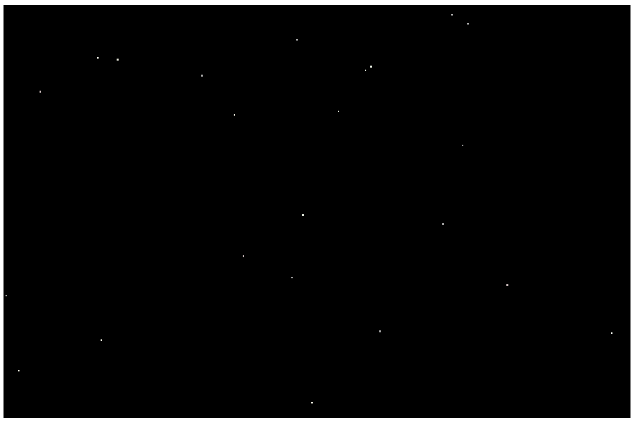
1. SettingPixels

get_linear_index(x,y) computes memory index by multiplying y index with the width and additioning the x index, which is implementing the row-major lay out. The color of each index, which is basically a pixel, is denoted by RBGx format. The RGBx format is represented in the row-major form by listing red, green, blue, and alpha values in order for each index.
In set_pixel_srgb(), the assert() function checks whether the pixel to be drawn is within the boundary of the surface. The origin of the surface coordinate is fixed to the bottom-left.
Implementation

```
void Surface::set_pixel_srgb( Index aX, Index aY, ColorU8_sRGB const& aColor
)
{
 assert( aX < mWidth && aY < mHeight ); // IMPORTANT! This line must remain
the first line in this function!
 Index idx = get_linear_index( aX, aY ) * 4;

 mSurface[idx + 0] = aColor.r;
 mSurface[idx + 1] = aColor.g;
 mSurface[idx + 2] = aColor.b;
 mSurface[idx + 3] = 0;
}
```

The output of running ./bin/main-debug-x64-gcc.exe

magnified view



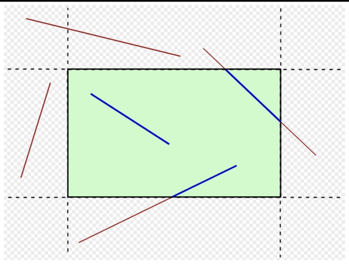
2. ClippingLines

clip_line() implements the Cohen–Sutherland algorithm. It encodes the 2D vector, that's given for drawing a line, based on its location relative to the clipping rectangle. It's encoded to 9 cases which are a representation of 9 spaces that are derived from extending the lines of the rectangle. The numbers that describes each cases are written in draw.hpp

```
const int INSIDE = 0b0000;
const int LEFT   = 0b0001;
const int RIGHT  = 0b0010;
const int BOTTOM = 0b0100;
const int TOP    = 0b1000
```

lamda function outcode_of() is defined inside clip_line() in order to have access to the local variables. outcode_of() encodes the 2D vector based on its location. Having obtained the encoded value of 2 of the 2D vectors for drawing the line, the intersection of the line and the clipping rectangle is derived by iterating the process of finding the intersection of both 2D vectors. They stop once both vectors and inside or on the rectangle, otherwise it will repeat calculating the intersection that is outside of the rectangle. It may take 2 iterations for a single vector since, for instance, it may need adjustment from finding the intersection with extended top line of the rectangle and then followed by finding the intersection of the right line of the rectangle.

	left	central	bottom
top	1001	1000	1010
central	0001	0000	0010
bottom	0101	0100	0110



The line is accepted when the OR operation value becomes 0. Since it means both are inside or on the clipping rectangle.

```
if ((code0 | code1) == 0) { // both inside
   return true;
```

The is rejected when the AND operation value isn't 0. Since if both endpoints lie outside the rectangle on the same side, then the line segment cannot cross the rectangle.

```
if (code0 & code1) { // doesn't intersect
   return false;
  }
```

Intersection is calculated for each case. For instance, when the vector is at the top of the rectangle, the intersection of the line will be calculated with the top extended line of the rectangle as shown in the picture below.

```
if (codeOut & TOP) {
   y = ymax;
   x = aBegin.x + (aEnd.x - aBegin.x) * (y - aBegin.y) / (aEnd.y - aBegin.y);
  }
```

3. DrawingLines

draw_clip_line_solid() makes sure the line is the thinnest by choosing the main axis and ensuring at most one pixel for each component of the opposite axis.

```
if (!clip_line(aSurface.clip_area(), aBegin, aEnd))
  return;
```

