bitbreeder

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1 bitbreeder.hs

```
module Main(main) where

import Control.Exception (handle, SomeException)
import Control.Monad (forM_, when)
import Control.Monad.Random (evalRandIO)
import Control.Concurrent (forkIO) -- , threadDelay)
import GHC.Conc (numCapabilities)
import Data.Maybe (listToMaybe)
import Data.Time.Clock (getCurrentTime, diffUTCTime)
import Data.Vector.Unboxed ((!), (//))
import System.IO (hSetBuffering, BufferMode(LineBuffering), hPutStrLn, stdout) ↙
   ↳ -- , stderr)

import Graphics.UI.Gtk
import Control.Concurrent.STM
import System.Process

import Expression
import Evolve
import Compile
import Population
import qualified Metric as M

gui :: (TVar [TVar Population], TBQueue Item) -> IO ()
gui (dbsV, toAudio) = do
  wi <- windowNew
  nb <- notebookNew
  visibleV <- newTVarIO 0
  _ <- nb `on` switchPage $ atomically . writeTVar visibleV
  let addTab tabname = do
        db <- atomically $ (readTVar . head) =<< readTVar dbsV
        databaseV <- newTVarIO db
        targetV <- newTVarIO M.emptyTarget
        weightV <- newTVarIO M.emptyWeight
        atomically $ modifyTVar dbsV (databaseV:)
        v <- vBoxNew False 5
        let resort = do
              t <- readTVar targetV
              w <- readTVar weightV
              modifyTVar databaseV $ target t w
            tSlider k = do
              t <- hScaleNewWithRange (-5) 5 0.01
              scaleSetDrawValue t False
              widgetSetSizeRequest t 512 24
              rangeSetValue t 0
              _ <- t `on` valueChanged $ do
                u <- rangeGetValue t
                atomically $ do
                  modifyTVar targetV (\(M.T z) -> M.T $ z // [(k, realToFrac u)↙
                     ↳ ])
                  resort
              return t
            wSlider k = do
              w <- hScaleNewWithRange 0 1 0.001
              scaleSetDrawValue w False
              widgetSetSizeRequest w 256 24
              rangeSetValue w 0
              _ <- w `on` valueChanged $ do
                u <- rangeGetValue w
                atomically $ do
                  modifyTVar weightV (\(M.W z) -> M.W $ z // [(k, realToFrac u)↙
                     ↳ ])
                  resort
              return w
            row k n = do
              h <- hBoxNew False 5
              l <- labelNew (Just n)
              widgetSetSizeRequest l 160 24
              t <- tSlider k
              w <- wSlider k
              boxPackStart h l PackNatural 0
              boxPackEnd h w PackGrow 0
              boxPackEnd h t PackGrow 0
              boxPackStart v h PackNatural 0
        forM_ (zip [0..] names) $ uncurry row
        widgetShowAll v
        page <- notebookAppendPage nb v tabname
        notebookSetCurrentPage nb page
        let topWatcher n = do
              n' <- atomically $ do
                mi <- listToMaybe . toAscList <$> readTVar databaseV
                case mi of
                  Just i | itemID i /= n -> do
                    vis <- (page ==) <$> readTVar visibleV
                    when vis $ writeTBQueue toAudio i
                    return (itemID i)
                  _ -> retry
              topWatcher n'
            visWatcher False = do
              atomically $ do
                vis <- (page ==) <$> readTVar visibleV
                if not vis then retry else do
                  mi <- listToMaybe . toAscList <$> readTVar databaseV
                  case mi of
                    Just i -> writeTBQueue toAudio i
                    _ -> return ()
              visWatcher True
            visWatcher True = do
              atomically $ do
                vis <- (page ==) <$> readTVar visibleV
                when vis retry
              visWatcher False
        _ <- forkIO $ topWatcher (-1)
        _ <- forkIO $ visWatcher False
        return ()
  namesV <- newTVarIO $ words "aardvark beaver chimp donkey elephant frog goat halibut iguana jackdaw kitten leopard manatee newt otter pigeon quail rabbit stoat tiger uncle velociraptor whale xtinct yow zzz"
  let addTab' = do
        name <- atomically $ do
          ~(n:ns) <- readTVar namesV
          writeTVar namesV ns
          return n
        addTab name
  b <- buttonNewFromStock stockAdd
  _ <- b `on` buttonActivated $ addTab'
  widgetShowAll b
  notebookSetActionWidget nb b PackStart
  set nb [notebookScrollable := True, notebookHomogeneous := True]
  set wi [windowTitle := "BitBreeder", containerChild := nb]
  widgetSetSizeRequest wi 1024 576
  windowMove wi 0 0
  _ <- wi `onDestroy` mainQuit
  widgetShowAll wi
  addTab'
  mainGUI

names :: [String]
names = [ m ++ " (" ++ p ++ ")" | m <- measurements, p <- parameters ] ++ ["novelty"]

measurements :: [String]
measurements =
  [ "loudness"
  , "tonality"
  , "centroid"
  , "variance"
  , "skewness"
  , "kurtosis"
  ]

parameters :: [String]
parameters =
  [ "average"
  , "variability"
  , "granularity"
  ]

main :: IO ()
main = do
  hSetBuffering stdout LineBuffering
  args <- initGUI
  gui =<< evolution args

breeder :: TVar [TVar Population] -> TBQueue E -> IO ()
breeder dbsV toJudge = loop
  where
    loop = do
      ess <- map (map itemExpr . toAscList) <$> atomically (mapM readTVar =<< readTVar dbsV)
      es <- evalRandIO (crossBreed ess)
      forM_ es $ atomically . writeTBQueue toJudge
      loop

judge :: TVar [TVar Population] -> TBQueue E -> Int -> Int -> IO ()
judge dbsV toJudge inc = loop
  where
    loop i = do
      e <- atomically $ readTBQueue toJudge
      ignoreErrors $ do
        let so = "./o/" ++ show i ++ ".so"
        compileSO e so
        (_, Just hout, _, p) <- createProcess (proc "./bitbreeder_judge" [so, show i]){ std_out = CreatePipe, std_err = Inherit }
        v@(M.A vv) <- M.read hout
        _ <- waitForProcess p
        when (vv ! 0 > 0) $ do
          let it = Item i e v
          atomically $ do
            dbs <- readTVar dbsV
            forM_ dbs $ \db -> modifyTVar db (update it)
      loop (i + inc)

ignoreErrors :: IO () -> IO ()
ignoreErrors = handle ((\_ -> return ()) :: SomeException -> IO ())

evolution :: [String] -> IO (TVar [TVar Population], TBQueue Item)
evolution args = do
  toJudge <- newTBQueueIO (fromIntegral $ 2 * numCapabilities)
  toAudio <- newTBQueueIO (fromIntegral $ 2 * numCapabilities)
  dbV <- newTVarIO empty
  dbsV <- newTVarIO [dbV]
  _ <- forkIO $ breeder dbsV toJudge
  _ <- forkIO $ audio args toAudio
  forM_ [0 .. numCapabilities - 1] $ forkIO . judge dbsV toJudge numCapabilities
  return (dbsV, toAudio)

audio :: [String] -> TBQueue Item -> IO ()
audio args toAudio = do
  (Just audioh, _, _, _) <- createProcess (proc "./bitbreeder_audio" []){ std_in↙
      ↳ = CreatePipe, std_err = Inherit }
  (Just videoh, _, _, _) <- createProcess (proc "./bitbreeder_video" args){ ↙
      ↳ std_in = CreatePipe, std_err = Inherit }
  hSetBuffering audioh LineBuffering
  hSetBuffering videoh LineBuffering
  hPutStrLn videoh (show (0 :: Double, I 0))
  start <- getCurrentTime
  let loop n = do
        it <- atomically $ readTBQueue toAudio
        when (itemID it /= n) $ do
          now <- getCurrentTime
          let frame :: Double
              frame = 25 * realToFrac (diffUTCTime now start + 4.5)
          hPutStrLn audioh ("./o/" ++ show (itemID it) ++ ".so")
          hPutStrLn videoh (show (frame, itemExpr it))
        loop (itemID it)
  loop (-1)
```

2 bitbreeder_video.hs

```
module Main(main) where

import Prelude hiding (init)

import Control.Exception (handle, SomeException)
import Control.Monad (forever, when)
import System.Environment (getArgs)
import System.IO (hSetBuffering, BufferMode(LineBuffering), stdin, stdout)

import Graphics.UI.GLFW

import Config (videoX, videoY, videoW, videoH)
import Expression
import Video

```

```
main :: IO ()
main = do
  hSetBuffering stdin LineBuffering
  hSetBuffering stdout LineBuffering
  args <- getArgs
  let record = ”--record” ‘elem‘ args
  True <- init
  windowHint $ WindowHint'Resizable False
  windowHint $ WindowHint'Decorated False
  Just window <- createWindow videoW videoH ”BitBreeder Expression” Nothing ↙
      ↳ Nothing
  setWindowPos window videoX videoY
  makeContextCurrent (Just window)
  s <- setupGL
  draw s (I 0)
  handle ((\_ -> return ()) :: SomeException -> IO ()) $ forever $ do
    ne@(n, e) <- readLn :: IO (Double, E)
    print ne
    draw s e
    swapBuffers window
    when record $ captureToPNG (pngFilename (floor n))
    pollEvents
  destroyWindow window
  terminate
```

