cs805 Assignment 2

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Abstract

This assignment is written in literate programming style, generated by noweb, rendered by LaTex, and compiled by clang++ with c++ 11 standard.
assignment paper is at latex/as2.pdf
c++ programs are at src/*
binary executable for OS X 10.8 is located at bin/run pdf and image generation script is extract.sh output result is result.jpg

1 function implementation

```
<<src/util.cpp>>=
#include "util.h"
#include <cmath>

//pixel iterator for img panel.
ImagePanel foreach_pixel_exec(ImagePanel img, std::function<int(Ray, Point)> ray_f
  int i = 0;
  for (int& pixel: img) { //foreach pixel in empty_img
    //using to_2d function to get x,y camera coordinates
    std::array<int, 2> cam_xy = to_2d(i);

    //construct Ray
    Ray ray = ray_construction(cam_xy[0], cam_xy[1]);

    //get shading value using the passed-in functor
    pixel = ray_func(ray, LRP);
    i++;
  }
  return img;
}

//ray constructor
Ray ray_construction(int x, int y) {
  //calculate x unit
  double x_delta = (xmax-xmin) / IMG_X;
  double y_delta = (ymax-ymin) / IMG_Y;

  //calculate the point on img panel with world coordinate
  double x_ = xmax - x_delta * x;
  double y_ = ymax - y_delta * y;

  //get vector v0. it is trival that VRP is p0
  Point p0 = VRP;
  Point p1_ = {x_, y_, focal};
  Point p1 = mul(Mcw, p1_);
```

```
  Vector v0_ = {p1[0] - p0[0],
    p1[1] - p0[1],
    p1[2] - p0[2]};
  Vector v0 = normalize(v0_);

  /*
  if ((x==0 ) || (x==511)) {
    std::cout<<"img: x:"<<x<<", y:"<<y;
    //std::cout<<"p0: x:"<<VRP[0]<<", y:"<<VRP[1]<<", z:"<<VRP[2]<<std::endl;
    //std::cout<<"p0: x:"<<p0[0]<<", y:"<<p0[1]<<", z:"<<p0[2]<<std::endl;
    std::cout<<"p1_: x:"<<p1_[0]<<", y:"<<p1_[1]<<", z:"<<p1_[2]<<"=====";
    std::cout<<"p1: x:"<<p1[0]<<", y:"<<p1[1]<<", z:"<<p1[2]<<"=====";
    std::cout<<"v0: x:"<<v0[0]<<", y:"<<v0[1]<<", z:"<<v0[2]<<"=====";
    std::cout<<std::endl;
  }
  */

  return { p0[0], p0[1], p0[2],
           v0[0], v0[1], v0[2]};
}

//initialize img panel to all 0s
ImagePanel init_img_panel(ImagePanel img) {
  for (auto& pixel: img) { //foreach pixel in empty_img
    pixel = 0;
  }
  return img;
}

//translate ray equation to an shading value
int ray_tracing(Ray ray, Point LRP) {
  Intersection p = ray_objects_intersection(ray);
  //std::cout<<"Intersection: x:"<<p.intersection[0]<<", y:"<<p.intersection[1]<<'
  return shading(p, LRP);
}

//calculate the ray object intersection point
Intersection ray_objects_intersection(Ray ray) {
```

```
  //this is hard-coded and ugly. should use a passed-in list structure instead in
  auto sphere_hit = ray_sphere_intersection(ray, obj1);
  auto polygon_hit = ray_polygon_intersection(ray, obj2);
  if (sphere_hit.kd < 0 && polygon_hit.kd < 0) {
    return {-1,-1,-1,
            -1,-1,-1,
            -1.0};
  } else if (polygon_hit.kd < 0) {
    return sphere_hit;
  } else if (sphere_hit.kd < 0) {
    return polygon_hit;
  } else if (closer(sphere_hit.intersection, polygon_hit.intersection, ray.ref)) {
    return sphere_hit;
  } else {
    return polygon_hit;
  }
}

Intersection ray_sphere_intersection(Ray ray, SPHERE obj) {
  //get A,B,C
  //A = Xd^2 + Yd^2 + Zd^2
  double A = pow(ray.direction[0], 2) +
