

Optimizing smallpt

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Haskell Exchange

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What is smallpt anyway?

2020-11-05

What is smallpt anyway?

- 1. **S**
- 2. Perfect for an optimization case study.
- 3. Plan: Quick walk through Haskell code, end up at C++ (clang++) performance.

What is smallpt anyway?

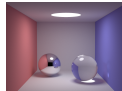


- ▶ 99 LoC C++: **small** path tracer.
- ▶ Ported to many languages, including Haskell! (Thanks to Vo Minh Thu/[noteed](#)).
- ▶ Start from [noteed](#)'s original source; SHA the output image from the Haskell source for baseline.

Optimizing smallpt

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What is smallpt anyway?



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- ▶ Ported to many languages, including Haskell! (Thanks to Vo Minh Thu/[noteed](#)).
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1. **S**
2. Perfect for an optimization case study.
3. Plan: Quick walk through Haskell code, end up at C++ (`clang++`) performance.

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 ...
};
```

Optimizing smallpt

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What is smallpt anyway?

1. S
2. Has geometric primitives: vectors, spheres, materials
3. Entirely number-based, no real data structure

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 radi; // 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?

1. **S**
2. Most of the compute cost is spent in the function that traces rays.
3. is called radiance

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?

1. **S**
2. Recursively calls itself a bunch of times



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  
}
```

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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  
    } else if ( )  
        radiance  
  
    if ( )  
        radiance  
  
        radiance  
        radiance  
}
```

1. S
2. Recursion is guarded by a lot of 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 ( ){
```

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

1. S
2. The control flow and computation is very numeric in nature

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 (erand48(Xi) ) else  
if ( ) {  
    erand48(Xi)    erand48(Xi)
```

```
    radiance  
} else if ( )  
    radiance
```

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

```
    erand48(Xi)  
    radiance  
    radiance  
}
```

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What is smallpt anyway?

1. S
2. We use erand48 for randomness

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 (erand48(Xi) ) else  
if ( ) {  
    erand48(Xi)    erand48(Xi)  
    radiance  
} else if ( )  
    radiance  
if ((cos2t=1-nnt*nnt*(1-ddn*ddn))<0)  
    radiance  
    erand48(Xi)  
    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?

1. S
2. The full code continues to be more of the same

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: 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 - BRANCHING
    DIFF -> do
      r1 <- ((2*pi)*) `fmap` erand48 xi -- RNG
```

```
      radiance
```

```
    SPEC -> do
```

```
      rad <- radiance -- RECURSION
```

```
    REFR -> do
```

```
      if
      then do
        rad <- radiance
      ...
```

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Initial Haskell Code: radiance (1×)

1. S
2. the original source has the same computation in haskell

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```
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radiance ray@(Ray o d) depth xi = case intersects ray of
  (Nothing,_) -> return zerov
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```

```
  continue f = case refl of - BRANCHING
    DIFF -> do
```

```
    radiance
    SPEC -> do
      rad <- radiance -- RECURSION
    REFR -> do
```

```
      if
      then do
        rad <- radiance
```

Initial Haskell Code: Data structures

```
data Vec = Vec {-# UNPACK #-} !Double {-# UNPACK #-} !Double {-# UNPACK #-} !Double
```

```
cross :: Vec -> Vec -> Vec
(.*) :: Vec -> Double -> Vec
infixl 7 .*
len :: Vec -> Double
norm :: Vec -> Vec
norm v = v .* recip (len v)
dot :: Vec -> Vec -> Double
maxv :: Vec -> Double
```

```
data Ray = Ray Vec 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
```

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Initial Haskell Code: Data structures

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```
data Vec = Vec {-# UNPACK #-} !Double {-# UNPACK #-} !Double {-# UNPACK #-} !Double
cross :: Vec -> Vec -> Vec
(.*) :: Vec -> Double -> Vec
infixl 7 .*
len :: Vec -> Double
norm :: Vec -> Vec
norm v = v .* recip (len v)
dot :: Vec -> Vec -> Double
maxv :: Vec -> Double

data Ray = Ray Vec 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
```

1. S
2. We implement the same data structures in Haskell
3. Note that Ray, Sphere not having unpack

Initial Haskell Code: scene data

