Optimizing `smallpt`

Davean Scies, Siddharth Bhat

Haskell Exchange

November 4th, 2020

What is smallpt anyway?

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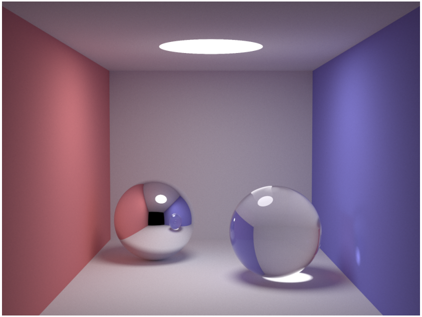
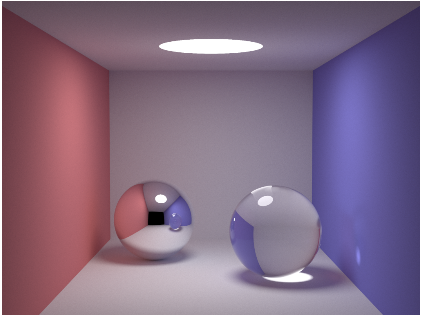
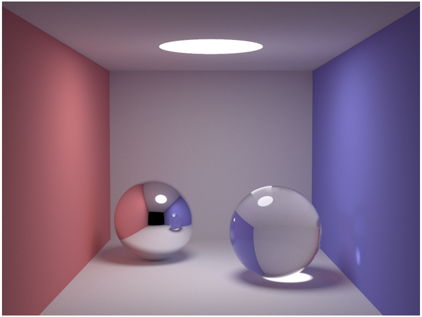


What is smallpt anyway?



- 100 LoC C demo of a raytracer

What is smallpt anyway?



- 100 LoC C demo of a raytracer
- Perfect for an optimization case study

What is smallpt anyway?

```
struct Vec {
  double x, y, z; // position, also color (r,g,b)
  ... methods...
};
struct Ray { Vec o, d; Ray(Vec o_, Vec d_) : o(o_), d(d_) {} };
enum Refl_t { DIFF, SPEC, REFR };  // material types, used in radiance()
struct Sphere {
  double rad;    // radius
  Vec p, e, c;   // position, emission, color
  Refl_t refl;   // reflection type (DIFFuse, SPECular, REFRactive)
  ... methods ...
  double intersect(const Ray &r) const // returns distance, 0 if nohit
};
Sphere spheres[] = {//Scene: radius, position, emission, color, material
  Sphere(1e5, Vec( 1e5+1,40.8,81.6), Vec(),Vec(.75,.25,.25),DIFF),//Left
  ... initialization ...
};
```

What is smallpt anyway?

```
Vec radiance(const Ray &r, int depth, unsigned short *Xi){













}
```

What is smallpt anyway?

```
Vec radiance(const Ray &r, int depth, unsigned short *Xi){











                          radiance

                          radiance




                          radiance




   radiance                      radiance
   radiance                      radiance
}
```

What is smallpt anyway?

```
Vec radiance(const Ray &r, int depth, unsigned short *Xi){






  if (          ) if (              )            else
  if (                ){



                          radiance
  } else if (            )
                          radiance



  if (                               )
                          radiance




    radiance                        radiance
    radiance                        radiance
}
```

What is smallpt anyway?

```
Vec radiance(const Ray &r, int depth, unsigned short *Xi){



  Vec x=r.o+r.d*t, n=(x-obj.p).norm(), nl=n.dot(r.d)<0?n:n*-1, f=obj.c;

  if (         ) if (             )            else
  if (                ){




                          radiance
  } else if (                )
                          radiance



  if ((cos2t=1-nnt*nnt*(1-ddn*ddn))<0)
                          radiance




    radiance                      radiance
    radiance                      radiance
}
```

