snowglobe

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Contents

1 back.png

mathr.co.uk

2 cards.sh

```
#!/bin/bash
pngtopnm < edge.png > edge.pgm
pngtopnm < back.png > back.pgm
mkdir 4x1
ls snowglobe-*.pgm | sort -R | xargs -n 4 pnmcat -lr | ( cd 4x1 ; pnmsplit )
```

```
mkdir 4x6
ls 4x1/* | xargs -n 6 pnmcat -tb | ( cd 4x6 ; pnmsplit )
mkdir 5x7
cd 4x6
for i in *
do
  pnmcat -tb -black ../edge.pgm $i ../edge.pgm |
  pgmtoppm white-black | ppmtopgm | pnmgamma 0.25 |
  pnmscale -xysize 1500 2100 | pnmcat -lr ../back.pgm - |
  pnmtopng -force -interlace -phys 11811 11811 1 > ../5x7/$i.png
done
cd ../5x7
ls -1sh
```

3 edge.png

4 .gitignore

```
dist
.cabal-sandbox
cabal.sandbox.config
```

5 Hyperbolic.hs

```
module Hyperbolic where

import Data.Complex
import Vector

newtype H4 = H4{ unH4 :: V4 }
newtype H2 = H2{ unH2 :: V2 }
newtype H = H{ unH :: R }

hdist :: H2 -> H2 -> H
hdist (H2 z) (H2 w) = H $ acosh (1 + 2 * norm2 (z ^-^ w) / ((1 - norm2 z) * (1 -↙
    ↳  norm2 w)))

h2e1 :: H -> R
h2e1 (H z) = sqrt ((cosh z - 1) / (cosh z + 1))

h2e2 :: H2 -> V2
h2e2 h@(H2 v) = norm v ^* h2e1 (hdist h (H2 o))
e2h1 :: R -> H
e2h1 z = hdist (H2 (V2 z 0)) (H2 o)

e2h2 :: V2 -> H2
e2h2 z = H2 (norm z ^* (unH $ e2h1 (sqrt (norm2 z))))

moebius :: H2 -> H4
moebius (H2 (V2 x y)) = H4 (V4 x y 1 0)

unmoebius :: H4 -> H2
```

```
unmoebius (H4 (V4 a b c d)) = let (x:+y) = (a:+b)/(c:+d) in H2 (V2 x y)

mlength :: H4 -> R
mlength (H4 (V4 a b c d)) = magnitude (a:+b) / magnitude (c:+d)

rotation :: R -> M4
rotation a = M4 c (-s) 0 0  s c 0 0  0 0 1 0  0 0 0 1
  where
    c = cos a
    s = sin a

translation :: H2 -> M4
translation (H2 (V2 x y))
  | l > 0 = rotation (-s) ^^*^^ m ^^*^^ rotation s
  | otherwise = m
  where
    m = M4 f 0 g 0  0 f 0 g  g 0 f 0  0 g 0 f
    s = phase (x:+y)
    l = magnitude (x:+y)
    e = exp l
    f = e + 1
    g = e - 1

rotationAbout :: H2 -> R -> M4
rotationAbout z@(H2 (V2 x y)) a = translation z ^^*^^ rotation a ^^*^^ ↙
  ↳ translation (H2 (V2 (-x) (-y)))

ecircle :: H2 -> H -> (V2, R)
ecircle c@(H2 (V2 cx cy)) (H hr) = (ec, er)
  where
    p = phase (cx :+ cy)
    a = unmoebius . H4 $ translation (H2 (V2 (-hr * cos p) (-hr * sin p))) ^^*^ ↙
      ↳ unH4 (moebius c)
    b = unmoebius . H4 $ translation (H2 (V2 ( hr * cos p) ( hr * sin p))) ^^*^ ↙
      ↳ unH4 (moebius c)
    ea = h2e2 a
    eb = h2e2 b
    ec = (ea ^+^ eb) ^* 0.5
    er = 0.5 * (sqrt $ norm2 (ea ^-^ eb))
```

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might be different; for a GUI interface, you would use an "about box".

  You should also get your employer (if you work as a programmer) or school,
if any, to sign a "copyright disclaimer" for the program, if necessary.
For more information on this, and how to apply and follow the GNU GPL, see
<http://www.gnu.org/licenses/>.

  The GNU General Public License does not permit incorporating your program
into proprietary programs.  If your program is a subroutine library, you
may consider it more useful to permit linking proprietary applications with
the library.  If this is what you want to do, use the GNU Lesser General
Public License instead of this License.  But first, please read
<http://www.gnu.org/philosophy/why-not-lgpl.html>.
```

7 Setup.hs

```
import Distribution.Simple
main = defaultMain
```

8 snowglobe.cabal

```
Name:                snowglobe
Version:             3.0.0.3
Synopsis:            randomized fractal snowflakes demo
Description:         @snowglobe@ generates random snowflakes using iterated
                     function systems via OpenGL texture feedback.  The
                     snowflakes interact in a particle system.
                     .
                     Keyboard controls:
                     .
                       * f, F11: toggle full screen
                     .
                       * shift-R: toggle recording PPM images to stdout
                     .
                       * shift-S: toggle recording PGM images of each
                         generated flake to the current working directory
                     .
                       * any other key: quit
```

```
                    .
                    Blog posts:
                    .
                      * <https://mathr.co.uk/blog/2012-01-12_snowglobe.html>
                    .
                      * <https://mathr.co.uk/blog/2014-12-19↙
                          ↳ _making_seasonal_cards_with_snowglobe.html>

homepage:           https://code.mathr.co.uk/snowglobe
License:            GPL-3
License-file:       LICENSE
Author:             Claude Heiland-Allen
Maintainer:         claude@mathr.co.uk
Category:           Demo
Build-type:         Simple
Cabal-version:      >=1.6

Executable snowglobe
  Main-is:            SnowGlobe.hs
  other-modules:      Vector
  GHC-options:        -Wall
  Build-depends:
    base < 5,
    bytestring,
    containers,
    gl-capture,
    GLUT,
    OpenGL == 3.0.*,
    OpenGLRaw,
    random

Source-repository head
  type:               git
  location:           https://code.mathr.co.uk/snowglobe.git

Source-repository this
  type:               git
  location:           https://code.mathr.co.uk/snowglobe.git
  tag:                v3.0.0.3
```

9 SnowGlobe.hs

