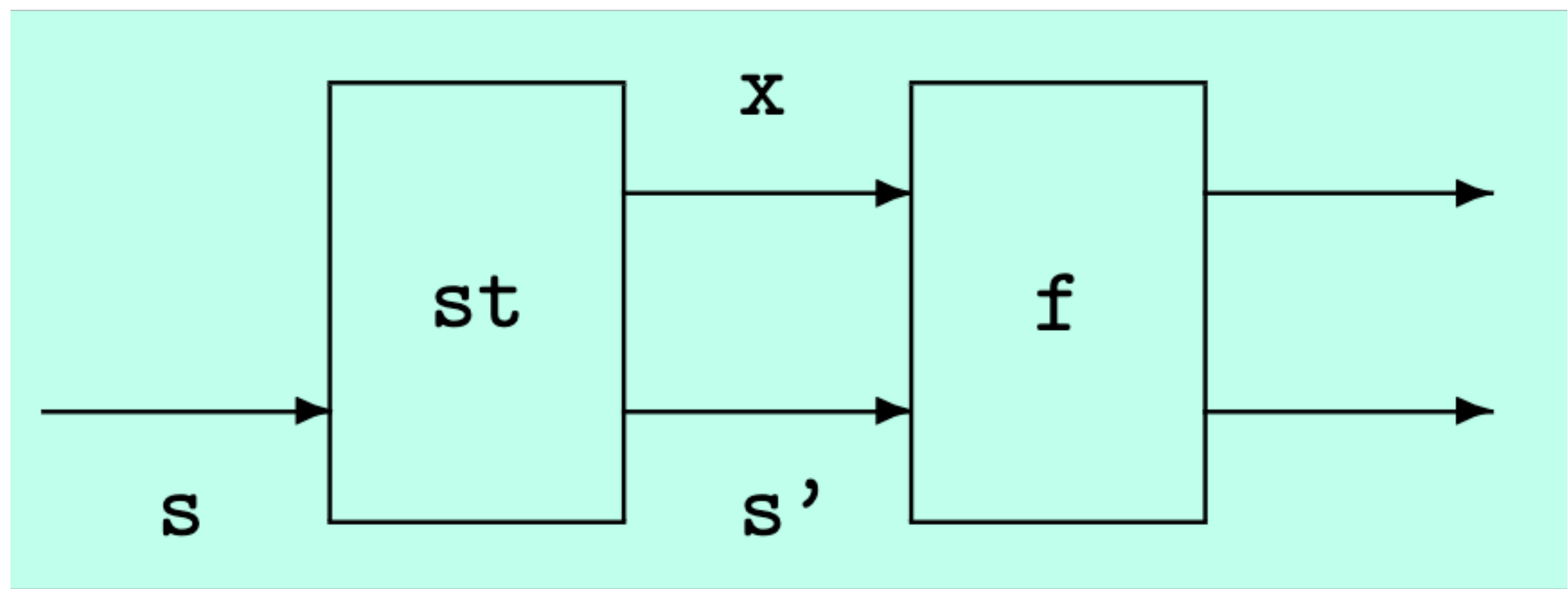
```
app (S f) s = f s
```

将 ST 声明为 Monad 的实例

```
instance Monad ST where
```

```
-- (>>=) :: ST a -> (a -> ST b) -> ST b
```

```
st >>= f = S $ \s -> let (x, s') = app st s  
                        in app (f x) s'
```



```
newtype ST a = S (State -> (a, State))  
app :: ST a -> State -> (a, State)  
app (S f) s = f s
```

The State Monad

这几张幻灯片讲的挺好的
下次不要再讲了

感觉讲了一些无用的废话

在我第一次看到State Monad时
内心的想法其实也和你们差不多



The State Monad 之 应用示例：树的重新标注

```
data Tree a = Leaf a | Node (Tree a) (Tree a)
              deriving Show

tree :: Tree Char
tree = Node (Node (Leaf 'a') (Leaf 'b')) (Leaf 'c')
```

- ✿ Consider the problem of defining a function that relabels each leaf in such a tree with a unique or fresh integer.

```
ghci> relabel tree
Node (Node (Leaf 0) (Leaf 1)) (Leaf 2)
```