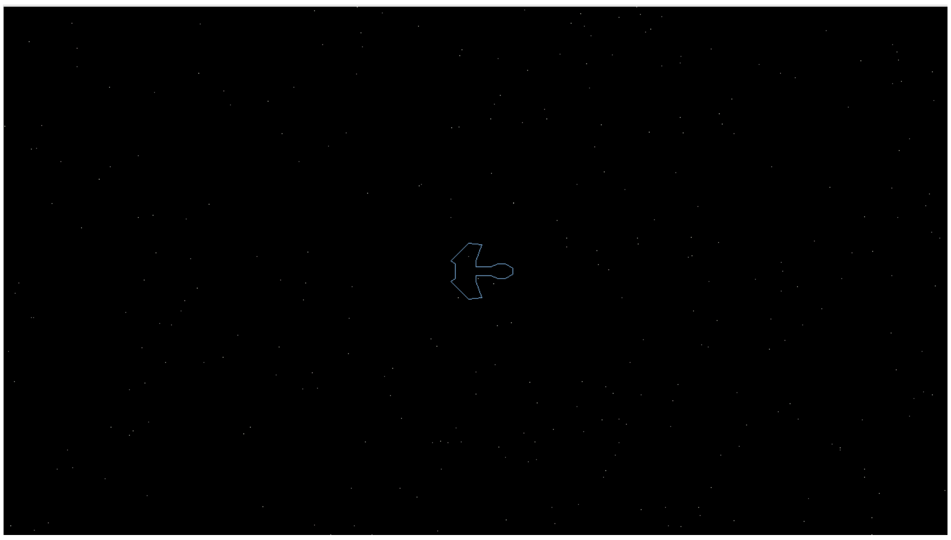
The function terminates if the line about to be drawn isn't within the clipping area. Meanwhile, the lambda function in_bounds() checks whether the coordinate is within the bound of the surface. This is to eliminate drawing the pixel that is out of bound which will trigger the assert() function to terminate the program in set_pixel_srgb(). The function will eliminate the degenerate case where the 2 vectors given are the same. Now the absolute value of dx and dy, which is defined as the picture below, will determine what will be the main axis.

```
 const float dx = aEnd.x - aBegin.x;
 const float dy = aEnd.y - aBegin.y;
```

If the absolute value of dx is bigger than dy, then the slope would be dy / dx, the starting point would be the vector with a smaller x value, and the number of steps to drawing the line, which is discrete, would be an absolute value of dx that is casted by an integer. Each integer x value is added on discretely by 1, whereas float y value would be added up by the float slope value which is then casted by an integer. For every pixel being drawn, the in_bounds() checks if it's within the surface bound.

```
if (fabs(dx) > fabs(dy)) {
  int x = (int)lround(startPoint.x);
  // float y = startPoint.y + (float(x) - startPoint.x) * slope;
  float y = startPoint.y;
  for (int i = 0; i < numberOfSteps; ++i) {
   if (in_bounds(x, (int)lround(y)))
    aSurface.set_pixel_srgb((Surface::Index)(int)x,
(Surface::Index)(int)lround(y), aColor);
   x += 1;
   y += slope;
  }
```

The spaceship drawn through this implementation



4. 2DRotation

* Operator definition for struct Mat22f and Vec2f is directly adopted from matrix multiplication.
* operator for Mat22f and Vec2f

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} ax + by \\ cx + dy \end{bmatrix}$$

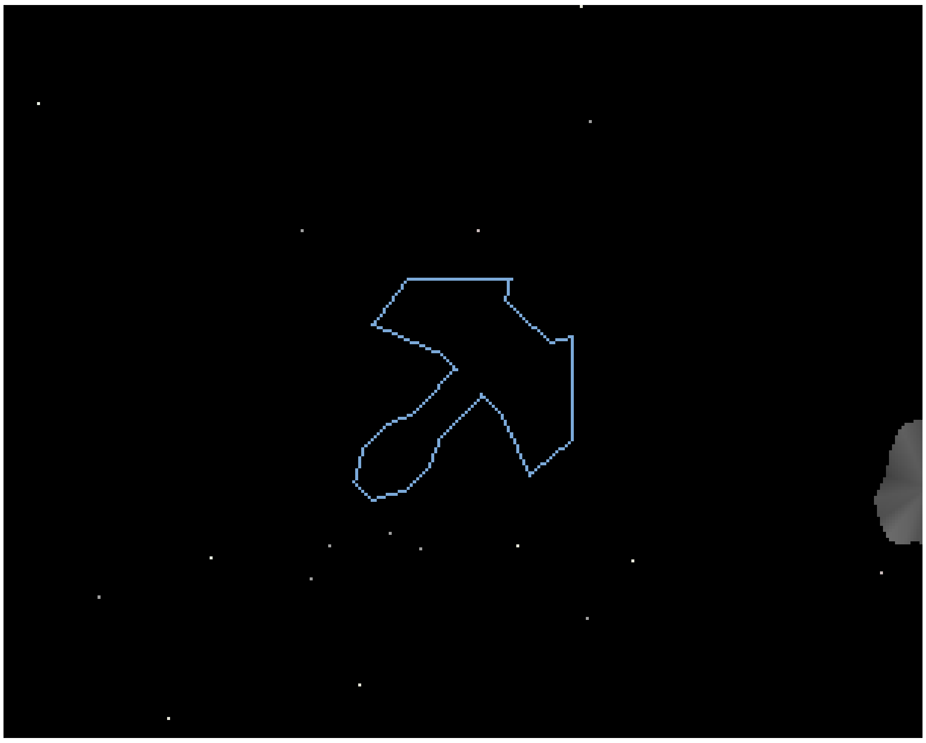
* operator for Mat22f and Mat22f

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} e & f \\ g & h \end{bmatrix} = \begin{bmatrix} ae + bg & af + bh \\ ce + dg & cf + dh \end{bmatrix}$$

For make_rotation_2d()

$$\begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} x\cos\theta - y\sin\theta \\ x\sin\theta + y\cos\theta \end{bmatrix}$$

Rotated ship



5. Drawingtriangles

In order to implement draw_triangle_interp() we define 6 functions. cross_product() defines the cross product calculation for determining whether the triangle is degenerate or not.

```
float area = cross_product(aP1 - aP0, aP2 - aP0);
 if (area == 0.0f) {
  return; // degenerate triangle
 }
```

