Lode's Computer Graphics Tutorial

Raycasting

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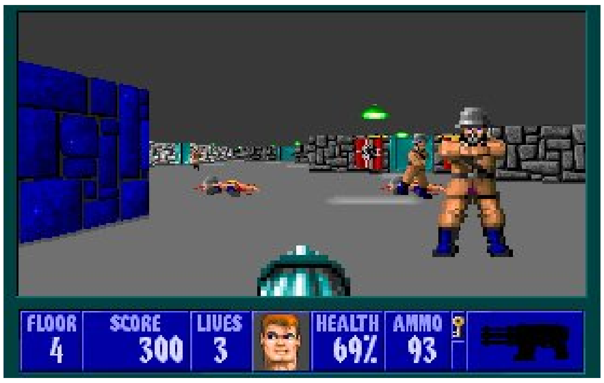
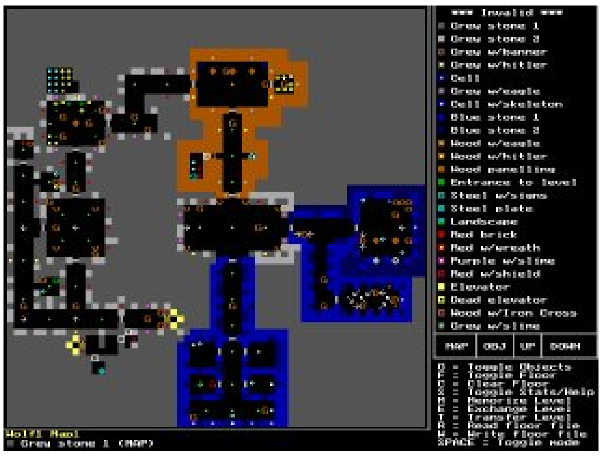
Introduction

Raycasting is a rendering technique to create a 3D perspective in a 2D map. Back when computers were slower it wasn't possible to run real 3D engines in realtime, and raycasting was the first solution. Raycasting can go very fast, because only a calculation has to be done for every vertical line of the screen. The most well known game that used this technique, is of course Wolfenstein 3D.



The raycasting engine of Wolfenstein 3D was very limited, allowing it to run on a even a 286 computer: all the walls have the same height and are orthogonal squares on a 2D grid, as can be seen in this screenshot from a mapeditor for Wolf3D:



Things like stairs, jumping or height differences are impossible to make with this engine. Later games such as Doom and Duke Nukem 3D also used raycasting, but much more advanced engines that allowed sloped walls, different heights, textured floors and ceilings, transparent walls, etc... The sprites (enemies, objects and goodies) are 2D images, but sprites aren't discussed in this tutorial for now.

Ray*casting* is not the same as ray*tracing*! Raycasting is a fast semi-3D technique that works in realtime even on 4MHz graphical calculators, while raytracing is a realistic rendering technique that supports reflections and shadows in true 3D scenes, and only recently computers became fast enough to do it in realtime for reasonably high resolutions and complex scenes.

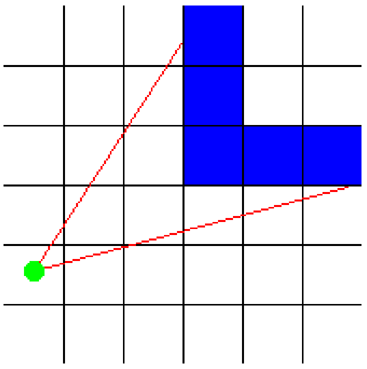
The code of the untextured and textured raycasters is given in this document completely, but it's quite long, you can also download the code instead:

raycaster_flat.cpp
raycaster_textured.cpp

The Basic Idea

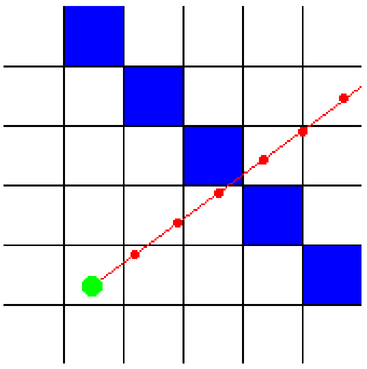
The basic idea of raycasting is as follows: the map is a 2D square grid, and each square can either be 0 (= no wall), or a positive value (= a wall with a certain color or texture).

For every x of the screen (i.e. for every vertical stripe of the screen), send out a ray that starts at the player location and with a direction that depends on both the player's looking direction, and the x-coordinate of the screen. Then, let this ray move forward on the 2D map, until it hits a map square that is a wall. If it hit a wall, calculate the distance of this hit point to the player, and use this distance to calculate how high this wall has to be drawn on the screen: the further away the wall, the smaller it's on screen, and the closer, the higher it appears to be. These are all 2D calculations. This image shows a top down overview of two such rays (red) that start at the player (green dot) and hit blue walls:

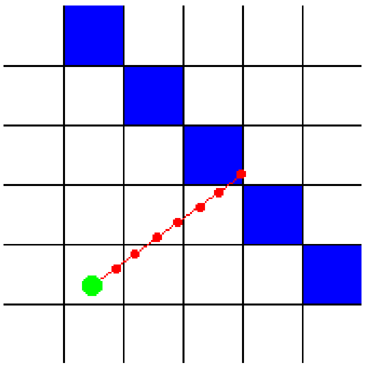


To find the first wall that a ray encounters on its way, you have to let it start at the player's position, and then all the time, check whether or not the ray is inside a wall. If it's inside a wall (hit), then the loop can stop, calculate the distance, and draw the wall with the correct height. If the ray position is not in a wall, you have to trace it further: add a certain value to its position, in the direction of the direction of this ray, and for this new position, again check if it's inside a wall or not. Keep doing this until finally a wall is hit.

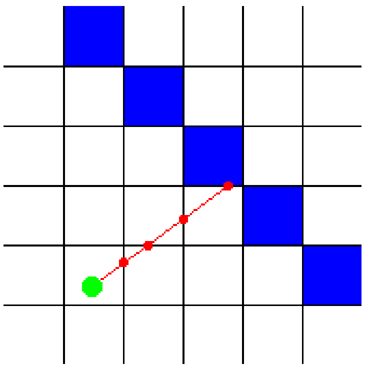
A human can immediatly see where the ray hits the wall, but it's impossible to find which square the ray hits immediatly with a single formula, because a computer can only check a finite number of positions on the ray. Many raycasters add a constant value to the ray each step, but then there's a chance that it may miss a wall! For example, with this red ray, its position was checked at every red spot:



As you can see, the ray goes straight through the blue wall, but the computer didn't detect this, because it only checked at the positions with the red dots. The more positions you check, the smaller the chance that the computer won't detect a wall, but the more calculations are needed. Here the step distance was halved, so now he detects that the ray went through a wall, though the position isn't completely correct:



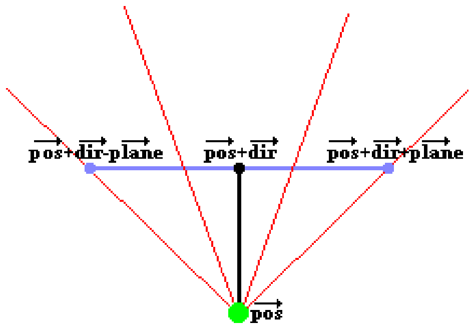
For infinite precision with this method, an infinitely small step size, and thus an infinite number of calculations would be needed! That's pretty bad, but luckily, there's a better method that requires only very few calculations and yet will detect every wall: the idea is to check at every side of a wall the ray will encounter. We give each square width 1, so each side of a wall is an integer value and the places in between have a value after the point. Now the step size isn't constant, it depends on the distance to the next side:



As you can see on the image above, the ray hits the wall exactly where we want it. In the way presented in this tutorial, an algorithm is used that's based on DDA or "Digital Differential Analysis". DDA is a fast algorithm typically used on square grids to find which squares a line hits (for example to draw a line on a screen, which is a grid of square pixels). So we can also use it to find which squares of the map our ray hits, and stop the algorithm once a square that is a wall is hit.

Some raytracers work with Euclidean angles to represent the direction of the player and the rays, and determinate the Field Of View with another angle. I found however that it's much easier to work with vectors and a camera instead: the position of the player is always a vector (an x and a y coordinate), but now, we make the direction a vector as well: so the direction is now determinated by two values: the x and y coordinate of the direction. A direction vector can be seen as follows: if you draw a line in the direction the player looks, through the position of the player, then every point of the line is the sum of the position of the player, and a multiple of the direction vector. The length of a direction vector doesn't really matter, only its direction. Multiplying x and y by the same value changes the length but keeps the same direction.

This method with vectors also requires an extra vector, which is the camera plane vector. In a true 3D engine, there's also a camera plane, and there this plane is really a 3D plane so two vectors (u and v) are required to represent it. Raycasting happens in a 2D map however, so here the camera plane isn't really a plane, but a line, and is represented with a single vector. The camera plane should always be perpendicular on the direction vector. The camera plane represents the surface of the computer screen, while the direction vector is perpendicular on it and points inside the screen. The position of the player, which is a single point, is a point in front of the camera plane. A certain ray of a certain x-coordinate of the screen, is then the ray that starts at this player position, and goes through that position on the screen or thus the camera plane.

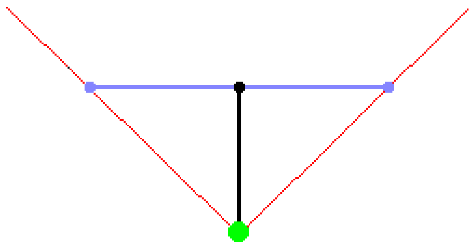

$\overrightarrow{pos}+\overrightarrow{dir}-\overrightarrow{plane}$
$\overrightarrow{pos}+\overrightarrow{dir}$
$\overrightarrow{pos}+\overrightarrow{dir}+\overrightarrow{plane}$
$\overrightarrow{pos}$

The image above represents such a 2D camera. The green spot is the position (vector "pos"). The black line, ending in the black spot, represents the direction vector (vector "dir"), so the position of the black dot is pos+dir. The blue line represents the full camera plane, the vector from the black dot to the right blue dot represents the vector "plane", so the position of the right blue point is pos+dir+plane, and the posistion of the left blue dot is pos+dir-plane (these are all vector additions).

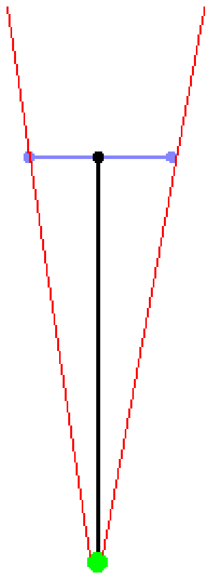
The red lines in the image are a few rays. The direction of these rays is easily calculated out of the camera: it's the sum of the direction vector of the camear, and a part of the plane vector of the camera: for example the third red ray on the image, goes through the right part of the camera plane at the point about 1/3th of its length. So the direction of this ray is dir + plane*1/3. This ray direction is the vector rayDir, and the X and Y component of this vector are then used by the DDA algorithm.

The two outer lines, are the left and right border of the screen, and the angle between those two lines is called the Field Of Vision or FOV. The FOV is determinated by the ratio of the length of the direction vector, and the length of the plane. Here are a few examples of different FOV's:

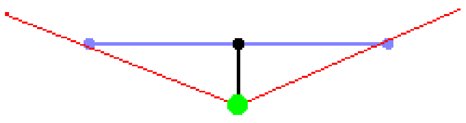
If the direction vector and the camera plane vector have the same length, the FOV will be 90°:



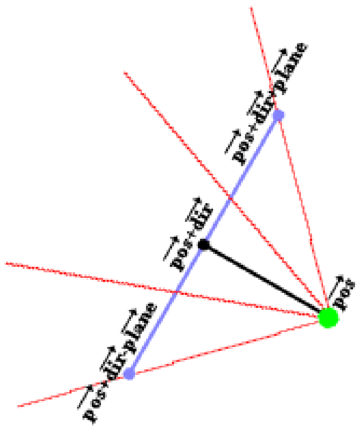
If the direction vector is much longer than the camera plane, the FOV will be much smaller than 90°, and you'll have a very narrow vision. You'll see everything more detailed though and there will be less depth, so this is the same as zooming in:



If the direction vector is shorter than the camera plane, the FOV will be larger than 90° (180° is the maximum, if the direction vector is close to 0), and you'll have a much wider vision, like zooming out:



When the player rotates, the camera has to rotate, so both the direction vector and the plane vector have to be rotated. Then, the rays will all automaticly rotate as well.


$\vec{pos}+\vec{dir}+\vec{plane}$
$\vec{pos}+\vec{dir}$
$\vec{pos}$
$\vec{pos}+\vec{dir}-\vec{plane}$

To rotate a vector, multiply it with the rotation matrix

```
[ cos(a) -sin(a) ]
[ sin(a)  cos(a) ]
```

If you don't know about vectors and matrices, try to find a tutorial with google, an appendix about those is planned for this tutorial later.

There's nothing that forbids you to use a camera plane that isn't perpendicular to the direction, but the result will look like a "skewed" world.

Untextured Raycaster

Download the source code here: raycaster_flat.cpp

To start with the basics, we'll begin with an untextured raycaster. This example also includes an fps counter (frames per second), and input keys with collision detection to move and rotate.

The map of the world is a 2D array, where each value represents a square. If the value is 0, that square represents an empty, walkthroughable square, and if the value is higher than 0, it represents a wall with a certain color or texture. The map declared here is very small, only 24 by 24 squares, and is defined directly in the code. For a real game, like Wolfenstein 3D, you use a bigger map and load it from a file instead. All the zero's in the grid are empty space, so basicly you see a very big room, with a wall around it (the values 1), a small room inside it (the values 2), a few pilars (the values 3), and a corridor with a room (the values 4). Note that this code isn't inside any function yet, put it before the main function starts.

```
#define mapWidth 24
#define mapHeight 24
#define screenWidth 640
#define screenHeight 480

int worldMap[mapWidth][mapHeight]=
{
  {1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1},
  {1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1},
  {1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1},
  {1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1},
  {1,0,0,0,0,0,2,2,2,2,2,0,0,0,0,3,0,3,0,3,0,0,0,1},
  {1,0,0,0,0,0,2,0,0,0,2,0,0,0,0,0,0,0,0,0,0,0,0,1},
  {1,0,0,0,0,0,2,0,0,0,2,0,0,0,0,3,0,0,0,3,0,0,0,1},
  {1,0,0,0,0,0,2,0,0,0,2,0,0,0,0,0,0,0,0,0,0,0,0,1},
  {1,0,0,0,0,0,2,2,0,2,2,0,0,0,0,3,0,3,0,3,0,0,0,1},
  {1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1},
  {1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1},
  {1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1},
  {1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1},
  {1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1},
  {1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1},
  {1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1},
  {1,4,4,4,4,4,4,4,4,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1},
  {1,4,0,4,0,0,0,0,4,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1},
  {1,4,0,0,0,0,5,0,4,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1},
  {1,4,0,4,0,0,0,0,4,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1},
  {1,4,0,4,4,4,4,4,4,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1},
  {1,4,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1},
  {1,4,4,4,4,4,4,4,4,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1},
  {1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1}
};
```

A first few variables are declared: posX and posY represent the position vector of the player, dirX and dirY represent the direction of the player, and planeX and planeY the camera plane of the player. Make sure the camera plane is perpendicular to the direction, but you can change the length of it. The ratio between the length of the direction and the camera plane determinates the FOV, here the direction vector is a bit longer than the camera plane, so the FOV will be smaller than 90° (more precisely, the FOV is 2 * atan(0.66/1.0)=66°, which is perfect for a first person shooter game). Later on when rotating around with the input keys, the values of dir and plane will be changed, but they'll always remain perpendicular and keep the same length.