```
-- SnowGlobe -- randomized fractal snowflakes demo
-- (GPL3+) 2012,2014,2015,2016 Claude Heiland-Allen <claude@mathr.co.uk>
-- tested with: ghc-7.6.3, ghc-7.8.2, ghc-7.10.1~rc2, ghc-8.0.1

import Vector hiding (i)
import Graphics.UI.GLUT hiding (scale, FramebufferObject)
import qualified Graphics.UI.GLUT as GL
import Graphics.GL
  ( glTexImage2D
  , glClampColor
  , glGenerateMipmap
  , glGenFramebuffers
  , glBindFramebuffer
  , glFramebufferTexture2D
  , glUniformMatrix3fv
```

```
    , glGetTexImage
    )
import Graphics.GL.Tokens
{-
  ( GL_TEXTURE_2D
  , GL_R32F
  , GL_RED
  , GL_RGBA
  , GL_UNSIGNED_BYTE
  , GL_FALSE
  , GL_CLAMP_VERTEX_COLOR
  , GL_CLAMP_READ_COLOR
  , GL_CLAMP_FRAGMENT_COLOR
  , GL_ALPHA
  , GL_FRAMEBUFFER
  , GL_COLOR_ATTACHMENT0
  )
-}
import Control.Exception (evaluate)
import Control.Monad (forM_, replicateM, when)
import Data.IORef (IORef, modifyIORef, newIORef, readIORef, writeIORef)
import Data.List (foldl', minimumBy)
import Data.Ord (comparing)
import Data.Map (Map)
import qualified Data.Map as M
import qualified Data.Set as S
import System.Exit (exitSuccess)
import System.IO (hPutStrLn, stderr, stdout, hPutStr, withBinaryFile, IOMode(↙
    ↪ WriteMode), hPutBuf)
import System.Random (randomRIO)
import Foreign (alloca, peek, nullPtr, withArray)
import Graphics.Rendering.OpenGL.Capture (capturePPM)
import Data.ByteString as BS (hPut, pack)
import Foreign (Ptr, allocaArray)
import Data.Word (Word8)

shader :: Maybe String -> Maybe String -> IO Program
shader mV mF = do
  p <- createProgram
  vs <- case mV of
    Nothing -> return []
    Just v -> do
      vert <- createShader VertexShader
      shaderSourceBS vert $= BS.pack (map (toEnum . fromEnum) v)
      compileShader vert
      msg <- get (shaderInfoLog vert)
      when (not (null msg)) $ hPutStrLn stderr msg
      return [vert]
  fs <- case mF of
    Nothing -> return []
    Just f -> do
      frag <- createShader FragmentShader
      shaderSourceBS frag $= BS.pack (map (toEnum . fromEnum) f)
      compileShader frag
      msg <- get (shaderInfoLog frag)
      when (not (null msg)) $ hPutStrLn stderr msg
      return [frag]
```

```
    attachedShaders p $= concat [vs, fs]
    linkProgram p
    msg <- get (programInfoLog p)
    when (not (null msg)) $ hPutStrLn stderr msg
    return p

type N = Int

sum' :: Num a => [a] -> a
sum' = foldl' (+) 0

size :: N
size = 2048

er :: R
er = 4

accuracy :: R
accuracy = 1 / fromIntegral size

tSize :: N
tSize = 1024

maxSpeed :: R
maxSpeed = 10

data SnowGlobe = SnowGlobe
  { pInitial :: Program, pInitial'er, pInitial'rho :: UniformLocation
  , pStep :: Program, pStep'er, pStep'ts, pStep'src :: UniformLocation
  , pColour :: Program, pColour'src, pColour'speed, pColour'colour :: ↙
      ↳ UniformLocation
  , tPing, tPong :: TextureObject, fBuffer :: FramebufferObject
  , sFlakes :: [Flake], sTextures :: Map N TextureObject
  , wSize :: Size, wFullScreen :: Maybe Size
  , sRenderFlake :: IO Render, sNextName :: N
  , sRecord, sRecordFlakes :: Bool
  }

data Flake = Flake
  { flakeName :: !N
  , flakeTime :: !R
  , flakePosition :: !V2
  , flakeVelocity :: !V2
  }

flakeMass :: Flake -> R
flakeMass f = let s = flakeSize f in 1 + s * s

flakeSize :: Flake -> R
flakeSize f = sin (pi * flakeTime f)

flakeForce :: Flake -> V2 -> V2
flakeForce f p =
  let d@(V2 x y) = p ^-^ flakePosition f
      m = let d2 = x * x + y * y in d2 * d2
  in  (flakeMass f / m) *^ d
```

```
flakeUpdate :: R -> [Flake] -> Flake -> Flake
flakeUpdate dt fs f = f
  { flakeTime = flakeTime f + dt / 2
  , flakePosition = flakePosition f ^+^ (dt *^ flakeVelocity f)
  , flakeVelocity = mapVector ((* maxSpeed) . tanh . (/ maxSpeed)) $ 0.999 *^ (↙
      ↳ flakeVelocity f ^+^ ((dt / flakeMass f) *^ (flakeField fs (flakePosition↙
      ↳  f))))
  }

mapVector :: (R -> R) -> V2 -> V2
mapVector f (V2 x y) = V2 (f x) (f y)

flakeField :: [Flake] -> V2 -> V2
flakeField fs p = foldl' (^+^) o [ flakeForce f (p ^+^ d) | f <- fs, p /= ↙
    ↳ flakePosition f, dx <- [-2,0,2], dy <- [-2,0,2], let d = V2 dx dy ]

flakeSpawn :: [Flake] -> N -> IO Flake
flakeSpawn fs name = do
  xs <- replicateM 32 $ randomRIO (-1, 1)
  ys <- replicateM 32 $ randomRIO (-1, 1)
  let ps = zipWith V2 xs ys
      p = fst . minimumBy (comparing snd) . map (\p' -> (p', norm2 (flakeField ↙
          ↳ fs p'))) $ ps
  return Flake{ flakeName = name, flakeTime = 0, flakePosition = p, ↙
      ↳ flakeVelocity = o }
  where
    norm2 (V2 x y) = x * x + y * y

flakesUpdate :: R -> [Flake] -> [Flake]
flakesUpdate dt fs =
  let gs = map (flakeUpdate dt fs) fs
      alive = filter ((< 1) . flakeTime) gs
  in  map flakeWrap alive

flakeWrap :: Flake -> Flake
flakeWrap f = f{ flakePosition = mapVector wrap (flakePosition f) }
  where
    wrap x =
      let y = (x + 1) / 2
          z = y - fromIntegral (floor y :: N)
      in  z * 2 - 1