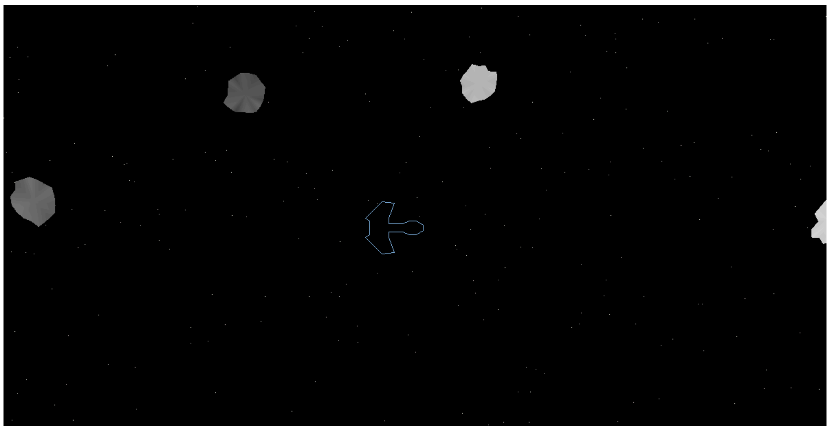
Meanwhile, we also define 2 structs that are defined in the headerfile.

```
struct bound_box_for_triangle {
 float xmin;
 float xmax;
 float ymin;
 float ymax;
};

barycentric_coords barycentric_from_cartesian(
 Vec2f const& aP,
 Vec2f const& aA,
 Vec2f const& aB,
 Vec2f const& aC
);
```

bounding_box_for_triangle() returns the bound_box_for_triangle value derived from the given triangle. clamping_box() edits the bound_box_for_triangle value based on the bounds of the surface. Now with the given bounding box area, we iterate each pixels in the bounding area by converting the cartesian value to barycentric and using the barycentric value to check if the pixel inside the triangle with inside_triangle(). If the pixel is within the triangle, we draw it using interpolation().

```
for (int x = box.xmin; x <= box.xmax; ++x) {
  for (int y = box.ymin; y <= box.ymax; ++y) {
   Vec2f p = Vec2f{ static_cast<float>(x) + 0.5f, static_cast<float>(y) + 0.5f }; // center
of the pixel
   barycentric_coords bary = barycentric_from_cartesian(p, aP0, aP1, aP2);
   if (inside_triangle(bary)) {
    ColorU8_sRGB color = interpolation(bary, aC0, aC1, aC2);
    aSurface.set_pixel_srgb((Surface::Index)x, (Surface::Index)y, color);
   }
  }
 }
```

The picture below is the execution with the implementation above.



6. Blittingimages

blit_masked() initially derives the starting point of the blitting based on 1. the size of the image and 2. the position of the image, which is expressed by the center of the image. Hence the initial starting point for blitting can be denoted as

```
 const int startX = static_cast<int>(std::floor(aPosition.x - imgWidth /
2.0f));
 const int startY = static_cast<int>(std::floor(aPosition.y - imgHeight /
2.0f));
```

Based on the starting point, you iterate drawing each pixel 1. checking if the pixel is within the surface bound, and if the alpha value is smaller than 128 which decides whether to draw that pixel or not. This method can be improved by calculating the intersection between 2 rectangles, and only iterating within that boundary.

```
const int x0 = min(0, startX);
 const int y0 = min(0, startY);
 const int x1 = max(surfWidth, startX + imgWidth);
 const int y1 = max(surfHeight, startY + imgHeight);
 if (x0 >= x1 || y0 >= y1) {
  return; // nothing to blit
 }
const int image_x0 = x0 - startX;
const int image_y0 = y0 - startY;
```

x0, x1, y1, y2 denotes the intersection of the rectangle that should be drawn to the surface. image_x0 and image_y0 represent the coordinate of the image. This process enables unnecessary iteration of pixels of the image that aren't going to be drawn to the surface by clipping the image prior to drawing it.

```
for (int y = y0, image_y = image_y0; y < y1; ++y, ++image_y) {

  for (int x = x0, image_x = image_x0; x < x1; ++x, ++image_x) {

   ColorU8_sRGB_Alpha color_of_pixel =
aImage.get_pixel((ImageRGBA::Index)image_x, (ImageRGBA::Index)image_y);
   if (color_of_pixel.a >= 128) {
    aSurface.set_pixel_srgb((Surface::Index)pixel_x, (Surface::Index)pixel_y,
     ColorU8_sRGB{ color_of_pixel.r, color_of_pixel.g, color_of_pixel.b });
   }
  }
 }
```

7. Testing: lines

Tests are implemented using the <catch2/catch_amalgamated.hpp> library which involves macros such as TEST_CASE(), SECTION(), and REQUIRE(). Each scenario is divided by TEST_CASE() and for each scenario are 4 cases described by SECTION() which includes multiple assertions enabled by REQUIRE().

For scenario 1, the test splits in 4 cases of horizontal, vertical, 45 degree diagonal (where dx = dy) and when it's completely horizontal. It uses max_pixel__neighbour_check() function that asserts each case with the use of the helper function max_col_pixel_count() and max_row_pixel_count(). Distinctive from the original definition, horizontal label in the test means when the absolute value of dx is bigger than dy. In such case, every column should have 1 pixel and the maximum pixel of the row should be bigger than 1, which is denoted as

```
REQUIRE(max_col_pixel_count(surf) == 1);
        REQUIRE(max_row_pixel_count(surf) > 1);
```

The same logic applies to vertical and 45 degree diagonal.