3 Compile.hs

```
module Compile (compile, compileSO) where

import System.Process (rawSystem)

import Expression

compile :: E -> String
compile X = ”t”
compile (I i) = show i
compile (U u e) = compileU u (”(” ++ compile e ++ ”)”)
compile (B b e f) = compileB b (”(” ++ compile e ++ ”)”) (”(” ++ compile f ++ ”)↙
    ↳ ”)
compile (T e f g) = ”(” ++ compile e ++ ”)?(” ++ compile f ++ ”):(” ++ compile g↙
    ↳ ++ ”)”

compileU :: U -> String -> String
compileU Neg s = ”-” ++ s
compileU LNot s = ”-(!” ++ s ++ ”)”
compileU BNot s = ”˜” ++ s

compileB :: B -> String -> String -> String
compileB Add = op ”+”
compileB Sub = op ”-”
compileB Mul = op ”*”
compileB Div = fn ”safe_div”
compileB Mod = fn ”safe_mod”
compileB BAnd = op ”&”
compileB LAnd = \l r -> ”-(” ++ op ”&&” l r ++ ”)”
compileB BOr = op ”|”
compileB LOr = \l r -> ”-(” ++ op ”||” l r ++ ”)”
compileB XOr = op ”ˆ”
compileB ShL = op ”<<”
compileB ShR = op ”>>”
compileB Lt  = \l r -> ”-(” ++ op ”<” l r ++ ”)”
compileB Gt  = \l r -> ”-(” ++ op ”>” l r ++ ”)”

op, fn :: String -> String -> String -> String
op o a b = a ++ o ++ b
fn f a b = f ++ ”(” ++ a ++ ”,” ++ b ++ ”)”

compileSO :: E -> FilePath -> IO ()
compileSO e so = do
  let code = compile e
  _ <- rawSystem ”gcc”
          [ ”-std=c99”, ”-w”, ”-O3”, ”-shared”, ”-fPIC”, ”go.c”
          , ”-o”, so, ”-DT=” ++ code, ”-DCODE=\”” ++ code ++ ”\””
          ]
  return ()
```

4 Config.hs

```
module Config where

videoW, videoH, videoX, videoY :: Int

videoW = 1920
videoH = 540

videoX = screen1W - videoW
videoY = 0

{-
videoW = screen2W
videoH = (9 * videoW) `div` 16

videoX = screen1W
videoY = (screen2H - videoH) `div` 2
-}

screen1W, screen1H, screen2W, screen2H :: Int

screen1W = 1920
screen1H = 1080

screen2W = 1024
screen2H = 768
```

5 Database.hs

```
module Database(DB(), empty, insert, sortOn, toAscList, splitAt, fromList) where

import Prelude hiding (splitAt)

import Data.List (insertBy, sortBy)
import qualified Data.List as L (splitAt)
import Data.Ord (comparing)
```

```
data DB a = DB
  { _insert     :: a -> DB a
  , _sortOn     :: (a -> Double) -> DB a
  , _toAscList :: [a]
  , _splitAt :: Int -> (DB a, DB a)
  }

empty :: DB a
empty = mkDB (const 0) []

insert :: a -> DB a -> DB a
insert = flip _insert

sortOn :: (a -> Double) -> DB a -> DB a
sortOn = flip _sortOn

toAscList :: DB a -> [a]
toAscList = _toAscList

splitAt :: Int -> DB a -> (DB a, DB a)
splitAt = flip _splitAt

fromList :: [a] -> DB a
fromList = foldr insert empty

-- invariants
--   list == L.sortBy (comparing snd) list
--   all [metric x == y | (x, y) <- list]
mkDB :: (a -> Double) -> [(a, Double)] -> DB a
mkDB metric list = DB
  { _insert = \item     -> mkDB metric  (insertBy (comparing snd) (item, metric item) list)
  , _sortOn = \metric' -> mkDB metric' (sortBy   (comparing snd) (map (\(x, _) -> (x, metric' x)) list))
  , _toAscList = map fst list
  , _splitAt = \n -> let (lo, hi) = L.splitAt n list in (mkDB metric lo, mkDB metric hi)
  }
```

6 debug.c

```
#include <stdio.h>
#include <dlfcn.h>

int main(int argc, char **argv) {
  void *dl = dlopen(argv[1], RTLD_NOW);
  const char *code = dlsym(dl, "code");
  printf("%s\n", code);
  return 0;
}
```

7 deps.sh

```
#!/bin/sh
cabal sandbox init
cabal install alex happy
cabal install gtk2hs-buildtools
cabal install GLFW-b gtk MonadRandom OpenGLRaw stm syb syz Vector
```

8 encode.sh

```
#!/bin/bash
SESSION="${1}"
if [ "x${SESSION}" = "x" ]
then
  exit
fi
time ./bitbreeder_video --record < "${SESSION}.out" > /dev/null
FRAMES="$(( $(avprobe -v quiet -show_streams -i "${SESSION}.wav" -of json | grep↙
    ↳ duration_ts | sed 's|.*: \(.*\),.*|\1|g') / 1920 ))"
pushd "${SESSION}"
PREVFRAME="00000000.png"
for FRAME in $(seq "$(( FRAMES - 125 ))")
do
  THISFRAME="$(printf "%08d" "${FRAME}").png"
  if [ -f "${THISFRAME}" ]
  then
    PREVFRAME="${THISFRAME}"
  else
    ln -s "${PREVFRAME}" "${THISFRAME}"
  fi
done
for FRAME in $(seq "$(( FRAMES - 124 ))" "${FRAMES}")
do
  THISFRAME="$(printf "%08d" "${FRAME}").png"
  ln -s "00000000.png" "${THISFRAME}"
done
popd
avconv -i "${SESSION}/%08d.png" -i "${SESSION}.wav" -shortest "${SESSION}.mkv"
```

9 Evolve.hs

```haskell
module Evolve (crossBreed) where

import Control.Monad (replicateM, forM)
import Control.Monad.Random (MonadRandom, getRandomR)

import Expression
import Genetics (nodes, exchange)

mutateI :: (Applicative m, MonadRandom m) => E -> m E
mutateI X = return X
mutateI (I i) = do
  k <- coin 0.1
  if k
    then do
      j <- getRandomR (1, 64)
      return (I j)
    else return (I i)
mutateI (U u e) = U u <$> mutateI e
mutateI (B b e f) = B b <$> mutateI e <*> mutateI f
mutateI (T e f g) = T <$> mutateI e <*> mutateI f <*> mutateI g

coin :: (Functor m, MonadRandom m) => Double -> m Bool
coin p = (< p) <$> getRandomR (0, 1)

terminal :: (Functor m, MonadRandom m) => m E
terminal = do
  c <- coin 0.5
  if c then return X else I <$> getRandomR (1, 64)

data F
  = FU U
  | FB B
  | FT
  deriving (Read, Show, Eq)

getRandomE :: (Functor m, MonadRandom m, Enum e, Bounded e) => m e
getRandomE = self
  where
    self = do
      mi <- return minBound `asTypeOf` self
      ma <- return maxBound `asTypeOf` self
      toEnum <$> getRandomR (fromEnum mi, fromEnum ma)

function :: (Functor m, MonadRandom m) => m F
function = do
  c <- coin 0.05
  if c then FU <$> getRandomE else do
    d <- coin 0.05
    if d then return FT else FB <$> getRandomE

grow :: (Applicative m, MonadRandom m) => Int -> m E
grow 0 = terminal
grow d = do
  c <- coin 0.25
  if c then terminal else do
    f <- function
    case f of
      FU u -> U u <$> grow (d - 1)
      FB b -> B b <$> grow (d - 1) <*> grow (d - 1)
      FT   -> T   <$> grow (d - 1) <*> grow (d - 1) <*> grow (d - 1)

breed :: (Applicative m, MonadRandom m) => E -> E -> m [E]
breed e0 e1 = do
  n0 <- getRandomR (0, nodes e0 - 1)
  n1 <- getRandomR (0, nodes e1 - 1)
  let (f0, f1) = exchange e0 n0 e1 n1
  return [f0, f1]

crossBreed :: (Applicative m, MonadRandom m) => [[E]] -> m [E]
crossBreed ess = do
  ws <- replicateM 2 $ getRandomR (0, length ess - 1)
  ~[e0, e1] <- forM ws $ \w -> do
    let es = take minPopCount (ess !! w)
    if length es < minPopCount then grow 5 else do
      n <- getRandomR (0, minPopCount - 1)
      mutateI (es !! n)
  e2 <- grow 5
  (e2:) <$> breed e0 e1
```

```
minPopCount :: Int
minPopCount = 64
```

10 Expression.hs

```
{-# LANGUAGE DeriveDataTypeable #-}
module Expression where

import Data.Data (Data)
import Data.Typeable (Typeable)

data E = X | I Int | U U E | B B E E | T E E E
  deriving (Read, Show, Eq, Ord, Data, Typeable)

data U = Neg | LNot | BNot
  deriving (Read, Show, Eq, Ord, Enum, Bounded, Data, Typeable)

data B = Add | Sub | Mul | Div | Mod | BAnd | LAnd | BOr | LOr | XOr | ShL | ShR | Lt | Gt
  deriving (Read, Show, Eq, Ord, Enum, Bounded, Data, Typeable)

count :: Integer -> Integer
count 0 = 0
count 1 = 65
count n = 3 * count (n - 1) + sum [ 14 * (count l + count r) | l <- [1 .. n - 2], let r = n - 1 - l ]
```

11 expr.frag

```
#version 400 compatibility

uniform sampler2D     glyphs;
uniform sampler2DRect expression;

const float yf  = 4.0/6.0;
const float ylo = 1.0/6.0;
const float yhi = 5.0/6.0;

float myTextureQueryLod(sampler2D tex, vec2 tc) {
  return textureQueryLod(tex, tc).y;
  //return max(0.0, 10.0 + log2(max(length(dFdx(tc)), length(dFdy(tc)))));
}

void main() {
  vec2 tc = gl_TexCoord[0].xy * vec2(0.125, 0.25 * yf);
  float lod = myTextureQueryLod(glyphs, tc);
  vec2 gc = floor(gl_TexCoord[0].xy * vec2(1.0, yf));
  vec3 glyph = texture2DRect(expression, gc).xyz;
  vec2 glyphCoord = glyph.xy;
  vec2 subCoord = fract(gl_TexCoord[0].xy * vec2(1.0, yf));
  if (subCoord.y < ylo) {
    glyphCoord = vec2(0.125, 0.75);
  } else if (yhi < subCoord.y) {
    glyphCoord = vec2(0.125, 0.75);
    subCoord.y += ylo - yhi;
  }
  subCoord.y -= ylo;
  subCoord *= vec2(0.125, 0.25 / yf);
  vec3 glyphRGB = textureLod(glyphs, glyphCoord + subCoord, lod).xyz;
  gl_FragColor = vec4(glyphRGB, 1.0);
}
```