-- amortized rendering over several frames
data Render = Done TextureObject | Step (IO Render)

-- initial pass
flakeRenderStart :: IORef SnowGlobe -> IO Render
flakeRenderStart sR = do
  s0 <- readIORef sR
  p <- replicateM 4 $ randomRIO (0.02, 0.98)
  let rts = flakeTransforms p
      rho = maximum (map fst rts)
      ts = map snd rts
      passes = clamp 4 256 . round . logBase rho $ accuracy
  loadIdentity
  ortho2D 0 1 0 1
  viewport $= (Position 0 0, Size (fromIntegral size) (fromIntegral size))
```

```
180     currentProgram $= Just (pInitial s0)
        uniform (pInitial'er s0) $= TexCoord1 (realToFrac er :: GLfloat)
        uniform (pInitial'rho s0) $=  TexCoord1 (realToFrac rho :: GLfloat)
        bindFBO (fBuffer s0) (tPing s0)
        unitQuad
185     unbindFBO
        currentProgram $= Nothing
        return $ Step (flakeRenderPass sR ts passes passes)

    getUniformLocation :: UniformLocation -> GLint
190 getUniformLocation (UniformLocation u) = u

    -- multi step passes
    flakeRenderPass :: IORef SnowGlobe -> [M3] -> N -> N -> IO Render
    flakeRenderPass sR _  passes 0 = flakeRenderFinish sR passes
195 flakeRenderPass sR ts passes n = do
      s0 <- readIORef sR
      loadIdentity
      ortho2D 0 1 0 1
      viewport $= (Position 0 0, Size (fromIntegral size) (fromIntegral size))
200   currentProgram $= Just (pStep s0)
      uniform (pStep'er s0) $= TexCoord1 (realToFrac er :: GLfloat)
      uniform (pStep'src s0) $= TexCoord1 (0 :: GLint)
      withArray (map ((realToFrac :: Float -> GLfloat) . (realToFrac :: Double -> ↙
          ↳ Float)) . concatMap matrixToList $ ts) $ glUniformMatrix3fv (↙
          ↳ getUniformLocation $ pStep'ts s0) 6 1
      bindFBO (fBuffer s0) (tPong s0)
205   textureBinding Texture2D $= Just (tPing s0)
      unitQuad
      textureBinding Texture2D $= Nothing
      unbindFBO
      writeIORef sR s0{ tPing = tPong s0, tPong = tPing s0 }
210   currentProgram $= Nothing
      if even n
        then return $ Step (flakeRenderPass sR ts passes (n - 1))
        else               flakeRenderPass sR ts passes (n - 1)

215 matrixToList :: M3 -> [R]
    matrixToList (M3 a b c d e f g h i) = [a,b,c,d,e,f,g,h,i]

    -- colourize pass
    flakeRenderFinish :: IORef SnowGlobe -> N -> IO Render
220 flakeRenderFinish sR passes = do
      s0 <- readIORef sR
      t <- newTexRGBA tSize
      bindFBO (fBuffer s0) t
      loadIdentity
225   ortho2D (-1) 1 (-1) 1
      viewport $= (Position 0 0, Size (fromIntegral tSize) (fromIntegral tSize))
      textureBinding Texture2D $= Just (tPong s0)
      currentProgram $= Just (pColour s0)
      uniform (pColour'src s0) $= TexCoord1 (0 :: GLint)
230   uniform (pColour'speed s0) $= TexCoord1 (1 / fromIntegral passes :: GLfloat)
      uniform (pColour'colour s0) $= TexCoord3 1 1 (1 :: GLfloat)
      fullQuad
      currentProgram $= Nothing
      unbindFBO
```

```
235     textureBinding Texture2D $= Just t
        glGenerateMipmap GL_TEXTURE_2D
        textureBinding Texture2D $= Nothing
        return $ Done t

240   transformRST :: R -> R -> V2 -> M3
      transformRST a l (V2 x y) = M3 c s x  (-s) c y  0 0 1
        where c = l * cos a
              s = l * sin a

245   flakeTransforms :: [R] -> [(R, M3)]
      flakeTransforms [a,b,c,d] = [(la,inv ta),(lb,inv tb),(lc,inv tc1),(ld,inv td1),(↙
          ↳ lc,inv tc2),(ld,inv td2)]
        where
          lx = a + b
          ly = 2 * (c + d)
250       la  = a / lx
          lb  = b / lx
          lc  = c / ly
          ld  = d / ly
          u   = V2 0 0
255       v   = V2 0 la
          l   =     pi / 3
          ll  = 2 * pi / 3
          r   = -l
          rr  = -ll
260       ta  = transformRST  0 la u
          tb  = transformRST  0 lb v
          tc1 = transformRST  l lc v
          tc2 = transformRST  r lc v
          td1 = transformRST ll ld v
265       td2 = transformRST rr ld v
      flakeTransforms _ = error "flakeTransforms"

      main :: IO ()
      main = do
270     _ <- getArgsAndInitialize
        let wSize' = Size 1280 720
        initialWindowSize $= wSize'
        initialDisplayMode $= [DoubleBuffered]
        _ <- createWindow "SnowGlobe"
275     pInitial'     <- shader Nothing (Just $ unlines
          [ "uniform float er;"
          , "uniform float rho;"
          , ""
          , "void main() {"
280       , "  vec2 p = er * (gl_TexCoord[0].xy * 2.0 - vec2(1.0));"
          , "  float l = length(p);"
          , "  float n;"
          , "  if (l >= er) {"
          , "    n = 0.0;"
285       , "  } else if (er > l && l >= rho * er) {"
          , "    n = (log(er) - log(l)) / -log(rho);"
          , "  } else {"
          , "    n = -1.0;"
          , "  }"
290       , "  gl_FragData[0] = vec4(n);"
```