树的重新标注 之 方法一：朴实无华~隐入尘烟

```
rlabel :: Tree a -> Int -> (Tree Int, Int)
rlabel (Leaf _) n = (Leaf n, n+1)
rlabel (Node l r) n = (Node l' r', n'')
    where (l', n') = rlabel l n
          (r', n'') = rlabel r n'
```

```
relabel :: Tree a -> Tree Int
relabel t = fst (rlabel t 0)
```

缺点： rlabel 的定义中
需要显式维护中间状态

```
ghci> relabel tree
```

```
Node (Node (Leaf 0) (Leaf 1)) (Leaf 2)
```


树的重新标注 之 方法二：Applicative

```
fresh :: ST Int
```

```
fresh = S $ \n -> (n, n+1)
```

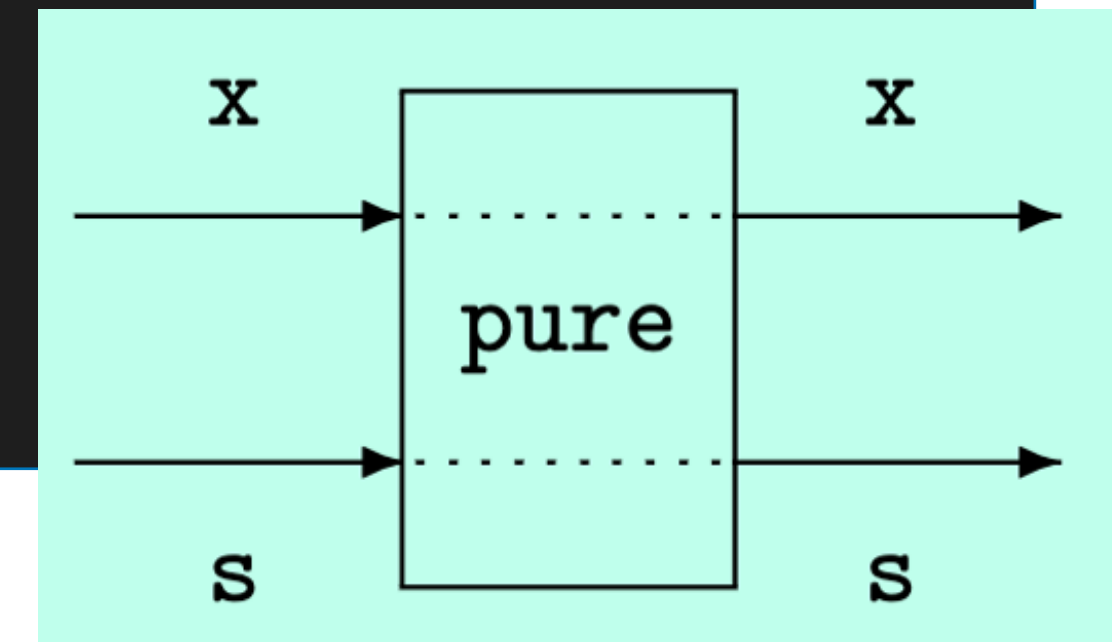
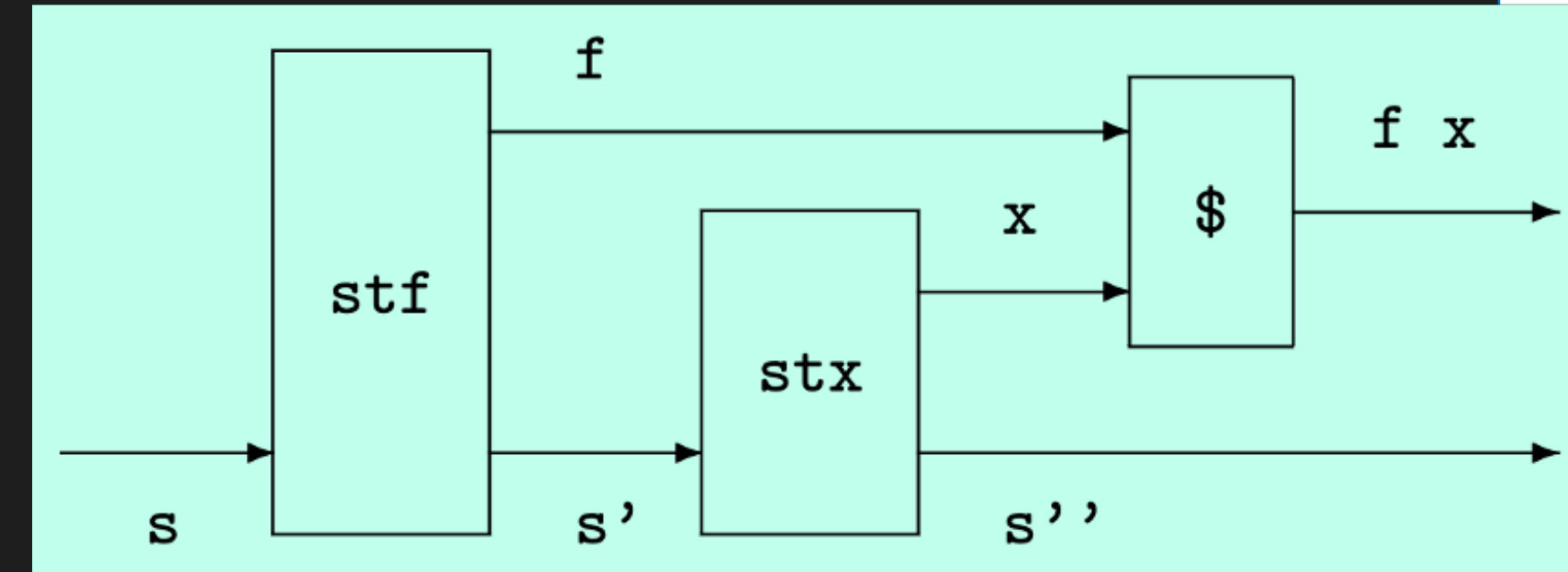
```
alabel :: Tree a -> ST (Tree Int)
```

```
alabel (Leaf _) = Leaf <$> fresh
```

```
alabel (Node l r) = Node <$> alabel l <*> alabel r
```

```
relabel' :: Tree a -> Tree Int
```

```
relabel' t = fst $ app (alabel t) 0
```