```
spheres :: [Sphere]
spheres =
  [ Sphere 1e5 (Vec (1e5+1) 40.8 81.6) 0 (Vec 0.75 0.25 0.25) DIFF --Left
  , Sphere 1e5 (Vec (99-1e5) 40.8 81.6) 0 (Vec 0.25 0.25 0.75) DIFF --Rght
  , Sphere 1e5 (Vec 50 40.8 1e5) 0 0.75 DIFF --Back
  , Sphere 1e5 (Vec 50 40.8 (170-1e5)) 0 0 DIFF --Frnt
  , Sphere 1e5 (Vec 50 1e5 81.6) 0 0.75 DIFF --Botm
  , Sphere 1e5 (Vec 50 (81.6-1e5) 81.6) 0 0.75 DIFF --Top
  , Sphere 16.5 (Vec 27 16.5 47) 0 0.999 SPEC --Mirr
  , Sphere 16.5 (Vec 73 16.5 78) 0 0.999 REFR --Glas
  , Sphere 600 (Vec 50 681.33 81.6) 12 0 DIFF] --Lite
```

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Initial Haskell Code: scene data

```
Initial Haskell Code: scene data

spheres :: [Sphere]
spheres =
  [ Sphere 1e5 (Vec (1e5+1) 40.8 81.6) 0 (Vec 0.75 0.25 0.25) DIFF --Left
  , Sphere 1e5 (Vec (99-1e5) 40.8 81.6) 0 (Vec 0.25 0.25 0.75) DIFF --Rght
  , Sphere 1e5 (Vec 50 40.8 1e5) 0 0.75 DIFF --Back
  , Sphere 1e5 (Vec 50 40.8 (170-1e5)) 0 0 DIFF --Frnt
  , Sphere 1e5 (Vec 50 1e5 81.6) 0 0.75 DIFF --Botm
  , Sphere 1e5 (Vec 50 (81.6-1e5) 81.6) 0 0.75 DIFF --Top
  , Sphere 16.5 (Vec 27 16.5 47) 0 0.999 SPEC --Mirr
  , Sphere 16.5 (Vec 73 16.5 78) 0 0.999 REFR --Glas
  , Sphere 600 (Vec 50 681.33 81.6) 12 0 DIFF] --Lite
```

1. S
2. this list will be walked many times, as it contains our scene information.

Initial Haskell code: Sphere intersection

```
intersect :: Ray -> Sphere -> Maybe Double
intersect (Ray o d) (Sphere r p _e _c _refl) =
  if det<0 then Nothing else f (b-sdet) (b+sdet)
  where op = p - o -- Numeric
        eps = 1e-4
        b = dot op d
        det = b*b - dot op op + r*r -- Numeric
        sdet = sqrt det
        f a s = if a>eps then Just a else if s>eps then Just s else Nothing
intersects :: Ray -> (Maybe Double, Sphere)
intersects ray = (k, s)
  where (k,s) = foldl' f (Nothing,undefined) spheres -- Spheres iterated over
        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)
```

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Initial Haskell code: Sphere intersection

```
intersect :: Ray -> Sphere -> Maybe Double
intersect (Ray o d) (Sphere r p _e _c _refl) =
  if det<0 then Nothing else f (b-sdet) (b+sdet)
  where op = p - o -- Numeric
        eps = 1e-4
        b = dot op d
        det = b*b - dot op op + r*r -- Numeric
        sdet = sqrt det
        f a s = if a>eps then Just a else if s>eps then Just s else Nothing
intersects :: Ray -> (Maybe Double, Sphere)
intersects ray = (k, s)
  where (k,s) = foldl' f (Nothing,undefined) spheres -- Spheres iterated over
        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)
```

1. S
2. Responsible for figuring out what the ray hits.
3. We iterate over the list of spheres.
4. Once again, numeric heavy.
5. Use a Maybe to indicate whether we've found an answer or not.

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
    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)))
                into = n`dot`nl > 0
                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
            then do
              rad <- radiance reflRay depth' xi
            ...
```

