A Domain-Specific Language for Animation

COS 441 Slides 8

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Agenda

- The last few weeks
  - the principles of functional programming
    - defining new functions: functional abstraction for code reuse
    - defining new types: type abstraction
    - higher-order programming: using functions as data
    - the same algorithm over different data: parametric polymorphism
    - related operations over different types: ad hoc polymorphism via type classes

- This time:
  - Bringing it all together: developing a domain-specific language for functional animation

SHAPES, REGIONS & PICTURES

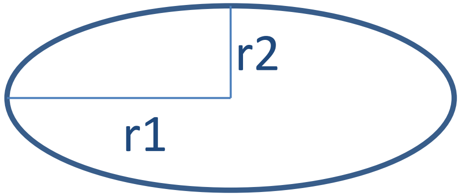
Shapes

```
data Shape =
    Rectangle Side Side
  | Ellipse Radius Radius
  | RtTriangle Side Side
  | Polygon [Vertex]
 deriving (Show)

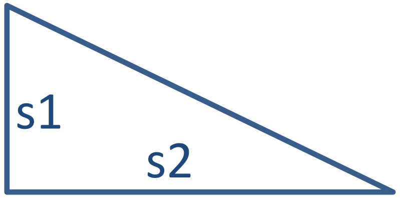
type Side = Float
type Radius = Float
type Vertex = (Float, Float)
```

Rectangle s1 s2 =

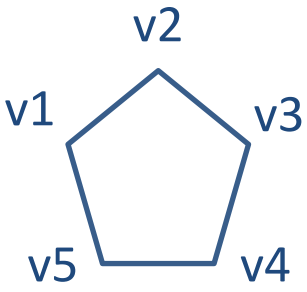
Ellipse r1 r2 =



RtTriangle s1 s2 =



Polygon [v1, ...,v5] =



Shapes

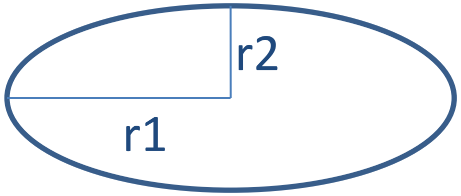
```
data Shape =
    Rectangle Side Side
  | Ellipse Radius Radius
  | RtTriangle Side Side
  | Polygon [Vertex]
  deriving (Show)

type Side = Float
type Radius = Float
type Vertex = (Float, Float)

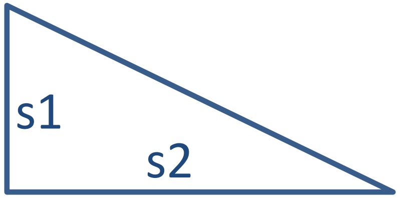
s1 = Rectangle 3 2
s2 = Ellipse 1 1.5
s3 = RtTriangle 3 2
s4 = Polygon [(-2.5, 2.5)
             ,(-3, 0)
             ,(-1.7,-1.0)
             ,(-1.1,0.2)
             ,(-1.5,2.0) ]
```

Rectangle s1 s2 =

Ellipse r1 r2 =



RtTriangle s1 s2 =



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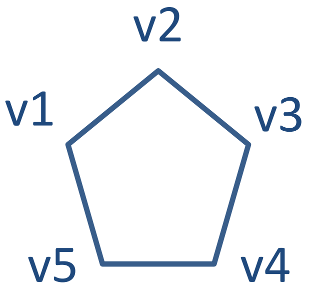

Regions

- Regions are compositions of basic shapes:

```
data Region =
  Shape Shape                          -- primitive shape
| Translate Vector Region              -- translated region
| Scale Vector Region                  -- scaled region
| Complement Region                    -- inverse of region
| Region `Union` Region                -- union of regions
| Region `Intersect` Region            -- intersection of regions
| Region `Xor` Region                  -- XOR of regions
| Empty                                -- empty region
deriving Show

type vector = (Int, Int)
```