The variables time and oldTime will be used to store the time of the current and the previous frame, the time difference between these two can be used to determinate how much you should move when a certain key is pressed (to move a constant speed no matter how long the calculation of the frames takes), and for the FPS counter.

```
int main(int /*argc*/, char */*argv*/[])
{
  double posX = 22, posY = 12;  //x and y start position
  double dirX = -1, dirY = 0; //initial direction vector
  double planeX = 0, planeY = 0.66; //the 2d raycaster version of camera plane

  double time = 0; //time of current frame
  double oldTime = 0; //time of previous frame
```

The rest of the main function starts now. First, the screen is created with a resolution of choice. If you pick a large resolution, like 1280*1024, the effect will go quite slow, not because the raycating algorithm is slow, but simply because uploading a whole screen from the CPU to the video card goes so slow.

```
  screen(screenWidth, screenHeight, 0, "Raycaster");
```

After setting up the screen, the gameloop starts, this is the loop that draws a whole frame and reads the input every time.

```
  while(!done())
  {
```

Here starts the actual raycasting. The raycasting loop is a for loop that goes through every x, so there isn't a calculation for every pixel of the screen, but only for every vertical stripe, which isn't much at all! To begin the raycasting loop, some variables are delcared and calculated:

The ray starts at the position of the player (posX, posY).

cameraX is the x-coordinate on the camera plane that the current x-coordinate of the screen represents, done this way so that the right side of the screen will get coordinate 1, the center of the screen gets coordinate 0, and the left side of the screen gets coordinate -1. Out of this, the direction of the ray can be calculated as was explained earlier: as the sum of the direction vector, and a part of the plane vector. This has to be done both for the x and y coordinate of the vector (since adding two vectors is adding their x-coordinates, and adding their y-coordinates).

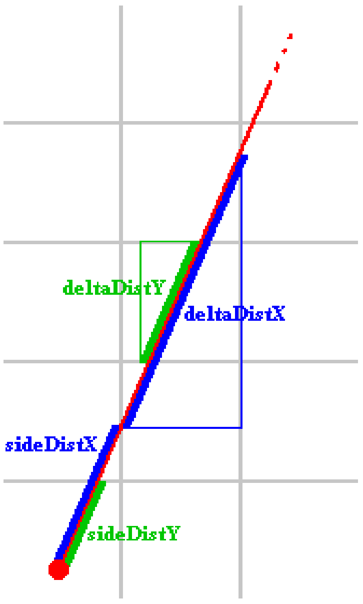
```
  for(int x = 0; x < w; x++)
  {
    //calculate ray position and direction
    double cameraX = 2 * x / double(w) - 1; //x-coordinate in camera space
    double rayDirX = dirX + planeX * cameraX;
    double rayDirY = dirY + planeY * cameraX;
```

In the next code piece, more variables are declared and calculated, these have relevance to the DDA algorithm:

mapX and mapY represent the current square of the map the ray is in. The ray position itself is a floating point number and contains both info about in which square of the map we are, and *where* in that square we are, but mapX and mapY are only the coordinates of that square.

sideDistX and sideDistY are initially the distance the ray has to travel from its start position to the first x-side and the first y-side. Later in the code they will be incremented while steps are taken.

deltaDistX and deltaDistY are the distance the ray has to travel to go from 1 x-side to the next x-side, or from 1 y-side to the next y-side. The following image shows the initial sideDistX, sideDistY and deltaDistX and deltaDistY:



When deriving deltaDistX geometrically you get, with Pythagoras, the formulas below. For the blue triangle (deltaDistX), one side has length 1 (as it is exactly one cell) and the other has length raydirY / raydirX because it is exaclty the amount of units the ray goes in the y-direction when taking 1 step in the X-direction. For the green triangle (deltaDistY), the formula is similar.

deltaDistX = sqrt(1 + (rayDirY * rayDirY) / (rayDirX * rayDirX))
deltaDistY = sqrt(1 + (rayDirX * rayDirX) / (rayDirY * rayDirY))

But this can be simplified to:

deltaDistX = abs(|rayDir| / rayDirX)
deltaDistY = abs(|rayDir| / rayDirY)

Where |rayDir| is the length of the vector rayDirX, rayDirY (that is sqrt(rayDirX * rayDirX + rayDirY * rayDirY)): you can indeed verify that e.g. sqrt(1 + (rayDirY * rayDirY) / (rayDirX * rayDirX)) equals abs(sqrt(rayDirX *

rayDirX + rayDirY * rayDirY) / rayDirX). However, we can use 1 instead of |rayDir|, because only the *ratio* between deltaDistX and deltaDistY matters for the DDA code that follows later below, so we get:

deltaDistX = abs(1 / rayDirX)
deltaDistY = abs(1 / rayDirY)

Due to this, the deltaDist and sideDist values used in the code do not match the lengths shown in the picture above, but their relative sizes all still match.

[thanks to Artem for spotting this simplification]

The variable perpWallDist will be used later to calculate the length of the ray.

The DDA algorithm will always jump exactly one square each loop, either a square in the x-direction, or a square in the y-direction. If it has to go in the negative or positive x-direction, and the negative or positive y-direction will depend on the direction of the ray, and this fact will be stored in stepX and stepY. Those variables are always either -1 or +1.

Finally, hit is used to determinate whether or not the coming loop may be ended, and side will contain if an x-side or a y-side of a wall was hit. If an x-side was hit, side is set to 0, if an y-side was hit, side will be 1. By x-side and y-side, I mean the lines of the grid that are the borders between two squares.

```
      //which box of the map we're in
      int mapX = int(posX);
      int mapY = int(posY);

      //length of ray from current position to next x or y-side
      double sideDistX;
      double sideDistY;

       //length of ray from one x or y-side to next x or y-side
      double deltaDistX = (rayDirX == 0) ? 1e30 : std::abs(1 / rayDirX);
      double deltaDistY = (rayDirY == 0) ? 1e30 : std::abs(1 / rayDirY);
      double perpWallDist;

      //what direction to step in x or y-direction (either +1 or -1)
      int stepX;
      int stepY;

      int hit = 0; //was there a wall hit?
      int side; //was a NS or a EW wall hit?
```

NOTE: If rayDirX or rayDirY are 0, the division through zero is avoided by setting it to a very high value 1e30. If you are using a language such as C++, Java or JS, this is not actually needed, as it supports the IEEE 754 floating point standard, which gives the result Infinity, which works correctly in the code below. However, some other languages, such as Python, disallow division through zero, so the more generic code that works everywhere is given above. 1e30 is an arbitrarily chosen high enough number and can be set to Infinity if your programming language supports assiging that value.

Now, before the actual DDA can start, first stepX, stepY, and the initial sideDistX and sideDistY still have to be calculated.

If the ray direction has a negative x-component, stepX is -1, if the ray direciton has a positive x-component it's +1. If the x-component is 0, it doesn't matter what value stepX has since it'll then be unused.
The same goes for the y-component.

If the ray direction has a negative x-component, sideDistX is the distance from the ray starting position to the first side to the left, if the ray direciton has a positive x-component the first side to the right is used instead.
The same goes for the y-component, but now with the first side above or below the position.
For these values, the integer value mapX is used and the real position subtracted from it, and 1.0 is added in some of the cases depending if the side to the left or right, of the top or the bottom is used. Then you get the perpendicular distance to this side, so multiply it with deltaDistX or deltaDistY to get the real Euclidean distance.

```
      //calculate step and initial sideDist
      if (rayDirX < 0)
      {
        stepX = -1;
        sideDistX = (posX - mapX) * deltaDistX;
      }
      else
      {
        stepX = 1;
        sideDistX = (mapX + 1.0 - posX) * deltaDistX;
      }
      if (rayDirY < 0)
      {
        stepY = -1;
        sideDistY = (posY - mapY) * deltaDistY;
      }
      else
      {
        stepY = 1;
        sideDistY = (mapY + 1.0 - posY) * deltaDistY;
      }
```

Now the actual DDA starts. It's a loop that increments the ray with 1 square every time, until a wall is hit. Each time, either it jumps a square in the x-direction (with stepX) or a square in the y-direction (with stepY), it always jumps 1 square at once. If the ray's direction would be the x-direction, the loop will only have to jump a square in the x-direction everytime, because the ray will never change its y-direction. If the ray is a bit sloped to the y-direction, then every so many jumps in the x-direction, the ray will have to jump one square in the y-direction. If the ray is exactly the y-direction, it never has to jump in the x-direction, etc...

sideDistX and sideDistY get incremented with deltaDistX with every jump in their direction, and mapX and mapY get incremented with stepX and stepY respectively.

When the ray has hit a wall, the loop ends, and then we'll know whether an x-side or y-side of a wall was hit in the variable "side", and what wall was hit with mapX and mapY. We won't know exactly where the wall was hit however, but that's not needed in this case because we won't use textured walls for now.

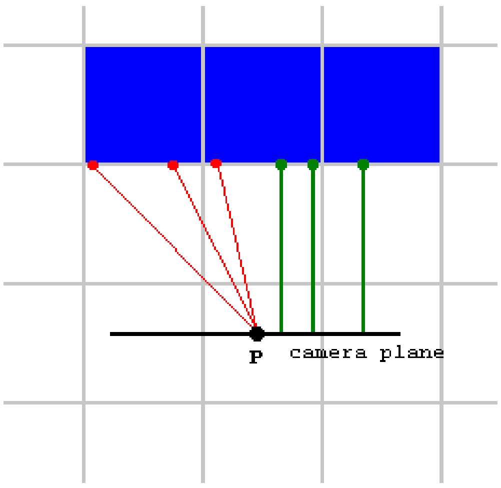
```
      //perform DDA
      while (hit == 0)
      {
        //jump to next map square, either in x-direction, or in y-direction
        if (sideDistX < sideDistY)
        {
          sideDistX += deltaDistX;
          mapX += stepX;
          side = 0;
        }
        else
        {
          sideDistY += deltaDistY;
          mapY += stepY;
          side = 1;
        }
        //Check if ray has hit a wall
        if (worldMap[mapX][mapY] > 0) hit = 1;
      }
```

After the DDA is done, we have to calculate the distance of the ray to the wall, so that we can calculate how high the wall has to be drawn after this.

We don't use the Euclidean distance to the point representing player, but instead the distance to the camera plane (or, the distance of the point projected on the camera direction to the player), to avoid the fisheye effect. The fisheye effect is an effect you see if you use the real distance, where all the walls become rounded, and can make you sick if you rotate.

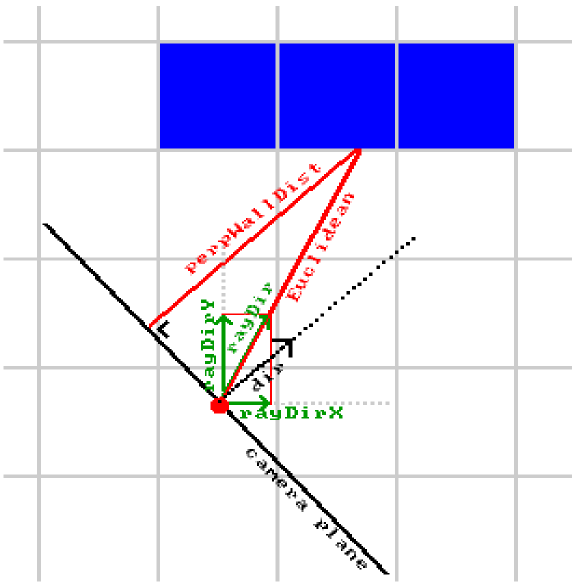
The following image shows why we take distance to camera plane instead of player. With P the player, and the black line the camera plane: To the left of the player, a few red rays are shown from hitpoints on the wall to the player, representing Euclidean distance. On the right side of the player, a few green rays are shown going from hitpoints on the wall directly to the camera plane instead of to the player. So the lengths of those green lines are examples of the perpendicular distance we'll use instead of direct Euclidean distance.

In the image, the player is looking directly at the wall, and in that case you would expect the wall's bottom and top to form a perfectly horizontal line on the screen. However, the red rays all have a different lenght, so would compute different wall heights for different vertical stripes, hence the rounded effect. The green rays on the right all have the same length, so will give the correct result. The same still apllies for when the player rotates (then the camera plane is no longer horizontal and the green lines will have different lengths, but still with a constant change between each) and the walls become diagonal but straight lines on the screen. This explanation is somewhat handwavy but gives the idea.



Note that this part of the code isn't "fisheye correction", such a correction isn't needed for the way of raycasting used here, the fisheye effect is simply avoided by the way the distance is calculated here. It's even easier to calculate this perpendicular distance than the real distance, we don't even need to know the exact location where the wall was hit.

This perpenducular distance is called "perpWallDist" in the code. One way to compute it is to use the formula for shortest distance from a point to a line, where the point is where the wall was hit, and the line is the camera plane:



However, it can be computed simpler than that: due to how deltaDist and sideDist were scaled by a factor of |rayDir| above, the length of sideDist already almost equals perpWallDist. We just need to subtract deltaDist once from it, going one step back, because in the DDA steps above we went one step further to end up inside the wall.

Depending on whether the ray hit an X side or Y side, the formula is computed using sideDistX, or sideDistY.

```
    //Calculate distance projected on camera direction (Euclidean distance would give fisheye effect!)
    if(side == 0) perpWallDist = (sideDistX - deltaDistX);
    else          perpWallDist = (sideDistY - deltaDistY);
```

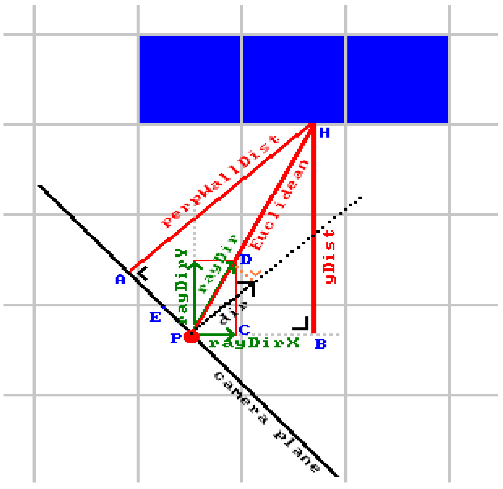
A more detailed derivation of the perpWallDist formula is depicted in the image below, for the side == 1 case.

Meaning of the points:

- P: position of the player, (posX, posY) in the code
- H: hitpoint of the ray on the wall. Its y-position is known to be mapY + (1 - stepY) / 2
- yDist matches "(mapY + (1 - stepY) / 2 - posY)", this is the y coordinate of the Euclidean distance vector, in world coordinates. Here, (1 - stepY) / 2) is a correction term that is 0 or 1 based on positive or negative y direction, which is also used in the initialization of sideDistY.
- dir: the main player looking direction, given by dirX,dirY in the code. The length of this vector is always exactly 1. This matches the looking direction in the center of the screen, as opposed to the direction of the current ray. It is perpendicular to the camera plane, and perpWallDist is parallel to this.
- orange dotted line (may be hard to see, use CTRL+scrollwheel or CTRL+plus to zoom in a desktop browser to see it better): the value that was added to dir to get rayDir. Importantly, this is parallel to the camera plane, perpendicular to dir.
- A: point of the camera plane closest to H, the point where perpWallDist intersects with camera plane
- B: point of X-axis through player closest to H, point where yDist crosses the world X-axis through the player
- C: point at player position + rayDirX
- D: point at player position + rayDir.
- E: This is point D with the dir vector subtracted, in other words, E + dir = D.
- points A, B, C, D, E, H and P are used in the explanation below: they form triangles which are considered: BHP, CDP, AHP and DEP.

The actual derivation:

- 1: Triangles PBH and PCD have the same shape but different size, so same ratios of edges
- 2: Given step 1, the triangles show that the ratio yDist / rayDirY is equal to the ratio Euclidean / |rayDir|, so now we can derive perpWallDist = Euclidean / |rayDir| instead.
- 3: Triangles AHP and EDP have the same shape but different size, so same ratios of edges. Length of edge ED, that is |ED|, equals length of dir, |dir|, which is 1. Similarly, |DP| equals |rayDir|.
- 4: Given step 3, the triangles show that the ratio Euclidean / |rayDir| = perpWallDist / |dir| = perpWallDist / 1.
- 5: Combining steps 4 and 2 shows that perpWallDist = yDist / rayDirY, where yDist is mapY + (1 - stepY) / 2) - posY
- 6: In the code, sideDistY - deltaDistY, after the DDA steps, equals (posY + (1 - stepY) / 2 - mapY) * deltaDistY (given that sideDistY is computed from posY and mapY), so yDist = (sideDistY - deltaDistY) / deltaDistY
- 7: Given that deltaDistY = 1 / |rayDirY|, step 6 gives that yDist = (sideDistY - deltaDistY) * |rayDirY|
- 8: Combining steps 5 and 7 gives perpWallDist = yDist / rayDirY = (sideDistY - deltaDistY) / |rayDirY| / rayDirY.
- 9: Given how cases for signs of sideDistY and deltaDistY in the code are handled the absolute value doesn't matter, and equals (sideDistY - deltaDistY), which is the formula used



[Thanks to Thomas van der Berg in 2016 for pointing out simplifications of the code (perpWallDist could be simplified and the value reused for wallX).
[Thanks to Roux Morgan in 2020 for helping to clarify the explanation of perpWallDist, the tutorial was lacking some information before this]
[Thanks to Noah Wagner and Elias for finding further simplifications for perpWallDist]

Now that we have the calculated distance (perpWallDist), we can calculate the height of the line that has to be drawn on screen: this is the inverse of perpWallDist, and then multiplied by h, the height in pixels of the screen, to bring it to pixel coordinates. You can of course also multiply it with another value, for example 2*h, if you want to walls to be higher or lower. The value of h will make the walls look like cubes with equal height, width and depth, while large values will create higher boxes (depending on your monitor).