Optimizing smallpt

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Initial Haskell Code: radiance (1×)

- 1. S
- 2. Branch heavy
- 3. Recursive
- 4. Uses an RNG



Initial Haskell Code: Entry point (1×)

```
smallpt :: Int -> Int -> Int -> IO ()
```

```
smallpt w h nsamps = do
```

```
...
c <- VM.replicate (w * h) 0
allocaArray 3 \xi -> -- Create mutable memory
  flip mapM_ [0..h-1] $ \y -> do -- Loop
    writeXi xi y
    for_ [0..w-1] \x -> do -- Loop
      let i = (h-y-1) * w + x
      for_ [0..1] \sy -> do -- Loop
        for_ [0..1] \sx -> do -- Loop
          r <- newIORef 0 -- Create mutable memory
          for_ [0..samps-1] \s -> do -- Loops, Loops
            r1 <- (2*) <$> erand48 xi
            ...
            rad <- radiance (Ray (org+d.*140) (norm d)) 0 xi -- Crunch
            ...
            modifyIORef r (+ rad .* recip (fromIntegral samps)) -- Write
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 -- Write
...
```

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Initial Haskell Code: Entry point (1×)

```
Initial Haskell Code: Entry point (1×)
smallpt :: Int -> Int -> Int -> IO ()
smallpt w h nsamps = do
  ...
  d <- VM.replicate (w * h) 0
  allocaArray 3 \xi -> -- Create mutable memory
  flip mapM_ [0..h-1] $ \y -> do -- Loop
    writeXi xi y
    for_ [0..w-1] \x -> do -- Loop
      let i = (h-y-1) * w + x
      for_ [0..1] \sy -> do -- Loop
        for_ [0..1] \sx -> do -- Loop
          r <- newIORef 0 -- Create mutable memory
          for_ [0..samps-1] \s -> do -- Loops, Loops
            r1 <- (2*) <$> erand48 xi
            ...
            rad <- radiance (Ray (org+d.*140) (norm d)) 0 xi -- Crunch
            ...
            modifyIORef r (+ rad .* recip (fromIntegral samps)) -- Write
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 -- Write
...
```

1. S
2. Uses mutability
3. Performs number crunchy loops
4. Finally, writes results out

Initial Haskell Code: File I/O (1×)

```
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)
```

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Initial Haskell Code: File I/O (1×)

```
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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: RNG (1×)

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

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Initial Haskell Code: RNG (1×)

Initial Haskell Code: RNG (1×)

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

1. **S**
2. We use the RNG to decide randomly in which direction to send rays
3. Point out the use of foreign CCall.

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
```

1. **S**
2. The very first thing to do is to let the compiler actually optimize.
3. Compiler can't know how exported functions are used.
4. Export lists not just about encapsulation.

Restrict export list to 'main' (1.13x)

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

- ▶ Exported functions could be used by something unknown.
- ▶ Original versions must be available.

Optimizing smallpt

2020-11-05

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

Restrict export list to 'main' (1.13x)

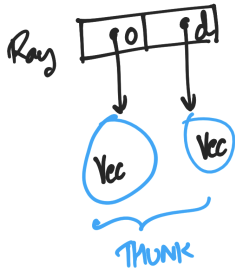
```
-module Main where
+module Main (main) where
```

- ▶ Exported functions could be used by something unknown
- ▶ Original versions must be available.

1. **S**
2. The very first thing to do is to let the compiler actually optimize.
3. Compiler can't know how exported functions are used.
4. Export lists not just about encapsulation.

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

```
data Ray = Ray Vec Vec
```



- ▶ By default, all fields are *thunks* to rest of computation
- ▶ Pure, allow equational reasoning.