Regions

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   Shape Shape                          -- primitive shape
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 | Region `Xor` Region                  -- XOR of regions
 | Empty                                -- empty region
deriving Show

type vector = (Int, Int)
```

```
r1 = Shape s1
r2 = Shape s2             reg0 = (Complement r2) `Union` r4
r3 = Shape s3
r4 = Shape s4             reg1 = r3 `Union` (r1 `Intersect` r0)
```

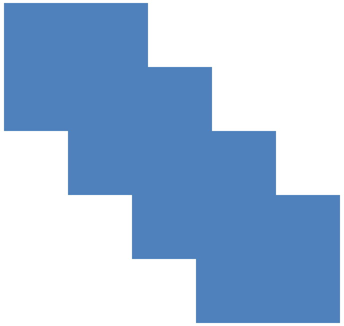
Regions

- Notice that regions are recursive data structures; consequently, they can be arbtrarily complex:

```
step = Shape (Rectangle 50 50)

stairs k =
  if k <= 0 then Empty
              else Translate (k*20, k*20) (step `Union` stairs (k-1))
```

stairs 4 =



Pictures

- Pictures add color to regions

```
data Picture =
  Region Color Region
| Picture `Over` Picture
| EmptyPic
deriving Show

type Color = Red | Yellow | ...
```

- Some pictures:

```
pic1 = Region Red reg1

r5 = Shape $ Rectangle 1 1
r6 = Shape $ Ellipse 0.5 0.5
reg2 = (Scale (2,2) r6) `Union`  (Translate (2,1) r6) `Union`  (Translate (-2,0) r5)
pic2 = Region Yellow reg2
pic3 = pic2 `Over` pic1
```

Drawing Pictures

- the SOE libraries have implemented a draw function for us:

```
type Title = String
draw :: Title -> Picture -> IO ()
```

- try it:

```
main1 = draw "Picture 1" pic1

main2 = draw "Picture 2" pic2

main3 = draw "Picture 3" pic3
```

- go to demo

FROM STATIC PICTURES
TO DYNAMIC ANIMATIONS

Animation

- We create animations by exploiting persistence of vision and rendering a series of images:
    1. Initialize image
    2. Render image
    3. Pause
    4. Change image
    5. Go to 1.

- At a low level, this is what will happen, but we'd like to build a library of combinators (ie: functions) that can be reused and that allow us to build complex animations from simpler parts

Key Idea

- We are going to represent an animation using a function

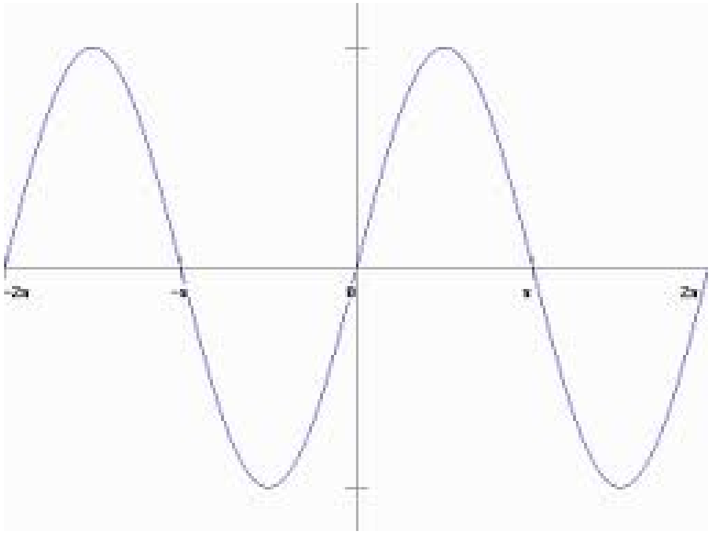
```
type Animation a = Time -> a
type Time = Float
```

- At every instant in time, the animation function generates an object with type a
- Since the animation type is polymorphic, we'll be able to animate many different kinds of things

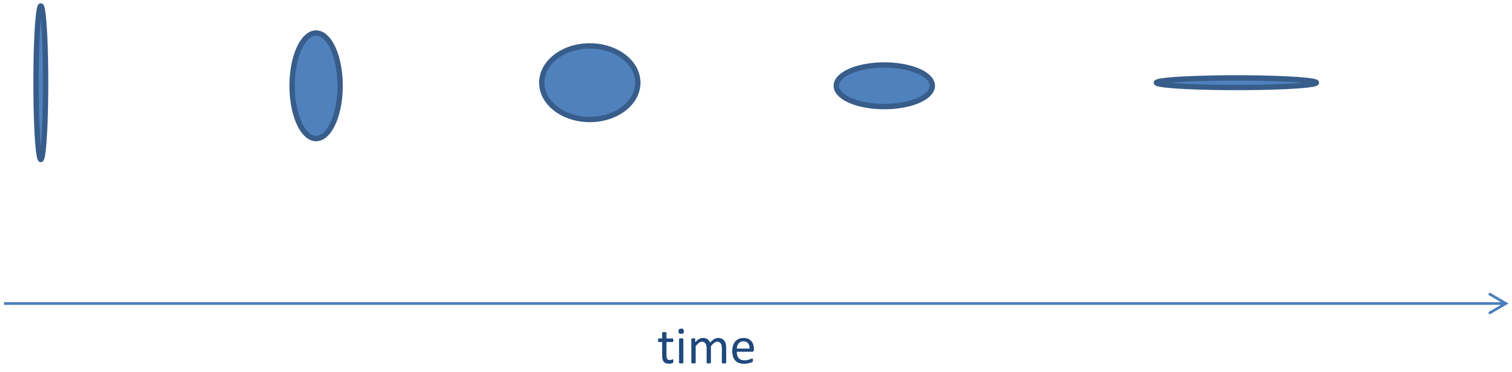
```
type PictureAnimation = Time -> Picture
type ShapeAnimation   = Time -> Shape
type StringAnimation  = Time -> String
```

A first animation

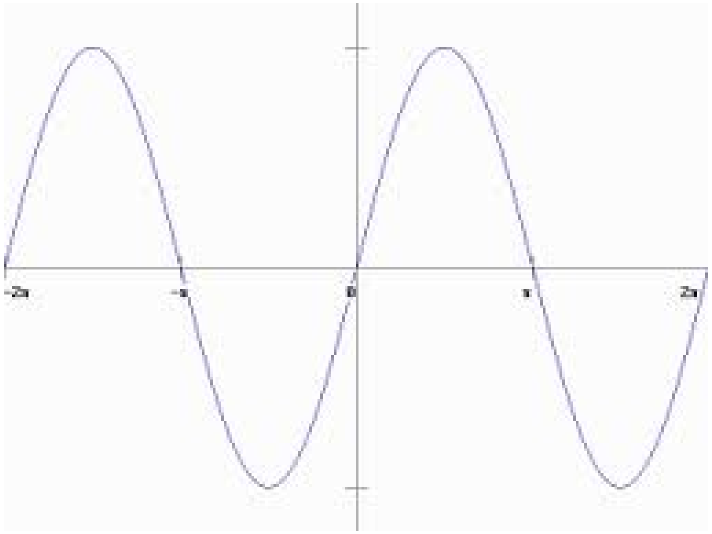
- Once you've thought of the right type, defining basic animations is easy:



```
rubberBall :: Animation Shape
rubberBall = \t -> Ellipse (sin t) (cos t)
```

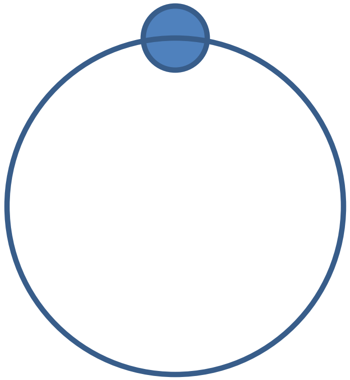


More Animations