Then out of this lineHeight (which is thus the height of the vertical line that should be drawn), the start and end position of where we should really draw are calculated. The center of the wall should be at the center of the screen, and if these points lie outside the screen, they're capped to 0 or h-1.

```
      //Calculate height of line to draw on screen
      int lineHeight = (int)(h / perpWallDist);

      //calculate lowest and highest pixel to fill in current stripe
      int drawStart = -lineHeight / 2 + h / 2;
      if(drawStart < 0)drawStart = 0;
      int drawEnd = lineHeight / 2 + h / 2;
      if(drawEnd >= h)drawEnd = h - 1;
```

Finally, depending on what number the wall that was hit has, a color is chosen. If an y-side was hit, the color is made darker, this gives a nicer effect. And then the vertical line is drawn with the verLine command. This ends the raycasting loop, after it has done this for every x at least.

```
      //choose wall color
      ColorRGB color;
      switch(worldMap[mapX][mapY])
      {
        case 1:  color = RGB_Red;  break; //red
        case 2:  color = RGB_Green;  break; //green
        case 3:  color = RGB_Blue;   break; //blue
        case 4:  color = RGB_White;  break; //white
        default: color = RGB_Yellow; break; //yellow
      }

      //give x and y sides different brightness
      if (side == 1) {color = color / 2;}

      //draw the pixels of the stripe as a vertical line
      verLine(x, drawStart, drawEnd, color);
    }
```

After the raycasting loop is done, the time of the current and the previous frame are calculated, the FPS (frames per second) is calculated and printed, and the screen is redrawn so that everything (all the walls, and the value of the fps counter) becomes visible. After that the backbuffer is cleared with cls(), so that when we draw the walls again the next frame, the floor and ceiling will be black again instead of still containing pixels from the previous frame.

The speed modifiers use frameTime, and a constant value, to determinate the speed of the moving and rotating of the input keys. Thanks to using the frameTime, we can make sure that the moving and rotating speed is independent of the processor speed.

```
    //timing for input and FPS counter
    oldTime = time;
    time = getTicks();
    double frameTime = (time - oldTime) / 1000.0; //frameTime is the time this frame has taken, in seconds
    print(1.0 / frameTime); //FPS counter
    redraw();
    cls();

    //speed modifiers
    double moveSpeed = frameTime * 5.0; //the constant value is in squares/second
    double rotSpeed = frameTime * 3.0; //the constant value is in radians/second
```

The last part is the input part, the keys are read.

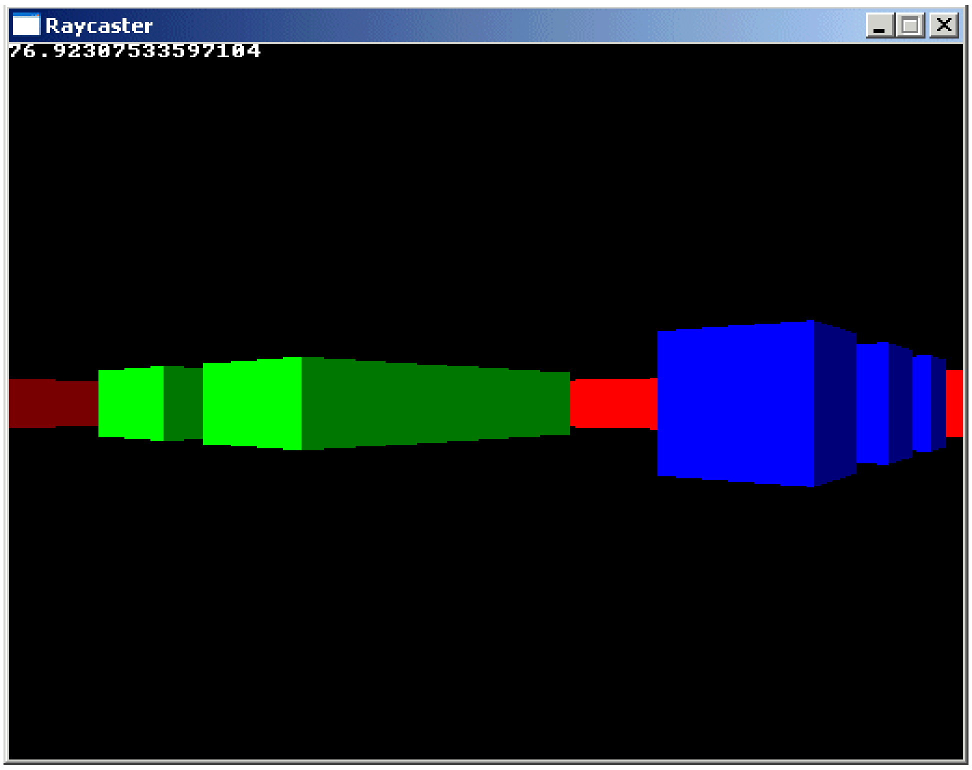
If the up arrow is pressed, the player will move forward: add dirX to posX, and dirY to posY. This assumes that dirX and dirY are normalized vectors (their length is 1), but they were initially set like this, so it's ok. There's also a simple collision detection built in, namely if the new position will be inside a wall, you won't move. This collision detection can be improved however, for example by checking if a circle around the player won't go inside the wall instead of just a single point.

The same is done if you press the down arrow, but then the direction is subtracted instead.

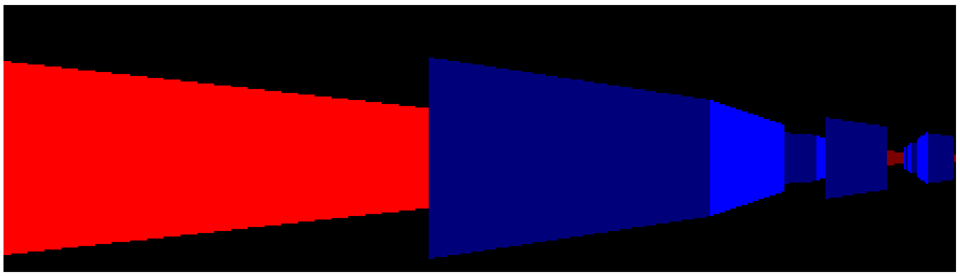
To rotate, if the left or right arrow is pressed, both the direction vector and plane vector are rotated by using the formulas of multiplication with the rotation matrix (and over the angle rotSpeed).

```

    readKeys();
    //move forward if no wall in front of you
    if (keyDown(SDLK_UP))
    {
      if(worldMap[int(posX + dirX * moveSpeed)][int(posY)] == false) posX += dirX * moveSpeed;
      if(worldMap[int(posX)][int(posY + dirY * moveSpeed)] == false) posY += dirY * moveSpeed;
    }
    //move backwards if no wall behind you
    if (keyDown(SDLK_DOWN))
    {
      if(worldMap[int(posX - dirX * moveSpeed)][int(posY)] == false) posX -= dirX * moveSpeed;
      if(worldMap[int(posX)][int(posY - dirY * moveSpeed)] == false) posY -= dirY * moveSpeed;
    }
    //rotate to the right
    if (keyDown(SDLK_RIGHT))
    {
      //both camera direction and camera plane must be rotated
      double oldDirX = dirX;
      dirX = dirX * cos(-rotSpeed) - dirY * sin(-rotSpeed);
      dirY = oldDirX * sin(-rotSpeed) + dirY * cos(-rotSpeed);
      double oldPlaneX = planeX;
      planeX = planeX * cos(-rotSpeed) - planeY * sin(-rotSpeed);
      planeY = oldPlaneX * sin(-rotSpeed) + planeY * cos(-rotSpeed);
    }
    //rotate to the left
    if (keyDown(SDLK_LEFT))
    {
      //both camera direction and camera plane must be rotated
      double oldDirX = dirX;
      dirX = dirX * cos(rotSpeed) - dirY * sin(rotSpeed);
      dirY = oldDirX * sin(rotSpeed) + dirY * cos(rotSpeed);
      double oldPlaneX = planeX;
      planeX = planeX * cos(rotSpeed) - planeY * sin(rotSpeed);
      planeY = oldPlaneX * sin(rotSpeed) + planeY * cos(rotSpeed);
    }
  }
}
```

This concludes the code of the untextured raycaster, the result looks like this, and you can walk around in the map:



Here's an example of what happens if the camera plane isn't perpendicular to the direction vector, the world appears skewed:



Textured Raycaster

Download the source code here: [raycaster_textured.cpp]()

The core of the textured version of the raycaster is almost the same, only at the end some extra calculations need to be done for the textures, and a loop in the y-direction is required to go through every pixel to determinate which texel (texture pixel) of the texture should be used for it.

The vertical stripes can't be drawn with the vertical line command anymore, instead every pixel has to be drawn seperately. The best way is to use a 2D array as screen buffer this time, and copy it to the screen at once, that goes a lot faster than using pset.

Of course we now also need an extra array for the textures, and since the "drawbuffer" function works with single integer values for colors (instead of 3 separate bytes for R, G and B), the textures are stored in this format as well. Normally, you'd load the textures from a texture file, but for this simple example some dumb textures are generated instead.

The code is mostly the same as the previous example, the bold parts are new. Only new parts are explained.

The screenWidth and screenHeight are now defined in the beginning because we need the same value for the screen function, and to create the screen buffer. Also new are the texture width and height that are defined here. These are obviously the width and height in texels of the textures.

The world map is changed too, this is a more complex map with corridors and rooms to show the different textures. Again, the 0's are empty walkthrougable spaces, and each positive number corresponds to a different texture.

```
#define screenWidth 640
#define screenHeight 480
#define texWidth 64
#define texHeight 64
#define mapWidth 24
#define mapHeight 24

int worldMap[mapWidth][mapHeight]=
{
  {4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,7,7,7,7,7,7,7,7},
  {4,0,0,0,0,0,0,0,0,0,0,0,0,0,0,4,0,0,0,0,0,0,0,7},
  {4,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,7},
  {4,0,2,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,7},
  {4,0,3,0,0,0,0,0,0,0,0,0,0,0,0,0,7,0,0,0,0,0,0,7},
  {4,0,4,0,0,0,0,5,5,5,5,5,5,5,5,5,7,7,0,7,7,7,7,7},
  {4,0,5,0,0,0,0,5,0,5,0,5,0,5,0,5,7,0,0,0,7,7,7,1},
  {4,0,6,0,0,0,0,5,0,0,0,0,0,0,0,5,7,0,0,0,0,0,0,8},
  {4,0,7,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,7,7,7,1},
  {4,0,8,0,0,0,0,5,0,0,0,0,0,0,0,5,7,0,0,0,0,0,0,8},
  {4,0,0,0,0,0,0,5,0,0,0,0,0,0,0,5,7,0,0,0,7,7,7,1},
  {4,0,0,0,0,0,0,5,5,5,5,0,5,5,5,5,7,7,7,7,7,7,7,1},
  {6,6,6,6,6,6,6,6,6,6,6,0,6,6,6,6,6,6,6,6,6,6,6,6},
  {8,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,4},
  {6,6,6,6,6,6,0,6,6,6,6,0,6,6,6,6,6,6,6,6,6,6,6,6},
  {4,4,4,4,4,4,0,4,4,4,6,0,6,2,2,2,2,2,2,2,3,3,3,3},
  {4,0,0,0,0,0,0,0,0,4,6,0,6,2,0,0,0,0,0,2,0,0,0,2},
  {4,0,0,0,0,0,0,0,0,0,0,0,6,2,0,0,5,0,0,2,0,0,0,2},
  {4,0,0,0,0,0,0,0,0,4,6,0,6,2,0,0,0,0,0,2,2,0,2,2},
  {4,0,6,0,6,0,0,0,0,4,6,0,0,0,0,0,5,0,0,0,0,0,0,2},
  {4,0,0,5,0,0,0,0,0,4,6,0,6,2,0,0,0,0,0,2,2,0,2,2},
  {4,0,6,0,6,0,0,0,0,4,6,0,6,2,0,0,5,0,0,2,0,0,0,2},
  {4,0,0,0,0,0,0,0,0,4,6,0,6,2,0,0,0,0,0,2,0,0,0,2},
  {4,4,4,4,4,4,4,4,4,4,1,1,1,2,2,2,2,2,2,3,3,3,3,3}
};
```

The screen buffer and texture arrays are declared here. The texture array is an array of std::vectors, each with a certain width * height pixels.

```
int main(int /*argc*/, char */*argv*/[])
{
  double posX = 22.0, posY = 11.5;  //x and y start position
  double dirX = -1.0, dirY = 0.0; //initial direction vector
  double planeX = 0.0, planeY = 0.66; //the 2d raycaster version of camera plane

  double time = 0; //time of current frame
  double oldTime = 0; //time of previous frame

  Uint32 buffer[screenHeight][screenWidth]; // y-coordinate first because it works per scanline
  std::vector texture[8];
  for(int i = 0; i < 8; i++) texture[i].resize(texWidth * texHeight);
```

The main function now begins with generating the textures. We have a double loop that goes through every pixel of the textures, and then the corresponding pixel of each texture gets a certain value calculated out of x and y. Some textures get a XOR pattern, some a simple gradient, others a sort of brick pattern, basicly it are all quite simple patterns, it's not going to look all that beautiful, for better textures see the next chapter.

```
  screen(screenWidth,screenHeight, 0, "Raycaster");

  //generate some textures
  for(int x = 0; x < texWidth; x++)
  for(int y = 0; y < texHeight; y++)
  {
    int xorcolor = (x * 256 / texWidth) ^ (y * 256 / texHeight);
    //int xcolor = x * 256 / texWidth;
    int ycolor = y * 256 / texHeight;
    int xycolor = y * 128 / texHeight + x * 128 / texWidth;
    texture[0][texWidth * y + x] = 65536 * 254 * (x != y && x != texWidth - y); //flat red texture with black cross
    texture[1][texWidth * y + x] = xycolor + 256 * xycolor + 65536 * xycolor; //sloped greyscale
    texture[2][texWidth * y + x] = 256 * xycolor + 65536 * xycolor; //sloped yellow gradient
    texture[3][texWidth * y + x] = xorcolor + 256 * xorcolor + 65536 * xorcolor; //xor greyscale
    texture[4][texWidth * y + x] = 256 * xorcolor; //xor green
    texture[5][texWidth * y + x] = 65536 * 192 * (x % 16 && y % 16); //red bricks
    texture[6][texWidth * y + x] = 65536 * ycolor; //red gradient
    texture[7][texWidth * y + x] = 128 + 256 * 128 + 65536 * 128; //flat grey texture
  }
```

This is again the start of the gameloop and initial declarations and calculations before the DDA algorithm. Nothing has changed here.

```
  //start the main loop
  while(!done())
  {
    for(int x = 0; x < w; x++)
    {
      //calculate ray position and direction
      double cameraX = 2*x/double(w)-1; //x-coordinate in camera space
      double rayDirX = dirX + planeX*cameraX;
      double rayDirY = dirY + planeY*cameraX;

      //which box of the map we're in
      int mapX = int(posX);
      int mapY = int(posY);

      //length of ray from current position to next x or y-side
      double sideDistX;
      double sideDistY;

      //length of ray from one x or y-side to next x or y-side
      double deltaDistX = sqrt(1 + (rayDirY * rayDirY) / (rayDirX * rayDirX));
      double deltaDistY = sqrt(1 + (rayDirX * rayDirX) / (rayDirY * rayDirY));
      double perpWallDist;

      //what direction to step in x or y-direction (either +1 or -1)
      int stepX;
      int stepY;

      int hit = 0; //was there a wall hit?
      int side; //was a NS or a EW wall hit?

      //calculate step and initial sideDist
      if (rayDirX < 0)
      {
        stepX = -1;
        sideDistX = (posX - mapX) * deltaDistX;
      }
      else
      {
        stepX = 1;
        sideDistX = (mapX + 1.0 - posX) * deltaDistX;
      }
      if (rayDirY < 0)
      {
        stepY = -1;
        sideDistY = (posY - mapY) * deltaDistY;
      }
      else
      {
        stepY = 1;
        sideDistY = (mapY + 1.0 - posY) * deltaDistY;
      }
```

This is again the DDA loop, and the calculations of the distance and height, nothing has changed here either.

```
      //perform DDA
      while (hit == 0)
      {
        //jump to next map square, either in x-direction, or in y-direction
        if (sideDistX < sideDistY)
        {
          sideDistX += deltaDistX;
          mapX += stepX;
          side = 0;
        }
        else
        {
          sideDistY += deltaDistY;
          mapY += stepY;
          side = 1;
        }
        //Check if ray has hit a wall
        if (worldMap[mapX][mapY] > 0) hit = 1;
      }

      //Calculate distance of perpendicular ray (Euclidean distance would give fisheye effect!)
      if(side == 0) perpWallDist = (sideDistX - deltaDistX);
      else          perpWallDist = (sideDistY - deltaDistY);

      //Calculate height of line to draw on screen
      int lineHeight = (int)(h / perpWallDist);

      //calculate lowest and highest pixel to fill in current stripe
      int drawStart = -lineHeight / 2 + h / 2;
      if(drawStart < 0) drawStart = 0;
      int drawEnd = lineHeight / 2 + h / 2;
      if(drawEnd >= h) drawEnd = h - 1;
```

The following calculations are new however, and replace the color chooser of the untextured raycaster.
The variable texNum is the value of the current map square minus 1, the reason is that there exists a texture 0, but map tile 0 has no texture since it represents an empty space. To be able to use texture 0 anyway, substract 1 so that map tiles with value 1 will give texture 0, etc...

