

Optimizing smallpt

Davean Scies, Siddharth Bhat

Haskell Exchange

November 4th, 2020

2020-11-02

Optimizing smallpt

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What is smallpt anyway?

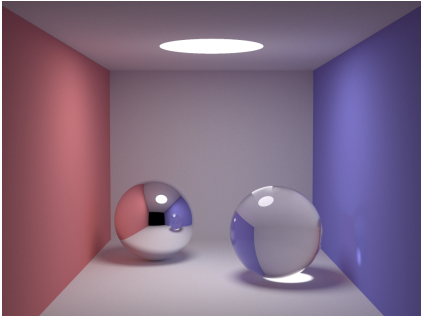
Optimizing smallpt

What is `smallpt` anyway?

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└ What is smallpt anyway?

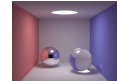
What is smallpt anyway?



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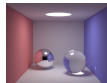
What is smallpt anyway?



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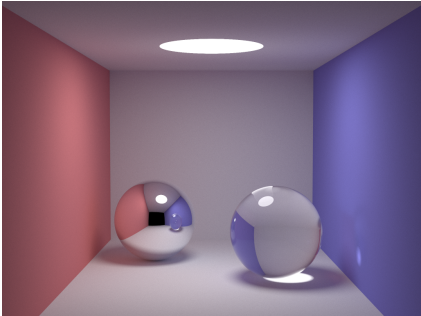
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What is smallest anyway?



- ▶ 100 LoC C demo of a raytracer

What is smallpt anyway?

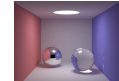


- ▶ 100 LoC C demo of a raytracer
- ▶ Perfect for an optimization case study

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Optimizing smallpt

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 ...
};
```

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What is smallpt anyway?

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```
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){
```

}

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└─What is smallpt anyway?

What is smallest anyway?

```
var smallest = Math.min(10, 100, 1000, 10000, 100000, 1000000);
```

What is smallpt anyway?

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

radiance

radiance

radiance

```

    radiance      radiance
    radiance      radiance
}

```

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└ What is smallpt anyway?

What is smallest anyway?

```
var radiance[green] Ray(r, cos theta, unsigned short *B);
```

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
    }
```

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What is smallpt anyway?

```
What is smallpt anyway?

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

    if ( /* */ ) if ( /* */ ) else
    if ( /* */ ){

        radiance
        radiance

    } else if ( /* */
        radiance
        )
        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
}
```

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What is smallpt anyway?

```
What is smallpt anyway?

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

    Vec w=vec(0.0f,0.0f,0.0f);
    if ( ) if ( ) else
    if ( ) if ( )
    } else if ( )
    }
    if ((cos2t=1-nnt*nnt*(1-ddn*ddn))<0)
    }
    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);
}
```

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What is smallpt anyway?

```
What is smallpt anyway?
For 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
        ...
        ...
        ...
        ...
        ...
        ...
        rad <- radiance (Ray x d') depth' xi
        return $ e `addv` (f `mulv` rad)
      SPEC -> do
        ...
        ...
        rad <- radiance (Ray x d') depth' xi
        ...
      REFR -> do
        ...
        ...
        ...
        ...
        ...
        ...
        if ...
        then do
          rad <- radiance reflRay depth' xi
          ...
          ...
          ...
          ...
          ...
```

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Initial Haskell Code (1×)

```
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
        ...
        ...
        ...
        ...
        ...
        ...
        rad <- radiance (Ray x d') depth' xi
        return $ e `addv` (f `mulv` rad)
      SPEC -> do
        ...
        ...
        rad <- radiance (Ray x d') depth' xi
        ...
      REFR -> do
        ...
        ...
        ...
        ...
        ...
        ...
        if ...
        then do
          rad <- radiance reflRay depth' xi
          ...
          ...
          ...
          ...
          ...
```

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
    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
              return $ e `addv` (f `mulv` rad)
            else do
              let tdir = norm $ (d`mulvs`nnt `subv` (n`mulvs`(((if into then 1 else -1)*(ddn*nnt+sqrt cos2t))))
                  a=nt-nc
                  b=nt+nc

```

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- Initial Haskell Code (1x)

[illegible]

Restrict export list to 'main' (1.13x)

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

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Restrict export list to 'main' (1.13x)

```
Restrict export list to 'main' (1.13x)

-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
```

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

```
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
```

This optimization removes indirection and laziness.