```
revolvingBall :: Animation Region

revolvingBall = \t -> Translate (sin t, cos t) ball
    where ball = Shape (Ellipse 0.2 0.2)
```



More Animations

- Composition at work!
- By making animations functions, we can compose them using ordinary function application or function composition:

```
rubberBall :: Animation Shape
rubberBall = \t -> Ellipse (sin t) (cos t)

revolvingBall :: Animation Region
revolvingBall = \t -> Translate (sin t, cos t) ball
   where ball = Shape (Ellipse 0.2 0.2)

planets :: Animation Picture
planets t = p1 `Over` p2
   where p1 = Region Red $ Shape (rubberBall t)
            p2 = Region Yellow $ revolvingBall t
```

More Animations

- We can animate anything:

```
ticker :: Animation String

ticker t = "The time is :" ++ show t
```

- An animation is any time-varying value

Rendering Animations

- A Graphic is a data structure representing a static picture that can be rendered efficiently
- To render any animation, we need two things:
  - a function to convert an Animation a to an Animation Graphic
  - a function to render any Animation Graphic
- The second is supplied by the SOE library:

```
animate :: Title -> Animation Graphic -> IO ()
```

- The first can be developed provided we have some basic Graphic generators:

```
shapeToGraphic   :: Shape -> Graphic
regionToGraphic  :: Region -> Graphic
pictureToGraphic :: Picture -> Graphic
text             :: Point -> String -> Graphic
withColor        :: Color -> Graphic -> Graphic
```

Rendering Animations

- A simple example:

```
blueBall :: Animation Graphic
blueBall = withColor Blue . shapeToGraphic . rubberBall
```

- Check: does it have the right type?

```
rubberBall                                      :: Time -> Shape
shapeToGraphic                                  :: Shape -> Graphic
withColor Blue                                  :: Graphic -> Graphic
withColor Blue . shapeToGraphic . rubberBall :: Time -> Graphic
                                                = Animation Graphic
```

- Let's try to run it

Rendering Animations

- Let's look at some more:

```
main4 = animate "Shape" $ withColor Blue . shapeToGraphic . rubberBall

main5 = animate "Text" $ text (100,200) . ticker

main6 = animate "Region" $ withColor Yellow . regionToGraphic . revolvingBall

main7 = animate "Picture" $ picToGraphic . planets
```

Implementing Animate

- Some details of the animator (see script for more):

set up window

```
animate title anim = runGraphics $ do
   w <- openWindowEx title (Just (0,0)) (Just (xWin, yWin)) drawBufferedGraphic
   t0 <- timeGetTime
   animateLoop w t0 anim
```

begin animation loop with initial time

```
animateLoop w t0 anim = do
   t <- timeGetTime
   let ft = intToFloat (fromInteger (toInteger (t - t0))) / 1000
   setGraphic w (anim ft)
   spaceCloseEx w $ animateLoop w t0 anim
```

compute next time

draw the picture at the computed time

check for termination signal

continue

GOING FURTHER:
A DSL FOR ANIMATIONS

An Embedded DSL for Animations

- So far, we've built animations *bottom-up* with Time -> a functions
- But:
  - we can't (easily) transform or modify existing animations
  - we can't (easily) compose existing, fully-formed animations
  - we don't treat animations as abstract objects
- The next step:
  - Treat animations as abstract objects and define canonical transformers for them
  - Work entirely at the level of animations, hiding the implementation details
  - Our implementation might be called "a cool library" but ... we hide the underlying details so thoroughly we'll call the library an embedded, domain-specific language.
  - Haskell, with it's lightweight syntax and facilities for reuse and abstraction, is a terrific platform for developing new DSLs

DSL Design Strategy

- Choose primary abstract objects
  - define special types to represent them
  - in our case: a special abstract Behavior type

- Define operations over the abstract objects
  - make the above abstract objects instances of well-chosen type classes where appropriate so we can use compact, intuitive notation for manipulating our objects
  - in our case: make behaviors instances of type classes for graphical and numeric manipulation

A Taste of the DSL: Everything is a Behavior

primary abstract type