```
    , "}"
    ])
  pInitial'er' <- get $ uniformLocation pInitial' "er"
  pInitial'rho' <- get $ uniformLocation pInitial' "rho"
  pStep' <- shader Nothing (Just $ unlines
    [ "uniform float er;"
    , "uniform mat3 ts[6];"
    , ""
    , "uniform sampler2D src;"
    , ""
    , "void main() {"
    , "  vec2 p0 = er * (gl_TexCoord[0].xy * 2.0 - vec2(1.0));"
    , "  float m = -1.0;"
    , "  for (int i = 0; i < 6; ++i) {"
    , "    vec3 p = ts[i] * vec3(p0, 1.0);"
    , "    vec2 q = p.xy / p.z;"
    , "    float l = length(q);"
    , "    if (l < er) {"
    , "      m = max(m, texture2D(src, (q / er + vec2(1.0)) / 2.0).x);"
    , "    }"
    , "  }"
    , "  if (m >= 0.0) {"
    , "    m += 1.0;"
    , "  }"
    , "  m = max(m, texture2D(src, (p0 / er + vec2(1.0)) / 2.0).x);"
    , "  gl_FragData[0] = vec4(m);"
    , "}"
    ])
  pStep'er' <- get $ uniformLocation pStep' "er"
  pStep'ts' <- get $ uniformLocation pStep' "ts"
  pStep'src' <- get $ uniformLocation pStep' "src"
  pColour' <- shader Nothing (Just $ unlines
    [ "uniform sampler2D src;"
    , "uniform float speed;"
    , "uniform vec3 colour;"
    , ""
    , "void main() {"
    , "  vec2 p = gl_TexCoord[0].xy;"
    , "  float n = texture2D(src, p).x;"
    , "  p -= vec2(0.5);"
    , "  const mat2 r = mat2(0.5, 0.8660254037844386, -0.8660254037844386, 0.5)↙
      ↳ ;"
    , "  for (int i = 1; i < 6; ++i) {"
    , "    p = r * p;"
    , "    n = max(n, texture2D(src, p + vec2(0.5)).x);"
    , "  }"
    , "  if (n > 0.0) {"
    , "    n *= speed;"
    , "  } else {"
    , "    n = 0.0;"
    , "  }"
    , "  n *= n;"
    , "  n *= n;"
    , "  gl_FragData[0] = vec4(colour, n);"
    , "}"
    ])
  pColour'src' <- get $ uniformLocation pColour' "src"
```

```
    pColour'speed'<- get $ uniformLocation pColour' "speed"
    pColour'colour'<- get $ uniformLocation pColour' "colour"
    tPing'        <- newTex size
    tPong'        <- newTex size
    fBuffer'      <- newFBO
    glClampColor GL_CLAMP_VERTEX_COLOR   $ fromIntegral GL_FALSE
    glClampColor GL_CLAMP_READ_COLOR     $ fromIntegral GL_FALSE
    glClampColor GL_CLAMP_FRAGMENT_COLOR $ fromIntegral GL_FALSE
    sR <- newIORef SnowGlobe
      { pInitial = pInitial', pInitial'er = pInitial'er', pInitial'rho = pInitial'↙
          ↳ rho'
      , pStep = pStep', pStep'er = pStep'er', pStep'ts = pStep'ts', pStep'src = ↙
          ↳ pStep'src'
      , pColour = pColour', pColour'src = pColour'src', pColour'speed = pColour'↙
          ↳ speed', pColour'colour = pColour'colour'
      , tPing = tPing', tPong = tPong', fBuffer = fBuffer'
      , sFlakes = [], sTextures = M.empty, wSize = wSize', wFullScreen = Nothing
      , sNextName = 0, sRenderFlake = return undefined
      , sRecord = False, sRecordFlakes = False
      }
    modifyIORef sR $ \s'->s'{ sRenderFlake = flakeRenderStart sR }
    addTimerCallback 40 timer
    displayCallback $= display sR
    reshapeCallback $= Just (reshape sR)
    keyboardMouseCallback $= Just (keyboard sR)
    mainLoop

keyboard :: IORef SnowGlobe -> Key -> KeyState -> Modifiers -> Position -> IO ()
keyboard sR (SpecialKey KeyF11) Down _ _ = toggleFullScreen sR
keyboard sR (Char 'f') Down _ _ = toggleFullScreen sR
keyboard sR (Char 'R') Down _ _ = modifyIORef sR $ \s -> s{ sRecord = not (↙
    ↳ sRecord s) }
keyboard sR (Char 'S') Down _ _ = modifyIORef sR $ \s -> s{ sRecordFlakes = not ↙
    ↳ (sRecordFlakes s) }
keyboard _ (Char _) Down _ _ = exitSuccess
keyboard _ _ _ _ _ = return ()

toggleFullScreen :: IORef SnowGlobe -> IO ()
toggleFullScreen sR = do
  s <- readIORef sR
  case wFullScreen s of
    Nothing -> do
      writeIORef sR s{ wFullScreen = Just (wSize s) }
      cursor $= None
      fullScreen
    Just ws -> do
      writeIORef sR s{ wFullScreen = Nothing }
      cursor $= Inherit
      windowSize $= ws

reshape :: IORef SnowGlobe -> Size -> IO ()
reshape sR sz = do
  s <- readIORef sR
  writeIORef sR s{ wSize = sz }

timer :: IO ()
timer = do
```

```
    addTimerCallback 40 timer
    postRedisplay Nothing

display' :: IORef SnowGlobe -> IO ()
display' sR = do
  update sR
  s <- readIORef sR
  _ <- evaluate (sum' . map flakeName . sFlakes $ s)
  let names = S.fromList $ map flakeName (sFlakes s)
      expired = S.filter (`S.notMember` names) (M.keysSet (sTextures s))
      sTextures' = foldr M.delete (sTextures s) (S.toList expired)
  deleteObjectNames [sTextures s M.! n | n <- S.toList expired]
  modifyIORef sR $ \s'->s'{ sTextures = sTextures' }
  r <- sRenderFlake s
  case r of
    Done t -> do
      f <- flakeSpawn (sFlakes s) (sNextName s)
      modifyIORef sR $ \s'->s'
        { sRenderFlake = flakeRenderStart sR
        , sFlakes = f : sFlakes s'
        , sTextures = M.insert (flakeName f) t (sTextures s')
        , sNextName = sNextName s' + 1
        }
      when (sRecordFlakes s) $
        saveTexture t ("snowglobe-" ++ show (flakeName f) ++ ".pgm")
    Step sRenderFlake' ->
      modifyIORef sR $ \s'->s'{ sRenderFlake = sRenderFlake' }

update :: IORef SnowGlobe -> IO ()
update sR = do
  s <- readIORef sR
  let sFlakes' = flakesUpdate (1 / 256) (sFlakes s)
  writeIORef sR (s{ sFlakes = sFlakes' })

display :: IORef SnowGlobe -> IO ()
display sR = do
  s <- readIORef sR
  loadIdentity
  let Size w h = wSize s
      r = 0.7
      (x, y)
        | h < w     = (r, r * fromIntegral h / fromIntegral w)
        | otherwise = (r * fromIntegral w / fromIntegral h, r)
  ortho2D (-x) x (-y) y
  viewport $= (Position 0 0, wSize s)
  clearColor $= Color4 0 0 0.25 1
  clear [ColorBuffer]
  texture Texture2D $= Enabled
  blend $= Enabled
  blendFunc $= (SrcAlpha, OneMinusSrcAlpha)
  forM_ (sFlakes s) (flakeDraw s)
  blend $= Disabled
  texture Texture2D $= Disabled
  swapBuffers
  when (sRecord s) $ hPut stdout =<< capturePPM
  reportErrors
  display' sR
```