Optimizing smallpt

2020-11-05

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

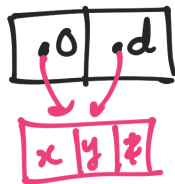
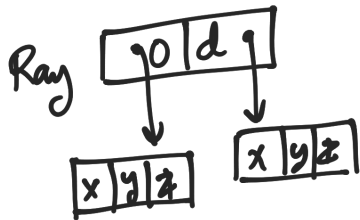
data Ray = Ray Vec Vec



- ▶ By default, all fields are *thunks* to rest of computation
- ▶ Pure, allow equational reasoning.

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

```
data Ray = Ray !Vec !Vec
```

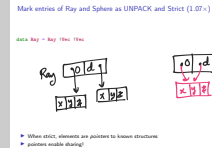


- ▶ When strict, elements are *pointers* to known structures
- ▶ pointers enable sharing!

Optimizing smallpt

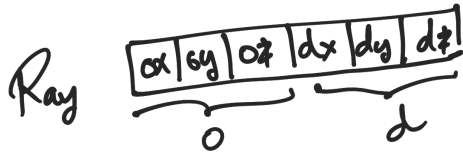
2020-11-05

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



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

```
data Ray = Ray {-# UNPACK #-} !Vec {-# UNPACK #-} !Vec
```



- ▶ When unpacked, elements are *members* of the parent.
- ▶ Larger, but eliminate pointer chasing.

Optimizing smallpt

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

```
data Ray = Ray {-# UNPACK #-} !Vec {-# UNPACK #-} !Vec
```



- ▶ When unpacked, elements are *members* of the parent.
- ▶ Larger, but eliminate pointer chasing.

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

```
data Vec = Vec {-# UNPACK #-} !Double
           {-# UNPACK #-} !Double
           {-# UNPACK #-} !Double
```

```
-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
```

```
struct Vec { double x, y, z; }
struct Ray { std::function<Vec()> v; std::function<Vec()> w; };
struct RayUnpack { double xv, yv, int zv;
                  double xw, yw, zw; };
```

Optimizing smallpt

2020-11-05

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

```
data Vec = Vec {-# UNPACK #-} !Double
              {-# UNPACK #-} !Double
              {-# UNPACK #-} !Double
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
struct Vec { double x, y, z; }
struct Ray { std::function<Vec()> v; std::function<Vec()> w; };
struct RayUnpack { double xv, yv, int zv;
                  double xw, yw, zw; };
```

1. D
2. Strictness in the arguments means that they're evaluated when instantiated, not when demanded.
3. Unpacking removes indirection from doing a memory lookup for components.
4. Means we have to copy everything into the data structure that it is unpacked into.
5. We don't unpack ray (Lots of calculations on its components, want those to fuse)
6. Unpack Sphere - its static

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
```

Optimizing smallpt

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

1. D
2. UnboxedSums are recent
3. UnboxedSums are very unpleasant
4. We're using an older trick to fake the unboxing here instead.
5. In this case it isn't much of a win, but it illustrates the technique.

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)

    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
...
    if depth'>5
    then do
        er <- erand48 xi
+    let !pr = maxv c
```

Optimizing smallpt

2020-11-05

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

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

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    depth' = depth + 1
    continue f = case refl of
        DIFF -> do
...
    if depth'>5
    then do
        er <- erand48 xi
+    let !pr = maxv c
```

1. D
2. finicky optimization.
3. Minimal usage of this function.
4. GHC does not evaluate at compile time, only has RULES

Convert erand48 to pure Haskell (1.09×)

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