$\<\$ \> = \text{`fmap`}$

or

$g \<\$ \> x = \text{pure } g \<*\> x$

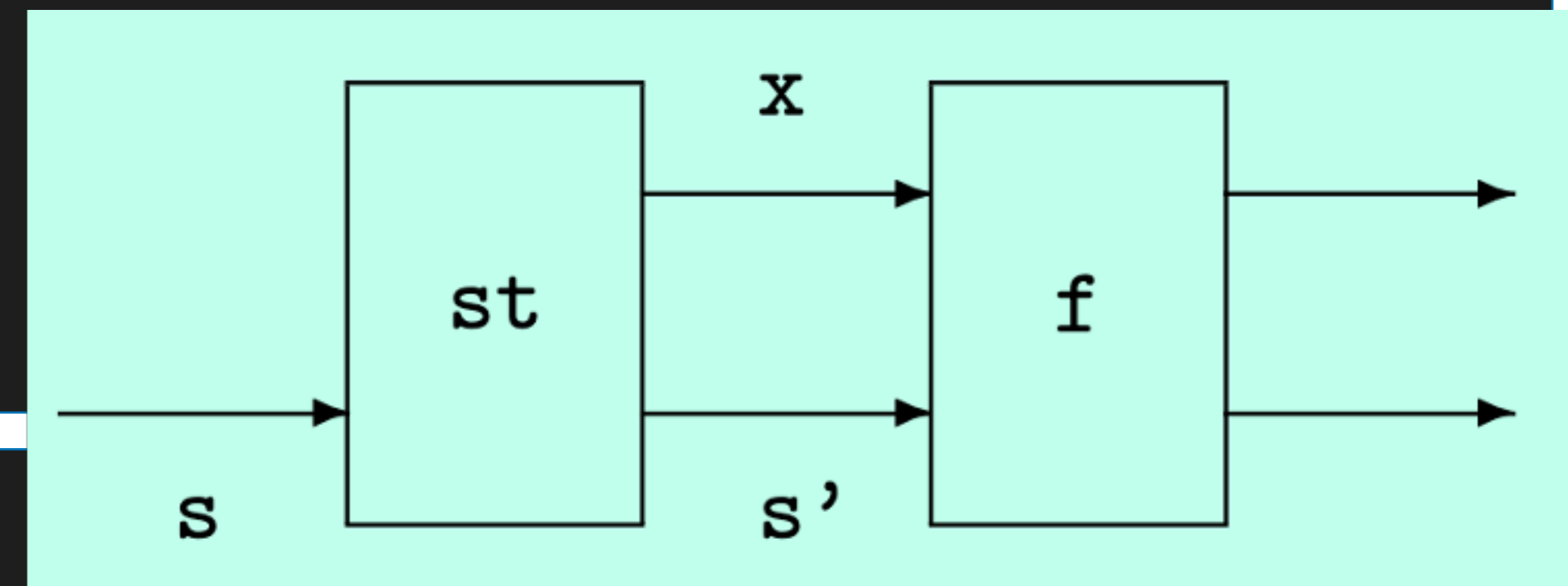
我时常在想，这些东西是永恒的吗？
如果是，它们栖身何处，以至可以被人类发现并表达