```
flakeDraw :: SnowGlobe -> Flake -> IO ()
flakeDraw s f = do
  let d :: GLdouble
      d = realToFrac $ flakeSize f / 4
      a :: GLdouble
      a = realToFrac $ 360 * flakeTime f * sin (fromIntegral (flakeName f))
      p :: GLdouble -> GLdouble -> IO ()
      p u v = do
        texCoord $ TexCoord2 ((1+u)/2) ((1+v)/2)
        vertex $ Vertex2 u v
      V2 x y = flakePosition f
  case flakeName f `M.lookup` sTextures s of
    Nothing -> return ()
    t -> do
      textureBinding Texture2D $= t
      unsafePreservingMatrix $ do
        translate $ Vector3 (realToFrac x :: GLdouble) (realToFrac y :: GLdouble↙
            ↳ ) 0
        rotate a (Vector3 0 0 1)
        GL.scale d d d
        renderPrimitive Quads $ p (-1) (-1) >> p 1 (-1) >> p 1 1 >> p (-1) 1
      textureBinding Texture2D $= Nothing

newTex :: N -> IO TextureObject
newTex s = do
  [t] <- genObjectNames 1
  textureBinding Texture2D $= Just t
  glTexImage2D GL_TEXTURE_2D 0 (fromIntegral GL_R32F) (fromIntegral s) (↙
      ↳ fromIntegral s) 0 GL_RED GL_UNSIGNED_BYTE nullPtr
  textureFilter Texture2D $= ((Linear', Nothing), Linear')
  textureWrapMode Texture2D S $= (Repeated, ClampToEdge)
  textureWrapMode Texture2D T $= (Repeated, ClampToEdge)
  textureBinding Texture2D $= Nothing
  return t

newTexRGBA :: N -> IO TextureObject
newTexRGBA s = do
  [t] <- genObjectNames 1
  textureBinding Texture2D $= Just t
  glTexImage2D GL_TEXTURE_2D 0 (fromIntegral GL_RGBA) (fromIntegral s) (↙
      ↳ fromIntegral s) 0 GL_RGBA GL_UNSIGNED_BYTE nullPtr
  textureFilter Texture2D $= ((Linear', Just Linear'), Linear')
  textureWrapMode Texture2D S $= (Repeated, ClampToEdge)
  textureWrapMode Texture2D T $= (Repeated, ClampToEdge)
  textureBinding Texture2D $= Nothing
  return t

saveTexture :: TextureObject -> FilePath -> IO ()
saveTexture t f = withBinaryFile f WriteMode $ \h -> do
  let header = "P5\n" ++ show tSize ++ " " ++ show tSize ++ "\n255\n"
      n = tSize * tSize
  hPutStr h header
  allocaArray n $ \p -> do
    textureBinding Texture2D $= Just t
    glGetTexImage GL_TEXTURE_2D 0 GL_ALPHA GL_UNSIGNED_BYTE (p :: Ptr Word8)
    textureBinding Texture2D $= Nothing
```

```
      hPutBuf h p n

newtype FramebufferObject = FramebufferObject GLuint

newFBO :: IO FramebufferObject
newFBO = fmap FramebufferObject (alloca $ \p -> glGenFramebuffers 1 p >> peek p)

bindFBO :: FramebufferObject -> TextureObject -> IO ()
bindFBO (FramebufferObject f) (TextureObject t) = do
  glBindFramebuffer GL_FRAMEBUFFER f
  glFramebufferTexture2D GL_FRAMEBUFFER GL_COLOR_ATTACHMENT0 GL_TEXTURE_2D t 0

unbindFBO :: IO ()
unbindFBO = do
  glFramebufferTexture2D GL_FRAMEBUFFER GL_COLOR_ATTACHMENT0 GL_TEXTURE_2D 0 0
  glBindFramebuffer GL_FRAMEBUFFER 0

fullQuad :: IO ()
fullQuad = do
  renderPrimitive Quads $ do
    t (0.5-r) (0.5+r) >> v (-r2) ( r2)
    t (0.5-r) (0.5-r) >> v (-r2) (-r2)
    t (0.5+r) (0.5-r) >> v ( r2) (-r2)
    t (0.5+r) (0.5+r) >> v ( r2) ( r2)
  where
    r = sqrt 0.5 / realToFrac er
    r2 = 1
    t, v :: GLdouble -> GLdouble -> IO ()
    t x y = texCoord (TexCoord2 x y)
    v x y = vertex (Vertex2 x y)

unitQuad :: IO ()
unitQuad = renderPrimitive Quads $ do
    t 0 1 >> v 0 1
    t 0 0 >> v 0 0
    t 1 0 >> v 1 0
    t 1 1 >> v 1 1
  where
    t, v :: GLdouble -> GLdouble -> IO ()
    t x y = texCoord (TexCoord2 x y)
    v x y = vertex (Vertex2 x y)

clamp :: Ord a => a -> a -> a -> a
clamp mi ma x = mi `max` x `min` ma
```

10 Vector.hs

```
{-# LANGUAGE MultiParamTypeClasses, TypeSynonymInstances #-}

module Vector where

type R = Double

data V1 = V1 !R deriving (Show, Eq, Ord)
data V2 = V2 !R !R deriving (Show, Eq, Ord)
data V3 = V3 !R !R !R deriving (Show, Eq, Ord)
data V4 = V4 !R !R !R !R deriving (Show, Eq, Ord)
```

```
class V a where
  o       :: a
  (^+^)   :: a -> a -> a
  (^-^)   :: a -> a -> a
  (*^)    :: R -> a -> a
  (^*)    :: a -> R -> a
  (^/)    :: a -> R -> a
  dot     :: a -> a -> R