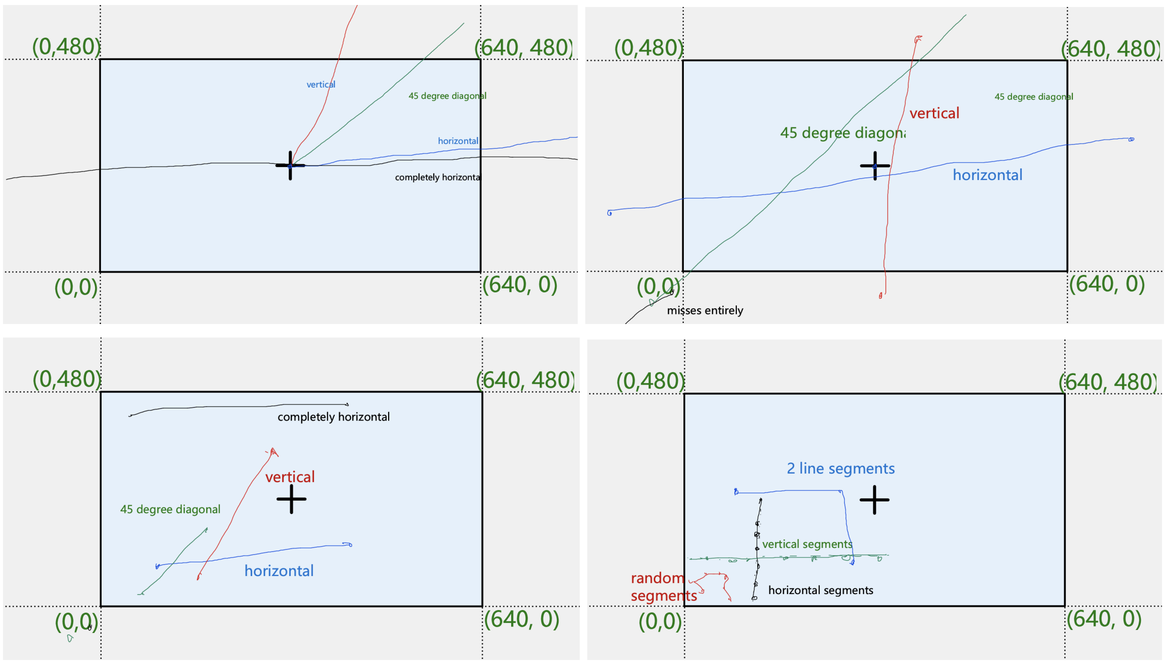
Meanwhile, neighbourCounts() uses count_pixel_neighbours() to assert if there are any pixels that are isolated or that are above 2 neighbours. reset() is used for every section to reuse the surface declared within each test.

Scenario 2 uses the identical cases except for the last section which is testing the line segment that is entirely out of bound.

Scenario 3 draws the same line segment on 2 different surfaces but in different direction and compares the surface value using same_buffer().

Scenario 4 involves more than 2 vectors to draw multiple line segments. The vectors are stored as std::vector<Vec2f> points and are stored using push_back() methods and cleared using .clear() end of each section. The first case is using 3 vectors and then the second is using 8 vectors to draw a poly line. Both third and fourth cases use iteration to store vectors that are horizontal and vertical, respectively. Each case checks if the drawn poly line has any gaps using neighbourCounts().

The picture below demonstrates the 4 cases for each 4 test scenarios.



Scenario 2 and 4 has few failed cases and hence has been added the [!mayfail] tag.

8. Testing: triangles

Two test cases for draw_triangle_interp() are implemented in scenarios.cpp. It uses similar help functions such as reset() that resets the surface and same_butter() that compares two buffers. The color for the drawing is defined as the picture shown below for all cases.

```
#define COLOR {1.f, 0.f, 0.f}
```

The first case compares the drawing of a triangle that is drawn clock wise and counter clock wise with the same set of vectors.

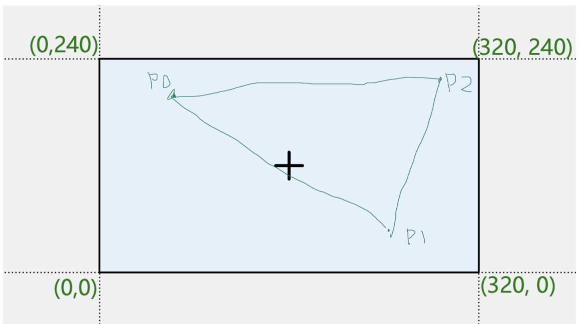
```
    //cw
    draw_triangle_interp( A, P0, p1, p2, COLOR, COLOR, COLOR );
    //ccw
    draw_triangle_interp( B, P0, p2, p1, COLOR, COLOR, COLOR );
```

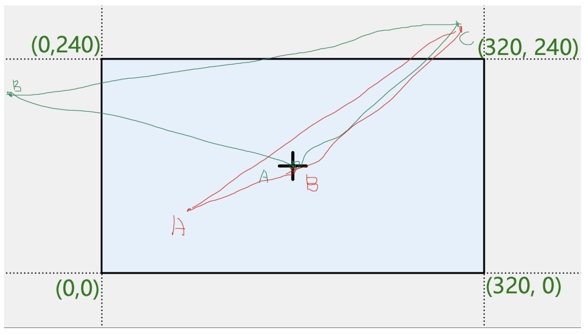
same_buffer() is used to compare surface A and B. It terminates the program once the contents of two buffers are different.