树的重新标注 之 方法三: Monad

```
mlabel :: Tree a -> ST (Tree Int)
mlabel (Leaf _) = fresh >>= \n -> return $ Leaf n
mlabel (Node l r) = mlabel l >>= \l' ->
                    mlabel r >>= \r' -> return $ Node l' r'
```

```
relabel'' :: Tree a -> Tree Int
relabel'' t = fst $ app (mlabel t) 0
```



```
mlabel (Leaf _) = do n <- fresh
                    return (Leaf n)
mlabel (Node l r) = do l' <- mlabel l
                       r' <- mlabel r
                       return $ Node l' r'
```

使用 do 改写 mlabel

Monad Laws

Left identity

`return a >>= h = h a`

Right identity

`m x >>= return = m x`

Associativity

`(m x >>= g) >>= h = m x >>= (\x -> g x >>= h)`

`(m x >>= \x -> g x) >>= h = m x >>= (\x -> g x >>= h)`

```
class Applicative m => Monad m where
```

```
  return :: a -> m a
```

```
  return = pure
```

```
  (>>=) :: m a -> (a -> m b) -> m b
```

```
  (>>)  :: m a -> m b -> m b
```

```
  m >> k = m >>= \_ -> k
```


Monad Laws: Another Form

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

```
-- The monad-composition operator
-- defined in Control.Monad
```

```
(>=>) :: Monad m => (a -> m b) -> (b -> m c) -> (a -> m c)
f >=> g    = \x -> f x >>= g
```

Left identity

`return a >>= h = h a`

`(\x -> return x >>= h) a = h a`

`(return >=> h) a = h a`

`return >=> h = h`

看！是不是 Left identity

Monad Laws: Another Form

```
-- The monad-composition operator  
-- defined in Control.Monad
```

```
(>=>) :: Monad m => (a -> m b) -> (b -> m c) -> (a -> m c)  
f >=> g      = \x -> f x >>= g
```

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

Right identity

<code>mb</code>	<code>>>=</code>	<code>return</code>	<code>=</code>	<code>mb</code>
<code>f a</code>	<code>>>=</code>	<code>return</code>	<code>=</code>	<code>f a</code>
<code>(\x -> f x</code>	<code>>>=</code>	<code>return) a</code>	<code>=</code>	<code>f a</code>
<code>(</code>	<code>>=></code>	<code>return) a</code>	<code>=</code>	<code>f a</code>
<code>f</code>	<code>>=></code>	<code>return</code>	<code>=</code>	<code>f</code>

我时常在想，“朝三暮四”是个贬义词吗？



Monad Laws: Another Form

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

```
-- The monad-composition operator
-- defined in Control.Monad
```

```
(>=>) :: Monad m => (a -> m b) -> (b -> m c) -> (a -> m c)
f >=> g    = \x -> f x >>= g
```

Assoc

$(mb \gg= g) \gg= h = mb \gg= (\lambda x \rightarrow g\ x \gg= h)$
$(f\ a \gg= g) \gg= h = f\ a \gg= (\lambda x \rightarrow g\ x \gg= h)$
$(f\ a \gg= g) \gg= h = f\ a \gg= (g \gg=> h)$
$(\lambda x \rightarrow f\ x \gg= g)\ a \gg= h = f\ a \gg= (g \gg=> h)$
$(f \gg=> g)\ a \gg= h = f\ a \gg= (g \gg=> h)$
$(\lambda x \rightarrow (f \gg=> g)\ x \gg= h)\ a = (\lambda x \rightarrow f\ x \gg= (g \gg=> h))\ a$
$((f \gg=> g) \gg=> h)\ a = (f \gg=> (g \gg=> h))\ a$
$(f \gg=> g) \gg=> h = f \gg=> (g \gg=> h)$