(|-|) :: V a => a -> a -> R
u |-| v = let d = u ^-^ v in d `dot` d

norm :: V a => a -> a
norm v = v ^/ sqrt (v`dot`v)

instance V V1 where
  o = V1 0
  V1 a ^+^ V1 x = V1 (a + x)
  V1 a ^-^ V1 x = V1 (a - x)
  k *^ V1 x = V1 (k * x)
  V1 a ^* k = V1 (a * k)
  V1 a ^/ k = V1 (a / k)
  V1 a `dot` V1 x = a * x

instance V V2 where
  o = V2 0 0
  V2 a b ^+^ V2 x y = V2 (a + x) (b + y)
  V2 a b ^-^ V2 x y = V2 (a - x) (b - y)
  k *^ V2 x y = V2 (k * x) (k * y)
  V2 a b ^* k = V2 (a * k) (b * k)
  V2 a b ^/ k = V2 (a / k) (b / k)
  V2 a b `dot` V2 x y = a * x + b * y

instance V V3 where
  o = V3 0 0 0
  V3 a b c ^+^ V3 x y z = V3 (a + x) (b + y) (c + z)
  V3 a b c ^-^ V3 x y z = V3 (a - x) (b - y) (c - z)
  k *^ V3 x y z = V3 (k * x) (k * y) (k * z)
  V3 a b c ^* k = V3 (a * k) (b * k) (c * k)
  V3 a b c ^/ k = V3 (a / k) (b / k) (c / k)
  V3 a b c `dot` V3 x y z = a * x + b * y + c * z

cross3 :: V3 -> V3 -> V3
cross3 (V3 a1 a2 a3) (V3 b1 b2 b3) =
  V3 (a2*b3-a3*b2) (a3*b1-a1*b3) (a1*b2-a2*b1)

instance V V4 where
  o = V4 0 0 0 0
  V4 a b c d ^+^ V4 x y z w = V4 (a + x) (b + y) (c + z) (d + w)
  V4 a b c d ^-^ V4 x y z w = V4 (a - x) (b - y) (c - z) (d - w)
  k *^ V4 x y z w = V4 (k * x) (k * y) (k * z) (k * w)
  V4 a b c d ^* k = V4 (a * k) (b * k) (c * k) (d * k)
  V4 a b c d ^/ k = V4 (a / k) (b / k) (c / k) (d / k)
  V4 a b c d `dot` V4 x y z w = a * x + b * y + c * z + d * w

data M1 = M1 !R deriving (Show, Eq, Ord)
```

```
data M2 = M2 !R !R  !R !R deriving (Show, Eq, Ord)
data M3 = M3 !R !R !R  !R !R !R  !R !R !R deriving (Show, Eq, Ord)
data M4 = M4 !R !R !R !R  !R !R !R !R  !R !R !R !R  !R !R !R !R deriving (Show, ↙
    ↳ Eq, Ord)

class M a where
  i       :: a
  (^^+^^) :: a -> a -> a
  (^^-^^) :: a -> a -> a
  (^^*^^) :: a -> a -> a
  (*^^)   :: R -> a -> a
  (^^*)   :: a -> R -> a
  (^^/)   :: a -> R -> a
  mdot    :: a -> a -> R
  det     :: a -> R
  inv     :: a -> a

(||-||) :: M a => a -> a -> R
u ||-|| v = let d = u ^^-^^ v in d `mdot` d

instance M M1 where
  i = M1 1
  M1 a11 ^^+^^ M1 b11 = M1 (a11 + b11)
  M1 a11 ^^-^^ M1 b11 = M1 (a11 - b11)
  M1 a11 ^^*^^ M1 b11 = M1 (a11 * b11)
  a *^^ M1 b11 = M1 (a * b11)
  M1 a11 ^^* b = M1 (a11 * b)
  M1 a11 ^^/ b = M1 (a11 / b)
  M1 a11 `mdot` M1 b11 = (a11 * b11)
  det (M1 a11) = a11
  inv (M1 a11) = M1 (1/a11)

instance M M2 where
  i = M2 1 0 0 1
  M2 a11 a12 a21 a22 ^^+^^ M2 b11 b12 b21 b22 =
    M2 (a11 + b11) (a12 + b12) (a21 + b21) (a22 + b22)
  M2 a11 a12 a21 a22 ^^-^^ M2 b11 b12 b21 b22 =
    M2 (a11 - b11) (a12 - b12) (a21 - b21) (a22 - b22)
  M2 a11 a12 a21 a22 ^^*^^ M2 b11 b12 b21 b22 =
    M2 (a11*b11 + a12*b21) (a11*b12 + a12*b22) (a21*b11 + a22*b21) (a21*b12 + ↙
        ↳ a22*b22)
  a *^^ M2 b11 b12 b21 b22 = M2 (a * b11) (a * b12) (a * b21) (a * b22)
  M2 a11 a12 a21 a22 ^^* b = M2 (a11 * b) (a12 * b) (a21 * b) (a22 * b)
  M2 a11 a12 a21 a22 ^^/ b = M2 (a11 / b) (a12 / b) (a21 / b) (a22 / b)
  M2 a11 a12 a21 a22 `mdot` M2 b11 b12 b21 b22 =
    a11*b11 + a12*b12 + a21*b21 + a22*b22
  det (M2 a11 a12 a21 a22) = a11 * a22 - a12 * a21
  inv a@(M2 a11 a12 a21 a22) = (M2 a22 (-a12) (-a21) a11) ^^/ det a

instance M M3 where
  i = M3 1 0 0 0 1 0 0 0 1
  M3 a11 a12 a13 a21 a22 a23 a31 a32 a33 ^^+^^ M3 b11 b12 b13 b21 b22 b23 b31 ↙
      ↳ b32 b33 =
    M3 (a11 + b11) (a12 + b12) (a13 + b13) (a21 + b21) (a22 + b22) (a23 + b23) (↙
        ↳ a31 + b31) (a32 + b32) (a33 + b33)
  M3 a11 a12 a13 a21 a22 a23 a31 a32 a33 ^^-^^ M3 b11 b12 b13 b21 b22 b23 b31 ↙
      ↳ b32 b33 =
```