What is smallpt anyway?

```
Vec radiance(const Ray &r, int depth, unsigned short *Xi){
  double t;                               // distance to intersection
  int id=0;                               // id of intersected object
  if (!intersect(r, t, id)) return Vec(); // if miss, return black
  const Sphere &obj = spheres[id];        // the hit object
  Vec x=r.o+r.d*t, n=(x-obj.p).norm(), nl=n.dot(r.d)<0?n:n*-1, f=obj.c;
  double p = f.x>f.y && f.x>f.z ? f.x : f.y>f.z ? f.y : f.z; // max refl
  if (++depth>5) if (erand48(Xi)<p) f=f*(1/p); else return obj.e; //R.R.
  if (obj.refl == DIFF){                  // Ideal DIFFUSE reflection
    double r1=2*M_PI*erand48(Xi), r2=erand48(Xi), r2s=sqrt(r2);
    Vec w=nl, u=((fabs(w.x)>.1?Vec(0,1):Vec(1))%w).norm(), v=w%u;
    Vec d = (u*cos(r1)*r2s + v*sin(r1)*r2s + w*sqrt(1-r2)).norm();
    return obj.e + f.mult(radiance(Ray(x,d),depth,Xi));
  } else if (obj.refl == SPEC)            // Ideal SPECULAR reflection
    return obj.e + f.mult(radiance(Ray(x,r.d-n*2*n.dot(r.d)),depth,Xi));
  Ray reflRay(x, r.d-n*2*n.dot(r.d));     // Ideal dielectric REFRACTION
  bool into = n.dot(nl)>0;                // Ray from outside going in?
  double nc=1, nt=1.5, nnt=into?nc/nt:nt/nc, ddn=r.d.dot(nl), cos2t;
  if ((cos2t=1-nnt*nnt*(1-ddn*ddn))<0)    // Total internal reflection
    return obj.e + f.mult(radiance(reflRay,depth,Xi));
  Vec tdir = (r.d*nnt - n*((into?1:-1)*(ddn*nnt+sqrt(cos2t)))).norm();
  double a=nt-nc, b=nt+nc, R0=a*a/(b*b), c = 1-(into?-ddn:tdir.dot(n));
  double Re=R0+(1-R0)*c*c*c*c*c,Tr=1-Re,P=.25+.5*Re,RP=Re/P,TP=Tr/(1-P);
  return obj.e + f.mult(depth>2 ? (erand48(Xi)<P ?   // Russian roulette
    radiance(reflRay,depth,Xi)*RP:radiance(Ray(x,tdir),depth,Xi)*TP) :
    radiance(reflRay,depth,Xi)*Re+radiance(Ray(x,tdir),depth,Xi)*Tr);
}
```

Initial Haskell Code (1×)

```
...
radiance :: Ray -> CInt -> Ptr CUShort -> IO Vec
radiance ray@(Ray o d) depth xi = case intersects ray of
  (Nothing,_) -> return zerov
  (Just t,Sphere _r p e c refl) -> do







        continue f = case refl of
          DIFF -> do







                radiance

          SPEC -> do

            rad <- radiance

          REFR -> do







            if
              then do
                rad <- radiance reflRay depth' xi
```

Sha256 hash of the output image — 4dac691082bb

Initial Haskell Code (1×)

```haskell
...
radiance :: Ray -> CInt -> Ptr CUShort -> IO Vec
radiance ray@(Ray o d) depth xi = case intersects ray of
  (Nothing,_) -> return zerov
  (Just t,Sphere _r p e c refl) -> do
    let x = o `addv` (d `mulvs` t)
        n = norm $ x `subv` p
        nl = if n `dot` d < 0 then n else n `mulvs` (-1)
        pr = maxv c
        depth' = depth + 1
        continue f = case refl of
          DIFF -> do
            r1 <- ((2*pi)*) `fmap` erand48 xi
            r2 <- erand48 xi
            let r2s = sqrt r2
                w@(Vec wx _ _) = nl
                u = norm $ (if abs wx > 0.1 then (Vec 0 1 0) else (Vec 1 0 0)) `cross` w
                v = w `cross` u
                d' = norm $ (u`mulvs`(cos r1*r2s)) `addv` (v`mulvs`(sin r1*r2s)) `addv` (w`mulvs`sqrt (1-r2))
            rad <- radiance (Ray x d') depth' xi
            return $ e `addv` (f `mulv` rad)
          SPEC -> do
            let d' = d `subv` (n `mulvs` (2 * (n`dot`d)))
            rad <- radiance (Ray x d') depth' xi
            return $ e `addv` (f `mulv` rad)
          REFR -> do
            let reflRay = Ray x (d `subv` (n `mulvs` (2* n`dot`d))) -- Ideal dielectric REFRACTION
                into = n`dot`nl > 0                -- Ray from outside going in?
                nc = 1
                nt = 1.5
                nnt = if into then nc/nt else nt/nc
                ddn= d`dot`nl
                cos2t = 1-nnt*nnt*(1-ddn*ddn)
            if cos2t<0    -- Total internal reflection
              then do
                rad <- radiance reflRay depth' xi
                ...

    if depth'>5
    ...
```

