Optimizing smallpt

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Haskell Exchange

November 4th, 2020

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2020-11-04

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What is smallpt anyway?

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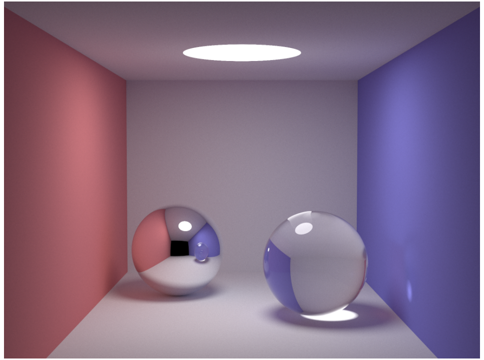

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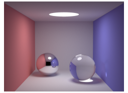

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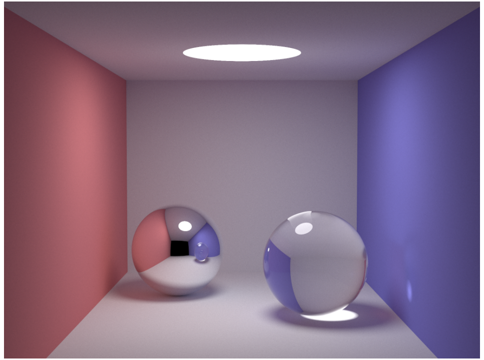

- 100 LoC C demo of a raytracer

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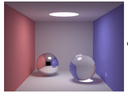

- 100 LoC C demo of a raytracer

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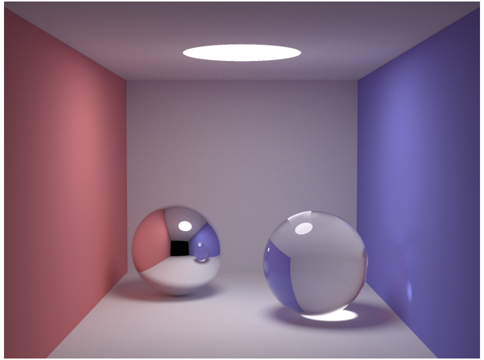
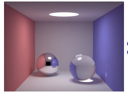


- 100 LoC C demo of a raytracer
- Perfect for an optimization case study

What is smallpt anyway?



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

Note for first slide: what is smallpt anyway?

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?

```
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){
}

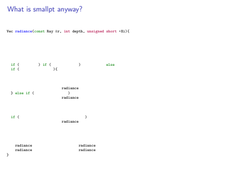
Say that the core function is radiance

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?

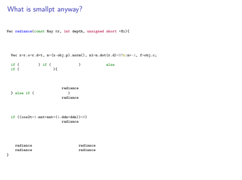
```
Vec radiance(const Ray &r, int depth, unsigned short *Xi){




  if (          ) if (               )            else
  if (                ){




  } else if (           radiance
                           )
                        radiance




  if (                                )
                        radiance




    radiance                      radiance
    radiance                      radiance
}
```

…with control flow

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 (                ){




  } else if (                radiance
                                )
                             radiance




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





    radiance                       radiance
    radiance                       radiance
}
```

and lots of arithmetic

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);
}
```


display the whole thing

Initial Haskell Code: `radiance` (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
```


show the same thing, this time in haskell

Initial Haskell Code: radiance (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
    ...
```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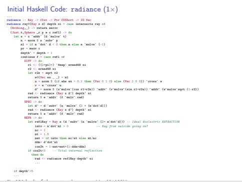
Initial Haskell Code: radiance (1×)



full code

Initial Haskell Code: Entry point (1×)

```haskell
smallpt :: Int -> Int -> Int -> IO ()
smallpt w h nsamps = do
  ...
  c <- VM.replicate (w * h) 0
  allocaArray 3 \xi ->
    flip mapM_ [0..h-1] $ \y -> do
      writeXi xi y
      for_ [0..w-1] \x -> do
        let i = (h-y-1) * w + x
        for_ [0..1] \sy -> do
          for_ [0..1] \sx -> do
            r <- newIORef 0
            for_ [0..samps-1] \_s -> do
              r1 <- (2*) <$> erand48 xi
              ...
              rad <- radiance (Ray (org+d.*140) (norm d)) 0 xi
              ...
              modifyIORef r (+ rad .* recip (fromIntegral samps))
            ci <- VM.unsafeRead c i
            Vec rr rg rb <- readIORef r
            VM.unsafeWrite c i $ ci + Vec (clamp rr) (clamp rg) (clamp rb) .* 0.25
```

Initial Haskell Code: File I/O (1×)