The value wallX represents the exact value where the wall was hit, not just the integer coordinates of the wall. This is required to know which x-coordinate of the texture we have to use. This is calculated by first calculating the exact x or y coordinate in the world, and then substracting the integer value of the wall off it. Note that even if it's called wallX, it's actually an y-coordinate of the wall if side==1, but it's always the x-coordinate of the texture.

Finally, texX is the x-coordinate of the texture, and this is calculated out of wallX.

```
      //texturing calculations
      int texNum = worldMap[mapX][mapY] - 1; //1 subtracted from it so that texture 0 can be used!

      //calculate value of wallX
      double wallX; //where exactly the wall was hit
      if (side == 0) wallX = posY + perpWallDist * rayDirY;
      else           wallX = posX + perpWallDist * rayDirX;
      wallX -= floor((wallX));

      //x coordinate on the texture
      int texX = int(wallX * double(texWidth));
      if(side == 0 && rayDirX > 0) texX = texWidth - texX - 1;
      if(side == 1 && rayDirY < 0) texX = texWidth - texX - 1;
```

Now that we know the x-coordinate of the texture, we know that this coordinate will remain the same, because we stay in the same vertical stripe of the screen. Now we need a loop in the y-direction to give each pixel of the vertical stripe the correct y-coordinate of the texture, called texY.

The value of texY is calculated by increasing by a precomputed step size (which is possible because this is constant in the vertical stripe) for each pixel. The step size tells how much to increase in the texture coordinates (in floating point) for every pixel in vertical screen coordinates. It then needs to cast the floating point value to integer to select the actual texture pixel.

NOTE: a faster integer-only bresenham or DDA algorithm may be possible for this.

NOTE: The stepping being done here is affine texture mapping, which means we can interpolate linearly between two points rather than have to compute a different division for each pixel. This is not perspective correct in general, but for perfectly vertical walls (and also perfectly horizontal floors/ceilings) it is, so we can use it for raycasting.

The color of the pixel to be drawn is then simply gotten from texture[texNum][texX][texY], which is the correct texel of the correct texture.

Like the untextured raycaster, here too we'll make the color value darker if an y-side of the wall was hit, because that looks a little bit better (like there is a sort of lighting). However, because the color value doesn't exist out of a separate R, G and B value, but these 3 bytes sticked together in a single integer, a not so intuitive calculation is used.

The color is made darker by dividing R, G and B through 2. Dividing a decimal number through 10, can be done by removing the last digit (e.g. 300/10 is 30: the last zero is removed). Similarly, dividing a binary number through 2, which is what is done here, is the same as removing the last bit. This can be done by bitshifting it to the right with >>1. But, here we're bitshifting a 24-bit integer (actually 32-bit, but the first 8 bits aren't used). Because of this, the last bit of one byte will become the first bit of the next byte, and that screws up the color values! So after the bitshift, the first bit of every byte has to be set to zero, and that can be done by binary "AND-ing" the value with the binary value 011111110111111101111111, which is 8355711 in decimal. So the result of this is indeed a darker color.

Finally, the current buffer pixel is set to this color, and we move on to the next y.

```
      // How much to increase the texture coordinate per screen pixel
   double step = 1.0 * texHeight / lineHeight;
   // Starting texture coordinate
   double texPos = (drawStart - h / 2 + lineHeight / 2) * step;
   for(int y = drawStart; y<drawEnd; y++)
   {
     // Cast the texture coordinate to integer, and mask with (texHeight - 1) in case of overflow
     int texY = (int)texPos & (texHeight - 1);
     texPos += step;
     Uint32 color = texture[texNum][texHeight * texY + texX];
     //make color darker for y-sides: R, G and B byte each divided through two with a "shift" and an "and"
     if(side == 1) color = (color >> 1) & 8355711;
     buffer[y][x] = color;
   }
  }
```

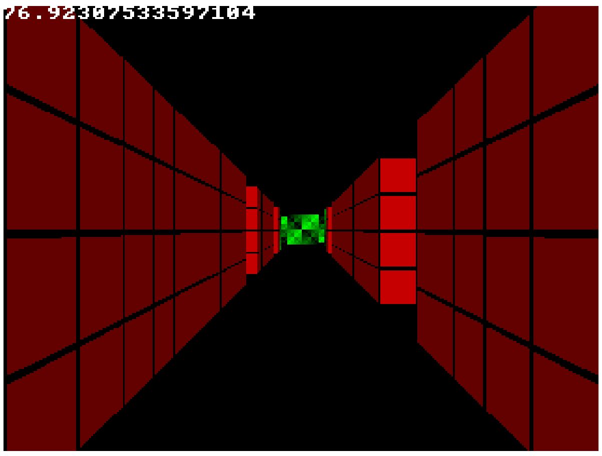
Now the buffer still has to be drawn, and after that it has to be cleared (where in the untextured version we simply had to use "cls". Ensure to do it in scanline order for speed thanks to memory locality for caching). The rest of this code is again the same.

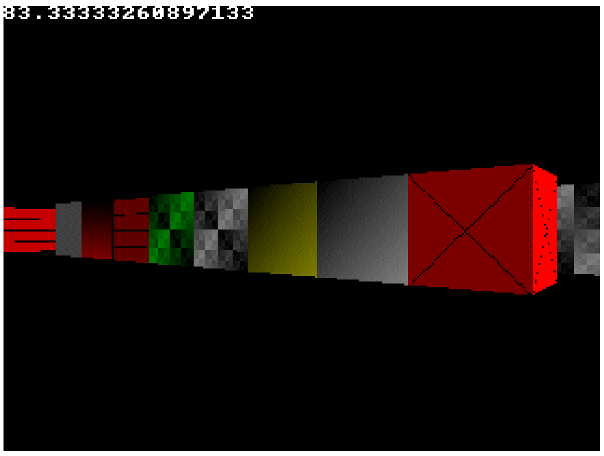
```
  drawBuffer(buffer[0]);
  for(int y = 0; y < h; y++) for(int x = 0; x < w; x++) buffer[y][x] = 0; //clear the buffer instead of cls()
  //timing for input and FPS counter
  oldTime = time;
  time = getTicks();
  double frameTime = (time - oldTime) / 1000.0; //frametime is the time this frame has taken, in seconds
  print(1.0 / frameTime); //FPS counter
  redraw();

  //speed modifiers
  double moveSpeed = frameTime * 5.0; //the constant value is in squares/second
  double rotSpeed = frameTime * 3.0; //the constant value is in radians/second
```

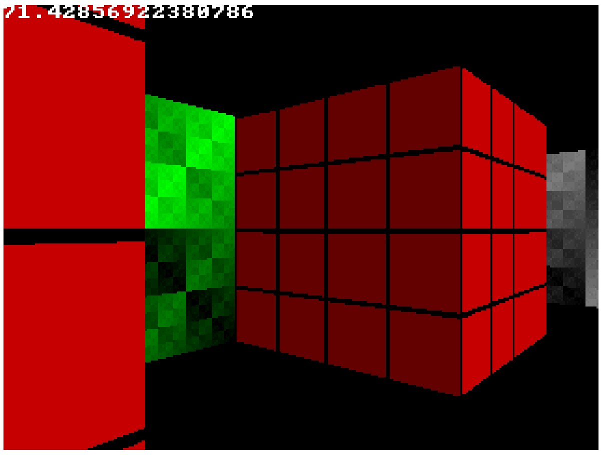
And here's again the keys, nothing has changed here either. If you like you can try to add strafe keys (to strafe to the left and right). These have to be made the same way as the up and down keys, but use planeX and planeY instead of dirX and dirY.

```
    readKeys();
    //move forward if no wall in front of you
    if (keyDown(SDLK_UP))
    {
      if(worldMap[int(posX + dirX * moveSpeed)][int(posY)] == false) posX += dirX * moveSpeed;
      if(worldMap[int(posX)][int(posY + dirY * moveSpeed)] == false) posY += dirY * moveSpeed;
    }
    //move backwards if no wall behind you
    if (keyDown(SDLK_DOWN))
    {
      if(worldMap[int(posX - dirX * moveSpeed)][int(posY)] == false) posX -= dirX * moveSpeed;
      if(worldMap[int(posX)][int(posY - dirY * moveSpeed)] == false) posY -= dirY * moveSpeed;
    }
    //rotate to the right
    if (keyDown(SDLK_RIGHT))
    {
      //both camera direction and camera plane must be rotated
      double oldDirX = dirX;
      dirX = dirX * cos(-rotSpeed) - dirY * sin(-rotSpeed);
      dirY = oldDirX * sin(-rotSpeed) + dirY * cos(-rotSpeed);
      double oldPlaneX = planeX;
      planeX = planeX * cos(-rotSpeed) - planeY * sin(-rotSpeed);
      planeY = oldPlaneX * sin(-rotSpeed) + planeY * cos(-rotSpeed);
    }
    //rotate to the left
    if (keyDown(SDLK_LEFT))
    {
      //both camera direction and camera plane must be rotated
      double oldDirX = dirX;
      dirX = dirX * cos(rotSpeed) - dirY * sin(rotSpeed);
      dirY = oldDirX * sin(rotSpeed) + dirY * cos(rotSpeed);
      double oldPlaneX = planeX;
      planeX = planeX * cos(rotSpeed) - planeY * sin(rotSpeed);
      planeY = oldPlaneX * sin(rotSpeed) + planeY * cos(rotSpeed);
    }
  }
}
```

Here's a few screenshots of the result:


76.92307533597104


83.33333260897133



Note: Usually images are stored by horizontal scanlines, but for a raycaster the textures are drawn as vertical stripes. Therefore, to optimally use the cache of the CPU and avoid page misses, it might be more efficient to store the textures in memory vertical stripe by vertical stripe, instead of per horizontal scanline. To do this, after generating the textures, swap their X and Y by (this code only works if texWidth and texHeight are the same):

```
//swap texture X/Y since they'll be used as vertical stripes
for(size_t i = 0; i < 8; i++)
for(size_t x = 0; x < texSize; x++)
for(size_t y = 0; y < x; y++)
std::swap(texture[i][texSize * y + x], texture[i][texSize * x + y]);
```

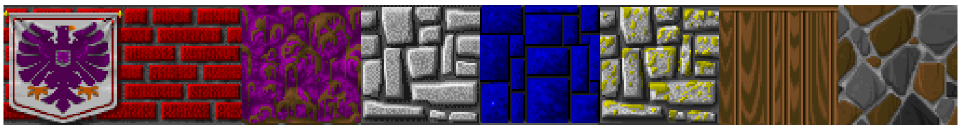
Or just swap X and Y where the textures are generated, but in many cases after loading an image or getting a texture from other formats you'll have it in scanlines anyway and have to swap it this way.

When getting the pixel from the texture then, use the following code instead:

```
Uint32 color = texture[texNum][texSize * texX + texY];
```

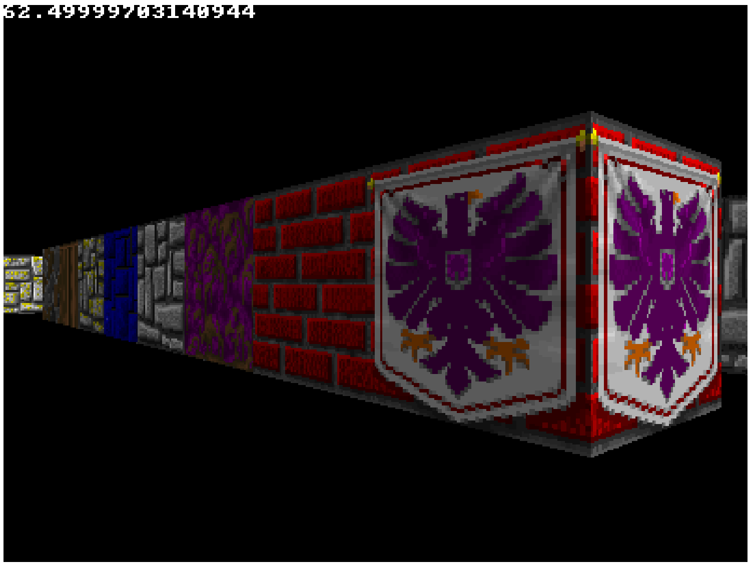
Wolfenstein 3D Textures

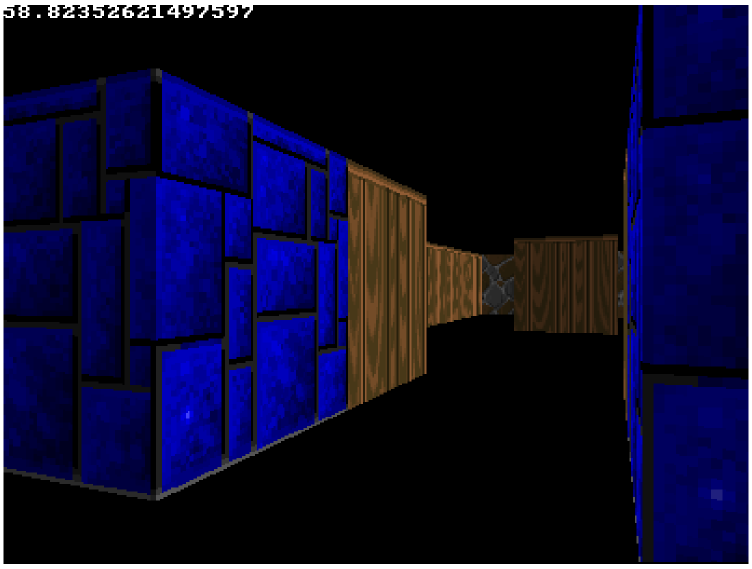
Instead of just generating some textures, let's load a few from images instead! For example the following 8 textures, which come from Wolfenstein 3D and are copyright by ID Software.