Restrict export list to ‘main‘ (1.13×)

```
-module Main where
+module Main (main) where
```

Mark entries of Ray and Sphere as UNPACK and Strict (1.07×)

```
-data Ray = Ray Vec Vec -- origin, direction
+data Ray = Ray {-# UNPACK #-} !Vec {-# UNPACK #-} !Vec -- origin, direction

 data Refl = DIFF | SPEC | REFR -- material types, used in radiance

 -- radius, position, emission, color, reflection
-data Sphere = Sphere Double Vec Vec Vec !Refl
+data Sphere = Sphere {-# UNPACK #-} !Double
+                     {-# UNPACK #-} !Vec
+                     {-# UNPACK #-} !Vec
+                     {-# UNPACK #-} !Vec !Refl
```

Use a pattern synonym to unpack Refl in Sphere (1.07×)

```
+{-# LANGUAGE PatternSynonyms #-}

-data Refl = DIFF | SPEC | REFR -- material types, used in radiance
+newtype Refl = Refl Int  -- material types, used in radiance
+pattern DIFF,SPEC,REFR :: Refl
+pattern DIFF = Refl 0
+pattern SPEC = Refl 1
+pattern REFR = Refl 2
+{-# COMPLETE DIFF, SPEC, REFR #-}

 -- radius, position, emission, color, reflection
 data Sphere = Sphere {-# UNPACK #-} !Double
                      {-# UNPACK #-} !Vec
                      {-# UNPACK #-} !Vec
-                     {-# UNPACK #-} !Vec !Refl
+                     {-# UNPACK #-} !Vec {-# UNPACK #-} !Refl
```

Change from `maximum` on a list to `max` (1.08×)

```
-maxv (Vec a b c) = maximum [a,b,c]
+maxv (Vec a b c) = max a (max b c)

@@ -84,7 +85,6 @@ radiance ray@(Ray o d) depth xi = case intersects ray of
     let x = o `addv` (d `mulvs` t)
         n = norm $ x `subv` p
         nl = if n `dot` d < 0 then n else n `mulvs` (-1)
-        pr = maxv c
         depth' = depth + 1
         continue f = case refl of
           DIFF -> do
@@ -140,6 +140,7 @@ radiance ray@(Ray o d) depth xi = case intersects ray of
     if depth'>5
       then do
         er <- erand48 xi
+        let !pr = maxv c
```

Convert erand48 to pure Haskell (1.09×)

```
-radiance :: Ray -> CInt -> Ptr CUShort -> IO Vec
+radiance :: Ray -> Int -> IORef Word64 -> IO Vec
 radiance ray@(Ray o d) depth xi = case intersects ray of
   (Nothing,_) -> return zerov
   (Just t,Sphere _r p e c refl) -> do
@@ -153,9 +153,8 @@ smallpt w h nsamps = do
       cx = Vec (fromIntegral w * 0.5135 / fromIntegral h) 0 0
       cy = norm (cx `cross` dir) `mulvs` 0.5135
   c <- VM.replicate (w * h) zerov
-  allocaArray 3 $ \xi ->
-      flip mapM_ [0..h-1] $ \y -> do
+  xi <- newIORef 0
+  flip mapM_ [0..h-1] $ \y -> do
       writeXi xi y
```