```haskell
withFile "image.ppm" WriteMode $ \hdl -> do
      hPrintf hdl "P3\n%d %d\n%d\n" w h (255::Int)
      flip mapM_ [0..w*h-1] \i -> do
        Vec r g b <- VM.unsafeRead c i
        hPrintf hdl "%d %d %d " (toInt r) (toInt g) (toInt b)
```


Initial Haskell Code: File I/O (1×)
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hPrintf hdl "%d %d %d " (toInt r) (toInt g) (toInt b)

Initial Haskell Code: RNG (1×)

```haskell
foreign import ccall unsafe "erand48"
  erand48 :: Ptr CUShort -> IO Double
```


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Initial Haskell Code: RNG (1×)

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foreign import ccall unsafe "erand48"
erand48 :: Ptr CUShort -> IO Double

Restrict export list to ‘main‘ (1.13×)

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


Restrict export list to ‘main‘ (1.13×)

-module Main where
+module Main (main) where

Knowing what functions are used how enables many optimizations that could otherwise would be detrimental or unsound (eg: changing signatures based on demands)

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
```


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

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 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
```

```
data Foo = Foo !Int
data OptFoo  = OptFoo {-# UNPACK #-} !Int ~= OptFoo Int#
```

```
struct Int { int64_t i; }
struct Foo { Int *iptr; }
struct OptFoo { int64_t i; }
```


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

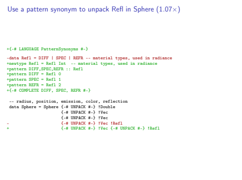
This optimization removes indirection and laziness.

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

```diff
+{-# 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
```

While we weren't able to unpack Refl in the last step because it is a sum type, we can if we use a trick modeled after an C Enum. The use of COMPLETE is unsafe here because other values could be constructed. For this small example though we rely on the fact that we create values of Refl via the patterns.

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
```


finicky optimization. GHC does not evaluate at compile time, making optimizations like these necessary

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
```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Convert erand48 to pure Haskell (1.09×)

Remove mutability: Erand48 Monad

```
...
-erand48 :: IORef Word64 -> IO Double
-erand48 !t =  do
-  r <- readIORef t
+data ET a = ET !Word64 !a deriving Functor
+newtype Erand48 a = Erand48 { runErand48' :: Word64 -> ET a } deriving Functor
+
+instance Applicative Erand48 where
...
+instance Monad Erand48 where
...
+runWithErand48 :: Int -> Erand48 a -> a
+runWithErand48 !y act =
+   let yw = fromIntegral y
+       prod = yw * yw * yw
+        ET _ !r = runErand48' act (prod `unsafeShiftL` 32) in r
...
+erand48 :: Erand48 Double
+erand48 =  Erand48 \ !r ->
   let x' = 0x5deece66d * r + 0xb
       d_word = 0x3ff0000000000000 .|. ((x' .&. 0xffffffffffff) `unsafeShiftL` 4)
       d = castWord64ToDouble d_word - 1.0
```

Remove mutation: Using Erand48

```
-radiance :: Ray -> Int -> IORef Word64 -> IO Vec
-radiance ray@(Ray o d) depth xi = case intersects ray of
+radiance :: Ray -> Int -> Erand48 Vec
+radiance ray@(Ray o d) depth = case intersects ray of
...
-            r1 <- (2*pi*) <$> erand48 xi
-            r2 <- erand48 xi
+            r1 <- (2*pi*) <$> erand48
+            r2 <- erand48
...
-                              then (.* rp) <$> radiance reflRay depth' xi
-                              else (.* tp) <$> radiance (Ray x tdir) depth' xi
+                              then (.* rp) <$> radiance reflRay depth'
+                              else (.* tp) <$> radiance (Ray x tdir) depth'
...
```


Remove mutation: Using Erand48

Removing mutation: eliminate IORef

