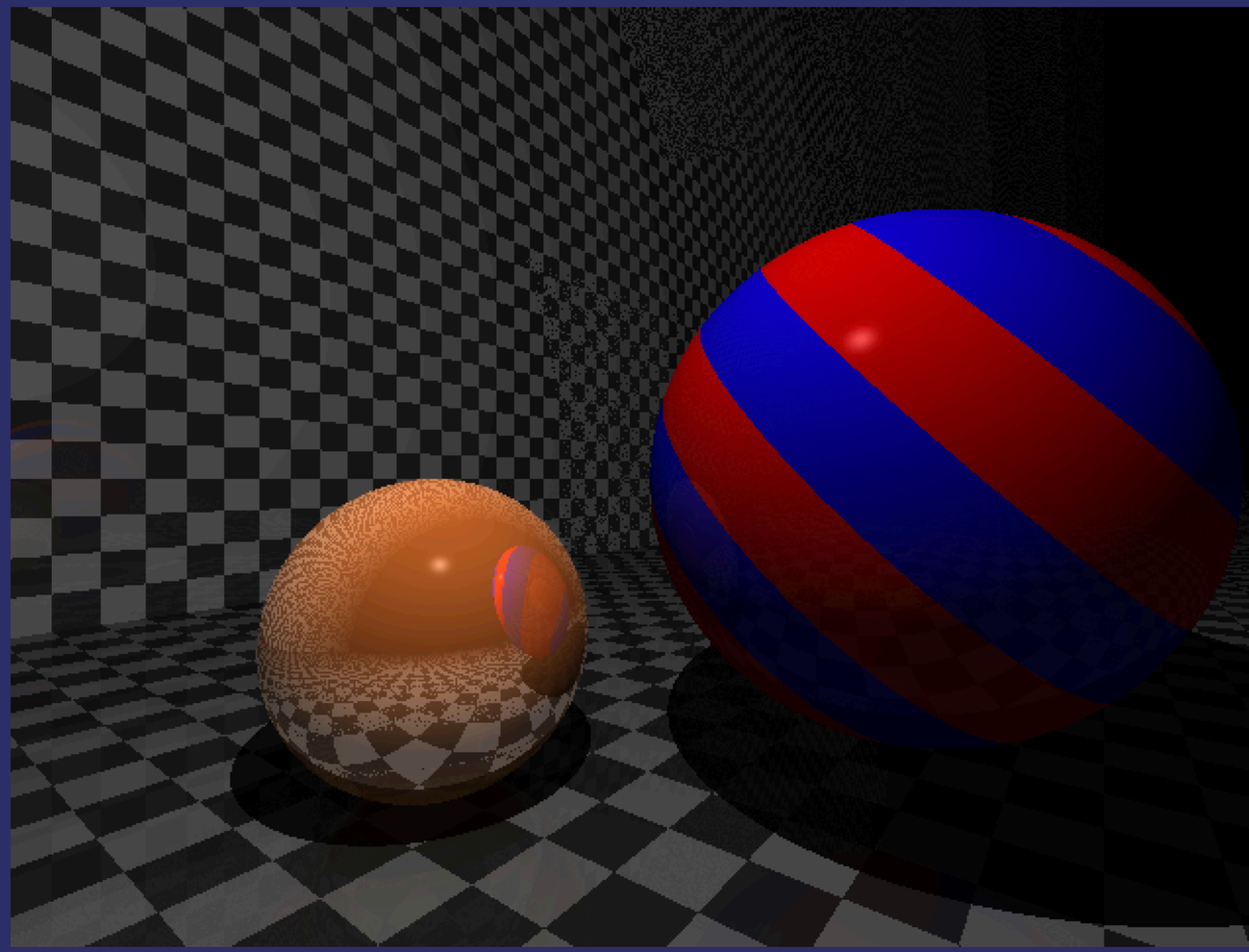
Environmental effects

A ray tracing exercise

BeeScala
Ljubljana - 23 Nov 2019



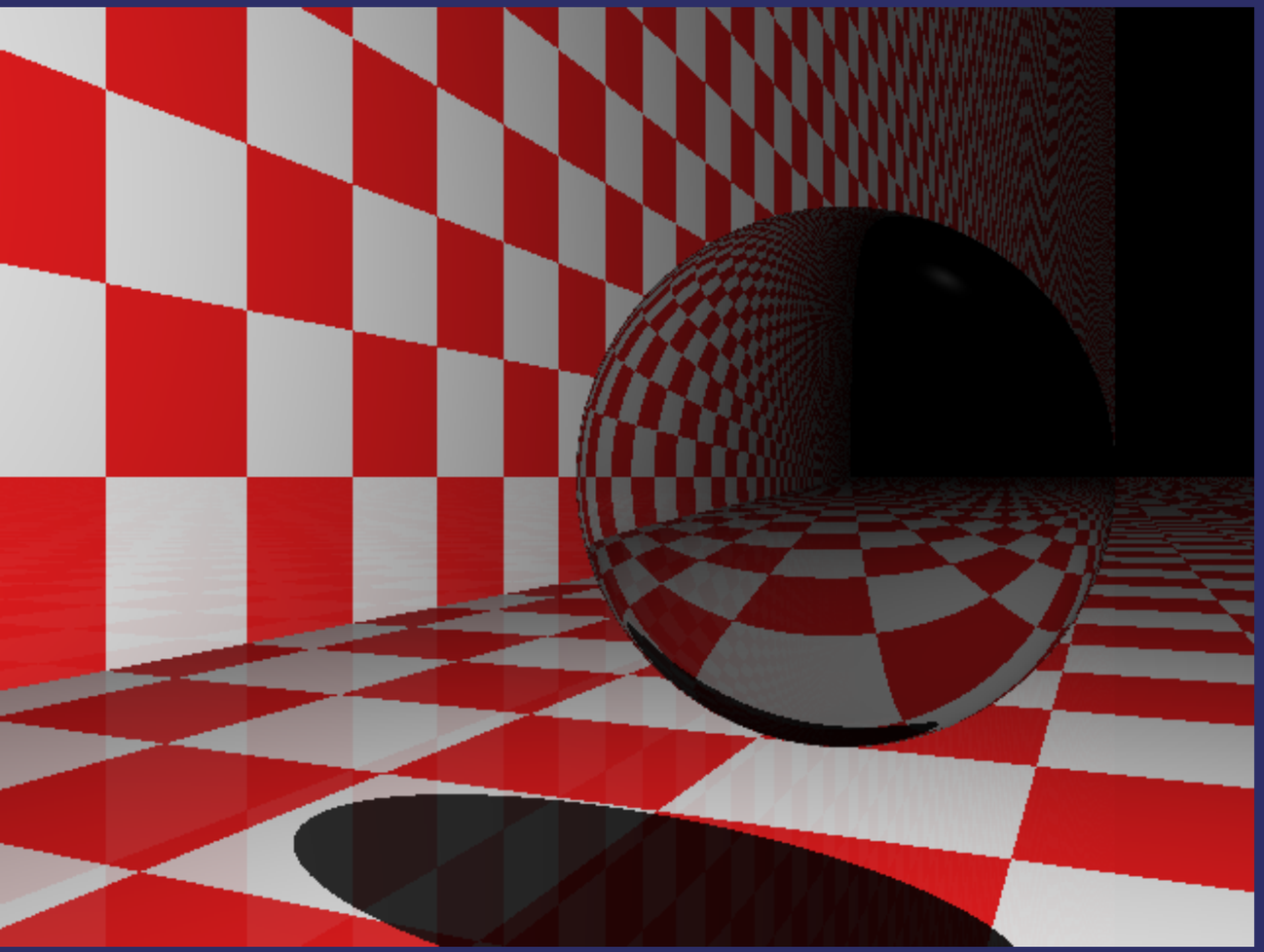
About me

Pierangelo Cecchetto

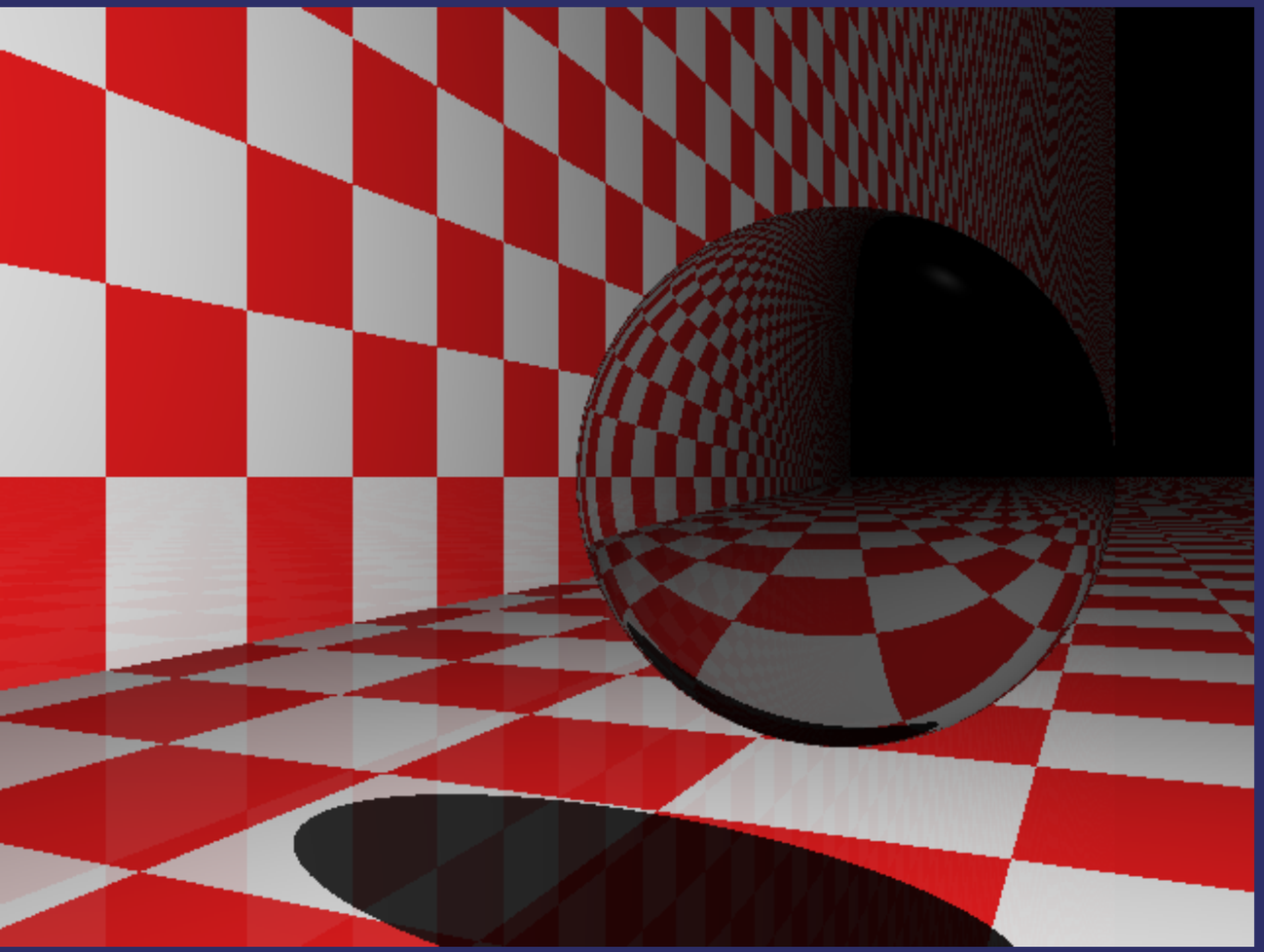
Scala Consultant - Amsterdam

 @pierangelocecc

 https://github.com/pierangeloc



This talk



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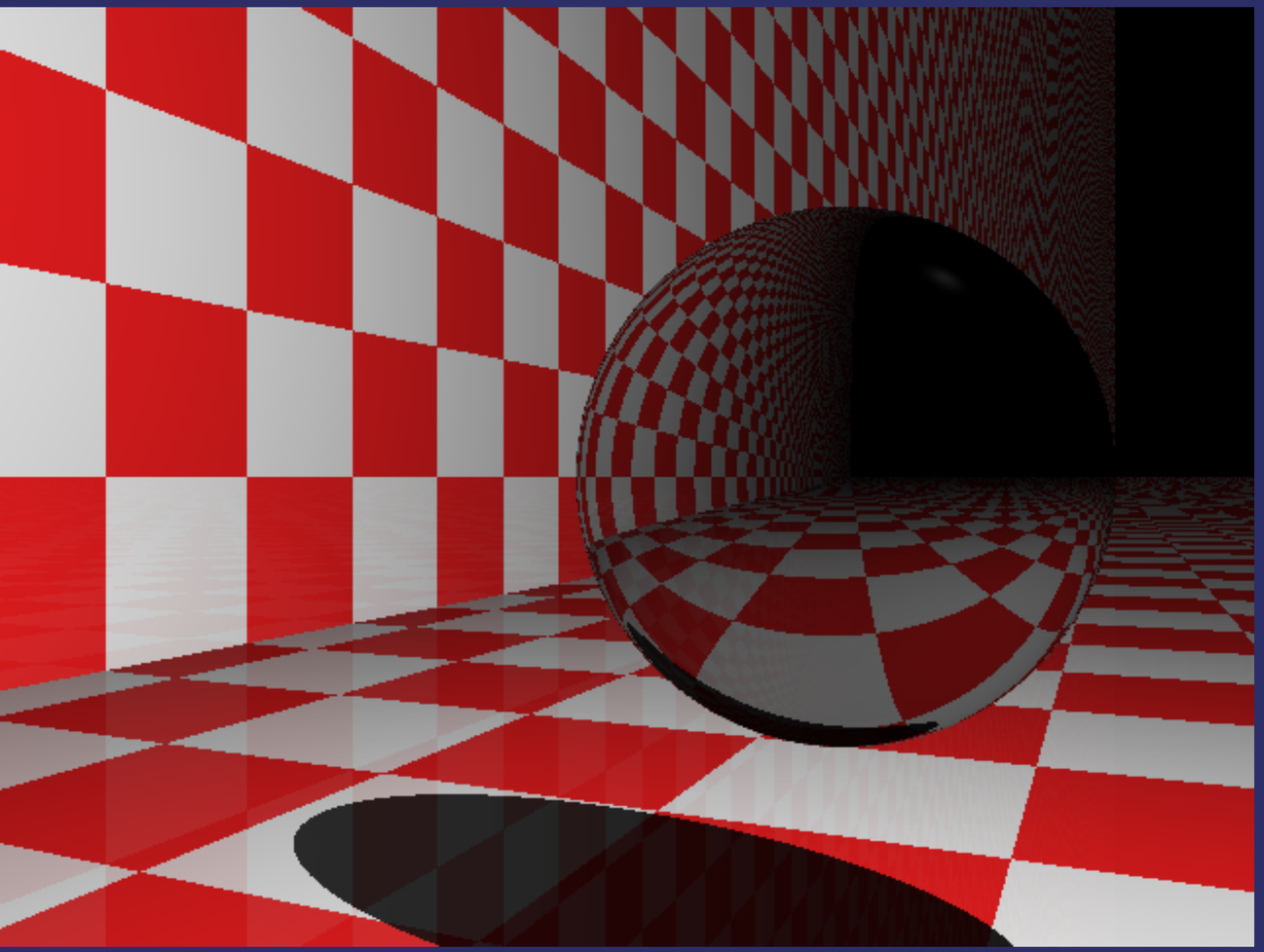

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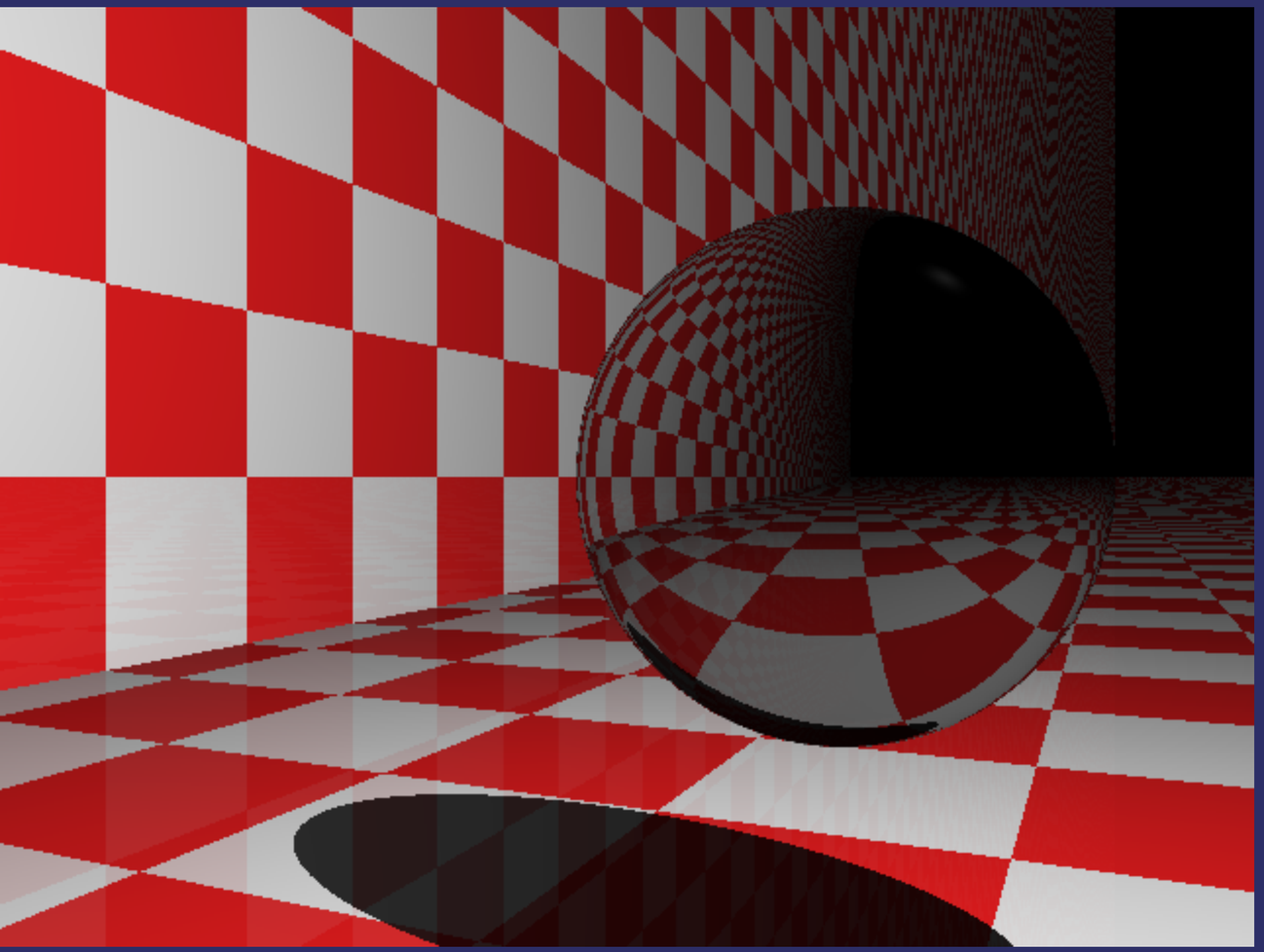

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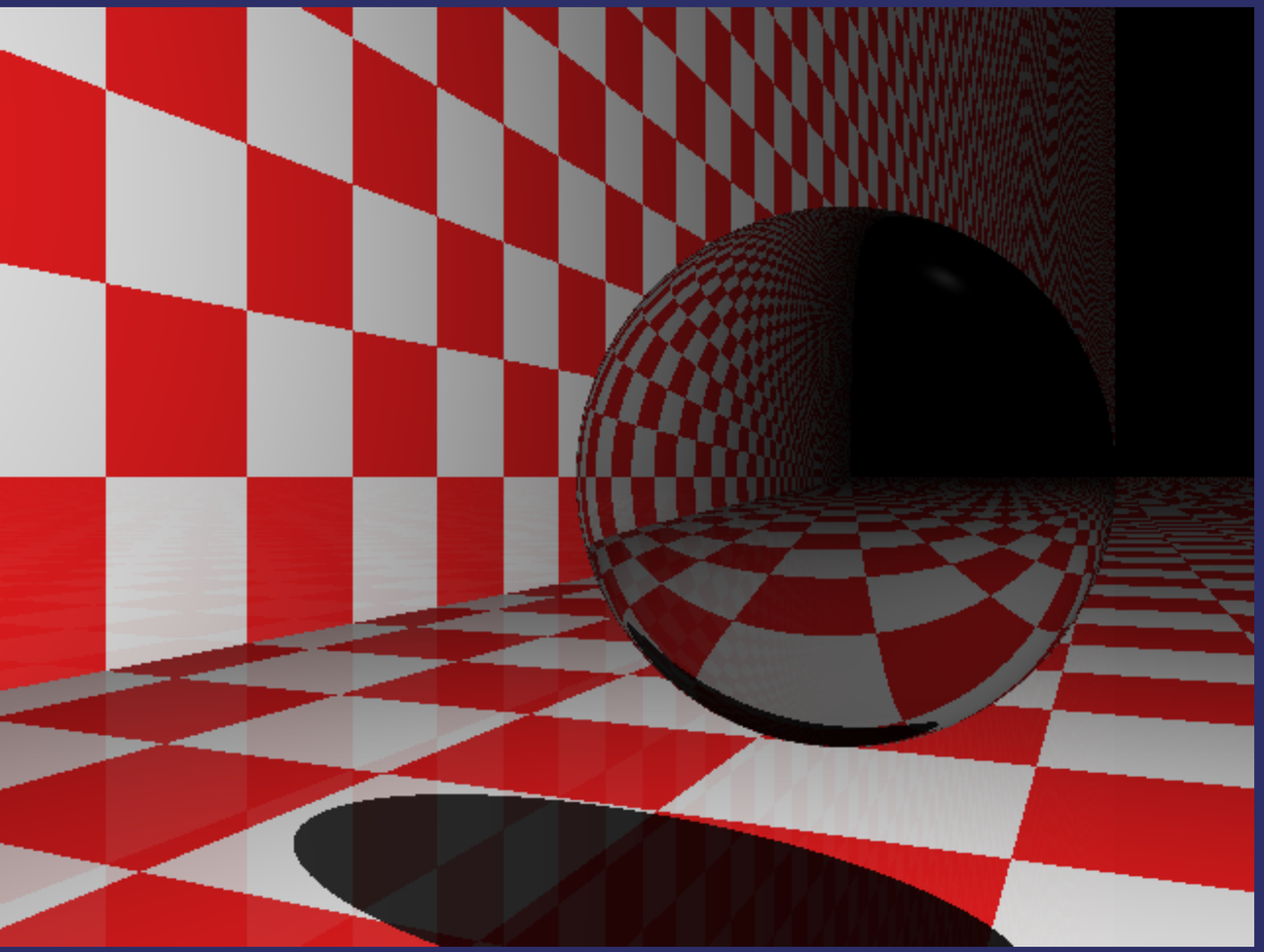

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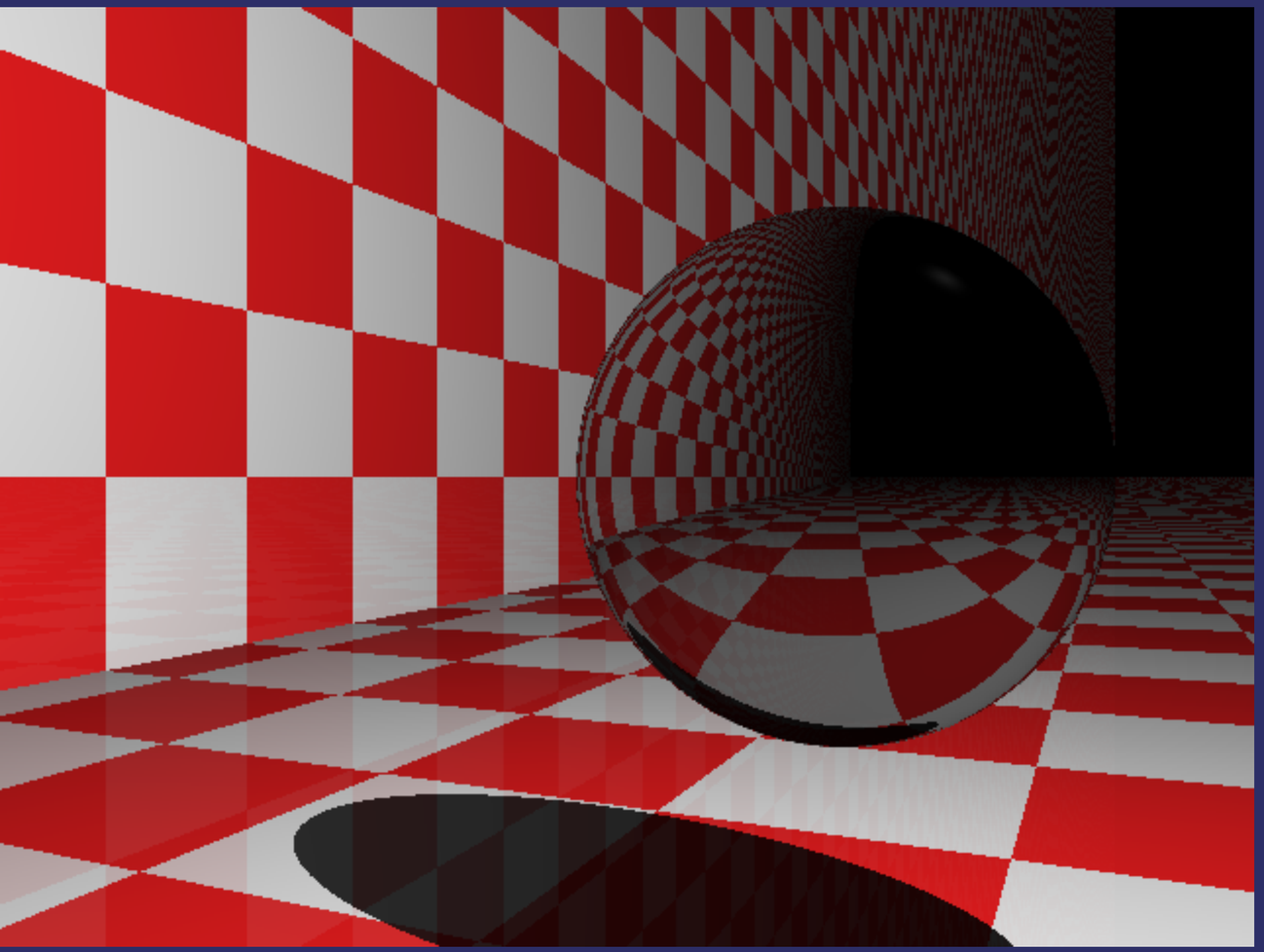

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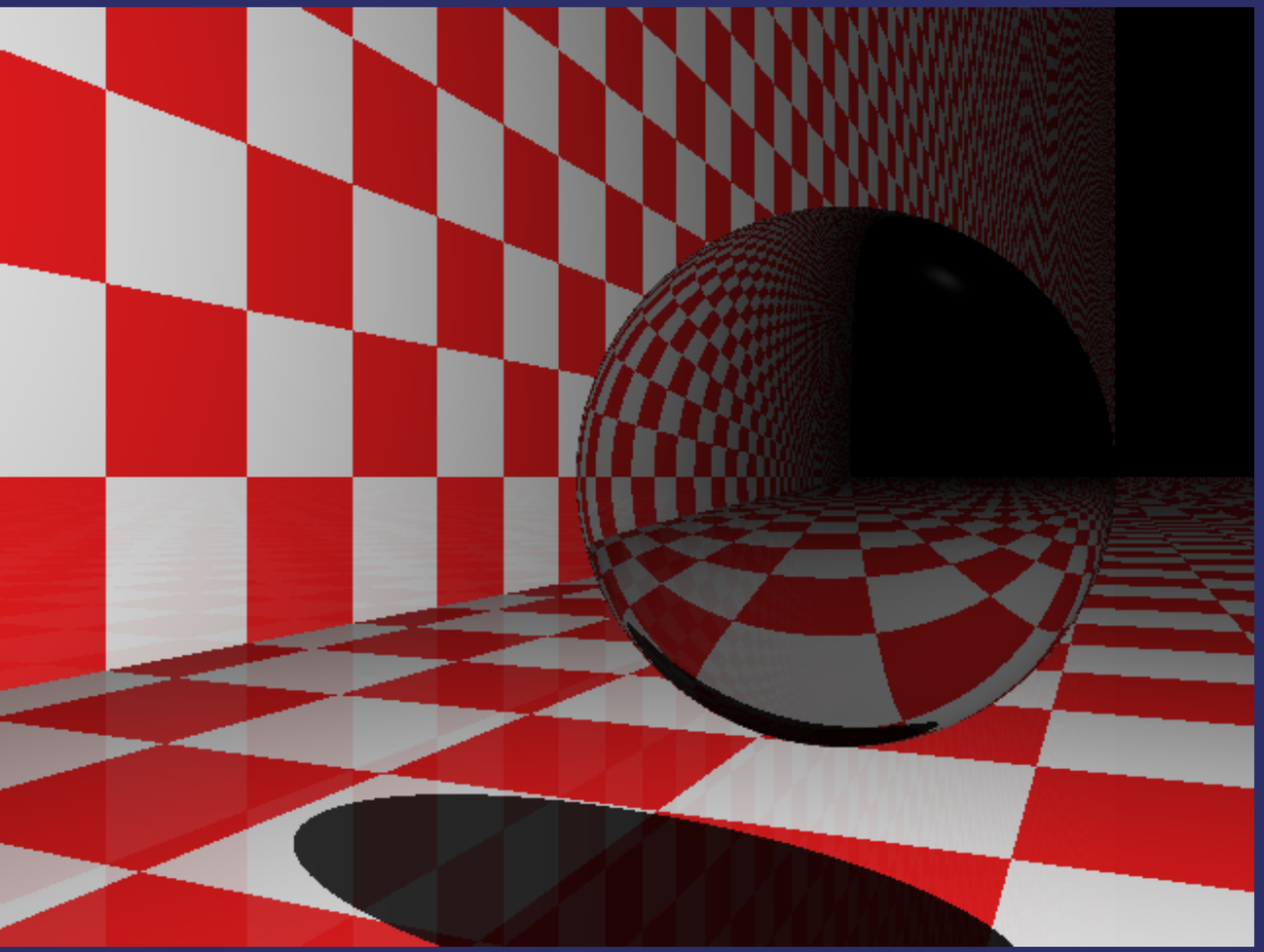

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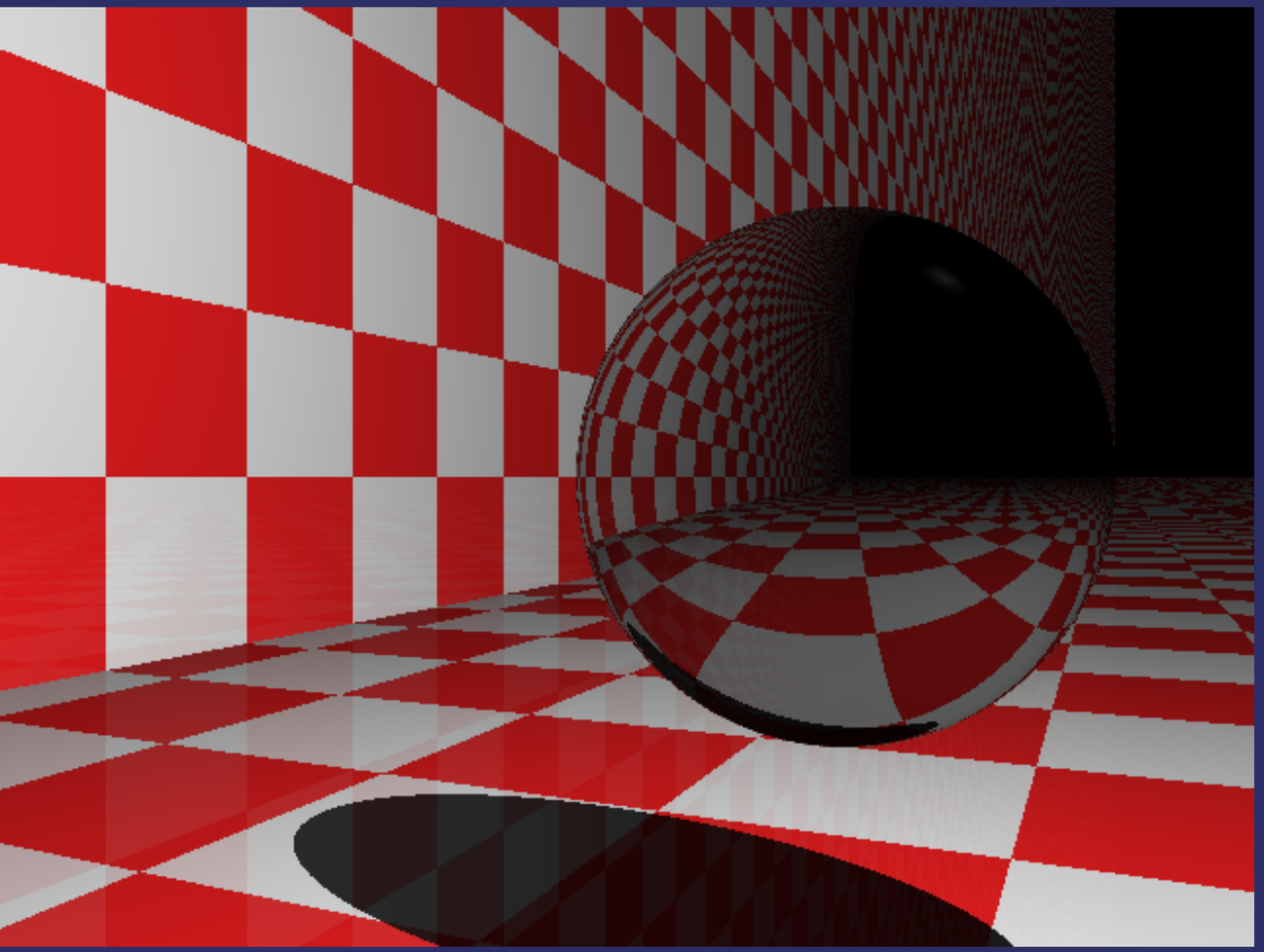

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- → **Will cover**
  - → ZIO environment
  - → Layered computations
  - → Testing
  - → How ray tracing works
- → **Will not cover**
- → Errors, Concurrency, fibers, cancellation, runtime

Agenda

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1. ZIO-101: the bare minimum

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2. Build foundations

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3. Build Ray Tracer components

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5. Wiring things together
6. Improving rendering
7. Show pattern at work

ZIO - 101

Program as values

```
val salutation = console.putStr("Zdravo, ")
val city = console.putStrLn("Ljubljana!!!")

val prg = salutation *> city
salutation.flatMap(_ => city)

// nothing happens!
runtime.unsafeRun(prg)

//>  Zdravo, Ljubljana!!!
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val prg: ZIO[Console, Nothing, Unit] = salutation *> city

ZIO[-R, +E, +A]
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R => IO[Either[E, A]]
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→ Produce `()` as output

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val prg: ZIO[Console, Nothing, Unit] = salutation *> city
val miniRT = new Runtime[Any]{}

// Provide console
val provided = prg.provide(Console.Live)
val provided: ZIO[Any, Nothing, Unit] = prg.provide(Console.Live)

miniRT.unsafeRun(provided)
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Environment introduction/elimination

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// INTRODUCE AN ENVIRONMENT
ZIO.access(f: R => A): ZIO[R, Nothing, A]

ZIO.accessM(f: R => ZIO[R, E, A]): ZIO[R, E, A]

// ELIMINATE AN ENVIRONMENT
val prg: ZIO[Console, Nothing, Unit]
prg.provide(Console.Live): ZIO[Any, Nothing, Unit]
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ZIO - 101

Types at work

```
type IO[+E, +A]    = ZIO[Any, E, A]

type UIO[+A]       = ZIO[Any, Nothing, A]
```

ZIO-101: Module Pattern

Example: A Metrics module (or Algebra)

```
// the module
trait Metrics {
  val metrics: Metrics.Service[Any]
}
object Metrics {
  // the service
  trait Service[R] {
    def inc(label: String): ZIO[R, Nothing, Unit]
  }