Change erand48 to IORefU (1.13×)

```
-radiance :: Ray -> Int -> IORef Word64 -> IO Vec
+radiance :: Ray -> Int -> IORefU Word64 -> IO Vec
 radiance ray@(Ray o d) depth xi = case intersects ray of
   (Nothing,_) -> return zerov
   (Just t,Sphere _r p e c refl) -> do
@@ -153,7 +154,7 @@ smallpt w h nsamps = do
       cx = Vec (fromIntegral w * 0.5135 / fromIntegral h) 0 0
       cy = norm (cx `cross` dir) `mulvs` 0.5135
   c <- VM.replicate (w * h) zerov
-  xi <- newIORef 0
+  xi <- newIORefU 0
   flip mapM_ [0..h-1] $ \y -> do
       writeXi xi y
       flip mapM_ [0..w-1] $ \x -> do
@@ -181,8 +182,8 @@ smallpt w h nsamps = do
           Vec r g b <- VM.unsafeRead c i
           hPrintf hdl "%d %d %d " (toInt r) (toInt g) (toInt b)

-writeXi :: IORef Word64 -> Int -> IO ()
-writeXi !xi !y = writeIORef xi (mkErand48Seed' y)
+writeXi :: IORefU Word64 -> Int -> IO ()
+writeXi !xi !y = writeIORefU xi (mkErand48Seed' y)
```

Rewrite the remaining IORef into a foldM (1.17×)

```
@@ -161,8 +161,7 @@ smallpt w h nsamps = do
         let i = (h-y-1) * w + x
         flip mapM_ [0..1] $ \sy -> do
           flip mapM_ [0..1] $ \sx -> do
-            r <- newIORef zerov
-            flip mapM_ [0..samps-1] $ \_s -> do
+            Vec rr rg rb <- (\f -> foldM f zerov [0..samps-1]) $ \ !r _s -> do
               r1 <- (2*) `fmap` erand48 xi
               let dx = if r1<1 then sqrt r1-1 else 1-sqrt(2-r1)
               r2 <- (2*) `fmap` erand48 xi
@@ -171,9 +170,8 @@ smallpt w h nsamps = do
-              modifyIORef r (`addv` (rad `mulvs` (1 / fromIntegral samps)))
+              pure (r `addv` (rad `mulvs` (1 / fromIntegral samps)))
             ci <- VM.unsafeRead c i
-            Vec rr rg rb <- readIORef r
```

Remove the Data.Vector.Mutable by being purer (1.17×)

```
-radiance :: Ray -> Int -> IORefU Word64 -> IO Vec
+radiance :: Ray -> Int -> STRefU s Word64 -> ST s Vec
...
-  c <- VM.replicate (w * h) zerov
-  xi <- newIORefU 0
-  flip mapM_ [0..h-1] $ \y -> do
-      writeXi xi y
-      flip mapM_ [0..w-1] $ \x -> do
-        let i = (h-y-1) * w + x
-        flip mapM_ [0..1] $ \sy -> do
-          flip mapM_ [0..1] $ \sx -> do
+      img = (`concatMap` [(h-1),(h-2)..0]) $ \y -> runST $ do
+        xi <- newSTRefU (mkErand48Seed' y)
+        forM [0..w-1] $ \x -> do
...

-erand48 :: IORefU Word64 -> IO Double
+erand48 :: STRefU s Word64 -> ST s Double
 erand48 !t =  do
-  r <- readIORefU t
+  r <- readSTRefU t
   let (r', d) = erand48' r
-  writeIORefU t r'
+  writeSTRefU t r'
   pure d
```

Set **everything** in smallpt to be strict (1.17×)

```
-  let samps = nsamps `div` 4
-      org = Vec 50 52 295.6
-      dir = norm $ Vec 0 (-0.042612) (-1)
-      cx = Vec (fromIntegral w * 0.5135 / fromIntegral h) 0 0
-      cy = norm (cx `cross` dir) `mulvs` 0.5135
+  let !samps = nsamps `div` 4
+      !org = Vec 50 52 295.6
+      !dir = norm $ Vec 0 (-0.042612) (-1)
+      !cx = Vec (fromIntegral w * 0.5135 / fromIntegral h) 0 0
+      !cy = norm (cx `cross` dir) `mulvs` 0.5135

-  r1 <- (2*) `fmap` erand48 xi
-  let dx = if r1<1 then sqrt r1-1 else 1-sqrt(2-r1)
-  r2 <- (2*) `fmap` erand48 xi
-  let dy = if r2<1 then sqrt r2-1 else 1-sqrt(2-r2)
-      d = ...
-  rad <- radiance (Ray (org`addv`(d`mulvs`140)) (norm d)) 0 xi
+  !r1 <- (2*) `fmap` erand48 xi
+  let !dx = if r1<1 then sqrt r1-1 else 1-sqrt(2-r1)
+  !r2 <- (2*) `fmap` erand48 xi
+  let !dy = if r2<1 then sqrt r2-1 else 1-sqrt(2-r2)
+      !d = ...
```