12 extra/bitbreeder.cabal

```
name:                bitbreeder
version:             0.1.0.0
synopsis:            evolve noisy arithmetic expressions
-- description:
homepage:            http://code.mathr.co.uk/bitbreeder
license:             GPL-3
license-file:        LICENSE
author:              Claude Heiland-Allen
maintainer:          claude@mathr.co.uk
category:            Sound
build-type:          Simple
cabal-version:       >=1.8

executable bitbreeder
  main-is:
    bitbreeder.hs
  other-modules:
    Compile
    Database
    Evolve
    Expression
    Genetics
    Metric
    Population
  build-depends:
    base < 5,
    MonadRandom,
    gtk,
    process,
    stm,
    syb,
    syz,
    time,
    vector

executable bitbreeder_video
  main-is:
    bitbreeder_video.hs
  other-modules:
    Expression
    Video
  build-depends:
    base < 5,
    cairo,
    gtk,
    gtkglext,
    OpenGLRaw

--executable bitbreeder_judge
--  c-sources:
```

```
--      judge.c
--    extra-libraries:
--      m, dl, fftw3f

--executable bitbreeder_audio
--    c-sources:
--      live.c
--    extra-libraries:
--      m, dl, jack
```

13 extra/LICENSE

```
                    GNU GENERAL PUBLIC LICENSE
                       Version 3, 29 June 2007

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```

```
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14 extra/Setup.hs

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

15 Genetics.hs

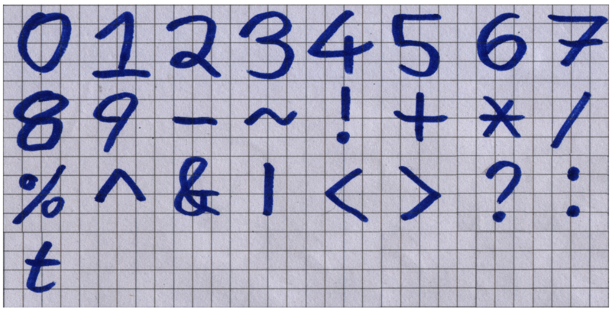
```haskell
{-# LANGUAGE ScopedTypeVariables, FlexibleInstances, Rank2Types,
    UndecidableInstances, DeriveDataTypeable #-}

-- Based on:

-- Module      :  GenProg.GenExpr.Data
-- Copyright   :  (c) 2010 Jan Snajder
-- License     :  BSD-3 (see the LICENSE file)
--
-- Maintainer  :  Jan Snajder <jan.snajder@fer.hr>
-- Stability   :  experimental
-- Portability :  non-portable
--
-- Implementation of the @GenProg.GenExpr@ interface for members of
-- the 'Data' typeclass. The implementation is based on SYB and SYZ
-- generic programming frameworks (see
-- <http://hackage.haskell.org/package/syb> and
-- <http://hackage.haskell.org/package/syz> for details).
--
-- NB: Subexpressions that are candidates for crossover points or
-- mutation must be of the same type as the expression itself, and
-- must be reachable from the root node by type-preserving traversal.
-- See below for an example.
--
------------------------------------------------------------------------------

module Genetics where

import Data.Generics
import Data.Generics.Zipper
import Data.Maybe
import Control.Monad


-- | This typeclass defines an interface to expressions
-- that can be genetically programmed.  The operations that must be
-- provided by instances of this class are used for the generation
-- of random individuals as well as crossover and mutation operations.
-- (An instance for members of the @Data@ typeclass is provided in
-- "GenProg.GenExpr.Data".)
--
-- Minimal complete definition: 'exchange', 'nodeMapM', 'nodeMapQ',
-- and 'nodeIndices'.
class GenExpr e where
  -- | Exchanges subtrees of two expressions:
  -- @exchange e1 n1 e2 n2@ replaces the subexpression of @e1@ rooted in node
  -- @n1@ with the subexpression of @e2@ rooted in @n2@, and vice versa.
  exchange :: e -> Int -> e -> Int -> (e, e)
  -- | Maps a monadic transformation function over the immediate
  -- children of the given node.
  nodeMapM :: Monad m => (e -> m e) -> e -> m e
  -- | Maps a query function over the immediate children of the given
  -- node and returns a list of results.
  nodeMapQ :: (e -> a) -> e -> [a]
  -- | A list of indices of internal (functional) and external
  -- (terminal) nodes of an expression.
  nodeIndices :: e -> ([Int], [Int])
  -- | Adjusts a subexpression rooted at the given node by applying a
  -- monadic transformation function.
  adjustM :: (Monad m) => (e -> m e) -> e -> Int -> m e
  -- | Number of nodes an expression has.
  nodes :: e -> Int
  -- | The depth of an expression. Equals 1 for single-node expressions.
  depth :: e -> Int

{-
  -- | Default method (expensive because it calls exchange twice).
  adjustM f e n = replace e n ‘liftM‘ f (get e n)
    where get e n = fst $ exchange e 0 e n
          replace e1 n1 e2 = fst $ exchange e1 n1 e2 0
-}
  nodes = (+1) . foldr (+) 0 . nodeMapQ nodes

  depth = (+1) . foldr max 0 . nodeMapQ depth


instance (Data a) => GenExpr a where

  -- | Exchanges two expression nodes. Works by using two generic
  -- zippers and exchanging their holes.
  exchange e1 n1 e2 n2 = (fromZipper y1, fromZipper y2)
    where z1 = typeMoveForUnsafe n1 $ toZipper e1
          z2 = typeMoveForUnsafe n2 $ toZipper e2
          (y1,y2) = exchangeHoles z1 z2

  -- | Adjust an expression node. Works by applying a monadic
  -- tranformation on a zipper hole.
  adjustM f e n = fromZipper ‘liftM‘ transM (mkM f) z
    where z = typeMoveForUnsafe n (toZipper e)

  nodeMapM f = gmapM (mkM f)

  nodeMapQ q (x::a) = concat $ gmapQ ([] ‘mkQ‘ (\(y::a) -> [q y])) x

  nodeIndices = index 0 [] [] . toZipper

-- Zipper moves

type Move a = Zipper a -> Maybe (Zipper a)

backtrack :: (Typeable a) => Move a
backtrack z = do
  z2 <- up z
```

```haskell
  right z2 `mplus` backtrack z2

repeatM :: (Monad m) => Int -> (a -> m a) -> a -> m a
repeatM 0 _ x = return x
repeatM n f x = f x >>= repeatM (n - 1) f

-- Moves zipper to next node in DFS order, but does not move down the
-- zipper if node satisfies query 'q'.
nextDfsQ :: Typeable a => GenericQ Bool -> Move a
nextDfsQ q z = (if query q z then Nothing else down' z)
  `mplus` right z `mplus` backtrack z

-- Moves the zipper to node 'n' from current position in DFS order,
-- skipping nodes not satisfying query 'q2' and descending only down
-- the nodes satisfying query 'q1'.
moveForQ :: (Typeable a) => GenericQ Bool -> GenericQ Bool -> Int -> Move a
moveForQ _  _  0 z = Just z
moveForQ q1 q2 n z = do
  z2 <- nextDfsQ q1 z
  moveForQ q1 q2 (if query q2 z2 then n - 1 else n) z2

-- Moves the zipper to node 'n' from current position in DFS order,
-- counting only nodes of type 'a', and not descending down the nodes
-- of other type.
typeMoveFor :: (Typeable a) => Int -> Move a
typeMoveFor n (z::Zipper a) =
  moveForQ (True `mkQ` (\(_::a) -> False)) (False `mkQ` (\(_::a) -> True)) n z

-- | Same as typeMoveFor, but throws an error if node index is out of
-- bound.
typeMoveForUnsafe :: (Typeable a) => Int -> Zipper a -> Zipper a
typeMoveForUnsafe n z = fromMaybe
  (error $ "Genetics.typeMoveForUnsafe: Nonexisting node.")
  (typeMoveFor n z)

-- | Exchanges two zipper holes.
exchangeHoles :: (Data a) => Zipper a -> Zipper a -> (Zipper a, Zipper a)
exchangeHoles (z1::Zipper a) (z2::Zipper a) = (y1,y2)
  where Just h1 = getHole z1 :: Maybe a
        Just h2 = getHole z2 :: Maybe a
        y1 = setHole h2 z1
        y2 = setHole h1 z2

index :: (Data a) => Int -> [Int] -> [Int] -> Zipper a -> ([Int], [Int])
index i is es (z :: Zipper a) =
  maybe (is2,es2) (index (i + 1) is2 es2) (typeMoveFor 1 z)
  where Just h = getHole z :: Maybe a
        (is2,es2) = if terminalQ h then (is,i:es) else (i:is,es)

terminalQ :: (Data a) => a -> Bool
terminalQ = null . nodeMapQ id

{- $Example

Suppose you have a datatype defined as

@
data E = A E E
        | B String [E]
        | C
  deriving (Eq,Show,Typeable,Data)
@

and an expression defined as

@
e = A (A C C) (B \"abc\" [C,C])
@

The subexpressions of a @e@ are considered to be only the subvalues of
@e@ that are of the same type as @e@.  Thus, the number of nodes of
expression @e@ is

>>> nodes e
5

because subvalues of node @B@ are of different type than expression
@e@ and therefore not considered as subexpressions.

Consequently, during a genetic programming run, subexpressions that
are of a different type than the expression itself, or subexpression
that cannot be reached from the root node by a type-preserving
traversal, cannot be chosen as crossover points nor can they be
mutated.

-}
```

16 .gitignore

```
*.hi
*.o
bitbreeder
bitbreeder_video
bitbreeder_audio
bitbreeder_judge
glyphs.ppm
glyphs.raw
a
v
o
.cabal-sandbox
cabal.sandbox.config
dist
dist-newstyle
```