```
type Behavior a
type Coordinates = (Behavior Float, Behavior Float)
```

selected operations over abstract objects

```
run      :: Behavior Picture -> IO ()

red      :: Behavior Color
ell      :: Behavior Radius -> Behavior Radius -> Behavior Shape
shape    :: Behavior Shape -> Behavior Region
reg      :: Behavior Color -> Behavior Region -> Behavior Picture
over     :: Behavior Picture -> Behavior Picture -> Behavior Picture

sin      :: Behavior Float -> Behavior Float
tx       :: Coordinates -> Behavior Picture -> Behavior Picture
timeTx   :: Behavior Time -> Behavior a -> Behavior a
rewind   :: Behavior a -> Behavior a
```

bootstrapping

```
lift0    :: a -> Behavior a
lift1    :: (a -> b) -> Behavior a -> Behavior b
lift2    :: (a -> b -> c) -> Behavior a -> Behavior b -> Behavior c
```

Examples

- A stationary ball:

```
demo1 = run $ reg yellow $ ballB
```

- Bouncing the ball:

```
demo2 = run $ reg yellow $ tx (0, sin time) ballB
```

- Bouncing a triangle:

```
demo2 = run $ reg yellow $ tx (0, sin time) pentaB
```

- Bouncing anything yellow:

```
bounce b = reg yellow $ tx (0, sin time) b
```

Examples

- Colors can vary with time. Why stick with constant yellow?

```
flash :: Behavior Color

demo4 = run $ reg flash $ tx (0, sin time) ballB
```

- Any animation can be composed with any other

```
demo5 = run $ a1 `over` a2
   where a1 = reg red $ tx (0, sin time) ballB
            a2 = reg yellow $ tx (sin time, 0) pentaB
```

Examples

- We can define new kinds of motions and apply them to many different kinds of objects

```
turn :: (Deformable a) => Float -> a -> a
lift2 :: (a -> b -> c) -> Behavior a -> Behavior b -> Behavior c
lift2 turn :: Behavior Float -> Behavior a -> Behavior a

demo6 = run $ a1 `over` a2
   where a1 = reg red $ tx (0, sin time) ballB
            a2 = reg yellow $ lift2 turn angle pentaB
            angle = pi * sin time
```

angle is a behavior. notice the overloading: type classes!

Examples

- We can manipulate time itself! Thereby delaying, slowing down or speeding up animations.

```
demo7 = run $ a1 `over` a2
  where a1 = reg red $ tx (sin time, cos time) ballB
        a2 = timeTx (2 + time) a1
```

notice the overloading: type classes!

a delayed animation composed with itself

```
demo8 = run $ a1 `over` a2
  where a1 = reg red $ tx (sin time, cos time) ballB
        a2 = timeTx (2 * time) a1
```

a fast-forwarded animation

Examples

- We can even put time in reverse and run an animation backwards. (Makes me wonder if we could do some DVR programming in Haskell ...)

```
demo0 = run $ a1 `over` a2
  where a1 = reg red $ tx (sin time, cos time) ballB
        a2 = timeTx (-1 * time) a1
```

run backwards

BUILDING THE DSL

The Behavior Type

- Whereas an animation was just a synonym for a function type, a behavior is abstract:

```
newtype Behavior a = Beh (Time -> a)
```

- There are a couple of reasons:
  - we would like to control the invariants governing Behaviors
  - we would like to hide implementation details from clients
  - we will be using some type classes, and type classes don't work properly with type synonyms
    - why? Intuitively because a synonym is completely interchangeable with its definition. Hence, we can't define a different behavior for the synonym than its definition. (If we could, they wouldn't be interchangeable.)
- Note: A newtype is a data type with just 1 constructor and no performance overhead for using it

Implementing the Animator