Reduce to only effectful strictnesses (1.17×)

```
-  let !samps = nsamps `div` 4
-      !org = Vec 50 52 295.6
-      !dir = norm $ Vec 0 (-0.042612) (-1)
-      !cx = Vec (fromIntegral w * 0.5135 / fromIntegral h) 0 0
-      !cy = norm (cx `cross` dir) `mulvs` 0.5135
+  let samps = nsamps `div` 4
+      org = Vec 50 52 295.6
+      dir = norm $ Vec 0 (-0.042612) (-1)
+      cx = Vec (fromIntegral w * 0.5135 / fromIntegral h) 0 0
+      cy = norm (cx `cross` dir) `mulvs` 0.5135

-              !r1 <- (2*) `fmap` erand48 xi
+              r1 <- (2*) `fmap` erand48 xi

-              !r2 <- (2*) `fmap` erand48 xi
+              r2 <- (2*) `fmap` erand48 xi

-              !rad <- radiance (Ray (org`addv`(d`mulvs`140)) (norm d)) 0 xi
+              rad <- radiance (Ray (org`addv`(d`mulvs`140)) (norm d)) 0 xi

-              pure $! (r `addv` (rad `mulvs` (1 / fromIntegral samps)))
-            pure $! ci `addv` (Vec (clamp rr) (clamp rg) (clamp rb) `mulvs` 0.25)
+              pure $ (r `addv` (rad `mulvs` (1 / fromIntegral samps)))
+            pure $ ci `addv` (Vec (clamp rr) (clamp rg) (clamp rb) `mulvs` 0.25)
```

Remove Maybe from intersect(s) (1.32×)

```
-intersect :: Ray -> Sphere -> Maybe Double
+intersect :: Ray -> Sphere -> Double
intersect (Ray o d) (Sphere r p _e _c _refl) =
-  if det<0 then Nothing else f (b-sdet) (b+sdet)
+  if det<0 then (1/0.0) else f (b-sdet) (b+sdet)
   where op = p `subv` o
        eps = 1e-4
         b = op `dot` d
         det = b*b - (op `dot` op) + r*r
         sdet = sqrt det
-        f a s = if a>eps then Just a else if s>eps then Just s else Nothing
+        f a s = if a>eps then a else if s>eps then s else (1/0.0)

-intersects :: Ray -> (Maybe Double, Sphere)
+intersects :: Ray -> (Double, Sphere)
 intersects ray = (k, s)
-  where (k,s) = foldl' f (Nothing,undefined) spheres
-        f (k',sp) s' = case (k',intersect ray s') of
-                  (Nothing,Just x) -> (Just x,s')
-                  (Just y,Just x) | x < y -> (Just x,s')
-                  _ -> (k',sp)
+  where (k,s) = foldl' f (1/0.0,undefined) spheres
+        f (k', sp) s' = let !x = intersect ray s' in if x < k' then (x, s') else (k', sp)

 radiance :: Ray -> Int -> STRefU s Word64 -> ST s Vec
 radiance ray@(Ray o d) depth xi = case intersects ray of
-  (Nothing,_) -> return zerov
-  (Just t,Sphere _r p e c refl) -> do
+  (t,_) | t == (1/0.0) -> return zerov
+  (t,Sphere _r p e c refl) -> do
```

Hand unroll the fold in intersects (1.35×)

```
 intersects :: Ray -> (Double, Sphere)
-intersects ray = (k, s)
-  where (k,s) = foldl' f (1/0.0,undefined) spheres
+intersects ray =
+    f (... (f (f (intersect ray sphLeft, sphLeft) sphRight) ...)
+  where
     f (k', sp) s' = let !x = intersect ray s' in if x < k' then (x, s') else (k', sp)

-spheres :: [Sphere]
-spheres = let s = Sphere ; z = zerov ; (.*) = mulvs ; v = Vec in
-  [ s 1e5 (v (1e5+1) 40.8 81.6)    z (v 0.75 0.25 0.25) DIFF --Left
-  , s 1e5 (v (-1e5+99) 40.8 81.6)  z (v 0.25 0.25 0.75) DIFF --Rght
...

+sphLeft, sphRight, ...  :: Sphere
+sphLeft  = Sphere 1e5  (Vec (1e5+1) 40.8 81.6)    zerov (Vec 0.75 0.25 0.25) DIFF
+sphRight = Sphere 1e5  (Vec (-1e5+99) 40.8 81.6)  zerov (Vec 0.25 0.25 0.75) DIFF
...
```