```
-  c <- VM.replicate (w * h) 0
-  xi <- newIORef 0
-  flip mapM_ [0..h-1] $ \y -> do
-      writeXi xi y
-      for_ [0..w-1] \x -> do
-        let i = (h-y-1) * w + x
-        for_ [0..1] \sy -> do
-          for_ [0..1] \sx -> do
-            r <- newIORef 0
-            for_ [0..samps-1] \_s -> do
-              r1 <- (2*) <$> erand48 xi
+      img = (`concatMap` [(h-1),(h-2)..0]) $ \y -> runWithErand48 y do
+        for [0..w-1] \x -> do
+          (\pf -> foldlM pf 0 [(sy, sx) | sy <- [0,1], sx <- [0,1]]) \ci (sy, sx) -> do
+            Vec rr rg rb <- (\f -> foldlM f 0 [0..samps-1]) \ !r _s -> do
+              r1 <- (2*) <$> erand48
...
-              modifyIORef r (+ rad .* recip (fromIntegral samps))
-            ci <- VM.unsafeRead c i
-            Vec rr rg rb <- readIORef r
-            VM.unsafeWrite c i $ ci + Vec (clamp rr) (clamp rg) (clamp rb) .* 0.25
+              pure (r + rad .* recip (fromIntegral samps))
+            pure (ci + Vec (clamp rr) (clamp rg) (clamp rb) .* 0.25)
...
```

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

```
smallpt :: Int -> Int -> Int -> IO ()
smallpt w h nsamps = do
-  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 = ...
...
+              pure $! r + rad .* recip (fromIntegral samps)
+            pure $! ci + Vec (clamp rr) (clamp rg) (clamp rb) .* 0.25
```


This does make a difference but a small one. The question is which ones matter.

Reduce to only useful strictnesses in `smallpt`(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) .* 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) .* 0.5135
...
-              !r1 <- (2*) <$> erand48
+              r1 <- (2*) <$> erand48
...
-              !r2 <- (2*) <$> erand48
+              r2 <- (2*) <$> erand48
...
-              !rad <- radiance (Ray (org+d.*140) (norm d)) 0
+              rad <- radiance (Ray (org+d.*140) (norm d)) 0
...
-              pure $! r + rad .* recip (fromIntegral samps)
-            pure $! ci + Vec (clamp rr) (clamp rg) (clamp rb) .* 0.25
+              pure (r + rad .* recip (fromIntegral samps))
+            pure (ci + Vec (clamp rr) (clamp rg) (clamp rb) .* 0.25)
```


Some inspection shows us which bang patters are actually carrying the weight. Most are unnecessary.

Use strictness strategically in entire project

```
...
-  if det<0 then Nothing else f (b-sdet) (b+sdet)
-  where op = p - o
-        eps = 1e-4
-        b = dot op d
-        det = b*b - dot op op + r*r
-        sdet = sqrt det
-        f a s = if a>eps then Just a else if s>eps then Just s else Nothing
+  if det<0
+  then Nothing
+  else
+    let !eps = 1e-4
+        !sdet = sqrt det
+        !a = b-sdet
+        !s = b+sdet
+    in if a>eps then Just a else if s>eps then Just s else Nothing
...
```

TODO: maybe more interesting to talk about places where having strictness was **not** useful

Use strictness strategically in entire project

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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
```


Our innermost functions are of critical importance. Here we remove a Maybe which significantly reduces the boxing (which could have been mitigated with a StrictMaybe) and the cases.
Since a Ray that fails to intersect something can be said to intersect at infinity, Double already actually covers the structure at play.

This also reduces allocation.

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
...
```

- Can also be realized using REWRITE rules.
- GHC does not attempt to partially evaluate.

Hand unroll the fold in intersects (1.35×)

This removes the list and this a potential level of indirections and branches. Sadly GHC did not do this for us even though the list was static.

Custom datatype for intersects parameter passing

```
-intersects :: Ray -> (Double, Sphere)
+data T = T !Double !Sphere
+
+intersects :: Ray -> T
 intersects ray =
-    f ( ... f (intersect ray sphLeft, sphLeft) sphRight) ... sphLite
+    f ( ... f (T (intersect ray sphLeft) sphLeft) sphRight) ... sphLite
   where
-    f (k', sp) s' =
-        let !x = intersect ray s' in if x < k' then (x, s') else (k', sp)
+    f !(T k' sp) !s' =
+        let !x = intersect ray s' in if x < k' then T x s' else T k' sp

 radiance :: Ray -> Int -> Erand48 Vec
 radiance ray@(Ray o d) depth = case intersects ray of
-  (!t,_) | t == 1/0.0 -> return 0
-  (!t,!Sphere _r p e c refl) -> do
+  (T t _) | t == 1/0.0 -> return 0
+  (T t (Sphere _r p e c refl)) -> do
    let !x = o + d .* t
        !n = norm $ x - p
        !nl = if dot n d < 0 then n else negate n
```