  // the accessor
  object > extends Service[Metrics] {
    def inc(label: String): ZIO[Metrics, Nothing, Unit] =
      ZIO.accessM(_.metrics.inc(label))
  }
}
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A Metrics module - Running

```
val prg2:
ZIO[Metrics with Log, Nothing, Unit] =
for {
  _ <- Log.>.info("Hello")
  _ <- Metrics.>.inc("salutation")
  _ <- Log.>.info("BeeScala")
  _ <- Metrics.>.inc("subject")
} yield ()

trait Prometheus extends Metrics {
  val metrics = new Metrics.Service[Any] {
    def inc(label: String): ZIO[Any, Nothing, Unit] =
      ZIO.effectTotal(counter.labels(label).inc(1))
  }
}

miniRT.unsafeRun(
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case class TestMetrics(incCalls: Ref[List[String]])
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}

val test =  for {
  ref <- Ref.make(List[String]())
  _   <- prg2.provide(new Log.Live with Metrics {
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miniRt.unsafeRun(test)
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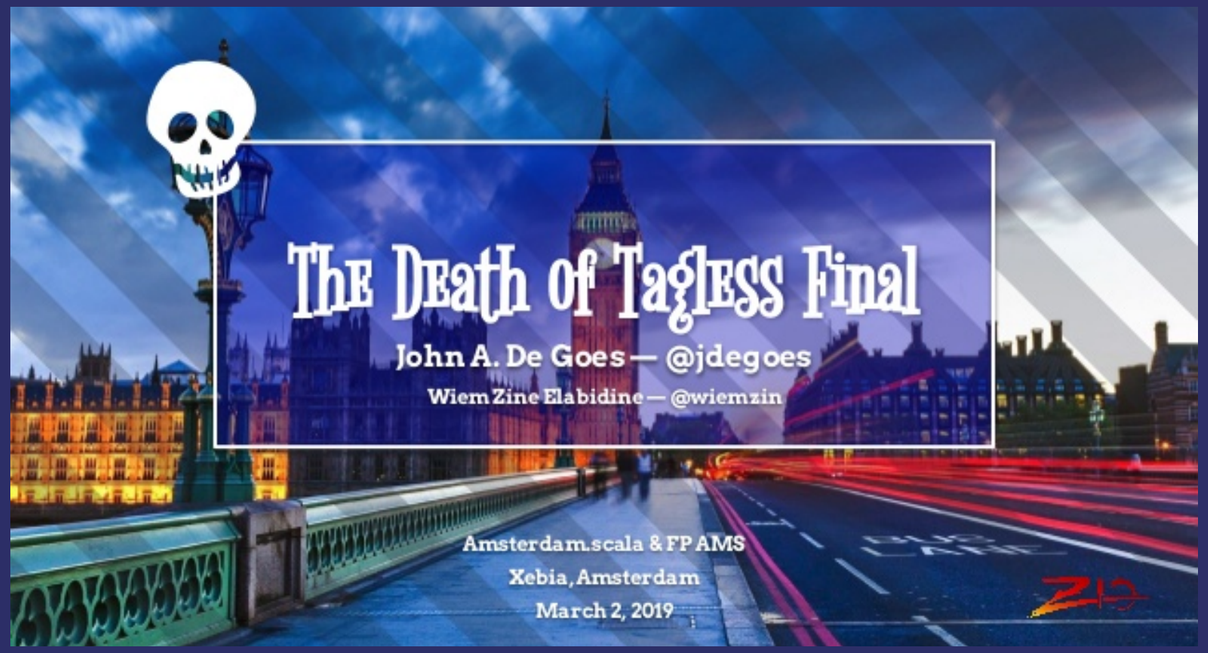
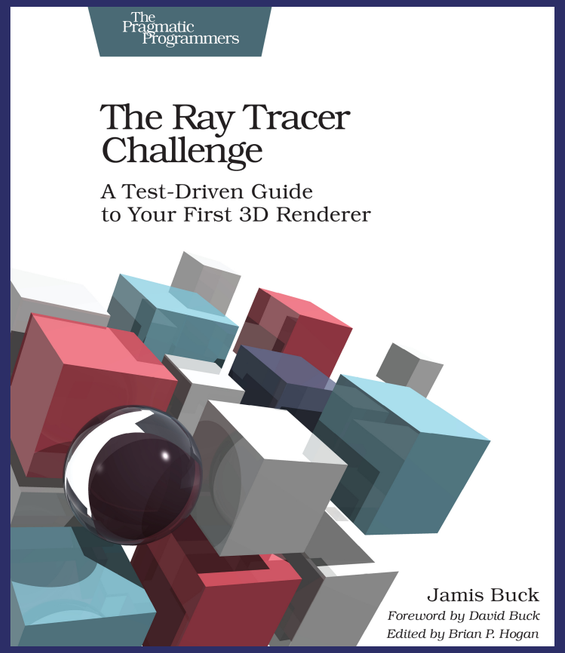
Ray tracing

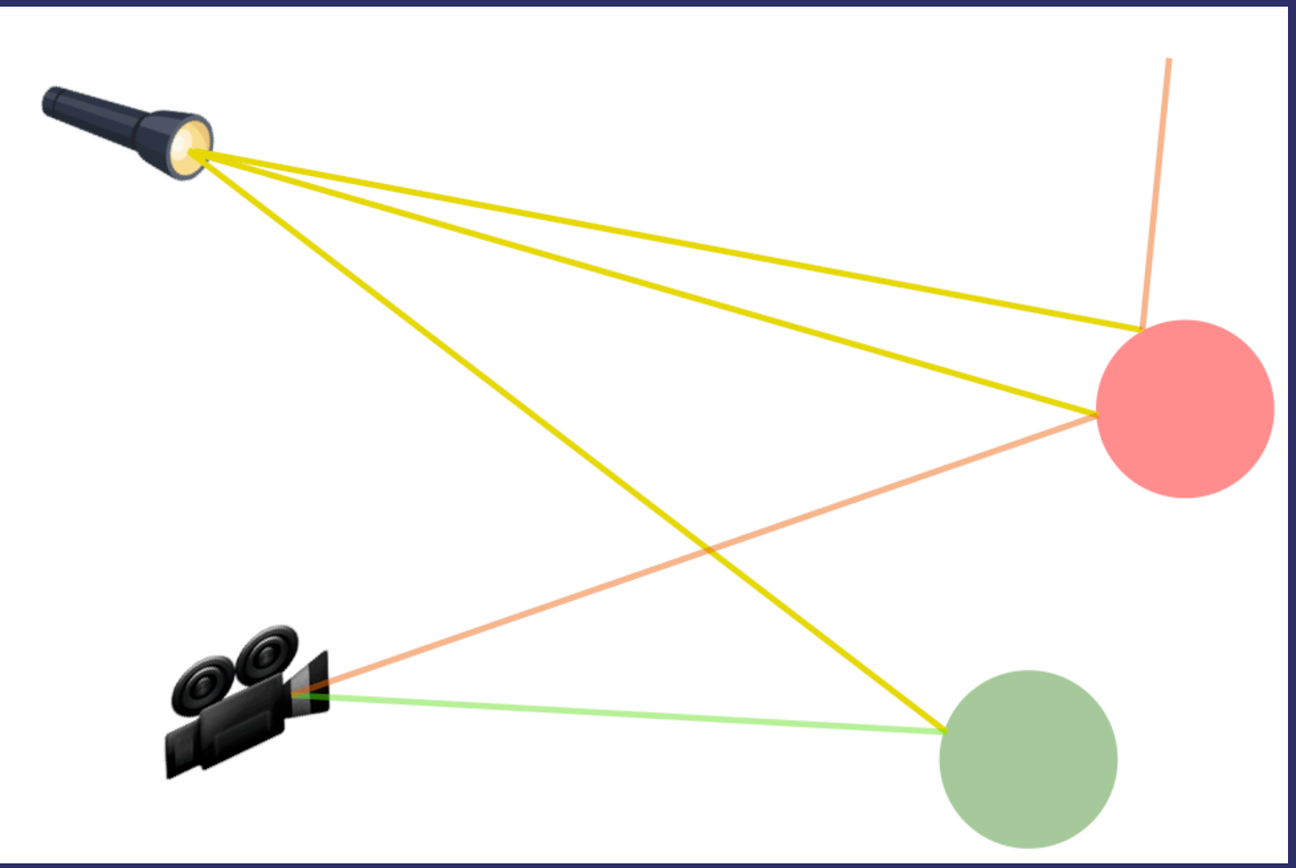
Why?



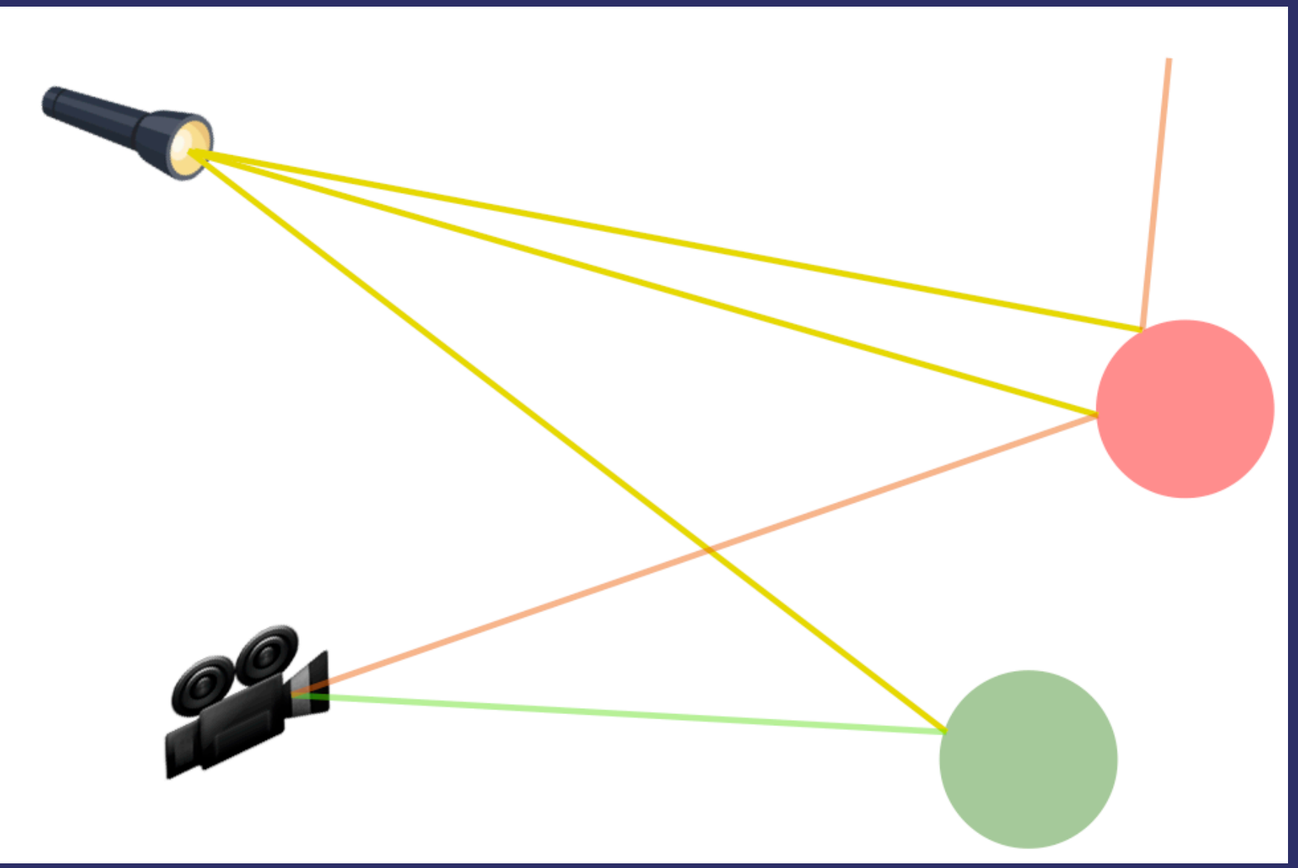


Presentation
Book

Ray tracing

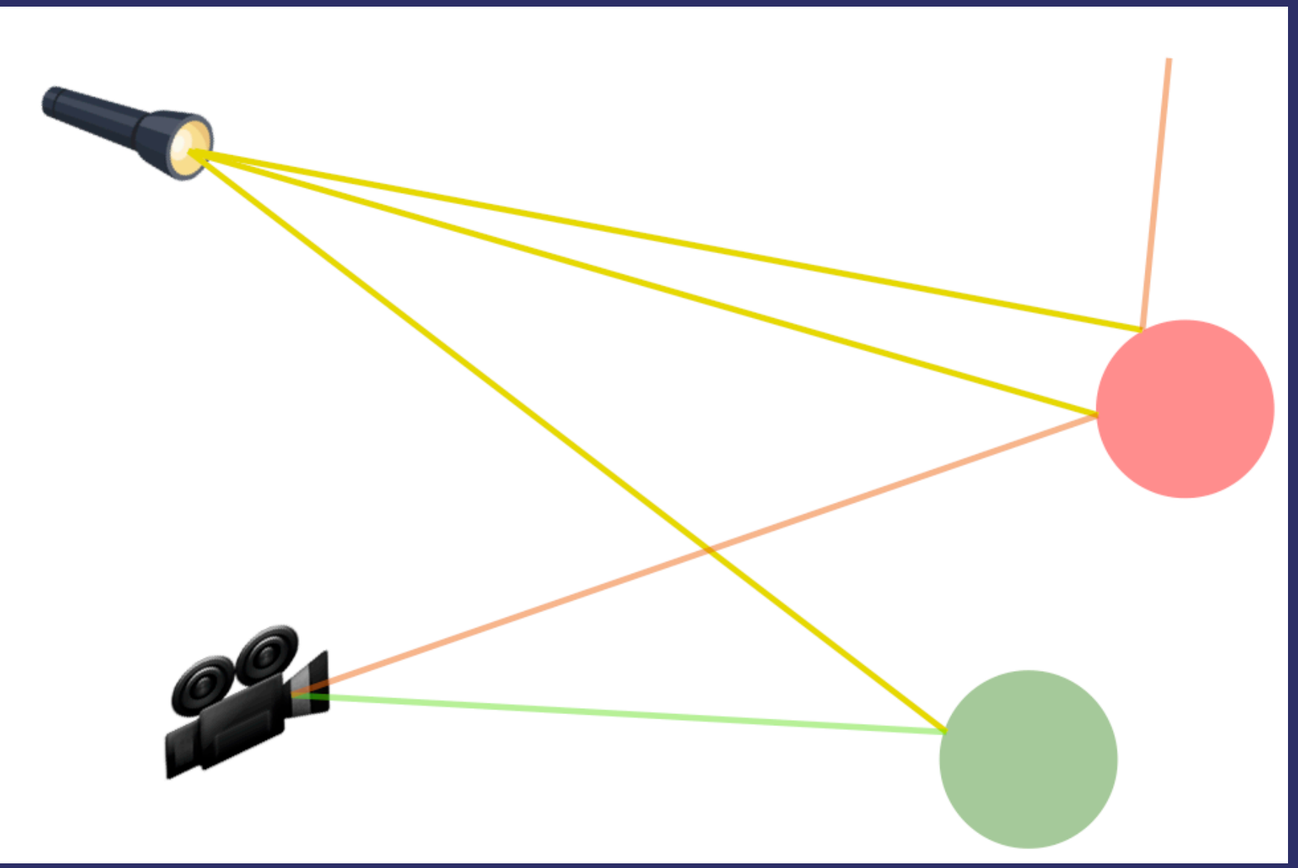


Ray tracing



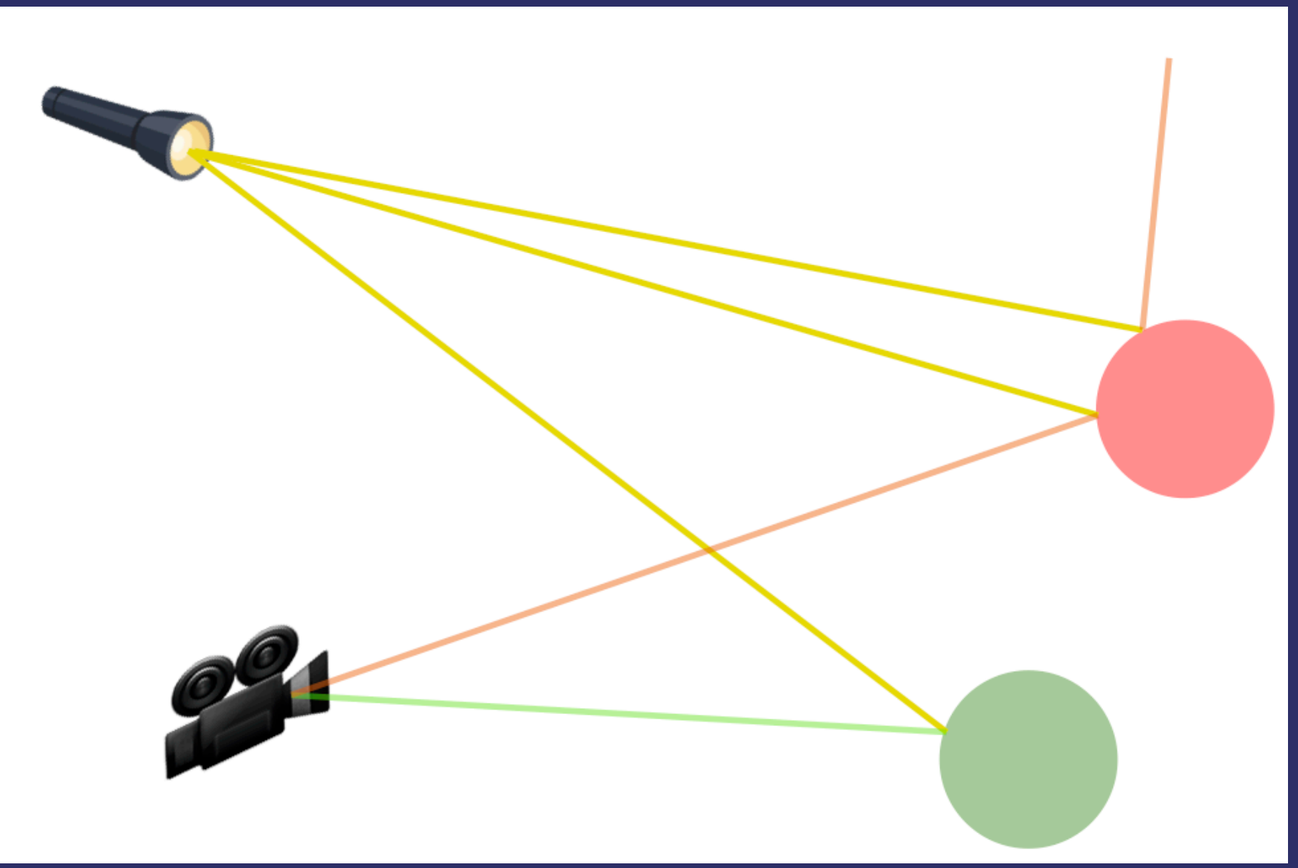
→ World (spheres), light source, camera

Ray tracing



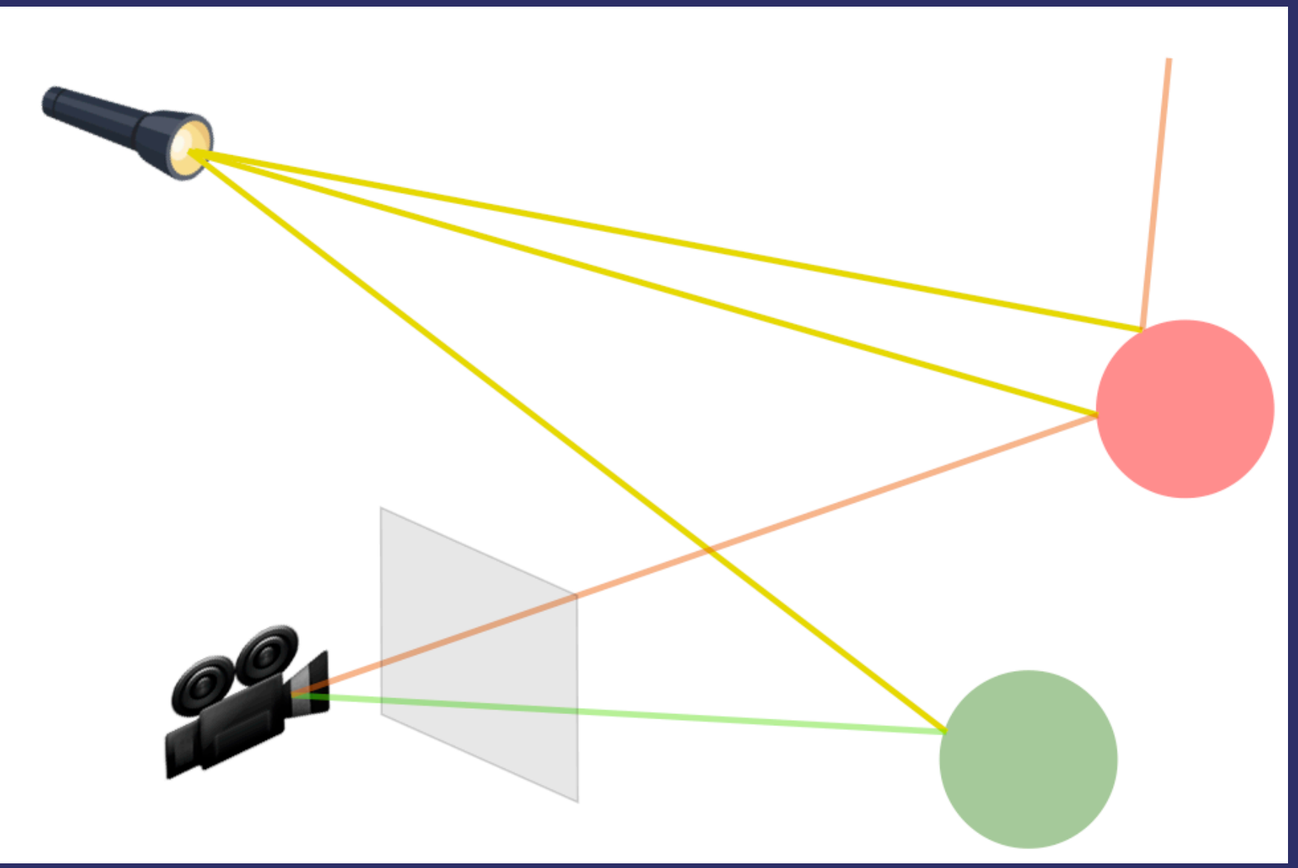
- → World (spheres), light source, camera
- → Incident rays

Ray tracing



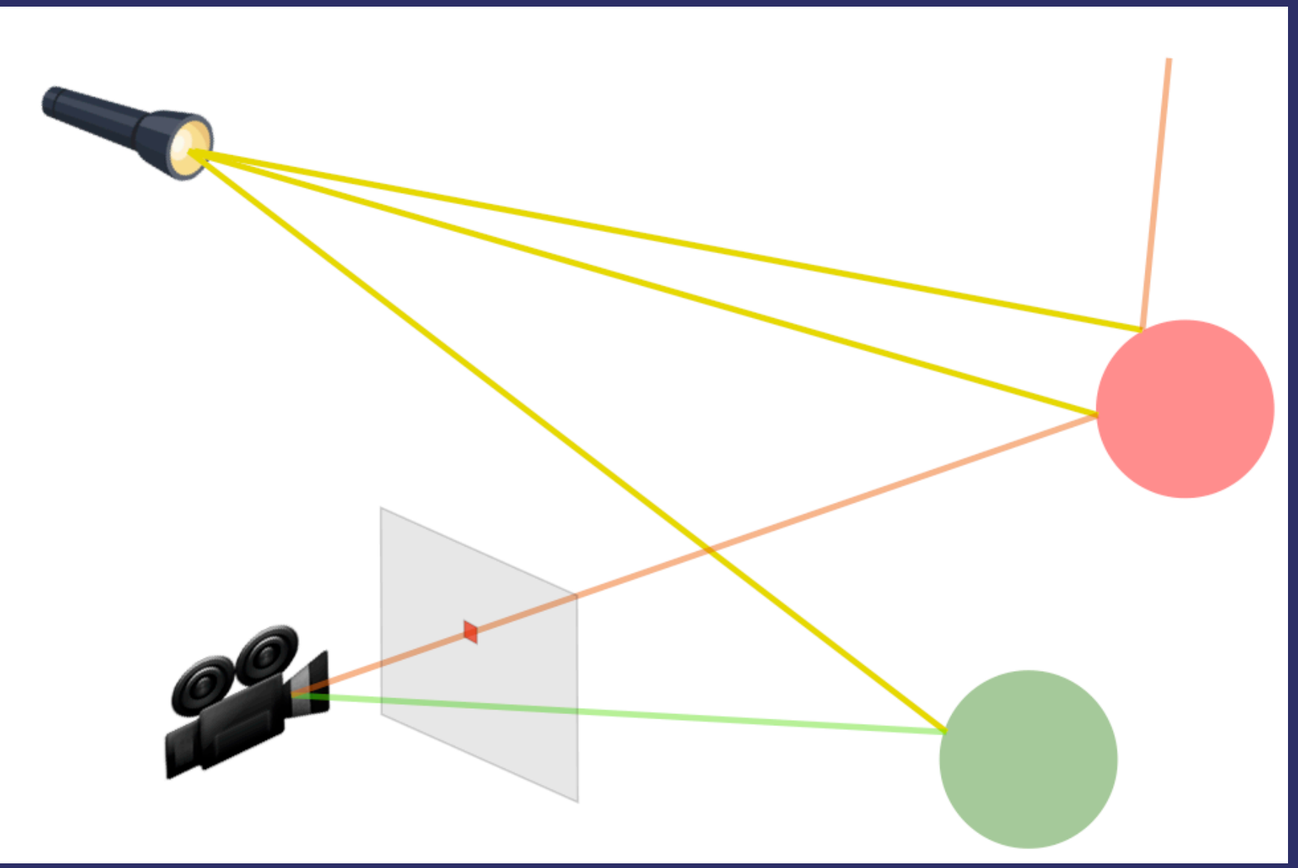
- → World (spheres), light source, camera
- → Incident rays
- → Reflected rays

Ray tracing



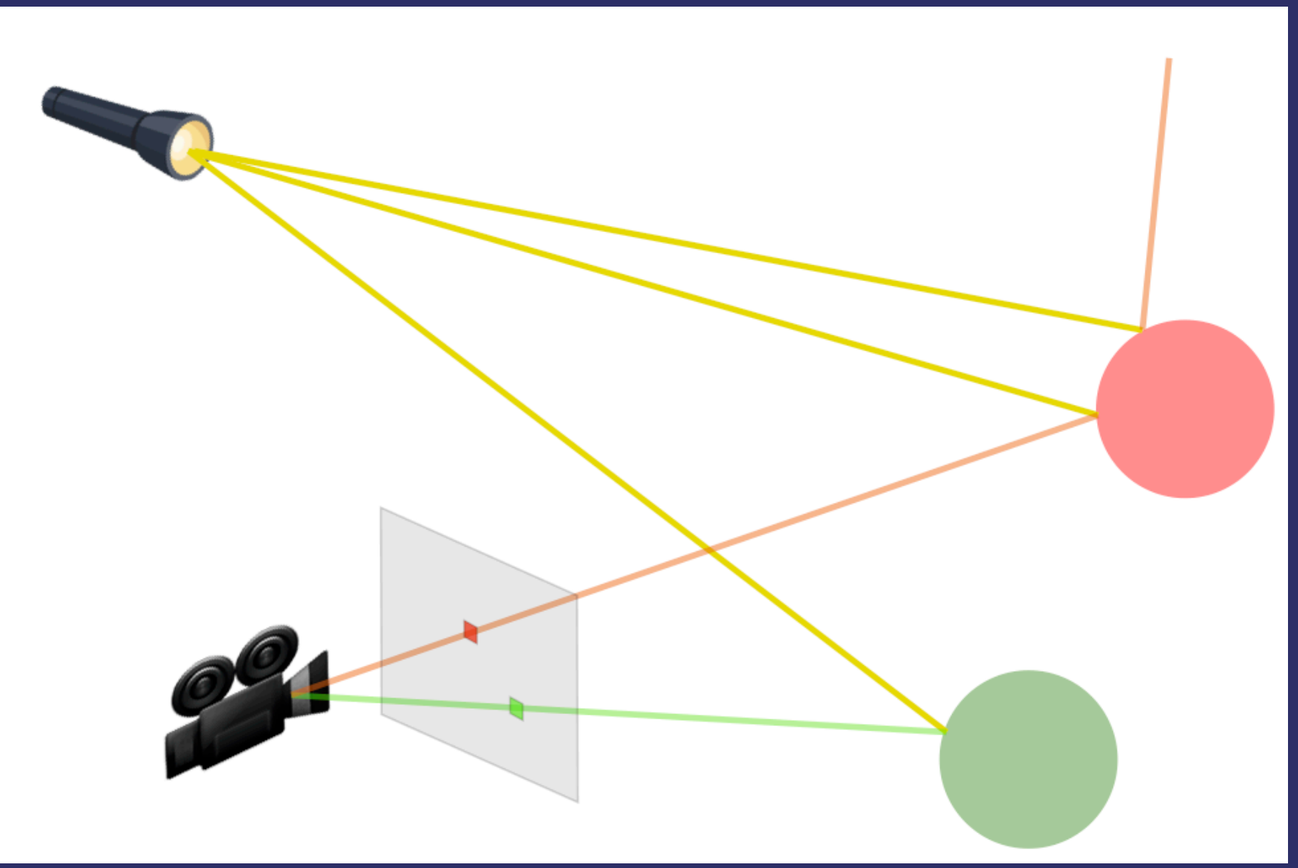
- → World (spheres), light source, camera
- → Incident rays
- → Reflected rays
- → Discarded rays
- → Canvas

Ray tracing



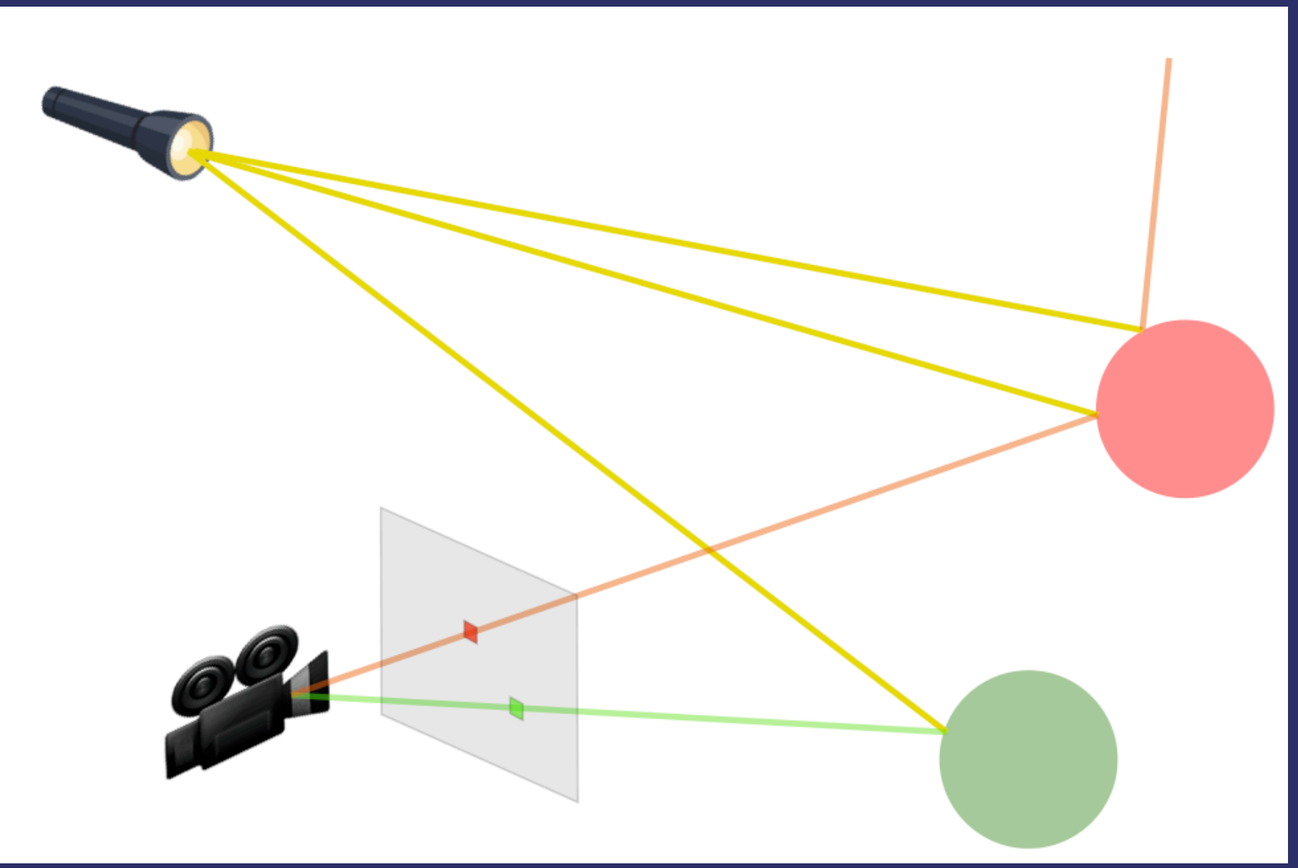
- → World (spheres), light source, camera
- → Incident rays
- → Reflected rays
- → Discarded rays
- → Canvas
- → Colored pixels

Ray tracing



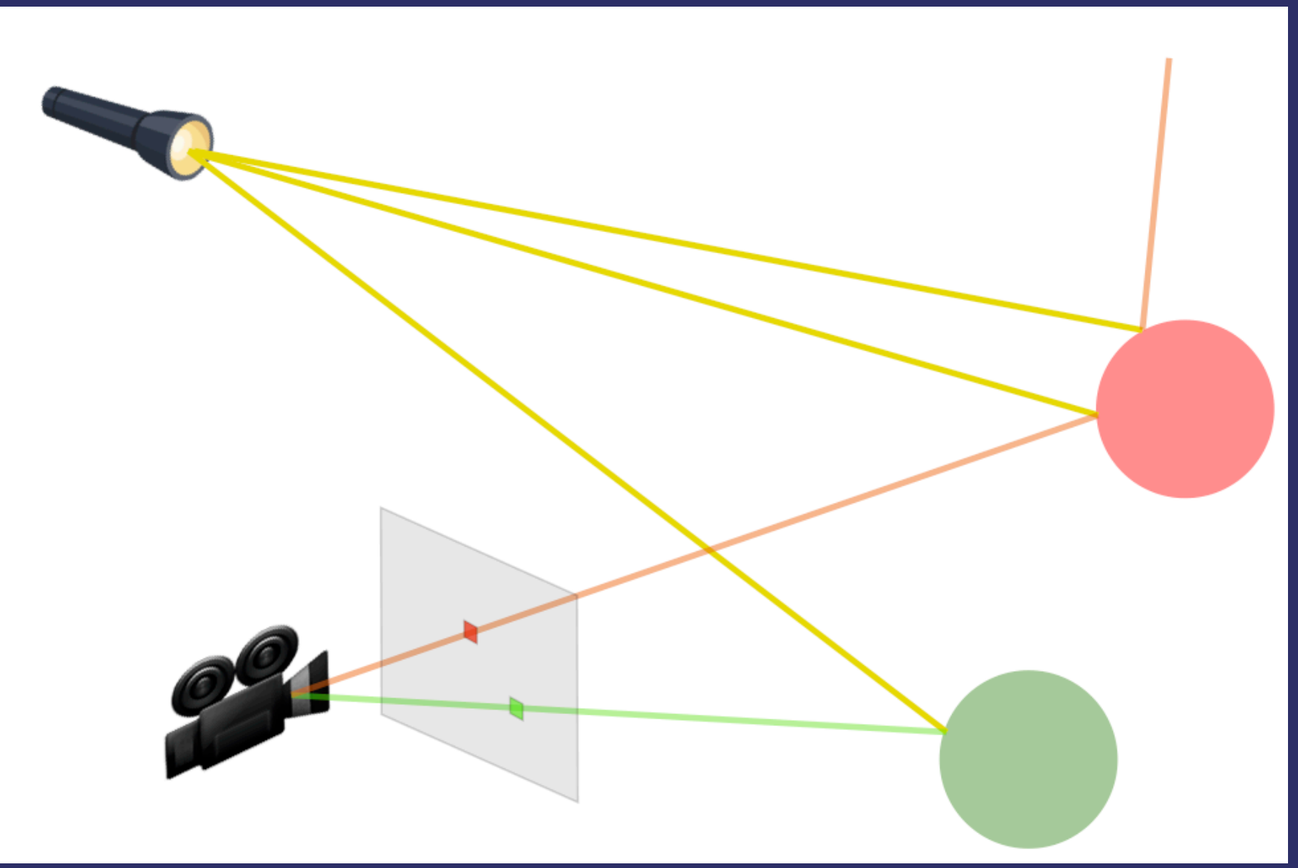
- → World (spheres), light source, camera
- → Incident rays
- → Reflected rays
- → Discarded rays
- → Canvas
- → Colored pixels

Ray tracing



Options:

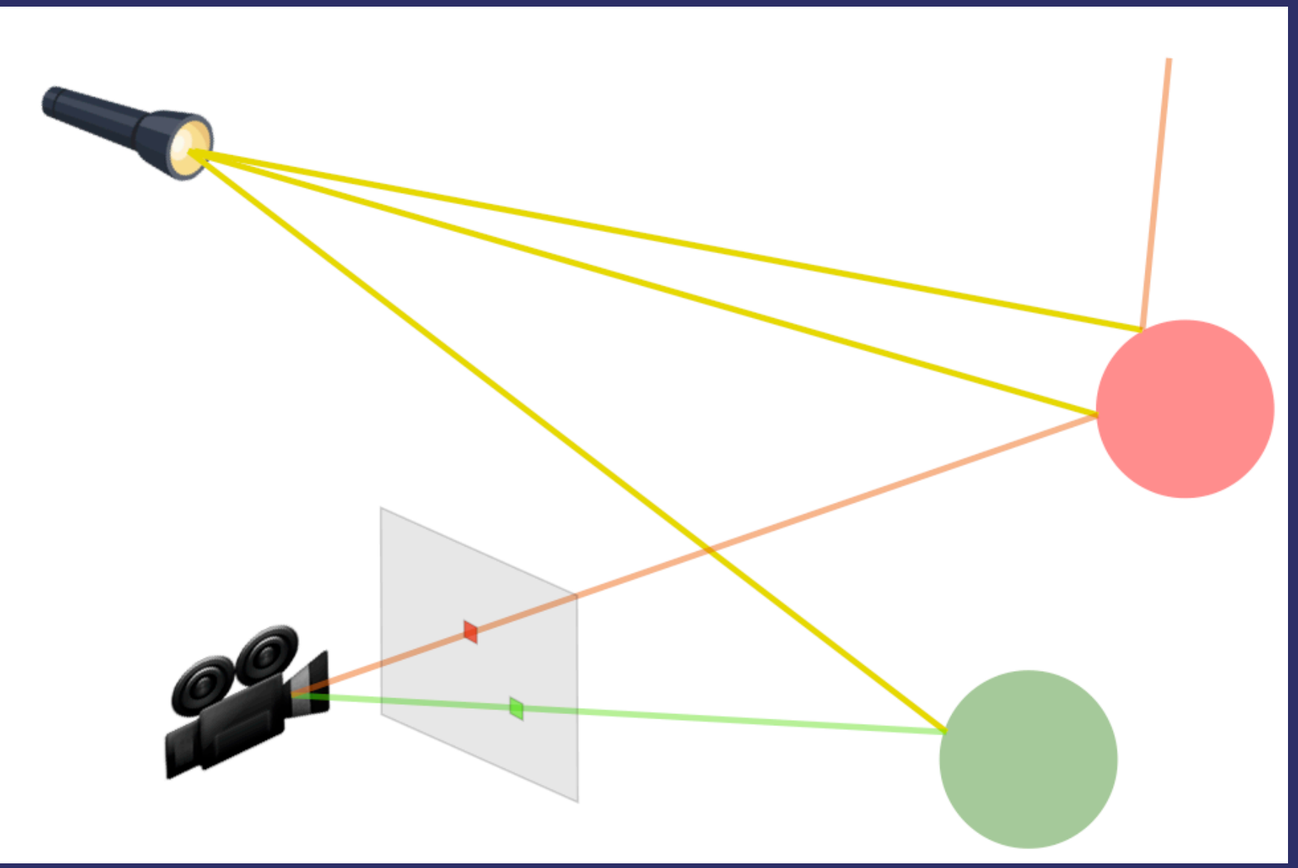
Ray tracing



Options:

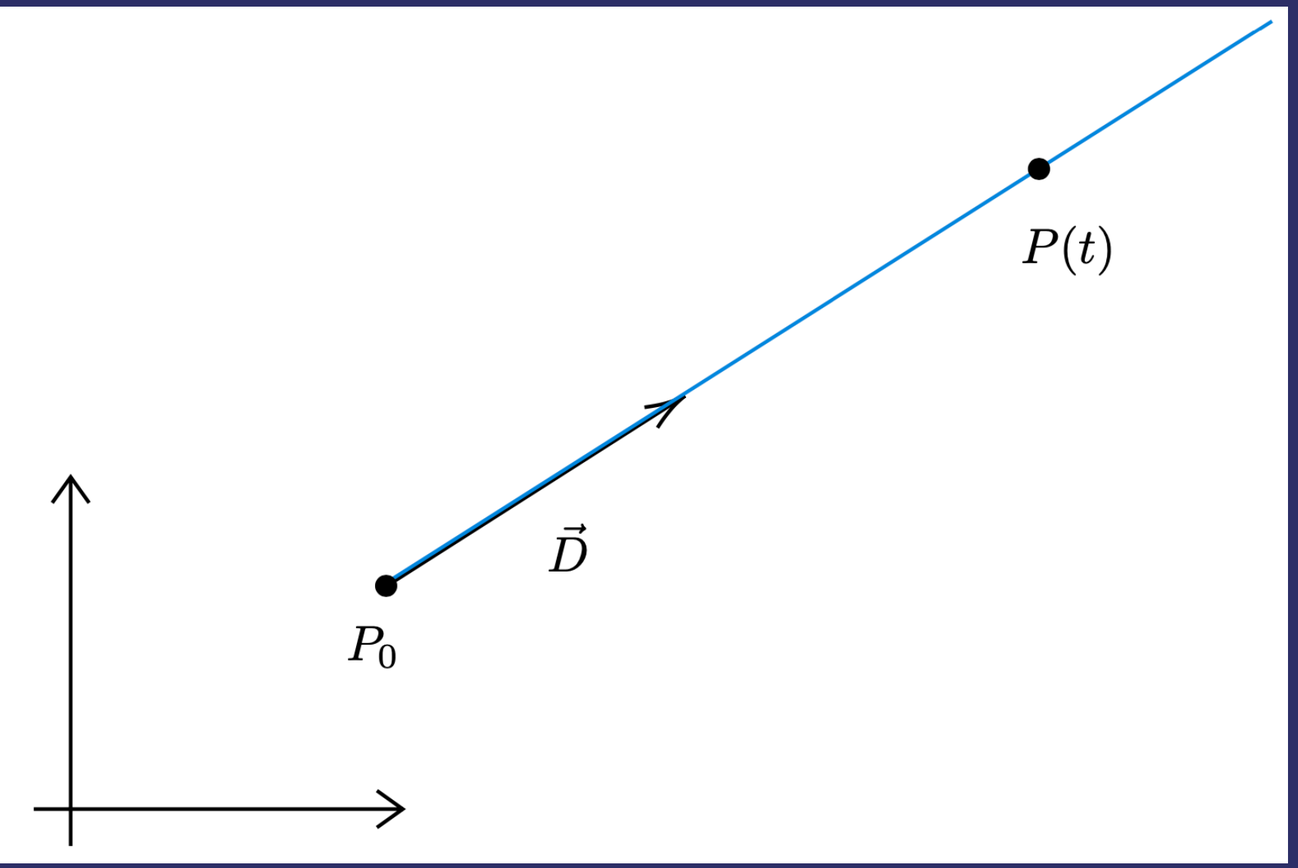
1. Compute all the rays (and discard most of them)

Ray tracing



Options:

1. Compute all the rays (and discard most of them)
2. Compute only the rays outgoing from the camera through the canvas, and determine how they behave on the surfaces

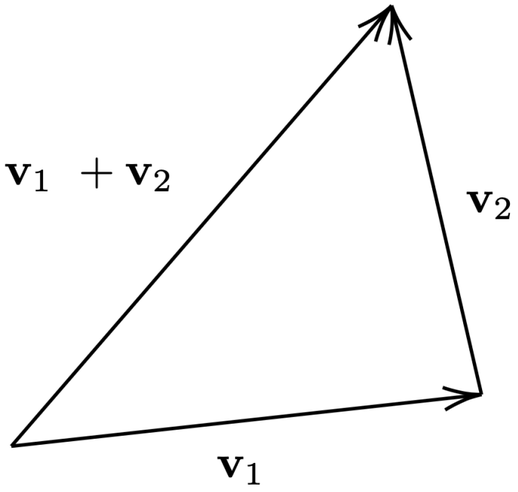


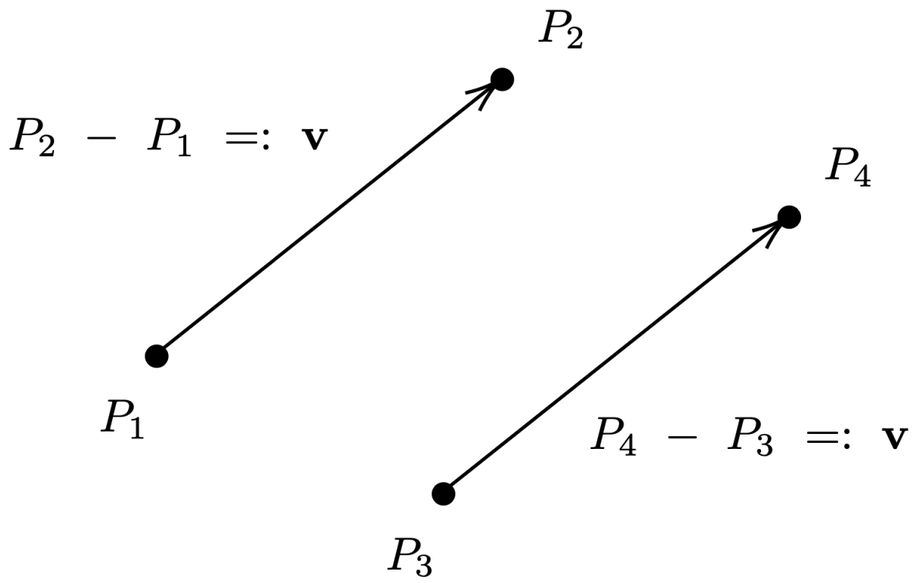
Ray

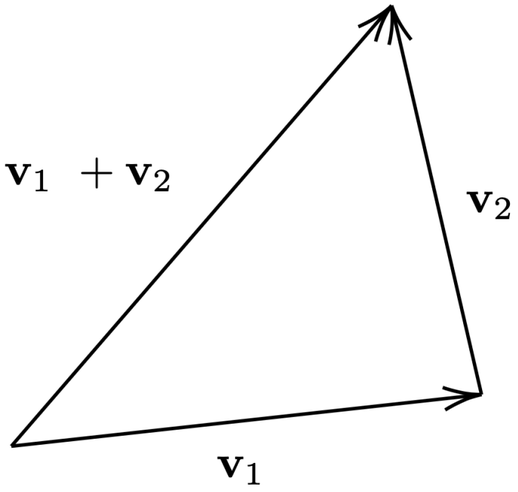
A ray is defined by the point it starts from, and its direction

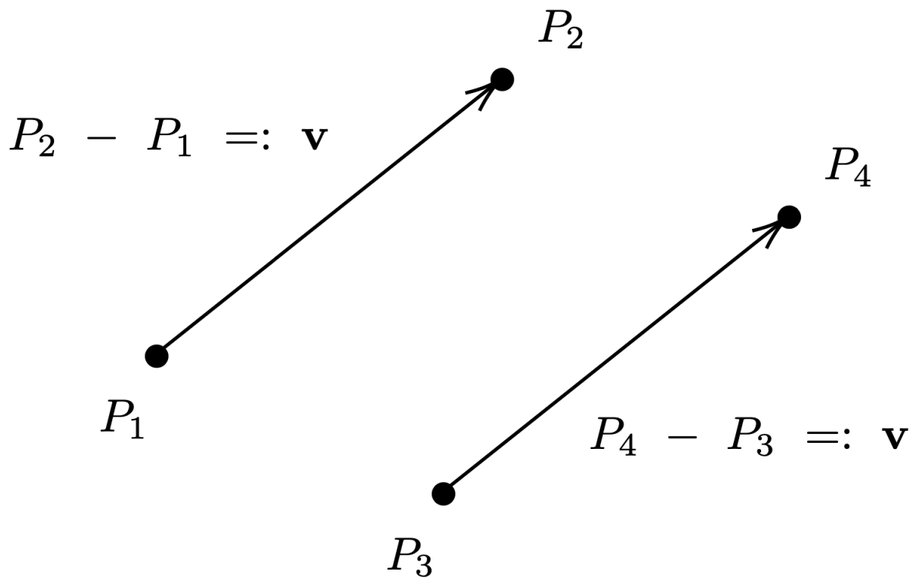
$$P(t) = P_0 + t\vec{D}, t > 0$$

Foundations



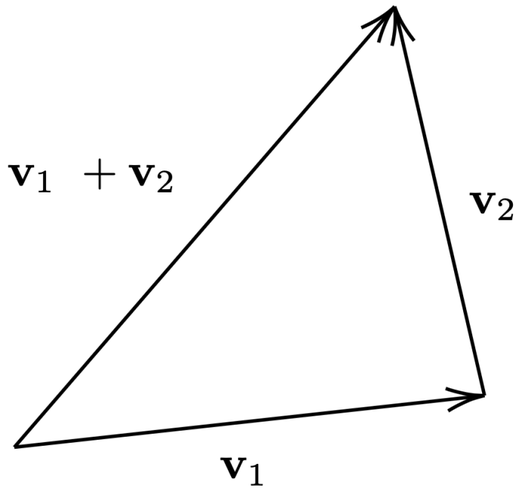


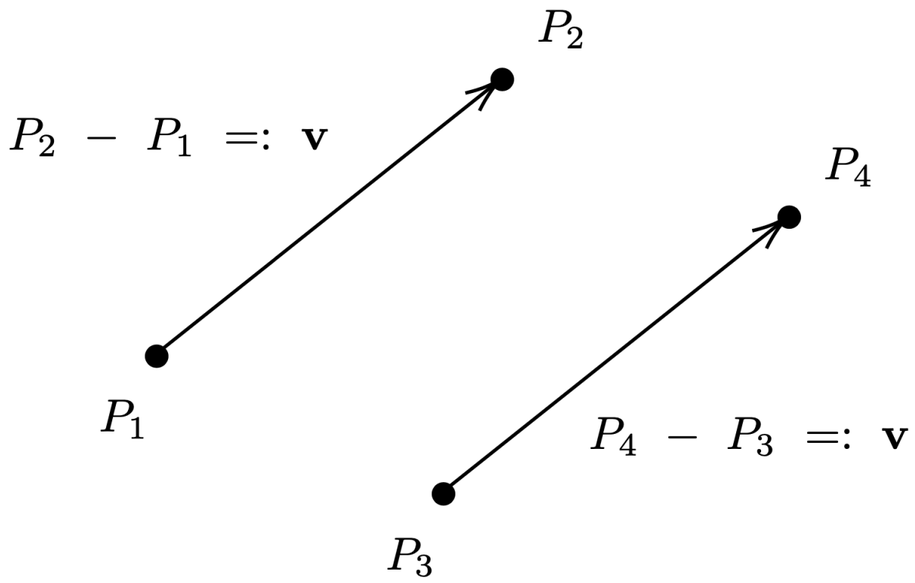




Foundations

→ Points and Vectors

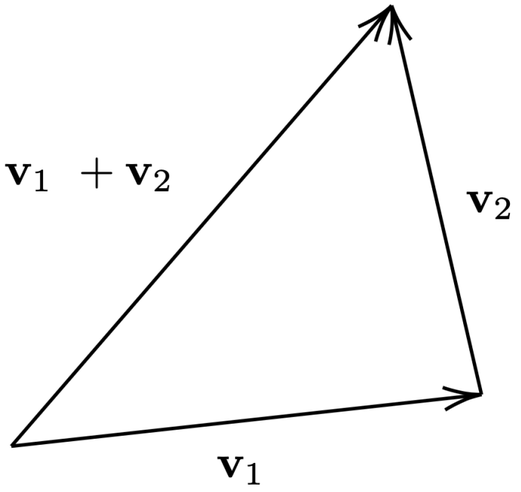




Foundations

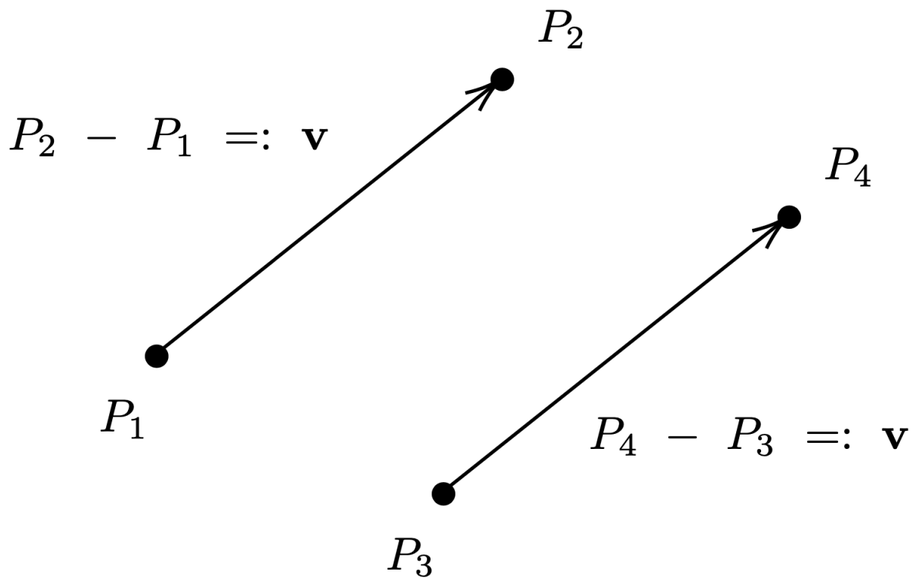
- → Points and Vectors
- → Transformations (rotate, scale, translate)

Points and Vectors

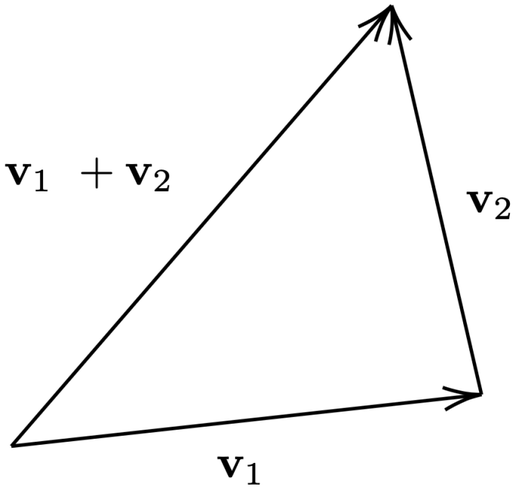