17 glyphs.png



18 go.c

```
#include <limits.h>

static inline int safe_div(int a, int b) { if ((b == 0) || (a == INT_MIN && b == -1)) { return 0; } else { return a / b; } }
static inline int safe_mod(int a, int b) { if ((b == 0) || (a == INT_MIN && b == -1)) { return 0; } else { return a % b; } }

const char code[] = CODE;
float F(int t) { return (((T)&255)-128)/256.0f; }

typedef struct {
  int t;
  int k;
  float a[4];
  float dc;
} S;

float go(S *s) {
  s->k += 1;
  if (s->k == 6) {
    s->k = 0;
    s->t += 1;
    s->a[0] = s->a[1];
    s->a[1] = s->a[2];
    s->a[2] = s->a[3];
    s->a[3] = F(s->t);
  }
  /*
    -- http://en.wikipedia.org/wiki/Cubic_Hermite_spline#Interpolation_on_the_unit_interval_without_exact_derivatives
    putStr . unlines . map (show . map (/2)) $ [
      [ -x^3 + 2*x^2 - x
      , 3 * x^3 - 5 * x^2 + 2
      , -3 * x^3 + 4 * x^2 + x
      , x^3 - x^2
      ] | i <- [0..5], let x = i / 6 ]
  */
  const float c[6][4] =
    { {0.0,1.0,0.0,0.0}
    , {-5.7870370370370364e-2,0.9375,0.13194444444444442,-1.1574074074074073e-2}
    , {-7.407407407407407e-2,0.7777777777777778,0.3333333333333333,-3.7037037037037035e-2}
    , {-6.25e-2,0.5625,0.5625,-6.25e-2}
    , {-3.7037037037037035e-2,0.33333333333333326,0.7777777777777777,-7.407407407407407e-2}
    , {-1.157407407407407e-2,0.13194444444444442,0.9375,-5.787037037037035e-2}
    };
  float a = c[s->k][0] * s->a[0] + c[s->k][1] * s->a[1] + c[s->k][2] * s->a[2] + c[s->k][3] * s->a[3];
  s->dc = s->dc * 0.99 + 0.01 * a;
  return a - s->dc;
}
```

19 gradient.ppm

20 judge.c

```
#define _POSIX_C_SOURCE 1
#include <signal.h>

#include <math.h>
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <time.h>
#include <limits.h>
#include <stdlib.h>

#ifdef JUDGE_SOUNDFILE
#include <sndfile.h>
#else
#include <dlfcn.h>
#endif

#include <fftw3.h>
#define wisdomfile "/run/shm/bitbreeder.fftw"

static const double pi = 3.141592653589793;
static const double sr = 8192.0;
#define blocksize 2048
#define overlap 4
#define BINS (blocksize / 2 + 1)
#define PARAMS 6
#define LEVELS 11

#define N (((1 << LEVELS) + overlap - 1) * blocksize / overlap)

struct audio {
  int length;
  float *data;
};

typedef float F_t(int);
```

```
struct audio *audio(const char *name) {
  struct audio *a = calloc(1, sizeof(*a));
  a->length = N;
  a->data = calloc(a->length, sizeof(*a->data));
#ifdef JUDGE_SOUNDFILE
  SF_INFO info; memset(&info, 0, sizeof(info));
  SNDFILE *in = sf_open(name, SFM_READ, &info);
  sf_readf_float(in, a->data, a->length);
  sf_close(in);
#else
  void *dl = dlopen(name, RTLD_NOW);
  F_t *cb;
  *(void **) (&cb) = dlsym(dl, ”F”);
  float dc = cb(0);
  for (int t = 0; t < a->length; ++t) {
    float x = cb(t);
    dc = dc * 0.99 + 0.01 * x;
    a->data[t] = x - dc;
  }
  dlclose(dl);
#endif
  return a;
}

struct frame {
  float loudness;
  float spectrum[BINS];
};

struct frames {
  int current;
  struct frame *frame;
};

struct frames *frames(struct audio *a) {
  struct frames *f = calloc(1, sizeof(*f));
  f->current = 0;
  f->frame = calloc(1 << LEVELS, sizeof(*f->frame));
  float *ibuf = fftwf_alloc_real(blocksize);
  float *obuf = fftwf_alloc_real(blocksize);
  fftwf_import_wisdom_from_filename(wisdomfile);
  fftwf_plan plan = fftwf_plan_r2r_1d(blocksize, ibuf, obuf, FFTW_R2HC, ↙
      ↳ FFTW_DESTROY_INPUT | FFTW_EXHAUSTIVE);
  fftwf_export_wisdom_to_filename(wisdomfile);
  float *window = calloc(blocksize, sizeof(*window));
  for (int t = 0; t < blocksize; ++t) {
    window[t] = 0.5 - 0.5 * cos(t * 2 * pi / blocksize);
  }
  float rsqrtblocksize = 1 / sqrtf(blocksize);
  for (int i = 0; i < 1 << LEVELS; ++i) {
    int b = i * blocksize / overlap;
    double l = 0;
    for (int t = 0; t < blocksize; ++t) {
      float x = a->data[b + t];
      ibuf[t] = window[t] * x;
      l += window[t] * x * x;
    }
    f->frame[i].loudness = sqrt(l) * rsqrtblocksize;
    fftwf_execute(plan);
    f->frame[i].spectrum[0     ] = fabsf(obuf[0]) * rsqrtblocksize;
    f->frame[i].spectrum[BINS-1] = fabsf(obuf[blocksize/2]) * rsqrtblocksize;
    for (int k = 1; k < BINS-1; ++k) {
      float re = obuf[k];
      float im = obuf[blocksize - k];
      f->frame[i].spectrum[k] = sqrtf(re * re + im * im) * rsqrtblocksize;
    }
  }
  return f;
}

enum {
  p_loudness = 0,
  p_tonality,       // min(1, (log10 m1 - 10 sum (log10 a_k) / sum 1)/60)
  p_centroid,       // m1 = sum a_k f_k / sum a_k
  p_deviation,      // m2 = sum (f_k - m1)^2 a_k / sum a_k; s^2 = m2
  p_skewness,       // m3 = sum (f_k - m1)^3 a_k / sum a_k; g1 = m3 / s^3
  p_kurtosis,       // m4 = sum (f_k - m1)^4 a_k / sum a_k; g2 = m4 / s^4
};

struct statistic {
  double s0, s1, s2;
};

void statistic(double x, struct statistic *s) {
  s->s0 = 1;
  s->s1 = x;
  s->s2 = x*x;
}

void wstatistic(double w, double x, struct statistic *s) {
  if (isnan(w)) { w = 0; }
  if (isnan(x)) { x = 0; }
  s->s0 = w;
  s->s1 = w*x;
  s->s2 = w*x*x;
}

void combine(struct statistic *x, struct statistic *y, struct statistic *r) {
  r->s0 = x->s0 + y->s0;
  r->s1 = x->s1 + y->s1;
  r->s2 = x->s2 + y->s2;
}

double mean(struct statistic *s) {
  if (! isnan(s->s1) && s->s0 > 0) {
    return s->s1 / s->s0;
  }
  return 0;
}

double stddev(struct statistic *s) {
  double d = sqrt(s->s0 * s->s2 - s->s1 * s->s1) / s->s0;
  if (! (d >= 0)) { d = 0; }
  return d;
```

```
}

struct analysis {
  struct statistic base;
  struct statistic levels[LEVELS+1];
};

void combines(int depth, struct analysis *x, struct analysis *y, struct analysis *r) {
  combine(&x->base, &y->base, &r->base);
  for (int level = 0; level < depth; ++level) {
    combine(&x->levels[level], &y->levels[level], &r->levels[level]);
  }
  statistic(stddev(&r->base), &r->levels[depth]);
}

struct analyses {
  struct analysis param[PARAMS];
};

void analyse(struct frames *f, struct analyses *a) {
  struct frame *s = &f->frame[f->current++];
  statistic(s->loudness, &a->param[p_loudness].base);
  {
    double s0 = 0, s1 = 0, s2 = 0, s3 = 0, s4 = 0;
    for (int k = 0; k < BINS; ++k) {
      double x = s->spectrum[k];
      double f = k * 2.0 / blocksize;
      s0 += x;
      s1 += x * f;
    }
    if (! (s0 > 0)) { s0 = 1; }
    double m1 = s1 / s0;
    for (int k = 0; k < BINS; ++k) {
      double x = s->spectrum[k];
      double f = k * 2.0 / blocksize;
      double y = f - m1;
      s2 += x * y * y;
      s3 += x * y * y * y;
      s4 += x * y * y * y * y;
    }
    double m2 = s2 / s0;
    double m3 = s3 / s0;
    double m4 = s4 / s0;
/*
    statistic(m1,                &a->param[p_centroid ].base);
    statistic(sqrt(m2),          &a->param[p_deviation].base);
    statistic(m3 / pow(m2, 1.5), &a->param[p_skewness ].base);
    statistic(m4 / pow(m2, 2),   &a->param[p_kurtosis ].base);
*/
    double l = s->loudness;
    wstatistic(l, m1,                &a->param[p_centroid ].base);
    wstatistic(l, sqrt(m2),          &a->param[p_deviation].base);
    wstatistic(l, m3 / pow(m2, 1.5), &a->param[p_skewness ].base);
    wstatistic(l, m4 / pow(m2, 2),   &a->param[p_kurtosis ].base);
  }
  {
    double s0 = 0, s1 = 0, sL = 0;
    for (int k = 0; k < BINS; ++k) {
      double x = s->spectrum[k] + 1e-6;
      s0 += 1;
      s1 += x * x;
      sL += log(x * x);
    }
    double tonality = 1 - exp(sL / s0) / (s1 / s0);
    if (! (0 < tonality)) { tonality = 0; }
    if (! (1 > tonality)) { tonality = 1; }
/*
    statistic(tonality, &a->param[p_tonality].base);
*/
    wstatistic(s->loudness, tonality, &a->param[p_tonality].base);
  }
}

void combiness(int depth, struct analyses *x, struct analyses *y, struct analyses *r) {
  for (int param = 0; param < PARAMS; ++param) {
    combines(depth, &x->param[param], &y->param[param], &r->param[param]);
  }
}

void recurse(struct frames *f, int depth, struct analyses *a) {
  if (depth) {
    struct analyses x, y;
    recurse(f, depth - 1, &x);
    recurse(f, depth - 1, &y);
    combiness(depth - 1, &x, &y, a);
  } else {
    analyse(f, a);
  }
}

struct result {
  double average, variability, granularity;
};

struct results {
  struct result result[PARAMS];
  double novelty;
};

void judge(struct frames *f, struct results *r) {
  struct analyses a;
  recurse(f, LEVELS, &a);
  for (int param = 0; param < PARAMS; ++param) {
    r->result[param].average     = mean(&a.param[param].base);
    r->result[param].variability = mean(&a.param[param].levels[0]);
    struct statistic s, t;
    wstatistic(0, 0, &t);
    for (int level = 1; level < LEVELS; ++level) {
      wstatistic(level, mean(&a.param[param].levels[level]), &s);
      combine(&s, &t, &t);
    }
    r->result[param].granularity = mean(&t);
  }
}

const char *name = 0;

void fpe_handler(int s) {
  (void) s;
  fprintf(stderr, "SIGFPE %s\n", name);
  exit(1);
}

int main(int argc, char **argv) {
  (void) argc;
  name = argv[1];
  struct sigaction act, old;
  act.sa_handler = fpe_handler;
  sigemptyset(&act.sa_mask);
  sigaction(SIGFPE, &act, &old);
  struct results r;
  judge(frames(audio(argv[1])), &r);
  r.novelty = atoi(argv[2]);
  fwrite(&r, sizeof(r), 1, stdout);
  sigaction(SIGFPE, &old, 0);
  return 0;
}
```