             pow(ray.direction[1], 2) +
             pow(ray.direction[2], 2);
  //B = 2 * (Xd * (X0 - Xc) + Yd * (Y0 - Yc) + Zd * (Z0 - Zc))
  double B = 2 * (ray.direction[0] * (ray.ref[0] - obj.x) +
                  ray.direction[1] * (ray.ref[1] - obj.y) +
                  ray.direction[2] * (ray.ref[2] - obj.z) );
  //C = (X0 - Xc)^2 + (Y0 - Yc)^2 + (Z0 - Zc)^2 - Sr^2
  double C = pow(ray.ref[0]-obj.x, 2) +
             pow(ray.ref[1]-obj.y, 2) +
             pow(ray.ref[2]-obj.z, 2) -
             pow(obj.radius, 2);

  //get discriminant
  double discriminant = pow(B,2) - 4*C;

  //return null if discriminant is less than 0
```

```
  Intersection null_ = {-1,-1,-1,
                        -1,-1,-1,
                        -1.0};
  if (discriminant < 0)
    return null_;

  //compute t0 = (- B - (B^2 - 4*C)^1/2) / 2
  double t0 = (-B - sqrt(discriminant)) / 2;
  double t1 = (-B + sqrt(discriminant)) / 2;

  //compute the intersection point Ri = [x0 + xd * ti ,  y0 + yd * ti,  z0 + zd *
  Point Ri;
  if (discriminant > 0) {
    Ri = {ray.ref[0] + ray.direction[0] * t0,
          ray.ref[1] + ray.direction[1] * t0,
          ray.ref[2] + ray.direction[2] * t0};
  } else {
    Ri = {ray.ref[0] + ray.direction[0] * t1,
          ray.ref[1] + ray.direction[1] * t1,
          ray.ref[2] + ray.direction[2] * t1};
  }

  //compute the surface normal SN = [(xi - xc)/Sr,   (yi - yc)/Sr,   (zi - zc)/Sr]
  Vector SN = { (Ri[0]-obj.x)/obj.radius,
                (Ri[1]-obj.y)/obj.radius,
                (Ri[2]-obj.z)/obj.radius };

  Intersection result = { Ri, SN, obj.kd };
  return result;
}

Intersection ray_polygon_intersection(Ray ray, POLY4 obj) {
  Intersection null_ = {-1,-1,-1, -1,-1,-1, -1.0};

  //compute ray plane intersection
  //first compute Pn  Rd = Vd
  double Vd = dot_product(obj.N, ray.direction);
```

```
  //Vd = 0: ray is parallel to the plane
  if (Vd == 0)
    return null_;

  //Vd > 0: plane facing away from the ray
  if (Vd > 0)
    return null_;

  //second compute V0 = -(Pn R0 + D)
  double V0 = - (dot_product(obj.N, ray.ref) + get_D_poly4(obj));

  double t = V0/Vd;

  //If t < 0 then the ray intersects plane at the negative side of the ray
  if (t<0)
    return null_;

  //compute intersection point: Pi = [Xi Yi Zi] = [X0 + Xd * t Y0 + Yd * t Z0 + Zd
  Point Pi = { ray.ref[0] + ray.direction[0]*t,
               ray.ref[1] + ray.direction[1]*t,
               ray.ref[2] + ray.direction[2]*t };

  //check if intersection point is inside the polygon
  if (in_poly4(Pi, obj))
    return { Pi, obj.N, obj.kd };
  else
    return null_;
}

//calculate shading value from 0~255 accordingly to intersection info
int shading(Intersection p, Point LRP) {
  //when p.kd < 0, then it is null. let us give null value a black color for now
  if (p.kd < 0) {
    return -255;
  }

  //calculate the light vector
  Vector light = { p.normal[0] - LRP[0],
```

```
                 p.normal[1] - LRP[1],
                 p.normal[2] - LRP[2] };

  //normalize light vector;
  light = normalize(light);

  //calculate shading value
  return Ip*p.kd*dot_product(p.normal, light);
}

//==========helper functions==========

//save image panel to binary file
void save_to_file(ImagePanel img) {
  FILE * pFile;
  pFile = fopen ( "output.raw" , "wb" );