Marking `interesects f` parameters strict (1.41×)

```
 intersects ray = ...
   where
-    f (k', sp) s' = let !x = intersect ray s' in if x < k' then (x, s') else (k', sp)
+    f !(!k', !sp) !s' = let !x = intersect ray s' in if x < k' then (x, s') else (k', sp)
```

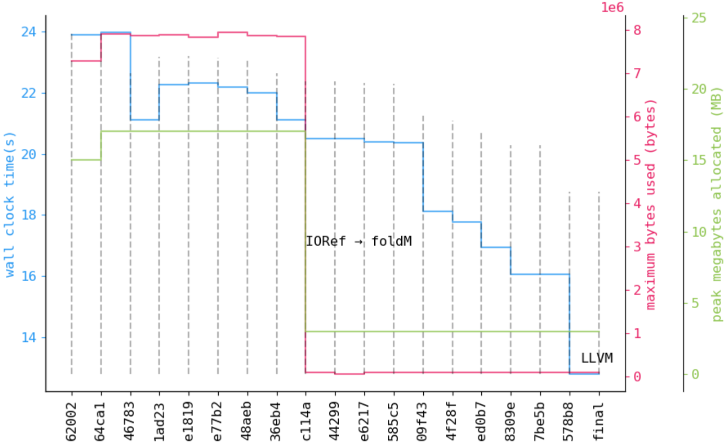
Strategic application of strictness ($1.49\times$)

```
-  if det<0 then (1/0.0) else f (b-sdet) (b+sdet)
-  where op = p `subv` o
-        eps = 1e-4
-        b = op `dot` d
-        det = b*b - (op `dot` op) + r*r
-        sdet = sqrt det
-        f a s = if a>eps then a else if s>eps then s else (1/0.0)
+  if det<0
+  then (1/0.0)
+  else
+    let !eps = 1e-4
+        !sdet = sqrt det
+        !a = b-sdet
+        !s = b+sdet
+    in if a>eps then a else if s>eps then s else (1/0.0)
+  where
+    !det = b*b - (op `dot` op) + r*r
+    !b = op `dot` d
+    !op = p `subv` o

-  (t,_) | t == (1/0.0) -> return zerov
-  (t,Sphere _r p e c refl) -> do
-    let x = o `addv` (d `mulvs` t)
-        n = norm $ x `subv` p
-        nl = if n `dot` d < 0 then n else n `mulvs` (-1)
-        depth' = depth + 1
+  (!t,_) | t == (1/0.0) -> return zerov
+  (!t,!Sphere _r p e c refl) -> do
+    let !x = o `addv` (d `mulvs` t)
+        !n = norm $ x `subv` p
+        !nl = if n `dot` d < 0 then n else n `mulvs` (-1)
+        !depth' = depth + 1

-                    a=nt-nc
-                    b=nt+nc
-                    r0=a*a/(b*b)
-                    c' = 1-(if into then -ddn else tdir`dot`n)
-                    re=r0+(1-r0)*c'*c'*c'*c'*c'
-                    tr=1-re
-                    pp=0.25+0.5*re
-                    rp=re/pp
-                    tp=tr/(1-pp)
+                    !r0=4.0e-2
```

Use `LLVM` backend (1.87×)

```
+packages: .
+
+package smallpt-opt
+  ghc-options: -fllvm
```

The view from the mountaintop



Takeaways

- Haskell can be fast, given some sensitivity to performance.
- Having performance leads to a faster baseline (unpacking, bang-patterns, `max`, `LLVM` by default, exporting `main`, ...)
- Some others (unrolling `f`) is more subtle.
- Accumulate optimizations to accrue performance wins.