Just replace the part of the code that generates the texture patterns with the following (and make sure those textures are in the correct path). You can download the textures here.

```
//generate some textures
unsigned long tw, th;
loadImage(texture[0], tw, th, "pics/eagle.png");
loadImage(texture[1], tw, th, "pics/redbrick.png");
loadImage(texture[2], tw, th, "pics/purplestone.png");
loadImage(texture[3], tw, th, "pics/greystone.png");
loadImage(texture[4], tw, th, "pics/bluestone.png");
loadImage(texture[5], tw, th, "pics/mossy.png");
loadImage(texture[6], tw, th, "pics/wood.png");
loadImage(texture[7], tw, th, "pics/colorstone.png");
```





In the original Wolfenstein 3D, the colors of one side was also made darker than the color of the other side of a wall to create the shadow effect, but they used a seperate texture every time, a dark and a light one. Here however, only one texture is used for each wall and the line of code that divided R, G and B through 2 is what makes the y-sides darker.

Performance Considerations

On a modern computer, when using high resolution (4K, as of 2019), this software raycaster will be slower than some much more complex 3D graphics get rendered on the GPU with a 3D graphics card.

There are at least two issues holding back speed of the raycaster code in this tutorial, which you can take into account if you'd like to make a super fast raycaster for very high resolutions:

- Raycasting works with vertical stripes, but the screen buffer in memory is laid out with horizontal scanlines. So drawing vertical stripes is bad for memory locality for caching (it is in fact a worst case scenario), and the loss of good caching may hurt the speed more than some of the 3D computations on modern machines. It may be possible to program this with better caching behavior (e.g. processing multiple stripes at once, using a cache-oblivious transpose algorithm, or having a 90 degree rotated raycaster), but for simplicity the rest of this tutorial ignores this caching issue.
- This is using software blitting with SDL (in QuickCG, in redraw()), which is slow for large resolutions compared to hardware rendering. Likely QuickCG's usage of SDL itself is not optimal and e.g. using OpenGL (even for software rendering) may be faster, so that may be fixable behind the scenes. Since this CG tutorial is about software rendering this issue is ignored here as well.

Next Part

Go directly to part II

Last edited: 2020

Lode's Computer Graphics Tutorial

Raycasting II: Floor and Ceiling

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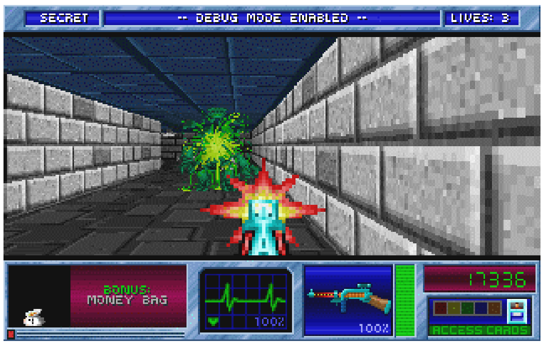
Introduction

In the previous raycasting article was shown how to render flat untextured walls, and how to render textured ones. The floor and ceiling have always remained flat and untextured however. If you want to keep the floor and ceiling untextured, no extra code is needed, but to have them textured too, more calculations are needed.
Wolfenstein 3D didn't have floor or ceiling textures, but some other raycasting games that followed soon after Wolf3D had them, for example Blake Stone 3D:



You can download the full source code of this tutorial here.

How it Works

Unlike the wall textures, the floor and ceiling textures are horizontal so they can't be drawn the same way as the wall with vertical stripes. Instead, they're drawn with horizontal scanlines. The perspective is similar to that of walls but 90 degrees rotated, but unlike the walls which used exactly 1 texture per vertical stripes, multiple floor textures (or the same one repeatedly) may cross our horizontal line.

Drawing the ceiling happens the same way as drawing the floor, so only the floor is explained here.

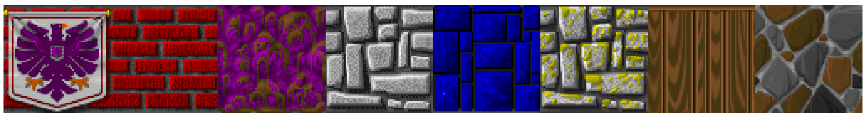
The floor casting is done before the walls, so first we draw the entire floor (and ceiling), then overwrite part of the pixels with the walls, as before, in the next step.
In short, the floor casting works as follows: work scanline by scanline. For the current scanline, compute the position on the floor matching the left pixel of the scanline, and the position matching the right pixel. This can be computed as where the ray starting from the camera, going through that pixel of the camera plane, hits the floor. The formulas and explanation for this are in the floor casting code further below.

We can then linearly interpolate between this leftmost and rightmost point to get the floor coordinates matching the other pi xels of this scanline. This works because the floor texture is perfectly horizontal. If it were slanted, we would need to do more expensive perspective correct texture mapping instead.

NOTE: Ádám Tóth contributed the idea and demo code for the horizontal scanline technique in 2019. Before this, this tutorial described a vertical stripe based technique, but the horizontal technique is faster and matches how raycasting games really worked. The vertical technique is moved to a separate chapter at the end.

The Code

The code tries to load the wolfenstein textures from the previous raycasting tutorial, you can download them here (copyright by id Software). If you don't want to load textures, you can use the part of code that generates textures from the previous raycasting tutorial instead, but it looks less good.



The first part of the code is exactly the same as in the previous raycasting tutorial, but is given here to situate where the new code will be. There's also a new map. This piece of code declares all needed variables, loads the textures, and draws textured vertical wall stripes. For the loading of the textures, please see the previous raycasting tutorial about getting the images or using an alternative way to generate the textures.

```
#define screenWidth 640
#define screenHeight 480
#define texWidth 64
#define texHeight 64
#define mapWidth 24
#define mapHeight 24

int worldMap[mapWidth][mapHeight]=
{
  {8,8,8,8,8,8,8,8,8,8,8,4,4,6,4,4,6,4,6,4,4,4,6,4},
  {8,0,0,0,0,0,0,0,0,0,8,4,0,0,0,0,0,0,0,0,0,0,0,4},
  {8,0,3,3,0,0,0,0,0,8,8,4,0,0,0,0,0,0,0,0,0,0,0,6},
  {8,0,0,3,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,6},
  {8,0,3,3,0,0,0,0,0,8,8,4,0,0,0,0,0,0,0,0,0,0,0,4},
  {8,0,0,0,0,0,0,0,0,0,8,4,0,0,0,0,0,6,6,6,0,6,4,6},
  {8,8,8,8,0,8,8,8,8,8,8,4,4,4,4,4,4,6,0,0,0,0,0,6},
  {7,7,7,7,0,7,7,7,7,0,8,0,8,0,8,0,8,4,0,4,0,6,0,6},
  {7,7,0,0,0,0,0,0,7,8,0,8,0,8,0,8,8,6,0,0,0,0,0,6},
  {7,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,8,6,0,0,0,0,0,4},
  {7,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,8,6,0,6,0,6,0,6},
  {7,7,0,0,0,0,0,0,7,8,0,8,0,8,0,8,8,6,4,6,0,6,6,6},
  {7,7,7,7,0,7,7,7,7,8,8,4,0,6,8,4,8,3,3,3,0,3,3,3},
  {2,2,2,2,0,2,2,2,2,4,6,4,0,0,6,0,6,3,0,0,0,0,0,3},
  {2,2,0,0,0,0,0,2,2,4,0,0,0,0,0,0,4,3,0,0,0,0,0,3},
  {2,0,0,0,0,0,0,0,2,4,0,0,0,0,0,0,4,3,0,0,0,0,0,3},
  {1,0,0,0,0,0,0,0,1,4,4,4,4,4,6,0,6,3,3,0,0,0,3,3},
  {2,0,0,0,0,0,0,0,2,2,2,1,2,2,2,6,6,0,0,5,0,5,0,5},
  {2,2,0,0,0,0,0,2,2,2,0,0,0,2,2,0,5,0,5,0,0,0,5,5},
  {2,0,0,0,0,0,0,0,2,0,0,0,0,0,2,5,0,5,0,5,0,5,0,5},
  {1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,5},
  {2,0,0,0,0,0,0,0,2,0,0,0,0,0,2,5,0,5,0,5,0,5,0,5},
  {2,2,0,0,0,0,0,2,2,2,0,0,0,2,2,0,5,0,5,0,0,0,5,5},
  {2,2,2,2,1,2,2,2,2,2,2,1,2,2,2,5,5,5,5,5,5,5,5,5}
};

Uint32 buffer[screenHeight][screenWidth]; // y-coordinate first because it works per scanline

int main(int /*argc*/, char */*argv*/[])
{
  double posX = 22.0, posY = 11.5;  //x and y start position
  double dirX = -1.0, dirY = 0.0; //initial direction vector
  double planeX = 0.0, planeY = 0.66; //the 2d raycaster version of camera plane

  double time = 0; //time of current frame
  double oldTime = 0; //time of previous frame

  std::vector<Uint32> texture[8];
  for(int i = 0; i l-< 8; i++) texture[i].resize(texWidth * texHeight);

  screen(screenWidth,screenHeight, 0, "Raycaster");

  //load some textures
  unsigned long tw, th, error = 0;
  error |= loadImage(texture[0], tw, th, "pics/eagle.png");
  error |= loadImage(texture[1], tw, th, "pics/redbrick.png");
  error |= loadImage(texture[2], tw, th, "pics/purplestone.png");
  error |= loadImage(texture[3], tw, th, "pics/greystone.png");
  error |= loadImage(texture[4], tw, th, "pics/bluestone.png");
  error |= loadImage(texture[5], tw, th, "pics/mossy.png");
  error |= loadImage(texture[6], tw, th, "pics/wood.png");
  error |= loadImage(texture[7], tw, th, "pics/colorstone.png");
  if(error) { std::cout << "error loading images" << std::endl; return 1; }

  //start the main loop
  while(!done())
  {
```

Now comes the new floor casting code, going line by line instead of vertical stripe by vertical stripe.

The formula for rowDistance, the horizontal distance from camera to the floor for the current row, which is posZ / p with p the current pixel distance from the screen center, can be explained as follows:

The camera ray goes through the following two points: the camera itself, which is at a certain height (posZ), and a point in front of the camera (through an imagined vertical plane containing the screen pixels) with horizontal distance 1 from the camera, and vertical position p lower than posZ (posZ - p). When going through that point, the line has vertically traveled by p units and horizontally by 1 unit. To hit the floor, it instead needs to travel by posZ units. It will travel the same ratio horizontally. The ratio was 1 / p for going through the camera plane, so to go posZ times farther to reach the floor, we get that the total horizontal distance is posZ / p.

NOTE: The stepping being done here is affine texture mapping, which means we can interpolate linearly between two points rather than have to compute a different division for each pixel. This is not perspective correct in general, but for perfectly horizontal floors/ceilings (and also perfectly vertical walls) it is, so we can use it for raycasting.

```
    //FLOOR CASTING
    for(int y = 0; y < h; y++)
    {
      // rayDir for leftmost ray (x = 0) and rightmost ray (x = w)
      float rayDirX0 = dirX - planeX;
      float rayDirY0 = dirY - planeY;
      float rayDirX1 = dirX + planeX;
      float rayDirY1 = dirY + planeY;

      // Current y position compared to the center of the screen (the horizon)
      int p = y - screenHeight / 2;

      // Vertical position of the camera.
      float posZ = 0.5 * screenHeight;

      // Horizontal distance from the camera to the floor for the current row.
      // 0.5 is the z position exactly in the middle between floor and ceiling.
      float rowDistance = posZ / p;

      // calculate the real world step vector we have to add for each x (parallel to camera plane)
      // adding step by step avoids multiplications with a weight in the inner loop
      float floorStepX = rowDistance * (rayDirX1 - rayDirX0) / screenWidth;
      float floorStepY = rowDistance * (rayDirY1 - rayDirY0) / screenWidth;

      // real world coordinates of the leftmost column. This will be updated as we step to the right.
      float floorX = posX + rowDistance * rayDirX0;
      float floorY = posY + rowDistance * rayDirY0;

      for(int x = 0; x < screenWidth; ++x)
      {
        // the cell coord is simply got from the integer parts of floorX and floorY
        int cellX = (int)(floorX);
        int cellY = (int)(floorY);

        // get the texture coordinate from the fractional part
        int tx = (int)(texWidth * (floorX - cellX)) & (texWidth - 1);
        int ty = (int)(texHeight * (floorY - cellY)) & (texHeight - 1);

        floorX += floorStepX;
        floorY += floorStepY;

        // choose texture and draw the pixel
        int floorTexture = 3;
        int ceilingTexture = 6;
        Uint32 color;

        // floor
        color = texture[floorTexture][texWidth * ty + tx];
        color = (color >> 1) & 8355711; // make a bit darker
        buffer[y][x] = color;

        //ceiling (symmetrical, at screenHeight - y - 1 instead of y)
        color = texture[ceilingTexture][texWidth * ty + tx];
        color = (color >> 1) & 8355711; // make a bit darker
        buffer[screenHeight - y - 1][x] = color;
      }
    }
```

Next is the wall casting code, this is exactly the same as the previous tutorial, nothing new here, only inserted here to complete the full code. It's done right after the floor casting. This one goes vertical stripe by vertical stripe, not line by line like the floor casting code above.

```
    //WALL CASTING
    for(int x = 0; x < w; x++)
    {
      //calculate ray position and direction
      double cameraX = 2 * x / double(w) - 1; //x-coordinate in camera space
      double rayDirX = dirX + planeX * cameraX;
      double rayDirY = dirY + planeY * cameraX;

      //which box of the map we're in
      int mapX = int(posX);
      int mapY = int(posY);

      //length of ray from current position to next x or y-side
      double sideDistX;
      double sideDistY;

      //length of ray from one x or y-side to next x or y-side
      double deltaDistX = (rayDirX == 0) ? 1e30 : std::abs(1 / rayDirX);
      double deltaDistY = (rayDirY == 0) ? 1e30 : std::abs(1 / rayDirY);
      double perpWallDist;

      //what direction to step in x or y-direction (either +1 or -1)
      int stepX;
      int stepY;

      int hit = 0; //was there a wall hit?
      int side; //was a NS or a EW wall hit?

      //calculate step and initial sideDist
      if (rayDirX < 0)
      {
        stepX = -1;
        sideDistX = (posX - mapX) * deltaDistX;
      }
      else
      {
        stepX = 1;
        sideDistX = (mapX + 1.0 - posX) * deltaDistX;
      }
      if (rayDirY < 0)
      {
        stepY = -1;
        sideDistY = (posY - mapY) * deltaDistY;
      }
      else
      {
        stepY = 1;
        sideDistY = (mapY + 1.0 - posY) * deltaDistY;
      }
      //perform DDA
      while (hit == 0)
      {
        //jump to next map square, either in x-direction, or in y-direction
        if (sideDistX < sideDistY)
        {
          sideDistX += deltaDistX;
          mapX += stepX;
          side = 0;
        }
        else
        {
          sideDistY += deltaDistY;
          mapY += stepY;
          side = 1;
        }
        //Check if ray has hit a wall
        if (worldMap[mapX][mapY] > 0) hit = 1;
      }

      //Calculate distance of perpendicular ray (Euclidean distance would give fisheye effect!)
      if(side == 0) perpWallDist = (sideDistX - deltaDistX);
      else          perpWallDist = (sideDistY - deltaDistY);

      //Calculate height of line to draw on screen
      int lineHeight = (int)(h / perpWallDist);

      //calculate lowest and highest pixel to fill in current stripe
      int drawStart = -lineHeight / 2 + h / 2;
      if(drawStart < 0) drawStart = 0;
      int drawEnd = lineHeight / 2 + h / 2;
      if(drawEnd >= h) drawEnd = h - 1;
      //texturing calculations
      int texNum = worldMap[mapX][mapY] - 1; //1 subtracted from it so that texture 0 can be used!

      //calculate value of wallX
      double wallX; //where exactly the wall was hit
      if (side == 0) wallX = posY + perpWallDist * rayDirY;
      else           wallX = posX + perpWallDist * rayDirX;
      wallX -= floor((wallX));

      //x coordinate on the texture
      int texX = int(wallX * double(texWidth));
      if(side == 0 && rayDirX > 0) texX = texWidth - texX - 1;
      if(side == 1 && rayDirY < 0) texX = texWidth - texX - 1;

      // How much to increase the texture coordinate per screen pixel
      double step = 1.0 * texHeight / lineHeight;
      // Starting texture coordinate
      double texPos = (drawStart - h / 2 + lineHeight / 2) * step;
      for(int y = drawStart; y<drawEnd; y++)
      {
        // Cast the texture coordinate to integer, and mask with (texHeight - 1) in case of overflow
        int texY = (int)texPos & (texHeight - 1);
        texPos += step;
        Uint32 color = texture[texNum][texWidth * texY + texX];
        //make color darker for y-sides: R, G and B byte each divided through two with a "shift" and an "and"
        if(side == 1) color = (color >> 1) & 8355711;
        buffer[y][x] = color;
      }
```