```
      M3 (a11 - b11) (a12 - b12) (a13 - b13) (a21 - b21) (a22 - b22) (a23 - b23) (↙
          ↳ a31 - b31) (a32 - b32) (a33 - b33)
    M3 a11 a12 a13 a21 a22 a23 a31 a32 a33 ^^*^^ M3 b11 b12 b13 b21 b22 b23 b31 ↙
        ↳ b32 b33 =
      M3 (a11*b11 + a12*b21 + a13*b31) (a11*b12 + a12*b22 + a13*b32) (a11*b13 + ↙
          ↳ a12*b23 + a13*b33)
         (a21*b11 + a22*b21 + a23*b31) (a21*b12 + a22*b22 + a23*b32) (a21*b13 + ↙
             ↳ a22*b23 + a23*b33)
         (a31*b11 + a32*b21 + a33*b31) (a31*b12 + a32*b22 + a33*b32) (a31*b13 + ↙
             ↳ a32*b23 + a33*b33)
    a *^^ M3 b11 b12 b13 b21 b22 b23 b31 b32 b33 =
      M3 (a * b11) (a * b12) (a * b13) (a * b21) (a * b22) (a * b23) (a * b31) (a ↙
          ↳ * b32) (a * b33)
    M3 a11 a12 a13 a21 a22 a23 a31 a32 a33 ^^* b =
      M3 (a11 * b) (a12 * b) (a13 * b) (a21 * b) (a22 * b) (a23 * b) (a31 * b) (↙
          ↳ a32 * b) (a33 * b)
    M3 a11 a12 a13 a21 a22 a23 a31 a32 a33 ^^/ b =
      M3 (a11 / b) (a12 / b) (a13 / b) (a21 / b) (a22 / b) (a23 / b) (a31 / b) (↙
          ↳ a32 / b) (a33 / b)
    M3 a11 a12 a13 a21 a22 a23 a31 a32 a33 `mdot` M3 b11 b12 b13 b21 b22 b23 b31 ↙
        ↳ b32 b33 =
      a11*b11 + a12*b12 + a13*b13 +
      a21*b21 + a22*b22 + a23*b23 +
      a31*b31 + a32*b32 + a33*b33
    det (M3 a11 a12 a13 a21 a22 a23 a31 a32 a33) =
      let m11 = M2 a22 a23 a32 a33
          m12 = M2 a21 a23 a31 a33
          m13 = M2 a21 a22 a31 a32
      in a11 * det m11 - a12 * det m12 + a13 * det m13
    inv a@(M3 a11 a12 a13 a21 a22 a23 a31 a32 a33) =
      let m11 =   a33 * a22 - a32 * a23
          m12 = -(a33 * a12 - a32 * a13)
          m13 =   a23 * a12 - a22 * a13
          m21 = -(a33 * a21 - a31 * a23)
          m22 =   a33 * a11 - a31 * a13
          m23 = -(a23 * a11 - a21 * a13)
          m31 =   a32 * a21 - a31 * a22
          m32 = -(a32 * a11 - a31 * a12)
          m33 =   a22 * a11 - a21 * a12
      in (M3 m11 m12 m13 m21 m22 m23 m31 m32 m33) ^^/ det a

instance M M4 where
  i = M4 1 0 0 0 0 1 0 0 0 0 1 0 0 0 0 1
  M4 a11 a12 a13 a14 a21 a22 a23 a24 a31 a32 a33 a34 a41 a42 a43 a44 ^^+^^ M4 ↙
      ↳ b11 b12 b13 b14 b21 b22 b23 b24 b31 b32 b33 b34 b41 b42 b43 b44 =
    M4 (a11 + b11) (a12 + b12) (a13 + b13) (a14 + b14)
       (a21 + b21) (a22 + b22) (a23 + b23) (a24 + b24)
       (a31 + b31) (a32 + b32) (a33 + b33) (a34 + b34)
       (a41 + b41) (a42 + b42) (a43 + b43) (a44 + b44)
  M4 a11 a12 a13 a14 a21 a22 a23 a24 a31 a32 a33 a34 a41 a42 a43 a44 ^^-^^ M4 ↙
      ↳ b11 b12 b13 b14 b21 b22 b23 b24 b31 b32 b33 b34 b41 b42 b43 b44 =
    M4 (a11 - b11) (a12 - b12) (a13 - b13) (a14 - b14)
       (a21 - b21) (a22 - b22) (a23 - b23) (a24 - b24)
       (a31 - b31) (a32 - b32) (a33 - b33) (a34 - b34)
       (a41 - b41) (a42 - b42) (a43 - b43) (a44 - b44)
  M4 a11 a12 a13 a14 a21 a22 a23 a24 a31 a32 a33 a34 a41 a42 a43 a44 ^^*^^ M4 ↙
      ↳ b11 b12 b13 b14 b21 b22 b23 b24 b31 b32 b33 b34 b41 b42 b43 b44 =
```