```
+erand48 :: IRef Word64 -> IO Double
+erand48 !t = do -- | Some number crunching thing.
+  r <- readIORef t
+  let x' = 0x5deece66d * r + 0xb
+      d_word = 0x3ff0000000000000 .|. ((x' .&. 0xffffffff) `unsafeShiftL` 4)
+      d = castWord64ToDouble d_word - 1.0
+  writeIORef t x'
+  pure d
...
-radiance :: Ray -> CInt -> Ptr CUSHort -> IO Vec
+radiance :: Ray -> Int -> IRef Word64 -> IO Vec -- IRef with state
radiance ray@(Ray o d) depth xi = case intersects ray of
  ...
  c <- VM.replicate (w * h) zeroV
-  allocArray 3 $ \xi -> -- Old RNG state
-    flip mapM_ [0..h-1] $ \y -> do
+  xi <- newIORef 0 -- New RNG state
+  flip mapM_ [0..h-1] $ \y -> do
    writeXi xi y
```

Optimizing smallpt

2020-11-05

Convert erand48 to pure Haskell (1.09x)

[illegible]

1. **S**
2. The entire premise of this talk is that Haskell can be as fast as C.
3. We're opening the black box of what `erand48` does to GHC
4. Further any impedance mismatch, such as FFI almost universally has to have, carries some bookkeeping overhead.
5. If our Haskell code was as fast as the C code moving the code into Haskell would be a win, if it was slightly slower it could still be a win.
6. Often considering your Haskell code's performance is a better option and easier than reimplementing something in C.
7. As is the way with optimizations, this is not universally true.

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
+erand48 :: Erand48 Double
+...
-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'
```

Optimizing smallpt

2020-11-05

Remove mutability: Erand48 Monad

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+instance Applicative Erand48 where
+instance Monad Erand48 where
+runWithErand48 :: Int -> Erand48 a -> a
+erand48 :: Erand48 Double
+...
-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*) <$> erand48 xi
+  r2 <- erand48 xi
+  r3 <- erand48 xi
+...
+  when (* rp) <$> radiance reflRay depth' xi
+  when (* tp) <$> radiance (Ray x tdir) depth' xi
+  when (* rp) <$> radiance reflRay depth'
+  when (* tp) <$> radiance (Ray x tdir) depth'
```

1. D
2. All these mutability locations throw in extra RTS code, extra sequencing that blocks the compiler's optimization, and dependency chains.
3. Sometimes we need mutability for performance.
4. SSA is normal to compilers though.
5. We almost start at SSA as a functional language.
6. don't break it when you don't have a good reason.

Removing mutation: eliminate IORef and Data.Vector.Mutable

```
- 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)
+
+ ...
```

Optimizing smallpt

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Removing mutation: eliminate IORef and Data.Vector.Mutable

```
- w <- 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 -> multiWithIORef 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)
+
+ ...
```

1. D

Set everything in smallpt to be strict (1.17x)

```
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
```

Optimizing smallpt

2020-11-05

Set everything in smallpt to be strict (1.17x)

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-   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
+   !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 = ...
...
+   pure $! r + rad .* recip (fromIntegral samps)
+   pure $! ci + Vec (clamp rr) (clamp rg) (clamp rb) .* 0.25
```

Don't senselessly bang everything in sight.

1. D
2. This is not a recommendation, this is a warning.
3. We get a speedup here but it can also regress performance. Some of these bangs are regressions that are hidden.

Why strictness may be bad

```
let foo = let x = error "ERR" in \y -> y
let foo' = let !x = error "ERR" in \y -> y
```

Optimizing smallpt

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Why strictness may be bad

Why strictness may be bad

```
let foo = let x = error "ERR" in \y -> y
let foo' = let !x = error "ERR" in \y -> y
```

1. **S**
2. bangs remove freedom from the compiler
3. bangs force large objects to be evaluated
4. Haskell is awesome because equational reasoning.
5. Bangs are not great with equational reasoning.
6. judiciously use bangs. Too many remove choice from the compiler.

Why strictness may be bad

```
let foo = let x = error "ERR" in \y -> y
let foo' = let !x = error "ERR" in \y -> y

let fooOpt = \y -> y
let foo'Opt = \y -> y  -- ERROR! forcing foo' should give "ERR"
```

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Why strictness may be bad

Why strictness may be bad

```
let foo = let x = error "ERR" in \y -> y
let foo' = let !x = error "ERR" in \y -> y
let fooOpt = \y -> y
let foo'Opt = \y -> y  -- ERROR! forcing foo' should give "ERR"
```

1. **S**
2. bangs remove freedom from the compiler
3. bangs force large objects to be evaluated
4. Haskell is awesome because equational reasoning.
5. Bangs are not great with equational reasoning.
6. judiciously use bangs. Too many remove choice from the compiler.