Finally, the screen is drawn and cleared again, and the input is handled. This code is the same as before again.

```
    drawBuffer(buffer[0]);
    for(int y = 0; y < h; y++) for(int x = 0; x < w; x++) buffer[y][x] = 0; //clear the buffer instead of cls()

    //timing for input and FPS counter
    oldTime = time;
    time = getTicks();
    double frameTime = (time - oldTime) / 1000.0; //frametime is the time this frame has taken, in seconds
    print(1.0 / frameTime); //FPS counter
    redraw();

    //speed modifiers
    double moveSpeed = frameTime * 3.0; //the constant value is in squares/second
    double rotSpeed = frameTime * 2.0; //the constant value is in radians/second
    readKeys();
    //move forward if no wall in front of you
    if (keyDown(SDLK_UP))
    {
      if(worldMap[int(posX + dirX * moveSpeed)][int(posY)] == false) posX += dirX * moveSpeed;
      if(worldMap[int(posX)][int(posY + dirY * moveSpeed)] == false) posY += dirY * moveSpeed;
    }
    //move backwards if no wall behind you
    if (keyDown(SDLK_DOWN))
    {
      if(worldMap[int(posX - dirX * moveSpeed)][int(posY)] == false) posX -= dirX * moveSpeed;
      if(worldMap[int(posX)][int(posY - dirY * moveSpeed)] == false) posY -= dirY * moveSpeed;
    }
    //rotate to the right
    if (keyDown(SDLK_RIGHT))
    {
      //both camera direction and camera plane must be rotated
      double oldDirX = dirX;
      dirX = dirX * cos(-rotSpeed) - dirY * sin(-rotSpeed);
      dirY = oldDirX * sin(-rotSpeed) + dirY * cos(-rotSpeed);
      double oldPlaneX = planeX;
      planeX = planeX * cos(-rotSpeed) - planeY * sin(-rotSpeed);
      planeY = oldPlaneX * sin(-rotSpeed) + planeY * cos(-rotSpeed);
    }
    //rotate to the left
    if (keyDown(SDLK_LEFT))
    {
      //both camera direction and camera plane must be rotated
      double oldDirX = dirX;
      dirX = dirX * cos(rotSpeed) - dirY * sin(rotSpeed);
      dirY = oldDirX * sin(rotSpeed) + dirY * cos(rotSpeed);
      double oldPlaneX = planeX;
      planeX = planeX * cos(rotSpeed) - planeY * sin(rotSpeed);
      planeY = oldPlaneX * sin(rotSpeed) + planeY * cos(rotSpeed);
    }
  }
}
```

Here's what it looks like at lower resolution:

47.61904761904761

This raycaster is very slow at high resolutions and certainly has room for optimizations.

Special Tricks

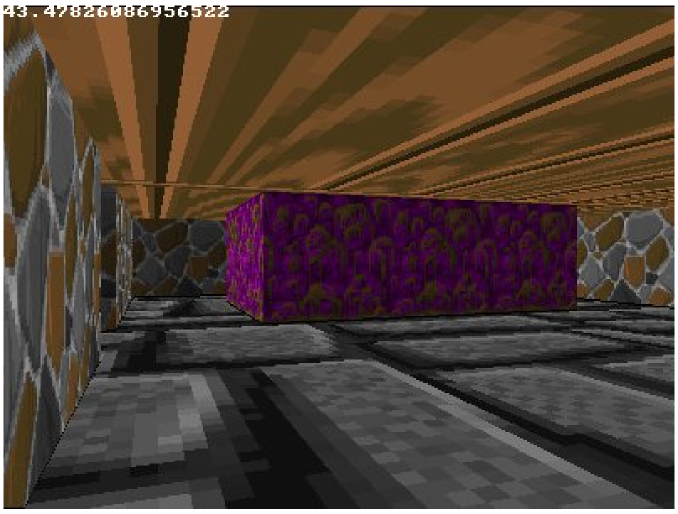
These tricks actually aren't that special, it's just things that you can modify to get other results.

To resize the floor and ceiling textures, for example to make them 4 times larger, you can modify this part of the code:

```
        int floorTexX, floorTexY;
        floorTexX = int(currentFloorX * texWidth) % texWidth;
        floorTexY = int(currentFloorY * texHeight) % texHeight;
```

into

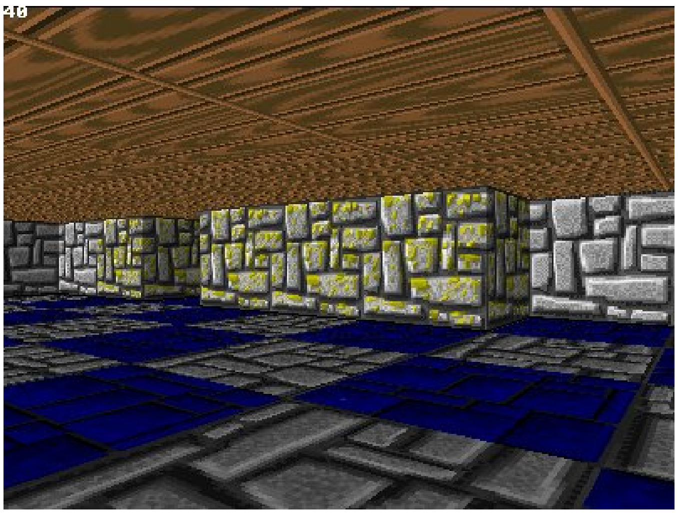
```
        int floorTexX, floorTexY;
        floorTexX = int(currentFloorX * texWidth / 4) % texWidth;
        floorTexY = int(currentFloorY * texHeight / 4) % texHeight;
```



So far, the whole level had the same floor texture everywhere. Since, in the way the level is described, all non-walls have code 0, this can't be used to give each square its own floortile texture. You could make non-wall tiles 0 or negative instead, then while raycasting a negative number means no wall, and the value can be used to say what floor texture has to be used there. If you want to do the same with the ceiling, you'd need another value for the ceiling textures too, so you could also consider using a separate map for the walls, floor and ceiling. Instead of doing that, here will now be demonstrated how to give each tile its own texture based on its coordinates: if the sum of its x and y coordinate on the map is even, it gets texture 3, if it's odd, it gets texture 4, this will give a checkerboard pattern.

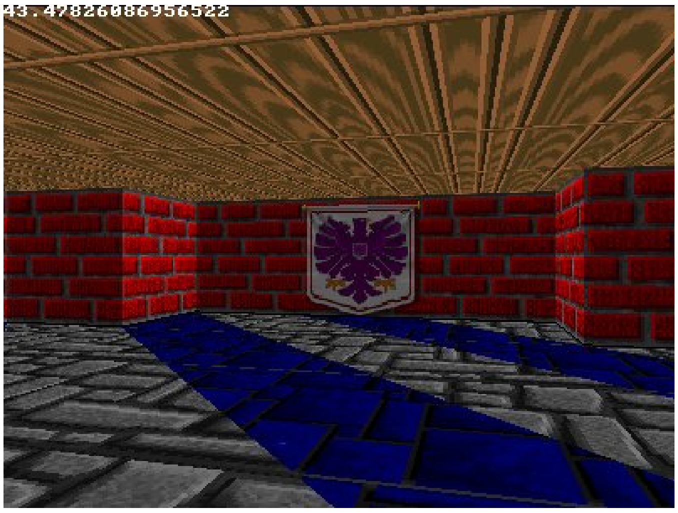
To get the x and y coordinate of the current tile in the map, take the integer part of currentFloorX and currentFloorY. To get this, the for loop of the floor casting part is changed into this (the bold parts are new or changed):

```
 //draw the floor from drawEnd to the bottom of the screen
 for(int y = drawEnd + 1; y < h; y++)
 {
  currentDist = h / (2.0 * y - h); //you could make a small lookup table for this instead

  double weight = (currentDist - distPlayer) / (distWall - distPlayer);

  double currentFloorX = weight * floorXWall + (1.0 - weight) * posX;
  double currentFloorY = weight * floorYWall + (1.0 - weight) * posY;

  int floorTexX, floorTexY;
  floorTexX = int(currentFloorX * texWidth) % texWidth;
  floorTexY = int(currentFloorY * texHeight) % texHeight;

  int checkerBoardPattern = (int(currentFloorX) + int(currentFloorY))) % 2;
  int floorTexture;
  if(checkerBoardPattern == 0) floorTexture = 3;
  else floorTexture = 4;

  //floor
  buffer[y][x] = (texture[floorTexture][texWidth * floorTexY + floorTexX] >> 1) & 8355711;
  //ceiling (symmetrical!)
  buffer[h - y][x] = texture[6][texWidth * floorTexY + floorTexX];
 }
}
```



In a similar way, it's also possible to choose the floor texture for each tile based on a map instead. The integer part of currentFloorX gives the coordinates of the current floortile in the map, while the fractional part gives the coordinate of the texel on the texture.

If you modify the checkerboard code from "`(int(currentFloorX) + int(currentFloorY)) % 2`" into "`(int(currentFloorX + currentFloorY)) % 2`", you don't get a checkerboard pattern but diagonal stripes instead, because now the fractional parts are added as well.



Vertical Version

As an alternative to the horizontal scanline based floor casting technique described above, it's also possible to work vertically. This allows to continue drawing the same vertical stripe a current wall stripe was drawn. However, this technique is slower because it requires perspective correct texture mapping, doing a division for every single pixel. In addition, the scanline based technique is also faster because scanline order is faster to render thanks to locality for memory caching.

The result looks the same (the floors are still horizontal), it's just rendered in a different way.

This technique works as follows: after you've drawn a vertical stripe from the wall, you do the floor casting for every pixel below the bottom wall pixel until the bottom of the screen. You need to know the exact coordinates of two points of the floor that are inside the current stripe, two such points that can easily be found are: the position of the player, and, the point of the floor right in front of the wall. Then, for every pixel, calculate the distance its projection on the floor has to the player. With that distance, you can find the exact location of the floor that pixel represents by using linear interpolation between the two points you found (the one at the wall and the one at your position).

Once you've done all the floor calculations, out of the exact position you can easily find the coordinates of the texel from the texture to get the color of the pixel you need to draw. Because the floor and ceiling are symmetrical, you know the texel coordinates of the ceiling texture are the same, you just draw it at the corresponding pixel in the upper half of the screen instead and can use a different texture for the ceiling and the floor.

The distance the projection of the current pixel is to the floor can be calculated as follows:

- If the pixel is in the center of the screen (in vertical direction), the distance is infinite.
- If the pixel is at the bottom of the screen, you can choose a certain distance, for example 1
- So all the pixels between those are between 1 and infinite, the distance the pixel represents in function of its height in the bottom half of the screen is inversely related as 1 / height. You can use the formula "currentDist = h / (2.0 * y - h)" for the distance of the current pixel.
- You can also precalculate a lookup table for this instead, since there are only h / 2 possible values (one half of the screen in vertical direction).

The linear interpolation, to get the exact floor location based on the current distance and the two known distances, can be done with a weight factor. This weight factor is "weight = (currentDist - distPlayer) / (distWall - distPlayer)", and since the current pixel will always be between the wall and the position of the player, the exact position is then: "currentFloorPos = weight * floorPosWall + (1.0 - weight) * playerPos". Note that distPlayer is actually 0, so the weight is actually "currentDist / distWall".

The code is not given in full this time, the floor casting is now done right after the wall casting, in the same x-loop. Don't forget to remove or disable the other floor casting code before adding this.

Right after the walls are drawn, the floor casting can begin. First the position of the floor right in front of the wall is calculated, and there are 4 different cases possible depending if a north, east, south or west side of a wall was hit. After this position and the distances are set, the for loop in the y direction that goes from the pixel below the wall until the bottom of the screen starts, it calculates the current distance, out of that the weight, out of that the exact position of the floor, and out of that the texel coordinate on the texture. With this info, both a floor and a ceiling pixel can be drawn. The floor is made darker.

```
for(int x = 0; x < w; x++)
{
  //WALL CASTING
  // [SNIP... the floor casting code goes in the same x-for-loop as the wall casting, wall casting code not duplicated here]
```

```
      //FLOOR CASTING (vertical version, directly after drawing the vertical wall stripe for the current x)
      double floorXWall, floorYWall; //x, y position of the floor texel at the bottom of the wall

      //4 different wall directions possible
      if(side == 0 && rayDirX > 0)
      {
        floorXWall = mapX;
        floorYWall = mapY + wallX;
      }
      else if(side == 0 && rayDirX < 0)
      {
        floorXWall = mapX + 1.0;
        floorYWall = mapY + wallX;
      }
      else if(side == 1 && rayDirY > 0)
      {
        floorXWall = mapX + wallX;
        floorYWall = mapY;
      }
      else
      {
        floorXWall = mapX + wallX;
        floorYWall = mapY + 1.0;
      }

      double distWall, distPlayer, currentDist;

      distWall = perpWallDist;
      distPlayer = 0.0;

      if (drawEnd < 0) drawEnd = h; //becomes < 0 when the integer overflows

      //draw the floor from drawEnd to the bottom of the screen
      for(int y = drawEnd + 1; y < h; y++)
      {
        currentDist = h / (2.0 * y - h); //you could make a small lookup table for this instead

        double weight = (currentDist - distPlayer) / (distWall - distPlayer);

        double currentFloorX = weight * floorXWall + (1.0 - weight) * posX;
        double currentFloorY = weight * floorYWall + (1.0 - weight) * posY;

        int floorTexX, floorTexY;
        floorTexX = int(currentFloorX * texWidth) % texWidth;
        floorTexY = int(currentFloorY * texHeight) % texHeight;

        //floor
        buffer[y][x] = (texture[3][texWidth * floorTexY + floorTexX] >> 1) & 8355711;
        //ceiling (symmetrical!)
        buffer[h - y][x] = texture[6][texWidth * floorTexY + floorTexX];
      }
    }
```

Next Part

Go directly to part III

Last edited: 2019

Lode's Computer Graphics Tutorial

Raycasting III: Sprites

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Introduction

The articles Raycasting and Raycasting II described how to make textured walls and floors, but something is missing. In a game, a world with only walls and floors is empty, for a game to work, there have to be goodies, enemies, objects like barrels or trees, ... These can't be drawn as wall or floor, and, in the time when raycasting games were made, can't be drawn as 3D models either. Instead, they used sprites, 2D pictures always facing to you (so they're easy to draw and require a single picture), but that become smaller if they're further away.

You can download the full source code of this tutorial here.

How it Works

The technique used to draw the sprites is totally different from the raycasting technique. Instead, it works very similar to how sprites are drawn in a 3D engine with projections, like in the "Points, Sprites and Moving" article. Only, we have to do the projection only in 2D, and some extra techniques to combine it with raycasting are used.

Drawing the sprites is done after the walls and floor are already drawn. Here are the steps used to draw the sprites:

- 1: While raycasting the walls, store the perpendicular distance of each vertical stripe in a 1D ZBuffer
- 2: Calculate the distance of each sprite to the player
- 3: Use this distance to sort the sprites, from furthest away to closest to the camera
- 4: Project the sprite on the camera plane (in 2D): subtract the player position from the sprite position, then multiply the result with the inverse of the 2x2 camera matrix
- 5: Calculate the size of the sprite on the screen (both in x and y direction) by using the perpendicular distance
- 6: Draw the sprites vertical stripe by vertical stripe, don't draw the vertical stripe if the distance is further away than the 1D ZBuffer of the walls of the current stripe
- 7: Draw the vertical stripe pixel by pixel, make sure there's an invisible color or all sprites would be rectangles

You don't have to update the ZBuffer while drawing the stripes: since they're sorted, the ones closer to you will be drawn last, so they're drawn over the further away ones.