  std::cout<<"img size written to output.raw: "<<img.size()<<std::endl;
  fwrite (img.data() , sizeof(int), img.size() , pFile );
  fclose (pFile);
  return;
}

//get the D of Ax+By+Cz+D=0 from POLY4
double get_D_poly4(POLY4 obj) {
  return -(obj.N[0]*obj.v1[0]+obj.N[1]*obj.v1[1]+obj.N[2]*obj.v1[2]);
}

//check if point is inside a 4 side polygon
bool in_poly4(Point p, POLY4 obj) {
  //flatten the polygon and the point
  POLY4_2D obj2d = flatten(obj, p);

  //tranlate flatten polygon to origin
  obj2d.v1[0] = obj2d.v1[0] - obj2d.p[0];
  obj2d.v1[1] = obj2d.v1[1] - obj2d.p[1];
  obj2d.v2[0] = obj2d.v2[0] - obj2d.p[0];
  obj2d.v2[1] = obj2d.v2[1] - obj2d.p[1];
  obj2d.v3[0] = obj2d.v3[0] - obj2d.p[0];
```

```
  obj2d.v3[1] = obj2d.v3[1] - obj2d.p[1];
  obj2d.v4[0] = obj2d.v4[0] - obj2d.p[0];
  obj2d.v4[1] = obj2d.v4[1] - obj2d.p[1];

  //count intersections with v=0 (u>0) (u<0) and u=0 (v>0) (v<0)
  Four_counter counter = {0,0,0,0};
  counter = count_intersection(obj2d.v1, obj2d.v2, counter);
  counter = count_intersection(obj2d.v2, obj2d.v3, counter);
  counter = count_intersection(obj2d.v3, obj2d.v4, counter);
  counter = count_intersection(obj2d.v4, obj2d.v1, counter);

  //std::cout<<"count: "<<counter[0]<<", "<<counter[1]<<", "<<counter[2]<<", "<<co

  if (counter[0] %2 != 0 && counter[1] %2 != 0 && counter[2] %2 != 0 && counter[3]
    return true;
  else
    return false;
}

//count intersections of edge v1-v2 with u and v axises
Four_counter count_intersection(Point2D v1, Point2D v2, Four_counter counter) {
  int u_plus_count = counter[0];
  int u_minus_count = counter[1];
  int v_plus_count = counter[2];
  int v_minus_count = counter[3];

  //if v2[1]-v1[1] is 0
  if (v2[1]-v1[1] == 0) {
    /*
             |
             |v1--v2
        -----|---->
             |
             |
    */
    if (v2[0]*v1[0] > 0) {
      return {u_plus_count, u_minus_count, v_plus_count, v_minus_count};
    }
```

```
  /*
           |
       v1--|--v2
      -----|---->
           |
           |
  */
  if (v2[0]*v1[0] < 0) {
    if (v1[1] >= 0) {
      v_plus_count++;
      return {u_plus_count, u_minus_count, v_plus_count, v_minus_count};
    } else {
      v_minus_count++;
      return {u_plus_count, u_minus_count, v_plus_count, v_minus_count};
    }
  }
}

//if v2[0]-v1[0] is 0
if (v2[0]-v1[0] == 0) {
  /*
       v1 |
       |  |
       v2 |
      ----|--->
          |
          |
  */
  if (v2[1]*v1[1] > 0) {
    return {u_plus_count, u_minus_count, v_plus_count, v_minus_count};
  }
  /*
       v1 |
       |  |
      -|--|--->
       |  |
       v2 |
  */
```

```
  if (v2[1]*v1[1] < 0) {
    if (v1[0] >= 0) {
      u_plus_count++;
      return {u_plus_count, u_minus_count, v_plus_count, v_minus_count};
    } else {
      u_minus_count++;
      return {u_plus_count, u_minus_count, v_plus_count, v_minus_count};
    }
  }
}

//first calcualte the slope m = (y2  y1)/(x2  x1)
double m = (v2[1] - v1[1]) / (v2[0] - v1[0]);

//when v = 0, u = -y1/m + x1
/*
     v1     |
      \     |
    ---*----|--->
        \   |
         v2 |
*/
double u = - v1[1]/m + v1[0];
Point2D intersection1 = {u, 0};
if (inside_bounding(v1, v2, intersection1)) {
  if (u>=0) {
    return {u_plus_count+1, u_minus_count, v_plus_count, v_minus_count};
  } else {