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)
```

Optimizing smallpt

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└ Reduce to only useful strictnesses in smallpt(1.17×)

```
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*) <$> erand48
- !r2 <- (2*) <$> erand48
+ r1 <- (2*) <$> erand48
+ r2 <- (2*) <$> erand48
...
- !rad <- radiance (Ray (org+d.*140) (norm d)) 0
- !ci <- radiance (Ray (org+d.*140) (norm d)) 0
+ rad <- radiance (Ray (org+d.*140) (norm d)) 0
+ ci <- 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)
```

1. D
2. Bangs force evaluation.
3. The computation might diverge.
4. Thus the compiler can no longer move the computation around or simplify it.
5. Useless work.
6. A little thinking about how the variables are used or looking at core allows us to select which ones we bang selectively.

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
...
```

Optimizing smallpt

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Use strictness strategically in entire project

```
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...
- 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
...
```

1. **D**
2. Sometimes (point out 'intersect') we have to rearrange the code though when we use bangs.
3. Bangs tell the compiler to make more efficient code, but take away the compiler's options in how to do so.
4. Only take away the compiler's liberties when it's using them poorly.
5. Becomes intuitive.

Remove Maybe from intersect(s) (1.32x)

| Old: Use Maybe Double to represent (was-hit?:bool, hit-distance: Double)

| New: use (1/0) to represent not (was-hit?)

-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

...

- 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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```

1. S
2. This is a far more performance critical version of what we saw with 'maximum' vs. 'max'.
3. innermost functions are of critical importance. remove Maybe which significantly reduces the boxing
4. Since a Ray that fails to intersect something can be said to intersect at infinity, Double already actually covers the structure at play
5. This also reduces allocation.

Hand unroll the fold in intersects (1.35x)

```
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 (1.35x)

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+...
```

1. D
2. 'intersects' is very hot
3. Loop unrolling
4. Many compilers do this for us, and there are special versions of it like Duff's Device.
5. Sadly GHC doesn't
6. Can do variants by hand.
7. RULE could handle each one specifically (only exactly that one)?

Custom datatype for intersects parameter passing

Old: Tuple with possibly-unevaluated Double and Sphere

New: Reference to a guaranteed-to-be-evaluated Double and Sphere

```
-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
```

Optimizing smallpt

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Custom datatype for intersects parameter passing

1. D
2. We can optimize data passing.
3. Want: Data strict, but not unpacked.
4. Compiler knows its evaluated but no copying
5. A normal tuple lacks strictness information.
6. An unboxed tuple forces copying
7. Strict Tuple.
8. This exists in libraries of course, but we wanted to illustrate it.

```
Old: Tuple with possibly-unevaluated Double and Sphere  
New: Reference to a guaranteed-to-be-evaluated Double and Sphere  
-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)  
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-   (!t,!Sphere _r p e c refl) -> do  
+   (T t _) | t == 1/0.0 -> return 0  
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    let !x = o + d .* t  
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    !nl = if dot n d < 0 then n else negate n
```

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 -- O(1) concatenation

+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" <> -- efficient builders for ASCII

+ 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)