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

```
+{-# 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
```

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

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

+{-# 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 (1.08x)

```
-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
```

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Change from maximum on a list to max (1.08x)

```
-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

Convert erand48 to pure Haskell (1.09x)

```
-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 (1.09x)

```
-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)
```

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Change erand48 to IORefU (1.13×)

```
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)
```

This just removes yet one more layer of indirection, but on a fairly hot function this time.

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
```

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Rewrite the remaining IORef into a foldM (1.17×)

```
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@@ -161,8 +161,7 @@ smallpt w h nsamps = do
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    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
```

This removes another source of mutability, and potentially indirection. This use of an IORef wasn't very Haskellly, so unlike erand48 where the IORef was in a way appropriate, it made more sense to just remove this one.

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

```
-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
```

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

```
--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
```

Theres a few things going on here. First we stop being in IO and create a new STRefU for each Y row. This is slightly more allocation but breaks the dependency between y rows which would be useful if parallel. Second remove the vector, and instead directly accumulate into the result. Third, since we're generating results directly, we just produce a list, and don't bother with the 'i' variable placement, which means we want to reorder which y rows we generate first. So we generate them in the reverse order (but this does potentially change edge cases and parameter validation should be added to cover). This notably removes a decent number of lines of code and might even be clearer.

Set everything in smallpt to be strict (1.17x)

```
- 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 = ...
```

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+ 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
+ !dx = if r1<1 then sqrt r1-1 else 1-sqrt(2-r1)
+ !r2 <- (2*) `fmap` erand48 xi
+ !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
```

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

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)
```

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Reduce to only effectful strictnesses (1.17×)

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
- !r2 <- (2*) `fmap` erand48 xi
+ r1 <- (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)
```

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

Remove Maybe from intersect(s) (1.32x)

```
-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
```

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Remove Maybe from intersect(s) (1.32x)

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.

```
Remove Maybe from intersect(s) (1.32x)

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 --Right
-  ...

+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
+...
```

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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 ; a = arcos ; (.*) = mulvs ; v = Vec in
  [ s 1e5 (v (1e5+1) 40.8 81.6)    a (v 0.75 0.25 0.25) DIFF --Left
  , s 1e5 (v (-1e5+99) 40.8 81.6)  a (v 0.25 0.25 0.75) DIFF --Right
  ...

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

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.

Marking intersects f parameters strict (1.41x)

```
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)
```

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Marking intersects f parameters strict (1.41x)

Marking intersects' f parameters strict. Again, its clear these will get used.

```
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 (1.49x)

```
- 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)
+         !x0=4.0e2
```

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Strategic application of strictness (1.49x)

Here we go through the program and apply some considered strictness to it. Forcing computation we don't need to do, or often forcing it to far before we need it is a loss. When we put a bang pattern in, GHC doesn't move it so we have to hand float it to an appropriate location.



Use LLVM backend (1.87×)

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

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└─ Use LLVM backend (1.87×)

```
Use LLVM backend (1.87×)  
  
+packages: .  
+  
+package smallpt-opt  
+ ghc-options: -fllvm
```

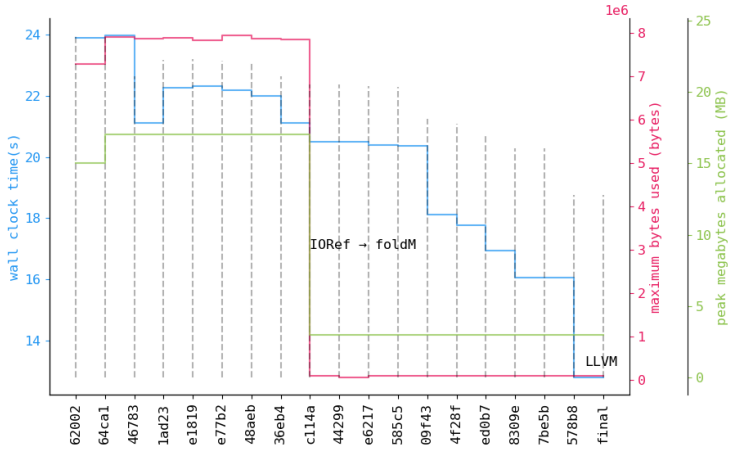
The LLVM backend can pick up assembly level optimizations that GHC has missed. Some types of code runs worse with LLVM, but since this code is number crunching heavy, this does well.

The view from the mountaintop

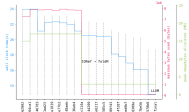
Optimizing smallpt

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The view from the mountaintop



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.

Takeaways

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