```scala
case class Vec(x: Double, y: Double, z: Double) {
  def +(other: Vec): Vec    =
    Vec(x + other.x, y + other.y, z + other.z)
  def unary_- : Vec =
    Vec(-x, -y, -z)
}

case class Pt(x: Double, y: Double, z: Double) {
  def -(otherPt: Pt): Vec =
    Vec(x - otherPt.x, y - otherPt.y, z - otherPt.z)
  def +(vec: Vec)          =
    Pt(x + vec.x, y + vec.y, z + vec.z)
}
```

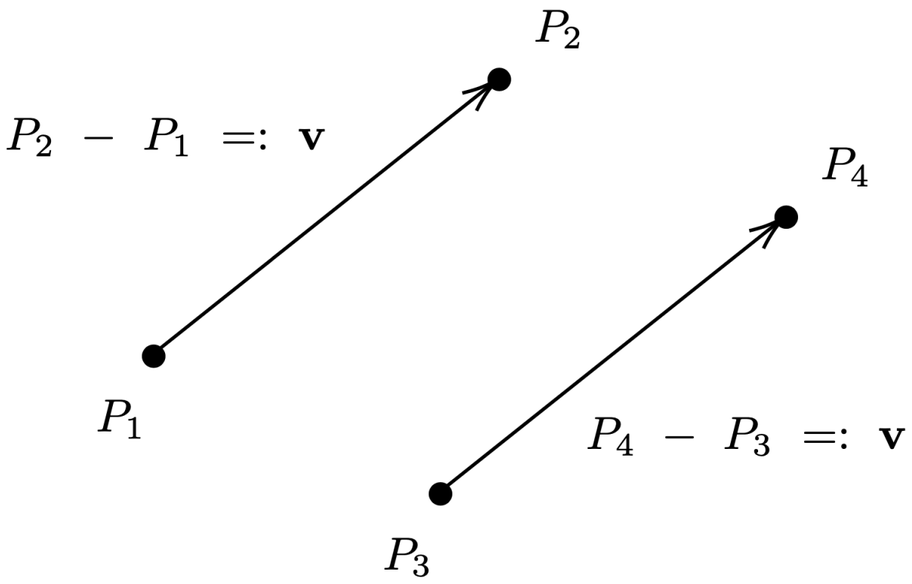


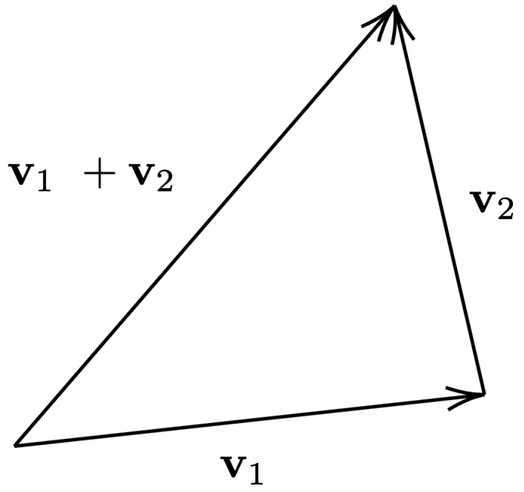
Points and Vectors

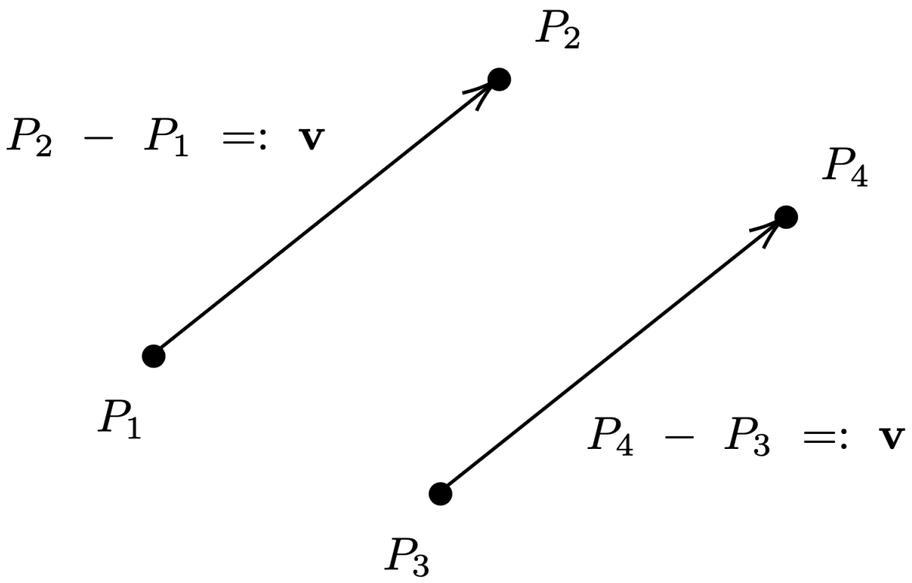



```scala
case class Vec(x: Double, y: Double, z: Double) {
  def +(other: Vec): Vec    =
    Vec(x + other.x, y + other.y, z + other.z)
  def unary_- : Vec =
    Vec(-x, -y, -z)
}

case class Pt(x: Double, y: Double, z: Double) {
  def -(otherPt: Pt): Vec =
    Vec(x - otherPt.x, y - otherPt.y, z - otherPt.z)
  def +(vec: Vec)          =
    Pt(x + vec.x, y + vec.y, z + vec.z)
}
```





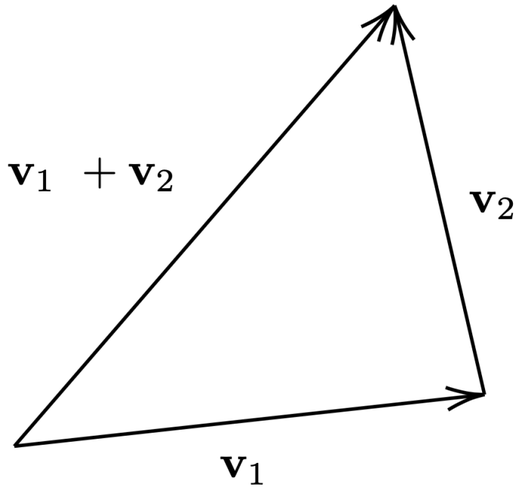


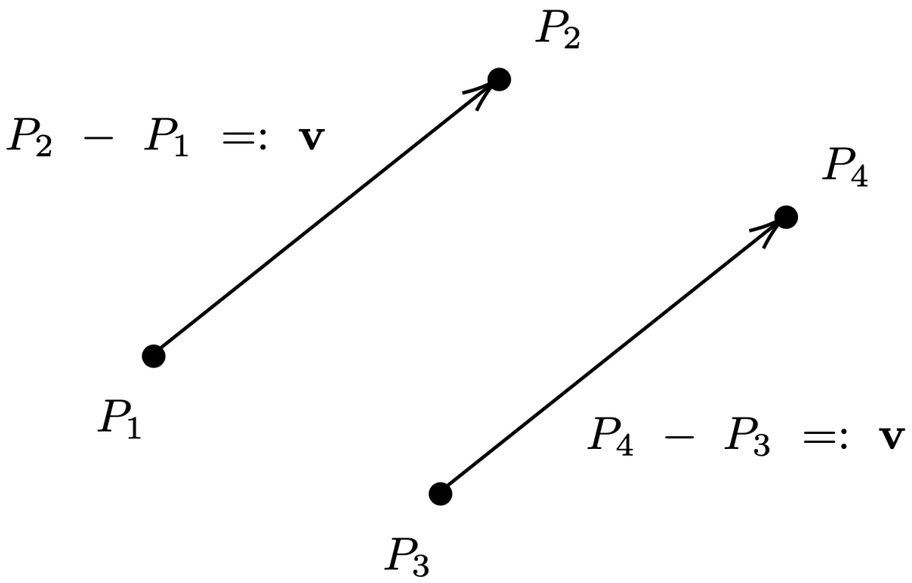
Points and Vectors

zio-test for PBT

```
testM("vectors form a group")(
  check(vecGen, vecGen, vecGen) { (v1, v2, v3) =>
    assertApprox  (v1 + (v2 + v3), (v1 + v2) + v3) &&
    assertApprox (v1 + v2 , v2 + v1) &&
    assertApprox (v1 + Vec.zero , Vec.zero + v1)
  }
),


testM("vectors and points form an affine space") (
  check(ptGen, ptGen) { (p1, p2) =>
    assertApprox (p2, p1 + (p2 - p1))
  }
)
```



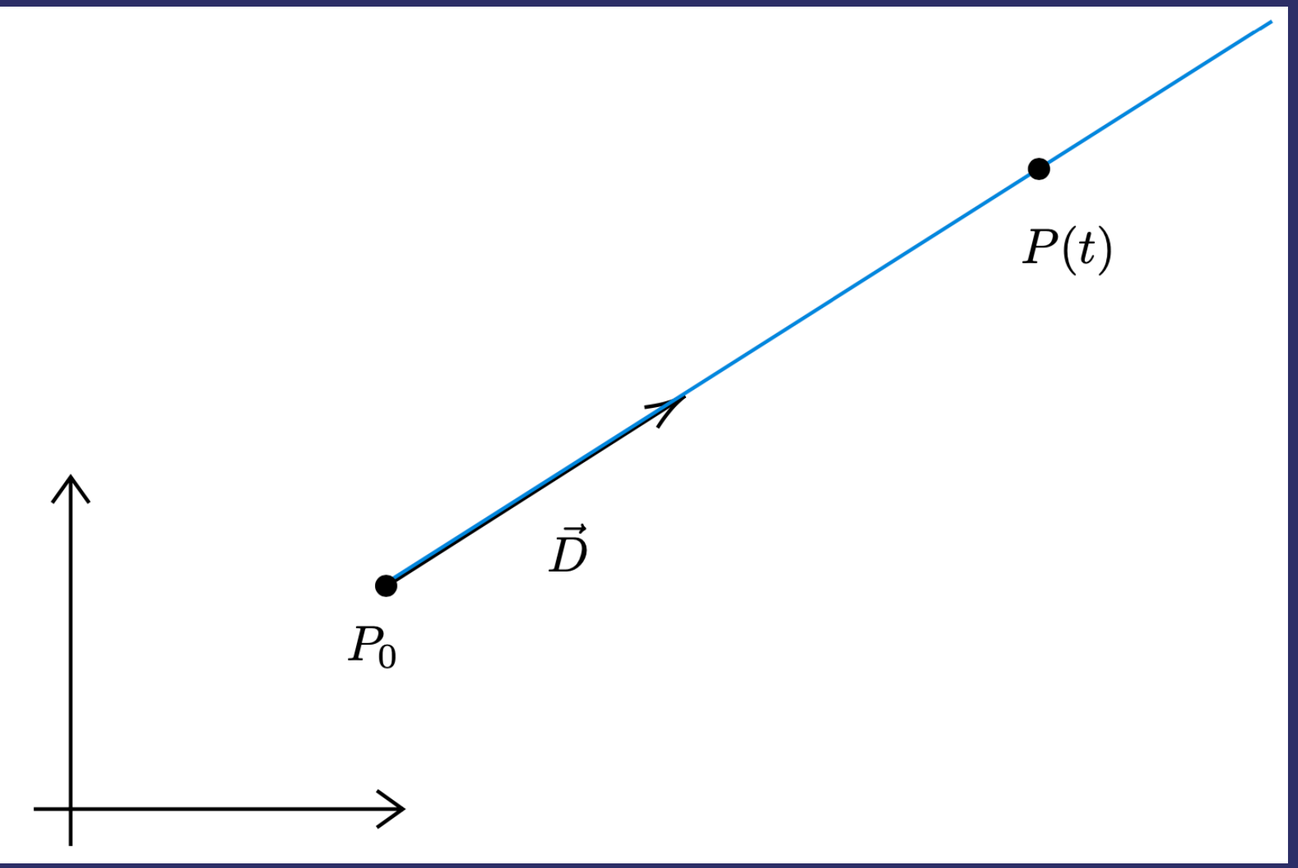


Points and Vectors

zio-test for PBT

```
testM("vectors form a group")(
  check(vecGen, vecGen, vecGen) { (v1, v2, v3) =>
    assertApprox  (v1 + (v2 + v3), (v1 + v2) + v3) &&
    assertApprox (v1 + v2 , v2 + v1) &&
    assertApprox (v1 + Vec.zero , Vec.zero + v1)
  }
),
```

```
testM("vectors and points form an affine space") (
  check(ptGen, ptGen) { (p1, p2) =>
    assertApprox (p2, p1 + (p2 - p1))
  }
)
```



Ray

$$P(t) = P_0 + t\vec{D}, t > 0$$

```
case class Ray(origin: Pt, direction: Vec) {
  def positionAt(t: Double): Pt =
    origin + (direction * t)
}
```

Transformations

```scala
trait AT
/* Module */
trait ATModule {
  val aTModule: ATModule.Service[Any]
}

object ATModule {
  /* Service */
  trait Service[R] {
    def applyTf(tf: AT, vec: Vec): ZIO[R, ATError, Vec]
    def applyTf(tf: AT, pt: Pt): ZIO[R, ATError, Pt]
    def compose(first: AT, second: AT): ZIO[R, ATError, AT]
  }

  /* Accessor */
  object > extends Service[ATModule] {
    def applyTf(tf: AT, vec: Vec): ZIO[ATModule, ATError, Vec] =
      ZIO.accessM(_.aTModule.applyTf(tf, vec))
    def applyTf(tf: AT, pt: Pt): ZIO[ATModule, ATError, Pt] =
      ZIO.accessM(_.aTModule.applyTf(tf, pt))
    def compose(first: AT, second: AT): ZIO[ATModule, ATError, AT] =
      ZIO.accessM(_.aTModule.compose(first, second))
  }
}
```

Transformations

```scala
trait AT
/* Module */
trait ATModule {
  val aTModule: ATModule.Service[Any]
}

object ATModule {
  /* Service */
  trait Service[R] {
    def applyTf(tf: AT, vec: Vec): ZIO[R, ATError, Vec]
    def applyTf(tf: AT, pt: Pt): ZIO[R, ATError, Pt]
    def compose(first: AT, second: AT): ZIO[R, ATError, AT]
  }

  /* Accessor */
  object > extends Service[ATModule] {
    def applyTf(tf: AT, vec: Vec): ZIO[ATModule, ATError, Vec] =
      ZIO.accessM(_.aTModule.applyTf(tf, vec))
    def applyTf(tf: AT, pt: Pt): ZIO[ATModule, ATError, Pt] =
      ZIO.accessM(_.aTModule.applyTf(tf, pt))
    def compose(first: AT, second: AT): ZIO[ATModule, ATError, AT] =
      ZIO.accessM(_.aTModule.compose(first, second))
  }
}
```

Transformations

```scala
trait AT
/* Module */
trait ATModule {
  val aTModule: ATModule.Service[Any]
}

object ATModule {
  /* Service */
  trait Service[R] {
    def applyTf(tf: AT, vec: Vec): ZIO[R, ATError, Vec]
    def applyTf(tf: AT, pt: Pt): ZIO[R, ATError, Pt]
    def compose(first: AT, second: AT): ZIO[R, ATError, AT]
  }

  /* Accessor */
  object > extends Service[ATModule] {
    def applyTf(tf: AT, vec: Vec): ZIO[ATModule, ATError, Vec] =
      ZIO.accessM(_.aTModule.applyTf(tf, vec))
    def applyTf(tf: AT, pt: Pt): ZIO[ATModule, ATError, Pt] =
      ZIO.accessM(_.aTModule.applyTf(tf, pt))
    def compose(first: AT, second: AT): ZIO[ATModule, ATError, AT] =
      ZIO.accessM(_.aTModule.compose(first, second))
  }
}
```

Transformations

```scala
trait AT
/* Module */
trait ATModule {
  val aTModule: ATModule.Service[Any]
}

object ATModule {
  /* Service */
  trait Service[R] {
    def applyTf(tf: AT, vec: Vec): ZIO[R, ATError, Vec]
    def applyTf(tf: AT, pt: Pt): ZIO[R, ATError, Pt]
    def compose(first: AT, second: AT): ZIO[R, ATError, AT]
  }

  /* Accessor */
  object > extends Service[ATModule] {
    def applyTf(tf: AT, vec: Vec): ZIO[ATModule, ATError, Vec] =
      ZIO.accessM(_.aTModule.applyTf(tf, vec))
    def applyTf(tf: AT, pt: Pt): ZIO[ATModule, ATError, Pt] =
      ZIO.accessM(_.aTModule.applyTf(tf, pt))
    def compose(first: AT, second: AT): ZIO[ATModule, ATError, AT] =
      ZIO.accessM(_.aTModule.compose(first, second))
  }
}
```

Transformations

```scala
import zio.macros.annotation.accessible

trait AT
/* Module */
@accessible(">")
trait ATModule {
  val aTModule: ATModule.Service[Any]
}

object ATModule {
  /* Service */
  trait Service[R] {
    def applyTf(tf: AT, vec: Vec): ZIO[R, ATError, Vec]
    def applyTf(tf: AT, pt: Pt): ZIO[R, ATError, Pt]
    def compose(first: AT, second: AT): ZIO[R, ATError, AT]
  }

  /* Accessor is generated
  object > extends Service[ATModule] {
    def applyTf(tf: AT, vec: Vec): ZIO[ATModule, ATError, Vec] =
      ZIO.accessM(_.aTModule.applyTf(tf, vec))
    def applyTf(tf: AT, pt: Pt): ZIO[ATModule, ATError, Pt] =
      ZIO.accessM(_.aTModule.applyTf(tf, pt))
    def compose(first: AT, second: AT): ZIO[ATModule, ATError, AT] =
      ZIO.accessM(_.aTModule.compose(first, second))
  }
  */
}
```

Transformations

```
trait AT
/* Module */
@accessible(">")
trait ATModule {
  val aTModule: ATModule.Service[Any]
}

object ATModule {
  /* Service */
  trait Service[R] {
    def applyTf(tf: AT, vec: Vec): ZIO[R, ATError, Vec]
    def applyTf(tf: AT, pt: Pt): ZIO[R, ATError, Pt]
    def compose(first: AT, second: AT): ZIO[R, ATError, AT]
  }
}
```

Transformations

```
val rotatedPt =
  for {
    rotateX <- ATModule.>.rotateX(math.Pi / 2)
    _       <- Log.>.info("rotated of π/2")
    res     <- ATModule.>.applyTf(rotateX, Pt(1, 1, 1))
  } yield  res
```

Transformations

```
val rotatedPt: ZIO[ATModule with Log, ATError, Pt] =
  for {
    rotateX <- ATModule.>.rotateX(math.Pi / 2)
    _       <- Log.>.info("rotated of π/2")
    res     <- ATModule.>.applyTf(rotateX, Pt(1, 1, 1))
  } yield  res
```

Transformations - Live

```
val rotated: ZIO[ATModule, ATError, Vec] =
  for {
    rotateX <- ATModule.>.rotateZ(math.Pi/2)
    res     <- ATModule.>.applyTf(rotateX, Vec(x, y, z))
  } yield res
```

Transformations - Live

```
val rotated: ZIO[ATModule, ATError, Vec] =
  for {
    rotateX <- ATModule.>.rotateZ(math.Pi/2)
    res     <- ATModule.>.applyTf(rotateX, Vec(x, y, z))
  } yield res
```

→ `Vec(x, y, z)` $\Rightarrow [x, y, z, 0]^T$

Transformations - Live

```
val rotated: ZIO[ATModule, ATError, Vec] =
  for {
    rotateX <- ATModule.>.rotateZ(math.Pi/2)
    res     <- ATModule.>.applyTf(rotateX, Vec(x, y, z))
  } yield res
```

→ `Vec(x, y, z)` $\Rightarrow [x, y, z, 0]^T$

→ `Pt(x, y, z)` $\Rightarrow [x, y, z, 1]^T$

Transformations - Live

```
val rotated: ZIO[ATModule, ATError, Vec] =
  for {
    rotateX <- ATModule.>.rotateZ(math.Pi/2)
    res     <- ATModule.>.applyTf(rotateX, Vec(x, y, z))
  } yield res
```

→ `Vec(x, y, z)` $\Rightarrow [x, y, z, 0]^T$

→ `Pt(x, y, z)` $\Rightarrow [x, y, z, 1]^T$

→

$$\mathbf{rotated} = \begin{pmatrix} \cos \pi/2 & -\sin \pi/2 & 0 & 0 \\ \sin \pi/2 & \cos \pi/2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \\ 0 \end{pmatrix}$$

Transformations - Live

```
// Defined somewhere else
object MatrixModule {
  trait Service[R] {
    def add(m1: M, m2: M): ZIO[R, AlgebraicError, M]
    def mul(m1: M, m2: M): ZIO[R, AlgebraicError, M]
  }
}

trait Live extends ATModule {
  val matrixModule: MatrixModule.Service[Any]

  val aTModule: ATModule.Service[Any] = new ATModule.Service[Any] {
    def applyTf(tf: AT, vec: Vec): ZIO[Any, AlgebraicError, Vec] =
      for {
        col    <- PointVec.toCol(vec)
        colRes <- matrixModule.mul(tf, col)
        res    <- PointVec.colToVec(colRes)
      } yield res
```

Transformations - Live

```
// Defined somewhere else
object MatrixModule {
  trait Service[R] {
    def add(m1: M, m2: M): ZIO[R, AlgebraicError, M]
    def mul(m1: M, m2: M): ZIO[R, AlgebraicError, M]
  }
}

trait Live extends ATModule {
  val matrixModule: MatrixModule.Service[Any]

  val aTModule: ATModule.Service[Any] = new ATModule.Service[Any] {
    def applyTf(tf: AT, vec: Vec): ZIO[Any, AlgebraicError, Vec] =
      for {
        col    <- PointVec.toCol(vec)
        colRes <- matrixModule.mul(tf, col)
        res    <- PointVec.colToVec(colRes)
      } yield res
```

Transformations - running

```
val rotated: ZIO[ATModule, ATError, Vec]  = ...
val program = rotatedPt.provide(new ATModule.Live{})
// Compiler error:
// object creation impossible, since value matrixModule
// in trait Live of t ype matrix.MatrixModule.Service[Any] is not defined
// [error]   rotatedPt.provide(new ATModule.Live{})
```

Transformations - running

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```

Transformations - running

```
val rotated: ZIO[ATModule, ATError, Vec]  = ...
val program = rotatedPt.provide(
  new ATModule.Live with MatrixModule.BreezeLive
)
// Compiles!
runtime.unsafeRun(program)
// Runs!
```

Transformations - running

```
val rotated: ZIO[ATModule, ATError, Vec]  = ...
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  new ATModule.Live with MatrixModule.BreezeLive
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Transformations - running

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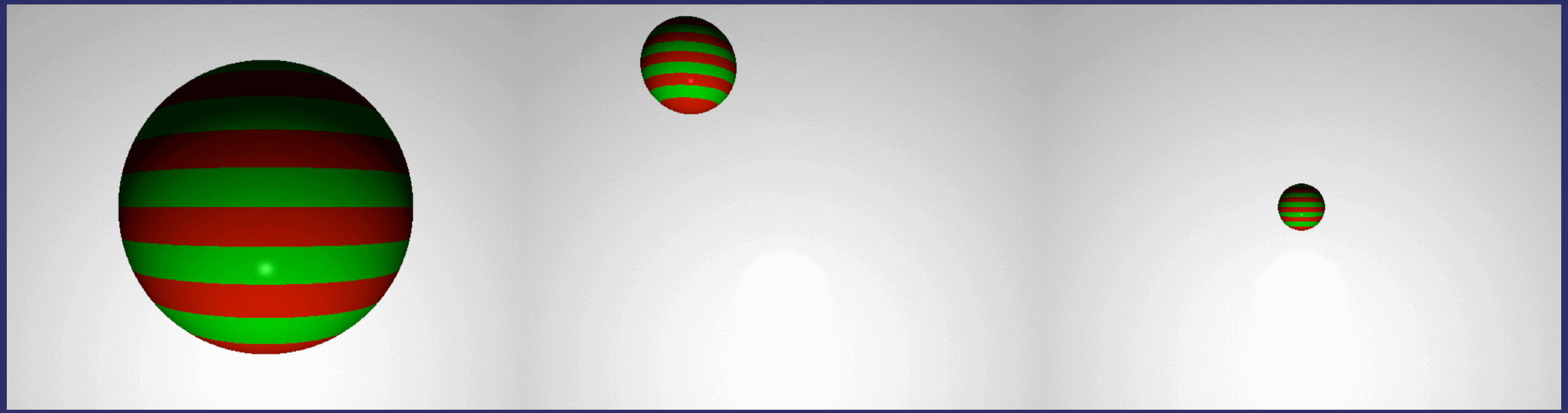
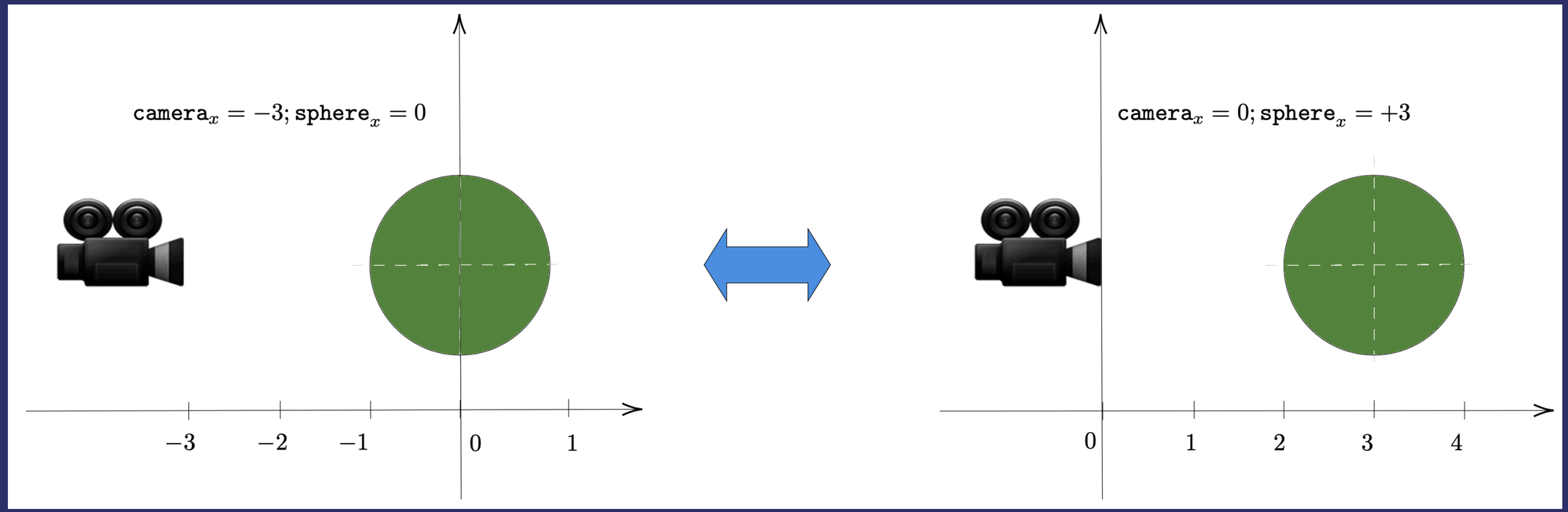
Layer 1: Transformations



Camera

Everything is relative!