Optimizing smallpt

2020-11-05

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- 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" <> -- efficient builders for ASCII
+   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)
```

1. D
2. Strings are inefficient
3. 'bytestring' has some efficient writing code, so we just convert to that for a modest gain.

Use LLVM backend (1.87x)

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

Optimizing smallpt

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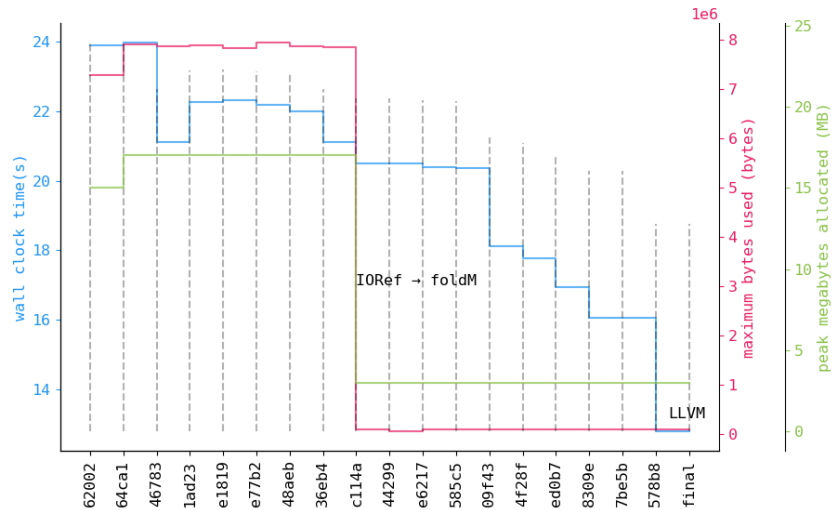
└ Use LLVM backend (1.87x)

Use LLVM backend (1.87x)

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

1. **S**
2. Finally, this particular code is quite numeric heavy.
3. There are optimizations for numeric heavy code we're missing in GHC.
4. LLVM has an extensive library of laws to optimize low level numeric ops.
5. LLVM is too low-level to understand haskell as haskell.
6. LLVM makes decisions with the tacit assumption that the assembly came from a C-like language, which is often to the detriment of a Haskell-like language.
7. In this case, as the code is "fortran-like", LLVM wins.

The view from the mountaintop

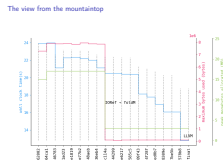


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Optimizing smallpt

The view from the mountaintop

1. D



Avoid CPU ieee754 slow paths

```
intersect :: Ray -> Sphere -> Double
intersect (Ray o d) (Sphere r p _e _c _refl) =
  if det<0
-   then 1/0.0
+   then 1e20
  else
    ...
-   in if a>eps then a else if s>eps then s else 1/0.0
+   in if a>eps then a else if s>eps then s else 1e20

...

radiance :: Ray -> Int -> Erand48 Vec
radiance ray@(Ray o d) depth = case intersects ray of
- (T t _) | t == 1/0.0 -> return 0
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...
```

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+ (T 1e20 _) -> return 0
...
```

1. D
2. We used +Inf to match the Maybeness
3. C++ code set 1e20 s the horizon
4. Mechanical sympathy is important.
5. Know how the CPU (abstractly) executes - slow path / fast path.

Fix differences with C++ version

```
-         if depth>2
+         if depth'>2 -- depth' = depth + 1
...

```

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- └ Fix differences with C++ version

Fix differences with C++ version

```
-         if depth>2
+         if depth>2 -- depth' = depth + 1
...

```

1. **S**
2. Since the sha1 of the output didn't match the C++ version we started investigating.
3. clang++, g++ actually produce different sha1s
4. unincremented depth was being used in one branch, causing us to do more work
5. now confident to say we're doing the same computation as C++

A second view from the mountaintop

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A second view from the mountaintop

A second view from the mountaintop

Takeaways

- ▶ The unrolling in 'intersects' is ugly.
- ▶ (We feel) the maintainability of this code hasn't been significantly harmed.
- ▶ We're faster than clang++ and within 6% of g++
- ▶ Haven't exhausted the optimization opportunities.
- ▶ GHC could learn to do several of these optimizations for us.
- ▶ Others are just good Haskell style.
- ▶ Clean Haskell is often performant Haskell.

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- ▶ The unrolling in 'intersects' is ugly.
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1. D

Raw data

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Raw data

Raw data

Experimental data

- ▶ All test were on an otherwise idle Equinix Metal c3.small.x86 (Intel Xeon E-2278G with 32GiB RAM, Ubuntu 20.04).

2020-11-05

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► All test were on an otherwise idle Equinox Metal c3.small.x86 (Intel Xeon E-22790 with 32GB RAM, Ubuntu 20.04).