How to project the sprite on screen is explained in full 3D rendering mathematics (with 3D matrices and camera), for true 3D rasterizer or ray*tracer* 3D engines, and is not explained here in the ray*caster* tutorial. However, here it's done in 2D and no fancy camera class is used. To bring the sprite's coordinates to camera space, first subtract the player's position from the sprite's position, then you have the position of the sprite relative to the player. Then it has to be rotated so that the direction is relative to the player. The camera can also be skewed and has a certain size, so it isn't really a rotation, but a transformation. The transformation is done by multiplying the relative position of the sprite with the inverse of the camera matrix. The camera matrix is in our case

```
[planeX   dirX]
[planeY   dirY]
```

And the inverse of a 2x2 matrix is very easy to calculate

```
____________1___________      [dirY      -dirX]
(planeX*dirY-dirX*planeY) * [-planeY  planeX]
```

Then you get the X and Y coordinate of the sprite in camera space, where Y is the depth inside the screen (in a true 3D engine, Z is the depth). To project it on screen, divide X through the depth, and then translate and scale it so that it's in pixel coordinates.

To place the objects in the level, many things can be done. Each object can have its own floating point coordinates, it doesn't have to be exactly in the center of floor tiles. You can make a list of each object and give its coordinates and texture one by one, or you can place the objects by making a second map (a 2D array), and for every tile coordinate place one or no object, the same way as placing the walls. If you do that, then let the program read that map and create a list of objects out of it, with every object placed in the center of the corresponding map tile. Coordinates in the center of a tile are a halve, e.g. (11.5, 15.5), while whole coordinates will be the corners of tiles.

The code presented below uses a small list of objects instead of a map.

The Code

The code tries to load the wolfenstein textures, with extra textures for 3 sprites, you can download them here (copyright by id Software). If you don't want to load textures, you can use the part of code that generates textures from the previous raycasting tutorial instead, but it looks less good. You'll also have to invent something yourself for the sprites, black is the invisible color.

The full code of the whole thing is given, it's similar to the code of Raycasting II, but with added code here and there.

The new variables for sprite casting are the struct Sprite, containing the position and texture of the sprite, the value numSprites: the number of sprites, the sprite array: defines the positions and textures of all the Sprites, the declaration of the bubbleSort function: this will sort the sprites, and the arrays used as arguments for this function: spriteOrder and spriteDistance, and finally, ZBuffer: this is the 1D equivalent of the ZBuffer in a true 3D engine. In the sprite array, every third number is the number of its texture, you can see which number means what there where the textures are loaded.

```
#define screenWidth 640
#define screenHeight 480
#define texWidth 64
#define texHeight 64
#define mapWidth 24
#define mapHeight 24

int worldMap[mapWidth][mapHeight] =
{
  {8,8,8,8,8,8,8,8,8,8,8,4,4,6,4,4,6,4,6,4,4,4,6,4},
  {8,0,0,0,0,0,0,0,0,0,8,4,0,0,0,0,0,0,0,0,0,0,0,4},
  {8,0,3,3,0,0,0,0,0,8,8,4,0,0,0,0,0,0,0,0,0,0,0,6},
  {8,0,0,3,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,6},
  {8,0,3,3,0,0,0,0,0,8,8,4,0,0,0,0,0,0,0,0,0,0,0,4},
  {8,0,0,0,0,0,0,0,0,0,8,4,0,0,0,0,0,6,6,6,0,6,4,6},
  {8,8,8,8,0,8,8,8,8,8,8,4,4,4,4,4,4,6,0,0,0,0,0,6},
  {7,7,7,7,0,7,7,7,7,0,8,0,8,0,8,0,8,4,0,4,0,6,0,6},
  {7,7,0,0,0,0,0,0,7,8,0,8,0,8,0,8,8,6,0,0,0,0,0,6},
  {7,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,8,6,0,0,0,0,0,4},
  {7,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,8,6,0,6,0,6,0,6},
  {7,7,0,0,0,0,0,0,7,8,0,8,0,8,0,8,8,6,4,6,0,6,6,6},
  {7,7,7,7,0,7,7,7,7,8,8,4,0,6,8,4,8,3,3,3,0,3,3,3},
  {2,2,2,2,0,2,2,2,2,4,6,4,0,0,6,0,6,3,0,0,0,0,0,3},
  {2,2,0,0,0,0,0,2,2,4,0,0,0,0,0,0,4,3,0,0,0,0,0,3},
  {2,0,0,0,0,0,0,0,2,4,0,0,0,0,0,0,4,3,0,0,0,0,0,3},
  {1,0,0,0,0,0,0,0,1,4,4,4,4,4,6,0,6,3,3,0,0,0,3,3},
  {2,0,0,0,0,0,0,0,2,2,2,1,2,2,2,6,6,0,0,5,0,5,0,5},
  {2,2,0,0,0,0,0,2,2,2,0,0,0,2,2,0,5,0,5,0,0,0,5,5},
  {2,0,0,0,0,0,0,0,2,0,0,0,0,0,2,5,0,5,0,5,0,5,0,5},
  {1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,5},
  {2,0,0,0,0,0,0,0,2,0,0,0,0,0,2,5,0,5,0,5,0,5,0,5},
  {2,2,0,0,0,0,0,2,2,2,0,0,0,2,2,0,5,0,5,0,0,0,5,5},
  {2,2,2,2,1,2,2,2,2,2,2,1,2,2,2,5,5,5,5,5,5,5,5,5}
};

struct Sprite
{
  double x;
  double y;
  int texture;
};

#define numSprites 19

Sprite sprite[numSprites] =
{
  {20.5, 11.5, 10}, //green light in front of playerstart
  //green lights in every room
  {18.5,4.5, 10},
  {10.0,4.5, 10},
  {10.0,12.5,10},
  {3.5, 6.5, 10},
  {3.5, 20.5,10},
  {3.5, 14.5,10},
  {14.5,20.5,10},

  //row of pillars in front of wall: fisheye test
  {18.5, 10.5, 9},
  {18.5, 11.5, 9},
  {18.5, 12.5, 9},

  //some barrels around the map
  {21.5, 1.5, 8},
  {15.5, 1.5, 8},
  {16.0, 1.8, 8},
  {16.2, 1.2, 8},
  {3.5,  2.5, 8},
  {9.5, 15.5, 8},
  {10.0, 15.1,8},
  {10.5, 15.8,8},
};

Uint32 buffer[screenHeight][screenWidth]; // y-coordinate first because it works per scanline

//1D Zbuffer
double ZBuffer[screenWidth];

//arrays used to sort the sprites
int spriteOrder[numSprites];
double spriteDistance[numSprites];

//function used to sort the sprites
void sortSprites(int* order, double* dist, int amount);

int main(int /*argc*/, char */*argv*/[])
{
  double posX = 22.0, posY = 11.5; //x and y start position
  double dirX = -1.0, dirY = 0.0; //initial direction vector
  double planeX = 0.0, planeY = 0.66; //the 2d raycaster version of camera plane

  double time = 0; //time of current frame
  double oldTime = 0; //time of previous frame

  std::vector<Uint32> texture[11];
  for(int i = 0; i < 11; i++) texture[i].resize(texWidth * texHeight);
```

3 new textures are loaded: the sprites. There's nothing that stops you from loading more textures, or making the textures higher resolution.

```
screen(screenWidth, screenHeight, 0, "Raycaster");

//load some textures
unsigned long tw, th, error = 0;
error |= loadImage(texture[0], tw, th, "pics/eagle.png");
error |= loadImage(texture[1], tw, th, "pics/redbrick.png");
error |= loadImage(texture[2], tw, th, "pics/purplestone.png");
error |= loadImage(texture[3], tw, th, "pics/greystone.png");
error |= loadImage(texture[4], tw, th, "pics/bluestone.png");
error |= loadImage(texture[5], tw, th, "pics/mossy.png");
error |= loadImage(texture[6], tw, th, "pics/wood.png");
error |= loadImage(texture[7], tw, th, "pics/colorstone.png");

//load some sprite textures
error |= loadImage(texture[8], tw, th, "pics/barrel.png");
error |= loadImage(texture[9], tw, th, "pics/pillar.png");
error |= loadImage(texture[10], tw, th, "pics/greenlight.png");
if(error) { std::cout << "error loading images" << std::endl; return 1; }
```

Here's the main loop which starts with raycasting the floors and walls, same code as before.

```
//start the main loop
while(!done())
{
  //FLOOR CASTING
  for(int y = 0; y < h; y++)
  {
    // rayDir for leftmost ray (x = 0) and rightmost ray (x = w)
    float rayDirX0 = dirX - planeX;
    float rayDirY0 = dirY - planeY;
    float rayDirX1 = dirX + planeX;
    float rayDirY1 = dirY + planeY;

    // Current y position compared to the center of the screen (the horizon)
    int p = y - screenHeight / 2;

    // Vertical position of the camera.
    float posZ = 0.5 * screenHeight;

    // Horizontal distance from the camera to the floor for the current row.
    // 0.5 is the z position exactly in the middle between floor and ceiling.
    float rowDistance = posZ / p;

    // calculate the real world step vector we have to add for each x (parallel to camera plane)
    // adding step by step avoids multiplications with a weight in the inner loop
    float floorStepX = rowDistance * (rayDirX1 - rayDirX0) / screenWidth;
    float floorStepY = rowDistance * (rayDirY1 - rayDirY0) / screenWidth;

    // real world coordinates of the leftmost column. This will be updated as we step to the right.
    float floorX = posX + rowDistance * rayDirX0;
    float floorY = posY + rowDistance * rayDirY0;

    for(int x = 0; x < screenWidth; ++x)
    {
      // the cell coord is simply got from the integer parts of floorX and floorY
      int cellX = (int)(floorX);
      int cellY = (int)(floorY);

      // get the texture coordinate from the fractional part
      int tx = (int)(texWidth * (floorX - cellX)) & (texWidth - 1);
      int ty = (int)(texHeight * (floorY - cellY)) & (texHeight - 1);

      floorX += floorStepX;
      floorY += floorStepY;

      // choose texture and draw the pixel
      int floorTexture = 3;
      int ceilingTexture = 6;
      Uint32 color;

      // floor
      color = texture[floorTexture][texWidth * ty + tx];
      color = (color >> 1) & 8355711; // make a bit darker
      buffer[y][x] = color;

      //ceiling (symmetrical, at screenHeight - y - 1 instead of y)
      color = texture[ceilingTexture][texWidth * ty + tx];
      color = (color >> 1) & 8355711; // make a bit darker
      buffer[screenHeight - y - 1][x] = color;
    }
  }

  // WALL CASTING
  for(int x = 0; x < w; x++)
  {
    //calculate ray position and direction
    double cameraX = 2 * x / double(w) - 1; //x-coordinate in camera space
    double rayDirX = dirX + planeX * cameraX;
    double rayDirY = dirY + planeY * cameraX;

    //which box of the map we're in
    int mapX = int(posX);
    int mapY = int(posY);

    //length of ray from current position to next x or y-side
    double sideDistX;
    double sideDistY;
```

```
      //length of ray from one x or y-side to next x or y-side
      double deltaDistX = (rayDirX == 0) ? 1e30 : std::abs(1 / rayDirX);
      double deltaDistY = (rayDirY == 0) ? 1e30 : std::abs(1 / rayDirY);
      double perpWallDist;

      //what direction to step in x or y-direction (either +1 or -1)
      int stepX;
      int stepY;

      int hit = 0; //was there a wall hit?
      int side; //was a NS or a EW wall hit?

      //calculate step and initial sideDist
      if (rayDirX < 0)
      {
        stepX = -1;
        sideDistX = (posX - mapX) * deltaDistX;
      }
      else
      {
        stepX = 1;
        sideDistX = (mapX + 1.0 - posX) * deltaDistX;
      }
      if (rayDirY < 0)
      {
        stepY = -1;
        sideDistY = (posY - mapY) * deltaDistY;
      }
      else
      {
        stepY = 1;
        sideDistY = (mapY + 1.0 - posY) * deltaDistY;
      }
      //perform DDA
      while (hit == 0)
      {
        //jump to next map square, either in x-direction, or in y-direction
        if (sideDistX < sideDistY)
        {
          sideDistX += deltaDistX;
          mapX += stepX;
          side = 0;
        }
        else
        {
          sideDistY += deltaDistY;
          mapY += stepY;
          side = 1;
        }
        //Check if ray has hit a wall
        if (worldMap[mapX][mapY] > 0) hit = 1;
      }

      //Calculate distance of perpendicular ray (Euclidean distance would give fisheye effect!)
      if(side == 0) perpWallDist = (sideDistX - deltaDistX);
      else          perpWallDist = (sideDistY - deltaDistY);

      //Calculate height of line to draw on screen
      int lineHeight = (int)(h / perpWallDist);

      //calculate lowest and highest pixel to fill in current stripe
      int drawStart = -lineHeight / 2 + h / 2;
      if(drawStart < 0) drawStart = 0;
      int drawEnd = lineHeight / 2 + h / 2;
      if(drawEnd >= h) drawEnd = h - 1;
      //texturing calculations
      int texNum = worldMap[mapX][mapY] - 1; //1 subtracted from it so that texture 0 can be used!

      //calculate value of wallX
      double wallX; //where exactly the wall was hit
      if (side == 0) wallX = posY + perpWallDist * rayDirY;
      else           wallX = posX + perpWallDist * rayDirX;
      wallX -= floor((wallX));

      //x coordinate on the texture
      int texX = int(wallX * double(texWidth));
      if(side == 0 && rayDirX > 0) texX = texWidth - texX - 1;
      if(side == 1 && rayDirY < 0) texX = texWidth - texX - 1;

      // How much to increase the texture coordinate per screen pixel
      double step = 1.0 * texHeight / lineHeight;
      // Starting texture coordinate
      double texPos = (drawStart - h / 2 + lineHeight / 2) * step;
      for(int y = drawStart; y<drawEnd; y++)
      {
        // Cast the texture coordinate to integer, and mask with (texHeight - 1) in case of overflow
        int texY = (int)texPos & (texHeight - 1);
        texPos += step;
        int color = texture[texNum][texWidth * texY + texX];
        //make color darker for y-sides: R, G and B byte each divided through two with a 'shift' and an 'and'
        if(side == 1) color = (color >> 1) & 8355711;
        buffer[y][x] = color;
      }
```

After raycasting the wall, the ZBuffer has to be set. This ZBuffer is 1D, because it only contains the distance to the wall of every vertical stripe, instead of having this for every pixel. This also ends the loop through every vertical stripe, because rendering the sprites will be done outside this loop.

```
      //SET THE ZBUFFER FOR THE SPRITE CASTING
      ZBuffer[x] = perpWallDist; //perpendicular distance is used
    }
```

After the floors and walls are finally drawn, the sprites can be drawn. This code is very unoptimized, a few improvements are explained later. First it sorts the sprites from far to close, so that the far ones will be drawn first. Then it projects each sprite, calculates the size it should have on screen, and draws it stripe by stripe. The matrix multiplication for the projection is very easy because it's only a 2x2 matrix. It comes in very handy again that they raycaster already used a 2D camera matrix, instead of representing the player with an angle and a position instead like some raycasters do.

The distance calculated for the sorting of the sprites is never used later on, because the perpendicular distance is used instead. For sorting the sprites it doesn't matter if you take the square root of the distance or not, so no calculation time is wasted for that.