21 live.c

```
#define _GNU_SOURCE
#include <stdio.h>
#include <stdlib.h>

#include <sys/types.h>
#include <sys/stat.h>
#include <unistd.h>

#include <dlfcn.h>

#include <jack/jack.h>

// per-sample callback implemented in go.so
typedef float callback(void *);

// default silent callback
static float deffunc(void *data) {
  return 0;
}

static struct {
  jack_client_t *client;
  jack_port_t *out;
  void *data;
  callback * volatile func;
} state;

// race mitigation
volatile int inprocesscb = 0;
```

```

static int processcb(jack_nframes_t nframes, void *arg) {
  inprocesscb = 1; // race mitigation
  jack_default_audio_sample_t *out = (jack_default_audio_sample_t *) ↙
      ↳ jack_port_get_buffer(state.out, nframes);
  callback *f = state.func;
  for (jack_nframes_t i = 0; i < nframes; ++i) {
    out[i] = f(state.data);
  }
  inprocesscb = 0; // race mitigation
  return 0;
}

static void errorcb(const char *desc) {
  fprintf(stderr, "JACK error: %s\n", desc);
}

static void shutdowncb(void *arg) {
  exit(1);
}

static void atexitcb(void) {
  jack_client_close(state.client);
}

int main(int argc, char **argv) {
  srand(time(0));
  state.func = deffunc;
  state.data = calloc(1, 1024 * 1024);
  jack_set_error_function(errorcb);
  if (!(state.client = jack_client_open("live", JackNoStartServer, 0))) {
    fprintf(stderr, "jack server not running?\n");
    return 1;
  }
  atexit(atexitcb);
  jack_set_process_callback(state.client, processcb, 0);
  jack_on_shutdown(state.client, shutdowncb, 0);
  // mono processing
  state.out = jack_port_register(state.client, "output_1", ↙
      ↳ JACK_DEFAULT_AUDIO_TYPE, JackPortIsOutput, 0);
  if (jack_activate(state.client)) {
    fprintf (stderr, "cannot activate JACK client");
    return 1;
  }
  // mono recording
  if (jack_connect(state.client, "live:output_1", "record:in_1")) {
    fprintf(stderr, "cannot connect to recorder\n");
  }
  // stereo output
  const char **ports;
  if ((ports = jack_get_ports(state.client, NULL, NULL, JackPortIsPhysical | ↙
      ↳ JackPortIsInput))) {
    int i = 0;
    while (ports[i] && i < 2) {
      if (jack_connect(state.client, jack_port_name(state.out), ports[i])) {
        fprintf(stderr, "cannot connect output port\n");
      }
```

```
        i++;
      }
      free(ports);
    }
    void *old_dl = 0;
    void *new_dl = 0;
    char *soname = 0;
    while (1 == scanf("%ms", &soname)) {
      if ((new_dl = dlopen(soname, RTLD_NOW))) {
        callback *new_cb;
        *(void **) (&new_cb) = dlsym(new_dl, "go");
        if (new_cb) {
          // race mitigation: dlclose with jack running in .so -> boom
          while (inprocesscb) ;
          state.func = new_cb;
          if (old_dl) {
            dlclose(old_dl);
          }
          old_dl = new_dl;
        } else {
          dlclose(new_dl);
          new_dl = 0;
        }
      } else {
      }
      free(soname);
      soname = 0;
    }
    return 0;
  }
```

22 Makefile

```
all: bitbreeder bitbreeder_video bitbreeder_audio bitbreeder_judge glyphs.raw

clean:
	rm -f bitbreeder bitbreeder.o bitbreeder_video bitbreeder_video.o bitbreeder_video.hi bitbreeder_audio bitbreeder_judge bitbreeder.hi Database.o Database.hi Population.o Population.hi Expression.hi Expression.o Evolve.hi Evolve.o Compile.hi Compile.o Video.hi Video.o Genetics.o Genetics.hi Metric.o Metric.hi Config.o Config.hi judge_sf debug glyphs.raw glyphs.ppm

bitbreeder: bitbreeder.hs Database.hs Population.hs Expression.hs Evolve.hs Compile.hs Genetics.hs Metric.hs Config.hs .cabal-sandbox
	cabal v1-exec -- ghc -Wall -threaded -O2 bitbreeder.hs

bitbreeder_video: bitbreeder_video.hs Expression.hs Video.hs Config.hs .cabal-sandbox
	cabal v1-exec -- ghc -Wall -threaded -O2 bitbreeder_video.hs

bitbreeder_audio: live.c
	gcc -std=c99 -Wall -pedantic -Wextra -Wno-unused-parameter -O3 -o bitbreeder_audio live.c `pkg-config --cflags --libs jack` -ldl -lm

bitbreeder_judge: judge.c
	gcc -std=c99 -Wall -pedantic -Wextra -O3 -ggdb -o bitbreeder_judge judge
```

```
            ↳ .c -lm -lfftw3f -ldl

judge_sf: judge.c
        gcc -std=c99 -Wall -pedantic -Wextra -O3 -ggdb -o judge_sf judge.c -lm -↙
            ↳ lfftw3f -lsndfile -DJUDGE_SOUNDFILE

debug: debug.c
        gcc -std=c99 -Wall -pedantic -Wextra -Wno-unused-parameter -O3 -o debug ↙
            ↳ debug.c -ldl

glyphs.raw: glyphs.png
        convert glyphs.png glyphs.ppm && tail -c 1572864 < glyphs.ppm > glyphs.↙
            ↳ raw

.cabal-sandbox:
        cabal v1-sandbox init
        cabal v1-install cairo MonadRandom GLFW-b gtk OpenGLRaw process stm syb ↙
            ↳ syz time vector --reorder-goals
```

23 Metric.hs

```
{-# LANGUAGE ForeignFunctionInterface #-}
module Metric where

import Prelude hiding (read, replicate, sum, zip, zip3, zipWith, zipWith3)

import Control.Monad (when)
import Data.Vector.Unboxed
import qualified Data.Vector.Storable as S (thaw, unsafeFreeze)
import qualified Data.Vector.Storable.Mutable as S (unsafeWith)

import Foreign (allocaBytes, copyBytes)
import System.IO (Handle, hGetBuf)
import System.IO.Error (mkIOError, eofErrorType)

newtype Metric   = M (Vector (Double, Double))
newtype Stats    = S (Vector (Double, Double, Double))
newtype Analysis = A (Vector Double)
newtype Weight   = W (Vector Double)
newtype Target   = T (Vector Double)
type    Score    = Double

emptyMetric    :: Metric
emptyMetric    =  M $ zip zero zero

emptyStats     :: Stats
emptyStats     =  S $ zip3 zero zero zero

emptyAnalysis  :: Analysis
emptyAnalysis  =  A zero

emptyWeight    :: Weight
emptyWeight    =  W zero

emptyTarget    :: Target
emptyTarget    =  T zero
```

```
zero :: Vector Double
zero = replicate elements 0

insert :: Analysis -> Stats -> Stats
insert (A as) (S ss) = S $ zipWith f as ss
  where
    f a (s0, s1, s2) = (s0 + 1, s1 + a, s2 + a * a)

delete :: Analysis -> Stats -> Stats
delete (A as) (S ss) = S $ zipWith f as ss
  where
    f a (s0, s1, s2) = (s0 - 1, s1 - a, s2 - a * a)

target :: Target -> Weight -> Stats -> Metric
target (T ts) (W ws) (S ss) = M $ zipWith3 f ws ts ss
  where
    f w t (s0, s1, s2)
      | isInfinite tt = (0, 0)
      | isNaN      tt = (0, 0)
      | isInfinite ww = (0, 0)
      | isNaN      ww = (0, 0)
      | otherwise     = (tt, ww)
      where
        mean = s1 / s0
        stddev = sqrt (s0 * s2 - s1 * s1) / s0
        tt = mean + stddev * t
        ww = w / stddev

score :: Metric -> Analysis -> Score
score (M ms) = \(A as) -> sum $ zipWith f ms as
  where
    f (t, w) = \a -> let d = w * (a - t) in d * d

read :: Handle -> IO Analysis
read h = allocaBytes bytes $ \ptr -> do
  bytes' <- hGetBuf h ptr bytes
  when (bytes /= bytes') $ ioError (mkIOError eofErrorType "" Nothing Nothing)
  m <- S.thaw (convert zero)
  S.unsafeWith m $ \q -> copyBytes q ptr bytes
  (A . convert) ‘fmap‘ S.unsafeFreeze m

bytes, elements, measurements, parameters :: Int
bytes = elements * 8
elements = measurements * parameters + 1
measurements = 6
parameters = 3
```