The second test case sets a vector that is inside the surface and outside the surface. There are two sections for the case where one of them is inside and the other two are outside and the case where one of them is outside and the other one is inside. Both cases draw a triangle and use find_most_red_pixel() which returns ColorU8_sRGB value with the biggest red value and find_least_red_nonzero_pixel() which returns ColorU8_sRGB value with the smallest red value. The test asserts whether the pixel with minimum red value and maximum red value has the same ColorU8_sRGB value, otherwise it will terminate the test.

```
REQUIRE(max.r == 255); REQUIRE(max.g == 0); REQUIRE(max.b == 0);
REQUIRE(min.r == 255); REQUIRE(min.g == 0); REQUIRE(min.b == 0);
```

[!mayfail] tags were added for both cases since both cases presented few failed results.
The picture below demonstrates 2 cases of the test.



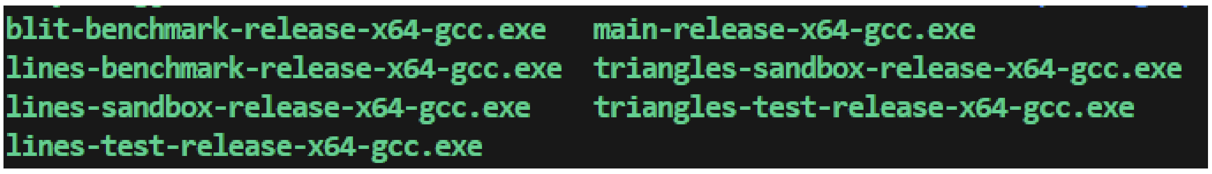


9. Benchmarking-Specs

The chart below demonstrates the relevant information for the system on which the benchmarks run.

CPU model name	11th Gen Intel(R) Core(TM) i5-1135G7 @ 2.40GHz
L1 data cache amount (core)	128 KiB
L2 cache amount (core)	192 KiB
System RAMamount	8247234560 bytes = 8Gib
System RAMtype &speed	3200 MT/s (SMBIOSMemoryType 26)
Operating system	Microsoft Windows 11 Home 10.0.26100
Compiler	GCC 14.2.0

All the benchmark applications are ran on release mode. It is done by make clean command (eliminate executable made by debug mode) and followed by make config=release_x64 -j6.
The bin directory will have the following files.

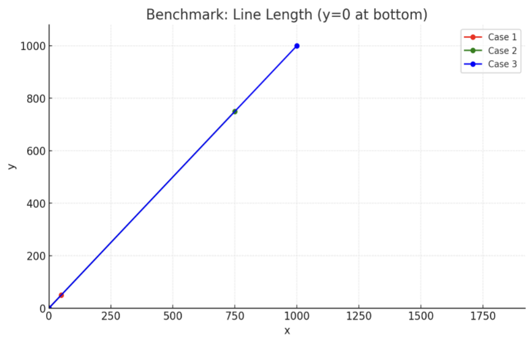


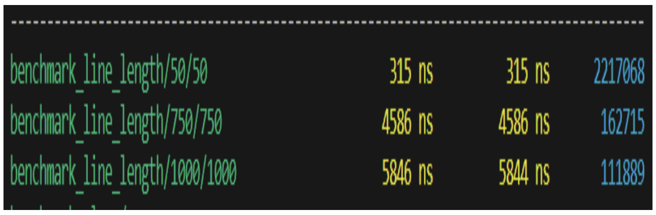
```
blit-benchmark-release-x64-gcc.exe   main-release-x64-gcc.exe
lines-benchmark-release-x64-gcc.exe  triangles-sandbox-release-x64-gcc.exe
lines-sandbox-release-x64-gcc.exe    triangles-test-release-x64-gcc.exe
lines-test-release-x64-gcc.exe
```

10. Benchmark:Lines

There are 3 variables that affect line drawing performance. Drawing performance refers to execution time, computational cost/scalability which is related to time complexity, and memory efficiency. The performance is primarily influenced by the number of loop iterations, memory access pattern, floating-point operations, and its efficiency in clipping.

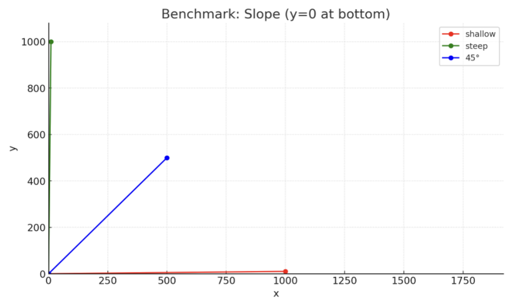
The first variable is the length of the line.The longer the line, the more loop iterations it goes through. This results in longer execution time in drawing the given line. The length of the line is varied in the test. All 3 lines have the same slope.