```
newtype Behavior a = Beh Time -> a

animateB :: String -> Behavior Picture -> IO ()
animateB s (Beh f) = animate s (picToGraphic . f)

run = animateB "Animation Window"
```

Bootstrapping

- Recall the map function: It took an ordinary function and made it into a function over lists:

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

- One might say that map "lifts" an ordinary function up in to the domain of list-processing functions
- Likewise, we will want to "lift" ordinary functions up in to the domain of behavior-processing functions:

```
lift1 :: (a -> b) -> Behavior a -> Behavior b
lift1 f (Beh g) = Beh (\t -> f (g t))
```

- Lift is a way to include all of Haskell's powerful function-definition facilities within our newly developed DSL

Bootstrapping

- Lift1 works with single-argument functions. We may need to do heavier lifting:

```
lift2 :: (a -> b -> c) -> Behavior a -> Behavior b -> Behavior c
lift2 f (Beh a) (Beh b) = Beh $ \t -> f (a t) (b t)

lift3 :: (a -> b -> c -> d) -> Behavior a -> Behavior b -> Behavior c -> Behavior d
lift3 f (Beh a) (Beh b) (Beh c) = Beh $ \t -> f (a t) (b t) (c t)
```

- You can think of a constant, like the color Red, as a 0-argument function. We'll want to lift constants too:

```
lift0 :: a -> Behavior a
lift0 x = Beh $ \t -> x
```

a constant function; it returns x all the time

Bootstrapping

- Since lists are so common in Haskell, we'll lift list-processing functions too
- Explore the details in your spare time:

```
liftXs :: ([t] -> a) -> [Behavior t] -> Behavior a
liftXs f bs = Beh (\t -> f (map (\(Beh b) -> b t) bs))
```

- But notice, even without looking at the code, how much information you get out of the type of the function:

```
liftXs :: ([t] -> a) -> ([Behavior t] -> Behavior a)
```

- There's really only 1 reasonable thing that liftXs could do, given its type

Numeric Behaviors

- Our examples involve managing coordinates, scaling factors and timewarp; we need support for numeric behaviors
- Let's define standard numeric operations over behaviors by making it an instance of the Num Class

```
instance Num a => Num (Behavior a) where
  (+) = lift2 (+)
  (*) = lift2 (*)
  negate = lift1 negate
  abs = lift1 abs
  signum = lift1 signum
  fromInteger = lift0 . fromInteger
```

Numeric Behaviors

- Unsure what (+) on Behaviors does? Run through an example using computation by calculation

```
instance Num a => Num (Behavior a) where
   (+) = lift2 (+)              ...

lift2 :: (a -> b -> c) -> Behavior a -> Behavior b -> Behavior c
lift2 f (Beh a) (Beh b) = Beh $ \t -> f (a t) (b t)

lift0 :: a -> Behavior a
lift0 x = Beh $ \t -> x

one  = Beh (\t -> 1)
time = Beh (\t -> t)
```

```
  (+) time one
= lift2 (+) time one
= lift2 (+) (Beh (\t -> t)) (Beh (\t -> 1))
= Beh (\t -> (+) ((\t -> t) t) ((\t -> 1) t))
= Beh (\t -> (+) t 1)
= Beh (\t -> t + 1)
```

It just adds the numbers from the same time instant!

Operations over Float Behaviors

```
instance Floating a => Floating (Behavior a) where
  pi = lift0 pi
  sqrt = lift1 sqrt
  exp = lift1 exp
  log = lift1 log
  sin = lift1 sin
  cos = lift1 cos
  tan = lift1 tan
  asin = lift1 asin
  acos = lift1 acos
  atan = lift1 atan
  sinh = lift1 sinh
  cosh = lift1 cosh
  tanh = lift1 tanh
  asinh = lift1 asinh
  acosh = lift1 acosh
  atanh = lift1 atanh
```

Once again, check our work by calculating

```
instance Floating a => Floating (Behavior a) where
  sin = lift1 sin
  ...