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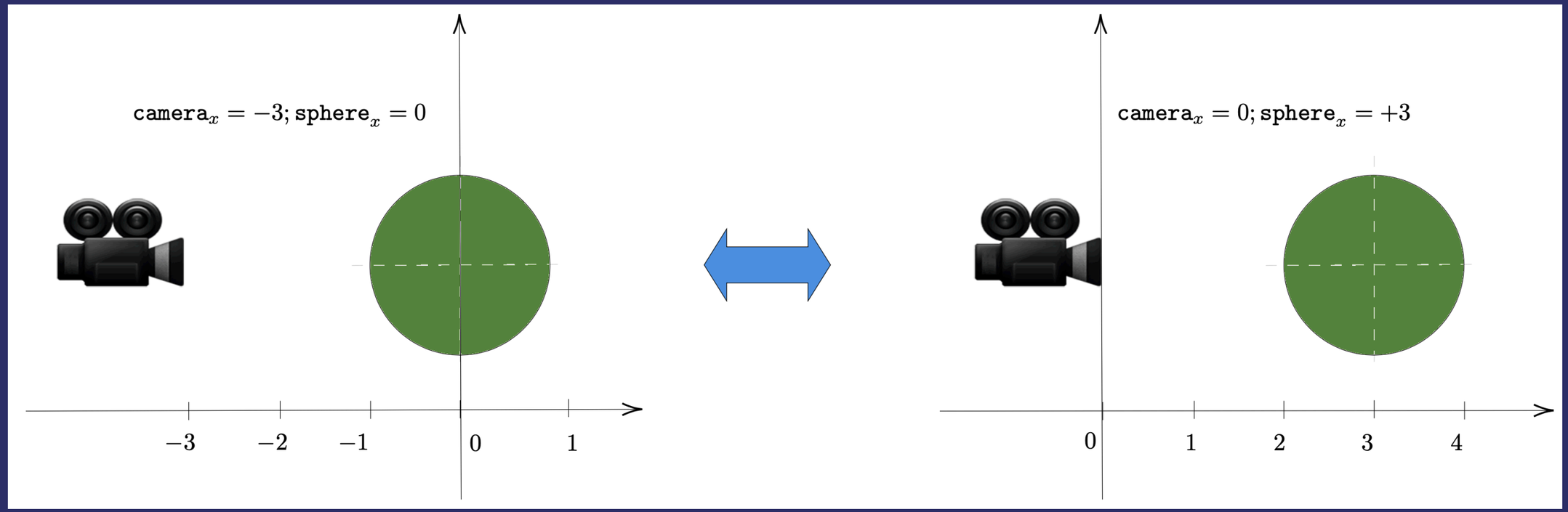
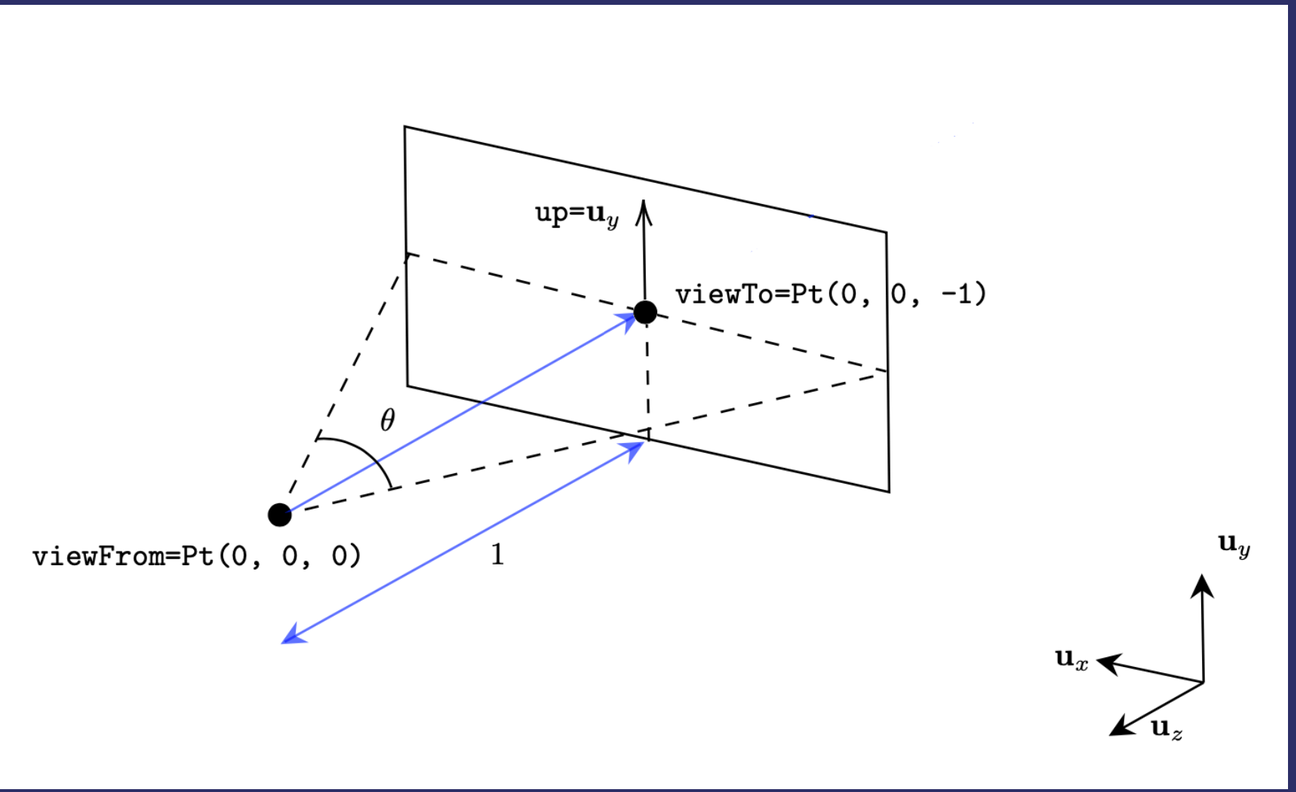


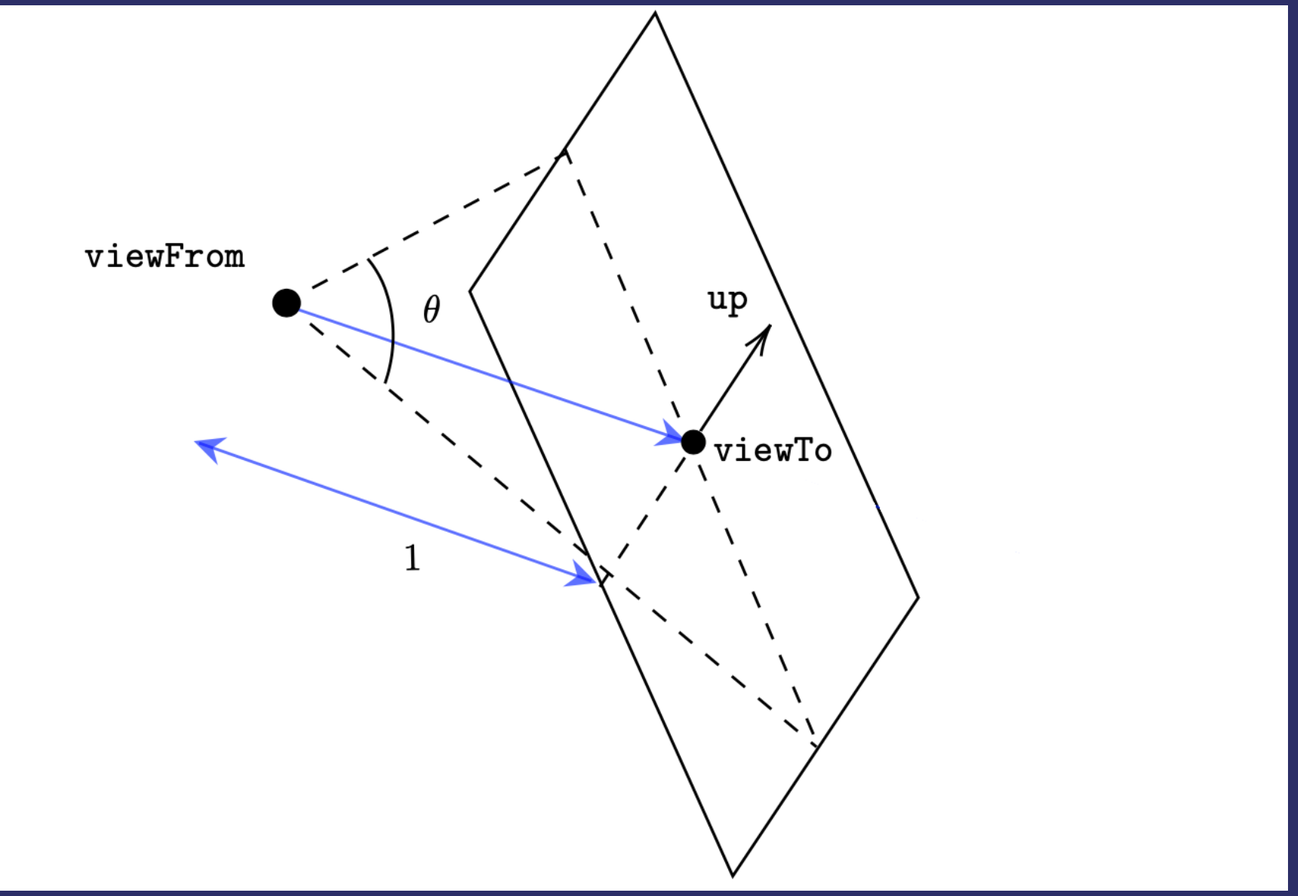
→ Canonical camera: observe always from `x = 0` and translate the world by `+3`

Camera - canonical




```
case class Camera (
  hRes: Int,
  vRes: Int,
  fieldOfViewRad: Double,
  tf: AT
)
```

Camera - generic

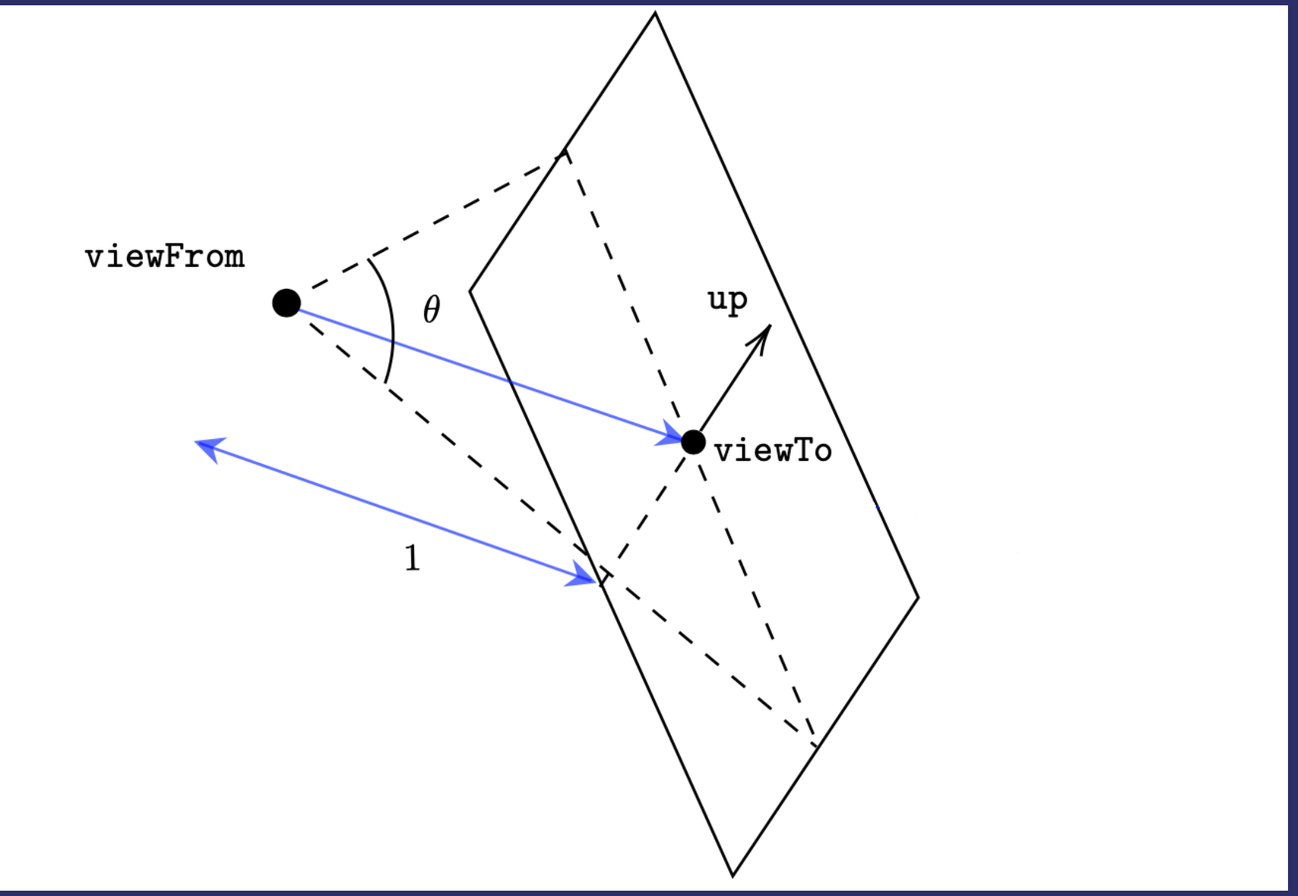



```
object Camera {

  def worldTransformation(from: Pt, to: Pt, up: Vec):
    ZIO[ATModule, Nothing, AT] = for {
    orientationAT <- // some prepration ...
    translateTf   <- ATModule.>.translate(-from.x, -from.y, -from.z)
    composed      <- ATModule.>.compose(translateTf,  orientationAT)
  } yield composed

  def make(
    viewFrom: Pt,
    viewTo: Pt,
    upDirection: Vec,
    visualAngleRad: Double,
    hRes: Int,
    vRes: Int):
    ZIO[ATModule, AlgebraicError, Camera] =
    worldTransformation(viewFrom, viewTo, upDirection).map {
      worldTf => Camera(hRes, vRes, visualAngleRad, worlfTf)
    }
```

Camera - generic

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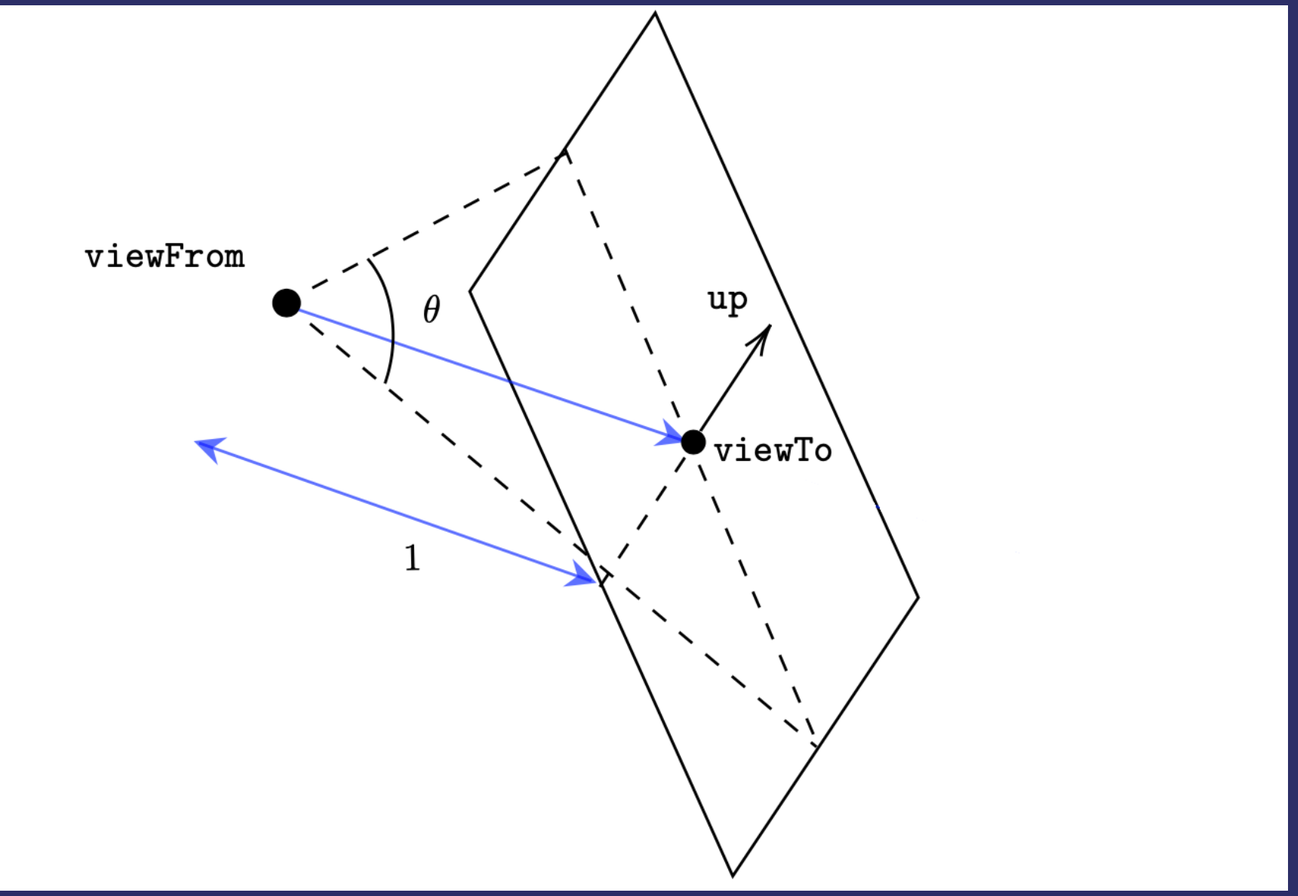


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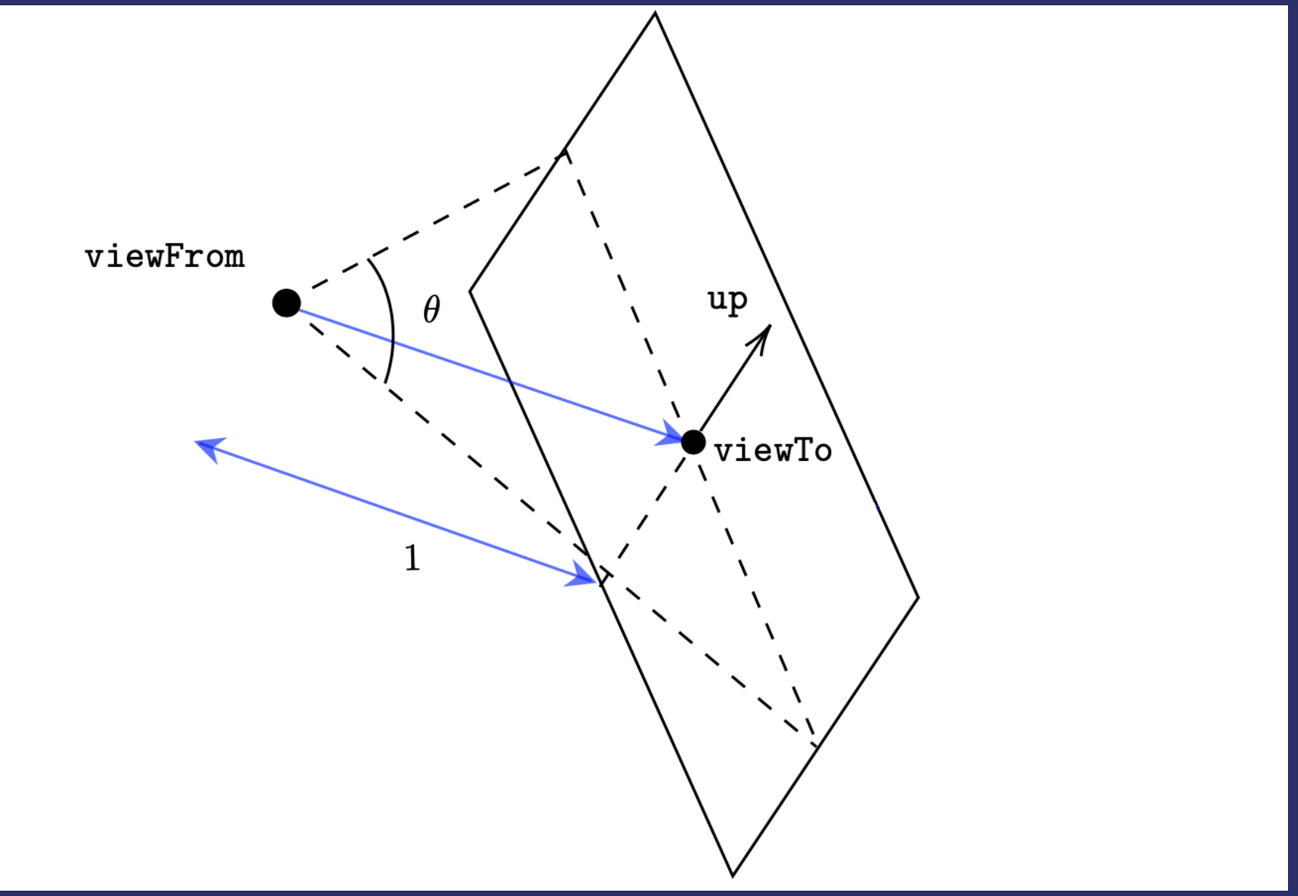


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    }
```

World

```
sealed trait Shape {
  def transformation: AT
  def material: Material
}

case class Sphere(transformation: AT, material: Material) extends Shape
case class Plane(transformation: AT, material: Material) extends Shape
```

World

→ `Sphere.canonical` $\{(x, y, z) : x^2 + y^2 + z^2 = 1\}$

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World

Make a world

```
object Sphere {
  def make(center: Pt, radius: Double, mat: Material): ZIO[ATModule, ATError, Sphere] = for {
    scale     <- ATModule.>.scale(radius, radius, radius)
    translate <- ATModule.>.translate(center.x, center.y, center.z)
    composed  <- ATModule.>.compose(scale, translate)
  } yield Sphere(composed, mat)
}

object Plane {
  def make(...): ZIO[ATModule, ATError, Plane] = ???
}

case class World(pointLight: PointLight, objects: List[Shape])
```

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→ Everything requires `ATModule`

World Rendering - Top Down

Rastering - Generate a stream of colored pixels

```
@accessible(">")
trait RasteringModule {
  val rasteringModule: RasteringModule.Service[Any]
}
object RasteringModule {
  trait Service[R] {
    def raster(world: World, camera: Camera):
      ZStream[R, RayTracerError, ColoredPixel]
  }

  trait AllWhiteTestRasteringModule extends RasteringModule {
    val rasteringModule: Service[Any] = new Service[Any] {
      def raster(world: World, camera: Camera): ZStream[Any, RayTracerError, ColoredPixel] =
        for {
          x <- ZStream.fromIterable(0 until camera.hRes)
          y <- ZStream.fromIterable(0 until camera.vRes)
        } yield ColoredPixel(Pixel(x, y), Color.white))
  }
```

World Rendering - Top Down

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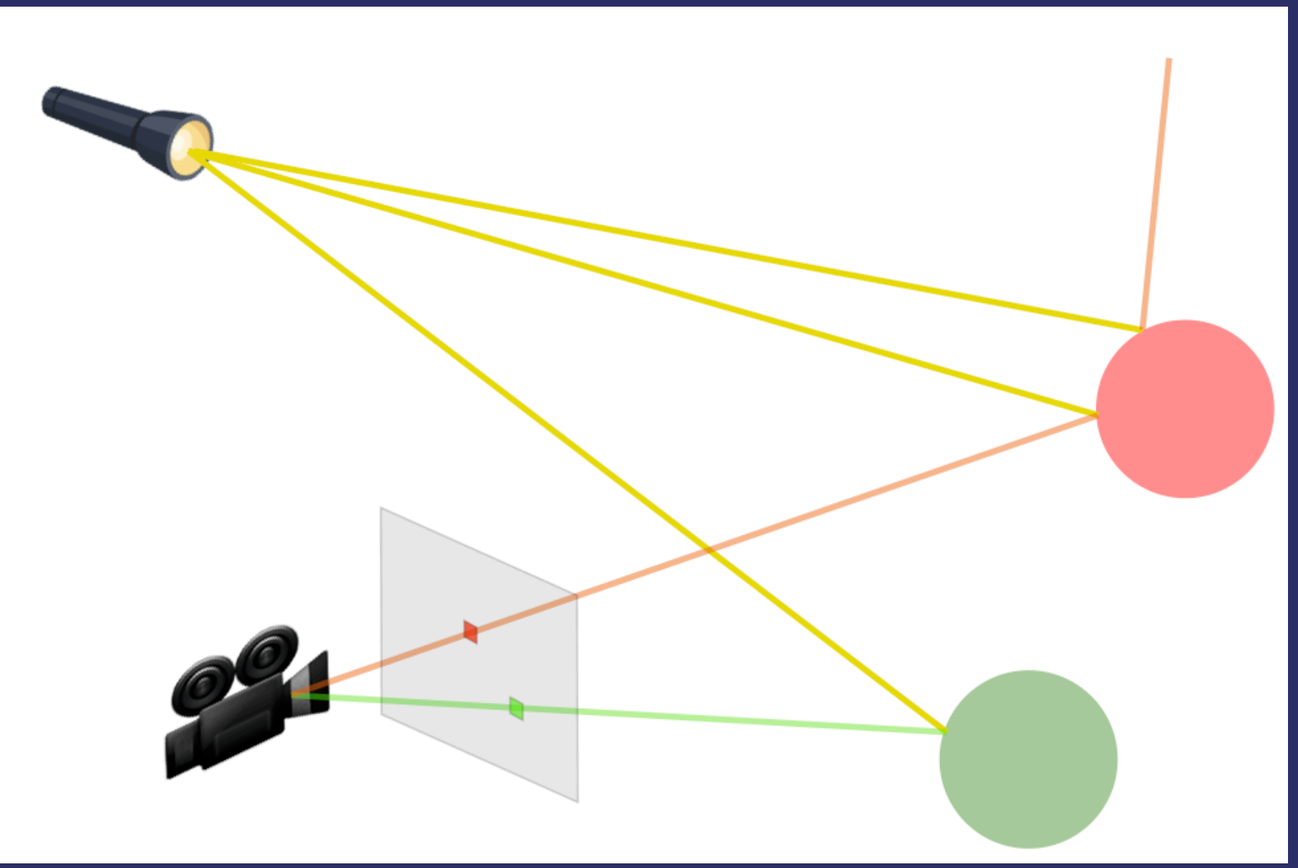
World Rendering - Top Down

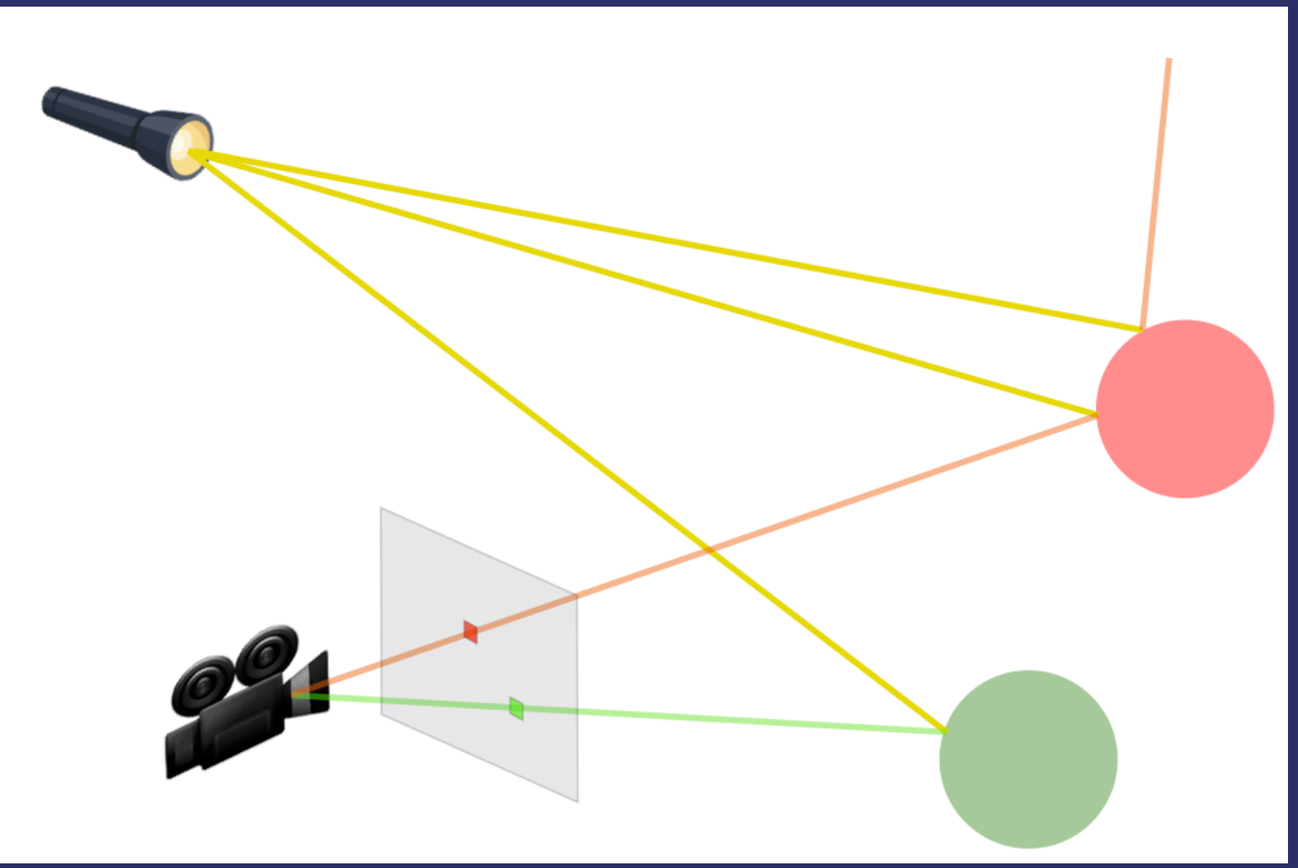


Rastering - Live

```
object CameraModule {
  trait Service[R] {
    def rayForPixel(
      camera: Camera, px: Int, py: Int
    ): ZIO[R, Nothing, Ray]
  }
}
```