    return {u_plus_count, u_minus_count+1, v_plus_count, v_minus_count};
  }
}

//when u = 0, v = -x1*m + y1
/*
       |
   ----|--->
     v1|
      \|
```

```
        *
        |\
        | v2
  */
  double v = - v1[0]*m + v1[1];
  Point2D intersection2 = {0, v};
  if (inside_bounding(v1, v2, intersection2)) {
    if (v>=0) {
      return {u_plus_count, u_minus_count, v_plus_count+1, v_minus_count};
    } else {
      return {u_plus_count, u_minus_count, v_plus_count, v_minus_count+1};
    }
  }

  return {u_plus_count, u_minus_count, v_plus_count, v_minus_count};
}

//check if third point is inside the bounding box from point 1 and 2
bool inside_bounding(Point2D v1, Point2D v2, Point2D p) {
  double u_max, u_min, v_max, v_min;

  if (v1[0] >= v2[0]) {
    u_max = v1[0];
    u_min = v1[0];
  } else {
    u_max = v2[0];
    u_min = v2[0];
  }

  if (v1[1] >= v2[1]) {
    v_max = v1[1];
    v_min = v1[1];
  } else {
    v_max = v2[1];
    v_min = v2[1];
  }

  if ( (p[0] > u_min) && (p[0] < u_max) &&
```

```
      (p[1] > v_min) && (p[1] < v_max) )
    return true;
  else
    return false;
}

//make 2D polygon from 3D polygon
POLY4_2D flatten(POLY4 obj, Point p) {
  //find out the dominated dimension
  int drop_i = find_max(obj.N[0], obj.N[1], obj.N[2]);

  //drop the dominated dimension
  if (drop_i == 0) {
    POLY4_2D result = {
      obj.v1[1], obj.v1[2],
      obj.v2[1], obj.v2[2],
      obj.v3[1], obj.v3[2],
      obj.v4[1], obj.v4[2],
      p[1], p[2]
      };
    return result;
  } else if (drop_i == 1) {
    POLY4_2D result = {
      obj.v1[0], obj.v1[2],
      obj.v2[0], obj.v2[2],
      obj.v3[0], obj.v3[2],
      obj.v4[0], obj.v4[2],
      p[0], p[2]
      };
    return result;
  } else if (drop_i == 2) {
    POLY4_2D result = {
      obj.v1[0], obj.v1[1],
      obj.v2[0], obj.v2[1],
      obj.v3[0], obj.v3[1],
      obj.v4[0], obj.v4[1],
      p[0], p[1]
      };
```

```
    return result;
  }

  POLY4_2D null_ = { -1,-1, -1,-1, -1,-1, -1,-1 };
  return null_;
}

//find out the max index for three doubles, 0: first, 1: second, 2: third
int find_max(double x, double y, double z) {
  if (fabs(x) >= fabs(y) && fabs(x) >= fabs(z)) {
    return 0;
  } else if (fabs(y) >= fabs(x) && fabs(y) >= fabs(z)) {
    return 1;
  } else if (fabs(z) >= fabs(x) && fabs(z) >= fabs(y)) {
    return 2;
  } else {
    return -1;
  }
}

//prints a matrix
void pmatrix(std::string str, Matrix m) {
  std::cout<<str<<std::endl;
  for (auto row : m) {
    for (auto num : row) {
      std::cout<<std::setw (10);
      std::cout<<num;
    }
    std::cout<<std::endl;
  }
  std::cout<<std::endl;
}

//get transformation matrix
Matrix get_T(Point vrp) {
  Row r1 = {1, 0, 0, -vrp[0]};
  Row r2 = {0, 1, 0, -vrp[1]};
  Row r3 = {0, 0, 1, -vrp[2]};
```

```
  Row r4 = {0, 0, 0, 1};
  return {r1, r2, r3, r4};
}

//get inverse transformation matrix
Matrix get_Ti(Point vrp) {
  Row r1 = {1, 0, 0, vrp[0]};
  Row r2 = {0, 1, 0, vrp[1]};
  Row r3 = {0, 0, 1, vrp[2]};
  Row r4 = {0, 0, 0, 1};
  return {r1, r2, r3, r4};
}

//get rotation matrix
Matrix get_R(Point vrp, Vector vpn, Vector vup) {
  //first get the translation matrix from world to view
  //auto mt = get_T(vrp);

  //we can see vpn_ and vup_ as vectors. such that we can apply them to get_uvn fu