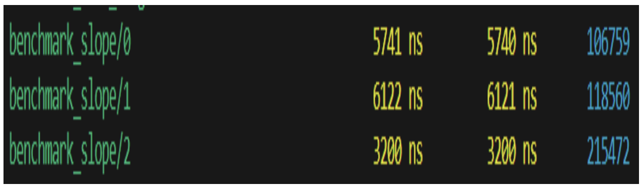




```
------------------------------------------------------------------------
benchmark_line_length/50/50          315 ns        315 ns      2217068
benchmark_line_length/750/750       4586 ns       4586 ns       162715
benchmark_line_length/1000/1000     5846 ns       5844 ns       111889
```

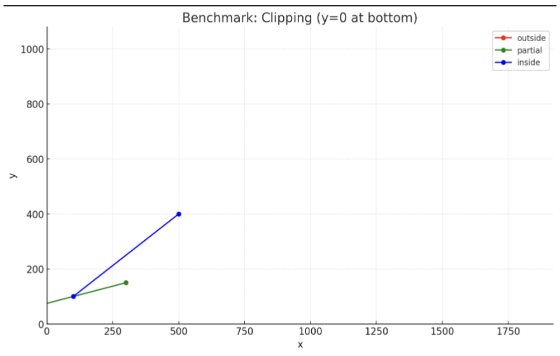
The second variable is the slope of the line. Considering surface implements a row-major buffer, it is reasonable to assume that it's more cache friendly for the memory when x changes by +1 each. Hence we can expect horizontally inclined lines (slope 0) to be rendered the fastest and the vertically inclined lines the slowest (slope 2).

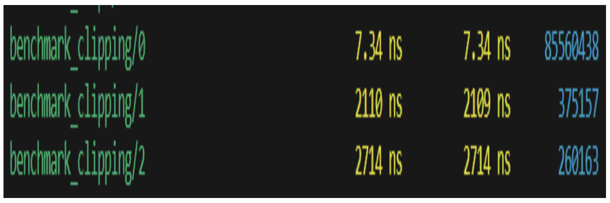




```
benchmark_slope/0        5741 ns       5740 ns       106759
benchmark_slope/1        6122 ns       6121 ns       118560
benchmark_slope/2        3200 ns       3200 ns       215472
```

The third variable is the clipping extent which refers to how much it is outside of the surface. clip_line() function repositions the two end points based on the given clipping rectangles. This may significantly reduce the lines that should be rendered contributing to the optimization of drawing the line. There are 3 cases, which are fully inside, partially inside, and fully clipped.





```
benchmark_clipping/0        7.34 ns       7.34 ns     85560438
benchmark_clipping/1        2110 ns       2109 ns       375157
benchmark_clipping/2        2714 ns       2714 ns       260163
```

11. Benchmark:Blitting

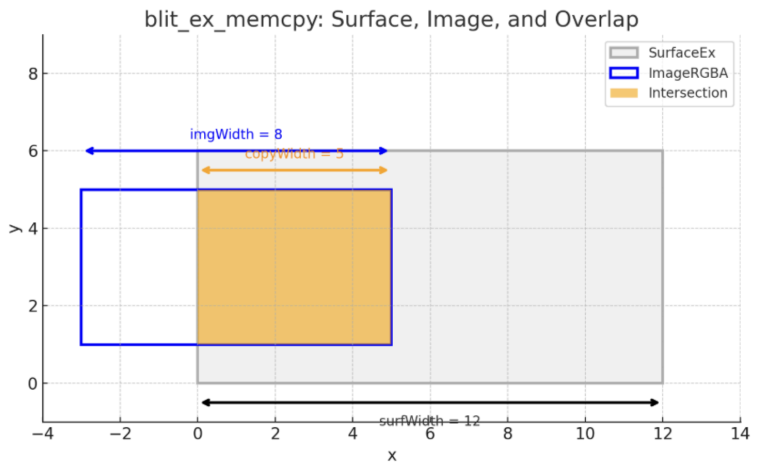
For blit_ex_solid() it's essentially an identical implementation to blit_masked() function in image.cpp without filtering out the pixels using the if (color_of_pixel.a >= 128) statement.
blit_ex_memcpy() uses the same method of deriving the intersected area of the rectangle between the surface and the image as blit_masked(), and then consecutively copies each corresponding row of the image to that intersected area.

```
const int surfRowBytes = surfWidth * 4;
 const int imgRowBytes = imgWidth * 4;
 // the width of the intersection of 2 rectangles in bytes
 const int copyBytes = (x1 - x0) * 4;
```

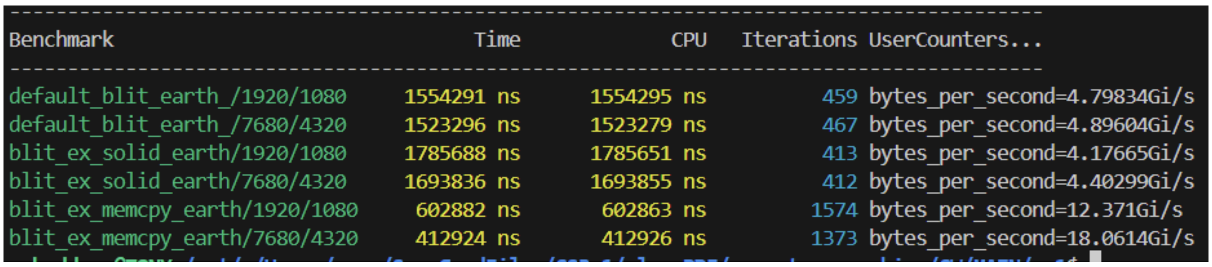
surfRowBytes, imgRowBytes, and copyBytes are used to skip through rows of the surface, the image, and the intersected area, respectively.

```
 for(; y0 < y1; ++y0, ++y0, ++image_y0) {

  imgRowPtr = imgBase + (image_y0 * imgRowBytes) + (image_x0 * 4);
  surfRowPtr = surfBase + (y0 * surfRowBytes) + (x0 * 4);

  std::memcpy( surfRowPtr, imgRowPtr, copyBytes );
 }
```

The code above demonstrates locating the location of the pixel on the surface and image based on the given coordinate of the intersected area.