```
object WorldModule {
  trait Service[R] {
    def colorForRay(
      world: World, ray: Ray
    ): ZIO[R, RayTracerError, Color]
  }
}
```

World Rendering - Top Down



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→ Camera module - Ray per pixel

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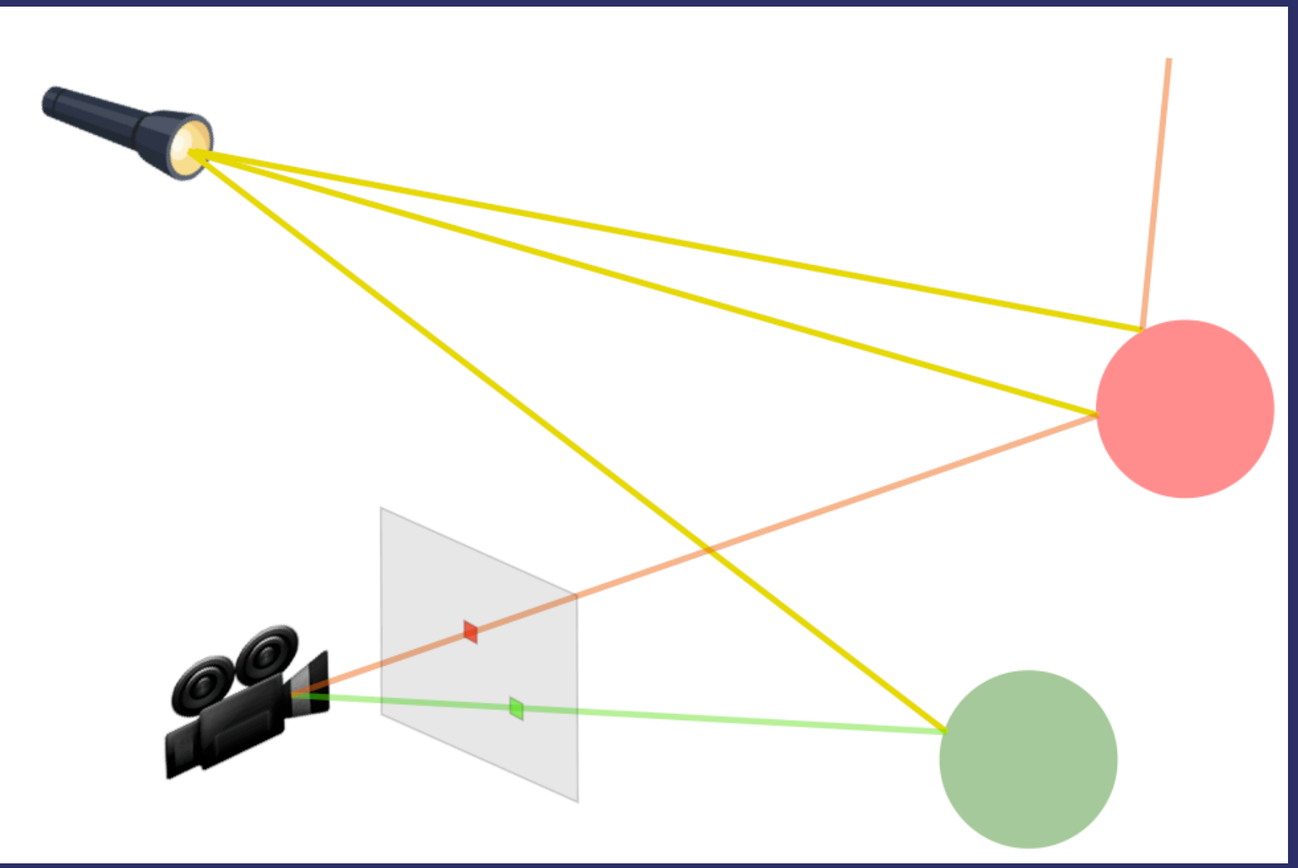
World Rendering - Top Down



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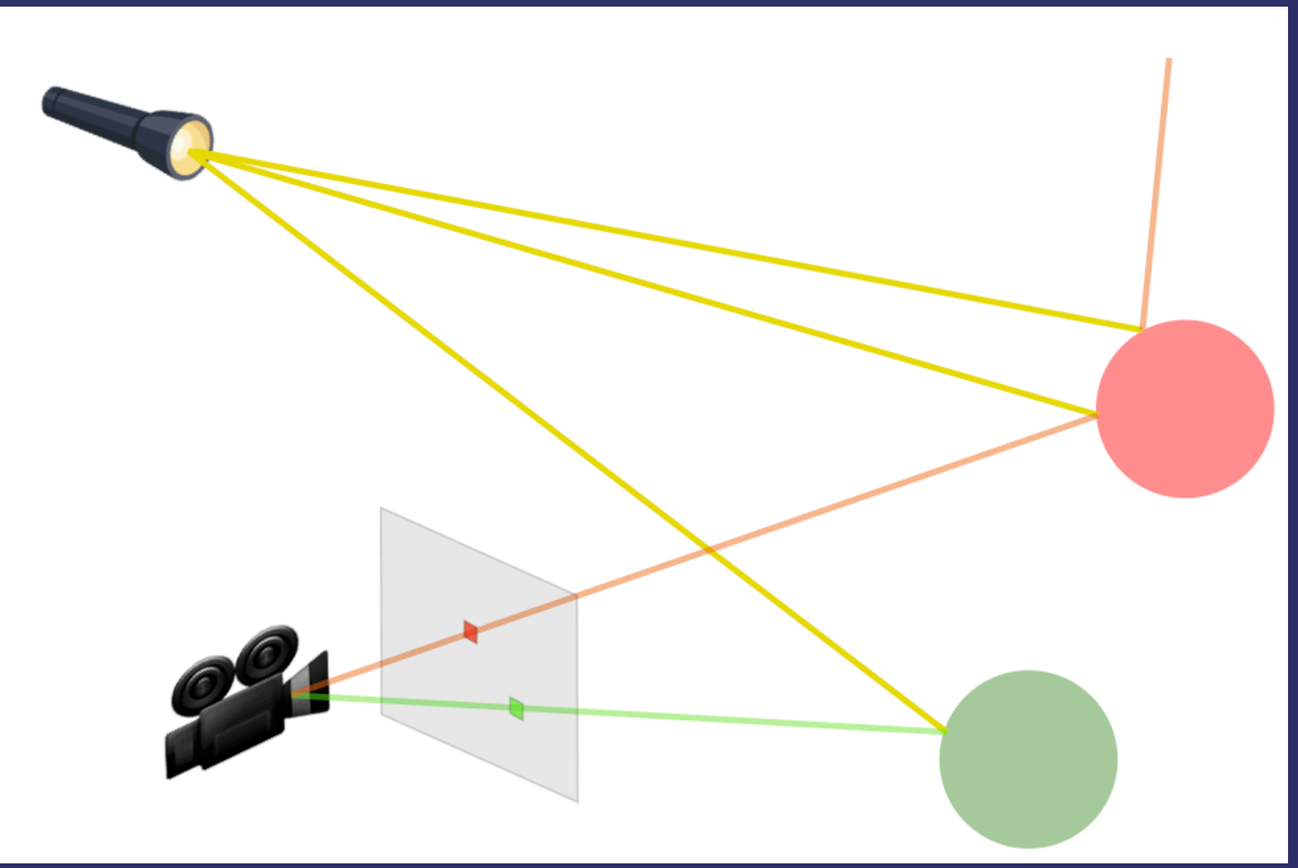
World Rendering - Top Down



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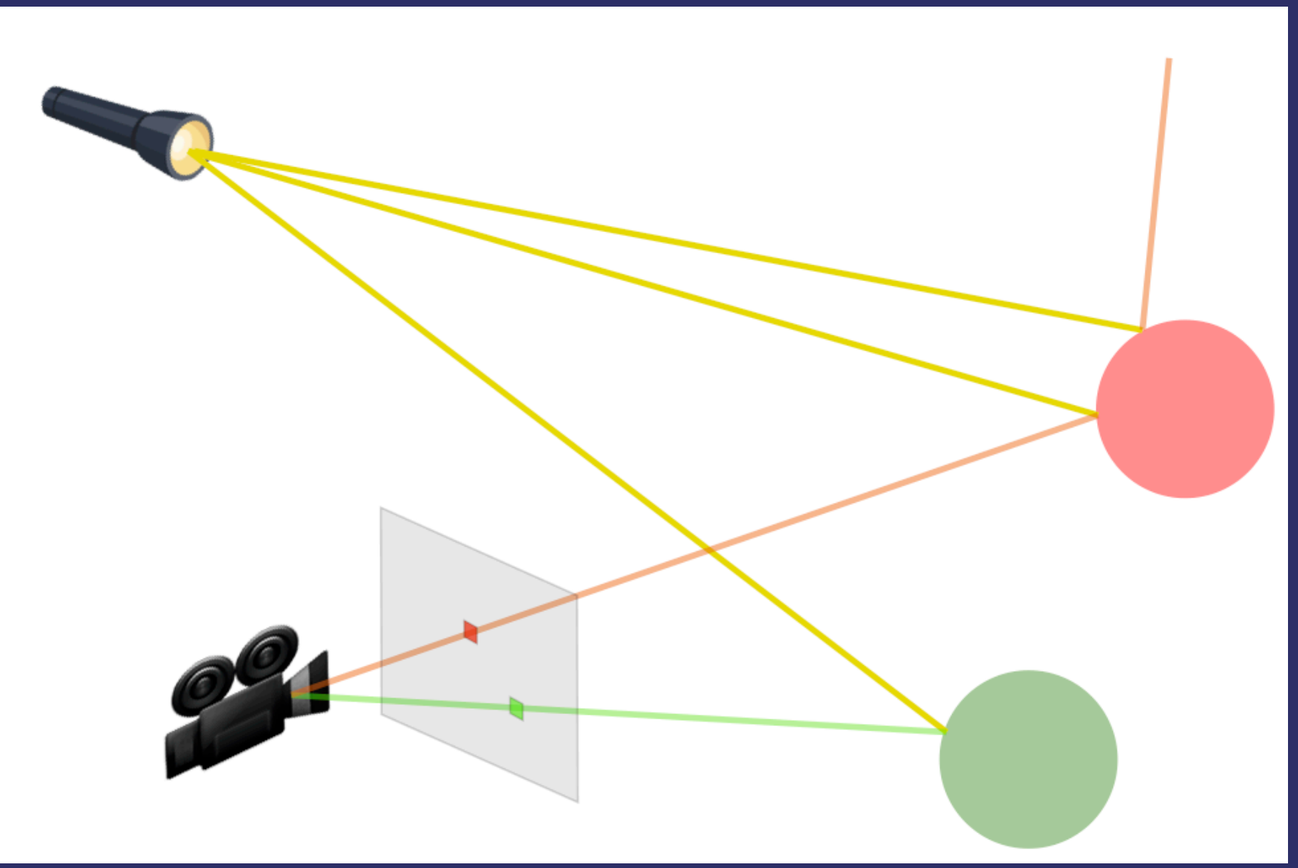

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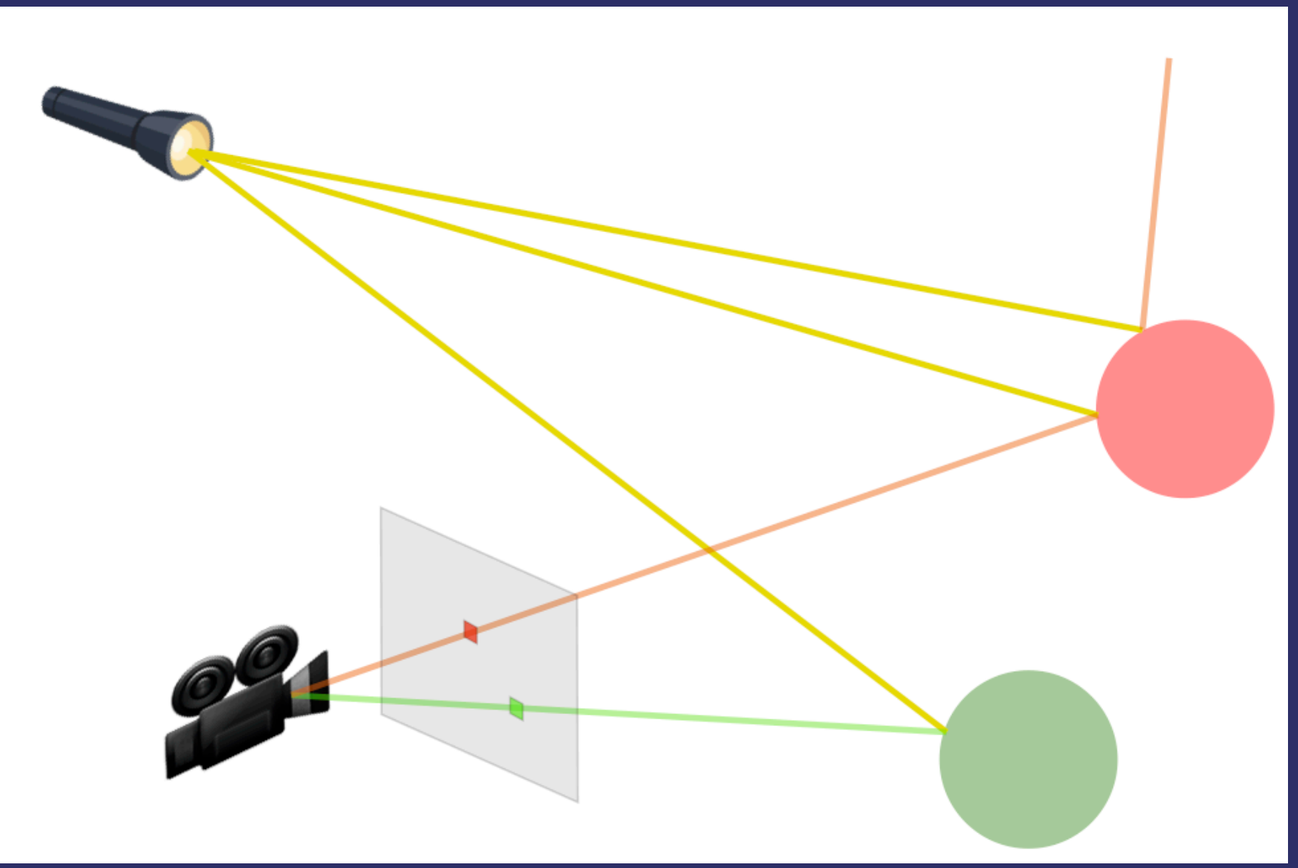

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→ World module - Color per ray

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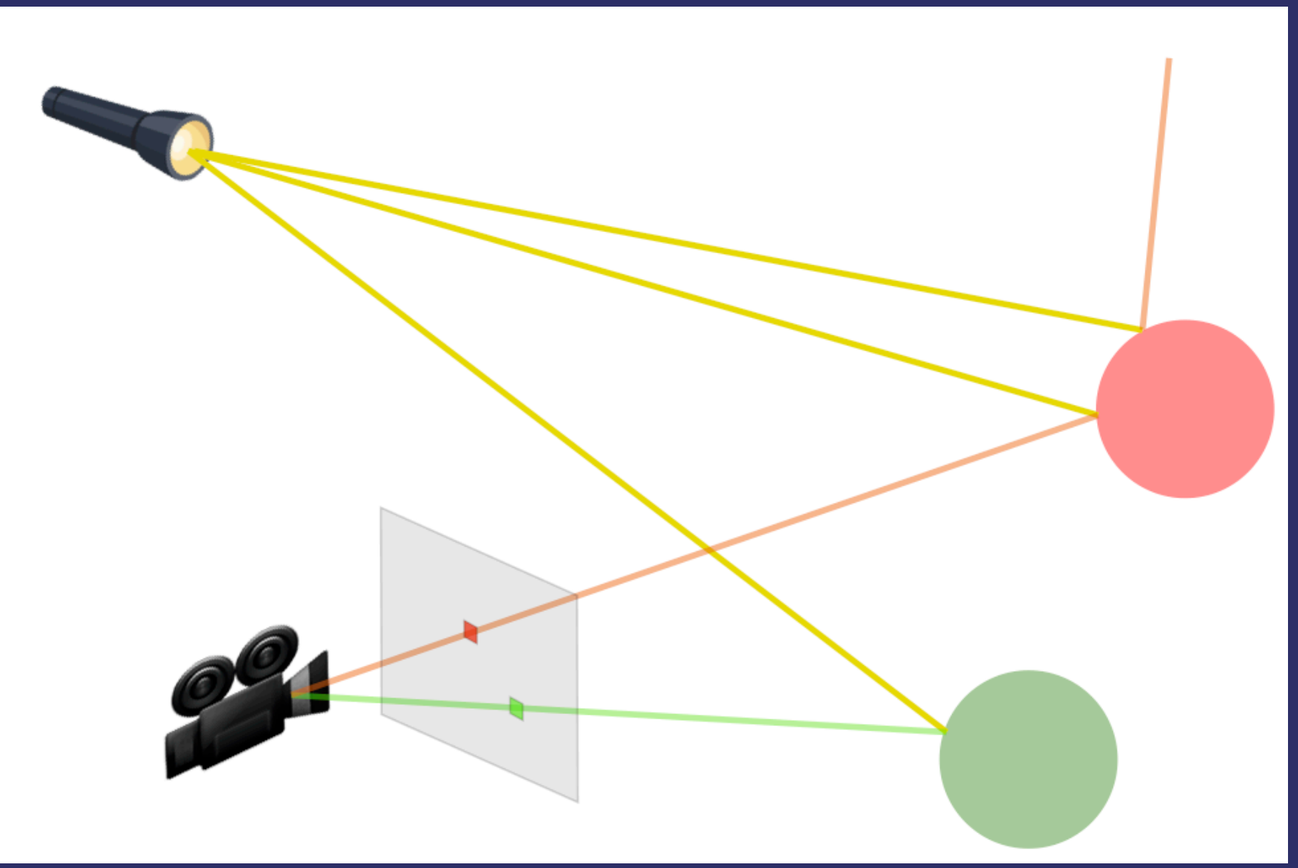

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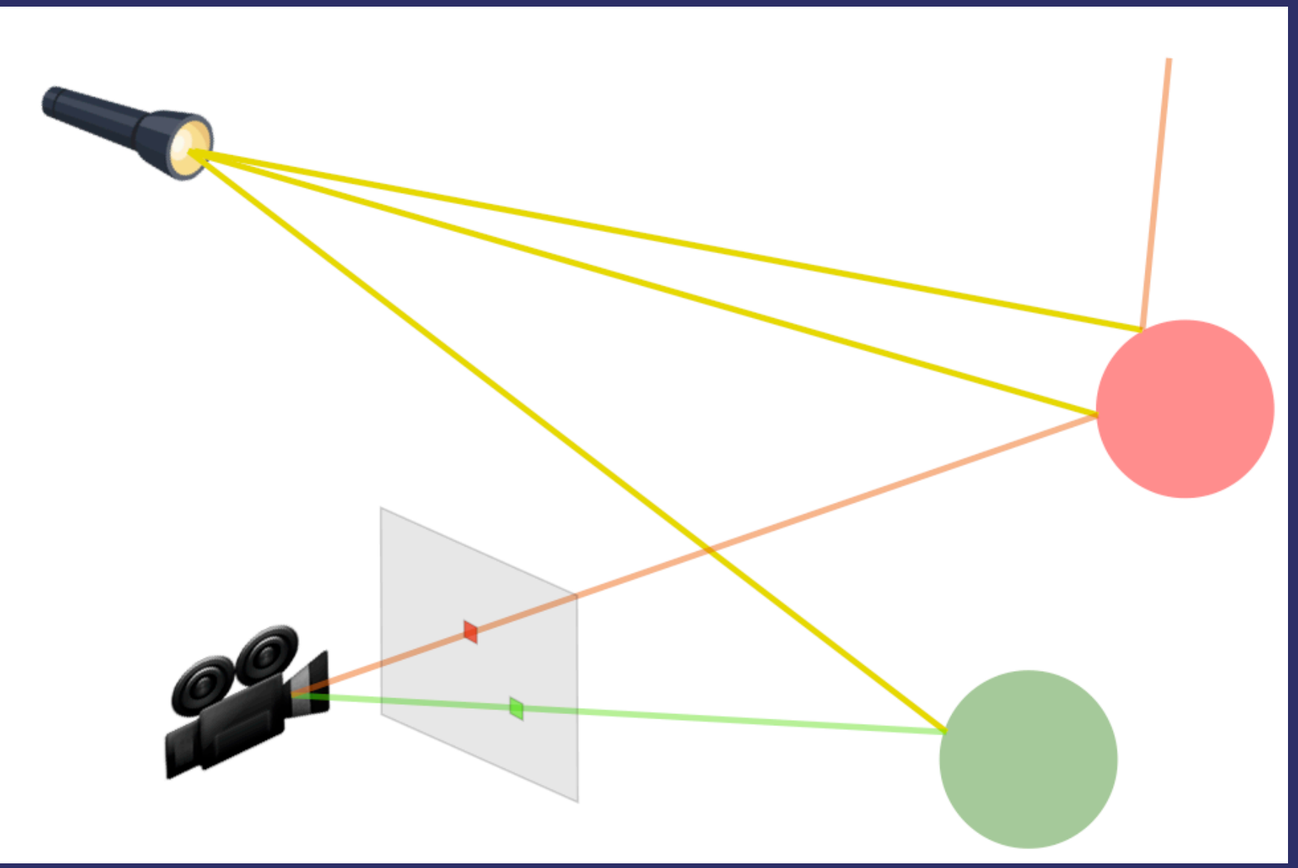

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  }
}
```

World Rendering - Top Down

Rastering - Live

```
trait LiveRasteringModule extends RasteringModule {
  val cameraModule: CameraModule.Service[Any]
  val worldModule: WorldModule.Service[Any]

  val rasteringModule: Service[Any] = new Service[Any] {
    def raster(world: World, camera: Camera): ZStream[Any, RayTracerError, ColoredPixel] = {
      val pixels: Stream[Nothing, (Int, Int)] = ???
      pixels.mapM{
        case (px, py) =>
          for {
            ray   <- cameraModule.rayForPixel(camera, px, py)
            color <- worldModule.colorForRay(world, ray)
          } yield data.ColoredPixel(Pixel(px, py), color)
      }
    }
  }
}
```

World Rendering - Top Down

Rastering - Live

```
trait LiveRasteringModule extends RasteringModule {
  val cameraModule: CameraModule.Service[Any]
  val worldModule: WorldModule.Service[Any]

  val rasteringModule: Service[Any] = new Service[Any] {
    def raster(world: World, camera: Camera): ZStream[Any, RayTracerError, ColoredPixel] = {
      val pixels: Stream[Nothing, (Int, Int)] = ???
      pixels.mapM{
        case (px, py) =>
          for {
            ray   <- cameraModule.rayForPixel(camera, px, py)
            color <- worldModule.colorForRay(world, ray)
          } yield data.ColoredPixel(Pixel(px, py), color)
      }
    }
  }
}
```

World Rendering - Top Down

Rastering - Live

```
trait LiveRasteringModule extends RasteringModule {
  val cameraModule: CameraModule.Service[Any]
  val worldModule: WorldModule.Service[Any]

  val rasteringModule: Service[Any] = new Service[Any] {
    def raster(world: World, camera: Camera): ZStream[Any, RayTracerError, ColoredPixel] = {
      val pixels: Stream[Nothing, (Int, Int)] = ???
      pixels.mapM{
        case (px, py) =>
          for {
            ray   <- cameraModule.rayForPixel(camera, px, py)
            color <- worldModule.colorForRay(world, ray)
          } yield data.ColoredPixel(Pixel(px, py), color)
      }
    }
  }
}
```

Test LiveRasteringModule

1 - Define the method under test

```
val world = /* prepare a world */
val camera = /* prepare a camera */

val appUnderTest: ZIO[RasteringModule, RayTracerError, List[ColoredPixel]] =
  RasteringModule.>.raster(world, camera)
    .flatMap(_.runCollect)
```

Test LiveRasteringModule

2 - Annotate the modules as mockable

```
import zio.macros.annotation.mockable

@mockable
trait CameraModule { ... }

@mockable
trait WorldModule { ... }
```

Test LiveRasteringModule

3 - Build the expectations

```
val rayForPixelExp: Expectation[CameraModule, Nothing, Ray] =
  (CameraModule.rayForPixel(equalTo((camera, 0, 0))) returns value(r1)) *>
  (CameraModule.rayForPixel(equalTo((camera, 0, 1))) returns value(r2))

val colorForRayExp: Expectation[WorldModule, Nothing, Color] =
  (WorldModule.colorForRay(equalTo((world, r1, 5))) returns value(Color.red)) *>
  (WorldModule.colorForRay(equalTo((world, r2, 5))) returns value(Color.green))
```

Test LiveRasteringModule

4 - Build the environment for the code under test

```
val appUnderTest: ZIO[RasteringModule, RayTracerError, List[ColoredPixel]] =
  RasteringModule.>.raster(world, camera)
    .flatMap(_.runCollect)

appUnderTest.provideManaged(
  worldModuleExp.managedEnv.zipWith(cameraModuleExp.managedEnv) { (wm, cm) =>
    new LiveRasteringModule {
      val cameraModule: CameraModule.Service[Any] = cm.cameraModule
      val worldModule: WorldModule.Service[Any] = wm.worldModule
        }
      }
    )
```

Test LiveRasteringModule

4 - Build the environment for the code under test

```
val appUnderTest: ZIO[RasteringModule, RayTracerError, List[ColoredPixel]] =
  RasteringModule.>.raster(world, camera)
    .flatMap(_.runCollect)

appUnderTest.provideManaged(
  worldModuleExp.managedEnv.zipWith(cameraModuleExp.managedEnv) { (wm, cm) =>
    new LiveRasteringModule {
      val cameraModule: CameraModule.Service[Any] = cm.cameraModule
      val worldModule: WorldModule.Service[Any] = wm.worldModule
        }
      }
    )
```

Test LiveRasteringModule

5 - Assert on the results

```
assert(res, equalTo(List(
  ColoredPixel(Pixel(0, 0), Color.red),
  ColoredPixel(Pixel(0, 1), Color.green),
  ColoredPixel(Pixel(1, 0), Color.blue),
  ColoredPixel(Pixel(1, 1), Color.white),
  ))
)
```

Test LiveRasteringModule

```
suite("LiveRasteringModule") {
  testM("raster should rely on cameraModule and world module") {
    val camera = Camera.makeUnsafe(Pt.origin, Pt(0, 0, -1), Vec.uy, math.Pi / 3, 2, 2)
    val world = World(PointLight(Pt(5, 5, 5), Color.white), List())
    val appUnderTest: ZIO[RasteringModule, RayTracerError, List[ColoredPixel]] =
      RasteringModule.>.raster(world, camera).flatMap(_.runCollect)

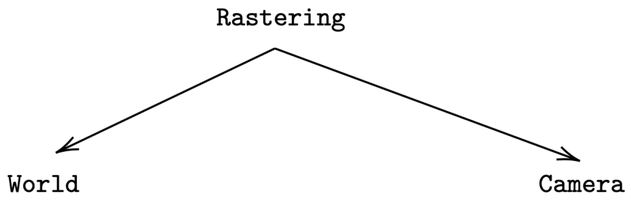
    for {
      (worldModuleExp, cameraModuleExp) <- RasteringModuleMocks.mockExpectations(world, camera)
      res <- appUnderTest.provideManaged(
        worldModuleExp.managedEnv.zipWith(cameraModuleExp.managedEnv) { (wm, cm) =>
          new LiveRasteringModule {
            val cameraModule: CameraModule.Service[Any] = cm.cameraModule
            val worldModule: WorldModule.Service[Any] = wm.worldModule
              }
            }
          )
      } yield assert(res, equalTo(List(
          ColoredPixel(Pixel(0, 0), Color.red),
          ColoredPixel(Pixel(0, 1), Color.green)
          )))
  }
}
```

Test

Takeaway: Implement and test every layer only in terms of the immediately underlying layer

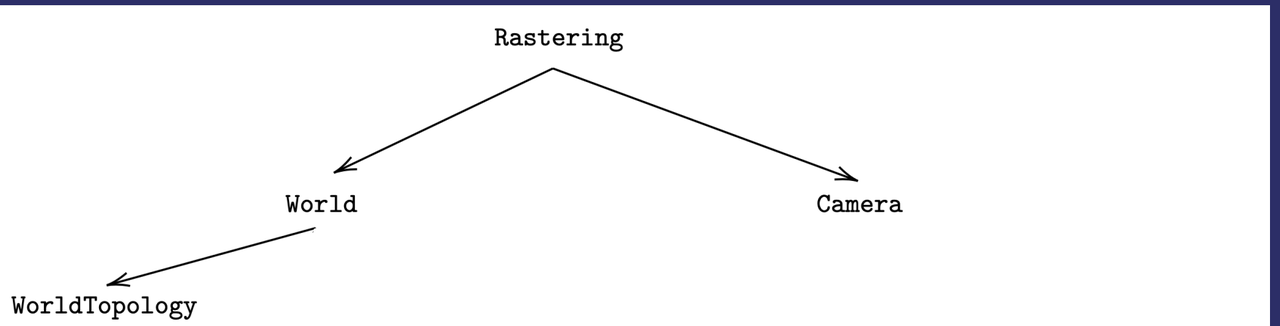

IT'S MODULES
ALL THE WAY DOWN
imgflip.com

Live CameraModule




```
trait Live extends CameraModule {
  val aTModule: ATModule.Service[Any]
  /* implementation */
}
```

Live WorldModule

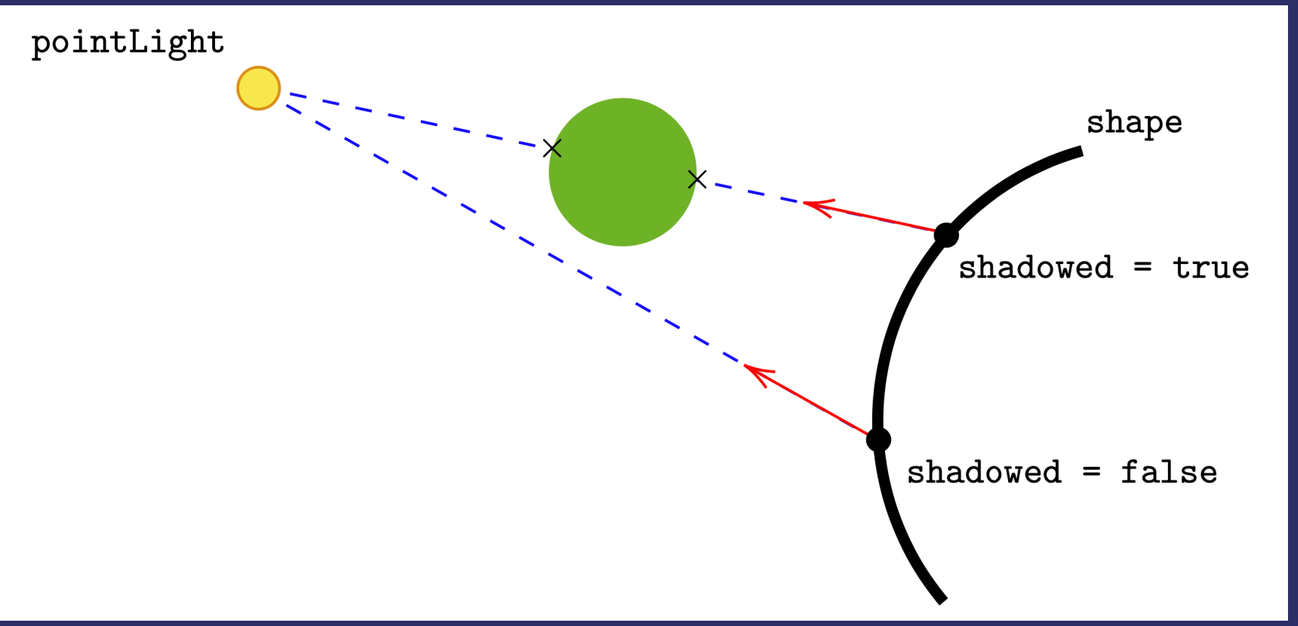


WorldTopologyModule

```
trait Live extends WorldModule {
  val worldTopologyModule: WorldTopologyModule.Service[Any]

  val worldModule: Service[Any] = new Service[Any] {
    def colorForRay(
      world: World, ray: Ray, remaining: Ref[Int]
    ): ZIO[Any, RayTracerError, Color] = {
      /* use other modules */
    }
  }
}
```

Live WorldModule

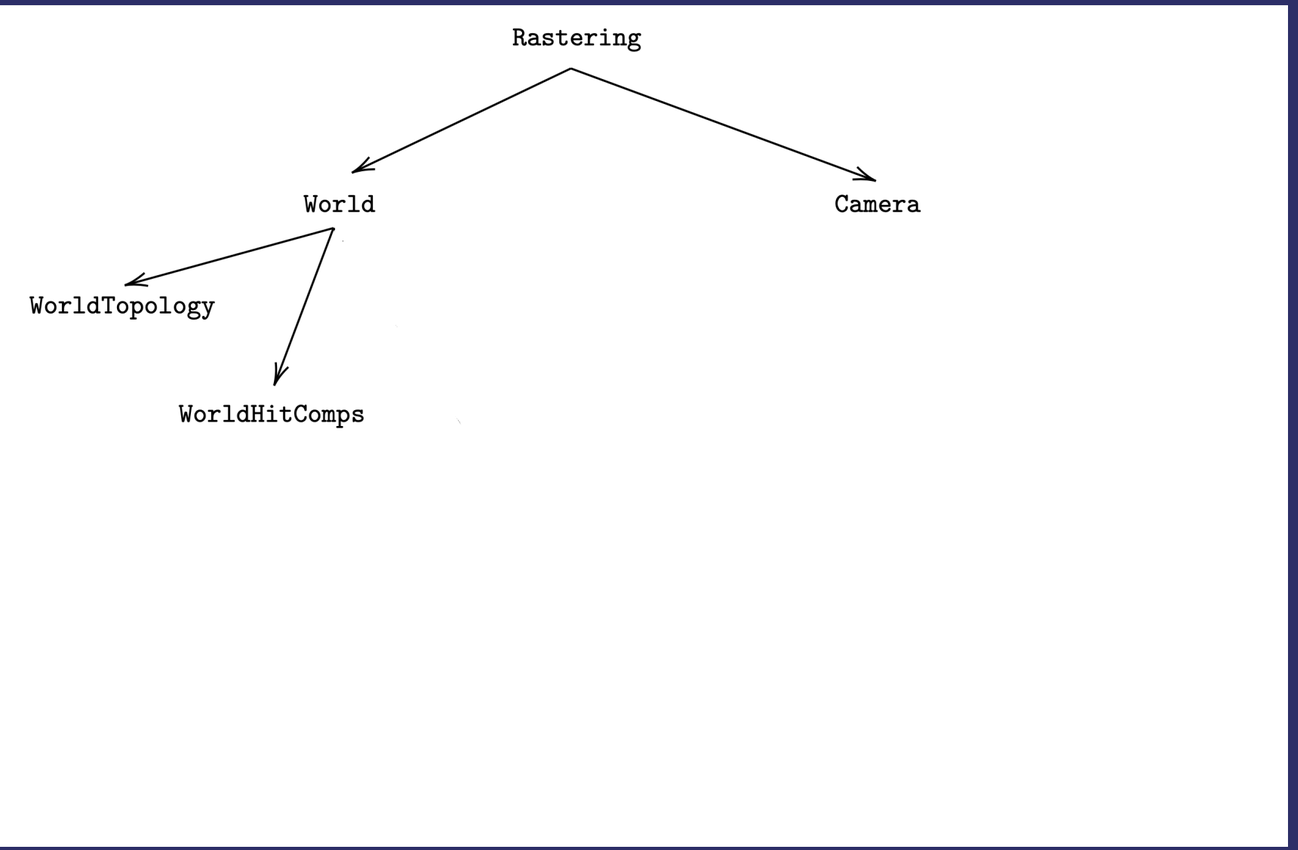


WorldTopologyModule

```
trait Live extends WorldModule {
  val worldTopologyModule: WorldTopologyModule.Service[Any]

  val worldModule: Service[Any] = new Service[Any] {
    def colorForRay(
      world: World, ray: Ray, remaining: Ref[Int]
    ): ZIO[Any, RayTracerError, Color] = {
      /* use other modules */
    }
  }
}
```

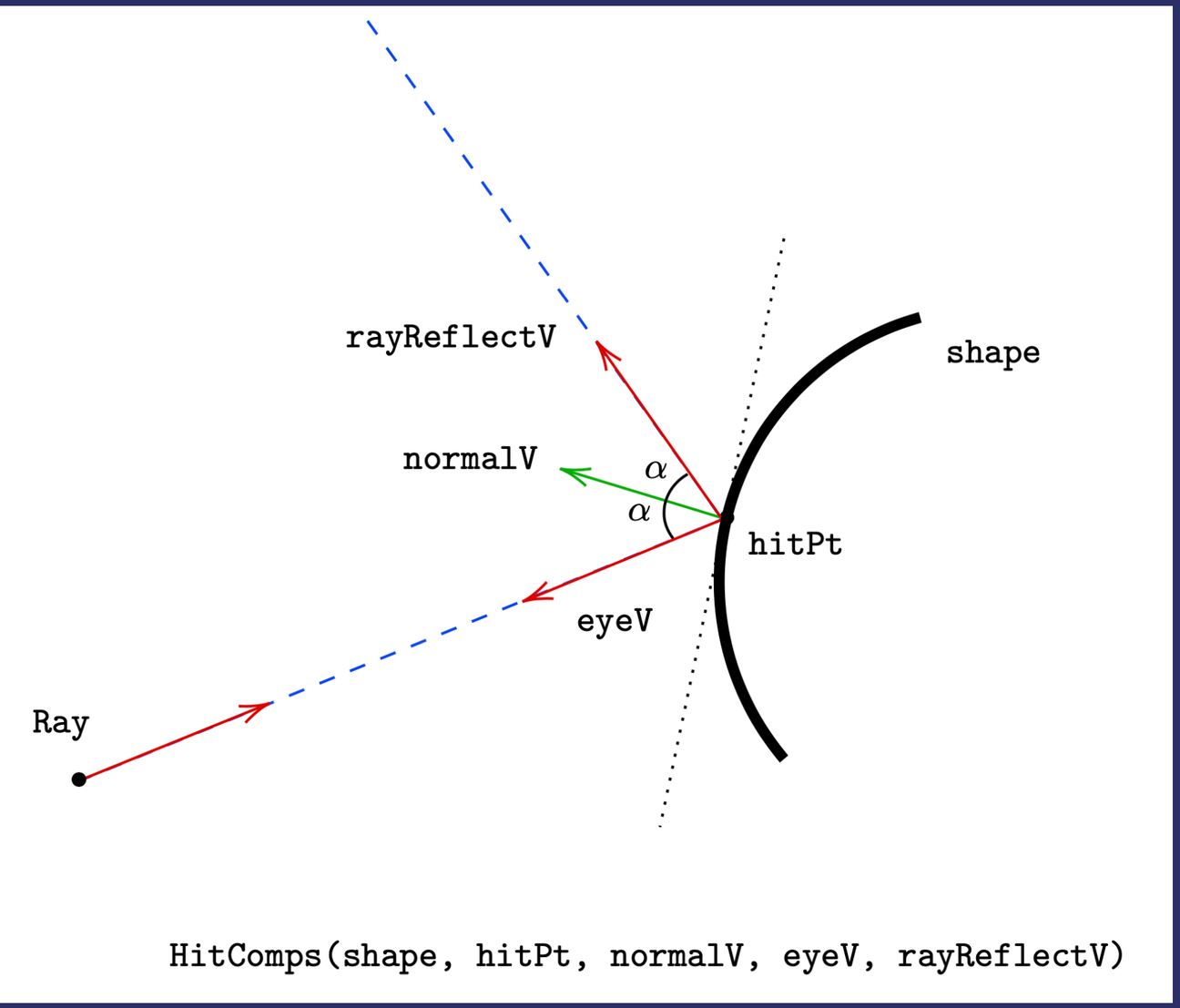
Live WorldModule



WorldHitCompsModule

```
trait Live extends WorldModule {
  val worldTopologyModule: WorldTopologyModule.Service[Any]
  val worldHitCompsModule: WorldHitCompsModule.Service[Any]

  val worldModule: Service[Any] = new Service[Any] {
    def colorForRay(
      world: World, ray: Ray, remaining: Ref[Int]
    ): ZIO[Any, RayTracerError, Color] = {
      /* use other modules */
    }
  }
}
```