Its clear that f will consume these, so making it strict can have some benefit. The problem is the right level here. One's first take might be to set the parameters of 'f' to be strict, and that can have benefits, but it leaves a lot on the table. Moving to and unboxed tuple performs the computation faster but introduces copying. Out 'T' datatype here has the right balance, it makes it clear the data is strict but doesn't copy.

Optimize file writing

```
   build-depends:
       base >= 4.12 && < 4.15
+    , bytestring ^>= 0.11

-toInt :: Double -> Int
-toInt x = floor $ clamp x ** recip 2.2 * 255 + 0.5
+toInt :: Double -> BB.Builder
+toInt x = BB.intDec (floor (clamp x ** recip 2.2 * 255 + 0.5)) <> BB.char8 ' '
...
   withFile "image.ppm" WriteMode $ \hdl -> do
-        hPrintf hdl "P3\n%d %d\n%d\n" w h (255::Int)
-        for_ img \(Vec r g b) -> do
-          hPrintf hdl "%d %d %d " (toInt r) (toInt g) (toInt b)
+        BB.hPutBuilder hdl $
+          BB.string8 "P3\n" <>
+          BB.intDec w <> BB.char8 ' ' <> BB.intDec h <> BB.char8 '\n' <>
+          BB.intDec 255 <> BB.char8 '\n' <>
+          (mconcat $ fmap (\(Vec r g b) -> toInt r <> toInt g <> toInt b) img)
```


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+          BB.string8 "P3\n" <>
+          BB.intDec w <> BB.char8 ' ' <> BB.intDec h <> BB.char8 '\n' <>
+          BB.intDec 255 <> BB.char8 '\n' <>
+          (mconcat $ fmap (\(Vec r g b) -> toInt r <> toInt g <> toInt b) img)
```


Strings are slow and the code was even using a slow conversion path to strings.

Use `LLVM` backend (1.87×)

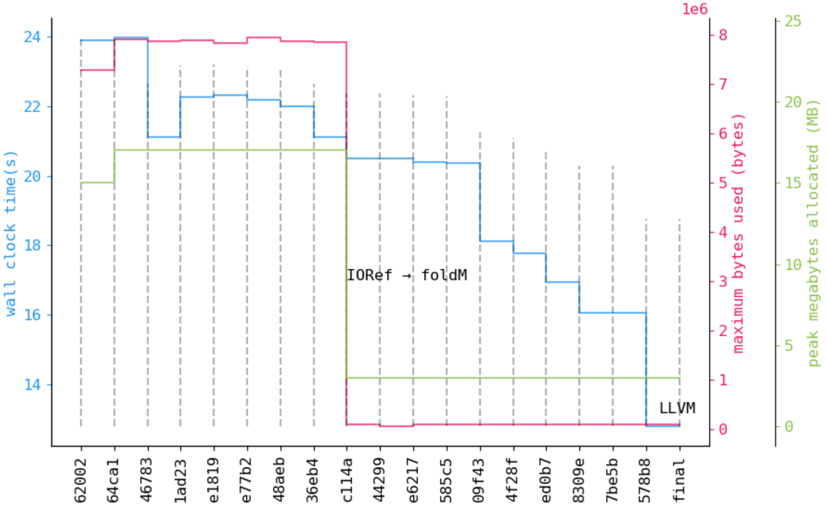
```
+package smallpt-opt
+  ghc-options: -fllvm
```


Use LLVM backend (1.87×)

+package smallpt-opt
+ ghc-options: -fllvm

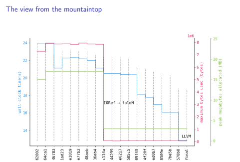
The LLVM backend can pick up assembly level optimizations that GHC has missed. Some types of code runs worse with LLVM, but since this code is number crunching heavy, this does well.

The view from the mountaintop



2020-11-04

└─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.

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- Haskell can be fast, given some sensitivity to performance.
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