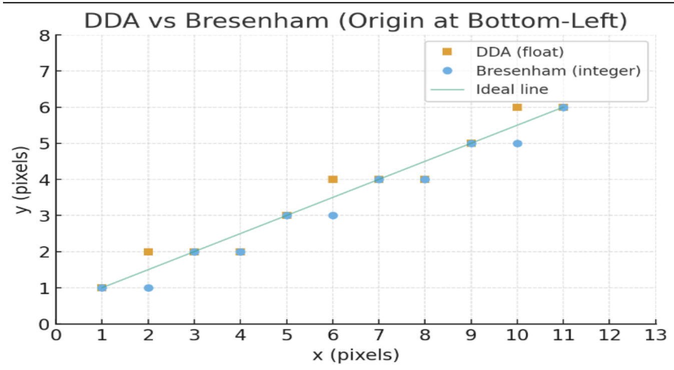
The picture above illustrates surfRowBytes, imgRowBytes, and copyBytes.
The picture below is the output of blit-benchmark. It shows significant improvement using blit_ex_memcpy() reducing time from 1554291 ns to 602882 ns for 1920 by 1080 surface. However, with blit_ex_solid which didn't use alpha masking, presented a slower rending time of 1785688 ns.



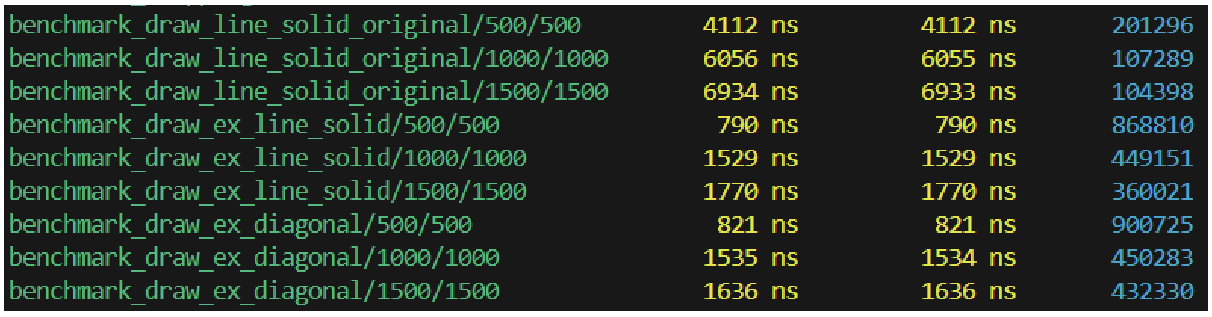
```
------------------------------------------------------------------------------------------
Benchmark                               Time            CPU   Iterations UserCounters...
------------------------------------------------------------------------------------------
default_blit_earth_/1920/1080     1554291 ns      1554295 ns          459 bytes_per_second=4.79834Gi/s
default_blit_earth_/7680/4320     1523296 ns      1523279 ns          467 bytes_per_second=4.89604Gi/s
blit_ex_solid_earth/1920/1080     1785688 ns      1785651 ns          413 bytes_per_second=4.17665Gi/s
blit_ex_solid_earth/7680/4320     1693836 ns      1693855 ns          412 bytes_per_second=4.40299Gi/s
blit_ex_memcpy_earth/1920/1080     602882 ns       602863 ns         1574 bytes_per_second=12.371Gi/s
blit_ex_memcpy_earth/7680/4320     412924 ns       412926 ns         1373 bytes_per_second=18.0614Gi/s
```

12. Benchmark:LinesII

draw_clip_line_solid() uses DDA which calculates pixel positions by taking steps based on the slope and rounding the results. It is slower due to floating-point operations and less accurate due to rounding. Whereas draw_ex_line_solid() uses a decision parameter that decides whether to move to the next pixel along the x-axis or the y-axis, avoiding the need for floating-point math. The logic used in draw_ex_line_solid() is called Bresenham's algorithm.