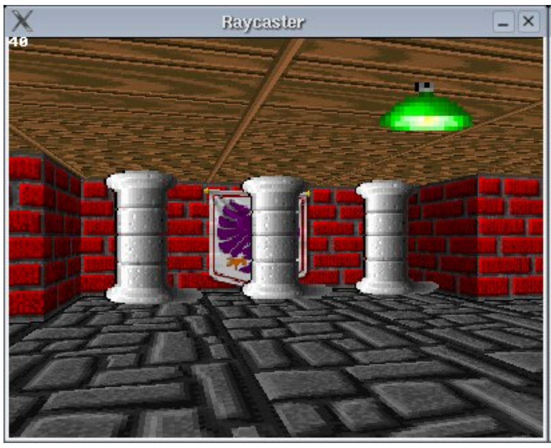
```
    //SPRITE CASTING
    //sort sprites from far to close
    for(int i = 0; i < numSprites; i++)
    {
      spriteOrder[i] = i;
      spriteDistance[i] = ((posX - sprite[i].x) * (posX - sprite[i].x) + (posY - sprite[i].y) * (posY - sprite[i].y)); //sqrt not taken, unneeded
    }
    sortSprites(spriteOrder, spriteDistance, numSprites);

    //after sorting the sprites, do the projection and draw them
    for(int i = 0; i < numSprites; i++)
    {
      //translate sprite position to relative to camera
      double spriteX = sprite[spriteOrder[i]].x - posX;
      double spriteY = sprite[spriteOrder[i]].y - posY;

      //transform sprite with the inverse camera matrix
      // [ planeX   dirX ] -1                                       [ dirY      -dirX ]
      // [               ]       =  1/(planeX*dirY-dirX*planeY) *   [                 ]
      // [ planeY   dirY ]                                          [ -planeY  planeX ]

      double invDet = 1.0 / (planeX * dirY - dirX * planeY); //required for correct matrix multiplication

      double transformX = invDet * (dirY * spriteX - dirX * spriteY);
      double transformY = invDet * (-planeY * spriteX + planeX * spriteY); //this is actually the depth inside the screen, that what Z is in 3D

      int spriteScreenX = int((w / 2) * (1 + transformX / transformY));

      //calculate height of the sprite on screen
      int spriteHeight = abs(int(h / (transformY))); //using 'transformY' instead of the real distance prevents fisheye
      //calculate lowest and highest pixel to fill in current stripe
      int drawStartY = -spriteHeight / 2 + h / 2;
      if(drawStartY < 0) drawStartY = 0;
      int drawEndY = spriteHeight / 2 + h / 2;
      if(drawEndY >= h) drawEndY = h - 1;

      //calculate width of the sprite
      int spriteWidth = abs( int (h / (transformY)));
      int drawStartX = -spriteWidth / 2 + spriteScreenX;
      if(drawStartX < 0) drawStartX = 0;
      int drawEndX = spriteWidth / 2 + spriteScreenX;
      if(drawEndX >= w) drawEndX = w - 1;

      //loop through every vertical stripe of the sprite on screen
      for(int stripe = drawStartX; stripe < drawEndX; stripe++)
      {
        int texX = int(256 * (stripe - (-spriteWidth / 2 + spriteScreenX)) * texWidth / spriteWidth) / 256;
        //the conditions in the if are:
        //1) it's in front of camera plane so you don't see things behind you
        //2) it's on the screen (left)
        //3) it's on the screen (right)
        //4) ZBuffer, with perpendicular distance
        if(transformY > 0 && stripe > 0 && stripe < w && transformY < ZBuffer[stripe])
        for(int y = drawStartY; y < drawEndY; y++) //for every pixel of the current stripe
        {
          int d = (y) * 256 - h * 128 + spriteHeight * 128; //256 and 128 factors to avoid floats
          int texY = ((d * texHeight) / spriteHeight) / 256;
          Uint32 color = texture[sprite[spriteOrder[i]].texture][texWidth * texY + texX]; //get current color from the texture
          if((color & 0x00FFFFFF) != 0) buffer[y][stripe] = color; //paint pixel if it isn't black, black is the invisible color
        }
      }
    }
```

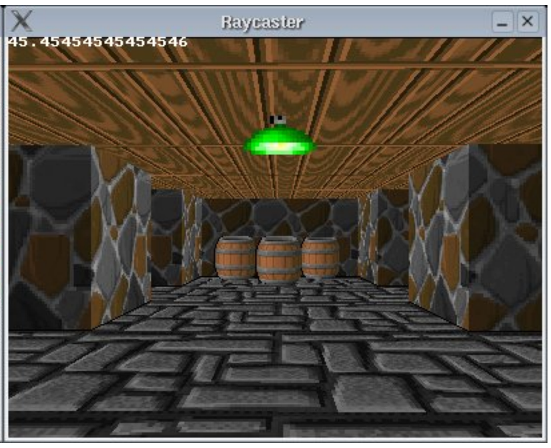
After it all is drawn, the screen is updated, and the input keys are handled.

```
    drawBuffer(buffer[0]);
    for(int y = 0; y < h; y++) for(int x = 0; x < w; x++) buffer[y][x] = 0; //clear the buffer instead of cls()

    //timing for input and FPS counter
    oldTime = time;
    time = getTicks();
    double frameTime = (time - oldTime) / 1000.0; //frametime is the time this frame has taken, in seconds
    print(1.0 / frameTime); //FPS counter
    redraw();

    //speed modifiers
    double moveSpeed = frameTime * 3.0; //the constant value is in squares/second
    double rotSpeed = frameTime * 2.0; //the constant value is in radians/second
    readKeys();
    //move forward if no wall in front of you
    if (keyDown(SDLK_UP))
    {
      if(worldMap[int(posX + dirX * moveSpeed)][int(posY)] == false) posX += dirX * moveSpeed;
      if(worldMap[int(posX)][int(posY + dirY * moveSpeed)] == false) posY += dirY * moveSpeed;
    }
    //move backwards if no wall behind you
    if (keyDown(SDLK_DOWN))
    {
      if(worldMap[int(posX - dirX * moveSpeed)][int(posY)] == false) posX -= dirX * moveSpeed;
      if(worldMap[int(posX)][int(posY - dirY * moveSpeed)] == false) posY -= dirY * moveSpeed;
    }
    //rotate to the right
    if (keyDown(SDLK_RIGHT))
    {
      //both camera direction and camera plane must be rotated
      double oldDirX = dirX;
      dirX = dirX * cos(-rotSpeed) - dirY * sin(-rotSpeed);
      dirY = oldDirX * sin(-rotSpeed) + dirY * cos(-rotSpeed);
      double oldPlaneX = planeX;
      planeX = planeX * cos(-rotSpeed) - planeY * sin(-rotSpeed);
      planeY = oldPlaneX * sin(-rotSpeed) + planeY * cos(-rotSpeed);
    }
    //rotate to the left
    if (keyDown(SDLK_LEFT))
    {
      //both camera direction and camera plane must be rotated
      double oldDirX = dirX;
      dirX = dirX * cos(rotSpeed) - dirY * sin(rotSpeed);
      dirY = oldDirX * sin(rotSpeed) + dirY * cos(rotSpeed);
      double oldPlaneX = planeX;
      planeX = planeX * cos(rotSpeed) - planeY * sin(rotSpeed);
      planeY = oldPlaneX * sin(rotSpeed) + planeY * cos(rotSpeed);
    }
  }
}
```

The sortSprites sorts the sprites from farthest away to closest by distance. It uses the standard std::sort function provided by C++. But since we need to sort two arrays using the same order here (order and dist), most of the code is spent moving the data into and out of a vector of pairs.

```
//sort algorithm
//sort the sprites based on distance
void sortSprites(int* order, double* dist, int amount)
{
  std::vector<std::pair<double, int>> sprites(amount);
  for(int i = 0; i < amount; i++) {
    sprites[i].first = dist[i];
    sprites[i].second = order[i];
  }
  std::sort(sprites.begin(), sprites.end());
  // restore in reverse order to go from farthest to nearest
  for(int i = 0; i < amount; i++) {
    dist[i] = sprites[amount - i - 1].first;
    order[i] = sprites[amount - i - 1].second;
  }
}
}
```





The green light is a very small sprite, but the program still goes through all its invisible pixels to check their color. It could be made faster by telling which sprites have large invisible parts, and only drawing a smaller rectangular part of them containing all visible pixels.

To make some objects unwalkthroughable, you can either check the distance of the player to every object when he moves for collision detection, or, make another 2D map that contains for every square if it's walkthroughable or not, this can be used for walls as well.

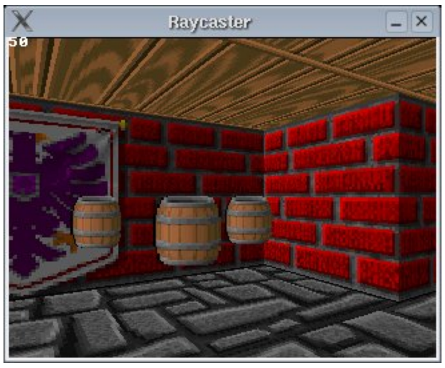
In for example Wolfenstein 3D, some objects (for example the soldiers) have 8 different pictures when viewing it from different angles, to make it appear as if the sprite is really 3D. You can get the angle of the object to the player for example with the atan2 function, and then choose 1 of 8 textures depending on the angle. You can also give the sprites even more textures for animation.

Scaling Sprites

It's pretty easy to let the program draw the sprites larger or smaller, and move the sprites up or down. To shrink the sprite, divide spriteWidth and spriteHeight through something. If you halve the height of the sprites, for example the pillar, then the bottom will move up so that the pillar appears to be floating. That's why in the code below, apart from the parameters uDiv and vDiv to shrink the sprite, also a parameter vMove is added to move the sprite down if it has to stand on the floor, or up if it has to hang on the ceiling. vMoveScreen is vMove projected on the screen by dividing it through the depth.

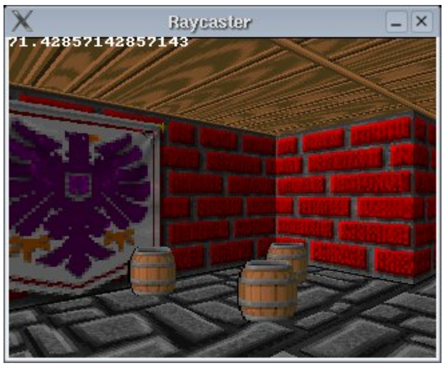
```
      //parameters for scaling and moving the sprites
      #define uDiv 1
      #define vDiv 1
      #define vMove 0.0
      int vMoveScreen = int(vMove / transformY);

      //calculate height of the sprite on screen
      int spriteHeight = abs(int(h / (transformY))) / vDiv; //using 'transformY' instead of the real distance prevents fisheye
      //calculate lowest and highest pixel to fill in current stripe
      int drawStartY = -spriteHeight / 2 + h / 2 + vMoveScreen;
      if(drawStartY < 0) drawStartY = 0;
      int drawEndY = spriteHeight / 2 + h / 2 + vMoveScreen;
      if(drawEndY >= h) drawEndY = h - 1;

      //calculate width of the sprite
      int spriteWidth = abs( int (h / (transformY))) / uDiv;
      int drawStartX = -spriteWidth / 2 + spriteScreenX;
      if(drawStartX < 0) drawStartX = 0;
      int drawEndX = spriteWidth / 2 + spriteScreenX;
      if(drawEndX >= w) drawEndX = w - 1;


      //loop through every vertical stripe of the sprite on screen
      for(int stripe = drawStartX; stripe < drawEndX; stripe++)
      {
        int texX = int(256 * (stripe - (-spriteWidth / 2 + spriteScreenX)) * texWidth / spriteWidth) / 256;
        //the conditions in the if are:
        //1) it's in front of camera plane so you don't see things behind you
        //2) it's on the screen (left)
        //3) it's on the screen (right)
        //4) ZBuffer, with perpendicular distance
        if(transformY > 0 && stripe > 0 && stripe < w && transformY < ZBuffer[stripe])
        for(int y = drawStartY; y < drawEndY; y++) //for every pixel of the current stripe
        {
          int d = (y-vMoveScreen) * 256 - h * 128 + spriteHeight * 128;  //256 and 128 factors to avoid floats
          int texY = ((d * texHeight) / spriteHeight) / 256;
          Uint32 color = texture[sprite[spriteOrder[i]].texture][texWidth * texY + texX]; //get current color from the texture
          if((color & 0x00FFFFFF) != 0) buffer[y][stripe] = color; //paint pixel if it isn't black, black is the invisible color
        }
      }
    }
```

When uDiv = 2, vDiv = 2, vMove = 0.0, the sprites are half as big, and float:



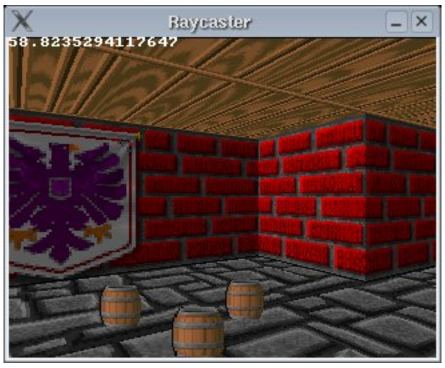
50

Put it back on the ground by setting vMove to 64.0 (the size of the texture):



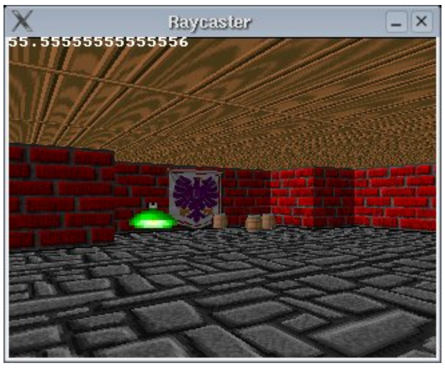
71.42857142857143

If you make vMove even higher to place the sprites under the ground, they'll still be drawn through the ground, because the ZBuffer is 1D and can only detect if the sprite is in front or behind a wall.



```
58.8235294117647
```

Of course, by lowering the barrels, the green light is lower too so it doesn't hang on the ceiling anymore. To make this useful, you have to give each sprite its own uDiv, vDiv and vMove parameters, for example you can put them in the sprite struct.



```
55.5555555555556
```

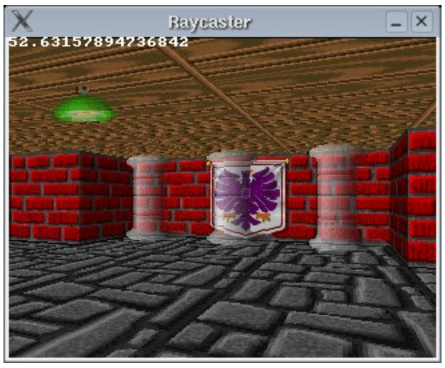
Translucent Sprites

Because we're working in RGB color, making sprites translucent is very simple. All you have to do is take the average of the old color in the buffer and the new color of the sprite. Old games like for example Wolfenstein 3D used a palette of 256 colors with no logical mathematical rules for the colors in the palette, so there translucency wasn't so easy. Change the following line of code

```
if((color & 0x00FFFFFF) != 0) buffer[y][stripe] = color; //paint pixel if it isn't black, black is the invisible color
```

into

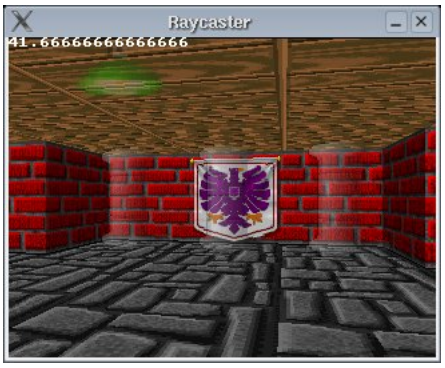
```
if((color & 0x00FFFFFF) != 0) buffer[y][stripe] = RGBtoINT(INTtoRGB(buffer[y][stripe]) / 2 + INTtoRGB(color) / 2); //paint pixel if it isn't black, black is the i
```



```
52.63157894736842
```

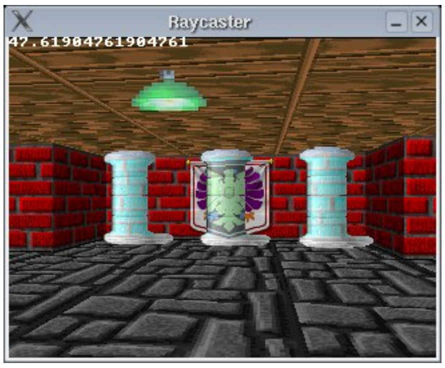
To make them more translucent, try something like

```
if((color & 0x00FFFFFF) != 0) buffer[y][stripe] = RGBtoINT(3 * INTtoRGB(buffer[y][stripe]) / 4 + INTtoRGB(color) / 4); //paint pixel if it isn't black, black is t
```



You can also try more special tricks, for example translucent sprites, that make the walls behind them of negative color:

```
if((color & 0x00FFFFFF) != 0) buffer[y][stripe] = RGBtoINT((RGB_White - INTtoRGB(buffer[y][stripe])) / 2 + INTtoRGB(color) / 2); //paint pixel if it isn't black,
```



To be useful for a game, it would be more handy to give each sprite its own translucency effect (if any), with an extra parameter in the sprite struct. For example the green light could be translucent, but a pillar certainly not.

Last edited: 2020