Monad Laws

Left identity

`return a >>= h = h a`

Right identity

`m x >>= return = m x`

Associativity

`(m x >>= g) >>= h = m x >>= (\x -> g x >>= h)`

`(m x >>= \x -> g x) >>= h = m x >>= (\x -> g x >>= h)`

```
class Applicative m => Monad m where
```

```
  return :: a -> m a
```

```
  return = pure
```

```
  (>>=) :: m a -> (a -> m b) -> m b
```

```
  (>>)  :: m a -> m b -> m b
```

```
  m >> k = m >>= \_ -> k
```

Monad Laws: Another Form

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

```
-- The monad-composition operator
-- defined in Control.Monad
```

```
(>=>) :: Monad m => (a -> m b) -> (b -> m c) -> (a -> m c)
f >=> g    = \x -> f x >>= g
```

Left identity

`return a >>= h = h a`

`(\x -> return x >>= h) a = h a`

`(return >=> h) a = h a`

`return >=> h = h`

看！是不是 Left identity

Monad Laws: Another Form

```
-- The monad-composition operator  
-- defined in Control.Monad
```

```
(>=>) :: Monad m => (a -> m b) -> (b -> m c) -> (a -> m c)  
f >=> g      = \x -> f x >>= g
```

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

Right identity

mb	>>=	return	=	mb
f a	>>=	return	=	f a
(\x -> f x	>>=	return) a	=	f a
(f	>=>	return) a	=	f a
f	>=>	return	=	f

我时常在想，“朝三暮四”是个贬义词吗？



Monad Laws: Another Form

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

```
-- The monad-composition operator
-- defined in Control.Monad
```

```
(>=>) :: Monad m => (a -> m b) -> (b -> m c) -> (a -> m c)
f >=> g    = \x -> f x >>= g
```

Assoc

$(mb \gg= g) \gg= h = mb \gg= (\lambda x \rightarrow g x \gg= h)$
$(f a \gg= g) \gg= h = f a \gg= (\lambda x \rightarrow g x \gg= h)$
$(f a \gg= g) \gg= h = f a \gg= (g \gg=> h)$
$(\lambda x \rightarrow f x \gg= g) a \gg= h = f a \gg= (g \gg=> h)$
$(f \gg=> g) a \gg= h = f a \gg= (g \gg=> h)$
$(\lambda x \rightarrow (f \gg=> g) x \gg= h) a = (\lambda x \rightarrow f x \gg= (g \gg=> h)) a$
$((f \gg=> g) \gg=> h) a = (f \gg=> (g \gg=> h)) a$
$(f \gg=> g) \gg=> h = f \gg=> (g \gg=> h)$

Monad Laws in practice

Left identity

```
do { x' <- return x; f x' }
```

```
return x >>= \x' -> f x'
```

```
return x >>= f
```

```
f x
```

```
do { f x }
```


Monad Laws in practice

Right identity

```
do { x <- mx; return x }
```

```
mx >>= \x -> return x
```

```
mx >>= return
```

```
mx
```

```
do { mx }
```

Monad Laws in practice

Associativity

```
do { y <- do { x <- mx; f x }; g y }
```

```
do { x <- mx; f x } >>= \y -> g y
```

```
( mx >>= \x -> f x ) >>= \y -> g y
```

```
( mx >>= f ) >>= g
```

```
mx >>= (\x -> f x >>= g)
```

```
do { x <- mx; do { y <- f x; g y } }
```

```
do { x <- mx; y <- f x; g y }
```

Monad Laws in practice

```
skip_and_get = do unused <- getLine  
                 line  <- getLine  
                 return line
```

|| Right identity

```
skip_and_get = do unused <- getLine  
                 getLine
```

Monad Laws in practice

```
main = do answer <- skip_and_get  
        putStrLn answer
```

|| inlining

```
main = do answer <- do { unused <- getLine;  
                        getLine }  
        putStrLn answer
```

|| Associativity

```
main = do unused <- getLine  
        answer <- getLine  
        putStrLn answer
```

这些law根本不是什么约束
而是天然就应该存在的

Monads as computation

- ❖ Monadic computations have results.
 - ▶ This is reflected in the types. Given a monad M , a value of type $M\ t$ is a computation resulting in a value of type t .
- ❖ For any value, there is a computation which "does nothing", and produces that result.
 - ▶ `return :: (Monad m) => a -> m a`