24 Population.hs

```
module Population(Item(..), Population, empty, update, target, toAscList) where

import Database (DB)
import qualified Database as D
import Metric (Stats, Analysis, Target, Weight)
import qualified Metric as S
import Expression (E())
```

```
data Item = Item{ itemID :: !Int, itemExpr :: E, itemMetric :: Analysis }

type Population = (DB Item, Stats, Target, Weight)

empty :: Population
empty = (D.empty, S.emptyStats, S.emptyTarget, S.emptyWeight)

insert :: Item -> Population -> Population
insert it (d, s, t, w) = (D.insert it d, S.insert (itemMetric it) s, t, w)

toAscList :: Population -> [Item]
toAscList (d, _, _, _) = D.toAscList d

prune :: Int -> Population -> Population
prune n p@(d, s, t, w) = case fmap D.toAscList $ D.splitAt n d of
  (_, []) -> p
  (keep, discard) -> (keep, foldr S.delete s $ map itemMetric discard, t, w)
{-
   foldr S.insert S.emptyStats . map itemMetric . D.toAscList $ k, t, w)
  let (keep, discard) = D.splitAt n d
  in  (keep,  . D.toAscList $ discard, t, w)
-}

sort :: Population -> Population
sort (d, s, t, w) = (D.sortOn (S.score (S.target t w s) . itemMetric) d, s, t, w)

update :: Item -> Population -> Population
update it = prune maxPopCount . insert it

target :: Target -> Weight -> Population -> Population
target t w (d, s, _, _) = sort (d, s, t, w)

maxPopCount :: Int
maxPopCount = 1024
```

25 README

```
BitBreeder
==========


BitBreeder evolves noisy expressions.


Build Requirements
------------------

BitBreeder is written in Haskell and C.  You need GHC (tested with ghc-7.6.2)
and (at least) these libraries from Hackage (or elsewhere):

  cairo gtk gtkglext MonadRandom OpenGLRaw process stm syb syz time vector

You need GCC (tested with gcc-4.7.2) and (at least) these libraries:

  m dl jack fftw3f

You need ImageMagick for PNG to PPM conversion.

You need Make to build it all.


Runtime Requirements
--------------------

You need JACK (running at 48000Hz), GCC (BitBreeder generates source code and
compiles it) and ecasound (for recording).  After running you can encode a
video, which needs recent versions of avprobe and avconv (tested with 1.0.5
for Debian Wheezy from deb-multimedia repository, older versions like stock
Wheezy will cause problems).


Usage
-----

qjackctl &   # set up JACK and start jackd; stop the transport and rewind it
for CPU in 0 1 2 3 ... ; do sudo cpufreq-set -c ${CPU} -g performance ; done
./start.sh
./encode.sh a/SESSION
mplayer a/SESSION.mkv

The main BitBreeder window has a bunch of sliders.  Each row corresponds to
an audio descriptor, the left slider is the normalized target value and the
right slider is the weighting.  The other window displays the currently
sounding expression, which is the fittest expression matching the current
tab.  You can create more tabs, each with their own fitness target/weights.
BitBreeder cross-breeds and mutates the expression populations from each tab.

Targets are normalized: the center of the slider range is the mean of the
population, and the extremes of the slider range are +/- a few standard
deviations of the population.   Weighting is from 0 at the left increasing
to the right, changing a target will have no effect when its weight is 0.
When all weights are zero each newly generated expression is deemed the
fittest.


Implementation
--------------

BitBreeder consists of a few programs: user interface and control logic
(bitbreeder), the visualisation of the expression (bitbreeder_video),
live audio generation (bitbreeder_audio), and expression audio analysis
(bitbreeder_judge).


bitbreeder
----------

FIXME cross-breeding, mutation, populations, compilation


bitbreeder_judge
----------------

The judge loads an .so containing the compiled expression, and generates
```

a couple of minutes of audio with it. The main loop is a tree structure:

```
    recursion depth
    :    /
    2   /\
       /  \
    1 /\  /\
    0/\/\/\/\/
     01234567.. audio frames
```

Each audio frame is an FFT spectrum and RMS volume for that block (which are windowed and overlapped).

At the lowest level of the tree the basic instantaneous descriptors are calculated (tonality, spectral centroid, etc...), each stored as a statistic (weight, weight * value, weight * value^2) with the weight usually based on the RMS volume.

Each subsequent level combines statistics from all the previous levels - each node (for each basic descriptor) combines pairwise two lists of statistics (ordered by level) and adds a new statistic as the mean of the level below it.

Example (assuming weight is 1):

```
-> input descriptor sequence
  7
  4
  5
  1
-> base level
  1 7 49
  1 4 16
  1 5 25
  1 1  1
-> next level
  2 11 98     1 5.5 30.25
  2  6 36     1 3     9
-> top level
  4 17 134    2 8    39.25     1 4 16
-> final results
  mean(0) = 17/4 = 4.25
  stddev(0) = sqrt(4 * 134 - 17^2) / 4 = 3.929
  stddev(1) = sqrt(2 * 39.25 - 8^2) / 2 = 1.936
  stddev(2) = sqrt(1 * 16 - 4^2) / 1 = 0
  granularity = centroid of stddev(level)
    = (0 * 3.929 + 1 * 1.936 + 2 * 0) / (0 + 1 + 2)
    = 0.64549
-> output
  mean(0), stddev(0), granularity
```

bitbreeder_audio

The main loop watches stdin for names of an .so containing a compiled expression. For each line, it loads the .so and swaps the JACK process

```
callback to the new expression (taking care not to unload code that is
currently running).

FIXME sample rate conversion, DC offset removal


bitbreeder_video
----------------

The main loop watches stdin for expressions in Haskell's Show syntax.
For each line, it parses the expression, lays it out as a tree, and
displays it.

FIXME glyph map, textureQueryLod


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--
https://mathr.co.uk
```

26 spectrogram.c

```c
#include <math.h>
#include <stdio.h>
#include <stdint.h>
#include <stdlib.h>
#include <string.h>
#include <sndfile.h>
#include <fftw3.h>

#define wisdomfile "/run/shm/bitbreeder.fftw"

static const double pi = 3.141592653589793;
static const double sr = 8192.0;
static const int bs = 2048;
static const int ol = 4;

struct audio {
  int channels;
  int frames;
  float *data;
};

static struct audio *audio_load(const char *filename) {
  struct audio *audio = calloc(1, sizeof(*audio));
  if (! audio) {
    return 0;
  }
  SF_INFO info; memset(&info, 0, sizeof(info));
  SNDFILE *in = sf_open(filename, SFM_READ, &info);
  if (! in) {
    free(audio);
    return 0;
  }
  audio->channels = info.channels;
  audio->frames = info.frames;
  audio->data = calloc(audio->channels * audio->frames, sizeof(*audio->data));
  if (! audio->data) {
    sf_close(in);
    free(audio);
    return 0;
  }
  sf_readf_float(in, audio->data, audio->frames);
  sf_close(in);
  return audio;
}

struct fft {
  float *window;
  float *in;
  float *out;
  float *ibuf;
  float *obuf;
  fftwf_plan plan;
};

static struct fft *fft_init() {
  struct fft *fft = calloc(1, sizeof(*fft));
  if (! fft) {
    return 0;
  }
  fft->window = calloc(bs, sizeof(*fft->window));
  fft->in = calloc(bs, sizeof(*fft->in));
  fft->out = calloc(bs, sizeof(*fft->out));
  fft->ibuf = fftwf_alloc_real(bs);
  fft->obuf = fftwf_alloc_real(bs);
  for (int t = 0; t < bs; ++t) {
    fft->window[t] = 0.5 - 0.5 * cos(t * 2 * pi / bs);
  }
  fftwf_import_wisdom_from_filename(wisdomfile);
  fft->plan = fftwf_plan_r2r_1d(bs, fft->ibuf, fft->obuf, FFTW_R2HC, ↙
      ↳ FFTW_DESTROY_INPUT | FFTW_EXHAUSTIVE);
  fftwf_export_wisdom_to_filename(wisdomfile);
  return fft;
}

static void fft_compute(struct fft *fft) {
  for (int k = 0; k < bs; ++k) {
    fft->ibuf[k] = fft->window[k] * fft->in[k];
  }
  fftwf_execute(fft->plan);
  fft->out[0] = fft->obuf[0] * fft->obuf[0] / sqrtf(bs);
  fft->out[bs/2] = fft->obuf[bs/2] * fft->obuf[bs/2] / sqrtf(bs);
  for (int k = 1; k < bs/2; ++k) {
    float re = fft->obuf[k];
    float im = fft->obuf[bs - k];
    fft->out[k] = sqrtf(re * re + im * im) / sqrtf(bs);
  }
}

struct plane {
  int width;
  int height;
  float *data;
};

struct planes {
  int count;
  struct plane *plane;
};

static void planes_copy(float *src, int count, struct planes *planes, int p, int x) {
  for (int i = 0; i < count; ++i) {
    planes->plane[p].data[planes->plane[p].width * i + x] = src[i];
  }
}

static void audio_copy(float *dst, int count, struct audio *audio, int t0, int c) {
  int t = t0;
  for (int i = 0; i < count; ++i) {
    if (0 <= t && t < audio->frames) {
      dst[i] = audio->data[t * audio->channels + c];
    } else {
      dst[i] = 0;
    }
    ++t;
  }
}

static struct planes *planes_init(struct audio *audio, struct fft *fft, int count) {
  struct planes *planes = calloc(1, sizeof(*planes)); // FIXME cleanup
  planes->count = count;
  planes->plane = calloc(planes->count, sizeof(*planes->plane)); // FIXME cleanup
  int i = 0;
//  for (int i = 0; i < planes->count; ++i) {
//    fprintf(stderr, ”%d\n”, i);
    double frames = 2 * bs + audio->frames;
    planes->plane[i].width = ceil(frames * ol / bs);
    planes->plane[i].height = bs;
    planes->plane[i].data = calloc(planes->plane[i].width * planes->plane[i].height, sizeof(*planes->plane[i].data)); // FIXME cleanup
    int x = 0;
    for (int t = -bs; t < bs + audio->frames; t += bs / ol) {
      for (int c = 0; c < audio->channels; ++c) {
        audio_copy(fft->in, bs, audio, t, c);
        fft_compute(fft);
        planes_copy(fft->out, bs, planes, i, x);
      }
      ++x;
    }
```

```
//     struct audio *audio2 = audio_downsample(audio);
//     free(audio);
//     audio = audio2;
//   }
  return planes;
}

struct image {
  int width;
  int height;
  unsigned char *data;
};

static struct image *image_init(int frames) {
  struct image *image = calloc(1, sizeof(*image));
  if (! image) {
    return 0;
  }
  image->height = 128;
  double dframes = frames;
  image->width = ceil(dframes * ol / bs);
  image->data = calloc(1, image->width * image->height);
  if (! image->data) {
    free(image);
    return 0;
  }
  return image;
}

static void image_write(struct image *image, const char *filename) {
  FILE *out = fopen(filename, "wb");
  if (out) {
    fprintf(out, "P5\n%d %d\n255\n", image->width, image->height);
    fwrite(image->data, image->width * image->height, 1, out);
    fclose(out);
  }
}

static double planes_lookup(struct planes *planes, double f0, double f1, double t0) {
  double y0 = f0 / sr * planes->plane[0].height;
  double y1 = f1 / sr * planes->plane[0].height;
  int v0 = floor(y0);
  int v1 = ceil(y1);
  double z = 0;
  double t = t0;
  double x = ol * t / bs;
  int u = floor(x);
  int k = 0;
  for (int v = v0; v < v1; ++v) {
    if (0 <= u && u < planes->plane[0].width && 0 <= v && v < planes->plane[0].height) {
      z += planes->plane[0].data[planes->plane[0].width * v + u];
      k += 1;
    }
  }
  if (k == 0) { k = 1; }
  return z / k;
}

static void compute(struct planes *planes, struct image *image) {
  unsigned char *data = image->data;
  for (int y = 0; y < image->height; ++y) {
    double f0 = (pow(2, (y     - image->height) * 1.0 / image->height) - 0.5) * sr;
    double f1 = (pow(2, (y + 1 - image->height) * 1.0 / image->height) - 0.5) * sr;
    for (int x = 0; x < image->width; ++x) {
      double t = (x * bs) / ol + (ol - 1) * bs/ol;
      double v = planes_lookup(planes, f0, f1, t);
      unsigned char g = fmin(fmax(255 * v, 0), 255);
      *data++ = g;
    }
  }
}

int main(int argc, char **argv) {
  if (argc < 3) {
    return 1;
  }
  int retval = 1;
  struct audio *audio = audio_load(argv[1]);
  if (audio) {
    struct fft *fft = fft_init();
    if (fft) {
      int frames = audio->frames;
      struct planes *planes = planes_init(audio, fft, 1);
      if (planes) {
        struct image *image = image_init(frames);
        if (image) {
          compute(planes, image);
          image_write(image, argv[2]);
          retval = 0;
//          image_free(image);
        }
//        planes_free(planes);
      }
//      fft_free(fft);
    }
  }
  return retval;
}
```