```
      M4 (a11*b11 + a12*b21 + a13*b31 + a14*b41) (a11*b12 + a12*b22 + a13*b32 + a14*b42) (a11*b13 + a12*b23 + a13*b33 + a14*b43) (a11*b14 + a12*b24 + a13*b34 + a14*b44)
         (a21*b11 + a22*b21 + a23*b31 + a24*b41) (a21*b12 + a22*b22 + a23*b32 + a24*b42) (a21*b13 + a22*b23 + a23*b33 + a24*b43) (a21*b14 + a22*b24 + a23*b34 + a24*b44)
         (a31*b11 + a32*b21 + a33*b31 + a34*b41) (a31*b12 + a32*b22 + a33*b32 + a34*b42) (a31*b13 + a32*b23 + a33*b33 + a34*b43) (a31*b14 + a32*b24 + a33*b34 + a34*b44)
         (a41*b11 + a42*b21 + a43*b31 + a44*b41) (a41*b12 + a42*b22 + a43*b32 + a44*b42) (a41*b13 + a42*b23 + a43*b33 + a44*b43) (a41*b14 + a42*b24 + a43*b34 + a44*b44)
    a *^^ M4 b11 b12 b13 b14 b21 b22 b23 b24 b31 b32 b33 b34 b41 b42 b43 b44 =
      M4 (a * b11) (a * b12) (a * b13) (a * b14)
         (a * b21) (a * b22) (a * b23) (a * b24)
         (a * b31) (a * b32) (a * b33) (a * b34)
         (a * b41) (a * b42) (a * b43) (a * b44)
    M4 a11 a12 a13 a14 a21 a22 a23 a24 a31 a32 a33 a34 a41 a42 a43 a44 ^^* b =
      M4 (a11 * b) (a12 * b) (a13 * b) (a14 * b)
         (a21 * b) (a22 * b) (a23 * b) (a24 * b)
         (a31 * b) (a32 * b) (a33 * b) (a34 * b)
         (a41 * b) (a42 * b) (a43 * b) (a44 * b)
    M4 a11 a12 a13 a14 a21 a22 a23 a24 a31 a32 a33 a34 a41 a42 a43 a44 ^^/ b =
      M4 (a11 / b) (a12 / b) (a13 / b) (a14 / b)
         (a21 / b) (a22 / b) (a23 / b) (a24 / b)
         (a31 / b) (a32 / b) (a33 / b) (a34 / b)
         (a41 / b) (a42 / b) (a43 / b) (a44 / b)
    M4 a11 a12 a13 a14 a21 a22 a23 a24 a31 a32 a33 a34 a41 a42 a43 a44 `mdot` M4 b11 b12 b13 b14 b21 b22 b23 b24 b31 b32 b33 b34 b41 b42 b43 b44 =
      a11*b11 + a12*b12 + a13*b13 + a14*b14 +
      a21*b21 + a22*b22 + a23*b23 + a24*b24 +
      a31*b31 + a32*b32 + a33*b33 + a34*b34 +
      a41*b41 + a42*b42 + a43*b43 + a44*b44
    det (M4 a11 a12 a13 a14 a21 a22 a23 a24 a31 a32 a33 a34 a41 a42 a43 a44) =
      let m11 = M3 a22 a23 a24 a32 a33 a34 a42 a43 a44
          m12 = M3 a21 a23 a24 a31 a33 a34 a41 a43 a44
          m13 = M3 a21 a22 a24 a31 a32 a34 a41 a42 a44
          m14 = M3 a21 a22 a23 a31 a32 a33 a41 a42 a43
      in a11 * det m11 - a12 * det m12 + a13 * det m13 - a14 * det m14
    inv (M4 a11 a12 a13 a14 a21 a22 a23 a24 a31 a32 a33 a34 a41 a42 a43 a44) =
      let a = M2 a11 a12 a21 a22
          b = M2 a13 a14 a23 a24
          c = M2 a31 a32 a41 a42
          d = M2 a33 a34 a43 a44
          a1 = inv a
          ca1 = c ^^*^^ a1
          dcab1 = inv (d ^^-^^ (ca1 ^^*^^ b))
          a1bdcab1 = a1 ^^*^^ (b ^^*^^ dcab1)
          M2 m11 m12 m21 m22 = a1 ^^+^^ (a1bdcab1 ^^*^^ ca1)
          M2 m13 m14 m23 m24 = (-1) *^^ a1bdcab1
          M2 m31 m32 m41 m42 = (-1) *^^ (dcab1 ^^*^^ ca1)
          M2 m33 m34 m43 m44 = dcab1
      in M4 m11 m12 m13 m14 m21 m22 m23 m24 m31 m32 m33 m34 m41 m42 m43 m44

class MV m v where
  (^^*^) :: m -> v -> v
  (^*^!) :: v -> v -> m
```

```
reflector :: (M m, V v, MV m v) => v -> m
reflector v = i ^^-^^ (2 *^^ (v ^*^! v))

instance MV M1 V1 where
  M1 m ^^*^ V1 v = V1 (m * v)
  V1 a ^*^! V1 b = M1 (a * b)

instance MV M2 V2 where
  M2 m11 m12 m21 m22 ^^*^ V2 v1 v2 =
    V2 (m11*v1 + m12*v2)
       (m21*v1 + m22*v2)
  V2 a1 a2 ^*^! V2 b1 b2 =
    M2 (a1 * b1) (a1 * b2)
       (a2 * b1) (a2 * b2)

instance MV M3 V3 where
  M3 m11 m12 m13 m21 m22 m23 m31 m32 m33 ^^*^ V3 v1 v2 v3 =
    V3 (m11*v1 + m12*v2 + m13*v3)
       (m21*v1 + m22*v2 + m23*v3)
       (m31*v1 + m32*v2 + m33*v3)
  V3 a1 a2 a3 ^*^! V3 b1 b2 b3 =
    M3 (a1 * b1) (a1 * b2) (a1 * b3)
       (a2 * b1) (a2 * b2) (a2 * b3)
       (a3 * b1) (a3 * b2) (a3 * b3)

instance MV M4 V4 where
  M4 m11 m12 m13 m14 m21 m22 m23 m24 m31 m32 m33 m34 m41 m42 m43 m44 ^^*^ V4 v1 ↙
     ↳ v2 v3 v4 =
    V4 (m11*v1 + m12*v2 + m13*v3 + m14*v4)
       (m21*v1 + m22*v2 + m23*v3 + m24*v4)
       (m31*v1 + m32*v2 + m33*v3 + m34*v4)
       (m41*v1 + m42*v2 + m43*v3 + m44*v4)
  V4 a1 a2 a3 a4 ^*^! V4 b1 b2 b3 b4 =
    M4 (a1 * b1) (a1 * b2) (a1 * b3) (a1 * b4)
       (a2 * b1) (a2 * b2) (a2 * b3) (a2 * b4)
       (a3 * b1) (a3 * b2) (a3 * b3) (a3 * b4)
       (a4 * b1) (a4 * b2) (a4 * b3) (a4 * b4)

cross4 :: V4 -> V4 -> V4 -> V4
cross4 (V4 u0 u1 u2 u3) (V4 v0 v1 v2 v3) (V4 w0 w1 w2 w3) =
{-
  let vw01 = v0 * w1 - v1 * w0
      vw02 = v0 * w2 - v2 * w0
      vw03 = v0 * w3 - v3 * w0
      vw12 = v1 * w2 - v2 * w1
      vw13 = v1 * w3 - v3 * w1
      vw23 = v2 * w3 - v3 * w2
      r0 =   u1 * vw23 - u2 * vw13 + u3 * vw12
      r1 = - u0 * vw23 + u2 * vw03 - u3 * vw02
      r2 =   u0 * vw13 - u1 * vw03 + u3 * vw02
      r3 = - u0 * vw12 + u1 * vw02 - u2 * vw01
  in V4 r0 r1 r2 r3
-}
  let m0 = M3 u1 u2 u3 v1 v2 v3 w1 w2 w3
      m1 = M3 u0 u2 u3 v0 v2 v3 w0 w2 w3
      m2 = M3 u0 u1 u3 v0 v1 v3 w0 w1 w3
```

```
        m3 = M3 u0 u1 u2 v0 v1 v2 w0 w1 w2
    in V4 (det m0) (-(det m1)) (det m2) (-(det m3))
```