Monads as computation

- ✿ Given a pair of computations x and y , one can form the computation $x \gg y$, which intuitively "runs" the computation x , throws away its result, then runs y returning its result.
 - ▶ $(\gg) :: (\text{Monad } m) \Rightarrow m\ a \rightarrow m\ b \rightarrow m\ b$
- ✿ Further, we're allowed to use the result of the first computation to decide "what to do next", rather than just throwing it away.
 - ▶ $(\gg=) :: (\text{Monad } m) \Rightarrow m\ a \rightarrow (a \rightarrow m\ b) \rightarrow m\ b$
 - ▶ $x \gg= f$: a computation which runs x , then applies f to its result, getting a computation which it then runs.

Monads as computation

```
main :: IO ()
main = getLine >>= putStrLn
```

```
main :: IO ()
main = putStrLn "Enter a line of text:"
      >> getLine >>= \x -> putStrLn (reverse x)
```

- ✿ Because computations are typically going to be built up from long chains of `>>` and `>>=`, in Haskell, we have some syntax-sugar, called **do-notation**

```
main = do putStrLn "Enter a line of text:"
          x <- getLine
          putStrLn (reverse x)
```

Monads as computation

✿ The basic mechanical translation for the do-notation:

```
do { x } = x
```

```
do { x ; <stmts> }  
= x >> do { <stmts> }
```

```
do { v <- x ; <stmts> }  
= x >>= \v -> do { <stmts> }
```

```
do { let <decls> ; <stmts> }  
= let <decls> in do { <stmts> }
```


Monads as computation

- ▶ This gives monadic computations a bit of an imperative feel.
- ▶ But it's important to remember that **the monad in question gets to decide what the combination means, and so some unusual forms of control flow might actually occur.**
- ▶ In some monads (like parsers, or the list monad), **"backtracking"** may occur, and in others, even more exotic forms of control might show up.

Monads as computation

Some examples from Control.Monad

- ✿ A function which takes a list of computations of the same type, and builds from them a computation which will run each in turn and produce a list of the results.

```
sequence :: (Monad m) => [m a] -> m [a]
sequence []          = return []
sequence (x:xs)     = x >>= \v -> sequence xs >>= \vs -> return (v:vs)
```

```
sequence :: (Monad m) => [m a] -> m [a]
sequence []          = return []
sequence (x:xs)     = do v <- x
                        vs <- sequence xs
                        return (v:vs)
```

```
main = sequence [getLine, getLine] >>= print
```

Monads as computation

Some examples from Control.Monad

```
forM :: (Monad m) => [a] -> (a -> m b) -> m [b]
forM xs f = sequence (map f xs)
```

```
main = forM [1..10] $ \x -> do
    putStrLn "Looping: "
    print x
```

- ✿ There are variants of `sequence` and `forM`, called `sequence_` and `forM_`, which simply throw the results away as they run each of the actions.

```
sequence_ :: (Monad m) => [m a] -> m ()
sequence_ [] = return ()
sequence_ (x:xs) = x >> sequence_ xs

forM_ :: (Monad m) => [a] -> (a -> m b) -> m ()
forM_ xs f = sequence_ (map f xs)
```

Monads as computation

Some examples from Control.Monad

- ✿ Sometimes we only want a computation to happen when a given condition is true.

```
when :: (Monad m) => Bool -> m () -> m ()  
when p x = if p then x else return ()
```

课堂练习 1

- ✿ Define an instance of the Functor class for the following type of binary trees that have data in their nodes:

```
data Tree a = Leaf | Node (Tree a) a (Tree a) deriving (Show)
```

```
instance Functor Tree where
```

```
  -- fmap :: (a -> b) -> Tree a -> Tree b
```


课堂练习 1

- ❖ Define an instance of the Functor class for the following type of binary trees that have data in their nodes:

```
data Tree a = Leaf | Node (Tree a) a (Tree a) deriving (Show)
```

```
instance Functor Tree where
```

```
  -- fmap :: (a -> b) -> Tree a -> Tree b
```

```
  fmap g Leaf = Leaf
```

```
  fmap g (Node l x r) = Node (fmap g l) (g x) (fmap g r)
```

课堂练习 2

- ❖ Complete the following instance declaration to make the partially-applied function type `(->) a` into a functor:

```
instance Functor ((->) a) where
```

```
  -- fmap :: (a -> b) -> f a -> f b
```