27 start.sh

```
#!/bin/bash
# sudo cpufreq-set -c 0 -g performance
# sudo cpufreq-set -c 1 -g performance
ulimit -s unlimited
rm -rf o
rm -f v
make
SESSION="bitbreeder-$(date -u +%F-%H%M%S)"
mkdir -p o a "a/${SESSION}"
```

```
ln -s "a/${SESSION}/" v
ecasound -q -G:jack,record -f:f32,1,48000 -i:jack -o "a/${SESSION}.wav" &
sleep 5
time ./bitbreeder +RTS -N 2>"a/${SESSION}.err" >"a/${SESSION}.out"
sleep 5
kill %ecasound
echo "./encode.sh \"a/${SESSION}\""
```

28 Statistics.hs

```
type R = Double

data Stat = Stat !R !R !R

Stat s0 s1 s2 <> Stat t0 t1 t2 = Stat (s0 + t0) (s1 + t1) (s2 + t2)

stat :: R -> Stat
stat x = Stat 1 x (x*x)

mean :: Stat -> R
mean (Stat s0 s1 _) = s1 / s0

stddev :: Stat -> R
stddev (Stat s0 s1 s2)
  | t > 0 = t
  | otherwise = 0
  where t = sqrt (s0 * s2 - s1 * s1) / s0

type Stats = (Stat, [Stat])

merge :: Stats -> Stats -> Stats
merge (s, ss) (t, ts) = (r, stat (mean r) : zipWith (<>) ss ts)
  where r = s <> t

pairwise f (a:b:cs) = f a b : pairwise f cs
pairwise _ _ = [ ]

granularity :: [R] -> R
granularity
  = sum . zipWith (*) [0..] . map stddev
  . reverse . snd . head . last . takeWhile (not . null)
  . iterate (pairwise merge) . map (\x -> (stat x, []))

go :: (R -> R) -> IO ()
go f = print $ granularity [ f t | t <- [1 .. 2^16] ]

main :: IO ()
main = do
  go (\t -> sin (t / 10))
  go (\t -> sin (t / 1000))
  go (\t -> sin (t / 10) + 10 * sin (t / 1000))
  go (\t -> sin (10 / (t + 1)))

{-
6.305600061502868
43.442727416334165
434.64767794388223
0.5956135757335486
-}
```

29 stroke.frag

```
void main() {
  gl_FragColor = vec4(1.0, 0.7, 0.7, 1.0);
}
```