  auto uvn = get_uvn(vpn, vup);
  //finally contruct our roation matrix using method 2 on class notes
  Row r1 = { uvn[0][0],uvn[0][1],uvn[0][2],0 };
  Row r2 = { uvn[1][0],uvn[1][1],uvn[1][2],0 };
  Row r3 = { uvn[2][0],uvn[2][1],uvn[2][2],0 };
  Row r4 = { 0, 0, 0, 1 };
  return { r1, r2, r3, r4 };
}

//get inverse rotation matrix
Matrix get_Ri(Point vrp, Vector vpn, Vector vup) {
  Matrix m = get_R(vrp, vpn, vup);
  Row r1 = { m[0][0], m[1][0], m[2][0], m[3][0] };
  Row r2 = { m[0][1], m[1][1], m[2][1], m[3][1] };
  Row r3 = { m[0][2], m[1][2], m[2][2], m[3][2] };
  Row r4 = { m[0][3], m[1][3], m[2][3], m[3][3] };
  return {r1,r2,r3,r4};
}
```

```
//world to camera
Matrix get_M(Point vrp, Vector vpn, Vector vup) {
  return mul(get_R(vrp, vpn, vup), get_T(vrp));
}

//camera to world
Matrix get_Mi(Point vrp, Vector vpn, Vector vup) {
  return mul(get_Ti(vrp), get_Ri(vrp, vpn, vup));
}


//matrix multiplication
Point mul(Matrix m, Point x) {
  return mul(x, m);
}

Point mul(Point x, Matrix m) {
  double w =  m[3][0] * x[0]
        + m[3][1] * x[1]
        + m[3][2] * x[2]
        + m[3][3];
  return {(x[0]*m[0][0]+x[1]*m[0][1]+x[2]*m[0][2]+m[0][3])/w,
          (x[0]*m[1][0]+x[1]*m[1][1]+x[2]*m[1][2]+m[1][3])/w,
          (x[0]*m[2][0]+x[1]*m[2][1]+x[2]*m[2][2]+m[2][3])/w};
}

Matrix mul(Matrix m, Matrix n) {
  Row r1 = {m[0][0]*n[0][0]+m[0][1]*n[1][0]+m[0][2]*n[2][0]+m[0][3]*n[3][0],
            m[0][0]*n[0][1]+m[0][1]*n[1][1]+m[0][2]*n[2][1]+m[0][3]*n[3][1],
            m[0][0]*n[0][2]+m[0][1]*n[1][2]+m[0][2]*n[2][2]+m[0][3]*n[3][2],
            m[0][0]*n[0][3]+m[0][1]*n[1][3]+m[0][2]*n[2][3]+m[0][3]*n[3][3]};
  Row r2 = {m[1][0]*n[0][0]+m[1][1]*n[1][0]+m[1][2]*n[2][0]+m[1][3]*n[3][0],
            m[1][0]*n[0][1]+m[1][1]*n[1][1]+m[1][2]*n[2][1]+m[1][3]*n[3][1],
            m[1][0]*n[0][2]+m[1][1]*n[1][2]+m[1][2]*n[2][2]+m[1][3]*n[3][2],
            m[1][0]*n[0][3]+m[1][1]*n[1][3]+m[1][2]*n[2][3]+m[1][3]*n[3][3]};
  Row r3 = {m[2][0]*n[0][0]+m[2][1]*n[1][0]+m[2][2]*n[2][0]+m[2][3]*n[3][0],
            m[2][0]*n[0][1]+m[2][1]*n[1][1]+m[2][2]*n[2][1]+m[2][3]*n[3][1],
            m[2][0]*n[0][2]+m[2][1]*n[1][2]+m[2][2]*n[2][2]+m[2][3]*n[3][2],
```

```
            m[2][0]*n[0][3]+m[2][1]*n[1][3]+m[2][2]*n[2][3]+m[2][3]*n[3][3]};
  Row r4 = {m[3][0]*n[0][0]+m[3][1]*n[1][0]+m[3][2]*n[2][0]+m[3][3]*n[3][0],
            m[3][0]*n[0][1]+m[3][1]*n[1][1]+m[3][2]*n[2][1]+m[3][3]*n[3][1],
            m[3][0]*n[0][2]+m[3][1]*n[1][2]+m[3][2]*n[2][2]+m[3][3]*n[3][2],
            m[3][0]*n[0][3]+m[3][1]*n[1][3]+m[3][2]*n[2][3]+m[3][3]*n[3][3]};
  return {r1,r2,r3,r4};
}

Row mul(Row x, Matrix m) {
  return {x[0]*m[0][0]+x[1]*m[0][1]+x[2]*m[0][2]+x[3]*m[0][3],
          x[0]*m[1][0]+x[1]*m[1][1]+x[2]*m[1][2]+x[3]*m[1][3],
          x[0]*m[2][0]+x[1]*m[2][1]+x[2]*m[2][2]+x[3]*m[2][3],
          x[0]*m[3][0]+x[1]*m[3][1]+x[2]*m[3][2]+x[3]*m[3][3]};
}

Row mul(Matrix m, Row x) {
  return mul(x, m);
}

//return if p1 is closer to p0 than p2
bool closer(Point p1, Point p2, Point p0) {
  Vector v1 = { (p1[0] - p0[0]), (p1[1] - p0[1]), (p1[2] - p0[2])};
  double d1 = get_length(v1);
  Vector v2 = { (p2[0] - p0[0]), (p2[1] - p0[1]), (p2[2] - p0[2])};
  double d2 = get_length(v2);
  return d1 < d2;
}

//Translate 2D array index of row column to 1D index.