lift1 :: (a -> b) -> Behavior a -> Behavior b
lift1 f (Beh g) = Beh (\t -> f (g t))

time :: Behavior Time
time = Beh (\t -> t)

sin time = lift1 sin time
         = lift1 sin (Beh (\t -> t))
         = \t -> sin ((\t -> t) t)
         = \t -> sin t
```

Add in Operations for Colors, Pictures, Regions

```
reg      = lift2 Region
shape    = lift1 Shape
poly     = liftXs Polygon
ell      = lift2 Ellipse
red      = lift0 Red
yellow   = lift0 Yellow
green    = lift0 Green
blue     = lift0 Blue

tx (Beh a1, Beh a2) (Beh r) = Beh (\t -> Translate (a1 t, a2 t) (r t))
```

- Ok, at this point, you've got to admit that whoever came up with the concept of "lifting" and the idea of defining the liftN functions was pretty smart -- they are getting a lot of play!

Creating Behavioral Shapes

- Our basic ball:

```
ballB :: Behavior Region
ballB = shape $ ell 0.2 0.2
```

- Our basic pentagon:

```
pentaB :: Behavior Region
pentaB = shape $ poly (map lift0 vs)
  where vs = [ ( 0.0, 0.8)
             , ( 0.3,-0.5)
             , (-0.3,-0.5)]
```

- A revolving balls and pentagons:

```
revolveRegion = tx (sin time, cos time)

revBallB = revolveRegion ballB
revPentaB = revolveRegion pentaB
```

Power Tools: Conditional Behaviors

- We can really start building a whole new language when we start adding conditional behaviors:

```
cond :: Behavior Bool -> Behavior a -> Behavior a -> Behavior a
cond = lift3 $ \b x y -> if b then x else y
```

- Behavioral comparisons:

```
(>*) = lift2 (>)
(<*) = lift2 (<)
```

- Alternating behaviors:

```
flash = cond (cos time >* 0) red yellow
flash' = cond (cos time >* 0) green blue
```

Power Tools: Domain-Specific Type Classes

- Are there operations that apply to several different abstractions within our DSL?
- What about the concept of “over” – one shape, region, picture or behavior “over” top of another?

```
class Combine a where
  empty :: a
  over     :: a -> a -> a
```

- Write functions to layer all elements of a list:

```
overMany :: Combine a => [a] -> a
overMany = foldr over empty
```

Power Tools: Domain-Specific Type Classes

```
class Combine a where
  empty :: a
  over    :: a -> a -> a
```

- Write instances of the new class for pictures and behaviors

```
instance Combine Picture where
    empty = EmptyPic
    over     = Over

instance Combine a => Combine (Behavior a) where
    empty = lift0 empty
    over     = lift2 over
```

Power Tools: Domain-Specific Type Classes

```
class Combine a where
  empty :: a
  over    :: a -> a -> a

instance Combine Picture where ...

instance Combine a => Combine (Behavior a) where ...
```

- Play with the new type classes:

```
overMany = foldr over empty

anim5 = animateB "Many Spheres" $ overMany [b1,b2,b3]
    where b1 = reg flash $ tx ((sin time)-1, cos time) ballB
               b2 = reg flash' $ tx ((sin time)+1, cos time) ballB
               b3 = reg flash'' $ tx (2 * sin time, cos time) pentaB
```

More Demos

- Check out the use of conditional animations and new type classes in these programs:

anim2

anim3

anim4

…

anim9

- Read through the rest of the animation notes

SUMMARY!

Summary

- Defining a new embedded DSL involves
  - defining key abstract types to be used by the client programs
  - defining reuseable operations over those abstract types
- Along the way, we saw:
  - heavy use of functions as data
  - the idea of lifting a Haskell function to a new abstract domain
  - the use of type classes
    - new instances for existing classes: related operations on new types
    - new classes: new domain-specific operations
- Historical note: Programming language researchers from 90s onward spent years defining and refining the basic principles of DSL design and looking for the right reusable, modular abstractions. And the research continues. Moreover, getting the specifics right is a fun, ongoing challenge in many domains.