30 Video.hs

```
module Video (setupGL, draw, pngFilename, captureToPNG) where

import Data.Maybe (mapMaybe)
import Data.List (intercalate, transpose)
import Foreign (allocaBytes, nullPtr, peek, peekArray, plusPtr, with, withArray)
import Foreign.C (peekCStringLen, withCString)
import System.IO (hPutStrLn, stderr, hGetBuf, withBinaryFile, IOMode(ReadMode))
import Graphics.Rendering.Cairo (Format(FormatRGB24), formatStrideForWidth, ↙
    ↳ surfaceWriteToPNG, withImageSurfaceForData)
import Graphics.GL

import Config (videoW, videoH)
import Expression

type Glyph  = Char

data Layout = Layout [Glyph] (Int, Int) [Layout]

layout :: E -> Layout
layout X = Layout ”t” (1, 1) []
layout (I i) = Layout s (length s, 1) [] where s = show i
layout (U u e) = Layout s (w ‘max‘ length s, h + 1) [l]
  where
    s = glyphsU u
    l@(Layout _ (w, h) _) = layout e
layout (B b e f) = Layout s (ew + fw + 1, (eh ‘max‘ fh) + 1) [el, fl]
  where
    s = glyphsB b
    el@(Layout _ (ew, eh) _) = layout e
    fl@(Layout _ (fw, fh) _) = layout f
layout (T e f g) = Layout ”?:” (ew + fw + gw + 2, (eh ‘max‘ fh ‘max‘ gh) + 1) [↙
    ↳ el, fl, gl]
  where
    el@(Layout _ (ew, eh) _) = layout e
    fl@(Layout _ (fw, fh) _) = layout f
    gl@(Layout _ (gw, gh) _) = layout g

type Position = (Float, Float)
type Edge = (Position, Position)

layoutEdges :: Layout -> (Position, [Edge])
layoutEdges (Layout _ (w, _) []) = ((fromIntegral w / 2, 0.5), [])
layoutEdges (Layout gs _ [l@(Layout _ _ _)]) = (t, (t, (tx, ty + 1)) : map ↙
    ↳ translate es)
  where
    t = (fromIntegral (length gs) / 2, 0.5)
    ((tx, ty), es) = layoutEdges l
    translate ((x0, y0), (x1, y1)) = ((x0, y0 + 1), (x1, y1 + 1))
layoutEdges (Layout gs _ [l@(Layout _ (lw, _) _), r]) = (t, (t, (lx, ly + 1)) : ↙
  ↳ (t, (rx + fromIntegral lw + 1, ry + 1)) : map translateL ls ++ map ↙
  ↳ translateR rs)
  where
    t = (fromIntegral lw + fromIntegral (length gs) / 2, 0.5)
    ((lx, ly), ls) = layoutEdges l
    ((rx, ry), rs) = layoutEdges r
    translateL ((x0, y0), (x1, y1)) = ((x0, y0 + 1), (x1, y1 + 1))
    translateR ((x0, y0), (x1, y1)) = ((x0 + fromIntegral lw + 1, y0 + 1), (x1 +↙
      ↳  fromIntegral lw + 1, y1 + 1))
layoutEdges (Layout gs _ [l@(Layout _ (lw, _) _), m@(Layout _ (mw, _) _), r]) =
  (t, (t, (lx, ly + 1)) :
      (t, (mx + fromIntegral lw + 1, my + 1)) :
      (t, (rx + fromIntegral lw + 1 + fromIntegral mw + 1, ry + 1)) :
      map translateL ls ++ map translateM ms ++ map translateR rs)
  where
    t = (fromIntegral lw + fromIntegral (length gs) / 2, 0.5)
    ((lx, ly), ls) = layoutEdges l
    ((mx, my), ms) = layoutEdges m
    ((rx, ry), rs) = layoutEdges r
    translateL ((x0, y0), (x1, y1)) = ((x0, y0 + 1), (x1, y1 + 1))
    translateM ((x0, y0), (x1, y1)) = ((x0 + fromIntegral lw + 1, y0 + 1), (x1 +↙
      ↳  fromIntegral lw + 1, y1 + 1))
    translateR ((x0, y0), (x1, y1)) = ((x0 + fromIntegral lw + 1 + fromIntegral ↙
      ↳ mw + 1, y0 + 1), (x1 + fromIntegral lw + 1 + fromIntegral mw + 1, y1 +↙
      ↳  1))

glyphsU :: U -> [Glyph]
glyphsU Neg  = "-"
glyphsU LNot = "!"
glyphsU BNot = "~"

glyphsB :: B -> [Glyph]
glyphsB Add = "+"
glyphsB Sub = "-"
glyphsB Mul = "*"
glyphsB Div = "/"
glyphsB Mod = "%"
glyphsB BAnd = "&"
glyphsB LAnd = "&&"
glyphsB BOr = "|"
glyphsB LOr = "||"
glyphsB XOr = "^"
glyphsB ShL = "<<"
glyphsB ShR = ">>"
glyphsB Lt = "<"
glyphsB Gt = ">"

pretty :: Layout -> [[(Glyph, Float)]]
pretty l@(Layout _ (w, h) _) = map (([space] ++).(++ [space])) $ [replicate w ↙
  ↳ space] ++ fst (pretty' h l [0..]) ++ [replicate w space] where space = (' ↙
  ↳ ', -1)
pretty' :: Int -> Layout -> [Float] -> ([[(Glyph, Float)]], [Float])
pretty' _ _ [] = error "pretty'"
pretty' h (Layout s (w, _) ls) (c:cs) = (take h (take w (replicate x space ++ (↙
    ↳ zip s (repeat c)) ++ repeat space) : combine [space] gs ++ repeat (↙
    ↳ replicate w space)), cs')
  where
    (gs, cs') = maps (pretty' (h - 1)) cs ls
    space = (' ', c)
    x = case ls of
          (Layout _ (w', _) _):_:_ -> w'
          _ -> 0

maps :: (Layout -> [Float] -> ([[(Glyph, Float)]], [Float])) -> [Float] -> [↙
    ↳ Layout] -> ([[[(Glyph, Float)]]], [Float])
maps _ cs [] = ([], cs)
maps p cs (l:ls) =
  let (g, cs') = p l cs
      (gs, cs'') = maps p cs' ls
  in  (g:gs, cs'')

combine :: [(Glyph, Float)] -> [[[(Glyph, Float)]]] -> [[(Glyph, Float)]]
combine space = map (intercalate space) . transpose

glyphMap :: [(Glyph, [Float])]
glyphMap = [ (g, [x/8, y/4]) | (gs, y) <- ["01234567", "89-~!+*/", "%^&|<>?:", "↙
    ↳ t "] `zip` [0..], (g, x) <- gs `zip` [0..] ]

uploadGlyphs :: [[(Glyph, Float)]] -> IO (Int, Int)
uploadGlyphs gss@(gs:_) = do
  let w = length gs
      h = length gss
      xyzs = concat . mapMaybe (\(g, z) -> fmap (++[z]) $ g `lookup` glyphMap) .↙
          ↳ concat $ gss
  withArray xyzs $ glTexImage2D GL_TEXTURE_RECTANGLE 0 (fromIntegral GL_RGB32F) ↙
      ↳ (fromIntegral w) (fromIntegral h) 0 GL_RGB GL_FLOAT
  return (w, h)
uploadGlyphs _ = return (0, 0)

toTexture :: Layout -> IO (Int, Int)
toTexture = uploadGlyphs . pretty

setupGL :: IO (GLuint, GLuint)
setupGL = do
  [t0, t1] <- withArray [0,0] $ \p -> glGenTextures 2 p >> peekArray 2 p
  glActiveTexture GL_TEXTURE1
  glBindTexture GL_TEXTURE_2D t1
  let width = 1024
      height = 512
      bytes = width * height * 3
  withBinaryFile "glyphs.raw" ReadMode $ \h -> allocaBytes bytes $ \p -> do
    _ <- hGetBuf h p bytes
    glTexImage2D GL_TEXTURE_2D 0 (fromIntegral GL_RGB) (fromIntegral width) (↙
        ↳ fromIntegral height) 0 GL_RGB GL_UNSIGNED_BYTE p
  glGenerateMipmap GL_TEXTURE_2D
  glTexParameteri GL_TEXTURE_2D GL_TEXTURE_MIN_FILTER (fromIntegral ↙
      ↳ GL_LINEAR_MIPMAP_LINEAR)
  glTexParameteri GL_TEXTURE_2D GL_TEXTURE_MAG_FILTER (fromIntegral GL_LINEAR)
  glTexParameteri GL_TEXTURE_2D GL_TEXTURE_WRAP_S (fromIntegral GL_CLAMP_TO_EDGE↙
      ↳ )
  glTexParameteri GL_TEXTURE_2D GL_TEXTURE_WRAP_T (fromIntegral GL_CLAMP_TO_EDGE↙
      ↳ )
  glActiveTexture GL_TEXTURE0
  glBindTexture GL_TEXTURE_RECTANGLE t0
  glTexParameteri GL_TEXTURE_RECTANGLE GL_TEXTURE_MIN_FILTER (fromIntegral ↙
      ↳ GL_NEAREST)
  glTexParameteri GL_TEXTURE_RECTANGLE GL_TEXTURE_MAG_FILTER (fromIntegral ↙
      ↳ GL_NEAREST)
  glTexParameteri GL_TEXTURE_RECTANGLE GL_TEXTURE_WRAP_S (fromIntegral ↙
      ↳ GL_CLAMP_TO_EDGE)
  glTexParameteri GL_TEXTURE_RECTANGLE GL_TEXTURE_WRAP_T (fromIntegral ↙
      ↳ GL_CLAMP_TO_EDGE)
  prog <- glCreateProgram
  frag <- glCreateShader GL_FRAGMENT_SHADER
  src <- readFile "expr.frag"
  withCString src $ \p -> with p $ \pp -> glShaderSource frag 1 pp nullPtr
  glCompileShader frag
  hPutStrLn stderr =<< shaderLog frag
  glAttachShader prog frag
  glLinkProgram prog
  hPutStrLn stderr =<< programLog prog
  glUseProgram prog
  withCString "glyphs" $ \s -> glGetUniformLocation prog s >>= \l -> glUniform1i↙
      ↳ l 1
  withCString "expression" $ \s -> glGetUniformLocation prog s >>= \l -> ↙
      ↳ glUniform1i l 0
  prog2 <- glCreateProgram
  frag2 <- glCreateShader GL_FRAGMENT_SHADER
  src2 <- readFile "stroke.frag"
  withCString src2 $ \p -> with p $ \pp -> glShaderSource frag2 1 pp nullPtr
  glCompileShader frag2
  hPutStrLn stderr =<< shaderLog frag2
  glAttachShader prog2 frag2
  glLinkProgram prog2
  hPutStrLn stderr =<< programLog prog2
  return (prog, prog2)

draw :: (GLuint, GLuint) -> E -> IO ()
draw (prog, prog2) e = do
  let l = layout e
      (_, es) = layoutEdges l
  (w, h') <- toTexture l
  let h  = 1.5 * fromIntegral h'
      w0 = 32 * h / 9
      h0 = 9 * fromIntegral w / 32
      x0 = negate (w0 - fromIntegral w) / 2
      x1 = x0 + w0
      y0 = negate (h0 - h) / 2
      y1 = y0 + h0
  if 9 * fromIntegral w > 32 * h
    then do
      glDisable GL_BLEND
      glUseProgram prog
      quad (0, fromIntegral w) (y1, y0)
      glEnable GL_BLEND
      glBlendFunc GL_DST_COLOR GL_ZERO -- multiplicative
      glUseProgram prog2
      glBegin GL_QUADS
      mapM_ (edge (0, fromIntegral w) (y1, y0)) es
      glEnd
    else do
      glDisable GL_BLEND
      glUseProgram prog
      quad (x0, x1) (h*1.5, 0)
      glEnable GL_BLEND
      glBlendFunc GL_DST_COLOR GL_ZERO -- multiplicative
      glUseProgram prog2
      glBegin GL_QUADS
      mapM_ (edge (x0, x1) (h*1.5, 0)) es
      glEnd
  where
    v vx vy tx ty = glTexCoord2f tx ty >> glVertex2f vx vy
    quad (x0, x1) (y0, y1) = do
      glBegin GL_QUADS
      v (-1) (-1) x0 y0
      v (-1)   1  x0 y1
      v   1    1  x1 y1
      v   1  (-1) x1 y0
      glEnd
    edge (x0, x1) (y0, y1) ((u0, v0), (u1, v1)) = do
      let p0 = ( u0+1      - x0) / (x1 - x0) * 2 - 1
          q0 = ((v0+1)*1.5 - y0) / (y1 - y0) * 2 - 1
          p1 = ( u1+1      - x0) / (x1 - x0) * 2 - 1
          q1 = ((v1+1)*1.5 - y0) / (y1 - y0) * 2 - 1
          dp' = p1 - p0
          dq' = q1 - q0
          d = sqrt (dp' * dp' + dq' * dq') * (x1 - x0)
          dp = 2 * 0.09 * ( dq') / d
          dq = 2 * 0.32 * (-dp') / d
      v (p0 - dp) (q0 - dq) 0 0
      v (p0 + dp) (q0 + dq) 0 1
      v (p1 + dp) (q1 + dq) 1 1
      v (p1 - dp) (q1 - dq) 1 0

programLog :: GLuint -> IO String
programLog prog = do
  l <- with 0 $ \p -> glGetProgramiv prog GL_INFO_LOG_LENGTH p >> peek p
  allocaBytes (fromIntegral l) $ \p -> with 0 $ \q -> do
    glGetProgramInfoLog prog (fromIntegral l) q p
    m <- peek q
    peekCStringLen (p, fromIntegral m)

shaderLog :: GLuint -> IO String
shaderLog prog = do
  l <- with 0 $ \p -> glGetShaderiv prog GL_INFO_LOG_LENGTH p >> peek p
  allocaBytes (fromIntegral l) $ \p -> with 0 $ \q -> do
    glGetShaderInfoLog prog (fromIntegral l) q p
    m <- peek q
    peekCStringLen (p, fromIntegral m)

pngFilename :: Int -> String
pngFilename n = "./v/" ++ (reverse . take 8 . (++ repeat '0') . reverse . show) ↙
    ↳ n ++ ".png"

captureToPNG :: String -> IO ()
```

```haskell
captureToPNG f = do
  let stride = formatStrideForWidth FormatRGB24 videoW
  allocaBytes (videoH * stride) $ \p -> do
    glPixelStorei GL_PACK_ROW_LENGTH (fromIntegral $ stride `div` 4)
    glReadPixels 0 0 (fromIntegral videoW) (fromIntegral videoH) GL_BGRA GL_UNSIGNED_BYTE p
    glPixelStorei GL_PACK_ROW_LENGTH 0
    let q = p `plusPtr` ((videoH - 1) * stride)
    withImageSurfaceForData q FormatRGB24 videoW videoH (-stride) $ \s -> do
      surfaceWriteToPNG s f
```