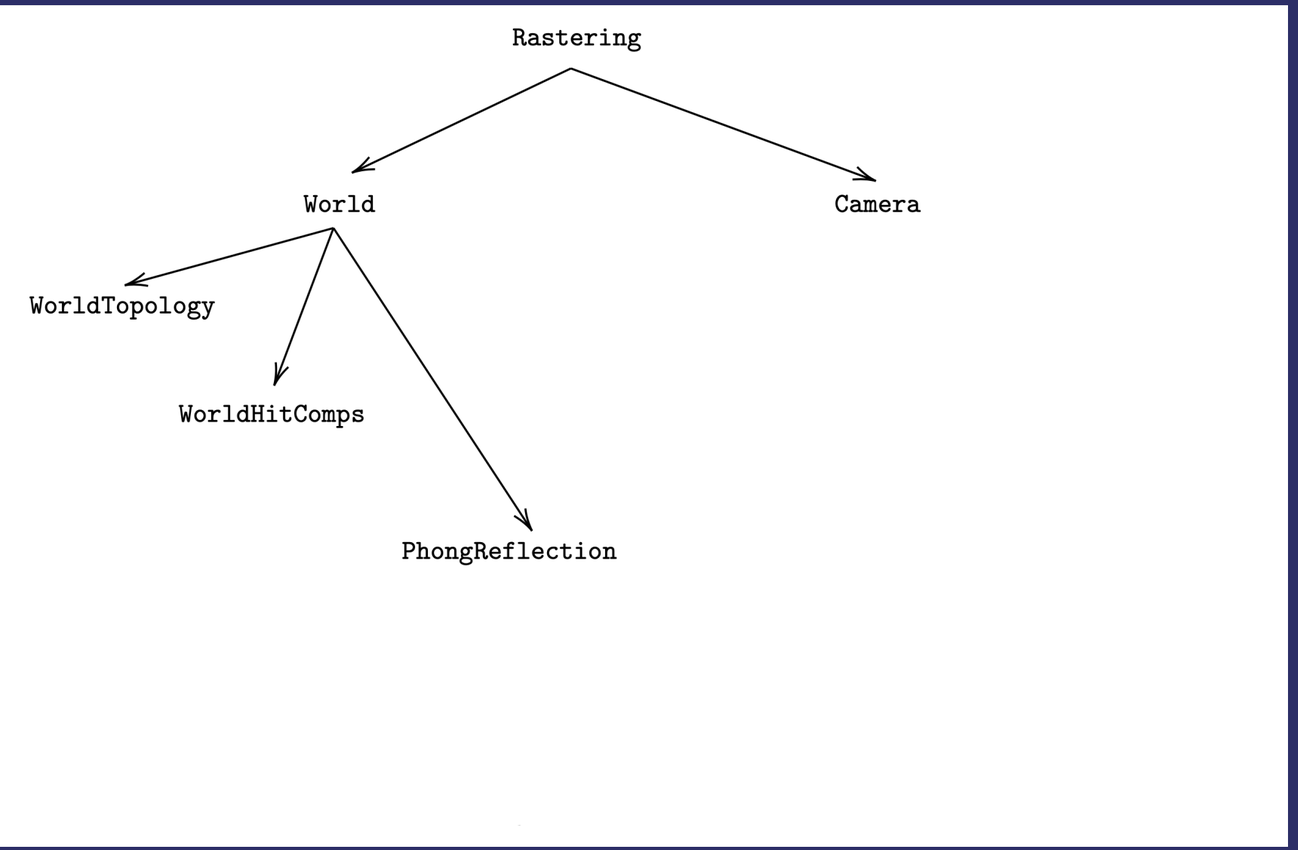
Live WorldModule

WorldHitCompsModule

```
case class HitComps(
  shape: Shape, hitPt: Pt, normalV: Vec, eyeV: Vec, rayReflectV: Vec
)

trait Service[R] {
  def hitComps(
   ray: Ray, hit: Intersection, intersections: List[Intersection]
  ): ZIO[R, Nothing, HitComps]
}
```

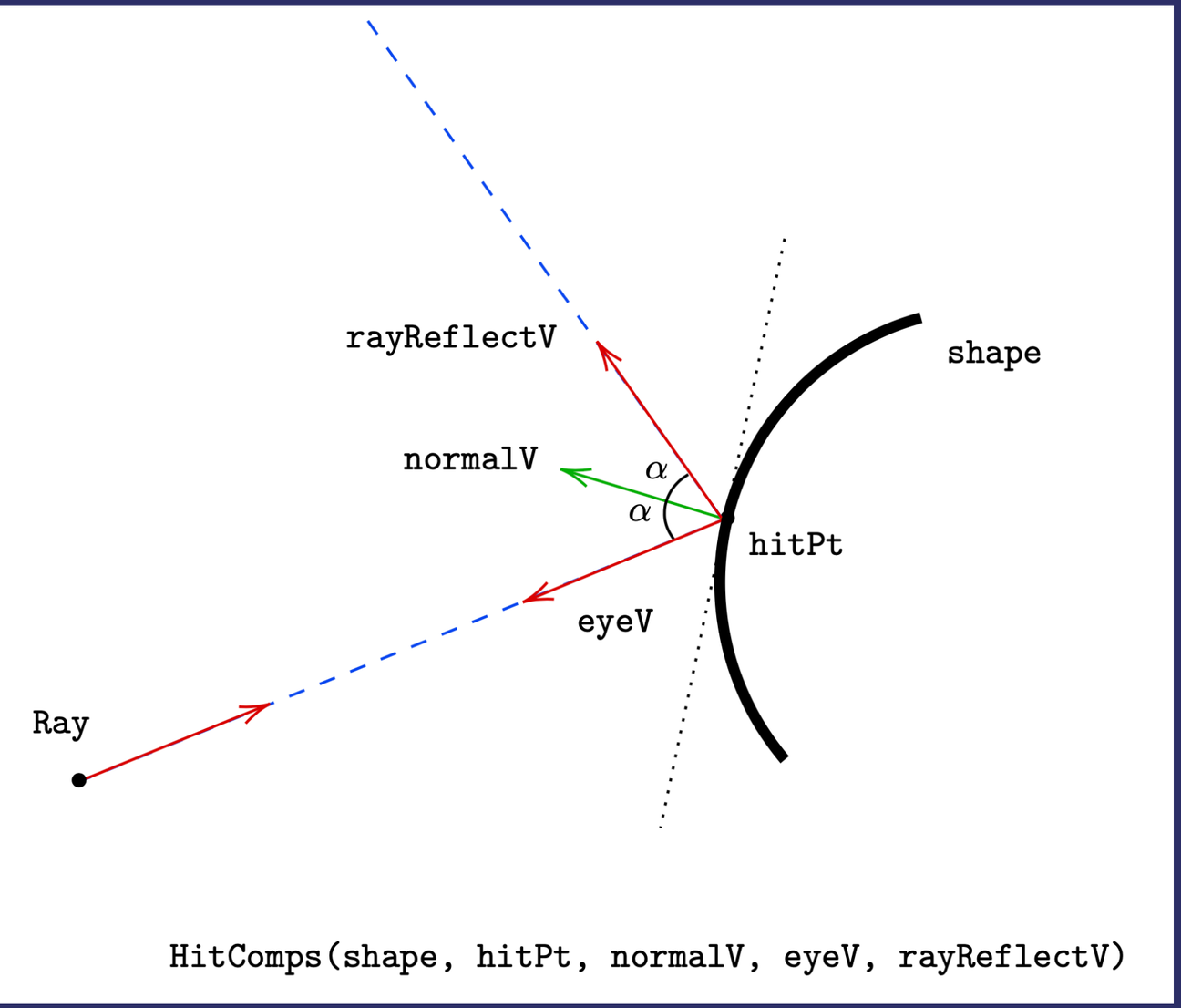
Live WorldModule



PhongReflectionModule

```
trait Live extends WorldModule {
  val worldTopologyModule: WorldTopologyModule.Service[Any]
  val worldHitCompsModule: WorldHitCompsModule.Service[Any]
  val phongReflectionModule: PhongReflectionModule.Service[Any]

  val worldModule: Service[Any] = new Service[Any] {
    def colorForRay(
      world: World, ray: Ray, remaining: Ref[Int]
    ): ZIO[Any, RayTracerError, Color] = {
      /* use other modules */
    }
  }
}
```

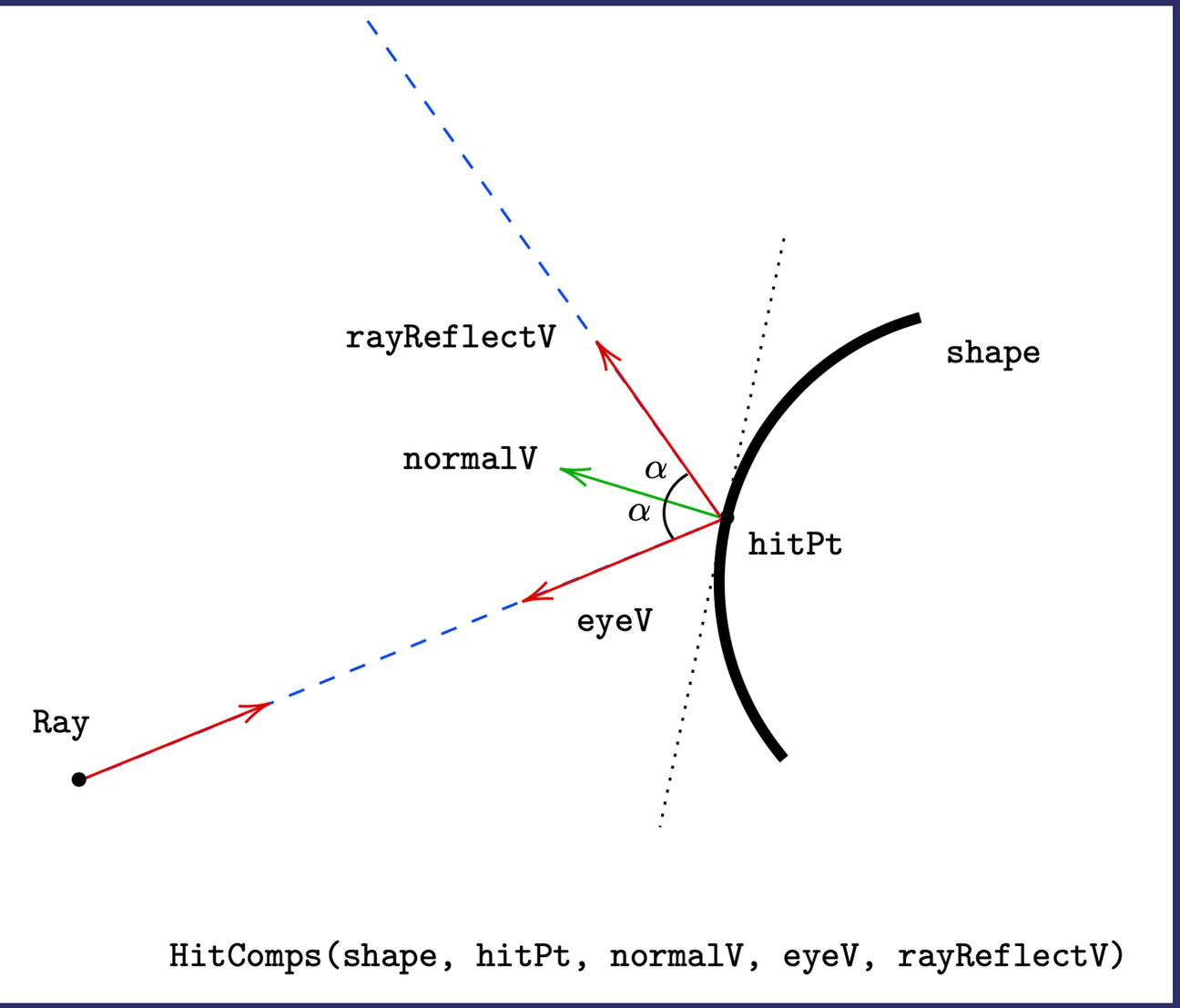


Live WorldModule

PhongReflectionModule

```
case class PhongComponents(
  ambient: Color, diffuse: Color, reflective: Color
) {
    def toColor: Color = ambient + diffuse + reflective
}

trait BlackWhite extends PhongReflectionModule {
  val phongReflectionModule: Service[Any] =
    new Service[Any] {
      def lighting(
        pointLight: PointLight, hitComps: HitComps, inShadow: Boolean
      ): UIO[PhongComponents] = {
        if (inShadow) UIO(PhongComponents.allBlack)
        else UIO(PhongComponents.allWhite)
    }
  }
}
```



Live WorldModule

PhongReflectionModule

```
case class PhongComponents(
  ambient: Color, diffuse: Color, reflective: Color
) {
    def toColor: Color = ambient + diffuse + reflective
}

trait BlackWhite extends PhongReflectionModule {
  val phongReflectionModule: Service[Any] =
    new Service[Any] {
      def lighting(
        pointLight: PointLight, hitComps: HitComps, inShadow: Boolean
      ): UIO[PhongComponents] = {
        if (inShadow) UIO(PhongComponents.allBlack)
        else UIO(PhongComponents.allWhite)
    }
  }
}
```

Display the first canvas / 1

```
def drawOnCanvasWithCamera(world: World, camera: Camera, canvas: Canvas):
  ZIO[RasteringModule, RayTracerError, Unit] =
  for {
    coloredPointsStream <- RasteringModule.>.raster(world, camera)
    _                   <- coloredPointsStream.mapM(cp => canvas.update(cp)).run(Sink.drain)
  } yield ()

def program(viewFrom: Pt):
  ZIO[CanvasSerializer with RasteringModule with ATModule, RayTracerError, Unit] =
  for {
    camera <- cameraFor(viewFrom: Pt)
    w      <- world
    canvas <- Canvas.create()
    _      <- drawOnCanvasWithCamera(w, camera, canvas)
    _      <- CanvasSerializer.>.serialize(canvas, 255)
  } yield ()
```

Display the first canvas / 2

```
def program(viewFrom: Pt):
  ZIO[CanvasSerializer with RasteringModule with ATModule, RayTracerError, Unit]

program(Pt(2, 2, -10))
  .provide(
    new CanvasSerializer.PPMCanvasSerializer
    with RasteringModule.ChunkRasteringModule
    with ATModule.Live
  )
// Members declared in zio.blocking.Blocking
// [error]   val blocking: zio.blocking.Blocking.Service[Any] = ???
// [error]
// [error]   // Members declared in modules.RasteringModule.ChunkRasteringModule
// [error]   val cameraModule: modules.CameraModule.Service[Any] = ???
// [error]   val worldModule: modules.WorldModule.Service[Any] = ???
// [error]
// [error]   // Members declared in geometry.affine.ATModule.Live
// [error]   val matrixModule: geometry.matrix.MatrixModule.Service[Any] = ???
```

Display the first canvas / 2

```
def program(viewFrom: Pt):
  ZIO[CanvasSerializer with RasteringModule with ATModule, RayTracerError, Unit]

program(Pt(2, 2, -10))
  .provide(
    new CanvasSerializer.PPMCanvasSerializer
    with RasteringModule.ChunkRasteringModule
    with ATModule.Live
  )
// Members declared in zio.blocking.Blocking
// [error]   val blocking: zio.blocking.Blocking.Service[Any] = ???
// [error]
// [error]   // Members declared in modules.RasteringModule.ChunkRasteringModule
// [error]   val cameraModule: modules.CameraModule.Service[Any] = ???
// [error]   val worldModule: modules.WorldModule.Service[Any] = ???
// [error]
// [error]   // Members declared in geometry.affine.ATModule.Live
// [error]   val matrixModule: geometry.matrix.MatrixModule.Service[Any] = ???
```

Display the first canvas / 2

```
def program(viewFrom: Pt):
  ZIO[CanvasSerializer with RasteringModule with ATModule, RayTracerError, Unit]

program(Pt(2, 2, -10))
  .provide(
    new CanvasSerializer.PPMCanvasSerializer
    with RasteringModule.ChunkRasteringModule
    with ATModule.Live
  )
// Members declared in zio.blocking.Blocking
// [error]   val blocking: zio.blocking.Blocking.Service[Any] = ???
// [error]
// [error]   // Members declared in modules.RasteringModule.ChunkRasteringModule
// [error]   val cameraModule: modules.CameraModule.Service[Any] = ???
// [error]   val worldModule: modules.WorldModule.Service[Any] = ???
// [error]
// [error]   // Members declared in geometry.affine.ATModule.Live
// [error]   val matrixModule: geometry.matrix.MatrixModule.Service[Any] = ???
```

Display the first canvas / 3

```
def program(viewFrom: Pt):
  ZIO[CanvasSerializer with RasteringModule with ATModule, RayTracerError, Unit]

program(Pt(2, 2, -10))
  .provide(
    new CanvasSerializer.PPMCanvasSerializer
    with RasteringModule.ChunkRasteringModule
    with ATModule.Live
    with CameraModule.Live
    with MatrixModule.BreezeLive
    with WorldModule.Live
    )
  )
// [error]   // Members declared in io.tuliplogic.raytracer.ops.model.modules.WorldModule.Live
// [error]   val phongReflectionModule: io.tuliplogic.raytracer.ops.model.modules.PhongReflectionModule.Service[Any] = ???
// [error]   val worldHitCompsModule: io.tuliplogic.raytracer.ops.model.modules.WorldHitCompsModule.Service[Any] = ???
// [error]   val worldReflectionModule: io.tuliplogic.raytracer.ops.model.modules.WorldReflectionModule.Service[Any] = ???
// [error]   val worldRefractionModule: io.tuliplogic.raytracer.ops.model.modules.WorldRefractionModule.Service[Any] = ???
// [error]   val worldTopologyModule: io.tuliplogic.raytracer.ops.model.modules.WorldTopologyModule.Service[Any] = ???
```

Display the first canvas - /4

Group modules in **trait**

```
trait BasicModules extends
  NormalReflectModule.Live
  with RayModule.Live
  with ATModule.Live
  with MatrixModule.BreezeLive
  with WorldModule.Live
  with WorldTopologyModule.Live
  with WorldHitCompsModule.Live
  with CameraModule.Live
  with RasteringModule.Live
  with Blocking.Live
```

Display the first canvas - /4

Group modules in **trait**

```
trait BasicModules extends
  NormalReflectModule.Live
  with RayModule.Live
  with ATModule.Live
  with MatrixModule.BreezeLive
  with WorldModule.Live
  with WorldTopologyModule.Live
  with WorldHitCompsModule.Live
  with CameraModule.Live
  with RasteringModule.Live
  with Blocking.Live
```

Display the first canvas - /5

How to group typeclasses?

```
program[F[_]
  : NormalReflectModule
  : RayModule
  : ATModule
  : MatrixModule
  : WorldModule
  : WorldTopologyModule
  : WorldHitCompsModule
  : CameraModule
  : RasteringModule
  : Blocking
]

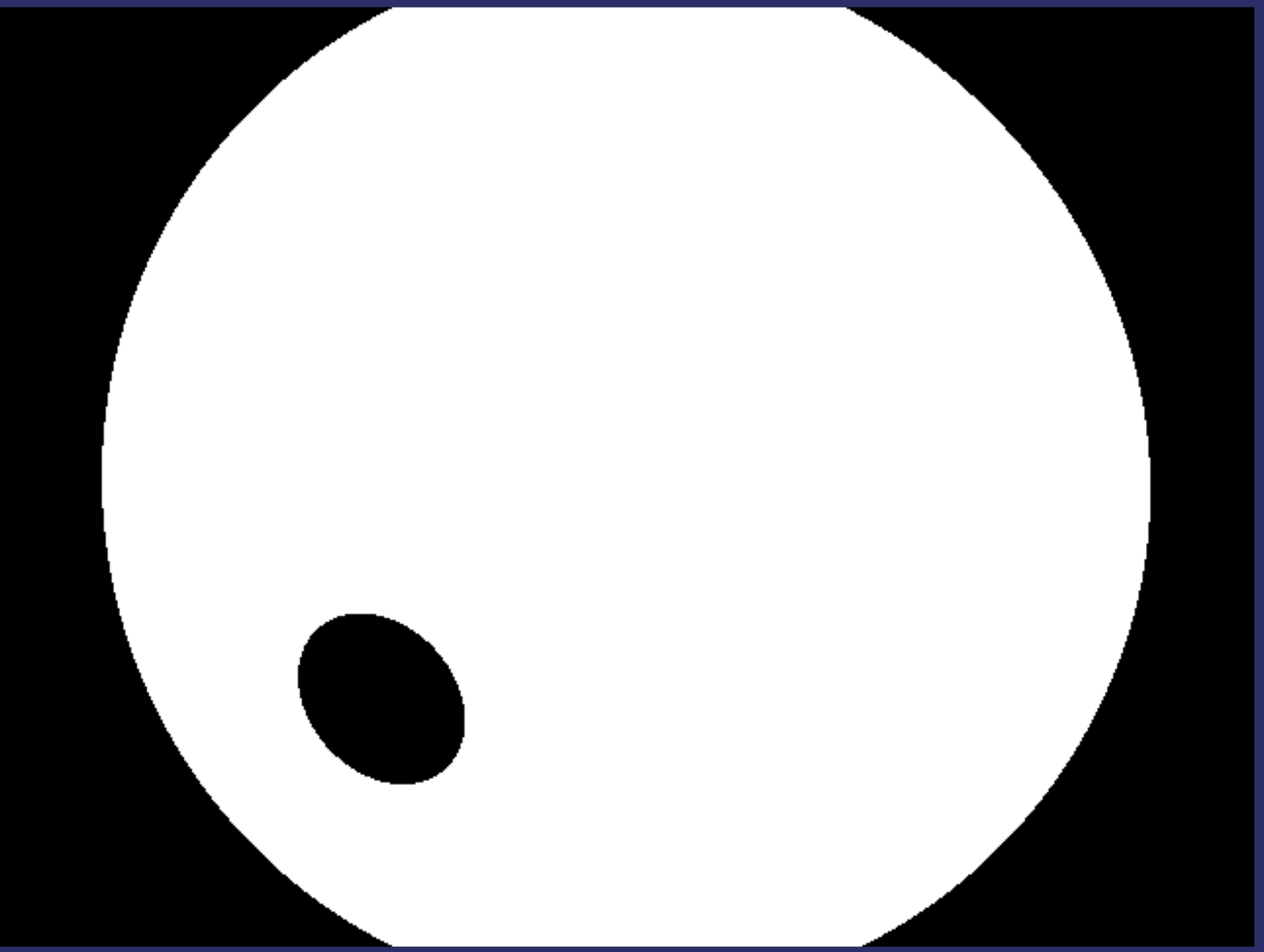
program[F[_]: BasicModules] //not so easy
```

Display the first canvas - /6

Group modules

```
def program(viewFrom: Pt):
  ZIO[CanvasSerializer with RasteringModule with ATModule, RayTracerError, Unit]

program(Pt(2, 2, -10))
  .provide(new BasicModules with PhongReflectionModule.BlackWhite)
```



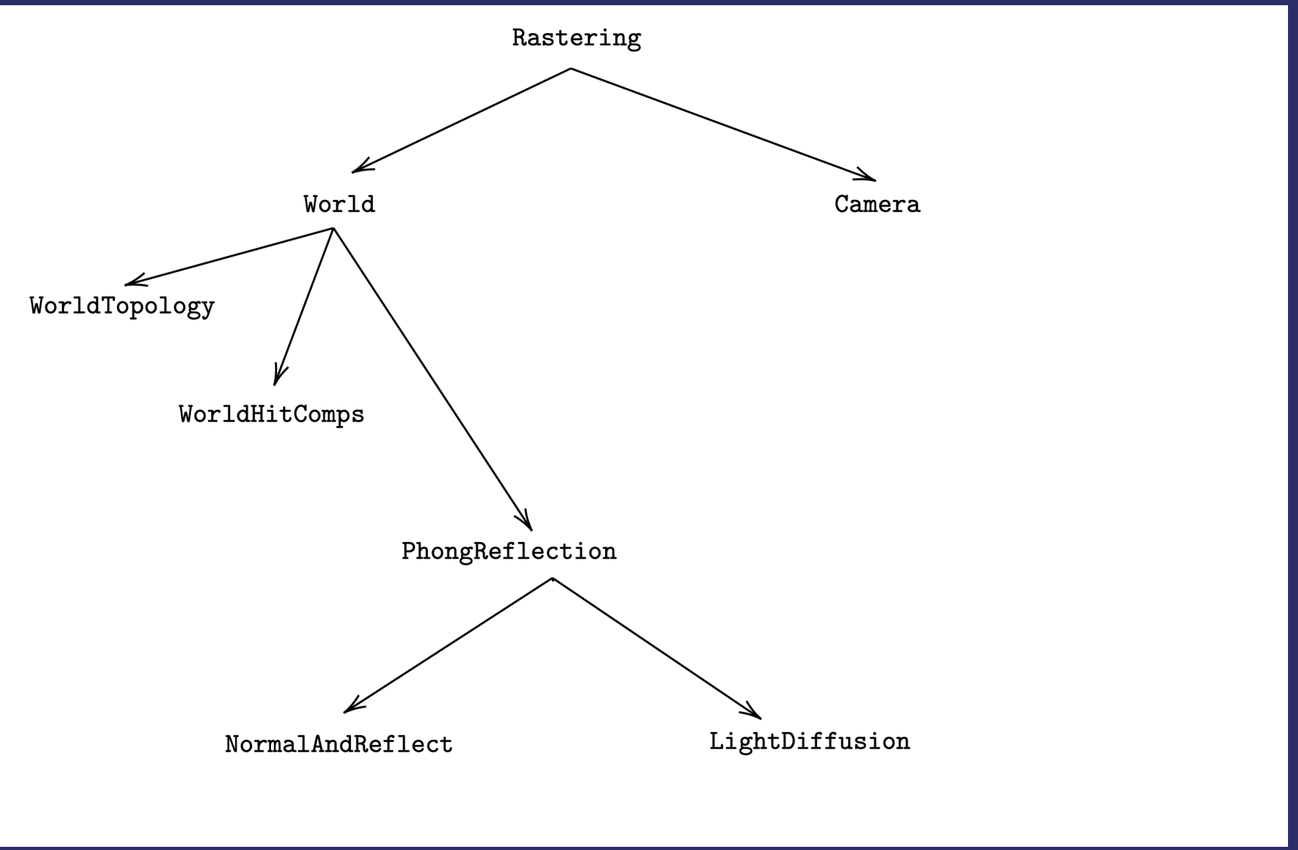
Display the first canvas - /7

Group modules

```
def program(viewFrom: Pt):
  ZIO[CanvasSerializer with RasteringModule with ATModule, RayTracerError, Unit]

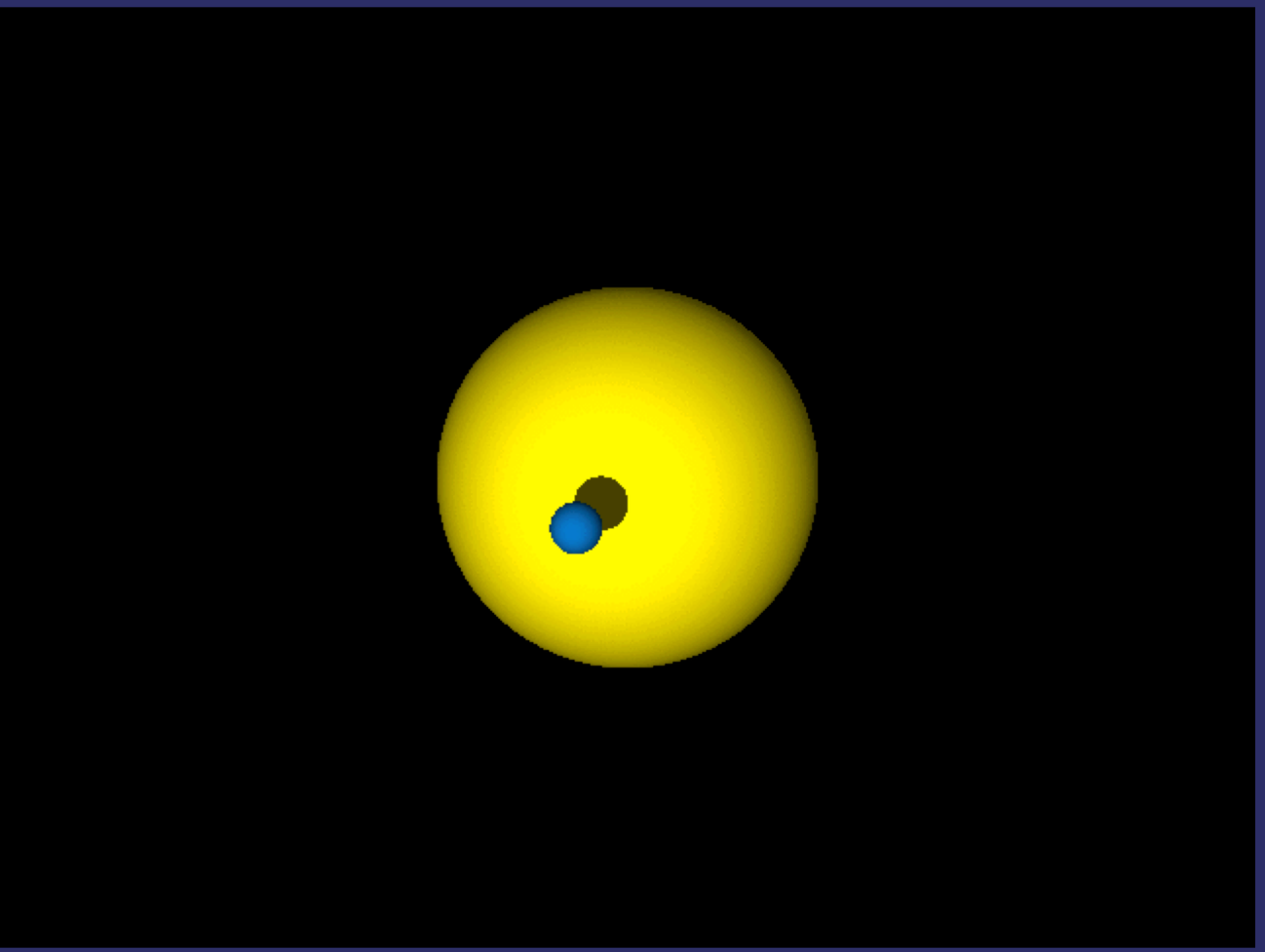
def run(args: List[String]): ZIO[ZEnv, Nothing, Int] =
    ZIO.traverse(-18 to -6)(z => program(Pt(2, 2, z))
      .provide(
        new BasicModules with PhongReflectionModule.BlackWhite
      )
    ).foldM(err =>
      console.putStrLn(s"Execution failed with: $err").as(1),
      _ => UIO.succeed(0)
    )
```

Live PhongReflectionModule



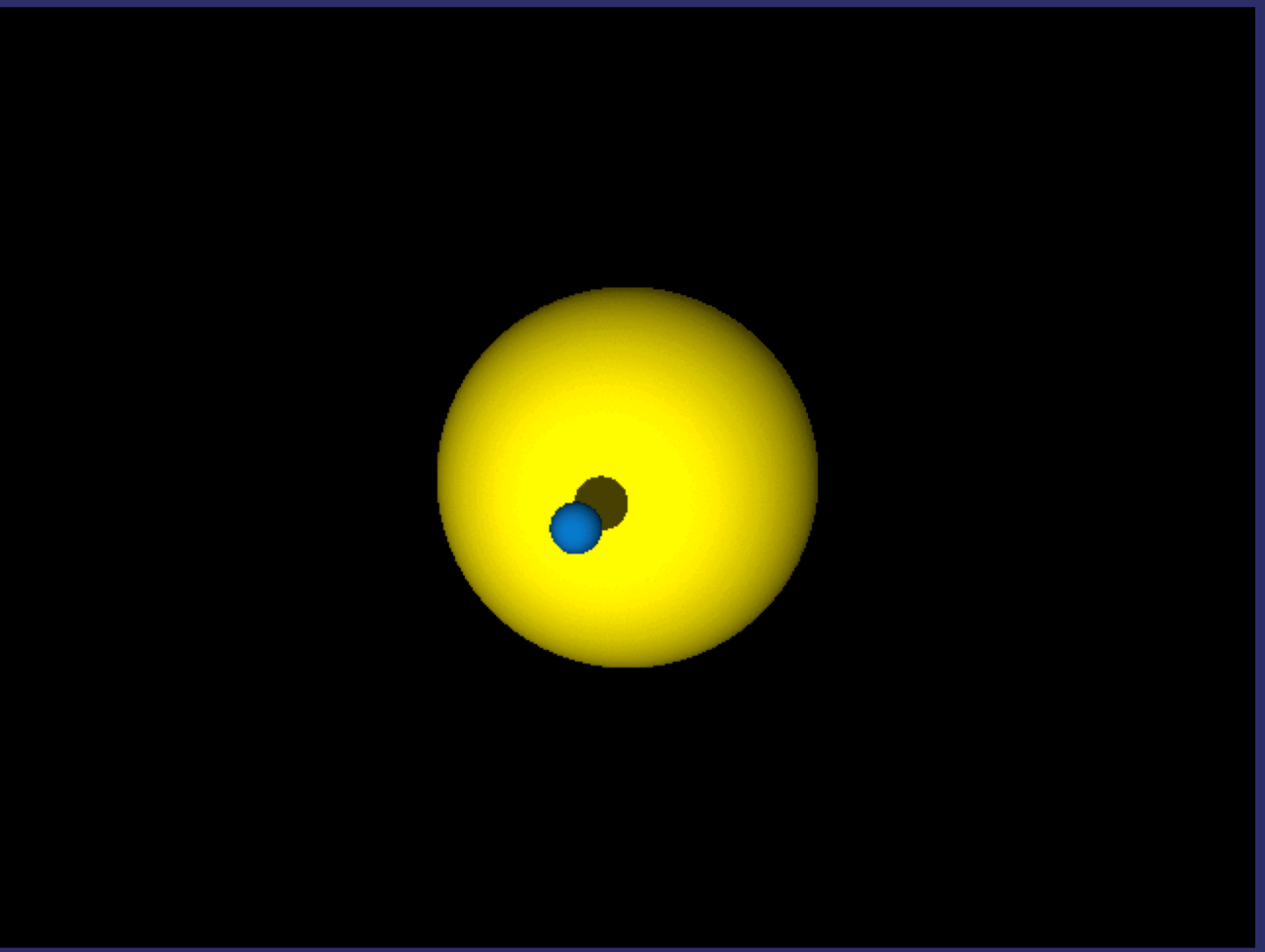

```
trait Live extends PhongReflectionModule {
  val aTModule: ATModule.Service[Any]
  val normalReflectModule: NormalReflectModule.Service[Any]
  val lightDiffusionModule: LightDiffusionModule.Service[Any]
}
```

Live PhongReflectionModule



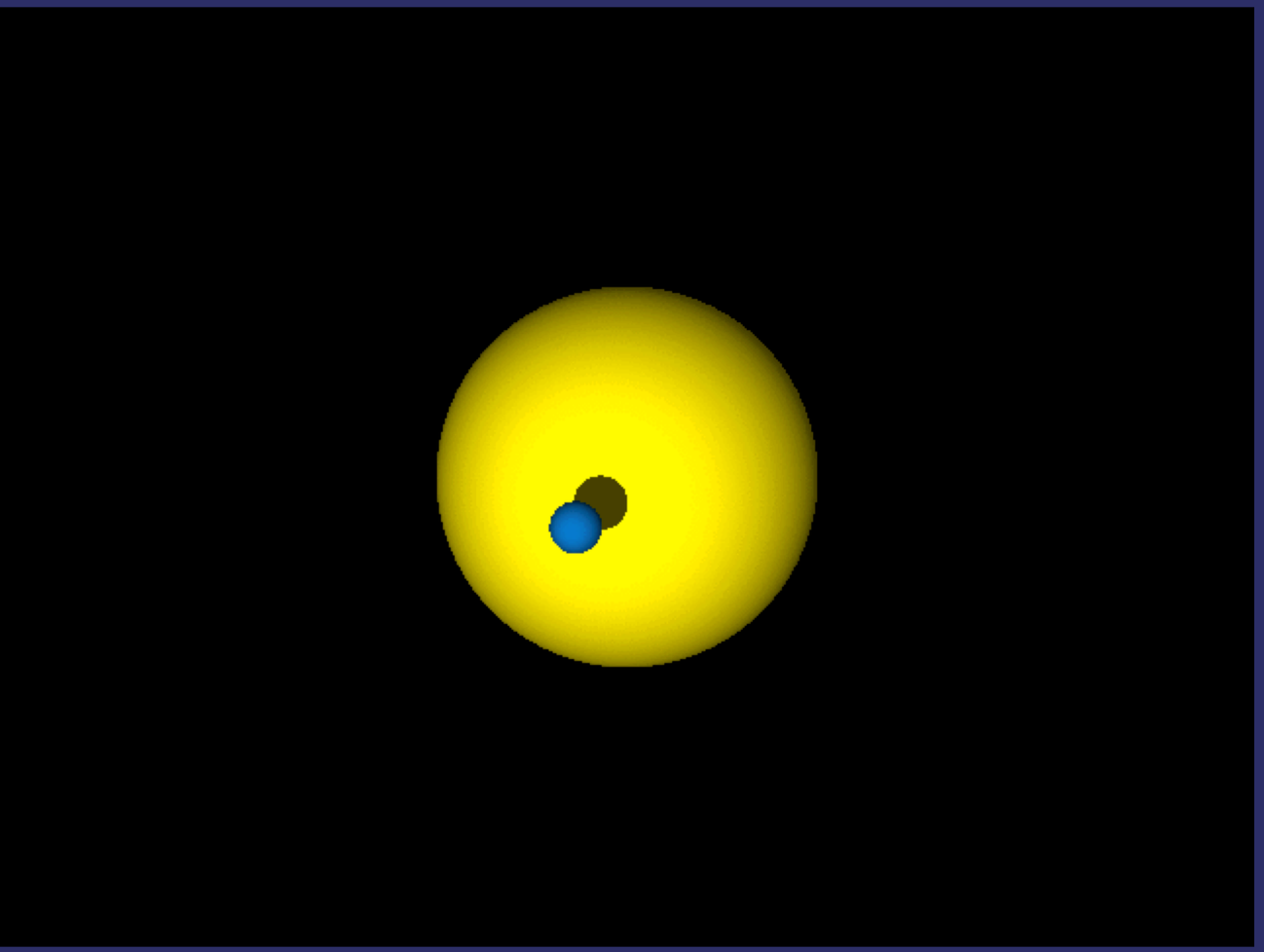
```
program(Pt(2, 2, -10))
  .provide(
    new BasicModules
    with PhongReflectionModule.Live
    // with PhongReflectionModule.BlackWhite
  )
```