//Notice that x, or column index, starts with 0.
//If return value is -1 then there is an out-of-bounce error.
int to_1d(int x, int y) {
  if (x >= IMG_X || x < 0)
    return -1;
  if (y >= IMG_Y || y < 0)
    return -1;
  return (IMG_Y*y + x);
}
```

```
//Translate 1d array index to 2d
std::array<int, 2> to_2d(int x) {
  if (x>=(IMG_X*IMG_Y) || x < 0) {
    return {-1,-1};
  }
  int y_ = x / IMG_X;
  int x_ = x % IMG_X;
  return {x_, y_};
}

//prints the img panel
void print_img_panel(ImagePanel img) {
  std::cout<<std::endl;
  for (auto& pixel : img) {
    std::cout<<pixel<<", ";
  }

  /* ascii art
  for (int i = 0; i<IMG_Y; i++) {
    for (int j = 0; j<IMG_X; j++) {
      if ( img[i*IMG_X+j] > 100 ) {
        std::cout<<"8";
      } else if ( img[i*IMG_X+j] > 0 ) {
        std::cout<<"5";
      } else if ( img[i*IMG_X+j] > -100 ) {
        std::cout<<"0";
      } else if ( img[i*IMG_X+j] > -200 ) {
        std::cout<<"1";
      } else {
        std::cout<<" ";
      }
    }
    std::cout<<std::endl;
  }
  */

  std::cout<<std::endl<<"Array size: "<<img.size()<<std::endl;
```

```
}

//get u,v,n from two non-collinear vectors
UVN get_uvn(Vector V1, Vector V2) {

  //get n, which is just normalized V1
  Vector n = normalize(V1);

  //get u, which is normalized V2 x V1
  Vector u = normalize(cross_product(V2, V1));

  //get v, which is normalized n x u
  Vector v = normalize(cross_product(n, u));

  return {u,v,n};
}

//normalize a Vector
Vector normalize(Vector x) {
  return { x[0]/get_length(x),
           x[1]/get_length(x),
           x[2]/get_length(x) };
}

//dot product
double dot_product(Vector x, Vector y) {
  return x[0]*y[0]+x[1]*y[1]+x[2]*y[2];

}

//calculates cross product of two Vectors
Vector cross_product(Vector x, Vector y) {
  return { x[1]*y[2] - x[2]*y[1],
           x[2]*y[0] - x[0]*y[2],
           x[0]*y[1] - x[1]*y[0]};
}

//calculates length of a Vector
```

```
double get_length(Vector x) {
  return sqrt(pow(x[0],2)+pow(x[1],2)+pow(x[2],2));
}

@
```

2 header

Here is an header file for typedefs and function declarations.

```
<<src/util.h>>=
#ifndef UTIL_H
#define UTIL_H

//define preprocessing vars
#define IMG_X 512
#define IMG_Y 512
#define IMG_LEN ( IMG_X * IMG_Y )
/* definition of the image buffer */
#define ROWS IMG_Y
#define COLS IMG_X

#include <array>
#include <functional>
#include <iostream>
#include <iomanip>
#include <stdio.h>

//types
typedef std::array<int, IMG_LEN> ImagePanel;
typedef std::array<double, 3> Point;
typedef std::array<double, 2> Point2D;
typedef std::array<double, 3> Vector;
typedef std::array<int, 4> Four_counter;
typedef std::array<Vector, 3> UVN;
typedef struct {
```

```
Point intersection; /* intersection point */
Vector normal; /* intersection polygon normal vector */
double kd; /* diffuse reflection coefficient of the surface */
} Intersection;
typedef struct {
Point ref; /* reference point, where the ray is from */
Vector direction; /* ray direction */
} Ray;
typedef std::array<double, 4> Row;
typedef std::array<Row, 4> Matrix;
typedef struct {
double x, y, z; /* center of the circle */
double radius; /* radius of the circle */
double kd; /* diffuse reflection coefficient */
} SPHERE;
typedef struct {
        Point v1;       /* list of vertices */
        Point v2;
        Point v3;