课堂练习 2

- ❖ Complete the following instance declaration to make the partially-applied function type `(->) a` into a functor:

```
instance Functor ((->) a) where
```

```
-- fmap :: (a -> b) -> f a -> f b
```

```
-- fmap :: (b -> c) -> f b -> f c
```


课堂练习 2

- ❖ Complete the following instance declaration to make the partially-applied function type `(->) a` into a functor:

```
instance Functor ((->) a) where
  -- fmap :: (a -> b) -> f a -> f b
  -- fmap :: (b -> c) -> f b -> f c
  -- fmap :: (b -> c) -> (->) a b -> (->) a c
```

课堂练习 2

- ❖ Complete the following instance declaration to make the partially-applied function type `(->) a` into a functor:

```
instance Functor ((->) a) where
  -- fmap :: (a -> b) -> f a -> f b
  -- fmap :: (b -> c) -> f b -> f c
  -- fmap :: (b -> c) -> (->) a b -> (->) a c
  -- fmap :: (b -> c) -> (a -> b) -> (a -> c)
```

如果一个东西可以被定义为Functor的实例，那么，只有一种fmap的定义方式

课堂练习 2

- ❖ Complete the following instance declaration to make the partially-applied function type `(->) a` into a functor:

```
instance Functor ((->) a) where
  -- fmap :: (a -> b) -> f a -> f b
  -- fmap :: (b -> c) -> f b -> f c
  -- fmap :: (b -> c) -> (->) a b -> (->) a c
  -- fmap :: (b -> c) -> (a -> b) -> (a -> c)
  fmap = (.)
```

如果一个东西可以被定义为Functor的实例，那么，只有一种fmap的定义方式

课堂练习 3

❖ Define an instance of the `Applicative` class for the type `(->) a`

```
instance Applicative ((->) a) where
```

```
  -- pure :: a -> f a
```

```
  
```

```
  
```

```
  
```

```
  -- (<*>) :: f (a -> b) -> f a -> f b
```

```
  
```

```
  
```

```
  
```


课堂练习 3

❖ Define an instance of the `Applicative` class for the type `(->) a`

```
instance Applicative ((->) a) where
```

```
-- pure :: a -> f a
```

```
-- pure :: b -> f b
```

```
-- (<*>) :: f (a -> b) -> f a -> f b
```

```
-- (<*>) :: f (b -> c) -> f b -> f c
```

课堂练习 3

❖ Define an instance of the `Applicative` class for the type `(->) a`

```
instance Applicative ((->) a) where
```

```
-- pure :: a -> f a  
-- pure :: b -> f b  
-- pure :: b -> a -> b
```

```
-- (<*>) :: f (a -> b) -> f a -> f b  
-- (<*>) :: f (b -> c) -> f b -> f c  
-- (<*>) :: (a -> b -> c) -> (a -> b) -> (a -> c)
```

课堂练习 3

❖ Define an instance of the `Applicative` class for the type `(->) a`

```
instance Applicative ((->) a) where
  -- pure :: a -> f a
  -- pure :: b -> f b
  -- pure :: b -> a -> b
  pure = const

  -- (<*>) :: f (a -> b) -> f a -> f b
  -- (<*>) :: f (b -> c) -> f b -> f c
  -- (<*>) :: (a -> b -> c) -> (a -> b) -> (a -> c)
```

课堂练习 3

❖ Define an instance of the `Applicative` class for the type `(->) a`

```
instance Applicative ((->) a) where
  -- pure :: a -> f a
  -- pure :: b -> f b
  -- pure :: b -> a -> b
  pure = const

  -- (<*>) :: f (a -> b) -> f a -> f b
  -- (<*>) :: f (b -> c) -> f b -> f c
  -- (<*>) :: (a -> b -> c) -> (a -> b) -> (a -> c)
  g <*> h = \x -> g x $ h x
```


作业

12-1 Define an instance of the **Monad** class for the type `(->) a`.

12-2 Given the following type of expressions

```
data Expr a = Var a | Val Int | Add (Expr a) (Expr a)
```

deriving Show

that contain variables of some type **a**, show how to make this type into instances of the **Functor**, **Applicative** and **Monad** classes. With the aid of an example, explain what the `>>=` operator for this type does.

第12章： Monads and More

就到这里吧