Live PhongReflectionModule



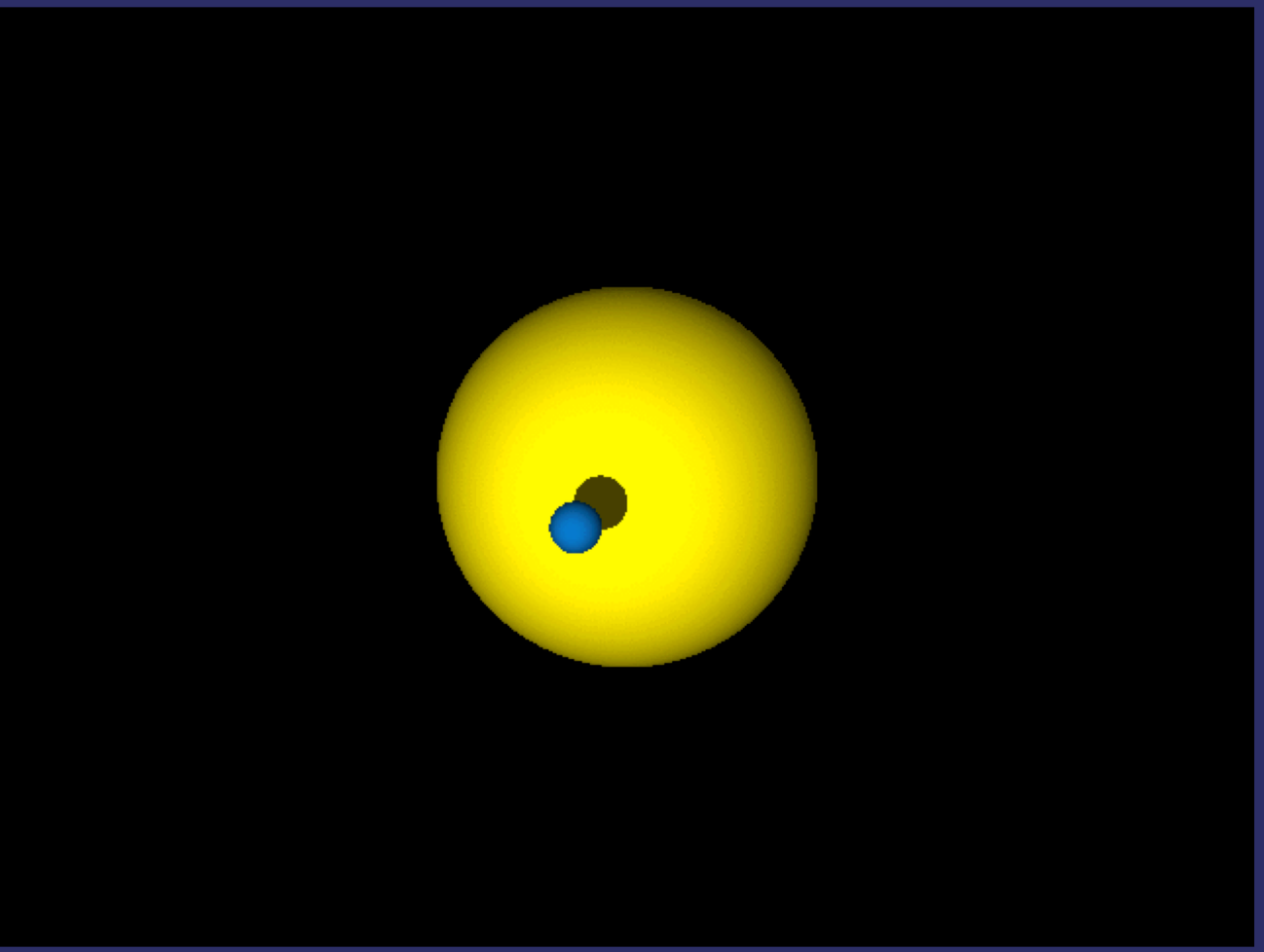
```
program(Pt(2, 2, -10))
  .provide(
    new BasicModules
    with PhongReflectionModule.Live
    // with PhongReflectionModule.BlackWhite
  )
```

Live PhongReflectionModule



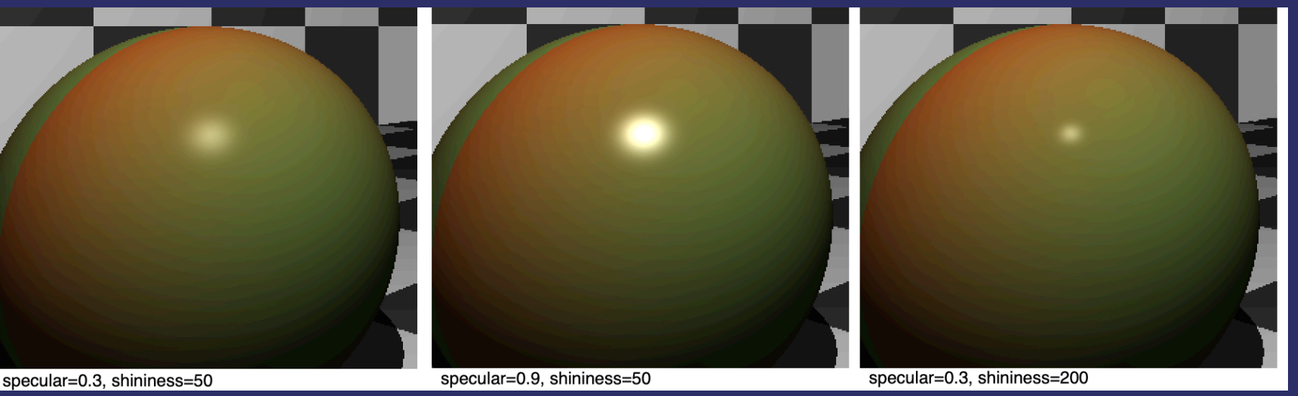
```
program(Pt(2, 2, -10))
  .provide(
    new BasicModules
    with PhongReflectionModule.Live
    // with PhongReflectionModule.BlackWhite
  )
```

Live PhongReflectionModule



```
program(Pt(2, 2, -10))
  .provide(
    new BasicModules
    with PhongReflectionModule.Live
    // with PhongReflectionModule.BlackWhite
  )
```

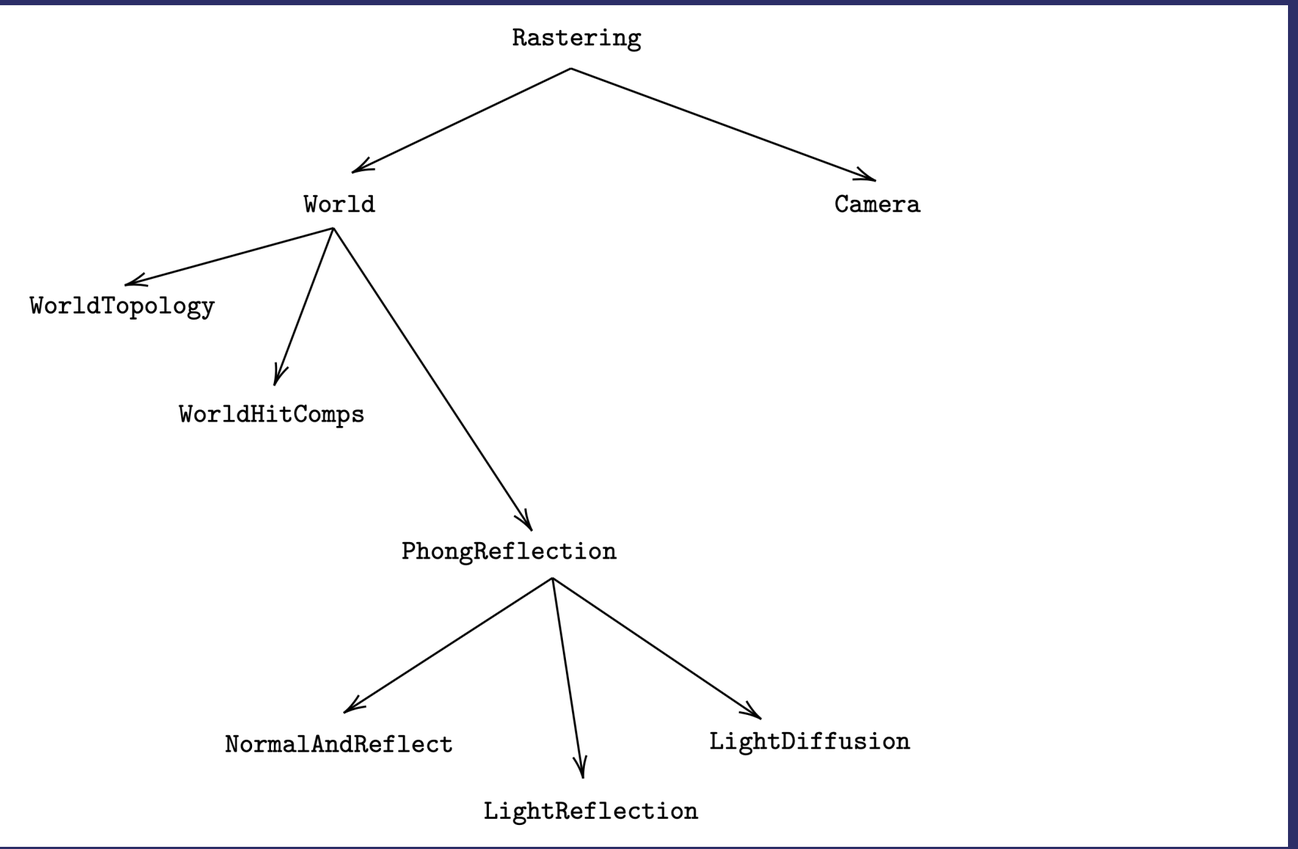
Reflect the ligtht source



Describe material properties

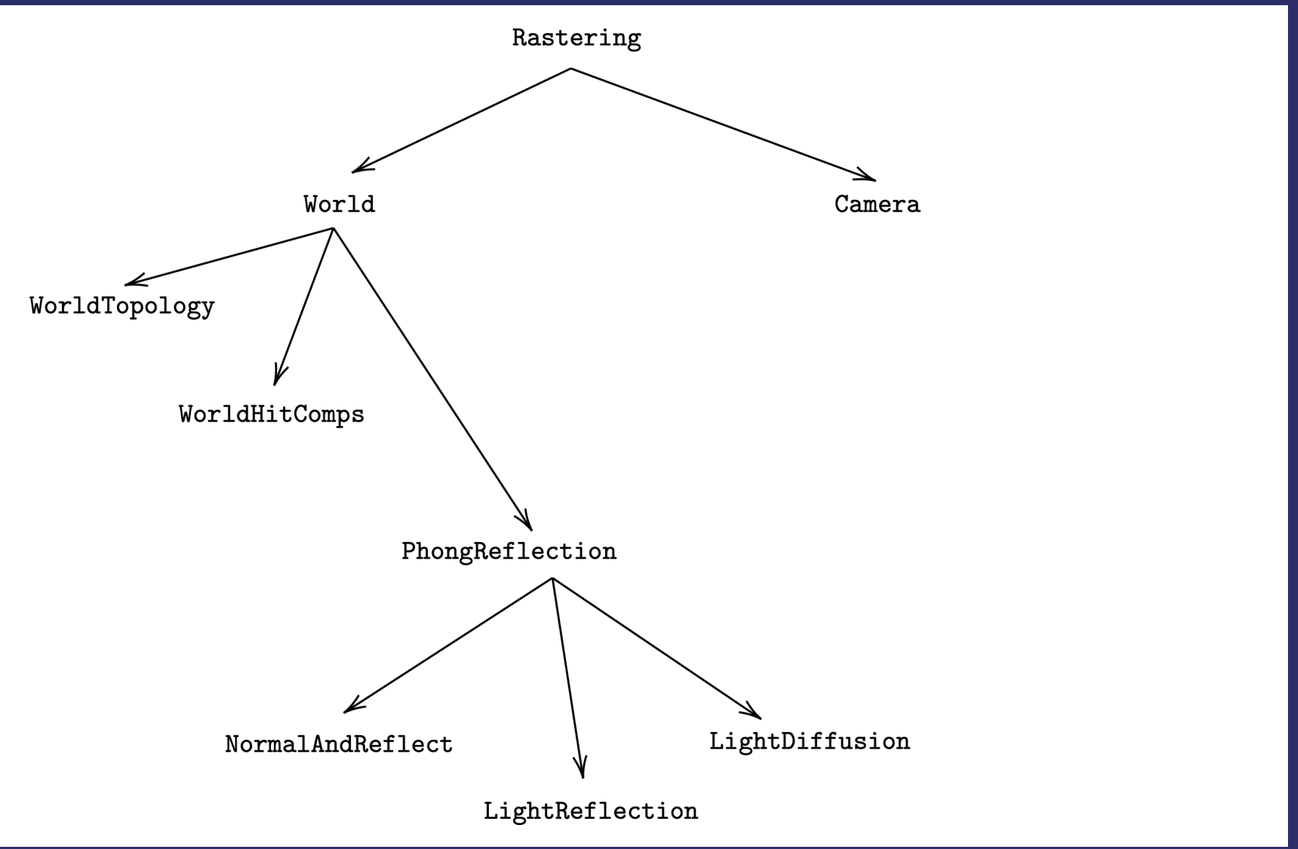
```
case class Material(
  color: Color, // the basic color
  ambient: Double,  // ∈ [0, 1]
  diffuse: Double,  // ∈ [0, 1]
  specular: Double, // ∈ [0, 1]
  shininess: Double, // ∈ [10, 200]
)
```

Live PhongReflectionModule



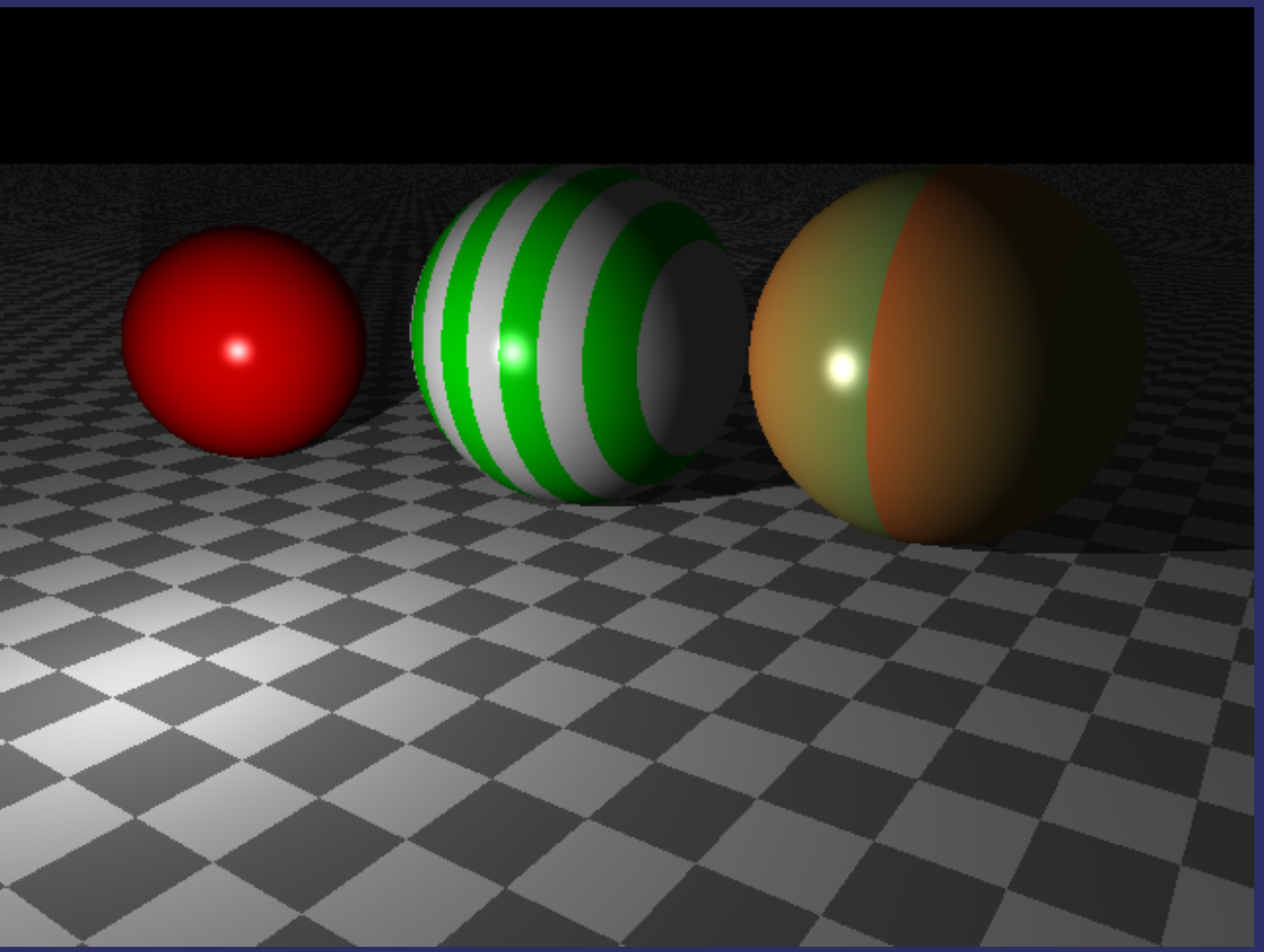

```
trait Live extends PhongReflectionModule {
  val aTModule: ATModule.Service[Any]
  val normalReflectModule: NormalReflectModule.Service[Any]
  val lightDiffusionModule: LightDiffusionModule.Service[Any]
  val lightReflectionModule: LightReflectionModule.Service[Any]
}
```

Live PhongReflectionModule




```
trait Live extends PhongReflectionModule {
  val aTModule: ATModule.Service[Any]
  val normalReflectModule: NormalReflectModule.Service[Any]
  val lightDiffusionModule: LightDiffusionModule.Service[Any]
  val lightReflectionModule: LightReflectionModule.Service[Any]
}
```

Render 3 spheres - reflect light source



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case class Material(
  pattern: Pattern, // the color pattern
  ambient: Double,  // ∈ [0, 1]
  diffuse: Double,  // ∈ [0, 1]
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  shininess: Double, // ∈ [10, 200]
  reflective: Double, // ∈ [0, 1]
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trait Live extends PhongReflectionModule {
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  val lightReflectionModule: LightReflectionModule.Service[Any]
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trait RenderingModulesV1
  extends PhongReflectionModule.Live
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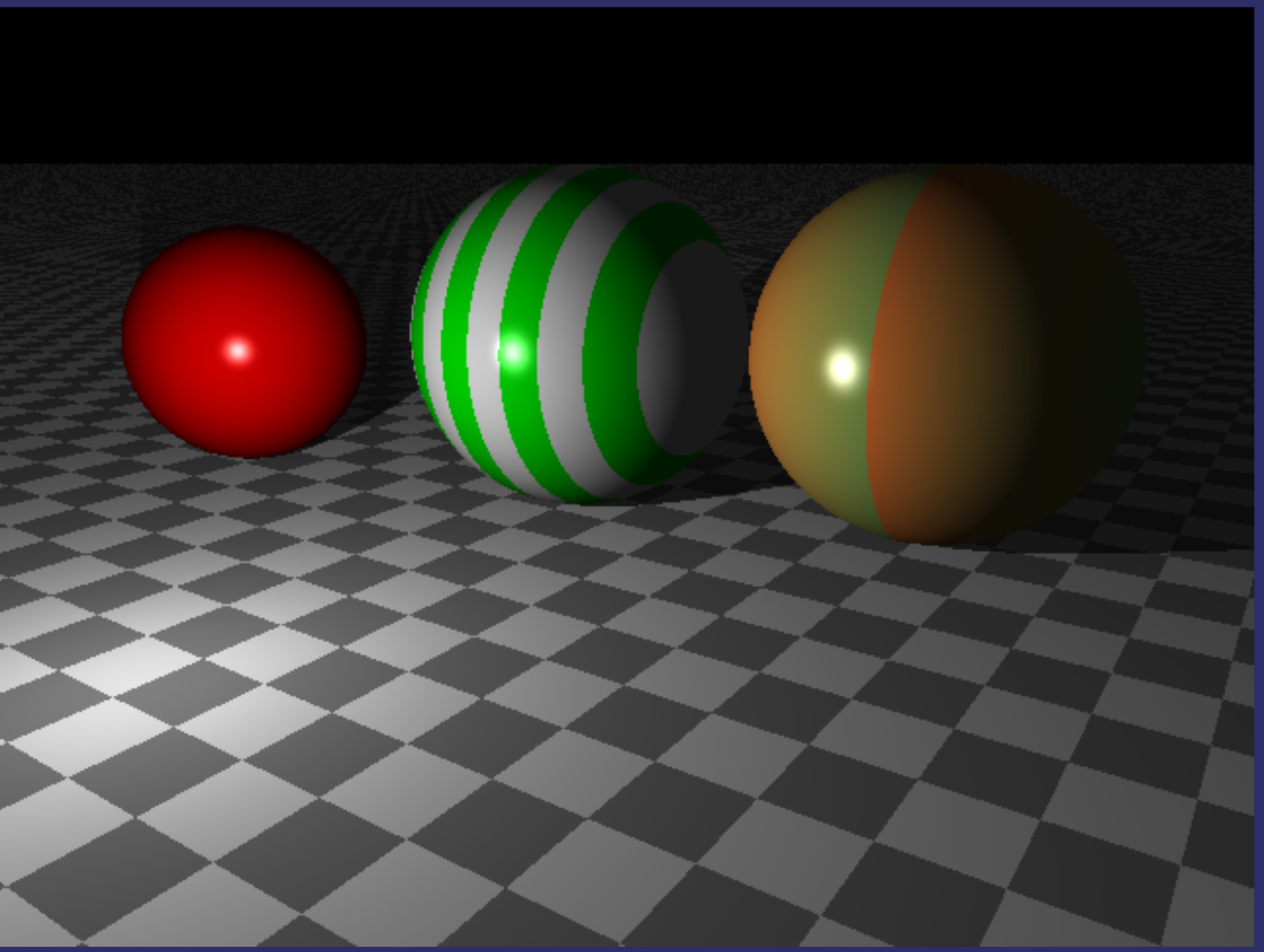

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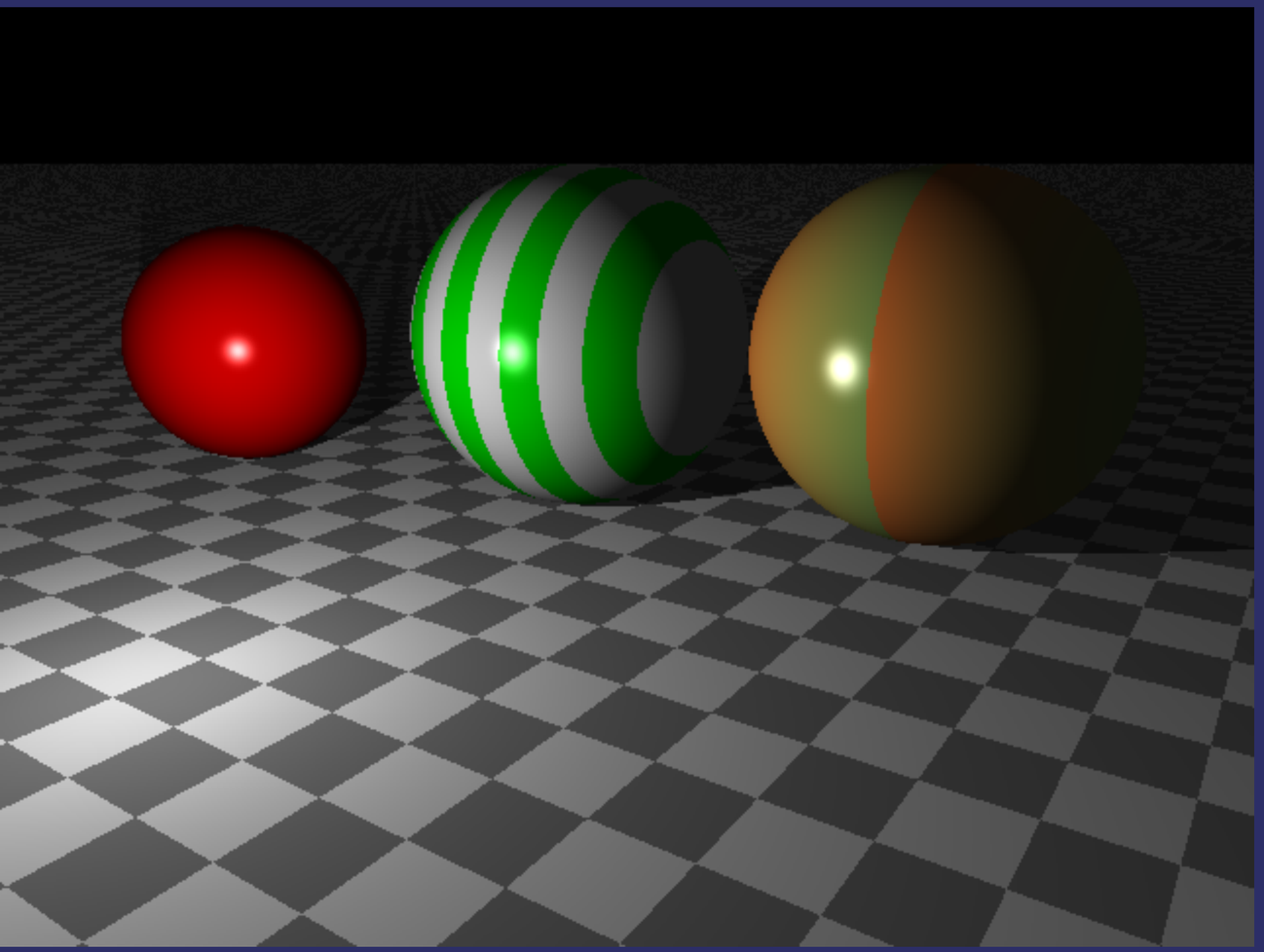

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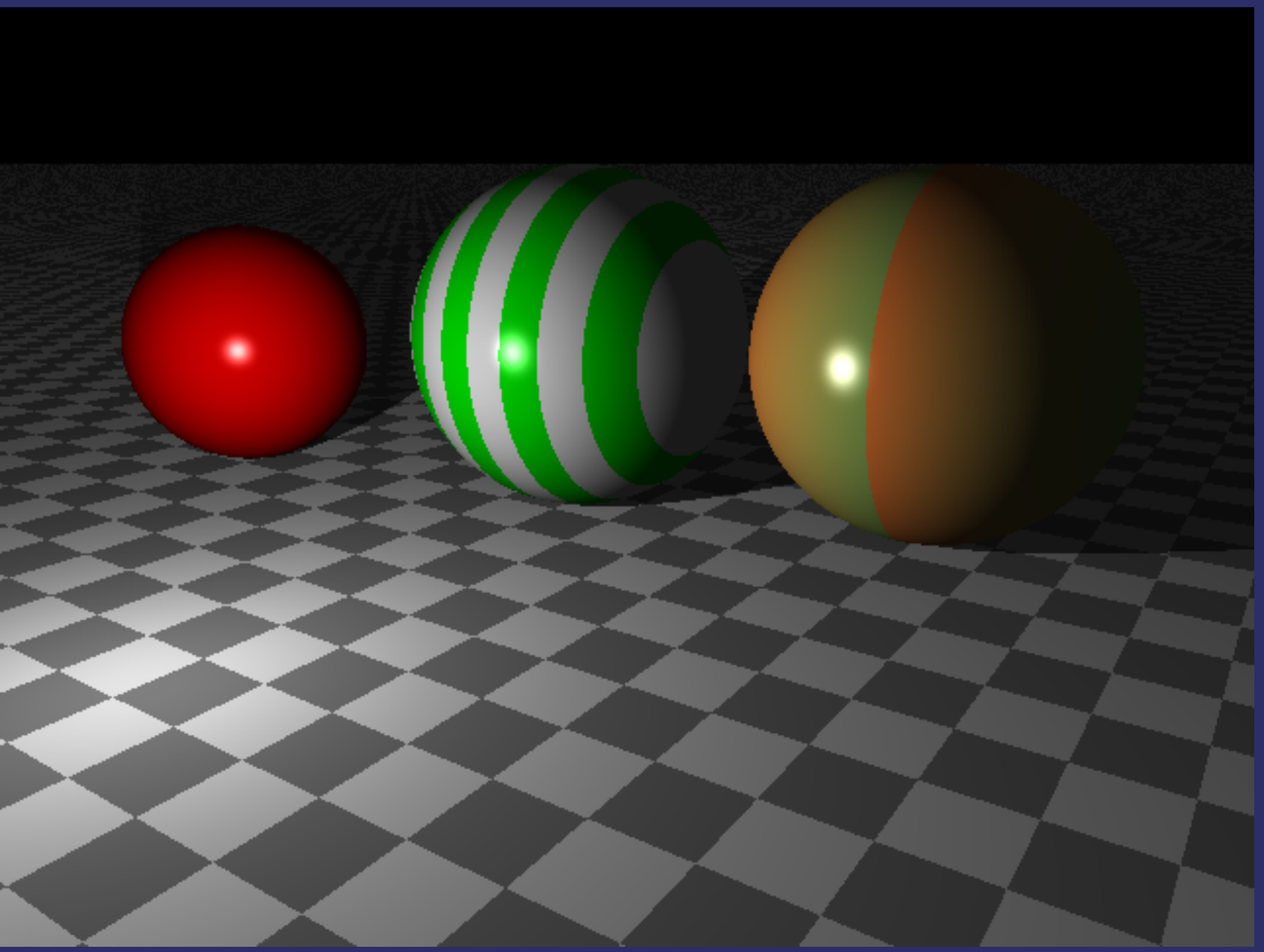

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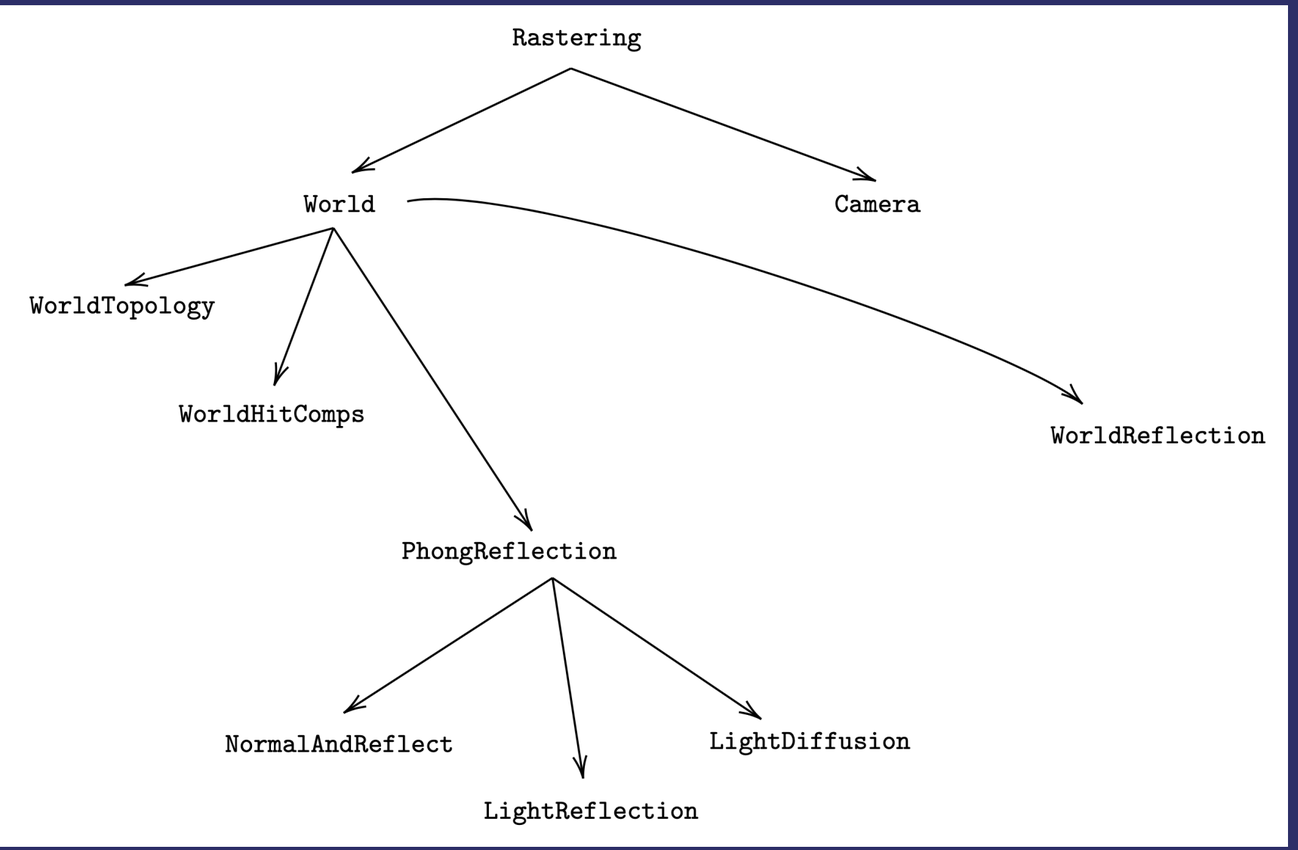
Reflective surfaces




```
trait Live extends WorldModule {
  val worldTopologyModule: WorldTopologyModule.Service[Any]
  val worldHitCompsModule: WorldHitCompsModule.Service[Any]
  val phongReflectionModule: PhongReflectionModule.Service[Any]
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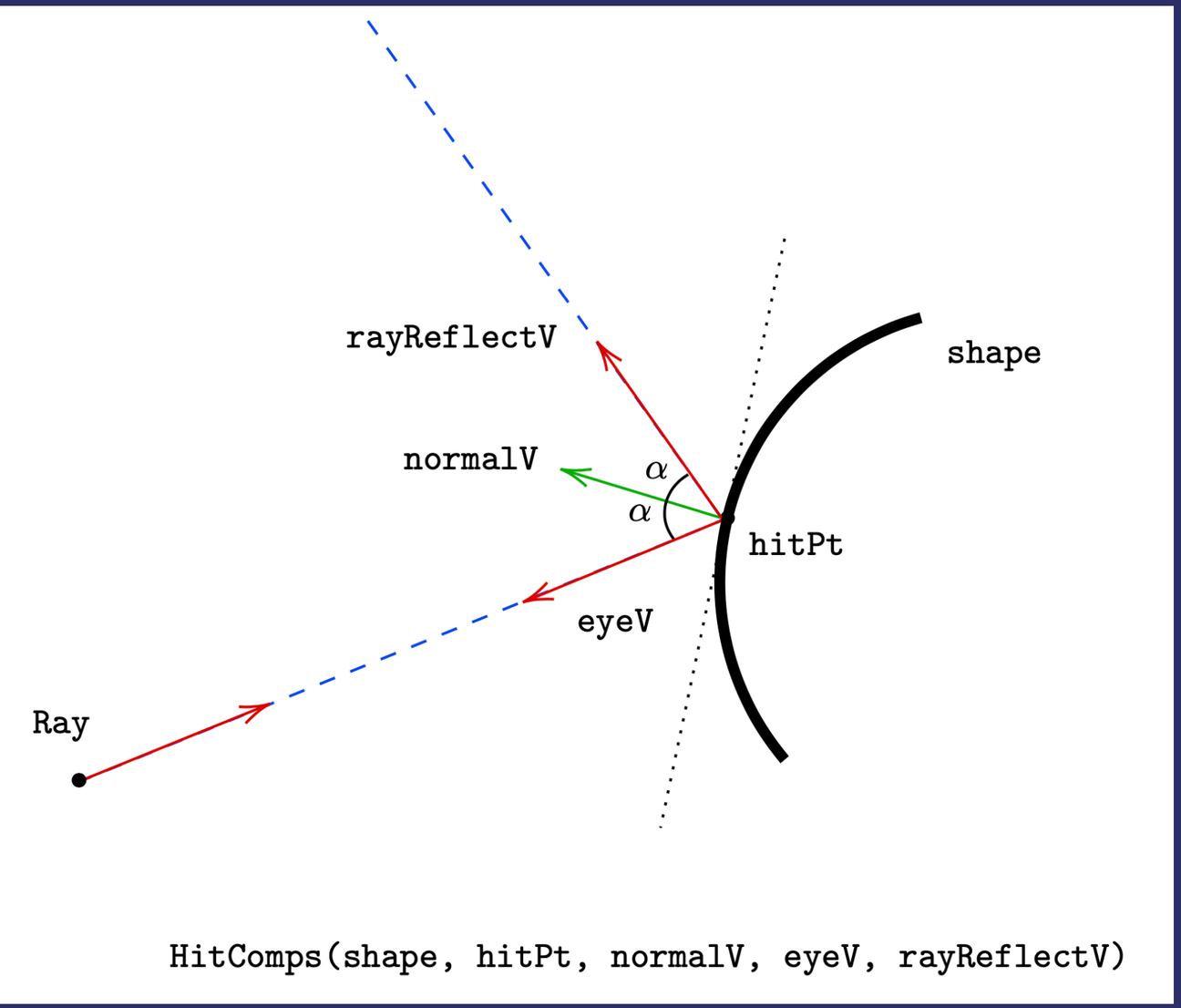
Reflective surfaces



HitComps(shape, hitPt, normalV, eyeV, rayReflectV)

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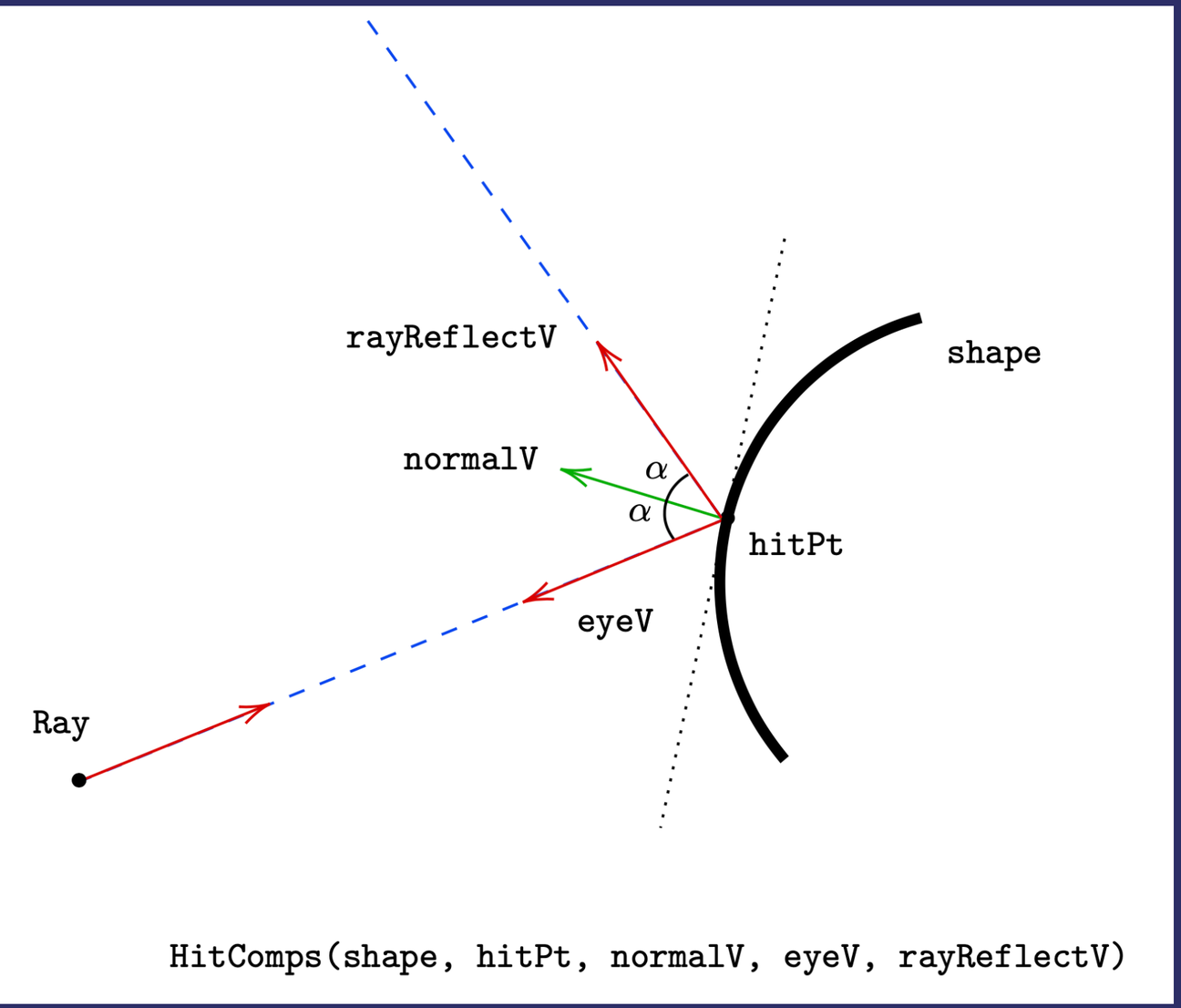
  val phongReflectionModule: PhongReflectionModule.Service[Any]
  val worldReflectionModule: WorldReflectionModule.Service[Any]

  val worldModule: Service[Any] =
    new Service[Any] {
      def colorForRay(world: World, ray: Ray): ZIO[Any, RayTracerError, Color] =
        {
          /* ...  */
          for {
            color <- /* standard computation of color */
            reflectedColor <- worldReflectionModule.reflectedColor(world, hc)
          } yield color + reflectedColor
        }
    }
}
```