        Point v4;
Vector N; /* normal of the polygon */
double kd; /* diffuse reflection coefficient */
} POLY4;
typedef struct {
        Point2D v1;
        Point2D v2;
        Point2D v3;
        Point2D v4;
        Point2D p;
} POLY4_2D;

//functions
POLY4_2D flatten(POLY4, Point);
ImagePanel foreach_pixel_exec(ImagePanel, std::function<int(Ray, Point)>);
ImagePanel init_img_panel(ImagePanel);
int ray_tracing(Ray, Point);
Intersection ray_objects_intersection(Ray);
int shading(Intersection, Point);
```

```
Intersection ray_sphere_intersection(Ray, SPHERE);
Intersection ray_polygon_intersection(Ray, POLY4);
Ray ray_construction(int, int);

//helper functions
bool inside_bounding(Point2D, Point2D, Point2D);
Four_counter count_intersection(Point2D, Point2D, Four_counter);
int find_max(double, double, double);
double get_D_poly4(POLY4);
bool in_poly4(Point, POLY4);
Point mul(Point, Matrix);
Point mul(Matrix, Point);
Matrix mul(Matrix, Matrix);
Row mul(Row, Matrix);
Row mul(Matrix, Row);
int to_1d(int, int);
std::array<int, 2> to_2d(int);
void print_img_panel(ImagePanel);
void pmatrix(std::string, Matrix);
bool closer(Point, Point, Point);
UVN get_uvn(Vector V1, Vector V2);
Matrix get_T(Point);
Matrix get_Ti(Point);
Matrix get_R(Point, Vector, Vector);
Matrix get_Ri(Point, Vector, Vector);
Matrix get_M(Point, Vector, Vector);
Matrix get_Mi(Point, Vector, Vector);
double get_length(Vector);
Vector cross_product(Vector, Vector);
double dot_product(Vector, Vector);
Vector normalize(Vector);
void save_to_file(ImagePanel);

//global vars
extern Matrix Mwc;
extern Matrix Rwc;
extern Matrix Twc;
extern Matrix Mcw;
```

```
extern Matrix Rcw;
extern Matrix Tcw;
extern Matrix Mwl;
extern Matrix Mlw;
extern double xmin;
extern double ymin;
extern double xmax;
extern double ymax;
extern Point VRP;
extern Vector VPN;
extern Vector VUP;
extern double focal;
extern Point LRP;
extern double Ip;
extern SPHERE obj1;
extern POLY4 obj2;
#endif
@
```

3 main funciton

```
<<src/main.cpp>>=
#include <iostream>
#include "util.h"

/* create a spherical object */
SPHERE obj1 = {1.0, 1.0, 1.0,/* center of the circle */
 1.0,/* radius of the circle */
 0.75}; /* diffuse reflection coefficient */

/* create a polygon object */
POLY4 obj2 = { 0.0, 0.0, 0.0,/* v0 */
0.0, 0.0, 2.0,/* v1 */
2.0, 0.0, 2.0,/* v2 */
2.0, 0.0, 0.0,/* v3 */
0.0, 1.0, 0.0,/* normal of the polygon */
```

```
0.8}; /* diffuse reflection coefficient */

//unsigned char img[ROWS][COLS];

/* definition of window on the image plane in the camera coordinates */
/* They are used in mapping (j, i) in the screen coordinates into */
/* (x, y) on the image plane in the camera coordinates */
/* The window size used here simulates the 35 mm film. */
double xmin = 0.0175;
double ymin = -0.0175;
double xmax = -0.0175;
double ymax = 0.0175;


/* definition of the camera parameters */
//Point VRP = {1.0, 2.0, 3.5};
//Vector VPN = {0.0, -1.0, -2.5};
//Vector VUP = {0.0, 1.0, 0.0};
Point VRP = {1.0, 1.0, 4.5};
Vector VPN = {0.0, 0.0, -1.0};
Vector VUP = {0.0, 1.0, 0.0};

double focal = 0.05; /* focal length simulating 50 mm lens */

/* definition of light source */
Point LRP = {-10.0, 10.0, 2.0}; /* light position */
double Ip = 200.0; /* intensity of the point light source */

/* Transformation from the world to the camera coordinates */