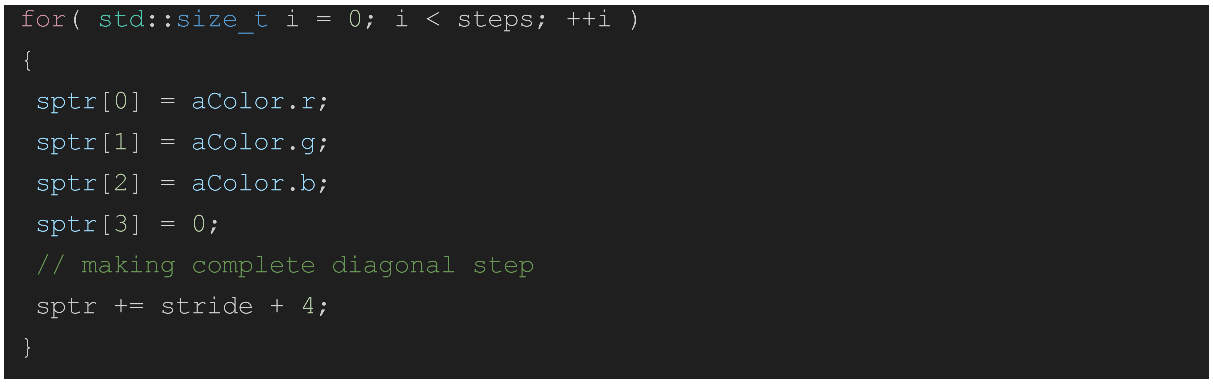
3 new benchmark functions were implemented to lines-benchmark/main.cpp and were tested with the same 3 arguments for each.



```
benchmark_draw_line_solid_original/500/500        4112 ns        4112 ns       201296
benchmark_draw_line_solid_original/1000/1000      6056 ns        6055 ns       107289
benchmark_draw_line_solid_original/1500/1500      6934 ns        6933 ns       104398
benchmark_draw_ex_line_solid/500/500               790 ns         790 ns       868810
benchmark_draw_ex_line_solid/1000/1000            1529 ns        1529 ns       449151
benchmark_draw_ex_line_solid/1500/1500            1770 ns        1770 ns       360021
benchmark_draw_ex_diagonal/500/500                 821 ns         821 ns       900725
benchmark_draw_ex_diagonal/1000/1000              1535 ns        1534 ns       450283
benchmark_draw_ex_diagonal/1500/1500              1636 ns        1636 ns       432330
```

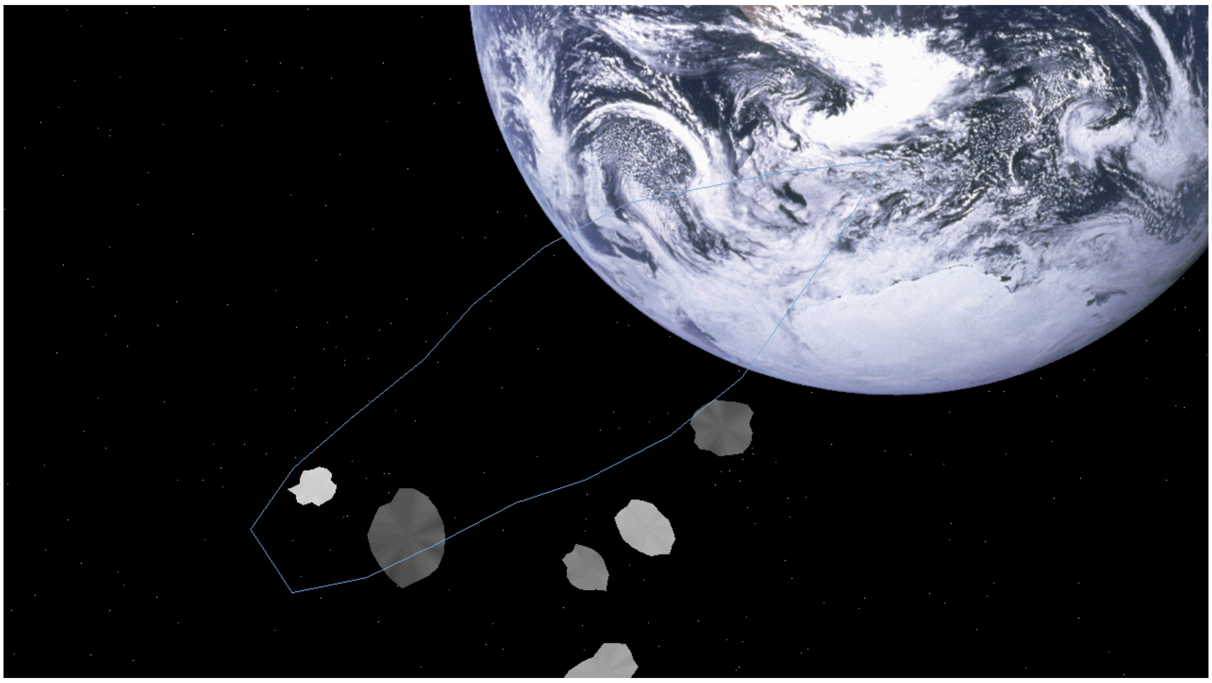
draw_ex_diagonal() was used as a threshold to compare its performance between draw_line_solid() and draw_ex_line_solid(). draw_ex_line_solid() which used Bresenham's algorithm simply excelled in performance compared to draw_line_solid() that used DDA.

Despite its effectiveness of the implementation of draw_ex_line_solid(), there are bottlenecks that can be discussed. We can inspect from the code that set_pixel_srgb() is being called each time it draws pixel. Inline function set_pixel_srgb() involves assert and index computation for each pixel which can be improved by directly accessing the memory using memcpy() as how it's used in blit_ex_memcpy(). Alternative we can simply locate the base pointer of the surface and assign each value manually as how it's done in draw_ex_diagonal().



```
for( std::size_t i = 0; i < steps; ++i )
{
 sptr[0] = aColor.r;
 sptr[1] = aColor.g;
 sptr[2] = aColor.b;
 sptr[3] = 0;
 // making complete diagonal step
 sptr += stride + 4;
}
```

13. Yourownspaceship



The spaceship is consisted of 20 points and its size is magnified by variable s. The size of the ship can be configured by changing this variable.

```
static constexpr float s = 5.0f;
```

The spaceship resembles the shape of a sphere reflecting its desire to penetrate through the earth.