Reflective surfaces



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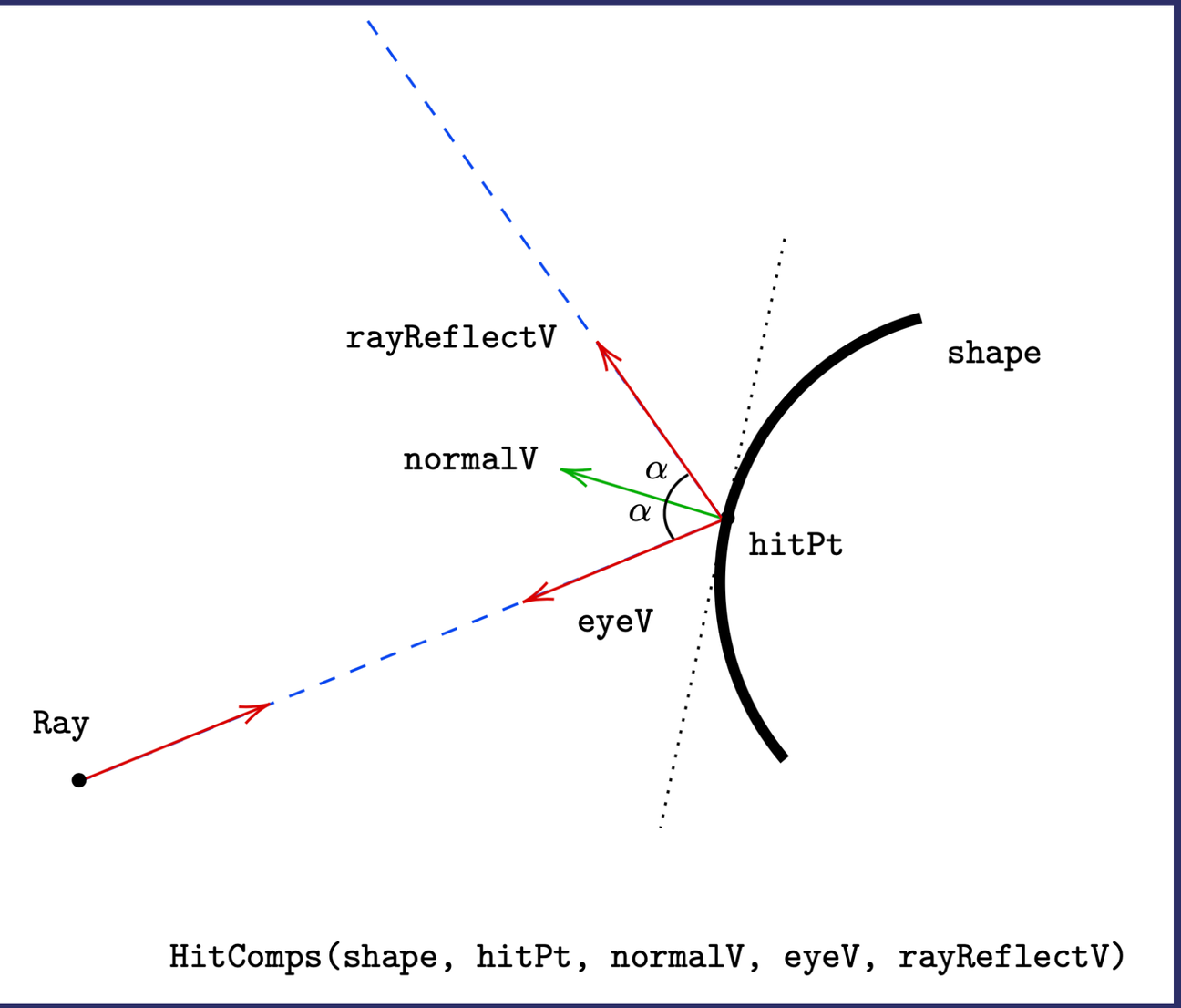

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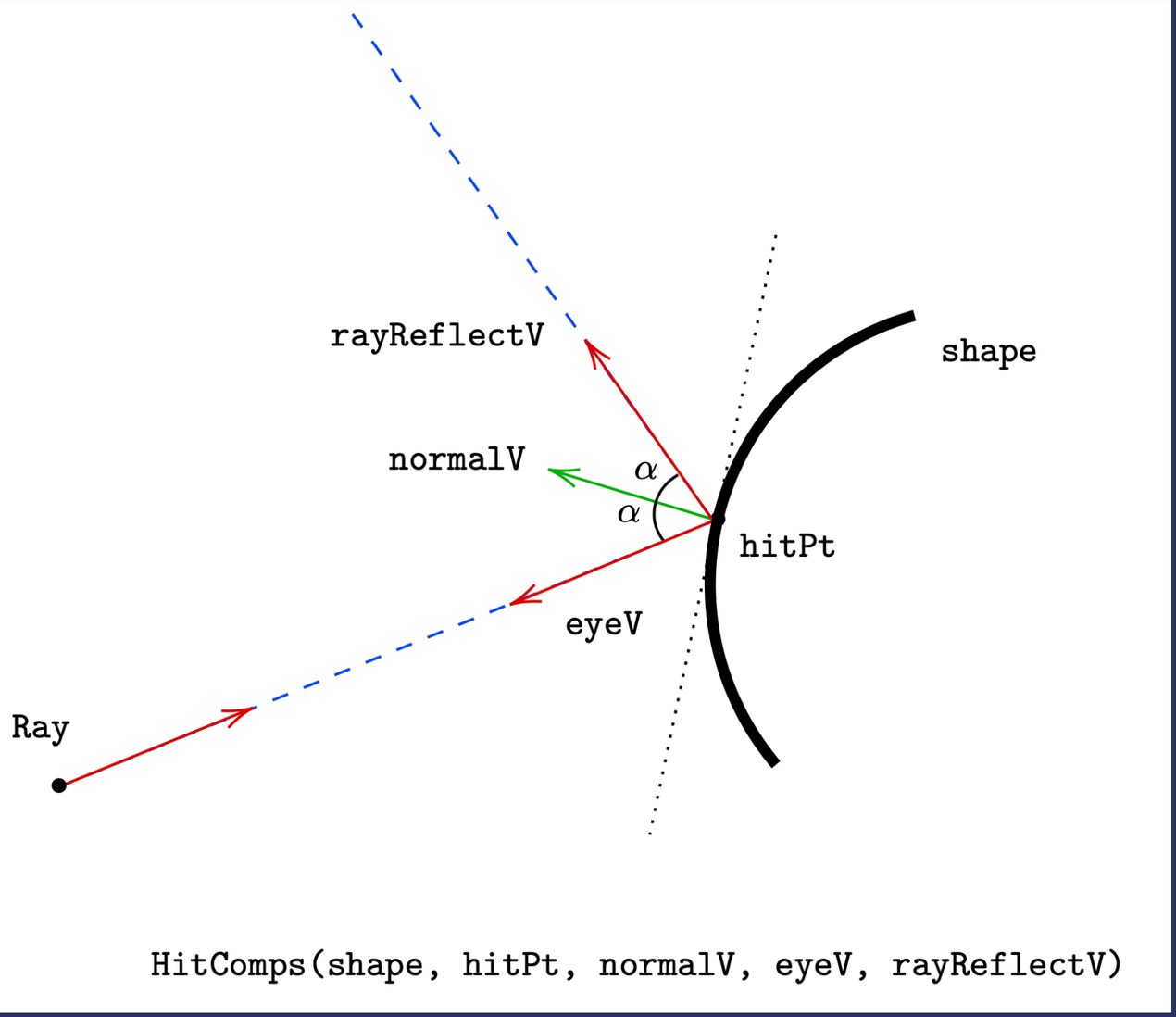
Reflective surfaces



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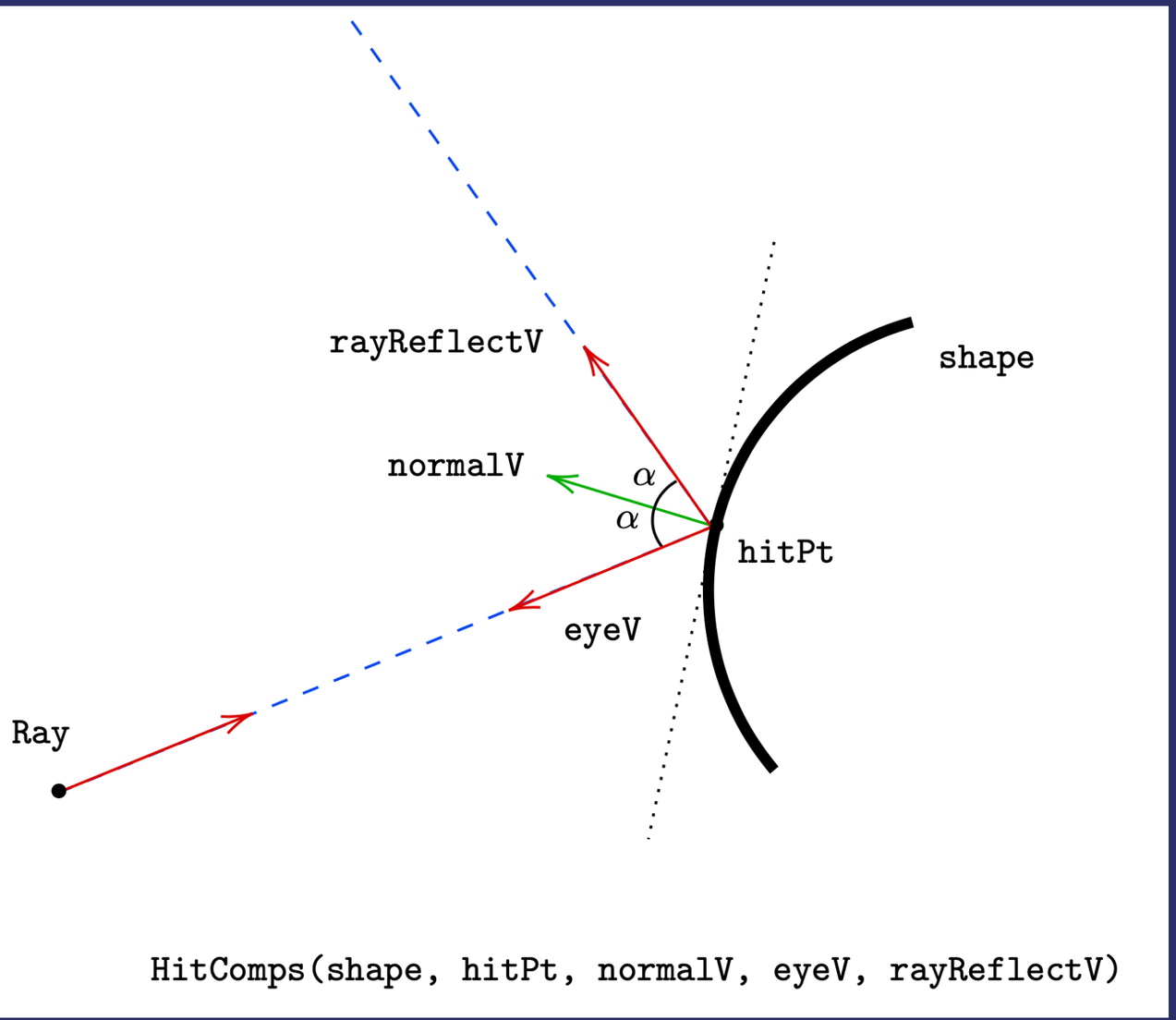
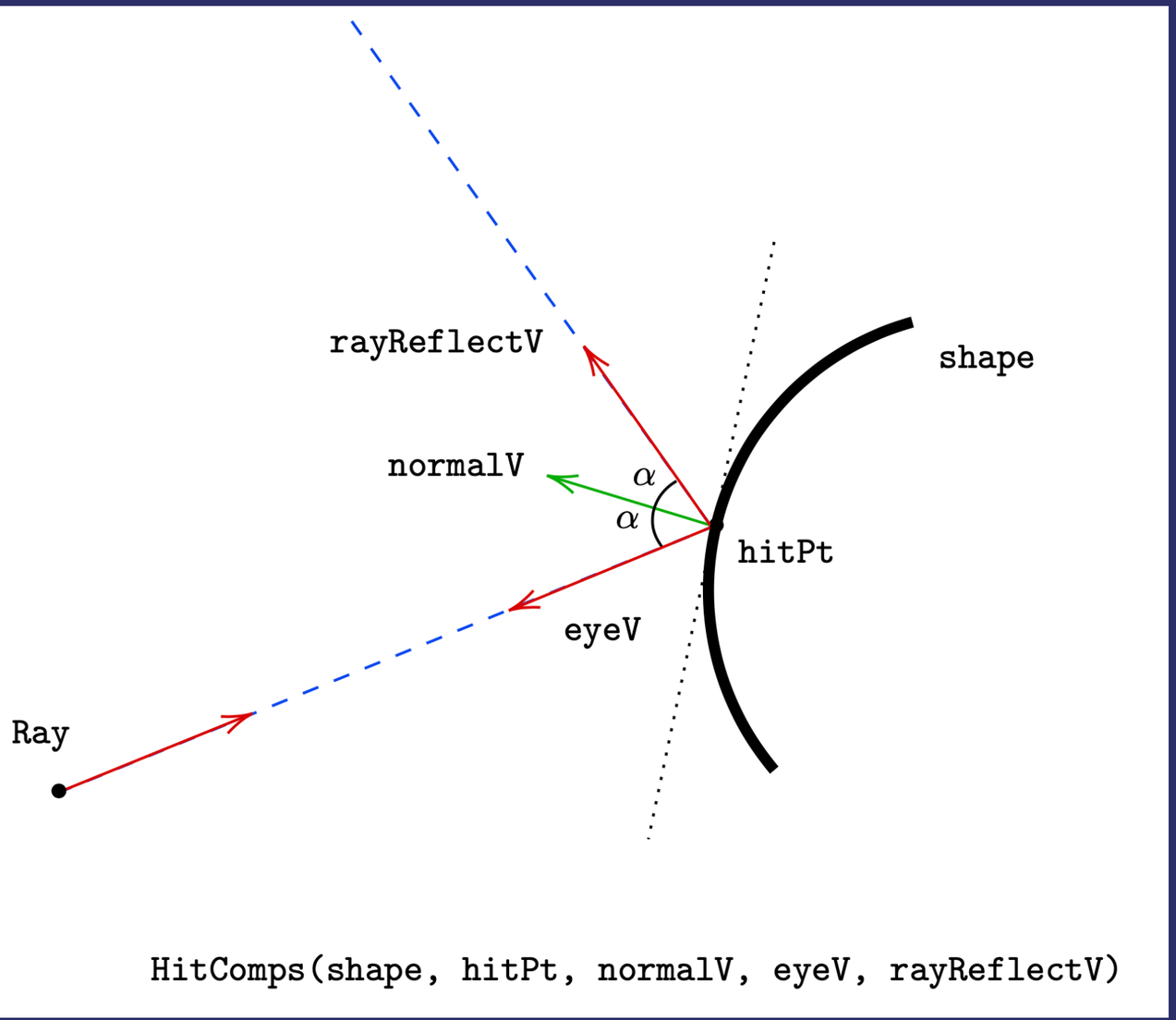


HitComps(shape, hitPt, normalV, eyeV, rayReflectV)

Handling reflection - Live

```
trait Live extends WorldReflectionModule {
  val worldModule: WorldModule.Service[Any]

  val worldReflectionModule = new WorldReflectionModule.Service[Any] {
    def reflectedColor(world: World, hitComps: HitComps, remaining: Int):
      ZIO[Any, RayTracerError, Color] =
      if (hitComps.shape.material.reflective == 0) {
        UIO(Color.black)
      } else {
        val reflRay = Ray(hitComps.overPoint, hitComps.rayReflectV)
        worldModule.colorForRay(world, reflRay, remaining).map(c =>
          c * hitComps.shape.material.reflective
        )
      }
  }
}
```



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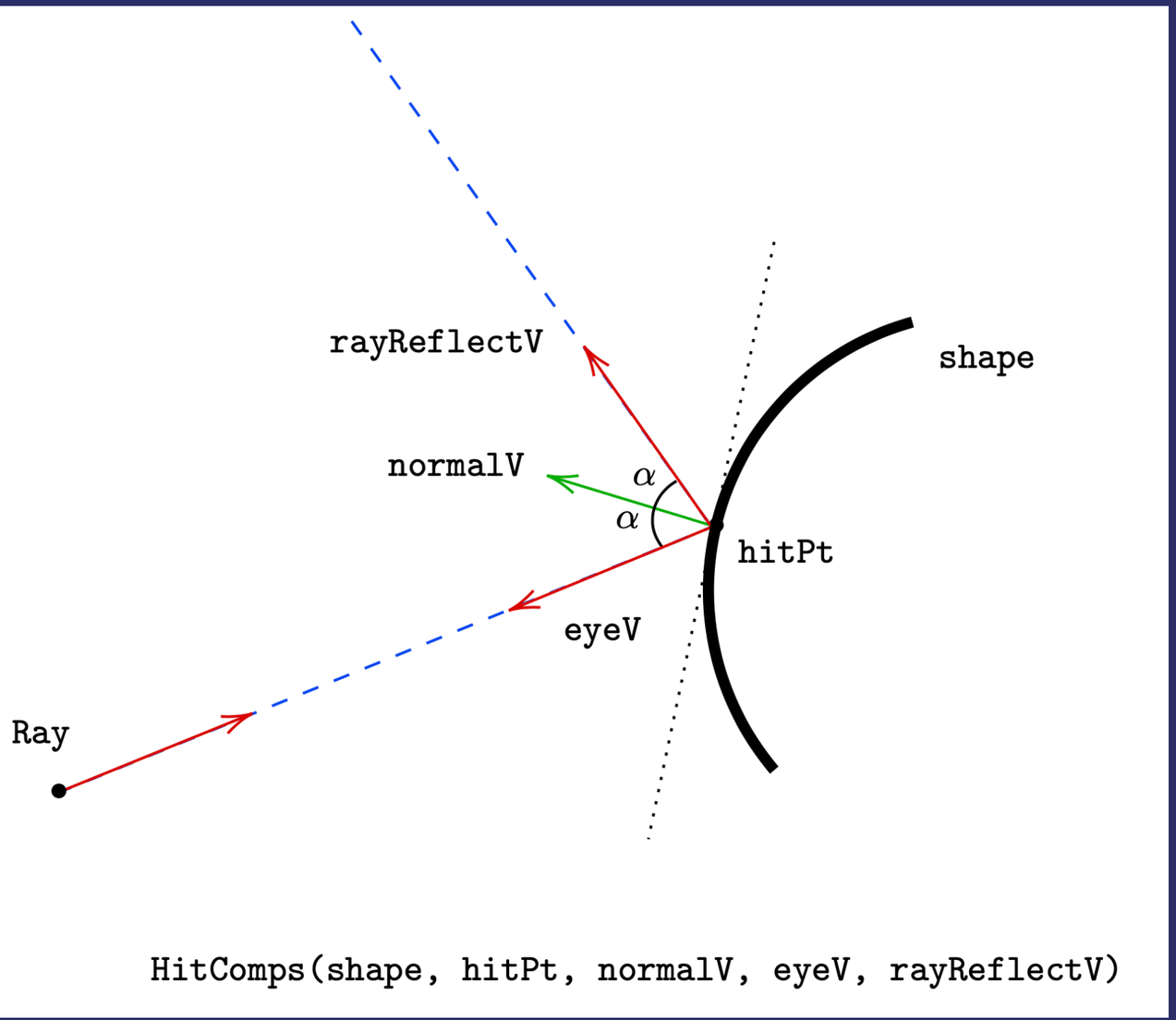

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        worldModule.colorForRay(world, reflRay, remaining).map(c =>
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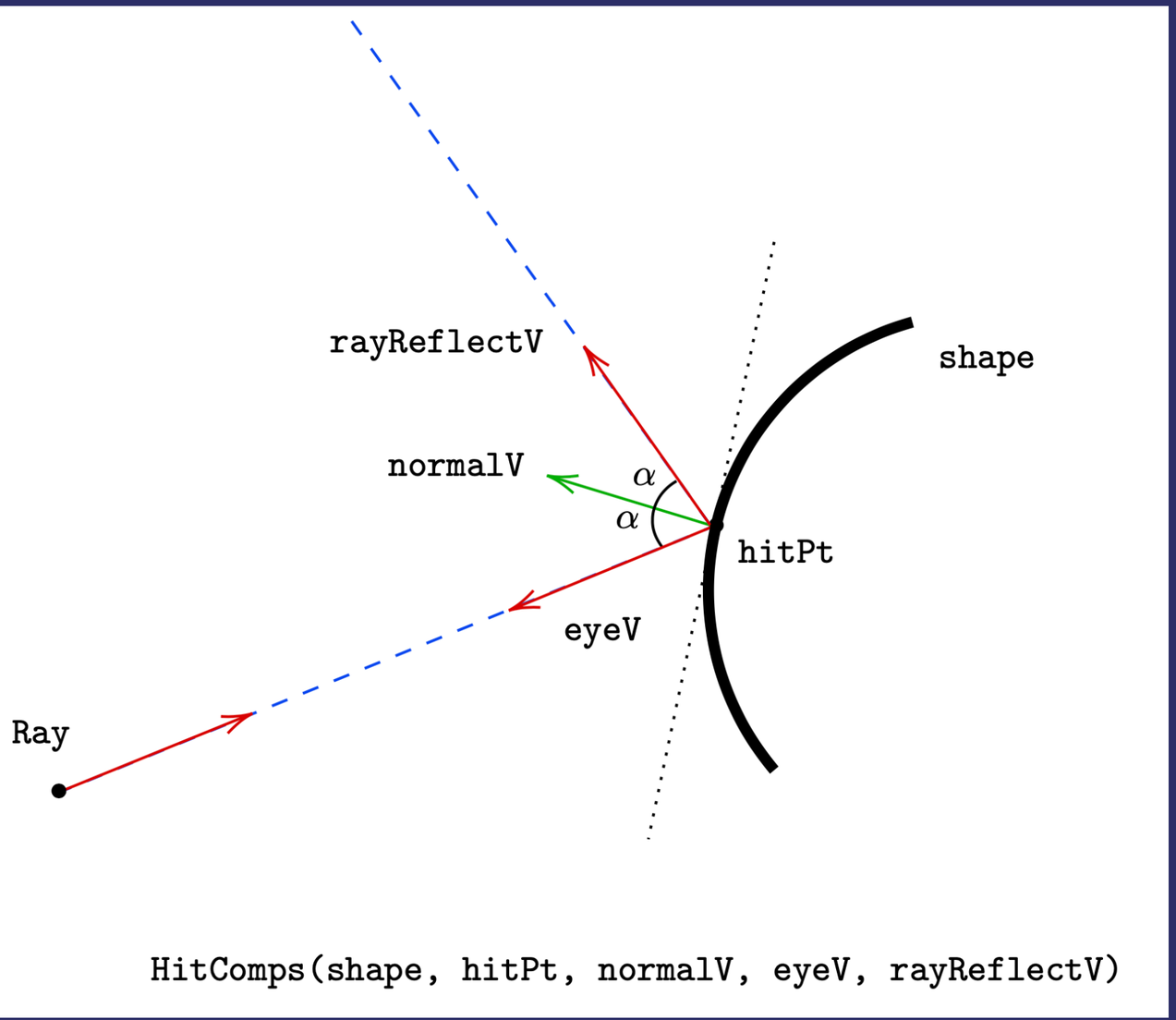
        )
      }
  }
}
```



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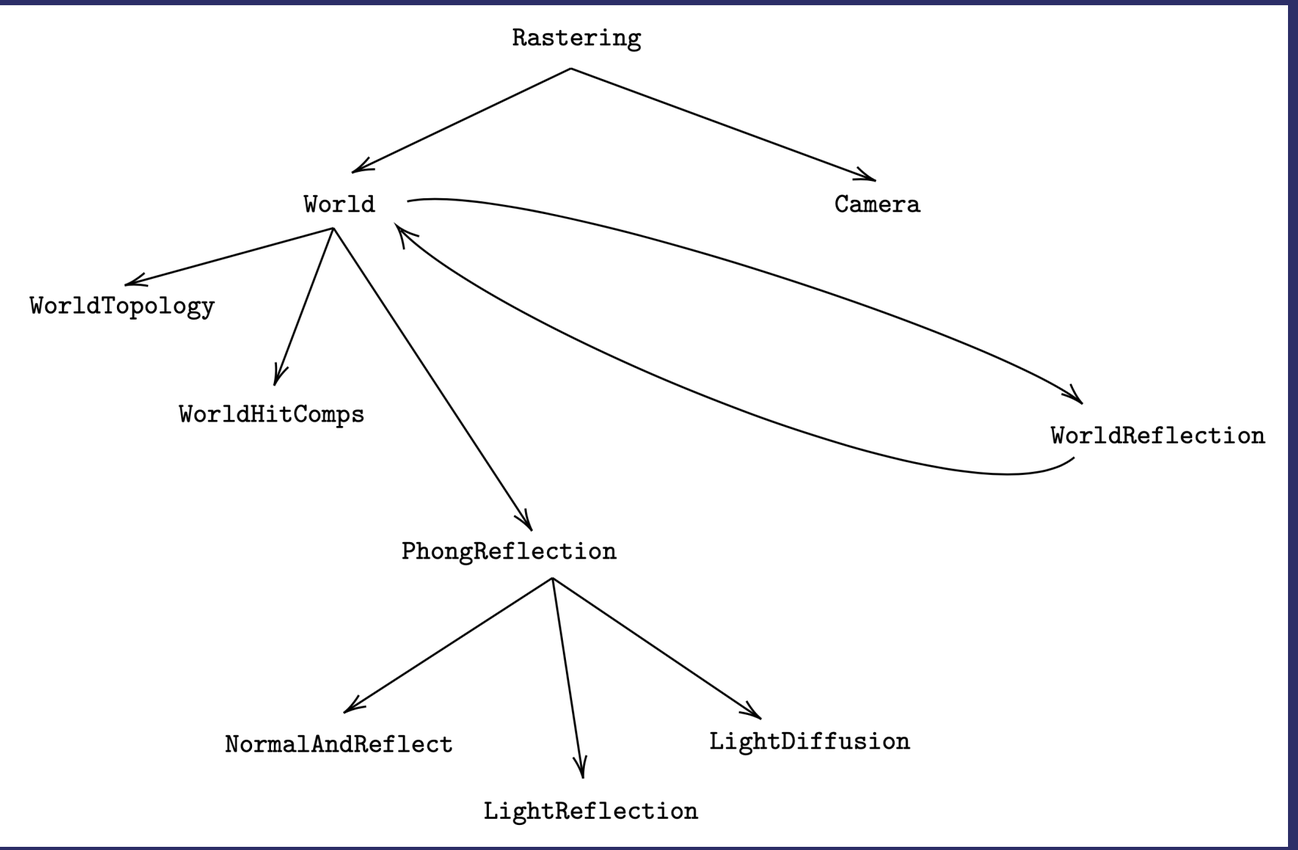
      }
  }
}
```



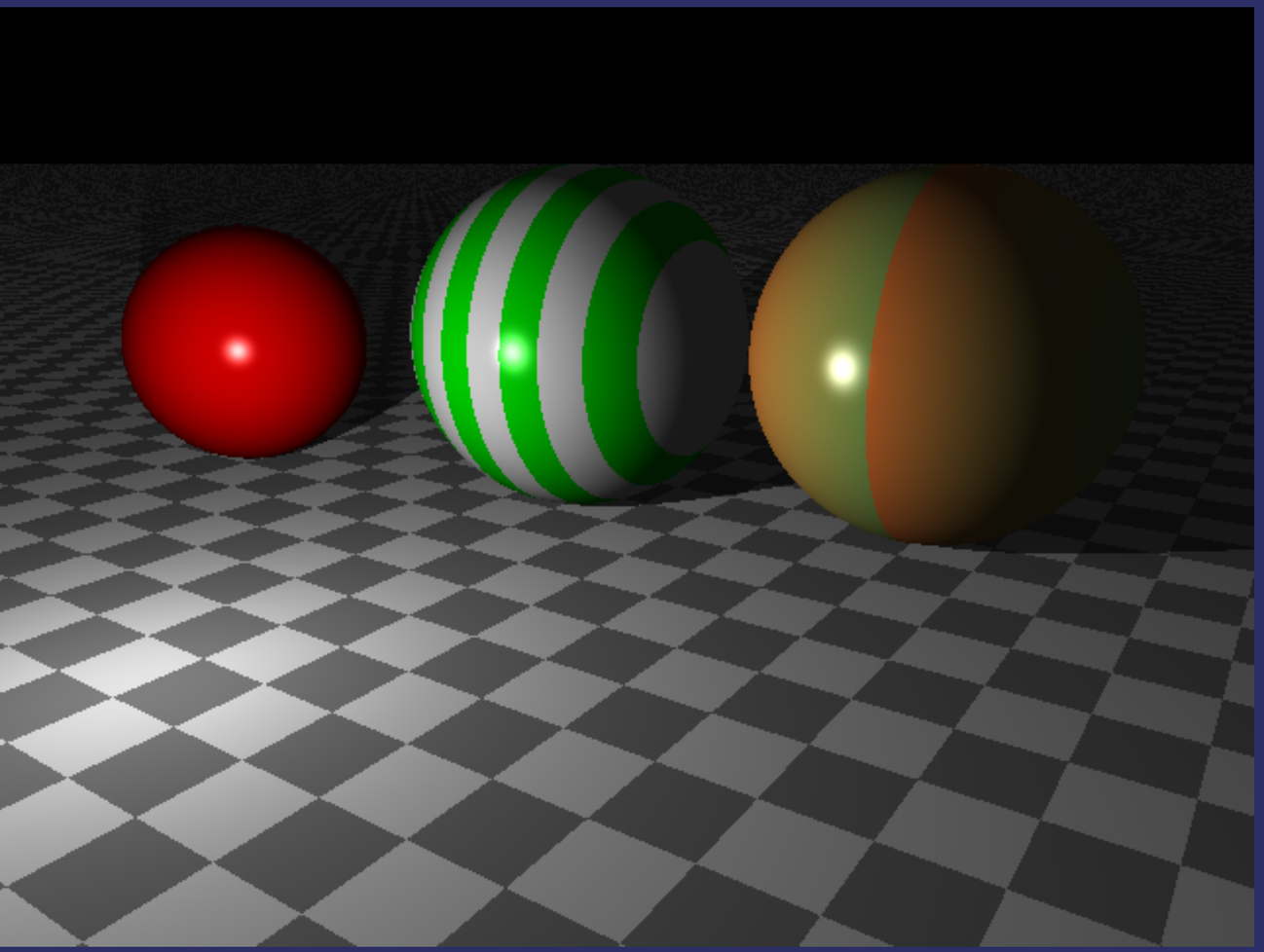
Reflective surfaces

Circular dependency

Handling reflection - Noop module

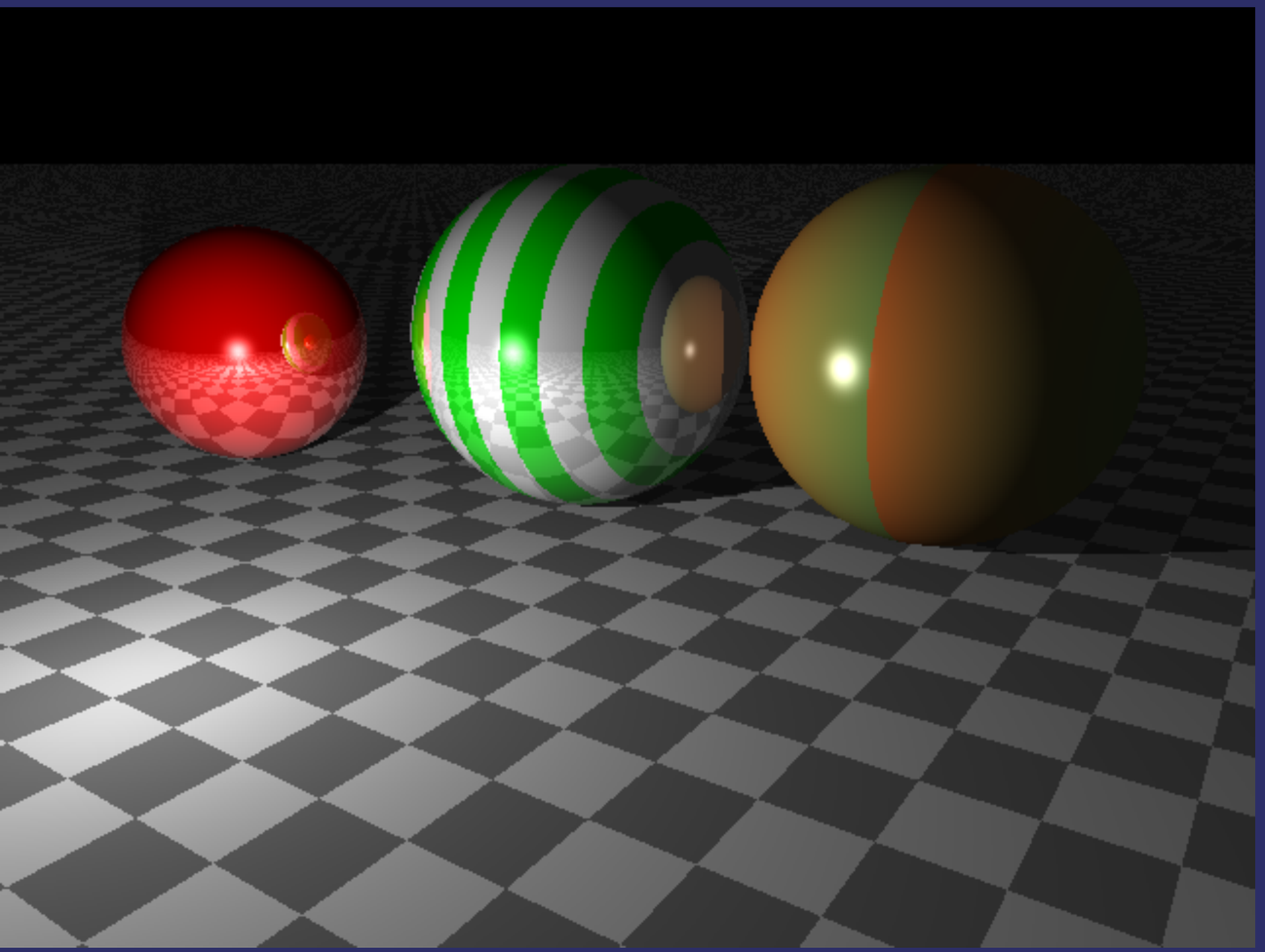
```
trait NoReflectionModule extends WorldReflectionModule {
  val worldReflectionModule = new WorldReflectionModule.Service[Any] {
    def reflectedColor(
      world: World,
      hitComps: HitComps,
      remaining: Int
    ): ZIO[Any, RayTracerError, Color] = UIO.succeed(Color.black)
  }
}
```

Handling reflection - Noop module



- → Red: reflective = 0.9
- → Green/white: reflective = 0.6

```
program(
  from = Pt(57, 20, z),
  to = Pt(20, 0, 20)
).provide {
  new BasicModules
  with PhongReflectionModule.Live
  with WorldReflectionModule.NoReflectionModule
}
```



Handling reflection - Live module

→ Red: reflective = 0.9

→ Green/white: reflective = 0.6

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  with WorldReflectionModule.Live
}
```

Alternative approach

Provide partial environments

```
val program: ZIO[RasteringModule, Nothing, Unit]

val partial = program
  .provideSome[WorldReflectionModule](
    f: WorldReflectionModule => RasteringModule
  ): ZIO[WorldReflectionModule, E, A]

partial.provide(new WorldReflectionModule.Live)
```

Conclusion - Environmental Effects

`ZIO[R, E, A]`

Build purely functional, testable, modular applications

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Build purely functional, testable, modular applications

→ Do not require HKT, typeclasses, etc

→ Do not abuse typeclasses

→ Can group capabilities

→ Can provide capabilities one at a time

→ Are not dependent on implicits (survive refactoring)

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→ Low entry barrier, very mechanical 🙌

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→ Join ZIO Discord channel 😊

Thank you! [1]

Questions?

 @pierangelocecc

 https://github.com/pierangeloc

[1] Ray Tracing with ZIO