Matrix Mwc = get_M(VRP, VPN, VUP);
Matrix Rwc = get_R(VRP, VPN, VUP);
Matrix Twc = get_T(VRP);
/* Transformation from the camera to the world coordinates */
Matrix Mcw = get_Mi(VRP, VPN, VUP);
Matrix Rcw = get_Ri(VRP, VPN, VUP);
Matrix Tcw = get_Ti(VRP);
/* Transformation from the world to light coordinates */
Matrix Mwl = get_T(LRP);
```

```
/* Transformation from the light to the world coordinates */
Matrix Mlw = get_Ti(LRP);

int main () {
  /*
  //tests
  Point vrp = {6.0, 10.0, -5.0};
  Vector vpn = {-6.0, -9.0, 5.0};
  Vector vup = {0.0, 1.0, 0.0};
  auto uvn = get_uvn(vpn, vup);
  std::cout<<"get_uvn function:"<<std::endl;
  for (auto vecotr : uvn) {//for each Vecotr in uvn
    for (auto num : vecotr) {//for each number in Vecotr
      std::cout<<num<<',';
    }
    std::cout<<std::endl;
  }

  Matrix mwc = get_M(vrp, vpn, vup);
  Matrix mcw = get_Mi(vrp, vpn, vup);
  Matrix twc = get_T(vrp);
  Matrix tcw = get_Ti(vrp);
  Matrix rwc = get_R(vrp, vpn, vup);
  Matrix rcw = get_Ri(vrp, vpn, vup);
  pmatrix("mwc:", mwc);
  pmatrix("twc:", twc);
  pmatrix("rwc:", rwc);
  pmatrix("mcw:", mcw);
  pmatrix("tcw:", tcw);
  pmatrix("rcw:", rcw);

  pmatrix("Mcw:", Mcw);

  std::cout<<"to_1d function, expected to be 512:"<<std::endl;
  std::cout<<to_1d(0, 1)<<std::endl;

  std::cout<<"to_2d function, expected to be 0, 1:"<<std::endl;
  std::cout<<to_2d(512)[0]<<std::endl;
```

```
std::cout<<to_2d(512)[1]<<std::endl;

std::cout<<"to_1d function, expected to be 513:"<<std::endl;
std::cout<<to_1d(1, 1)<<std::endl;

std::cout<<"to_2d function, expected to be 1,1:"<<std::endl;
std::cout<<to_2d(513)[0]<<std::endl;
std::cout<<to_2d(513)[1]<<std::endl;

std::cout<<"to_1d function, expected to be 1023:"<<std::endl;
std::cout<<to_1d(511, 1)<<std::endl;

std::cout<<"to_2d function, expected to be 511,1:"<<std::endl;
std::cout<<to_2d(1023)[0]<<std::endl;
std::cout<<to_2d(1023)[1]<<std::endl;

std::cout<<"to_1d function, expected to be -1:"<<std::endl;
std::cout<<to_1d(512, 1)<<std::endl;

std::cout<<"to_2d function, expected to be -1,-1:"<<std::endl;
std::cout<<to_2d(512*512)[0]<<std::endl;
std::cout<<to_2d(512*512)[1]<<std::endl;

std::cout<<"closer function, expected to be 1 and 0:"<<std::endl;
std::cout<<closer({1,1,1},{2,2,2},{0,0,0})<<std::endl;
std::cout<<closer({3,3,3},{2,2,2},{0,0,0})<<std::endl;

std::cout<<"mul function: point * matrix"<<std::endl;
Point a = {3,3,3};
std::cout<<mul(a, Mcw)[0]<<std::endl;
std::cout<<mul(Mcw, a)[1]<<std::endl;
std::cout<<mul(a, Mcw)[2]<<std::endl;

pmatrix("mul funciton: matrix*matrix:", mul(Mwc, Mcw));

std::cout<<"mul function: row * matrix"<<std::endl;
Row b = {3,3,3,3};
std::cout<<mul(b, Mcw)[0]<<std::endl;
```

```
  std::cout<<mul(Mcw, b)[1]<<std::endl;
  std::cout<<mul(b, Mcw)[2]<<std::endl;
  std::cout<<mul(b, Mcw)[3]<<std::endl;
  */

  //main program
  ImagePanel img;
  img = init_img_panel(img);
  img = foreach_pixel_exec(img, ray_tracing);
  //print_img_panel(img);

  //save result to binary file
  save_to_file(img);

  return 0;
}
@
```

4 compile script

Furthermore, this is the command to link these files. Notice that I am using -std=c++11 flag to enable c++ 11 features. The output binary executable is bin/run

```
<<compile.sh>>=
clang++ -std=c++11 -stdlib=libc++ -o bin/run src/main.cpp src/util.cpp
@
```